Th N101 03

Engineering Consistent Constraints for the Inversion of Changes in Pressure and Saturation on Ekofisk

M.Y. Wong* (Heriot-Watt University), C. MacBeth (Heriot-Watt University) & A. Bertrand (ConocoPhillips Norge)

SUMMARY

A high resolution, time lapse seismic inversion into pressure and saturation changes is performed. This provides insights into well performance and pressure distribution within a geo-mechanically active chalk reservoir (Ekofisk). The inversion is constrained by reservoir engineering concepts and predictions to reduce the non-uniqueness involved, and to maintain consistency with the physics of flow. At the heart of this inversion scheme is the effective union of engineering data and different seismic products such as reservoir time strain, percentage changes in elastic properties to influence the inversion. Quantitative interpretation on this field using the inversion results shows good agreement with well production data and helps to explain strong localised anomalies in both the Ekofisk and Tor formations. Analysis shows that the hardening signals around producers are due to lack of pressure support and reservoir compaction; whereas softening signals are attributed to high pressure flooding around injectors.

Introduction

Time-lapse (4-D) seismic has now become commonplace in oil and gas field development. One branch of active research is the evolution of quantitative evaluations and extraction of pressure and saturation changes from 4D seismic signals. Such dynamic properties have important implications in reservoir characterisation such as optimizing well production and injection rate, placement of new wells, and the prevention of mechanical failures. The method presented here not only yields such properties but can also assist applications such as seismic history matching and model updating. However, one needs to ensure that a forward model can adequately describe time lapse elastic properties as a function of the dynamic reservoir parameters, and that the inverted dynamic properties are realistic and engineering consistent (EC).

In this study, an inversion was performed on the 4D seismic data, in the form of percentage changes in elastic properties and time shift measurements, into variations in pressure and saturation for a geo-mechanically active chalk reservoir. The key difference between the recommended inversion scheme and existing inversion methods lies in the characteristics of the reservoir itself. Ekofisk is a compacted chalk reservoir, which is not only subject to dry compaction but also water weakening. The inversion is guided by a smooth starting model and associated weights from available seismic products. Most importantly, the inversion is also constrained with reservoir engineering predictions, which helps reduce the non-uniqueness involved and maintains consistency with the physics of flow.

The Ekofisk field is a remarkable example of compacted chalk field. It is a four way dip anticline and produces oil and gas from naturally fractured chalk reservoirs of the Masstrichtian (Tor) and Danian (Ekofisk) Formations. The reservoir thickness, which is around 300m on average is more prominent in the crestal area and thins towards the flanks. The reservoir has high porosity and low matrix permeability. During early production by pressure depletion, pressure was close to bubble point; gas exsolution and compaction of the reservoir were extensive. As part of the effort to increase productivity, a full field water injection programme was put on stream which increased oil production rate, stabilised field pressure; but also resulted in the water weakening of chalk. The permanent reservoir monitoring system initiated in 2010 was an effort to allow 4D seismic data for reservoir surveillance to optimise new well locations and trajectories, suggest and prioritise well interventions, as well as update the reservoir model and monitor the overburden (Bertrand et al. 2013). The inversion is applied to the second and the sixth of the LoFS (Life of Field Seismic) surveys acquired two and a half years apart. The main focus area is the south west part of the field.

Methodology and Inversion Workflow

This is a continued effort from Corzo et al. (2013) where initial porosity was considered as an important factor in inverting for pressure depletion in the Valhall field. In the usual way, impedances are modelled by a petro-elastic model to convert dynamic parameters from the simulation model. The modelled impedance is thereafter compared to the observed impedance. This rock physics model requires extensive calibration and also the exhaustive modelling of various data to describe the rock and fluid properties. To overcome this, a fast-track forward modelling equation (proxy model) is proposed to capture the relationship between the percentage change in impedance and dynamic changes. The proxy model is derived analytically through modelling of synthetic data. To compute the percentage changes in impedance, the proxy model requires a set of calibrated coefficients from the petro-elastic model (coefficients a_1, b_1 and c_1), changes in pressure and saturation (ΔP and ΔSw) and compaction curves from the laboratory expressed as a functions of initial porosity (F_{ww} and F_p). The proxy model is comprised of three distinct terms: a pressure term, a saturation term and a cross term between pressure and saturation that describes the water weakening behaviour of the chalk. The equation of the proxy model is given below:

$$\%\frac{\Delta Ip}{Ip} = a_1\mathbf{\Delta P} - b_1\left[F_p + \left(\frac{\mathbf{\Delta S_w}}{\Delta S_{wmax}}\right)\left(F_{ww} - F_p\right)\right]\mathbf{\Delta P} + c_1\mathbf{\Delta S_w} \tag{1}$$

The proxy model can also be used for inversion to make inferences about the changes in pressure and saturation inside the reservoir. The strength of this equation is that it leads to an accelerated estimation of the impedances. Most importantly, it is now amenable to linearized inversion, and as a consequence the inversion has a less complicated solution space. Finally, it also provides an intuitive relationship between data and model, essential to quality control the results.

