

Pore pressure and water saturation variations; Modification of Landrø's AVO approach

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Summary

Landrø (2001) used in his approach the amplitude-versus-offset (AVO) techniques to distinguish between effects of pore pressure and water saturation, and to quantify the changes in fluid-solid media over time. Meadows (2001) presented two improvements to this method. In this paper, we suggest a new approach to fit the relation between effective stress variations (resulting from overburden stress and pore pressure) and changes in seismic impedance. We also improve Meadows's (2001) second approach, where the changes in pore pressure and water saturation are inverted from impedances instead of intercept and gradient. In our approach we are able to quantify more accurately the changes in effective stress and water saturation.

Introduction

By monitoring time-lapse changes in AVO response, it is possible to distinguish between pressure and water saturation variations. Landrø (2001) used the slope and intercept of reflectivity to calculate the changes in pore pressure and water saturation. Meadows (2001) suggested two modifications to this approach. In his first modification, he inverted the rock physics time-lapse variations from the seismic impedances instead of from the intercept and gradient. In his second modification, he presented the changes in P-wave velocity as a quadratic function of water saturation changes. Landrø (2001) and Meadows (2001) used "North Sea" reservoir models to predict the changes in seismic parameters due to changes in rock physics parameters. In our approach, we improve the second modification of Meadows (2001), presenting the changes in seismic impedances as a logarithmic function of changes in effective stress (Koesoemadinata and McMechan, 2003). We also invert the changes in pore pressure and water saturation directly from the impedances as suggested by Meadows (2001) instead from the intercept and gradient.

Short review of Landrø's method

Landrø (2001) inverted time-lapse pressure and saturation changes from AVO data. He used a two layer model in which there are no time-lapse changes in the upper layer. He applied the fact that variations in water saturation affect the reflection response differently than pore pressure changes. His approach consists of three main steps:

- He used data from the "Gullfaks" field, to establish the rock physics model. Using this rock model, he generated several scenarios of effective stress and water saturation variations to determine the impact of time-lapse changes in seismic properties. Two maps presenting time-lapse changes in seismic parameters as function of water saturation and pore pressure effects are illustrated in Fig. 1 and 2. He fitted the curves from the water saturation map with linear equations while the changes in velocity are expressed as a quadratic function of net pressure variations. With the help of these links between rock physics and seismic properties, he approximated a relation between the time-lapse changes in seismic parameters and rock parameters to second order in effective stress ΔP and to first order in water saturation ΔS ;

$$\begin{aligned}\Delta\alpha/\langle\alpha\rangle &\approx k_\alpha\Delta S + l_\alpha\Delta P + m_\alpha\Delta P^2, \\ \Delta\beta/\langle\beta\rangle &\approx k_\beta\Delta S + l_\beta\Delta P + m_\beta\Delta P^2, \\ \Delta\rho/\langle\rho\rangle &\approx k_\rho\Delta S,\end{aligned}\quad (1)$$

where α denotes the P-wave velocity, β is the S-wave velocity and ρ is the density. Coefficients k , l and m are obtained from fitting the curves. Δ denotes the time-lapse changes in the lower layer, and $\langle \rangle$ is the average value of seismic parameters across the interface.

- Next Landrø (2001) extracted from the reflection response the intercept R_0 and gradient G (Mavko et al., 1998),

$$\begin{aligned}R &= R_0 + G \sin^2 \theta, \\ \Delta R &= \Delta R_0 + \Delta G \sin^2 \theta.\end{aligned}\quad (2)$$

