The impact of a quick 4D seismic survey and processing over the Halfdan Field, Danish North Sea

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Abstract

The quick turnaround of seismic processing of a 4D time lapse survey over the Halfdan oil field allowed for interpretation and integration of the new 4D results seven weeks after completion of the seismic acquisition. Analysis of the first fast track 4D dataset led to improved processing parameters and an additional demultiple application which yielded a significantly improved fast track dataset 11 weeks after the seismic acquisition was completed. The repeat 4D seismic survey was acquired in the summer of 2012 in order to provide a better understanding of the sweep efficiency from the line drive water flood, guide future well interventions and improve the reservoir model. The baseline 3D seismic data was acquired in 1992/1993, prior to field development, and the first monitor 3D seismic was acquired in 2005. The rock physics model shows that increased water saturation due to the water flooding along the injectors in the Tor oil-bearing reservoir dominates the 4D change in acoustic impedance yielding a hardening response. The rock physics model was used to convert the reservoir model pressure and saturation changes from the three time-steps to modelled acoustic impedance changes. Examples will be shown from the 4D time lapse and the reservoir model acoustic impedance changes.

Introduction

A repeat time-lapse seismic survey was acquired in 2012 over the Halfdan oil field, and the 800 km^2 surrounding area, located in the Danish North Sea Central Graben, approximately 250 km west of the Danish west coast. The main objectives of the survey were to understand the lateral and vertical sweep, identify unswept areas, guide future well interventions and to improve the reservoir model. A further technical objective was to deliver a fast-track 4D difference volume 11 weeks after the last shot to influence further processing steps and quickly integrate the 4D into the asset management plan. In reality, two fast-track amplitude difference volumes were delivered at seven weeks and 11 weeks after acquisition. Seismic inversion was performed as production effects have a large impact on the acoustic impedance within the chalk reservoir. The rock physics model was also used to model 4D acoustic impedance changes based on the pressure and saturation changes within the reservoir. The 4D data seismic volumes were quickly compared with the simulation data and the previous 2005 time-lapse seismic focusing on the changes in lateral and vertical sweep. Field-wide and reservoir specific examples of the time lapse response from 2005 to 2012 are presented.

Seismic acquisition and processing

The 2012 3D seismic acquisition covered several fields operated by Maersk Oil on behalf of the DUC, Danish Underground Consortium. The Halfdan field baseline 3D seismic survey was acquired in 1992 and 1993. The 2012 3D seismic survey was planned to ensure high repeatability with the 2005 3D seismic survey (Figure 1). All surveys were acquired in an E-W direction, with the exception of platform undershoots and oblique lines acquired around surface infrastructure. The 2012 acquisition parameters were designed to closely match the 2005 survey and both surveys benefited from streamer steering, however, the earlier survey had significant acquisition parameter differences. Some of the key differences are: array volume, number of streamers and source low frequency filter (Table 1).

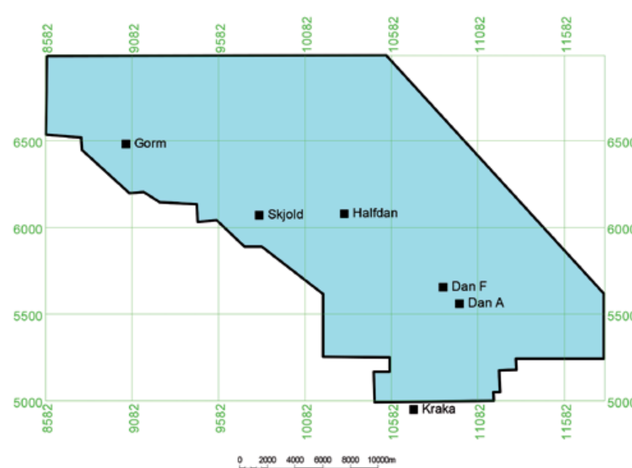

Figure 1 *Seismic acquisition outline showing 4D coverage.*

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These differences led to higher noise levels in the 4D difference volumes using the 1992/1993 seismic survey as the baseline.

