G031

Adaptive Engineering-based Scaling for Enhanced Dynamic Interpretation of 4D Seismic

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SUMMARY

In this study, importance is drawn to the role of engineering principles when interpreting and estimating dynamic information from 4D seismic data. It is found that in clastic reservoirs the principal parameters controlling mapped 4D signatures are not pressure and saturation changes per se, but the changes scaled by the corresponding thickness (or pore volume) of the reservoir volume that these effects occupy. Indeed, pressure and saturation changes cannot be recovered by themselves, and this is true for all data interpretation and inversion procedures. This understanding is validated both with numerical modelling and analytic calculation. Fluid flow studies also indicate that the impact of gas saturation on the seismic can be written using a linear term, and that inversion to gas saturation can only yield the thickness of the distribution. The above has provided a basis for a linear equation that can be used to easily invert for pressure and saturation changes. Quantitative updates of the simulation model can be achieved by comparing scaled dynamic changes from the simulator with the inverted observations.

Introduction

A widely recognised benefit of 4D seismic surveying is the ability to estimate reservoir pressure, and saturation changes of the mobile fluids between wells and across the field. From the reservoir engineering perspective this process is invaluable for updating the flow simulation model, as it can provide aerial information on reservoir connectivity, barriers and conduits. Indeed, there are many clastic reservoir examples where pressure up (Alsos et al. 2009), pressure down (Fletcher 2004) or saturation changes (Staples et al. 2006) have been directly inferred during production and recovery. In critical areas where pressure and saturation changes overlap significantly, specialised inversion techniques have also been developed to provide some degree of separation (Tura and Lumley 1999; Landrø 2001; MacBeth et al. 2004). Inversions are also possible in the presence of free gas (Floricich et al. 2006), and in this case a nonlinear gas saturation solution is required. In this current study, importance is drawn to the role of engineering principles when interpreting and estimating dynamic information from the seismic. In particular, it is known that pressure spreads across and down through the reservoir at a faster rate than the fluids can move and is relatively insensitive to net-to-gross variations, thus the vertical distribution of influence for each effect is different. Indeed, the thickness ranges for pressure, water saturation or gas saturation effects are distinctly different, and may also not agree with the total geological reservoir (interval) thickness. It is our understanding that the pressure and saturation changes influence the 4D signatures only through their scaling with the corresponding vertical thickness distribution. For amplitudes, this adaptive scaling phenomenon is analogous in principle to 4D tuning. It is shown here that recognition of these overlapping effects and the scaled pressure and saturation as the controlling parameters for mapped time-lapse seismic can lead to a clearer and more quantitative interpretation of the results of pressure and saturation change inversion.

Adaptive scaling of pressure and saturation

The development is guided by analytic calculation and simulator to seismic modelling from a fine-scale field simulation model, and is then applied to a North Sea dataset. The reservoir consists of a deepwater turbidite sand deposition with multiply stacked, inter-connecting and amalgamating channels combined with sheet-like sands. The field is thus highly compartmentalised and connectivity is one of the main reservoir management issues. During the course of production, lack of support from injectors and weak aquifer influx has led to strong pressure decrease, and a drop below bubble point with the consequent liberation of free gas from solution.

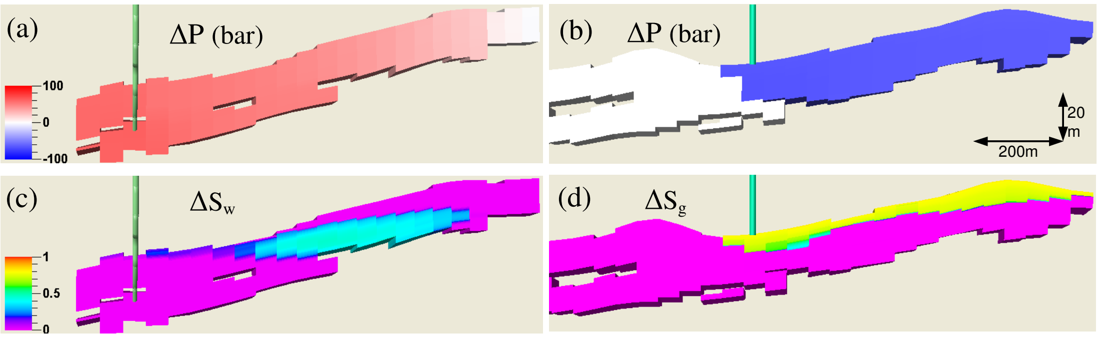

Figure 1 *Simulated changes between the monitor (2002) and baseline (1998) for two vertical sections through the field, highlighting the thickness distributions associated with the pressure and saturation changes. (a) and (b) pressure change; (c) water saturation and (d) gas saturation.*

