# Calibration of the petro-elastic model (PEM) for 4D seismic studies in multi-mineral rocks

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# Calibration of the Petro-elastic Model (PEM) for 4D Seismic Studies in Multimineral Rocks

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## SUMMARY

We propose a method to calibrate the petro-elastic model in a multi-well fashion, applicable to multimineral,multi-fluid rocks. We use a model that combines Gassmann's equations (1951) with the modified MacBeth (2004) rock stress sensitivity model (Alvarez & MacBeth, 2013) through a linear search optimisation algorithm, which allows modelling of the variations of the dry-frame elastic moduli with changes in porosity and mineralogy. The importance of the rock framework characterisation on PEM predictions is highlighted, and it is concluded that an over-simplification of the dry-frame characterisation in 4D seismic-related studies can lead to errors of the same magnitude as the 4D seismic signal and therefore these effects cannot be ignored.

## Introduction

Petro-elastic modelling (PEM) is the cornerstone of 4D seismic forward modelling. The results of 4D seismic feasibility studies, simulator to seismic modelling, quantitative 4D interpretation and seismic history matching fully depend on the correct calibration of the rock and fluid physics parameters. PEM has been extensively investigated in the literature and different fluid-substitution and stress-sensitivity models exist, which capture the effects of pore pressure and saturation changes on the elastic responses. However, comprehensive models applicable to heterogeneous sand/shale systems are limited. Furthermore, the calibration of these models to the specific field of study remains a challenge, particularly with respect to the characterisation of the dry-frame rock properties, which define the balance between the effects of pressure and saturation signals. In this work, we propose an optimisation algorithm that allows the calibration of the PEM and is applicable to multi-mineral and multi-fluid rocks. For this optimisation, we use a rock stress-sensitivity parameterisation based on the bulk modulus and shear modulus rather than velocities, which allows us to incorporate the rock stress sensitivity explicitly inside Gassmann's equations (1951).

## Dry-frame characterisation

In seismic petrophysical analysis, 'fluid substitution' refers to the prediction of changes in the seismic velocities due to changes in the fluid content of the saturated rock. Commonly, using DT, DTS and RHOB logs, Gassmann's theory is applied to calculate the dry-frame elastic moduli and the extracted moduli are used to model different saturation scenarios (e.g. Simm, 2007). Although this approach fits well for this purpose, PEM for 4D seismic modelling is beyond just a fluid substitution, as the dry-frame elastic moduli are also required to be modelled, to account for the effects of pore pressure variations. One of the most common practical forms of Gassmann's equations (Mavko, et al., 1998) is expressed as follows:

$$\kappa_{sat} = \kappa_{dry} + \frac{\left(1-\kappa_{dry}/\kappa_m\right)^2}{\varphi/\kappa_{fl} + (1-\varphi)/\kappa_m + \kappa_{dry}/\kappa_m{}^2} \quad , \qquad \mu_{sat} = \mu_{dry} \tag{1), (2}$$

where $\kappa_{sat}$ and $\mu_{sat}$ are the bulk modulus and shear modulus of the saturated rock, $\varphi$ is the porosity, $\kappa_m$ is the mineral bulk modulus, $\kappa_{dry}$ and $\mu_{dry}$ are the dry-frame bulk and shear modulus, and $\kappa_{fl}$ is the fluid bulk modulus. It should be noted that the Gassmann's model assumes one solid and one fluid component; therefore, effective medium theories are commonly used to calculate the effective elastic moduli of the solid as well as the effective bulk modulus of the fluid components. However, this approach fails to capture the variability in velocities associated with the dependence of the dry-frame on porosity and clay content.

