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Petro-elastic modelling and characterization of solid-filled reservoirs: Comparative analysis on a Triassic North Sea reservoir

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ABSTRACT

One of the most common problems in the North Sea is the occurrence of salt (solid) in the pores of Triassic sandstones. Many wells have failed due to interpretation errors based conventional substitution as described by the Gassmann equation. A way forward is to device a means to model and characterize the salt-plugging scenarios. Modelling the effects of fluid and solids on rock velocity and density will ascertain the influence of pore material types on seismic data. In this study, two different rock physics modelling approaches are adopted in solid-fluid substitution, namely the extended Gassmann theory and multi-mineral mixing modelling. Using the modified new Gassmann equation, solid-and-fluid substitutions were performed from gas or water filling in the hydrocarbon reservoirs to salt materials being the pore-filling. Inverse substitutions were also performed from salt-filled case to gas- and water-filled scenarios. The modelling results show very consistent results - Salt-plugged wells clearly showing different elastic parameters when compared with gas- and water-bearing wells. While the Gassmann equation-based modelling was used to discretely compute effective bulk and shear moduli of the salt plugs, the algorithm based on the mineral-mixing (Hashin-Shtrikman) can only predict elastic moduli in a narrow range. Thus, inasmuch as both of these methods can be used to model elastic parameters and characterize pore-fill scenarios, the New Gassmann-based algorithm, which is capable of precisely predicting the elastic parameters, is recommended for use in forward seismic modelling and characterization of this reservoir and other reservoir types. This will significantly help in reducing seismic interpretation errors.

1. Introduction

Geologically, pore-spaces of hydrocarbon reservoirs are filled with water, oil or gas; but sometimes, the pore-spaces are filled with solids (heavy oil, shale or salt). This study aims at providing solution to the challenge of determining the elastic response of hydrocarbon reservoir rocks filled with solid (halite in this case) materials in addition to fluid. This is one of the common challenges in the North Sea, where gas-bearing good-quality reservoir of the Triassic sandstones looks almost identical with salt-plugged rock.

Interpretation of acoustic and elastic response based on conventional substitution (fluids only) as described by the Gassmann equation has led to many wells failing. A way forward is to device a means to model and characterize the salt-plugging scenarios by performing fluid-and-solid substitutions and forward seismic modelling. This study focuses on the former aspect of the exercises i.e. modelling and characterizing the salt-plugging scenarios by performing fluid-and-solid substitutions. Distinguishing solid-filled reservoir rocks from potentially gas-bearing rocks is very crucial for the Oil and Gas industry.

The prediction of seismic properties for pores filled with different fluids is one of the most important problems in the rock physics analysis of logs, cores and seismic data (Mavko et al., 2009). Physical properties of porous rocks, such as seismic velocities (compressional and shear waves), depend on elastic properties of the porous frame and the materials filling the pore spaces. Modelling the effects of fluids and solids on rock velocity and density will ascertain the influence of pore material types on seismic data. The seismic response of reservoirs is directly controlled by compressional (P-wave) and shear (S-wave) velocities *Vp* and *Vs* respectively along with densities (De-Hua and Batzle, 2004). Han and Batzle in their work on 'fluid-saturation effects on seismic velocities' show how the measured dry and water-saturated P- and S-wave velocities of sandstone relate with differential pressure and density of the earth medium. The authors demonstrate that with water saturation, P-wave velocity increases slightly, whereas S-wave velocity decreases slightly.

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Brown and Korringa (1975) generalized the Gassmann equation (Gassmann, 1951) for anisotropic porous media. Recently, literatures have been published on the extension of the Gassmann equation for solid substitution in the pore space (Ciz and Shapiro, 2007; Ciz et al., 2008). Ciz and Shapiro (2007) generalized the Gassmann equations for porous media saturated with a solid material. As a way of validating the new theory, Ciz and Shapiro (2007) heuristically extended the elastic equations for the viscoelastic material filling the pore space, introducing complex bulk and shear moduli K_{if} and μ_{if} into the equations. Ciz et al. (2008) demonstrate the theory and applications of the extended Gassmann equations for porous rocks saturated with a solid material. The theoretical results obtained with numerically simulated data using the finite-element algorithm (FEM) of Arns et al. (2002) were compared. The algorithm uses a formulation of the static linear elastic equations, and finds the steady state solution by minimizing the strain energy of the system. The authors apply this algorithm to compute the effective elastic constants of the isotropic porous model "saturated" in the pore space with another elastic solid material. The numerical simulations provide the "static" effective bulk and shear moduli of such a model and the tests are performed on the Gaussian random field model GRF5 created and analyzed by Saenger et al. (2005).

In this study, two different rock physics modelling approaches are adopted in the solid-fluid substitution. The results of the two models are compared, from which the better option with optimum and more robust result is recommended for further modelling of seismic response of solid-and-fluid reservoir contents. One model is to treat the salt as a pore filling, similar to water and hydrocarbons, using the extended Gassmann theory which enables a substitution for solid and fluid pore fills (Auduson, 2013, Auduson, 2015). Another option is to treat the solid pore fill as part of the rock matrix, by classic multi-mineral mixing (Hashin and Shtrikman, 1963, Auduson, 2013). To this end, modelling codes were generated using industry-standard programming tools.

