4D seismic close-the-loop impacts business decisions at the Okume Complex, Equatorial Guinea

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Abstract

Time-lapse seismic "4D" close-the-loop (CtL) technology can play a significant role in creating robust static and dynamic models for deepwater reservoirs, as demonstrated by a case study in Equatorial Guinea, West Africa. Initial static and dynamic models for the field were built using well data and seismic attribute volumes, from prestack 3D and 4D simultaneous angle versus offset (AVO) inversions, in conjunction with rock-physics analysis. We then used seismic inversion technology to estimate static and dynamic reservoir properties over the field's life, including porosity, net-to-gross (NTG), and changes in both fluid saturations and pressures. To model changes, we used a baseline and two high-repeat 4D seismic surveys as input to the inversion work. The study shows how the many competing production effects and their combined nonunique 4D signatures posed a serious challenge to achieving history-matched dynamic models consistent with 4D seismic data. However, 4D CtL technology served as a guide for reservoir engineers updating the dynamic model simulations by providing direction and constraints for matching pressures, waterfronts, and gas breakout areas. Moreover, 4D CtL helped refine existing mental sweep models based on historic field performance and available tracer data. Previous models largely matched this data but used some undesirable manual edits in the simulation model. This has allowed for more geologically sound model adjustments, especially to the water-injection strategy, which obtained promising results. A number of targets were dropped based on 4D matched simulation models that showed elevated water saturations with a high chance for early water breakthrough and reduced well recovery. On the other hand, new targets similar to the one in this case study were identified and/or derisked. This successful case study demonstrates the potential of rock physics, especially when integrated with prestack AVO inversion techniques, to produce a set of attributes that accurately explain the time-lapse production effects observed on seismic.

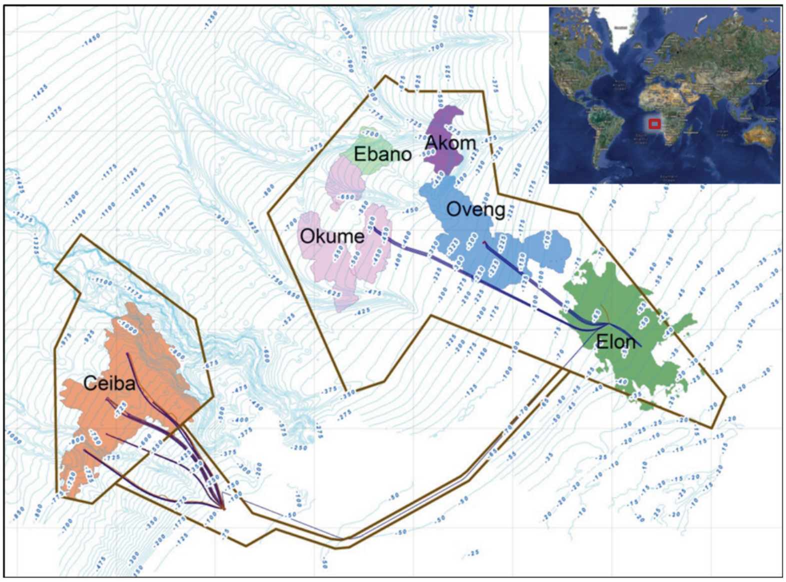

Figure 1. Location map of the five fields in the Okume Complex and the nearby Ceiba Field. Data for the case study are from sands in the Oveng Field.

Introduction

Reservoir surveillance during production is key to meeting the goals of reduced operating cost and maximized recovery. Differences between actual and predicted performance typically are used to update the reservoir's static and dynamic model and revise the depletion strategy. The changes in reservoir fluid saturation, pressure, and temperature that occur during production also induce changes in the properties of reservoir and bounding rocks that, under favorable conditions, may be detected by 4D seismic data.

This case study examines integrated reservoir dynamic model simulations and 4D seismic data acquired over the Oveng Field in the Okume Complex. The Okume Complex contains five brownfields located within the Rio Muni Basin, offshore Equatorial Guinea (Figure 1). In brownfields, the need for effective reservoir monitoring becomes increasingly critical in the face of diminishing reserves and growing urgency for infill drilling and optimized recovery. Therefore, mapping reservoir saturation and pressure changes is vital for targeting bypassed hydrocarbons, evaluating well integrity, and drafting an overall reservoir management strategy (Nasser et al., 2016). 4D seismic is a proven technology for mapping reservoir dynamic changes over time, manifested in a form of amplitudes and time shifts between seismic reflections. 4D close-the-loop (CtL) methodology, which uses dynamic model simulations as input, provides an efficient, quantitative way to interpret 4D seismic data.

