Time-shifts Interpretation of Legacy and Frequent Repeat Seismic Data in a Compacting Chalk Reservoir

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Introduction

Time lapse seismic has over the last few years become a common practice in the reservoir management cycle. Benefits achieved by practical reservoir monitoring include reservoir model updating, drilling infill wells, and optimising production workflows. We will demonstrate some of the benefits of the extensive use of 4D seismic data in the development and characterisation of a chalk field; where 4D results add information key to characterisation of the rock physics model.

Our field of interest is a chalk field with reservoir rocks having high porosity, often exceeding more than 40% but with a low permeability rarely reaching more than 5 mD. Production is therefore enhanced through a system of natural and induced fractures allowing commercial production from the field. The field was originally developed by pressure depletion; and as a result of compaction the water bottom has subsided. Due to the strong geomechanical behaviour of the chalk, the time shift measurement is central to the field's 4D seismic interpretation. Both conventional legacy and a modern frequent repeat survey were acquired in the field of interest, throughout the field's production period. The high repeatability surveys were acquired at least once to twice a year, where the data shows high correlation with well activities and high repeatability. In comparison to the legacy data, the 3D seismic using modern frequent repeat survey shows clear signals with a side lobe reduction, and faults in the overburden that are better defined. Due to the short turn-around in acquisition and processing coupled with frequent monitoring, production changes are more evident from time-lapse signals and thus easier to be interpreted in the frequent repeat surveys. The value of information from installing the frequent repeat system includes optimizing well locations and trajectories, suggesting well intervention, diagnosing mechanical issues and monitoring production impact such as injection, compaction and overburden subsidence. Prior to quantitative interpretation of the data, we compared the noise floor for both legacy and frequent repeat data, where the noise floor from both data type are taken by the mean of all the surveys in an area in which it is relatively quiet from well activities. The noise floor in the legacy survey is expectedly higher than the frequent repeat data due to higher non-repeatability, by almost a factor of three. This helps to place higher uncertainties on the interpretation using legacy data.

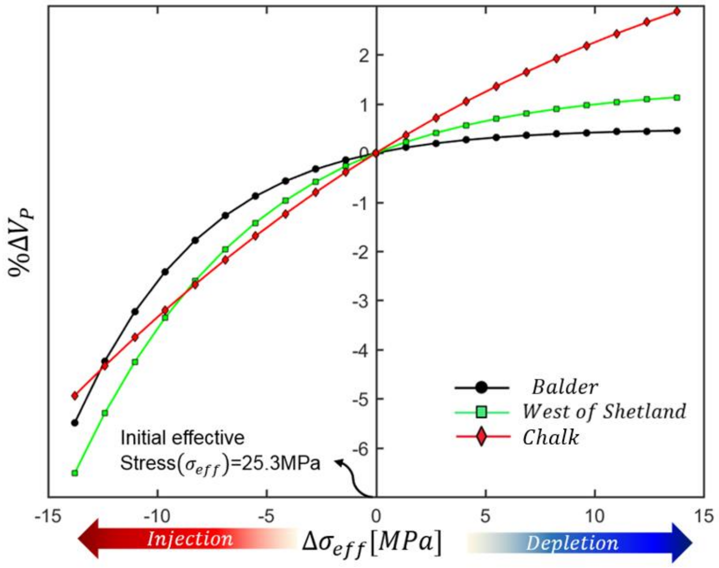


Figure 1 *P-wave velocity percentage change as a function of effective stress for chalk, West of Shetland and Balder sandstone.*

Stress Sensitivity

To estimate the pressure compliance of the dry rock frame, a pressure model from MacBeth (2004) is employed. Depending on the rock properties, each field has a very different stress sensitivity characteristics (Figure 1). For example, our field of interest which is a chalk is more stress sensitive than the West of Shetland sandstone. And in comparison, the West of Shetland sandstone is relatively more stress sensitive than the Balder sands. The stress sensitivity is also dependent on the loading (depletion, pressure relaxation) and unloading (injection, shut in of a producer well) mechanisms and the initial effective stress. The rock is usually more stress sensitive at low effective stress and also in an unloading events such as injection compared to depletion. By calibrating these characteristics via rock mechanic testing, we can quantify how stress sensitive is the rock due to production changes and what percentage change will that manifest in P-wave or even S-wave velocities.

