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The Effect of Shale Activation on 4D Seismic Interpretation of a UKCS Field

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SUMMARY

Shale typically has a low but non-negligible permeability of the order of nanodarcys that could affect magnitude and pattern of pressure diffusion over the lifetime of a producing field. The implications of this phenomenon for reservoir monitoring by 4D seismic can be significant, but depend on the geology of the field, the time-lines for production and recovery, and the timing of the seismic surveys. This study assesses pressure diffusion effects for an offshore Paleocene turbidite reservoir in the UKCS. First, we evaluate the petrophysical characteristics of the overburden, intra-reservoir and underburden shales. Next, we adjust the simulation model to activate the shale-related contributions, and then perform 3D and 4D seismic modelling. In our reservoir of interest, fluid flow simulation results indicate that gas dominates the 4D seismic signature. It is found that activation of the shale improves the overall reservoir connectivity, which in turn impacts strongly on the breakout and distribution of gas liberated from solution and improves the fit to the observed seismic data.

Introduction

Well known intrinsic property values have contributed to shales being regarded as impermeable rocks during modelling and simulation. This is considered valid as conventional fluid flow through pure shales is almost negligible during the hydrocarbon production time scale. This is the reason why they are represented in reservoir simulation models as inactive cells. Classical reservoir characterisation treats all shales as pure mudstones (almost 100% clay), when most intra and inter-reservoir shales are heterogeneous and anisotropic. It has been shown that shale permeability, even an order of a few nanodarcys, permits pressure diffusion that impacts production induced elastic changes in the reservoir recorded in time–lapse seismic monitoring (MacBeth et al. 2011). To further evaluate pressure diffusion in shales and the effect on 4D reservoir signatures, the approach of this study is to include the internal architecture of the shale in the classical 3D and 4D seismic modelling workflow. The start point is to recognize how the geological and simulation models represent shales and how to make them active, populating shale cells with static (NTG, porosity) and dynamic properties (permeability and transmissivity), estimated with a detailed geological analysis, upscaling, and honouring the log data. In this workflow, the modelling of shale's capillary pressure inhibit fluid interaction between shales and reservoir (pressure gradient is not high enough to change shale's saturation). Activating shales in the simulation model enables pressure diffusion with the reservoir, to analyse the effect of this process, simulation model outputs are used to perform synthetic seismic modelling. The mismatch between the observed 4D and the synthetic seismic responses for inactive and active shale models is compared to determinate the degree of shale contribution to the reservoir dynamic behaviour.

Field dataset

Our field of interest is an offshore oil and gas field located in the United Kingdom Continental Shelf, approximately 130 kilometres West of Shetland Islands in the North Atlantic Ocean. Discovered in 1993 and on stream since 1998, the reservoir is a Tertiary live black oil accumulation (25° API) with small local gas caps, developed under a down-dip water injection plan. The reservoir consist in stacked turbidite channels with good quality (porosities between 25 – 30% and permeabilities between 200 – 1000 mD). The turbidite sequences were deposited from North to South and are cross-cut by several W-E normal faults that divides the reservoir in four compartmentalised segments (Figure 1). In this case study, shales were activated only for Segment 1.