The 4D seismic processing included multiple projects, beginning with the 2012-2005 time-step for the entire 800 km^2. In addition, vintage processing was also performed for the 1992/1993, 2005 and 2012 time steps. However, at the time of this analysis only the legacy 2005-1992/1993 4D seismic was available for interpretation. The key differences between the 2012-2005 and 2005-1992/1993 processing flows were the migration algorithm, time shift calculations and seismic inversion. The previous 4D seismic processing flow included a pre-stack time migration (PSTM) and used a cross correlation technique to calculate time shifts and the acoustic impedance difference data were based on quadrature. The current 4D seismic processing flow included a transversely isotropic pre-stack depth migration (TTI PSDM) and used a geostatistical inversion for time strain (Cherrett et al., 2011). This time strain was then used as the low frequency model for the joint inversion producing a percent change in acoustic impedance for the 2012-2005 time-step.

A key technical objective of the new time-lapse survey was to deliver a fast track 2012-2005 4D difference volume 11 weeks after the last shot with the aim of influencing further processing steps and quickly integrating the 4D into the asset management. To aid this effort, the previous 1992/1993 and 2005 datasets were used to test 4D processing parameters. Key processing parameters were identified and applied allowing a fast track dataset to be produced for the entire 800 km^2 seven weeks after the acquisition was completed. Quick analysis of the first fast track 4D dataset led to improved processing parameters and an additional demultiple application which yielded a significantly improved second fast track dataset 11 weeks after seismic acquisition was completed (Table 2). Both fast-track datasets were then aligned using a geostatistical inversion for time strain and inverted to acoustic impedance. An example comparing the two datasets will be shown in a later section (Figure 10).

Survey year	1992	2005	2012
Direction	90 °	90 °	90 °
Inline spacing	6.25 m	6.25 m	6.25 m
Crossline spacing	25 m	25 m	25 m
Fold of recording	30	60	
Undershoot	Yes	Yes	Yes
Energy source			
Number of source arrays	2	2	2
Array volume	1060 cu.ins.	3147 cu.ins.	3450 cu.ins.
Source depth	5 m	5 m	5 m
Stream parameters			
Number of streamers	2	8	8
Streamer separation	100 m	100 m	100 m
Streamer length	3000 m	6000 m	4040 m
Number of groups	240	478	324
Group interval	12.5 m	12.5 m (group formed)	12.5 m
Streamer depth	7 m	7 m	7 m
Near offset	98 m	287 m	102 m
Recording system			
Low filter	8 Hz, 6 dB per oct.	3 Hz, 18 dB per oct.	2 Hz, 6 dB per oct.

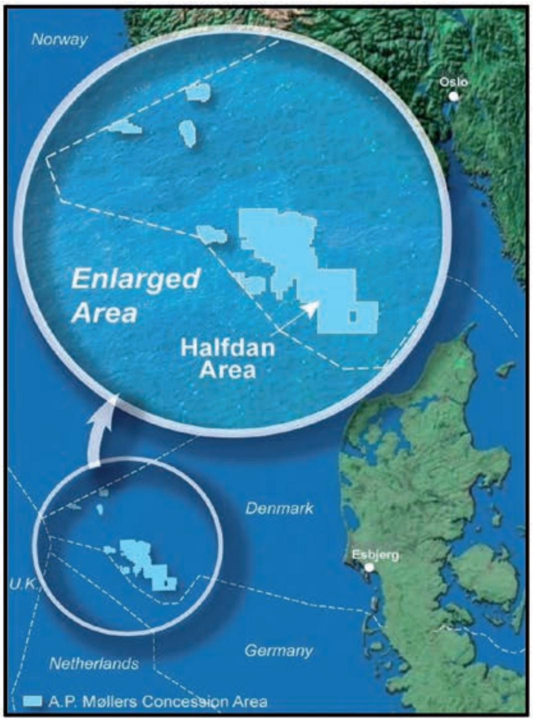
***Table 1** Seismic Acquisition parameters of the three different surveys are shown in the table. The 2012 seismic survey was planned to ensure high repeatability with the 2005 seismic survey.*