Studies to characterise the dry-frame stress-sensitivity are mainly based on laboratory data using core samples and can be classified into two strains. The first group discusses the static dependence of dry-frame moduli on intergranular porosity (Krief et al., 1990; Nur et al., 1995; Pride, 2005), and the second group studies the dynamic dependence of the dry-frame moduli on the effective stress (Shapiro & Troyan, 2002; MacBeth, 2004). In his paper, MacBeth (2004) measured the dependence of the dry-frame moduli on both porosity and effective stress; however the porosity dependence is not explicitly incorporated in his equations. In fact, studies that introduce a theory combining both effects are limited (Dvorkin & Gutierrez, 2002; Lee, 2005; Avseth & Skjei, 2011). MacBeth's (2004) equations were extended (Alvarez & MacBeth, 2013) to incorporate explicitly the dependence on porosity and effective stress variations into the dry-frame bulk and shear modulus. These equations are expressed as follows:

$$\kappa_{dry}(\sigma_{eff},\varphi) = \frac{\kappa_m(1-\varepsilon\varphi)}{1-E_\kappa e^{-\sigma_{eff}/P_\kappa}} \quad , \quad \mu_{dry}(\sigma_{eff},\varphi) = \frac{\mu_m(1-\varepsilon\varphi)}{1-E_\mu e^{-\sigma_{eff}/P_\mu}} \tag{3), (4}$$

where $E_\kappa$, $P_\kappa$, $E_\mu$, $P_\mu$ are the rock-stress constants from core measurements that define the shape of the stress-sensitivity curves, $\kappa_m$ and $\mu_m$ are the effective mineral bulk and shear modulus, $\sigma_{eff}$ is the effective stress and ε is a lithology dependent parameter. This model is incorporated into our calculations and a multi-linear regression (MLR) algorithm is used to construct $\varepsilon$ at different depths as a function of clay content and porosity.

**Petro-elastic model optimisation algorithm**

The use of the effective medium theories in Gassmann's fluid substitution is still an under-constrained problem; one of the challenges is to set the input parameters ($\kappa_m, \mu_m$, $\kappa_{dry}$, and $\mu_{dry}$). These parameters are reservoir dependent and the documented values in lookup tables may lead to erroneous results; in particular, the elastic properties of clay minerals are widely variable (Mavko et al., 1998). Similar to the clay properties but to a more limited extent, a range of values for elastic properties in the sand component should also be considered. Smith (2011) attributed this variability to the presence of minerals other than quartz, and to microstructural defects. Simm (2007) used the normalised bulk modulus versus porosity plot to QC the initial estimate of the moduli of clay components. However, this approach is based on trial and error and the criteria for selection of the appropriate parameters remain ambiguous.

In this study, we attempt to overcome those limitations by designing an optimisation algorithm using the theoretical models mentioned above. The inputs to the algorithm are the volume fraction of the rock components, in-situ acoustic properties of the fluids, and a reasonable range for the density and elastic moduli of the solid components. At each depth, a constrained linear search is performed in the parameter space through all possible combinations of the input parameters of the PEM, and the modelled velocities and density logs are compared with measured P-wave velocity, S-wave velocity and density logs. Finally, the set of input parameters ($\kappa_{sand}, \kappa_{shale}, \mu_{sand}, \mu_{shale}$, and $\varepsilon$) associated with the lowest misfit error are used for the implementation of PEM. The main advantage of this method is that the analysis is performed simultaneously over several wells to capture the most representative values over the reservoir rather than on a well by well basis. It should be stressed that to avoid bias in the results, it is essential that the input petrophysical evaluation is consistent from well to well, so global optimised multi-well multi-mineral evaluation methods are recommended prior to the PEM calibration process. Figure 1 shows the results of the optimisation algorithm over an appraisal well in a clastic reservoir in the North Sea where a 4D feasibility study was performed.

To demonstrate how the static dependence on porosity and lithology variability affects the 4D response, an exercise is performed using 1D simulator to seismic modelling. In this exercise, we use two different petro-elastic models to predict the impedance change due to pressure and saturation variation. PEM-1 considers only the variations of dry-frame moduli with effective stress, whereas PEM-2 incorporates the variations with clay content and porosity. It is observed that the porosity and clay effects may result in differences in the same order as the 4D response (Figure 2) and should not be ignored.