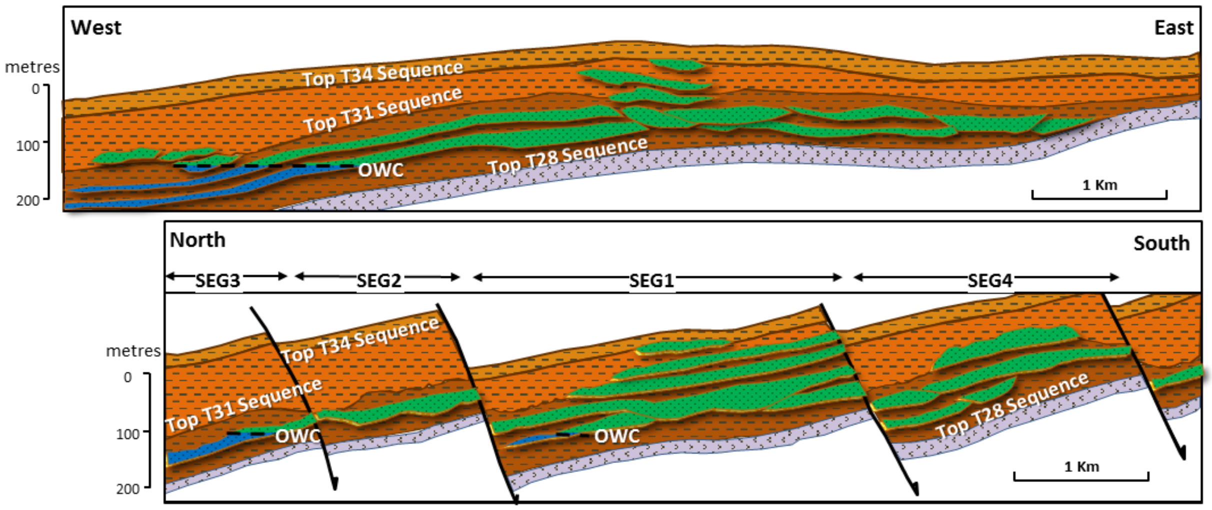

Figure 1 *Structural configuration for UKCS field used in this study. Redrawn from Leach et al. 1999.*

For the shale activation workflow, the dataset available for this study consisted of well log data, simulation model history matched to production data from August 1998 to January 2009, and the seismic data (1996 baseline, 2004, 2006 and 2008 monitor surveys).

Shale internal architecture and properties

Deep marine sediments are usually very well sorted. The distance from sediment source influx and frequency of high energy events are the parameters that determine the vertical variability in the sediments (lateral distribution can be very uniform). The internal architecture of shales associated with turbidite reservoirs is the consequence of the mixture of the energy regimes, between the permanent pelagic conditions (clay flocculation and settlement process never stops) and the episodic turbidite flows. To analyse the characteristics of shales in our field we use gamma ray well logs and compute volume of shale to establish lithological heterogeneity. Density and P-wave velocity logs determinate acoustic properties that are useful to identify sedimentation settlement patterns and compaction trends. According to these variations, shales in this field can be categorised from top to base in the following groups: overburden, inter-reservoir, intra-reservoir and underburden shales. An equal number of geobodies were created to represent these and to establish their transmissivities with the reservoir. As laboratory data is not available for this study to determinate shale composition, a regional analysis is performed coupled with an intensive log data characterisation to establish mineralogy and clay provenance. Shales in this field have an average composition of 65% clays and 35% of silt. Paleogeographic and sediment source analysis established that the clay fraction of shales in this area are dominated by illite (around 60% of clay volume), with a variable distribution of montmorillonite (more abundant at the base) and chlorite. Once that clay type and content was defined, shale static and dynamic properties are calculated by rock physics analysis and applying the empirical equations of Yang and Aplin (2007). The range of estimated values for the properties used to populate shale cells in simulation models is given in the table 1.

NTG	Porosity	Horizontal Permeability	Vertical Permeability
0.07 – 0.16	0.14 – 0.16	30 – 100 nD	7 – 14 nD

***Table 1** Range values for the static and dynamic properties for the shales in our field of interest.*

Reservoir modelling

In order to evaluate the effect of shales in this dataset, not only are inactive cells activated, but also the geometry of the simulation model is modified. 20 layers with constant thickness (1 metre) are added at the top of the reservoir as overburden, also 20 layers more are added to the base as the underburden. The lateral geometry and boundaries of the selected field segment are kept as originally delineated. The shale fluid-flow properties of capillary pressure and relative permeability are calculated using results from shale gas injection tests (Sigal, 2013) with similar pore throat geometry. Shale saturation (100% water) and pressure, were modelled creating an additional for the geobodies containing the different types of shales. Transmissivities were defined as only permeability dependent, so the value assigned for shale transmissibility was 1 between shale geobodies and the reservoir. Rock compaction tables and stress sensitivity were modelled using the equations of MacBeth (2004) for pressure dependence. To determine the impact on the reservoir connectivity four models were considered: an inactive (control), active shale model, and two equals' models (active and inactive shale) with all transmissivity multipliers removed.

