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"Inversion replaces the seismic signal by a blocky impedance response that is related to properties of the rock interval rather than to the interface, to which the seismic reflection amplitude responds, thereby facilitating interdisciplinary communication."

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Using simulation and production data to mitigate ambiguity in interpreting 4D seismic inverted impedance in the Norne Field benchmark case

Masoud Maleki

Introduction

Time-lapse seismic data (or 4D seismic) have become increasingly important to monitor and manage reservoirs over the last few decades. There are various applications for 4D seismic surveys but 4D data are mostly used to monitor changes in producing hydrocarbon reservoirs. To quantitatively identify those production activities responsible for 4D seismic variations observed on the Norne Field, Maleki et al. (2017) recommended inverting 4D seismic data to the impedance domain. However, interpretation of 4D seismic data posed many challenges in the Norne Field as the field experienced intense production activity from 1997 to 2006 (Maleki et al. 2018b), which included water and gas injection. This study focuses on analyzing and discussing the impedance anomalies derived from 4D inversion and predicted changes in time-lapse impedance for the Norne benchmark dataset. To thoroughly investigate inversion anomalies, we compare selected 4D inversion scenarios against well-history and engineering data to identify anomalies caused by production-related changes and the injected fluids. Furthermore, we analyze these scenarios and compare anomalies with the available flow-simulation model to suggest specific regions of the field where updates to the simulation model might be appropriate.

Norne Field and benchmark dataset

The Norne Field is located on a horst block in the Norwegian Sea,between the Vøring and Møre basins (Figure. 1a). In the Norne Field, the hydrocarbons are found in sandstone from the Middle and Early Jurassic age, and are subdivided into four different formations from top to base: the Garn and Ile formations of the Fangst Group; and the Tofte and Tilje formations of the Båt Group (Figure 1b). The time-lapse seismic dataset used in this study includes a 4D-processed, post-stack base seismic survey (2001) and a monitor seismic survey from 2006. Besides seismic data, the dataset also comprises well logs, production and injection history data up to 2006, and a simulation model. Additionally, in the current study, the base survey initial impedance model (for time-lapse inversion) is provided by Maleki et al. (2016).

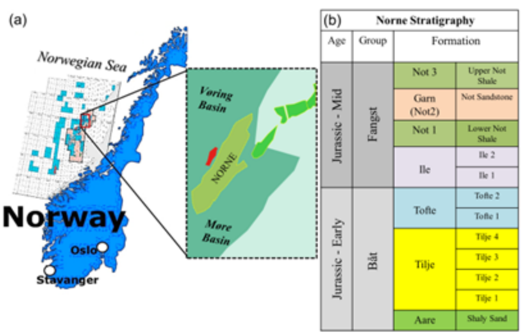

Figure 1: *a) Location of the Norne Field in the Norwegian Sea. (b) Stratigraphy of the Norne Field.*

Time-lapse inversion and interpretation

In this study, the interpretation is divided into two main steps. First, we inverted the Norne base and monitor surveys using a 4D post-stack, model-based inversion from Hampson-Russell Software. We then referenced the production activity and engineering data to comprehensively interpret the observed 4D impedance anomalies (softening or hardening signals) to suggest causal factors: pressure changes, fluid variations or changes unrelated to production activity.

The 4D inversion uses a post-stack, model-based inversion algorithm but with different initial models for each vintage. The method applies two separate 3D model-based inversions and computes the impedance change by straightforward subtraction of the inverted acoustic impedance volumes. The summarized workflow for the 4D model-based inversion follows:

(a) Volumetric interpretation by picking the main reservoir horizons in the base survey.

(b) Create the 3D P-impedance, time-domain starting model, using the main horizons picked in the base seismic survey (which act as geological markers), well-log data (from the previously mentioned nine wells) and a low-pass frequency filter that cuts frequencies above 10 Hz.

(c) Re-pick the main horizons in the monitor survey (without time-shift corrections) to capture the sought production-induced velocity changes in the reservoir.

(d) Update the low-frequency P-impedance model of the base survey (using velocity changes from step (c) and assuming that density is constant) to generate the monitor survey starting model.

(e) Analyze inversion parameters, and apply model-based inversion to the base and time-aligned monitor surveys to produce inverted base and time-aligned monitor impedance volumes.

Results and discussion

In the 4D seismic inversion results, we observed a wide range of hardening (increase in impedance over time) and softening signals (decrease in impedance over time) in the southern region of Norne Field. Segment C contains four injector wells: C-1H, C-3H and C-4AH (water and gas), and C-2H (water). Figure 2a maps acoustic impedance differences below the top of the Garn Formation and Figure 2b maps these below the top of the Ile Formation. The areas surrounding the producer wells showed slight changes in impedance, while greater differences in impedance were observed around the injector wells (anomalies SC-1, SC-2 and SC-3).