**Conclusions**

The importance of the dry-frame moduli in constructing the petro-elastic model for the 4D seismic analysis is highlighted. An optimisation algorithm is designed using the combination of Gassmann's theory (1951) and the modified MacBeth 2004 model (Alvarez & MacBeth, 2013) to calibrate the PEM parameters against the well-log data by taking into account the clay content and porosity variations. It is shown that the effect of the dependence of the dry-frame elastic moduli on porosity is not negligible and inappropriate parameterisation can lead to errors of similar magnitude as the 4D signal; therefore it is essential to include the dependence of dry-frame moduli on porosity, mineralogy and effective stress as part of the petro-elastic model calibration.

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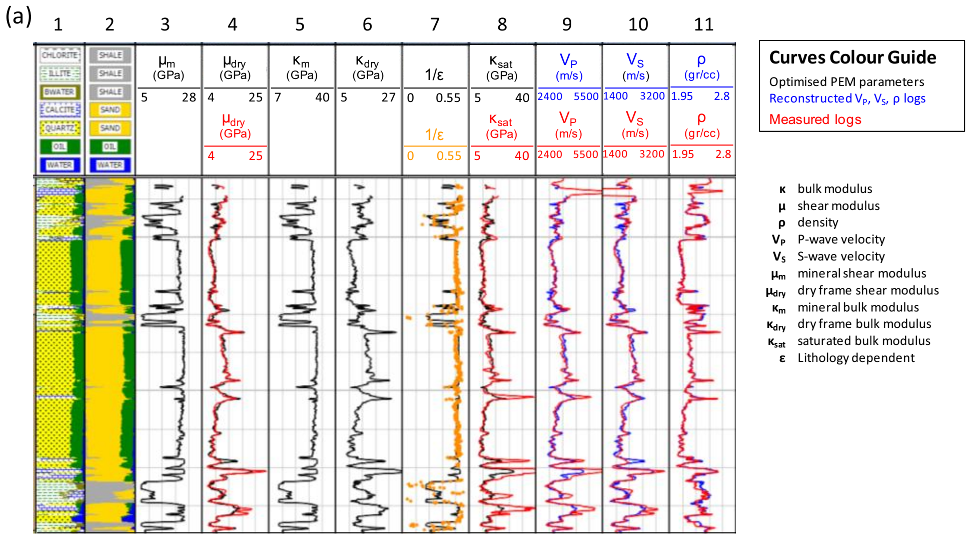
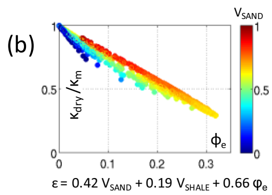
(a)




(b)




(c)

| | SAND | SHALE |
|---|---|---|
| κ (GPa) | 31 | 12 |
| μ (GPa) | 22 | 7 |
| ρ (gr/cc) | 2.64 | 2.37 |

**Figure 1** Results of the PEM calibration using the optimisation algorithm. **(a)** Track description: (1) multi-mineral/multi-fluid petrophysical interpretation, (2) equivalent sand/shale model based on effective porosity, (3) optimised effective mineral shear modulus, (4) optimised (black) vs. measured (red) effective dry-frame shear modulus, (5) optimised effective mineral bulk modulus, (6) optimised effective dry-frame bulk modulus, (7) the optimised (orange dots) and fitted curves from MLR (black) for ε, (8) optimised (black) vs. measured (red) effective saturated bulk modulus, (9) reconstructed (blue) vs. the measured $V_P$, (10) reconstructed (blue) vs. the measured (red) $V_S$, (11) reconstructed (blue) vs. the measured (red) density. **(b)** normalised bulk modulus vs. effective porosity plot, **(c)** calibrated mineral properties.