The first EC constraint imposed is in the water leg. No change was observed in saturation in the water leg from pre-production to current state; hence it is only logical to assume no changes in saturation, and a possible presence of subtle pressure signal in the water leg. An inequality constraint (above water-leg, $-0.10 \leq S_w \leq 0.5$) was applied, with the upper and lower boundaries extracted from simulation model statistics. For the second EC constraint, the solution space close to well perforations was constrained using a 3D Gaussian kernel; imposing tight upper and lower bounds for changes in pressure and saturation as estimated from the reservoir simulation. These constraints are realistic given that the model is history matched. Two assumptions are implicit in this technique:

- creep behaviour is not accounted for in this inversion; the creeping of chalk shows the rock weakens without any drop in pressure following the invasion of water; in which the rock will have a greater compaction later in time when pressure eventually drops (Barkved et al. 2003).
- gas exsolution is less detectable in seismic attributes; gas signals are transient and localised with weak signals. Gas is a second order effect; compaction could potentially mask the gas signal.

Inversion result using EC constraints

Firstly, data of across domains were reconciled into a common grid. The starting model is from the smooth simulation prediction. Figures 1a, 1b and 1c show the progressive improvement of the results by imposing constraints and adding more robust 4D signals such as the reservoir time strain onto inversion results. The results from the constrained inversion are far better than from the unconstrained solution; clearer delineation of pressure changes can be seen around wells. By adding the additional information from time strain, the objective function was modified by associating weights to the different data. The weights carry information on uncertainties and errors in the data; and show the relative contribution of each individual dataset to the joint objective function.

Hierarchical updating of inversion

The first pass inversion results informed us that some of the wells have a slightly poorer match between the production data and the simulated prediction, and could bias the solution. Hence the constraints around such wells were revised for both pressure and saturation respectively by relaxing the constraints. The end result of updating the misfit further improved the results.

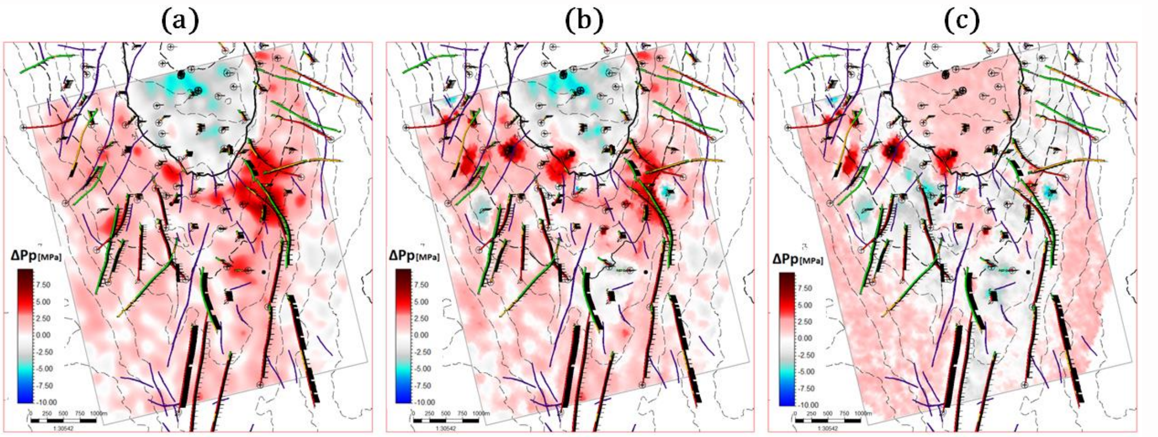


Figure 1 *A display of the progressive improvement of inverted pressure changes from our inversion scheme. (a) unconstrained, (b) EC constraints imposed and (c) with the additional observations from reservoir time strain.*

