Introduction

Landrø (2001) proposed a method to distinguish between pore pressure and water saturation effects as a result of production using AVO techniques. Both Landrø's approach and later modifications to this method are using the assumption that there are no time-lapse changes in the overburden induced by production. Several authors have looked at the effect of stress and compaction on 4D seismic in the overburden. Guilbot and Smith (2002) monitored the time-shift in the Ekofisk field as an effect of physical displacement (compaction) using a constrained tomography method. In their method they present about 7 [ms] time shift at the top of the reservoir. Stammeijer and Landrø (2003) presented a method for quantitative estimation of both compaction and stress-induced velocity changes using seismic attributes (amplitude and travel time) over time. In order to estimate the changes in the velocity and the layer thickness the authors looked both at prestack travel-time and amplitude changes, as well as at the full stack changes in travel-time and amplitude. Hatchell et al. (2003) use in their approach results from geomechanical modelling to predict strain and stress changes, that they relate to the time-shifts observed in time-lapse seismic data. They presented a good correlation between the predicted and observed time-shifts,. Hatchell and Bourne (2005) used geomechanical modelling together with a stress-strain dependent seismic velocity in order to compute the time-lapse changes in travel time in the overburden and at the reservoir level. They compared the results with the observations from real data examples. Based on a large number of case studies they demonstrated a good match between real data and synthetic data by using a linear strain-velocity relation. In this paper we use geomechanical modelling in order to simulate time-lapse changes both in the overburden and inside the reservoir. The aim is to quantify the error in reservoir pore pressure estimation when neglecting the overburden effects. To this end overburden effects are estimated in a forward model, but neglected in the inversion step using Angelov's method (2004). The observed differences are reported for a number of synthetic cases.

Forward Modelling and Stress Inversion

We used the finite element software package ("DIANA") to compute our geomechanical models. All the models are in a state of plane strain, implying that a 2.5D stress field is modelled, applying a linear stress-strain relationship. Six different models were compiled with an increasing stiffness of the reservoir, see Table 1. Changes in the pore pressure at the reservoir level are simulated for each of the models. Pore pressure decreases (as a consequence of production) of 5, 10 and 15 MPa with respect to the initial effective stress of 25 MPa are followed by pressure increases (as a consequence of injection) of 5, 10 and 15 MPa.

	Surrounding medium		
Elastic parameters	E_{sur} [GPa]	ν_{sur}	ρ_{sur}
	11.3	0.243	2319
	Reservoir		
Elastic parameters	E_{res} [GPa]	ν_{res}	ρ_{res}
Model 1	7.901	0.164	1962
Model 2	7.545	0.163	1943
Model 3	7.205	0.162	1923
Model 4	6.881	0.162	1903
Model 5	6.571	0.161	1884
Model 6	6.274	0.160	1864

Table 1 *The six different initial models used in the modeling part with the elastic parameters of the reservoir and surrounding medium.*

The changes in stress and strain over time, as an effect of pore pressure changes at the reservoir level, are simulated using the geomechanical output of "DIANA". Strain-velocity relationships (Hatchell and Bourne 2005) are used, in the forward modelling to compute the seismic velocities at different stages of pressure depletion and injection. The calculated velocities from the forward modelling are applied to invert the time-lapse changes of stress from the 4D changes of reflection coefficients (Angelov et al., 2004).

Results

The vertical strain resulting from geomechanical modelling is used to predict the 4D changes in the seismic velocities. The research has been carried out in two steps with an increasing level of complexity.