Figure 1 shows a vertical cross-section through the reservoir after numerical fluid flow simulation. It is observed that the 2002-1998 pressure change (Figure 1(a) and (b)) is uniformly spread throughout the geobody, although due to variable vertical connectivity there is a spread in its region of influence, typically up to 35m over a total reservoir interval of 10 to 45m. For the gas saturation (Figure 1(d)), the thickness of the gas volume is smaller (up to 13m) and more variable, whilst for the water saturation (Figure 1(c)) the thickness is somewhat larger (up to 27m). The volumes of change in pressure, gas and water clearly overlap to different extents across the field depending on the mechanism and timing of production and recovery processes. Numerical analysis shows that the mapped seismic expression of the pressure and saturation effects can be decomposed linearly

$$\Delta A(\Delta P, \Delta S_g, \Delta S_w) = \Delta A(\Delta P, 0, 0) + \Delta A(0, \Delta S_g, 0) + \Delta A(0, 0, \Delta S_w) \tag{1}$$

where A represents mapped amplitude or time-shift. This linearly additive behaviour, has been tested using synthetic modelling, and found to be valid for a wide range of geological and fluid conditions. Omission of the cross-terms introduces an error of less than 2%. It can be shown that each term in (1) can be further written

$$\Delta A(\Delta P, \Delta S_g, \Delta S_w) = h_p f_p(\Delta P) + h_g f_g(\Delta S_g) + h_w f_w(\Delta S_w) \tag{2}$$

where h_p, h_g and h_w are the thicknesses of the pressure, gas or water change volume respectively, and the independent variables are the vertical distributions of pressure change ΔP, gas saturation change ΔS_g and water saturation change ΔS_w. f_p, f_g and f_w are functions determined by the petroelastic model and the seismic wave behaviour. Finally, an important approximation of (2) can be made

$$\Delta A(\Delta P, \Delta S_g, \Delta S_w) \approx a\overline{\Delta P}' + b\Delta S'_g + c\overline{\Delta S}'_w \tag{3}$$

where the mapped seismic response is now dependent on the changes averaged over the volume of the effect and scaled by the thickness of the volume: $\overline{\Delta P}' = h_p \overline{\Delta P}$ and $\overline{\Delta S}'_w = h_w \overline{\Delta S}_w$. $\Delta S'_g$ deserves special attention as it is the product of h_g and a fixed value of gas saturation $\Delta S_g(\max)$ which is constant laterally and with depth for the reservoir to a good approximation. Thus, the seismic response for the gas is predicted to be controlled via the thickness of the gas volume. Finally, the coefficients