The expression (2) is for the P-P reflectivity for a plane P-wave. Landrø (2001) used the Shuey (1985) approximation for P-P reflection response, to relate the time-lapse changes in rock physics parameters with changes in intercept and gradient,

$$\begin{aligned}\Delta R(\theta) &\approx \frac{1}{2} \left(\frac{\Delta\rho}{\langle\rho\rangle} + \frac{\Delta\alpha}{\langle\alpha\rangle} \right) - \\ &\quad - 2 \frac{\langle\beta\rangle^2}{\langle\alpha\rangle^2} \left(\frac{\Delta\rho}{\langle\rho\rangle} + 2 \frac{\Delta\beta}{\langle\beta\rangle} \right) \sin^2 \theta + \\ &\quad + \frac{\Delta\alpha}{\langle\alpha\rangle} \tan^2 \theta.\end{aligned}\quad (3)$$

Landrø (2001) substituted Eqn. (3) in Eqn. (2) assuming small values of incident angle θ . Hence, the

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4-D changes in intercept and gradient are given by

$$\begin{aligned}\Delta R_0 &= (\Delta\alpha/\langle\alpha\rangle + \Delta\rho/\langle\rho\rangle)/2, \\ \Delta G &= -2(\langle\beta\rangle^2/\langle\alpha\rangle^2)(\Delta\rho/\langle\rho\rangle + 2\Delta\beta/\langle\beta\rangle + \Delta\alpha/\langle\alpha\rangle).\end{aligned}\quad (4)$$

- Finally Landrø (2001) combined Eqn. (1) and Eqn. (4) to quantify the rock physics (i.e. pore pressure and water saturation) time-lapse variations.

Meadows enhancements to Landrø's approach

Two important assumptions are made in the Landrø (2001) approach:

1. $\sin^2\theta \approx \tan^2\theta$, which is valid only for small values of P-wave, incident angle θ .
2. The relation between P-wave velocity and water saturation is assumed to be a linear function.

Measuring of the AVO gradient term often requires data recorded at mid-to-far offsets, which is not in agreement with the assumption that the incident angle should be small. Meadows (2001) suggested that changes in gradient should be calculated as a function of impedances and density instead of being measured from the reflectivity slope. In the Meadows (2001) paper, it is also presented how to invert ΔP and ΔS directly from variations in impedances. In his second modification, Meadows (2001) fitted the curve of P-wave velocity using second order terms of water saturation changes.

Our modifications to Landrø's method

Meadows (2001) used a quartic equation to estimate the effective stress variations. A quartic equation has four solutions. To select the solution with a physical meaning requires an estimation of ΔP from another method. It is necessary to use the relationships between rock physics and seismic parameters, which can be obtained from well logs and laboratory measurements. We base our modification on results published by Koesoemadinata and McMechan (2003) that gives some general relationships between seismic and rock physics parameters for typical "North Sea" sandstones,

$$\begin{aligned}\rho &= f(\phi, C, S), \\ V_P &= f(\phi, C, S, \ln P, f), \\ V_S &= f(\phi, C, S, \ln P, f),\end{aligned}\quad (5)$$

where ϕ is porosity, C is clay content, S is saturation, P is effective stress and f is frequency. Note that in these relationships, V_P and V_S are a function of $\ln P$. Therefore, we fit the changes in seismic parameters as a logarithmic function of effective stress. In this way, it is not necessary to apply higher order terms for the inversion

of rock physics properties. Moreover, we use impedances and density instead of intercept and gradient. We have calculated two maps (see Fig. 3 and Fig. 4) to illustrate how impedances and density vary as function of net stress and water saturation. To calculate these maps we used the relationships between rock physics and seismic parameters given by Mavko (1998). Our relationships between time-lapse changes in rock physics and seismic parameters are given by

$$\begin{aligned}\Delta I_P/\langle I_P \rangle &\approx j_P \Delta S^2 + k_P \Delta S + m_P \ln((\Delta P + P_0)/P_0) + n_P, \\ \Delta I_S/\langle I_S \rangle &\approx k_S \Delta S + m_S \ln((\Delta P + P_0)/P_0) + n_S, \\ \Delta \rho/\langle \rho \rangle &\approx k_\rho \Delta S,\end{aligned}\quad (6)$$