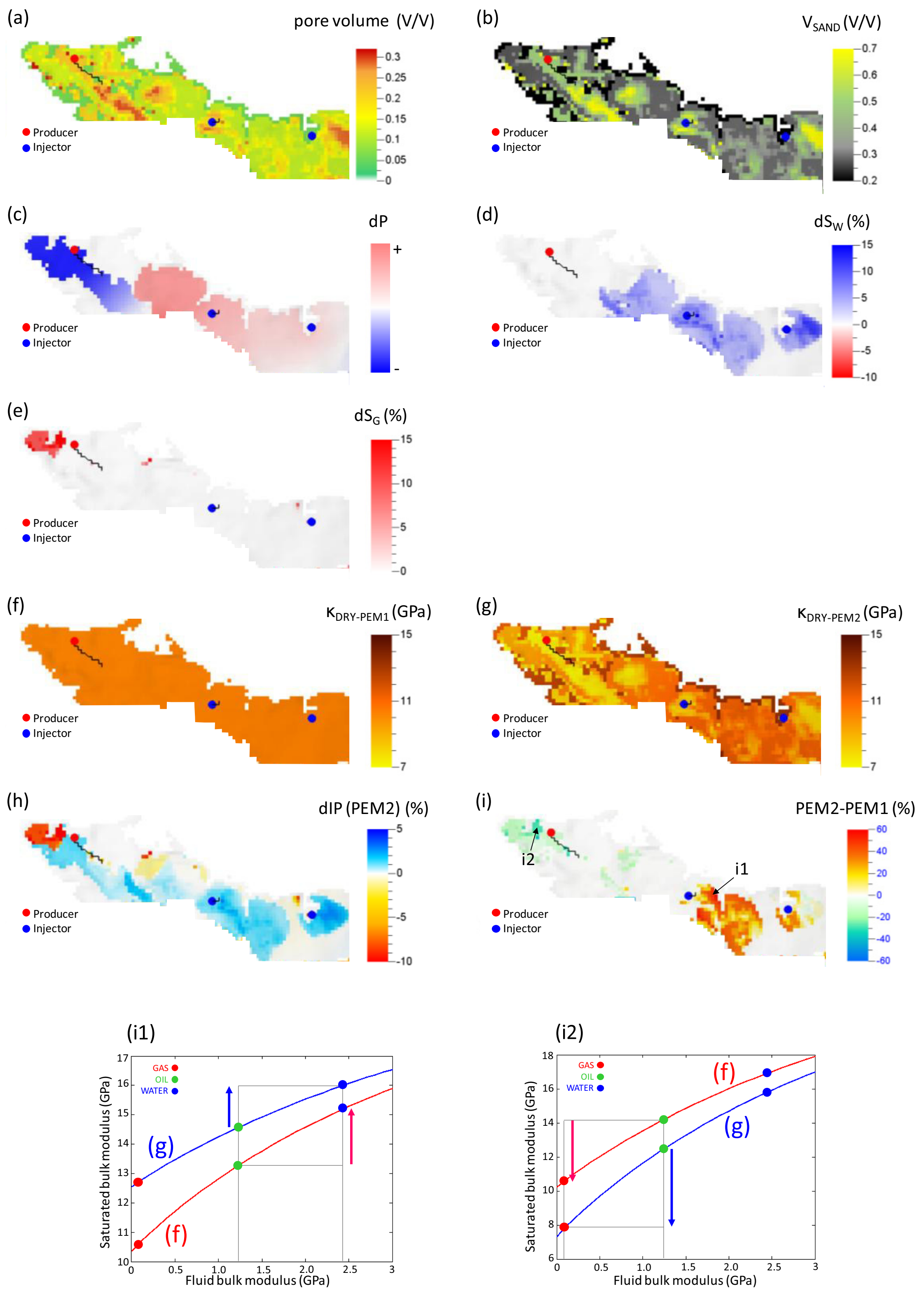



**Figure 2** Effect of the dry-frame moduli on the 4D response. **(a)** pore volume, **(b)** sand volume fraction, **(c)** change in pore pressure (+ build-up, - depletion), **(d)** water-flooded area (water saturation change), **(e)** gas breakout (gas saturation change), **(f)** dry-frame at baseline with no dependence on lithology (PEM-1), **(g)** dry-frame at baseline with dependence on lithology (PEM-2), **(h)** modelled 4D signal (impedance difference from PEM-2), **(i)** the difference in predictions between PEM-1 and PEM-2. In this case, compared to PEM-2, **(i1)** PEM-1 over-estimates the water flooding signal by less than 55%, and **(i2)** PEM-1 under-estimates the gas breakout signal by up to 30%.