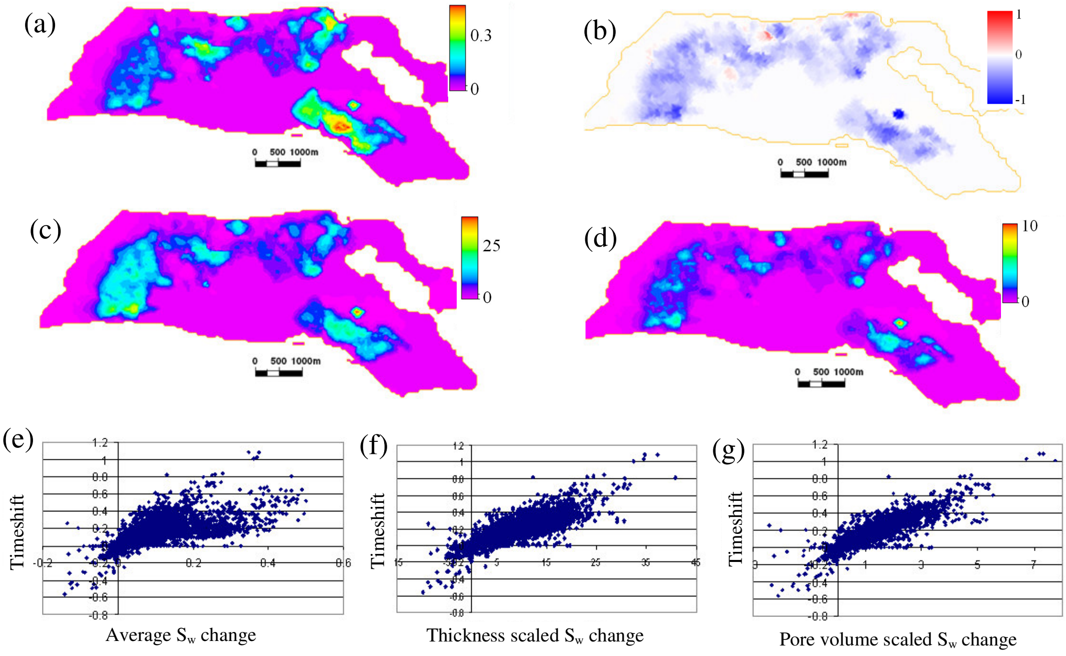

Figure 2 *a) Vertical average of water saturation change, b) synthetic timeshift for water saturation only, c) thickness scaled water saturation change and d) pore volume scaled water saturation change. e, f and g) represents timeshift against these changes.*

a, *b* and *c* represent the contributions from the petroelastic model - as these are proportional to effective porosity then the seismic in now controlled by the pore volume over which each effect extends. Equation (3) predicts that the effect of pressure or saturation change on the amplitudes or reservoir-related time-shifts must scale according to the thickness over which the effect of the change has spread. For amplitudes, this particular finding may be understood as relating to 4D tuning. This finding is illustrated numerically in Figure 2, where the time-shift attribute is observed to show a stronger linear relation to the scaled water saturation than water saturation itself. An important conclusion of this work is that the presence of gas now appears as a linear term in gas thickness only, rather than a non-linear function of gas saturation. This conclusion is based on the known narrow gas distribution for moderate to high permeability clastics (Falahat et al. 2010).

Inversion of observed data

To demonstrate how (3) may be of value in quantitative interpretation, the observed seismic data are inverted for pressure and saturation changes using this formulation and the approach of MacBeth et al. (2004). Four attributes are considered: full angle stack, gradient stack, envelope weighted frequency and finally the timeshift. It is assumed that the adaptive scaling principle applies to these attributes also. The unknown petroelastic parameters for each attribute are calibrated at nineteen wells. The results of the inversion are shown in Figure 3. It should be noted that the results have been obtained by linear inversion, and that the process produces a satisfactory cross-validation error when calibrated by the known well pressure and saturation data. The inversion produces products that are directly