The 4D close-the-loop workflow

Forward-looking 4D seismic feasibility studies determine whether an observable time-lapse signal due to production effects is a result of pressure depletion, saturation change, or both combined. However, in a 4D CtL study, the forward-modeled

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synthetic time-lapse seismic response is directly compared to time-lapse seismic data for evaluation and interpretation. In both cases, synthetic time-lapse seismic volumes are generated using a reservoir dynamic simulation model as input. Rock and fluid property relations derived from appropriate well logs and core measurements are combined in a single rock-physics model. The rock-physics model is used to establish the link between static and dynamic reservoir rock and fluid properties and their corresponding elastic properties. Uniaxial strain core laboratory measurements are used to determine the relationship between the rock's bulk and shear moduli and the changes in effective stress. A reasonable repeatability of the synthetic baseline survey, similar to that achieved in real seismic data, is assumed. Seismic amplitudes and/or elastic attributes, such as P-impedance and S-impedance at the reservoir level, are then extracted from the base and monitor synthetic data. The base and monitor synthetic data differences are then compared with real-data 4D differences for interpretation. Assuming a confident rock-physics model has been established, any mismatch between the synthetic and real 4D signal reflects the inaccuracy of the dynamic simulations and prompts an update of the reservoir dynamic model. Pressure and saturation changes are adjusted by modifying static and dynamic properties until a reasonable match is achieved.

This workflow, known as 4D CtL, is schematically illustrated in Figure 2. Moreover, the synthetic 4D response in Figure 2 is the final result of the CtL workflow for this case study. More possibilities for closing the loop with 3D and 4D seismic data, production data, and the simulation models have become increasingly possible with the advent of techniques to determine 4D impedance changes (El Ouair et al., 2005; Kjelstadli et al., 2005; Toinet et al., 2011; Nasser et al., 2016) and pressure and saturation changes (Tura and Lumley, 1999; Landrø, 2001; MacBeth et al., 2006; Ball et al., 2014; Nasser et al., 2016).

The success of the 4D CtL workflow requires that the initial static model, which the dynamic model and further simulations are based on, is consistent with seismic data. This was confirmed by conducting a 3D CtL study, using a series of static model scenarios as input, before the 4D CtL workflow. The synthetic seismic, elastic volumes, and attribute maps all were generated automatically for more efficient model-data evaluation. However, at this stage the model-data comparison was primarily qualitative, requiring careful inspection and evaluation. A more quantitative and automated approach might be necessary for greater efficiency.

Geologic setting

The Okume Complex is located within the Rio Muni Basin, offshore Equatorial Guinea. Five producing fields in the Okume Complex were deposited within two submarine canyons; the deeply incised Elon Canyon meanders northwest through the Elon, Oveng, Akom, and Ebano fields, while the Okume Canyon extends northwest from south of the Elon Field through the Okume Field (Figure 1). The canyons are separated by an erosional remnant that is locally cored by salt. Deposition of high-quality Campanian-aged turbidite sands occurred within a mid- to upper-slope environment. These sands have a higher degree of confinement at the proximal Elon Field, displaying several stacked sands and evolving into a weakly confined environment at the distal Okume and Ebano fields, which display less vertical stacking of sand units and more lateral movement of depositional axes. The preserved depositional architecture exhibits extreme permeability heterogeneity, especially perpendicular to the canyon axis, which leads to a high degree of connectivity complexity both vertically and horizontally within the reservoir section. This creates significant challenges for dynamic model simulations and 4D interpretation. Hydrocarbon-filled sands are of a lower acoustic impedance and lower V_P/V_S ratio compared to the bounding nonreservoir shales, resulting in a class 3 AVO seismic response. Clean sand porosities in the 30% range give rise to strong fluid effects on seismic, suggesting that saturation effects will override pressure sensitivities in a coupled saturation-pressure 4D scenario.

The reservoir section is primarily a mixture of quartz-rich high-porosity high-permeability sandstone and shale. To model the reservoir geology, a facies model was developed based on available core and well log data. This model was designed to be applicable during field development when only wireline log data would be obtained to facilitate geocellular modeling and property assignment. Sedimentary facies analysis of available conventional cores demonstrates that the reservoir elements were deposited by turbidity current and debris flow mechanisms. Interbedded and overlying mudstone intervals were deposited by waning turbidite flows and hemipelagic processes. Using well data and baseline seismic data acquired in 2003, three primary facies associations were identified and further divided into six total facies. Following

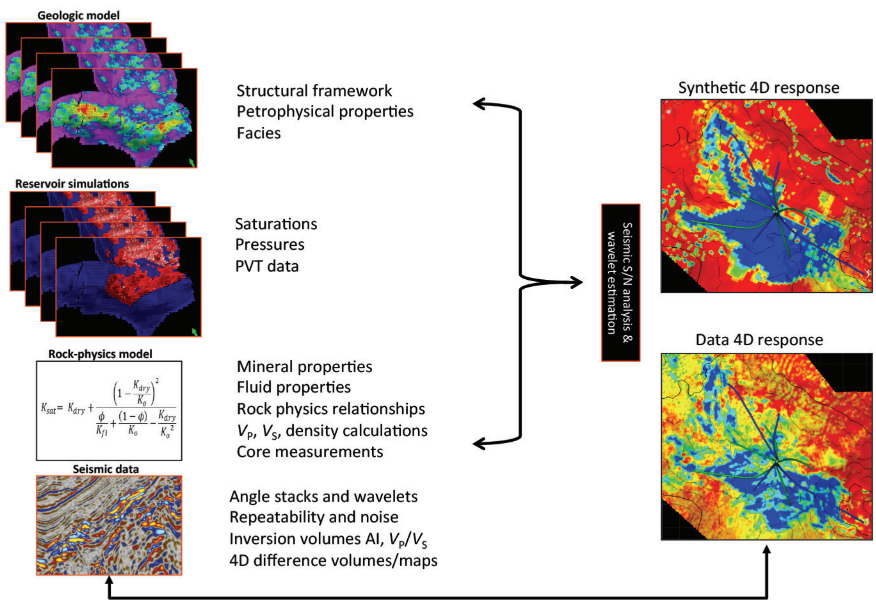

Figure 2. Schematic illustration of the 4D CtL workflow, showing the final 4D CtL result achieved for this case study and the synthetic 4D response, for comparison with the data 4D response.