Reservoir background, rock physics and forward modelling

The Halfdan field was discovered in 1998 and began producing at the end of 1999. The main reservoir is the Cretaceous chalk Tor Formation. In the Halfdan field the best part of the Tor Formation is characterized by porosities at 25-35% and associated permeability of 1-2mD with an oil column up to 250 ft thick (Figure 2). A thin, dense low permeability chalk layer, known as hardground, separates the Tor from the overlying Ekofisk Formation. The highest porosities are contained in the upper part of the Tor reservoir, decreasing deeper into the section. The hydrocarbons are trapped by a combination of stratigraphic and dynamic conditions as opposed to other fields in the region which are trapped below

7 Week Fast Track	11 Week Fast Track
Reformat and nav/seis merge	Reformat and nav/seis merge
Bad trace and spike editing	Bad trace and spike editing
Swell noise attenuation	Swell noise attenuation
Linear noise attenuation	Linear noise attenuation
Deconvolution in Tau-P domain	Shot interpolation
Radon antimultiple	SWD (Shallow Water Demultiple)
4D binning	K anti-alias filter
Regularisation to 1 trace per bin per offset	Drop interpolated data
Depth Migration (VTI)	Radon antimultiple
Stack	4D binning
Match DUC12 to DUC05	Regularisation to 1 trace per bin per offset
	Depth Migration (VTI)
	Stack
	Match DUC12 to DUC05

***Table 2** Seismic processing parameters for the two fast track 4D datasets. Key differences are highlighted in blue.*



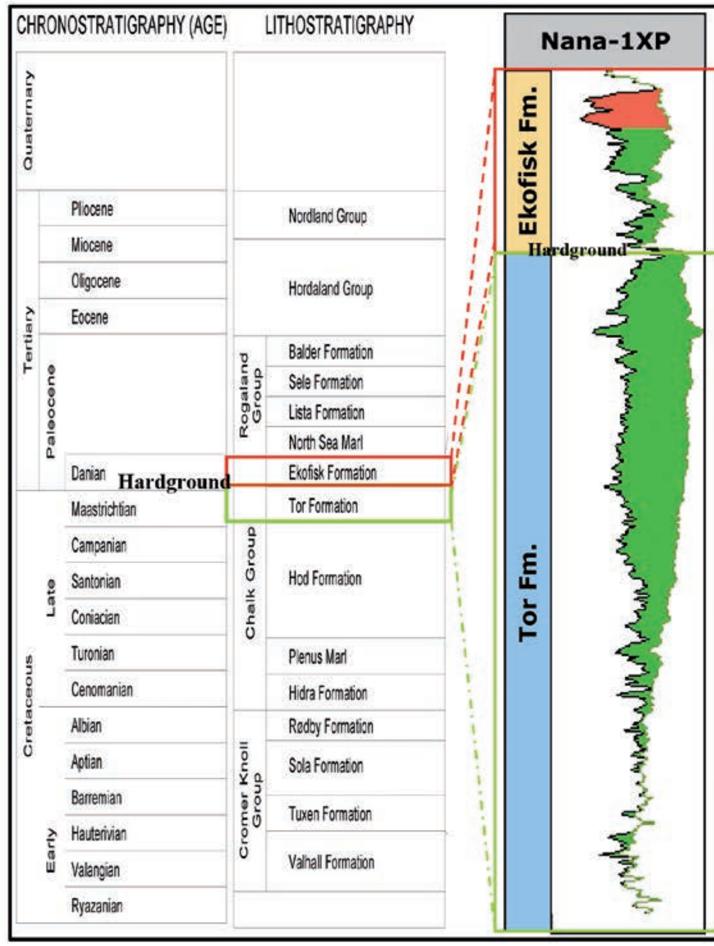


Figure 2 *Location map of the Halfdan field offshore Denmark. Type log from the centre of the development illustrating the Ekofisk and Tor hydrocarbons in the higher porosity interval. Porosity and Bulk Volume Water (BVW) logs are shown. A hardground separates the Ekofisk and Tor formations.*