Reservoir Time Shift between legacy data vs. modern frequent repeat survey data

The attribute we will employ in our analysis is the reservoir time-shift, defined as the difference of top and base reservoir time shift. This was first analyzed in the Valhall field by Corzo (2012), with proven success. A positive reservoir time-shift is a speed-up attributed to compaction or impedance hardening. A negative reservoir time-shift is a slow-down due to dilation or impedance softening. The time-shift magnitude estimated from legacy and frequent repeat survey varies in both resolution and magnitude, with the legacy data recording a maximum of 20ms between the baseline and the first monitor acquired a decade later. This is due to significant geomechanical changes in the overburden resulting from pore collapse and chemical weakening of the chalk. The frequent repeat surveys recorded a high resolution time-shift with a maximum of +/- 1.5ms between surveys. A general understanding of the relationship between reservoir time-shift and various production mechanisms in our chalk field is depicted in Figure 2(a). The first quadrant is attributed to a hardening signal resulting from pressure increase and a change in saturation: water replacing oil, gas going back into solution or a combination of both. In the second quadrant the time-shift signal shows hardening corresponding to a decrease in pressure, which could be a result of pressure relaxation such as a reduction in injection activities, shutting in of an injector or a pressure depletion, which might occur when producing oil from the reservoir. This effect, coupled with water invasion, leads to water weakening which often creates enhanced compaction of the chalk. The third quadrant shows slowdown in time-shifts due to pressure reduction as a result of pressure falling below bubble point and gas being liberated from solution. Fluid replacement of an incompressible oil with highly compressible gas creates significant softening. In the fourth quadrant, a pressure increase, such as when injecting into the water leg, creates a softening signal, but at a lower magnitude compared to gas exsolution signals. If 4D responses are expected but none is recorded in the presence of production changes, this could be attributed to a cancellation between pressure and saturation changes. Our analysis of the data will be based on this conceptual model.

Figure 2(a) shows cross-plotting of the frequent repeat time shift data of the field and it can be observed that most of the points lie in the second and fourth quadrants, which are pressure driven. The time-shift data are derived from polygons around wells with strong 4D seismic anomalies. The data points on the cross plots are the mean 4D signal and the standard deviation of the reservoir time-shift. The large pressure variation from the injectors show a relaxation trend and a pressure build-up trend. Circled in black is a cluster of points that show small hardening signals due to pressure depletion from producer wells; this agrees with the general observations that a pressure depletion signal strength is often more difficult to detect than pressure build-up. The legacy reservoir time-shift data tells a very different story. With most data points plotted in the first quadrant, the 4D seismic signals from the legacy data period are mostly saturation dominated.

Updating stress sensitivity with 4D seismic data

Our aim is to reconstruct the observed time-shift signals in Figure 2 for both (a) frequent repeat data and (b) legacy data with a rock physics model. The rock physics model consists of a compaction model (Sylte et al., 1999), and a calibrated pressure model using data from rock mechanics measurements. We suspected hysteresis in the stress sensitivity curves, as we failed to reconcile our modelled time-shifts with the observed legacy data. In addition, a significant loading event prior to an unloading event suggested different stress sensitivity should be applied to the model. From production start up to the baseline, we have 18 years of primary depletion, which resulted in compaction of the chalk. This essentially moves the stress sensitivity curve of the rock to a lower porosity curve. During the injection period that lasted 10 years after depletion (between baseline and monitor), pore pressure in the reservoir was expected to increase by about 5000 psi and more. A rock that has gone through an initial cycle of depletion followed by re-pressurisation becomes less stress sensitive compared to the same rock undergoing only injection, suggesting possible excess deformation due to internal defects from the first process (Holt, 2013). It was found that stress sensitivity was larger during the first unloading phase than the second unloading phase and post loading. This is possibly due to irreversible closing of cracks and mesoscale fractures. This understanding is tested in our rock physics modelling.