the acquisition and interpretation of the two repeat surveys in 2010 and 2014, 4D seismic signatures related to either reservoir saturation and/or pressure changes observed on 4D difference maps were used to influence the facies type and distribution in the geologic model. This has proven effective in quickly achieving a history-matched dynamic model, which was later refined using the 4D CtL methodology, providing a model that is consistent with seismic data.

Data

The Okume Complex was discovered in 2001 on a standard 3D marine seismic survey acquired in 1999. 3D seismic data acquired in 2003 formed the basis for full field interpretation and development and served as a baseline for subsequent monitor surveys acquired in 2010 and 2014. The repeatability of the monitor surveys is high with a normalized root mean square (Kragh and Christie, 2002) between 10% and 15% in areas of no production, making them appropriate for monitoring the field's time-lapse saturation and pressure changes. There are also approximately 60 exploration, appraisal, and development wells drilled in the Okume Complex; about 15 wells were used in the 3D and 4D prestack inversions for rock-physics calibration and seismic phase correction. This inversion work formed the basis for both 3D/4D interpretation and CtL workflows in which model elastic properties and their differences were compared to their seismic counterparts derived from rock-physics analysis and seismic AVO inversion (Nasser et al., 2016).

Reservoir static/dynamic model

Generally speaking, seismic data can be effective in identifying hydrocarbon-bearing sands that are at or above tuning thickness (Rayleigh's criterion); however, these data lack the resolution required for static and dynamic modeling. The data collected were unable to resolve approximately 30% of the estimated oil in place contained in subseismic resolution thin beds identified at the Okume Complex. Therefore, a two-tiered Bayesian facies population methodology was developed to address these data issues. This two-tiered approach combines the seismic data's ability to discriminate sand-prone and sand-poor regions with geostatistical methods to populate facies and rock properties at a resolution necessary for geomodeling. All potential seismic volumes (full stack data, acoustic impedance, shear impedance, V_P/V_S ratio, and oil saturation) resulting from a prestack seismic inversion were screened for their ability to discriminate sand-prone from sand-poor facies. Each volume was ranked based on the Bayes factor (discrimination uplift) achieved by both the sand-prone and sand-poor facies. A discrimination threshold value was selected that optimized both the Bayes factor and the gross rock volume affected. Based on petrophysical logs, six facies were identified in the Okume Complex reservoirs. 4D AVO inversion was used later to highlight areas and zones of potentially high- or low-quality sands, depending on the interpretation of the observed 4D signal.

An increase in P-impedance over time indicates acoustic "hardening," which could be related to water replacing oil or pressure depletion. A decrease in P-impedance indicates acoustic "softening," which could be related to either overpressure or gas out of solution. On the other hand, shear impedance is practically fluid blind, which means it is only affected by reservoir compaction/expansion due to changes in reservoir pressure. For example, an increase or decrease in S-impedance over time could be related to either pressure depletion or overpressure, respectively. Due to the high porosity and soft rock frame of the Okume Complex reservoir sands, the fluid replacement response dominates the pressure response on the P-impedance attribute. For example, a sand could be overpressured by 1000 psi due to water injection, but if the oil has been replaced by water, then the P-impedance will show hardening while the shear impedance will show softening (Nasser et al., 2016). This understanding of the 4D response and its relation to the underlying sand quality has been incorporated in the model-building workflow.

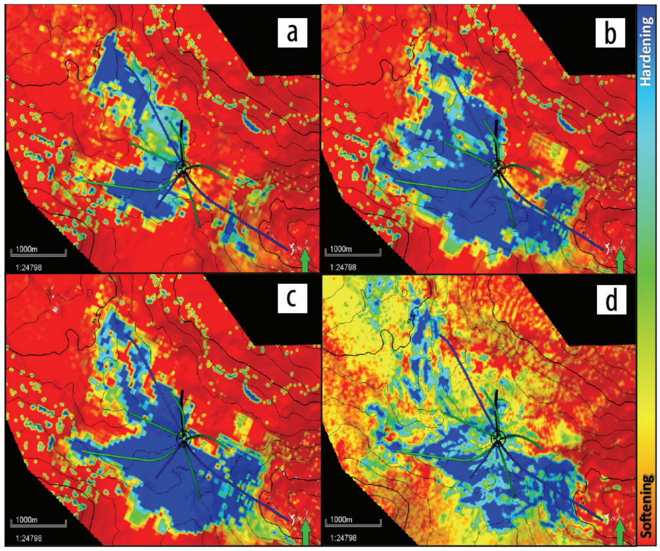

Figure 3. Panels (a), (b), and (c) show synthetic 4D seismic response and the changes required to achieve a history-matched reservoir model consistent with (d) the observed 4D seismic response. Green lines represent producing wells and blue lines represent injectors targeting stacked sands. All maps show the maximum change in P-impedance.