Pressure and saturation and production results

Because time dependency of shale pressure diffusion process, saturation and pressure results were studied at the end of the simulated period (10 years of production/injection). Regarding pressure changes, in the active shale models the build-up signal corresponding to water injection is spatially more extended and production induced depletion is lower due the addition of extra volume to the reservoir. Variations in saturation for active shale models display less gas exsolution in channels facies, but more in the overbank/levee deposits. Total oil, gas and water production (Figure 2) for the models without the transmissivity multipliers gave a better match to the historical production data when shales are activated. This indicated that for this field, the use of some multipliers appeared to be compensating for the effect of the shale.

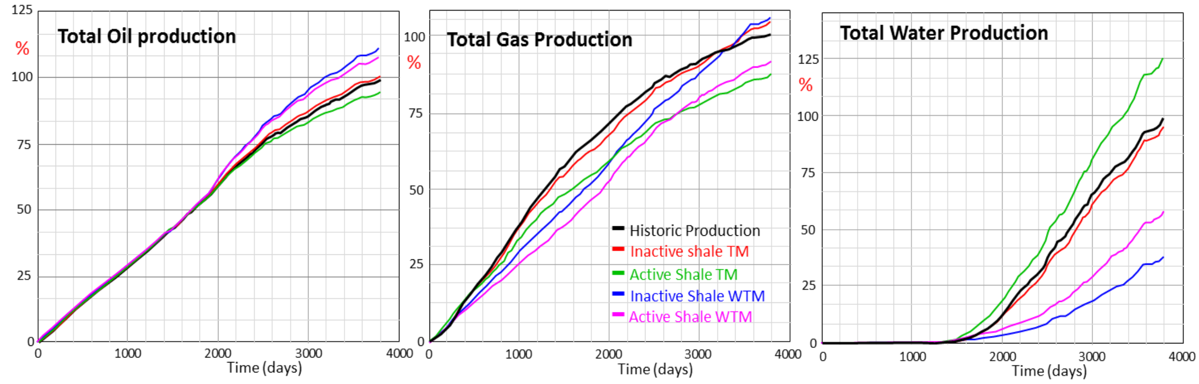

Figure 2 *Total oil, gas and water normalized production for the modelled scenarios, historic production data displayed as reference (black line that represent the accumulated 100%).TM=transmissivity multipliers included, WTM=transmissivity multipliers removed.*

Synthetic seismic modelling and 4D response

Simulator to seismic modelling is performed for the four scenarios, and 4D seismic differences computed between pre-production in August 1998 and August 2008, and these are compared with the observed 4D seismic response (Figure 3). The predicted 4D signal for active shale models not only better fits the hardening response (that is strongly influenced by the application of transmissivity multipliers), also the distribution of the softening signal is more accurate. This implies that pressure connectivity between reservoir facies through shales plays an important role in the process of gas exsolution. Indeed the distribution of the observed softening (Figure 3) matches the spatial distribution of the levee facies very well (see dark blue facies with NTG=0.2 in Figure 4). In the original model these are not connected to channel geobodies. Shale activation, creates a degree of pressure connectivity between those facies and as the reservoir's pressure (200 bars) is very close to bubble point (194 bars), any induced depletion will produce gas exsolution and consequently soften the 4D seismic signal.