structural closures (Dons et al., 2007). The main Halfdan oil field is developed via a line drive waterflood with alternating long, parallel horizontal production and injection wells placed 600 ft apart giving 1:1 producer-injector coverage (Figure 3) (Dons et al., 2007). Typically a well produces oil for up to six months prior to being converted to a water injector. The injectors are then fractured following the FAST (Fracture Aligned Sweep Technology) process whereby flow-induced stresses cause fractures to grow along the length of the wellbore. Aligning fractures with the well enables high injection rates to be maintained without threatening waterflood conformance (Jørgensen, 2002; Rod and Jørgensen, 2005; Calvert et al., 2014). The FAST technique produces a marked 4D seismic response associated with the water replacing oil along the length of the injectors. Additionally, the overlying Ekofisk Formation is a secondary reservoir producing predominantly gas in the NE area of Halfdan with one oil producer directly above the main Halfdan Tor oil field.

A rock physics analysis of these chalk reservoirs shows that water flooding along the injectors in the Tor oil-bearing reservoir yields an increase in acoustic impedance (hardening) when the fluid substitution impact is larger than that from the reservoir pressure increase (Figure 4) (Dons et al., 2007; Gommesen and Hansen, 2012). In contrast, gas breakout due

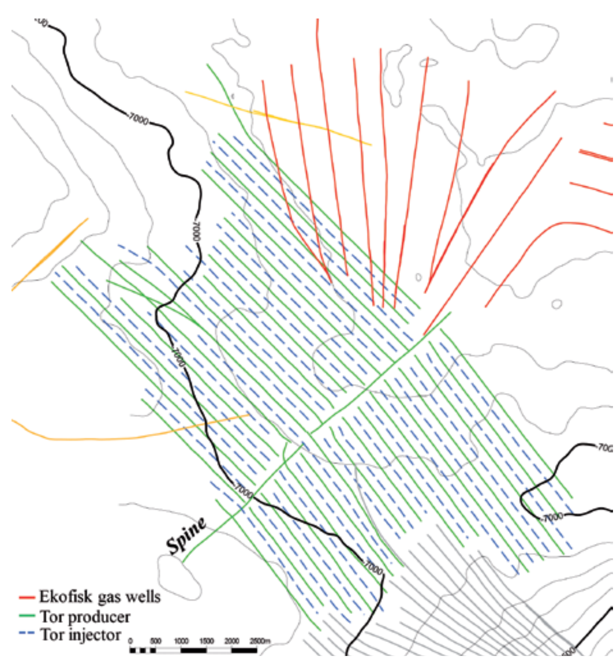


Figure 3 *Halfdan field development with producers shown in green and injectors in dashed blue. The spine divides the field into north and south sections. The overlying Ekofisk gas development wells are shown in red. Contours show the gentle dip in the area. Countour Interval is 100 ft. Wells in grey are from the Dan field west flank.*

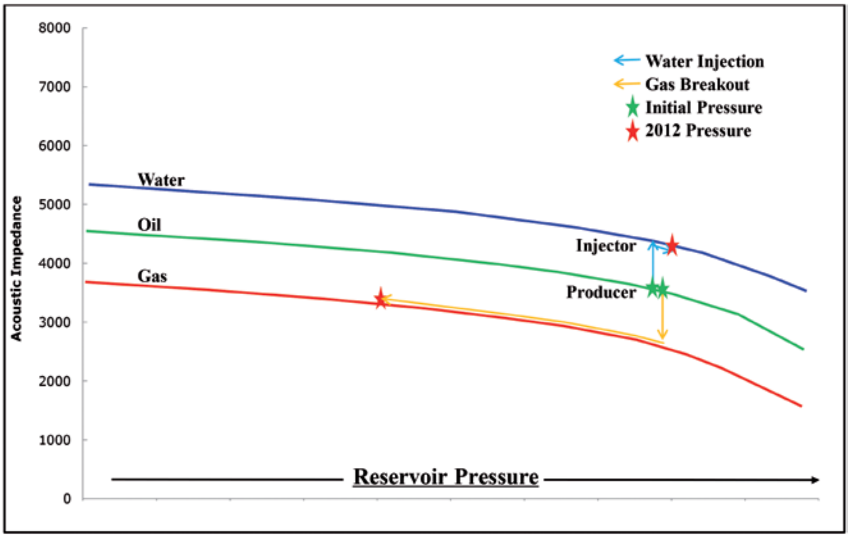


Figure 4 *Schematic illustration of AI change due to saturation and pressure changes in the Tor oil reservoir based on the rock physics model. Curves represent 100% Sw, So and Sg for each fluid type. The injector causes an increase in water saturation which yields an increase in AI even with a pressure increase (blue arrows). Lack of pressure support in a producer causes gas breakout and yields a decrease in AI (yellow arrows). In most cases saturation changes dominate over pressure changes.*