Time-lapse analysis

While the Bayesian facies population methodology proved very effective at populating the majority of hydrocarbon-bearing sands, there were still cases in which the seismic data was unable to discriminate between shale and thinly bedded sand-shale sequences due to resolution and resolvability challenges. This posed a significant challenge to achieving a history-matched model consistent with the 4D seismic data. Such thin sands were not present in the geologic model. Although such sands do not contribute significantly to the recoverable volume, they do influence fluid flow. Additionally, the geologic model did not properly capture connectivity between the high-quality sands, so it produced a history-matched model that was inconsistent with the seismic data.

Figure 3 shows a comparison between the history-matched model's synthetic 4D seismic response for one of the reservoir sands and the 4D seismic data response. All maps show the maximum change in P-impedance for the reservoir sand; blue indicates hardening that is primarily due to water injection, which is critical in this field. Despite the fact that the model has history matched the wells for this reservoir, it does not accurately predict flow patterns between the wells (Figures 3a and 3b). Multiple 4D CtL iterations were necessary to resolve the discrepancies between the history-matched dynamic model simulations (Figure 3c) and the 4D seismic data.

Figure 4 introduces another modeling challenge. It outlines the case study for drilling target, "T," highlighted with the white polygon. The 4D seismic data suggest the target has been overpressured by the first downdip injection well, "i1." These three maps indicate that the target sand has been overpressured, but the oil was not swept by injection water, while the model response shows no change (neither water sweep nor overpressure). Figures 5 and 6 further illustrate these observations. Figure 5 shows a cross section of the target with different pseudoimpedance seismic attributes (near and far), which indicate that the target is class 3 oil-bearing high-quality sand as also confirmed by the V_P/V_S ratio and oil saturation sections. Figure 6 shows the same cross section for the same target but with the corresponding 4D attributes. The change in the P-impedance cross sections indicates that some of the shallow sands have been swept by water or depleted, causing gas to come out of solution, while the target sand shows minor to no change due to either depletion or water sweep. However, the shear impedance change in Figures 6c and 6d indicate that the target sand has been overpressured significantly (by approximately 1000 psi, confirmed by the pressure volume estimated from the AVO inversion, Figure 9d) by the downdip injector i1. This is critical information, which will be considered when drilling this target.

Figure 7 shows the same cross section and attributes in the same order as in Figure 6, except that the attributes in Figure 7 were extracted from the history-matched dynamic model. A comparison of these cross sections shows that, despite using well-based history matching, the model was not successful in reproducing the changes seen in the 4D seismic data, especially the overpressure signal observed at the target sand. This discrepancy is likely due to the fact that the geologic model did not capture the subseismic thin sands connecting the target sand with the downdip injector.

Several iterations were made to update the geologic model, increasing the sand content and improving the communication between thin and thick sands. Figure 8 shows a much-improved match between the dynamic model simulations and the 4D seismic data. It has the same cross section and sequence of attributes as

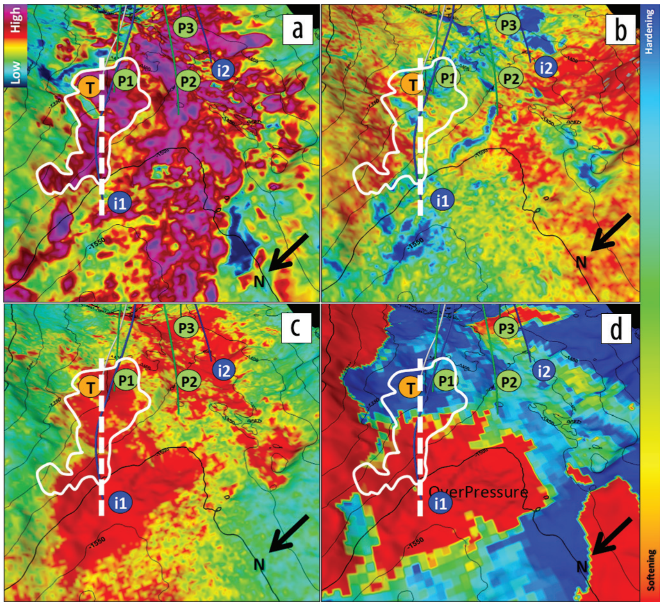

Figure 4. Attribute maps for 2003–2014. Panel (a) shows the data for oil saturation, and (b) shows the data for the maximum change in P-impedance. Panel (c) shows the observed minimum change in S-impedance, while (d) shows the dynamic simulation model's minimum change in S-impedance. Dashed line indicates location of the cross sections in Figures 5–9, while the white polygon highlights the target sand.