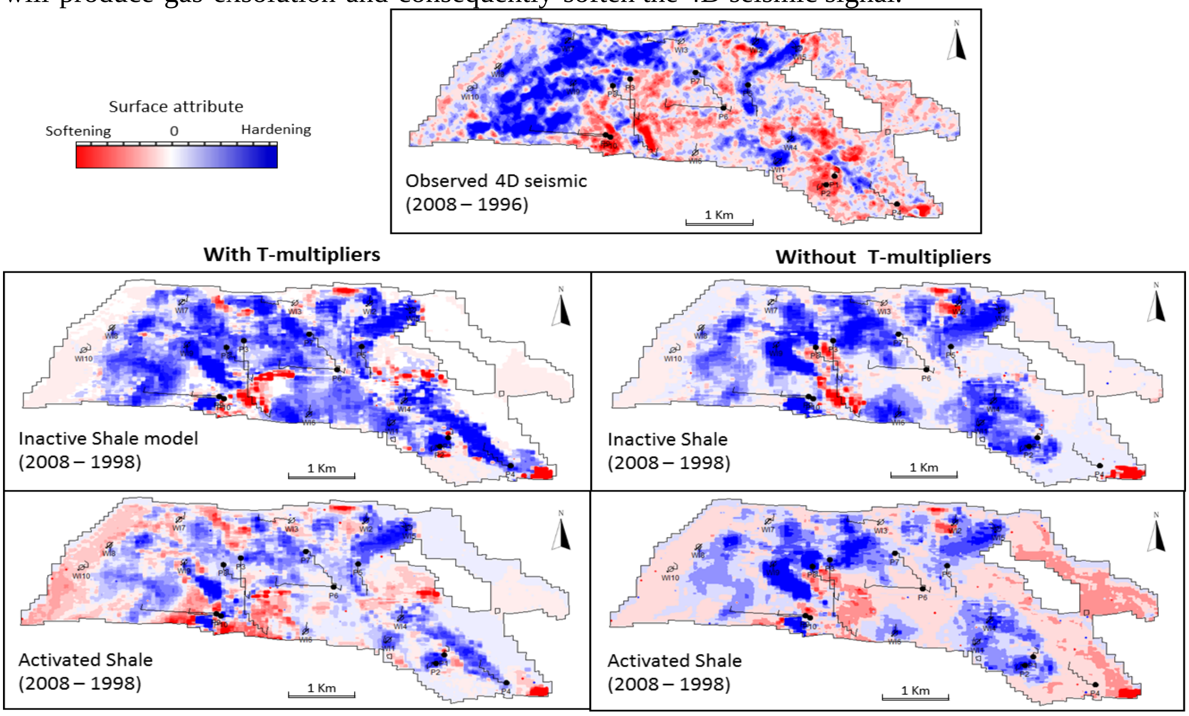

Figure 3 *Comparison between observed and synthetic 4D seismic response (differences between RMS Amplitudes from 1998 and 2008).*

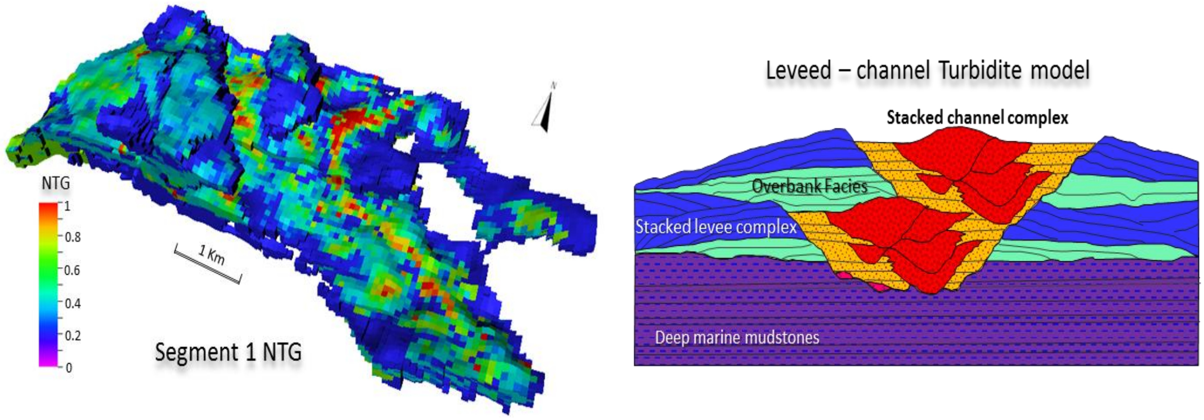

Figure 4 *Left: net to gross distribution in the segment of our study. Right: schematic model of a levee – channel turbidite model.*

Conclusions

The reservoir-related shales in the UKCS field studied indicate clear dynamic behavior. Their activation improves model fit to the 4D seismic data and helps to understand the reservoir connectivity by reducing the dependence on transmissivity multipliers inserted into the simulation model. Shale characterization provides a more accurate modelling of the synthetic seismic data. The specific pressure conditions of our field and the geometric relationships between the shale and reservoir sands, mean that shale pressure diffusion has a strong impact and is immediately visible via the process of gas exolution. Shales can therefore impact the distribution and polarity of the 4D seismic response and its consequent interpretation.

Acknowledgments

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