Interpretation

The next focus is to use the inverted results to explain some of observations close to wells on an area of the field with very interesting 4D seismic signals. The three major observations are shown in Figure 2. A potential pressure sink around the producers P1, P2 and P3 was identified, which is also correctly reflected in the inverted pressure change showing a pressure decrease close to 4MPa, and a strong pressure increase around injectors I1 and I2. Lastly, water encroaching towards the producers from the injectors was also observed. We support our arguments by cross checking with the production data made available such as RFT and downhole pressure gauge measurements acquired every six months. The RFT data shows that both injector I1 and I2 were originally water flooded, hence the 4D signals are predominantly pressure driven. The production data also demonstrated that the injectors were put on stream after LoFS2, and injected at a high constant rate; the inversion shows an increase in pressure greater than 10MPa. Production data indicated a steady increase in water cut, and an increase in gas production rate in P2, inferring a drop in pressure and that water from the nearby injectors could have invaded the producer, which is also consistent with the inversion results.

Figure 4 shows a cross section along these wells for time strain, changes in amplitude, elastic properties, pressure and saturation. Observation in section view agrees with the map description, such as the large pressure increase around injector I2, a higher pressure drop in the Ekofisk than in the Tor for P3, and the water invasion in P2 in the Tor interval but not in P3. The water cut in P2 is not only supported in the production data but also in PLTs acquired in 2006, showing a good 55% contribution from TA (first reservoir unit within the Tor formation).

Discussion and Conclusions

The decomposition of changes in pressure and saturation was successful by using an engineering based inversion approach. Application to the Ekofisk field revealed that over the course of two and a half years, the compaction effects due to pressure depletion and water flooding have dominated the 4D seismic signals. Quantitative interpretation on this field using the inversion results show good agreement with well production data, and help explained strong localised anomalies in both the Ekofisk and Tor formations. This work also shows the need to have a better understanding of the timing of the pressure and saturation changes. These in turn affect the magnitude and spatial distribution of compaction and help validate drainage and pressure support areas in the field.

Acknowledgements

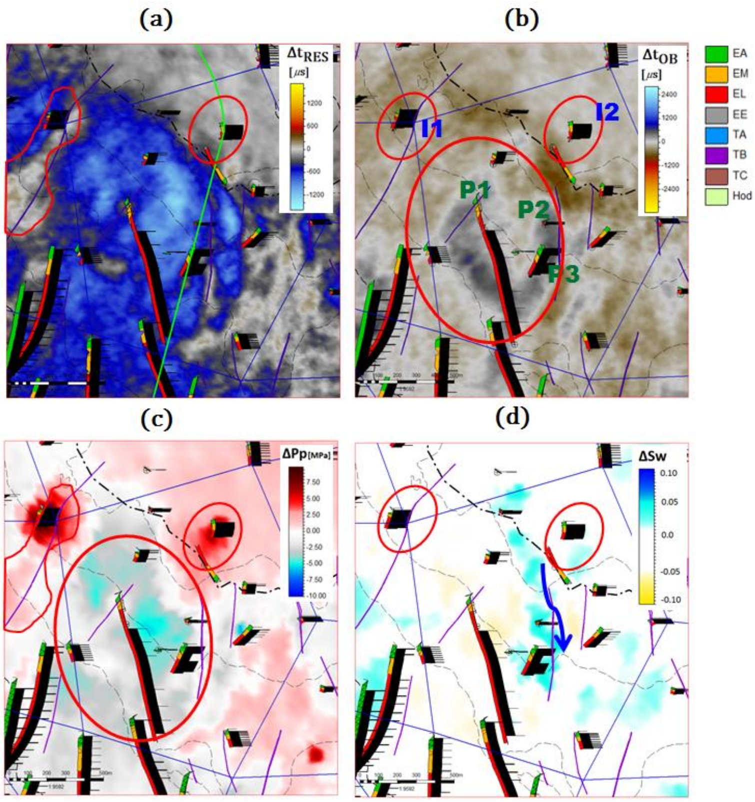
The authors would like to thank the sponsors of the Edinburgh Time-Lapse Project Phase V (BG, BP, CGG, Chevron, ConocoPhillips, ENI, ExxonMobil, Hess, Ikon Science, Landmark, Maersk, Nexen, Norsar, Petoro, Petrobras, RSI, Shell, Statoil, Suncor, Taqa, TGS and Total) for supporting this research. Also special thanks to ConocoPhillips Skandinavia AS and the PL018 Partnership (Total E&P Norge AS, ENI Norge AS, Statoil Petroleum AS and Petoro AS) for their permission to publish this work. Special gratitude goes to Carlos Pacheco, Jean De Lanlay, Evgeny Tolstukhin and Reidar Midtun.