- A simple model based on "Model 3" from Table 1 is taken in order to calculate the changes in seismic velocity as a function of pore pressure changes in the reservoir. It is assumed, that the seismic velocity and density in the model are homogeneous inside the layers (Figure 1 – left part). Hatchell and Bourne (2005) presented the following relation $\Delta V/V = -R\Delta Z/Z$ in order to link the changes in seismic velocity to the changes in layer thickness. As given by Hatchell and Bourne (2005) the dimensionless parameter R gets values around R=5 for rocks undergoing elongation and is in the range from R=1 to 3 for rocks undergoing contraction. Based upon this empirical relation the following values of R have been selected for our model: 1) R=1 for the reservoir and R=5 for the overburden rocks in case of pressure depletion and 2) the reverse, R=5 for the reservoir and R=1 for the overburden in case of pressure injection at the reservoir level. This leads to the expectation that time-lapse changes in the overburden have a large influence on the estimation of pore pressure in case of depletion, whereas in case of injection the changes in the seismic properties at the reservoir level are more significant than the changes in the overburden. This is corroborated by the results given in Table 2. The results from the pressure inversion using Angelov (2004), so erroneously ignoring the overburden changes by inverting the changes in pore pressure from the time-lapse variations in the seismic impedance, are completely incorrect for a depleting reservoir, whereas in case of injection the error is only about 20%.
- For the heterogeneous case the time-lapse changes in the seismic parameters are calculated for the six different models (see Table 1). A heterogeneous velocity model is assumed (Figure 1 – right part). The monitor velocity is estimated by using the changes in vertical strain (output of "DIANA") and the strain-velocity relation similar to the simple homogeneous model. The variations in the seismic velocities are much larger in the overburden than at the reservoir in case of pressure depletion. This caused erroneous results of pore pressure estimation, when neglecting time-lapse changes in the overburden in the pressure-inversion. In case of injection the observed errors for the pressure estimation are much smaller in the order of 20%. The error in pressure estimation tends to decrease with an increase of the reservoir's stiffness with respect to the overburden, see Figure 2.

Pore Pressure Depletion			
	Pore Pressure Changes [MPa]		
Real	5	10	15
Inverted	118	215	298
Pore Pressure Injection			
	Pore Pressure Changes [MPa]		
Real	5	10	15
Inverted	6	12	18

Table 2 *Real changes in pore pressure compared with values of pressure inversion, when overburden changes are ignored in the process of pressure estimation.*

Conclusions

From the results of our modelling study, including geomechanical simulations, we conclude that the overburden effects can not automatically be neglected when inverting pore pressure changes in producing reservoirs using AVO analysis on time-lapse seismic data. The effect of the overburden is larger for producing reservoirs (i.e. decreasing pore pressure in the reservoir) than for storage reservoirs with injection (i.e. increasing pore pressure in the reservoir). From our synthetic case studies we conclude that the overburden effect should be taken into account in order to achieve an accurate quantification of the rock physics properties. This can be achieved by including geomechanical modelling in the inversion process. In practice the estimation of the 4D changes in the rock physics properties from the time-lapse changes in seismic amplitudes can be unstable. Small changes in the input (amplitude variations) could give large changes in the output (rock properties estimation). it is recommended to observe the time-lapse changes in the AVO response together with the time-lapse changes in the travel time in order to find one stable solution.