to a reservoir pressure decrease will yield a decrease in acoustic impedance (softening) (Figure 4). The different fluid type curves in Figure 4 are based on 100% water, oil and gas saturations (Sw, So and Sg). This is a simplified illustration and in reality the fluid mixture is more complex. However, in most cases the saturation changes dominate the acoustic impedance change. This can also be seen when looking at the modelled acoustic impedance change based on the reservoir simulation (Figure 5). The rock physics model is used to relate the pressure and saturation changes to acoustic impedance. Figure 5 shows a cross section through the modelled pressure, Sw, Sg and acoustic impedance changes from 2005 to 2012 based on the reservoir model. In the centre of the cross section, an increase in reservoir pressure associated with the many years of water injection can be observed. This reservoir pressure increase causes a decrease in acoustic impedance. However, the Sw increase around these same injectors causes an even greater increase in acoustic impedance resulting in a total increase in acoustic impedance when combining the changes of pressure and Sw (Figure 5). The opposite takes place when the reservoir pressure drops and gas comes out of the solution (Figure 5). The softening from the gas break out dominates yielding a decrease in acoustic impedance. However, the softening due to gas breakout in the model is not as large as measured with the seismic. The rock physics model is currently being updated to adjust for this difference. Previous studies predict that chalk does not significantly compact when porosities are less than 35% (Dons et al., 2007) and therefore compaction is expected to have a minimal impact on the 4D response in most areas of the field.

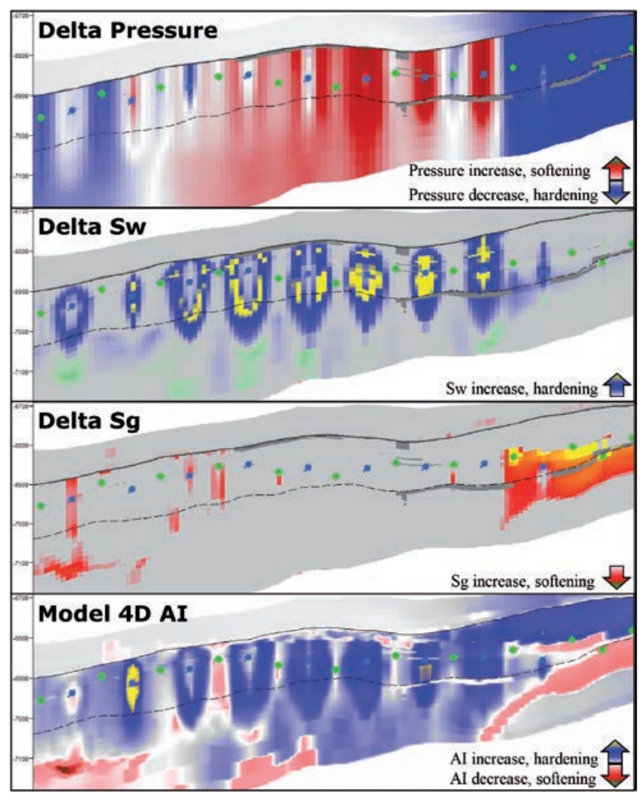


Figure 5 *A depth cross section (ft) through the modeled 4D change in pressure, Sw, Sg and AI from 2005 to 2012 reservoir model. Producers are in green, injectors in blue. The rock physics model is used to relate pressure and saturation changes to AI changes. Shape of the 4D AI response is dominated by the Sw change rather than the pressure change. In areas where pressure increases due to water injection, softening in upper figure, the AI is increasing due to the larger impact of the increases in Sw from the injectors. In areas where pressure decreases, hardening in upper figure, and Sg increases due to gas break out, the AI decreases due to the larger impact of the increases in Sg at the producers.*

Comparison of 2012 4D with simulation 4D

To gain insights into the potential 2012-2005 4D response prior to the arrival of the new 4D, the 2012-2005 4D seismic response was simulated using the reservoir model. The predicted response allowed rapid evaluation of the early results. In general, there was a good correlation between the actual and simulated 4D acoustic impedance change from 2005 to 2012 (Figure 6).