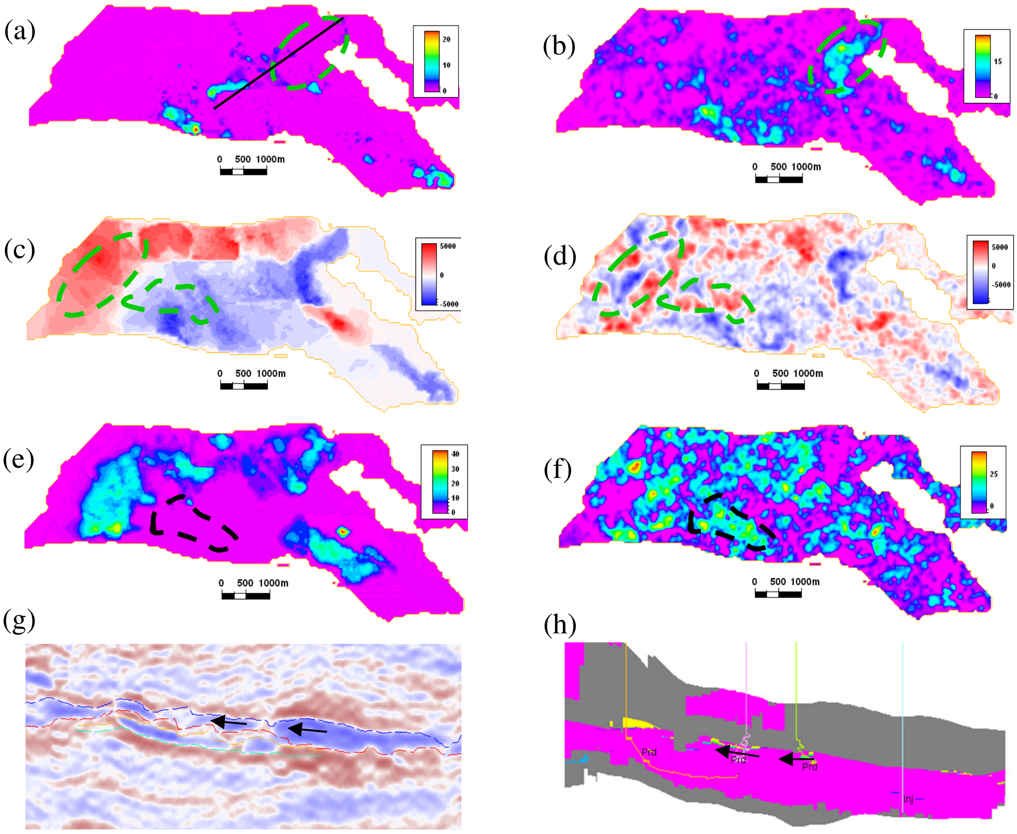

Figure 3 *(a), (c) and (e) are maps of thickness-scaled gas saturation change, pressure change and water saturation change respectively predicted from the simulation model. (b), (d) and (f) are the same maps but from the linear seismic inversion. g) 2002 seismic section, and h) vertical cross section from the simulation model for gas saturation along the same section as in (g).*

comparable only with the scaled pressure or saturation change quantities determined from the fluid flow simulation. However as the thicknesses of the individual volumes are not known in practice then it is not possible to convert the inversion results immediately to pressure and saturations. Hence, the products of inversion must instead be compared with the corresponding simulation predictions and used to update the simulation model directly. The results here show that the simulator appears to predict the observations fairly accurately with the exception of a few areas. For example, there is more exsolved gas in the north-east of the segment (green dashed area in Figure 3(a) and (b)). Vertical cross sections in this area (Figures 3(g) and (h)) highlight the need for a barrier between compartments to prevent liberated gas migration from right to left. For the dashed region in the centre of Figures 3(c), (d), (e) and (f), the seismic inversion indicates a possible connection with the north-east in order to increase both pressure and water saturation.

Discussion and conclusions

The principal parameters controlling mapped 4D signatures are not pressure and saturation changes per se, but these changes scaled by the corresponding thickness (or pore volume) of the reservoir volume that these effects occupy. This understanding is consistent with our expectations from both seismic modelling and the fluid flow physics. This is a conclusion that is generally valid for all data interpretation and inversion procedures that aim to invert solely for pressure and saturation changes. Reservoir fluid flow studies also indicate that the impact of gas saturation on the seismic can be written using a linear term on the basis of the gas flow physics. Thus, inversion to gas saturation yields only the thickness of the distribution. This has provided a basis for a linear equation (3) that can be used to easily invert for pressure and saturation changes. Note, however, that for amplitudes, it is also found that a quadratic term in pressure changes may still be required when pressure changes are large. Updates with the simulation model can be achieved only by comparing scaled dynamic changes from the simulator with the inverted observations.

Acknowledgments

We thank sponsors of the Edinburgh Time Lapse Project, Phase III and IV (BG, BP, Chevron, ConocoPhillips, EnCana, ENI, ExxonMobil, Hess, Ikon Science, Landmark, Maersk, Marathon, Norsar, Ohm, Petrobras, Shell, Statoil, Total and Woodside) for supporting this research. We thank Schlumberger-Geoquest for the use of their Petrel and Eclipse software. RF acknowledges financial support from NIOC.

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