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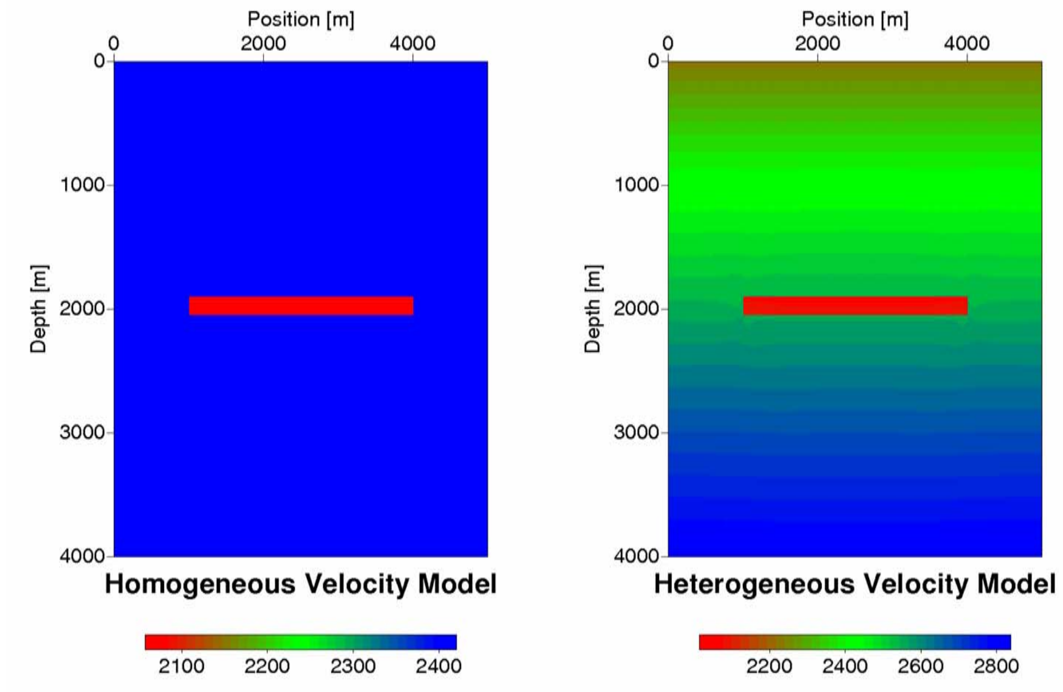

Figure 1 *Velocity Models used in the modelling part: Left – simple mode (constant velocity at the reservoir and in the surrounding media); Right – complex heterogeneous model.*

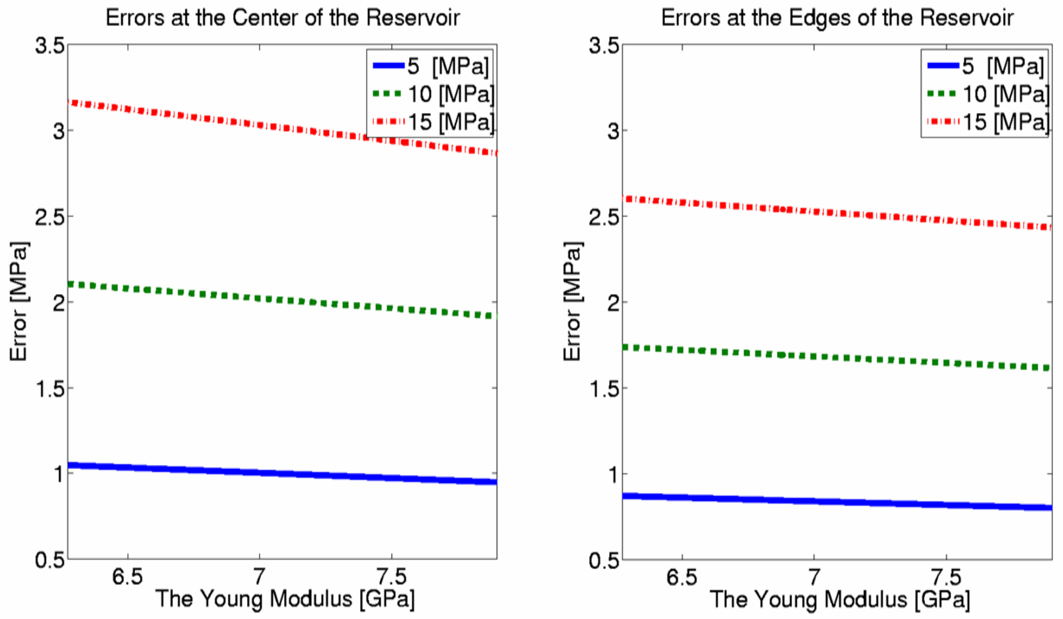

Figure 1 *Errors in pressure estimation on the Top of the reservoir. The vertical monitoring line is situated at the center of the reservoir (left plot) and close to the edge of the reservoir (right plot).*