where j,k,m,n are coefficients obtained after fitting the curves in Fig. 3 and Fig. 4. $\Delta/\langle \rangle$ is the relative time-lapse change in P-impedance (I_P), S-impedance (I_S) and density (ρ) as a result of production. P_0 is the initial value of the effective stress. The advantage of using $\ln((\Delta P + P_0)/P_0)$ instead of ΔP is that it is possible, more accurately, to quantify the changes in seismic parameters due to effective stress variations (see Fig. 5). A squared logarithmic function fits the curves in Fig. 3 even slightly better than the $\ln((\Delta P + P_0)/P_0)$, see Fig. 6. In this case we used just like Meadows (2001) a quartic equation to estimate the effective stress changes. The new improved relationship between rock physics and seismic properties are given by

$$\begin{aligned}\Delta I_P/\langle I_P \rangle &\approx j_P \Delta S^2 + k_P \Delta S + l_P (\ln((\Delta P + P_0)/P_0))^2 \\ &\quad + m_P \ln((\Delta P + P_0)/P_0) + n_P, \\ \Delta I_S/\langle I_S \rangle &\approx k_S \Delta S + l_S (\ln((\Delta P + P_0)/P_0))^2 \\ &\quad + m_S \ln((\Delta P + P_0)/P_0) + n_S, \\ \Delta \rho/\langle \rho \rangle &\approx k_\rho \Delta S.\end{aligned}\quad (7)$$

The changes in impedances and density are inverted from the reflectivity using the Goodway's (1998) approximation of the Zoeppritz's (Yilmaz, 2001) equations for P-P reflection response;

$$\begin{aligned}\Delta R(\theta) &= [(1 + \tan^2\theta)/2](\Delta I_P/\langle I_P \rangle) - \\ &\quad - [4K \sin^2\theta](\Delta I_S/\langle I_S \rangle) - \\ &\quad - [(\tan^2\theta)/2 - 2K \sin^2\theta](\Delta \rho/\langle \rho \rangle). \\ K &= \langle \beta \rangle^2/\langle \alpha \rangle^2.\end{aligned}\quad (8)$$

The changes in effective stress and water saturation can be estimated using Eqn. (7) or (8) and (6).

Modeling

We tested our theory using a typical "Gullfaks" field rock physics model. The solid-fluid model consists of unconsolidated sandstones and live oil, see (Mavko et al., 1998). We simulated the fluid flow process with respect to water saturation and pore pressure changes using

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the “Jason Geoscience Workbench” (JGW). Time-lapse variations of 30% water saturation increase and 5 MPa decrease in effective stress are simulated. We compared our approach with the time-lapse AVO techniques of Landrø (2001) and Meadows (2001), see table (1). Generally a representation of P-wave velocity as a linear

SCENARIO	ΔP [MPa]	ΔS [%]
<i>Simulated changes</i>	-5	30
<i>Landrø’s method</i>	-3.50	12
<i>Meadow’s method 1</i>	-4.10	14
<i>Meadow’s method 2</i>	-4.3	35
<i>Using ln function</i>	-5.12	25
<i>Using quadratic ln function</i>	-5.06	32

Table 1: Results obtained by different approaches, to estimate the changes in effective stress and water saturation.

function of water saturation leads to a poor estimation of the simulated changes (see the results from Landrø (2001) and Meadows (2001) first approach given in table 1). The Landrø (2001) approach underestimated the simulated effective stress changes on the order of 1.5 MPa. In the Meadows (2001) method, we obtained better results for the changes in net stress (-4.3 [MPa]). With the second Meadows (2001) modification, we calculated 35 % changes in water saturation which is more or less in agreement with the original changes (30%). This is because of the assumption that the P-wave change is a quadratic function of the water saturation variations. The results from our approach, where we used $\ln((\Delta P + P_0)/P_0)$ to fit the curves of seismic impedances (see Fig. 3), resemble rather well the true value of water saturation change. We also derived much better results than the two previous approaches for the effective stress changes (-5.12 and -5.06 [MPa]). For the water saturation, we obtained with our method better results than with the modification of Meadows (2001) although both methods use the same approach to calculate the relation between seismic parameters and water saturation. We explain this with:

1. We inverted ΔS from the P-impedance (obtained from the AVO data), which is very sensitive to the changes in water saturation (Tura and Lumley, 1999) instead from the AVO gradient.
2. Eqn. (1), (6) or (7) are used to calculate ΔS and ΔP . ΔS is presented as a function of ΔP . Next the change in the effective stress is calculated. Hence, the precision of the ΔS calculation is tied to the precision of the ΔP calculation.

Conclusions

We improved Landrø’s (2001) and Meadows’s (2001) method to distinguish between pore pressure and water saturation changes over time. We suggested a logarithmic relationship between impedances and effective stress. This fitting allows us to calculate more accurately the changes in net stress and water saturation. To invert

the rock physics parameters (i.e. pore pressure and water saturation), we used the seismic impedances. This approach allowed us to work with a wide range of incident angles. In addition it is possible to include a third rock physics parameter as variable (e.g. porosity, clay content, temperature, etc...). Cross-plotting of P- to S-impedance permits us to qualify the changes in pore pressure and water saturation, see Tura and Lumley (1999). Then based upon the modification in this paper, we can quantify the time-lapse variations of pore pressure and water saturation in the reservoirs rather accurately.

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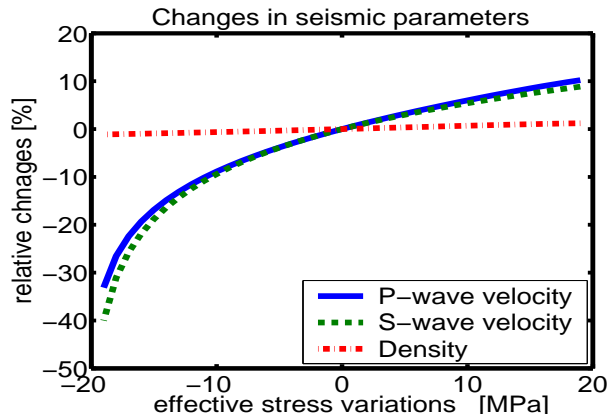


Fig. 1: Relative changes in seismic parameters as a function of variations in effective stress from -19 to 19 [MPa]. Only time-lapse changes due to effective stress are included.

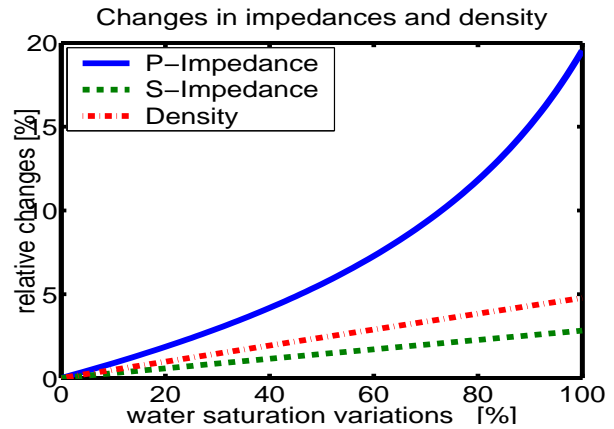


Fig. 4: Density, P- and S- impedances as a function of water saturation (0-100 [%]). Only time-lapse changes due to water saturation are included