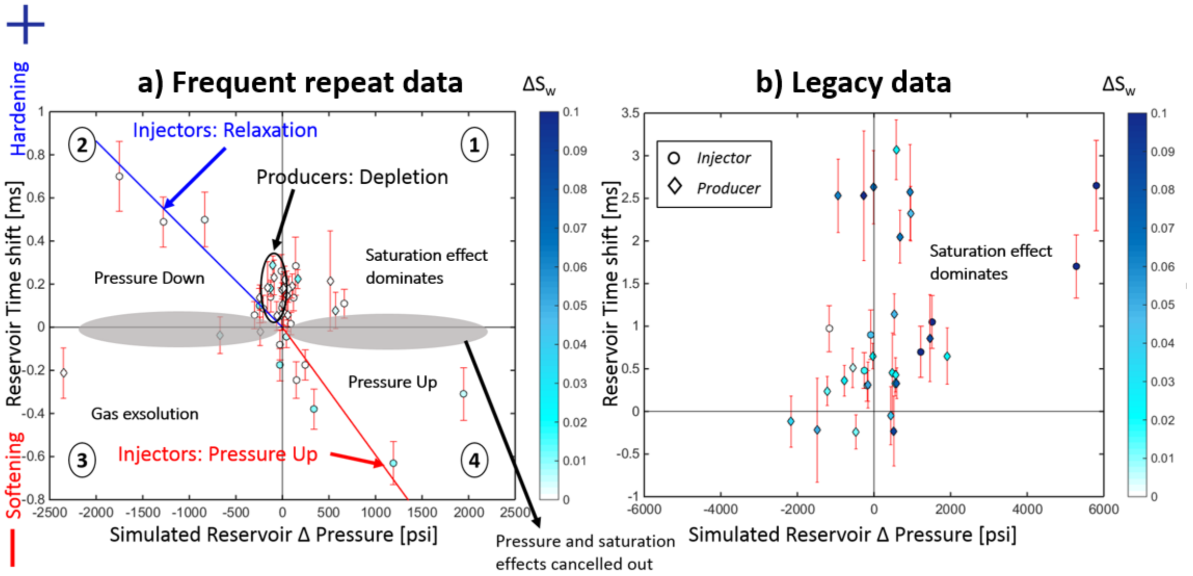
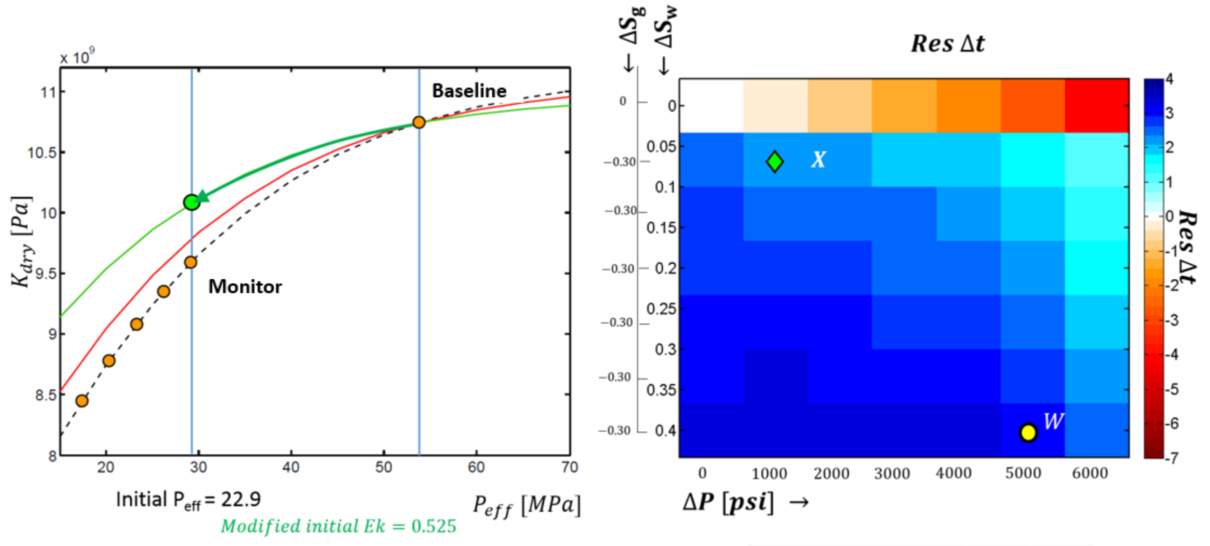


Figure 2 ***a)*** *Cross-plotting of reservoir time-shift for frequent repeat data with reservoir pressure change overlaid with conceptual model predictions.* ***b)*** *Legacy data reservoir time-shifts versus reservoir pressure change.*



Reservoir time shift	*X*	*W*
Δt_{data} (ms)	2.5	2.65
Δt_{model} (ms)	2.33	2.95

Figure 3 *(Left) Evolution of dry frame as a function of decrease in effective stress using modified stress sensitivity parameters. (Right) Reservoir time shifts modelling for well X and W. Bottom right table shows comparison between observed and modelled reservoir time shifts for well X and W.*

We first implemented Holt's (2013) observations into our modelling, by lowering the stress sensitivity parameters in the MacBeth 2004 pressure model in an unloading scenario. This resulted in a marginal improvement in our modelled reservoir time-shift. However, since these parameters from Holt (2013) were derived from experiments carried out on synthetic high porosity sandstone (mechanically similar to shallow, poorly cemented high porosity reservoir sand), we decided to modify the stress sensitivity unloading parameters further to match our observed reservoir time-shift. As a result of reducing the unloading parameters by 40% from their initial values (Figure 3 left – represented by green curve), our rock-physics modelling result shows a better agreement with the observed reservoir time shifts, showed in Figure 3(right). For the frequent repeat data, our modelling results are consistent with the observed reservoir time-shift recorded at the wells, in which the unloading (pressure increase) effect caused a stronger 4D reservoir time shift signal compared to loading (pressure relaxation). The 4D seismic data acquired after different production mechanisms provided us with a way to update the stress sensitivity parameters to accurately capture the loading and unloading characteristics of the chalk.

Conclusions

There is a strong correlation between time-lapse time-shift and the different production mechanisms in the field. The pursuit of understanding the reservoir level signature is an important one, in order to achieve that, we need to have a good handle on the different parameters that can affect the predictions of the reservoir signals via a rock physics model. Of all the parameters of the petro-elastic model, the rock stress sensitivity is the one which carries the highest uncertainty: the main reason for this is the difficulty of measuring this parameter using core samples. Core damage, frequency dispersion, geomechanical effects and the selection the effective stress coefficient could lead to underestimation of the rock stress sensitivity, whereas the rock drying processes, the presence of shales, imperfect stress recovery and stress asymmetry could lead to overestimating it. In the work, we showed how hysteresis or imperfect stress recovery could lead to overestimation of the unloading behavior of the rock, resulting in a lower speed up estimation for the reservoir time shifts attribute.

Acknowledgements

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