2. Backgrounds of modelling algorithms

2.1. Petroelastic tensional/force theory

Here, a porous rock of porosity φ is considered. It is possible that an elastic solid fills up the pore space by a process of diapirism. The external surface of the porous rock is taken as P, which cuts and seals the pores. The pore space is assumed to be interconnected, taking the form of the Biot's medium (Biot, 1962, as applied by Barryman, 1989). The surface of the pore space is defined as Θ. The external surface P coincides with the surface of the pore space Θ, where it cuts the pores. Their normal reactions are opposite at the interfacing points, i.e., $\omega_k' = -\omega_k$. There is a traction component (symbolized here as Γ_j) at any point, $\mathbf{p}$ of the external surface, P given by;

$$\Gamma_j = \delta^{\varsigma}_{jk}\omega_j(\mathbf{p}), \tag{1}$$

where $\omega_i(\mathbf{p})$ is the component of the outward normal of P and δ^{ς}_{jk} is the homogeneous confining stress.

Application of small uniform changes in both confining stress δ^{ς}_{jk} and pore stress δ^{p}_{jk}, is assumed. The pore stress term is now the stress field in the solid material filling the pore-space. If the material saturating pore-space is a fluid, the pore stress decreases to the pore pressure. In response to the overburden pressure, points of the external surface P are displaced by $d_i(\mathbf{p})$ to their final position. This displacement is assumed to be infinitesimal in comparison with the size of volume the rock being investigated.

Following the examples of Brown and Korringa (1975) and Shapiro and Kaselow (2005), the deformation υ, of a rock sample by symmetric tensors representing the deformation of the rock sample can be described as;

$$\omega_{jk} = \int_P \frac{1}{2}(d_j\omega_k + d_k\omega_j)\upsilon^2\,\mathbf{p} \tag{2}$$

and the deformation of the pore space described as;

$$\varepsilon_{jk} = \int_{\Theta}\frac{1}{2}(d_j\omega_k' + d_j\omega_i')\upsilon^2 \tag{3}$$

Applying Gauss' theorem for a continuous elastic body replacing the porous matrix and the continuous pore-filling elastic material (Eqs. (4) and (5)), we have;

$$\omega_{jk} = \int_V \frac{1}{2}(\partial_k d_j + \partial_j d_k)\upsilon^3\,\mathbf{p} \tag{4}$$

$$\varepsilon_{jk} = \int_{V_\phi} \frac{1}{2}(\partial_k d_j + \partial_j d_k)\upsilon^3\,\mathbf{p} \tag{5}$$

The integrands in Eqs. (4) and (5) represent the strain tensors. The volume-averaged strain of the bulk volume is depicted as the quantity ω_{jk}/V, while the quantity ε_{jk}/V represents a volume-averaged strain of the pore volume. In this case, V is the volume of the porous body and V_φ is the volume of all its connected pores. Thus, three fundamental compliances of an anisotropic porous body are introduced:

$$C^{dry}_{jklm} = \frac{1}{V}\left(\frac{\partial\omega_{ijk}}{\partial\delta^{e}_{lm}}\right)_{\delta^f} \tag{6}$$

$$C^{gr}_{jklM} = \frac{1}{V}\left(\frac{\partial\omega_{jk}}{\partial\delta^{f}_{lm}}\right)_{\delta^e} \tag{7}$$

$$C^{\varphi}_{jklm} = -\frac{1}{V_\varphi}\left(\frac{\partial\varepsilon_{jk}}{\partial\delta^{g}_{lm}}\right)_{\sigma^e} \tag{8}$$

where $\delta^e_{lm} = \delta^f_{lm} - \delta^g_{lm}$ is the differential stress, while the indices dry, gr, and φ are related to the dry porous frame, the grain material of the frame, and the pore space of the dry porous frame respectively. Expressions (6) to (8) represent the tensorial generalization of Brown and Korringa's (1975) models. There exists a fourth compliance tensor,

$$C'_{jklm} = -\frac{1}{V}\left(\frac{\partial\varepsilon_{jk}}{\partial\delta^{d}_{lm}}\right)_{\delta^g}, \tag{9}$$

which is not isolated due to the reciprocity theorem (Shapiro and Kaselow, 2005), relating to the tensorial force between the dry porous frame and the grain material of the frame only;

$$C'_{jklm} = C^{dry}_{jklm} - C^{gr}_{jklm}, \tag{10}$$

A fifth tensor is required to describe the compliance of the pore space filled by a solid material. It is heuristically defined in the following way:

$$S^{if}_{ijkl} = -\frac{1}{V_\varphi}\left(\frac{\partial\varepsilon_{jk}}{\partial\delta^{f}_{lm}}\right)_{con}, \tag{11}$$

where the index *if* (infill) is related to the body of the pore-space infill and the subscript *con* is a constant infill mass. This generalized (in the sense that the infill can be solid or fluid) compliance tensor C^{if}_{jklm}, is related to the volume-averaged strain of the pore space and therefore differs from the compliance tensor of the grain material of the pore infill C^{ifgr}_{jklm} (with the index *ifgr* denoting the pore-infill grain material). The effective compliance tensor of the composite porous rock with a solid