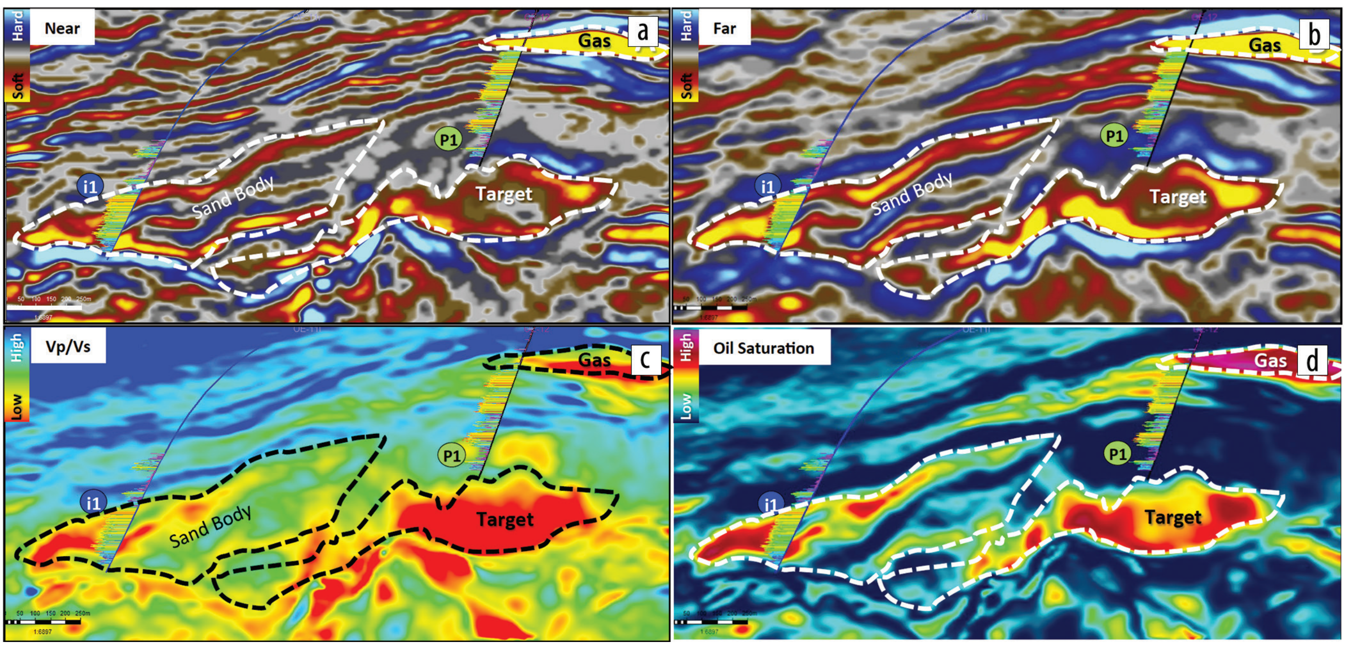

Figure 5. Cross sections through target "T." Panels (a), (b), (c), and (d) are the pseudoimpedance seismic attributes (near and far), V_P/V_S ratio, and oil saturation extracted from the baseline data.

previously shown but includes changes to the underlying facies distribution and sand connectivity. Overall, the model 4D response in Figure 8 is more consistent with the 4D seismic data response in Figure 6, especially for the target sand. The change in P-impedance primarily highlights the fluid-related changes (hardening due to water replacing oil and softening due to gas out of solution), while the change in S-impedance is practically fluid blind and only highlights pressure-related changes. The target sand in the model shows that it is significantly overpressured, in agreement with the 4D seismic data. Figure 9 shows the same cross section as previously, but highlights the underlying model's NTG and saturation as well as pressure changes (model versus data) from 2003 to 2014.

Business impact

The 4D CtL workflow helped not only in improving the geologic model's facies distributions and sand interconnectivity, but also in the target selection for infill drilling and the overall reservoir management strategy. 4D CtL helped refine existing mental sweep models based on historic field performance and