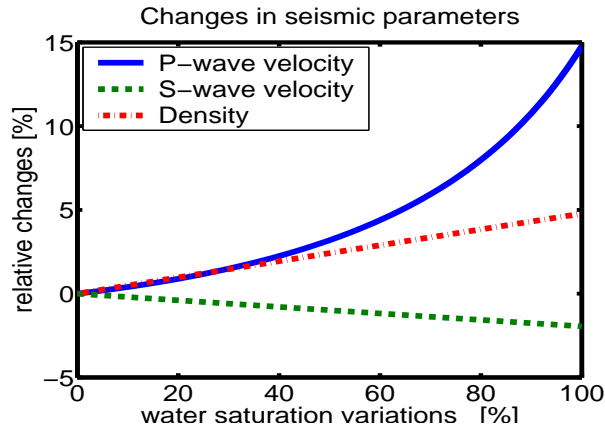


Fig. 2: Relative changes in seismic parameters as a function of water saturation (0-100 [%]). Only time-lapse changes due to water saturation are included

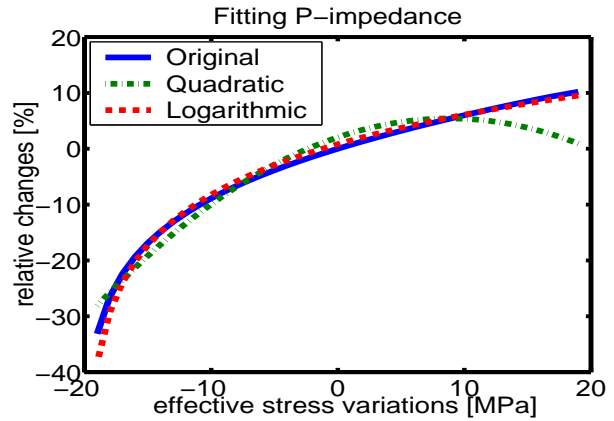


Fig. 5: Fitting the P-impedance with one quadratic - dot-dashed green line and logarithmic - dashed red line function. Effective stress changes vary from -19 to 19 [MPa].

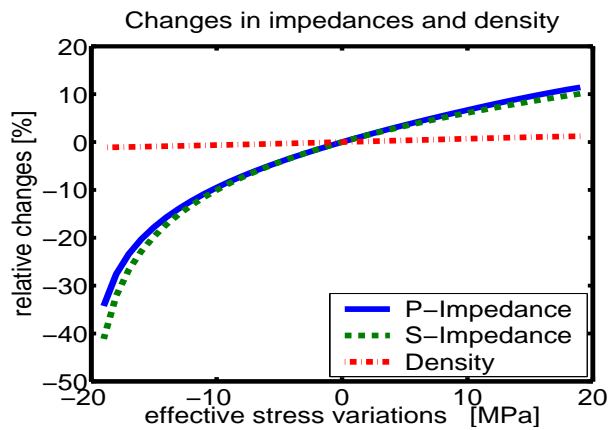


Fig. 3: Density, P- and S- impedances as a function of variations in effective stress from -19 to 19 [MPa]. Only time-lapse changes due to effective stress are included.

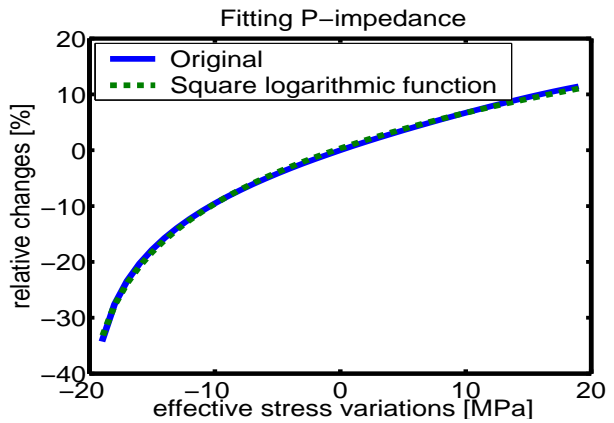


Fig. 6: Fitting the P-impedance with quadratic logarithmic function of effective stress. Effective stress changes vary from -19 to 19 [MPa].