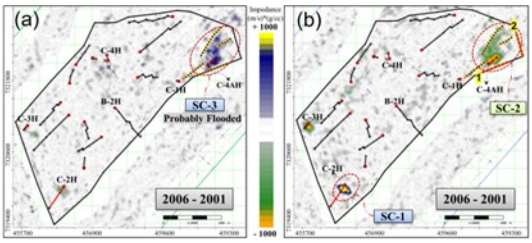

Figure 2: *4D acoustic impedance maps for (a) below the top of the Garn Formation and (b) below the top of the Ile Formation.*

Figure 3a illustrates the acoustic impedance changes around injector C-2H. Anomaly SC-1 is an increase in impedance, indicating strong hardening of the signal across the Ile Formation. Since the hardening signal is concentrated around the well location and C-2H injected water from 1999 until 2006, anomaly SC-1 might be solely driven by water-saturation increases and not a pressure-related anomaly. Furthermore, well B-2H started producing significantly more water after January 2004, highlighting that the detached area was partially flooded and the OWC rose to the upper part of the Ile Formation (see Figure 3a). Comparing the SC-1 anomaly with the simulated model, we note that the simulated pore pressure below the top of the Ile Formation remained almost constant (Figure 3b). Meanwhile, the water saturation in this region increased significantly from 2001 to 2006 (Figure 3c). However, the simulated water saturation spreads along the Ile Formation, and is not concentrated around injector C-2H and producer B-2H, as in Figure 3a.

Figure 3d illustrates the softening (anomaly SC-2) and slight hardening of the signal (anomaly SC-3) around gas and water injector C-4AH. Based on well information, C-4AH injected water into the Ile Formation until January 2005, which is a water-saturated layer in this region, and gas injection started in 2005, lasting 6 months. We therefore conclude that the likely cause of anomaly SC-2 is a combination of increased pore pressure and reduced fluid bulk modulus, due to the 6 month injection of gas. It is probable that anomaly SC-2 is concentrated around injector C-4AH because gas injection was relatively short. This would explain the almost-uniform increase in simulated pore pressure for the entire region (Figure 3e) which is not localized around injector C-4AH. We also cannot rule out that the hardening anomaly SC-3 could be a result of a significant increase in water saturation (Figure 3d) due to flooding from injector C-4AH reaching the Garn Formation. Alternatively, the simulated water-saturation change (Figure 3f) suggests that water from injector F-4H in segment G has crossed the segment boundary, reaching the top of the Garn Formation around anomaly SC-3. The analysis shows that compartmentalization in the simulation model may still require reconsideration, even when there is a good match with observed anomalies.

"Joint interpretation of time-lapse seismic inversion with the flow-simulation model results builds confidence in identifying the production effects in the Norne benchmark case, and provides valuable input for reservoir characterization and monitoring."

Conclusions

The challenges facing time-lapse seismic interpretation of the Norne benchmark case are significant due to the intense production activity between 2001 and 2006. We have shown that joint interpretation of time-lapse seismic inversion with the flow-simulation model results builds confidence in identifying the production effects in the Norne benchmark case. Indeed, combined interpretation is key to understanding production/injection effects within the reservoir segments of the Norne benchmark case. Additionally, these results could be used to guide a seismic history-matching procedure to update the simulation model in the parameterization phase, for instance. For more details refer to Maleki et al. (2018a).

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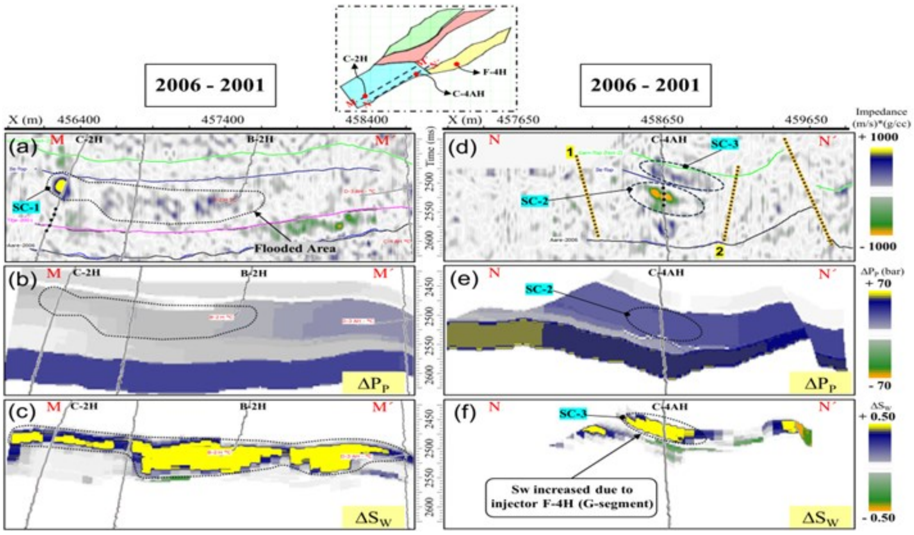

Figure 3: *Profiles of the inverted impedance difference and simulation model for segment C.*

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