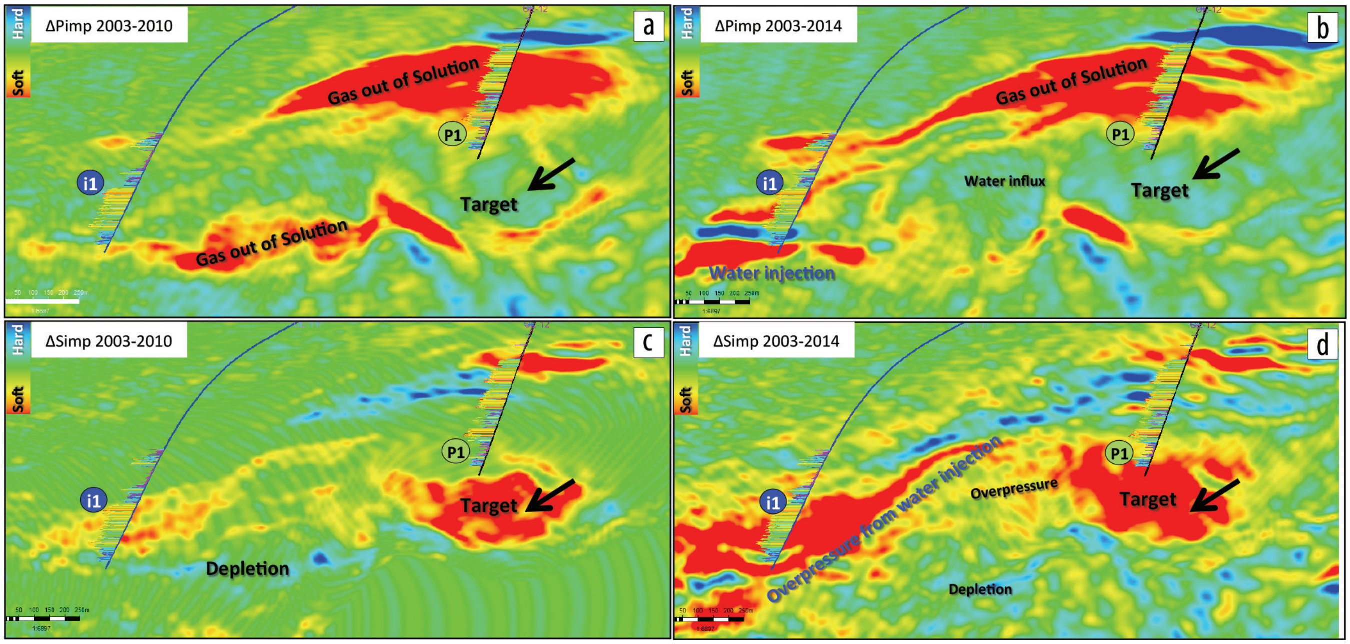

Figure 6. Cross sections through target "T." Panels (a) and (b) show the data change in P-impedance for 2003–2010 and 2003–2014, respectively. Panels (c) and (d) show the data change in S-impedance for 2003–2010 and 2003–2014, respectively.

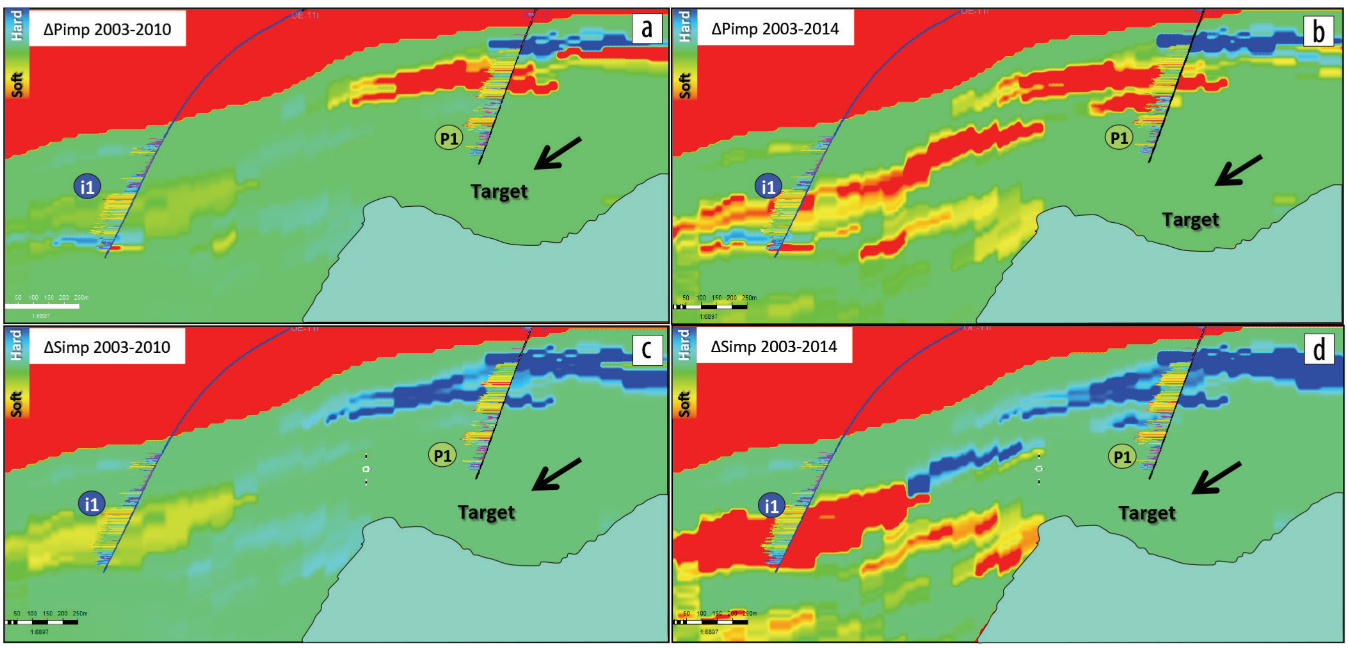

Figure 7. Cross sections through target "T." Panels (a) and (b) show the original history-matched change in P-impedance for 2003–2010 and 2003–2014, respectively. Panels (c) and (d) show the same change in S-impedance for 2003–2010 and 2003–2014, respectively.

available tracer data. Previous models largely matched this data but used some undesirable manual edits in the simulation model. These manual edits caused the initially poor match of the history-matched model with the 4D seismic data. 4D CtL identified highly permeable water sweep zones and the overall reservoir sweep pattern, which allowed for more geologically sound model adjustments. These adjustments to the water-injection strategy obtained initially promising results. Moreover, the improved understanding of sweep patterns significantly changed previous infill drilling plans. A number of targets were dropped based on 4D matched simulation models that showed elevated water saturations with a high chance for early water breakthrough and reduced well recovery. On the other hand, new targets similar to the one in this case study were identified and/or derisked. Initially, the volumes in the target sand of this case study had been deemed too small to support a pure depletion drive well or a producer injector pair, making it an unattractive target. However, the 4D CtL work identified pressure support from an existing injector, suggesting potential water drive and improved recovery, making it a more attractive target.