References

Barkved, O, Heavey, P, and Kjelstadli, R. [2003] Valhall Field – Still on plateau after 20 years of production. *SPE* 83957

Bertrand, A., Folstad, P.G., Grandi, A., Jeangeot, G., Haugvaldstad, H., Lyngnes, B., Midtun, R. and Haller, N. [2013] The Ekofisk Life of Field Seismic (LoFS) System: Experiences and results after two years in operation, 75th EAGE Conference, London.

Corzo, M., MacBeth, C. and Barkved, O. [2013] Estimation of pore-pressure change in a compacting reservoir from time-lapse seismic data. *Geophysical Prospecting* **61**, 1022-1034.



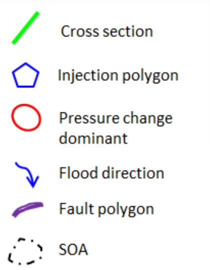
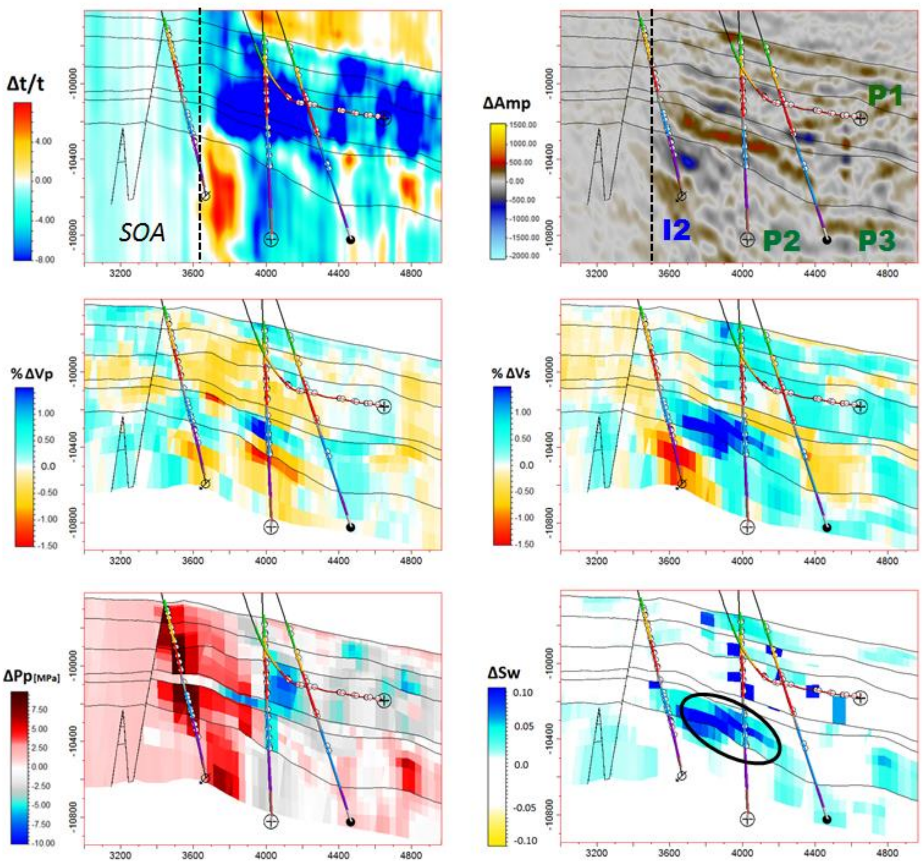


Figure 2 *Map comparison of (a) reservoir time shift (b) overburden time shift (c, d) inverted pressure and saturation changes. Legend on the right represents stratigraphic units intersected by wells in Ekofisk (EA, EM, and EL), tight zone, Tor (TA, TB, and TC) and underburden (Hod). The cross section location in Figure 3 is represented as a green line along well I2 in Figure 2(a).*



P2

P2	# Perfs	PLT Jul 2006
EA	2	11% Total
EM	1	
EL	4	34% Total
TA	4	55% Total
TB		
TC		
Total	11	100% Total

Figure 3 *4D effects and inverted results across wells P1, P2, P3 and I2 between LoFS2 and LoFS6. The water cut in P2 is not only supported by production data but also in the PLT acquired in 2006. Our interpretation in the section is in good agreement with our map description.*