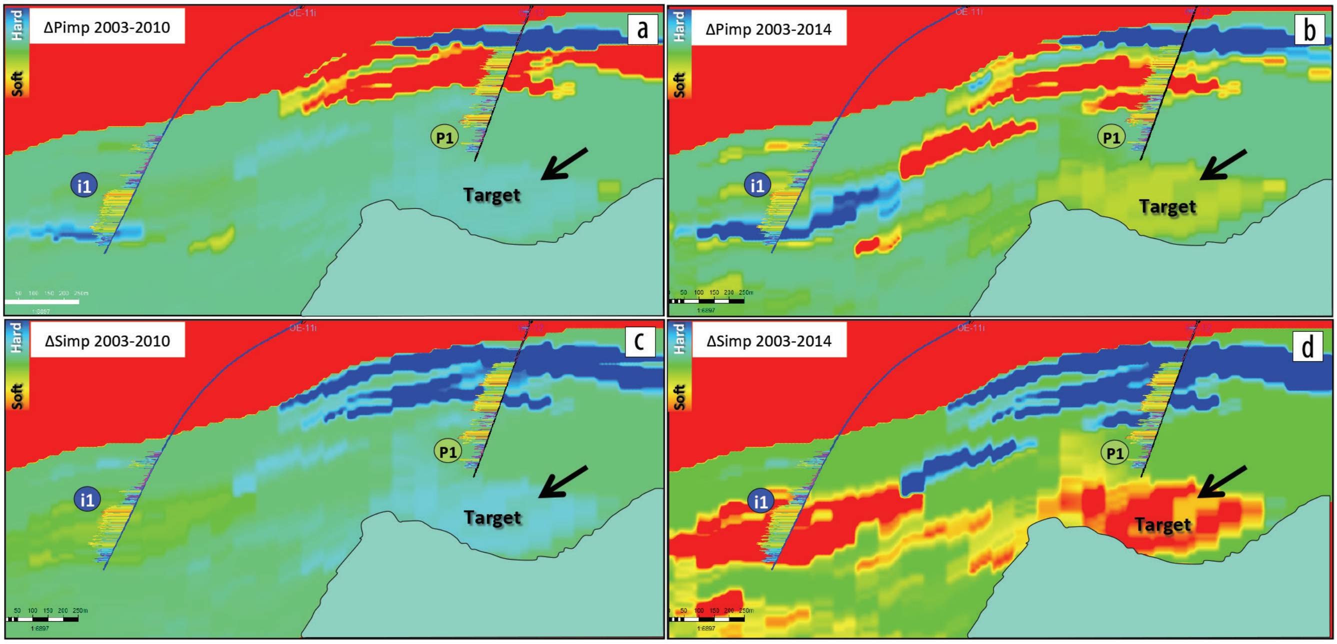

Figure 8. Cross sections through target "T." Panels (a) and (b) show the final history-matched change in P-impedance for 2003–2010 and 2003–2014, respectively. Panels (c) and (d) show the same change in S-impedance for 2003–2010 and 2003–2014, respectively.

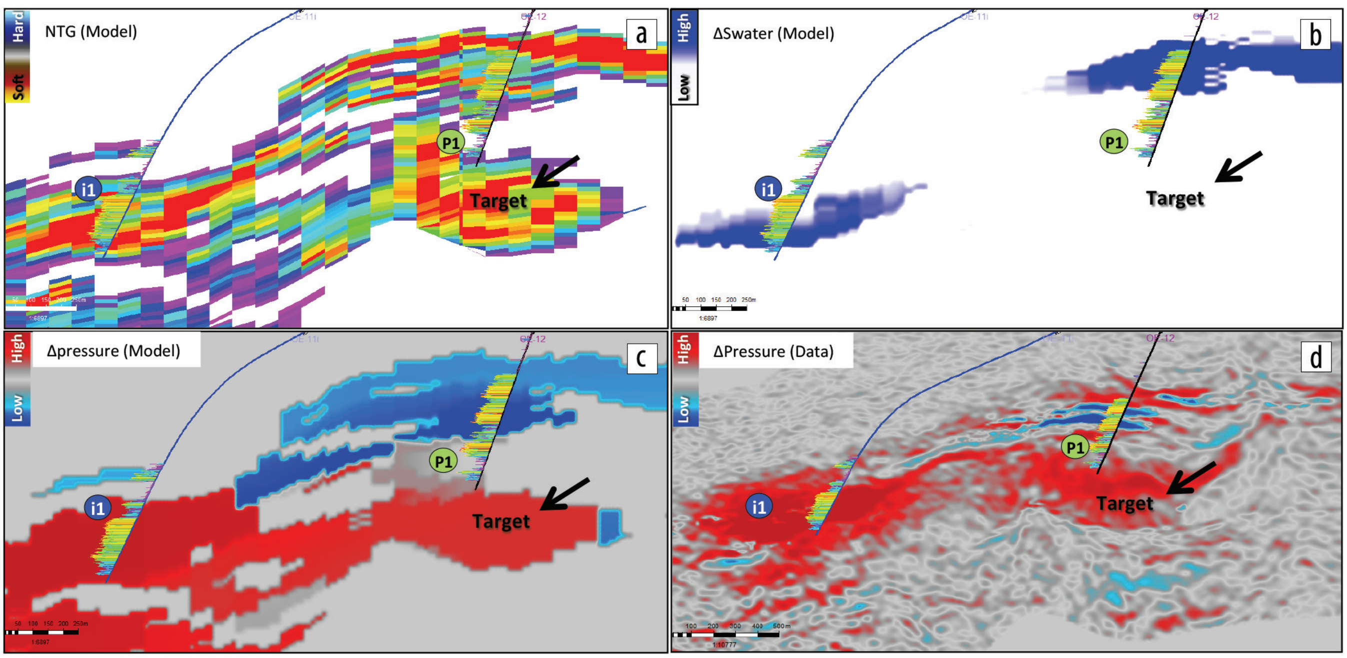

Figure 9. Cross sections through target "T." Panel (a) shows the NTG used in the final history-matched model. Panels (b), (c), and (d) show the model's change in reservoir water saturation, pressure compared to the pressure change derived from seismic data, respectively, for 2003–2014.

Conclusions

This case study shows that interpreting 4D seismic data with 4D CtL methodology enabled a more quantitative understanding of both data and models, especially when using attributes derived from a 3D and 4D AVO inversion for calibration. The 4D CtL workflow allowed the subsurface team to validate the integrity of the geologic model as well as the history-matched dynamic simulation model and led the team to adopt a more consistent data-driven improvement process for the model workflows. This was particularly important for zones where limitations in seismic resolution initially resulted in models that failed to identify thinly bedded sands. These sands may be insignificant for recoverable volume calculations but, as proven by the 4D seismic, are critical for fluid flow and overall reservoir connectivity. The example shown in this case study is one of many in which 4D differences highlighted drilling opportunities that were invisible on the 3D data. This supports the idea that 4D seismic data are particularly valuable because they can provide information about the unknown unknowns that cannot be accounted for in the initial field development plan. It also shows that conducting a value-of-information study to decide whether to acquire a 4D seismic survey before acquiring a 4D survey might not fully capture the potential value and thus might underestimate the incremental increase in net present value that a 4D survey would have added.

In this study, 4D CtL played a significant role in selecting high-quality infill targets and improved the overall reservoir management strategy. Furthermore, this 4D CtL study gave the subsurface team the opportunity to validate the geologic models and dynamic simulations in a nonconventional way and also led to much-improved communications, integration, and overall team dynamics. TLE

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References

Ball, V., J. P. Blangy, C. Schiott, and A. Chaveste, 2014, Relative rock physics: The Leading Edge, **33**, no. 3, 276–286, http://dx.doi.org/10.1190/tle33030276.1.

El Ouair, Y., M. Lygren, B. Osdal, O. Husby, and M. Springer, 2005, Integrated reservoir management approach: From time-lapse acquisition to reservoir model update at the Norne field: International Petroleum Technology Conference, IPTC-10894-MS, https://doi.org/10.2523/IPTC-10894-MS.

Kjelstadli, R. M., H. S. Lane, D. T. Johnson, O. I. Barkved, K. Buer, and T. G. Kristiansen, 2005, Quantitative history match of 4D seismic response and production data in the Valhall Field: Society of Petroleum Engineers, SPE-96317-MS, https://doi.org/10.2118/96317-MS.

Kragh, E., and P. Christie, 2002, Seismic repeatability, normalized rms, and predictability: The Leading Edge, **21**, no. 7, 640–647, http://dx.doi.org/10.1190/1.1497316.

Landrø, M., 2001, Discrimination between pressure and fluid saturation changes from time lapse seismic data: Geophysics, **66**, no. 3, 836–844, http://dx.doi.org/10.1190/1.1444973.

MacBeth, C., M. Floricich, and J. Soldo, 2006, Going quantitative with 4D seismic analysis: Geophysical Prospecting, **54**, no. 3, 303–317, http://dx.doi.org/10.1111/j.1365-2478.2006.00536.x.

Nasser, M., D. Maguire, H. J. Hansen, and C. Schiott, 2016, Prestack 3D and 4D seismic inversion for reservoir static and dynamic properties: The Leading Edge, **35**, no. 5, 415–422, http://dx.doi.org/10.1190/tle35050415.1.

Toinet, S., S. Maultzsch, V. Souvannavong, and O. Colnard, 2011, 4D prestack inversion workflow integrating reservoir model control and lithology supervised classification: First Break, **29**, no. 8, 59–66, http://dx.doi.org/10.3997/1365-2397.2011024.

Tura, A., and D. E. Lumley, 1999, Estimating pressure and saturation changes from time-lapse AVO data: 69th Annual International Meeting, SEG, Expanded Abstracts, 1655–1658, http://dx.doi.org/10.1190/1.1820849.