In Figure 6, the hardening response along the injectors can clearly be seen to move farther away laterally as the flood front progressively displaces more oil between 2005 and 2012.

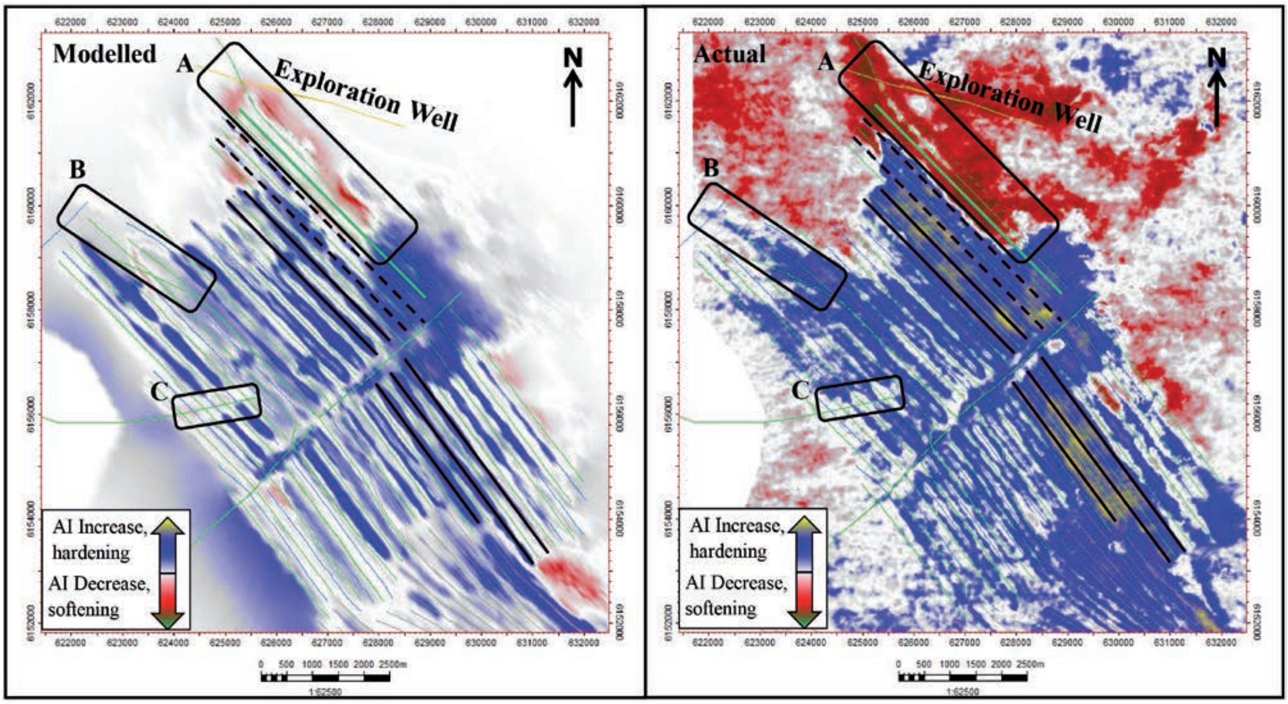


Figure 6 *Percent change in acoustic impedance in the Upper Tor from 2005 to 2012 based on the reservoir model (left) and the seismic data (right).*

This is illustrated in further detail in Figure 7. The well north of the spine has been injecting water into the Tor reservoir since 2010. During that time the water flood front has moved slowly towards the producers on either side as shown by the hardening response along the length of the wellbore. The water flood front location in 2012 has been outlined in Figure 7. In comparison, the well to the south of the spine began injecting water into the Tor reservoir in December 2001. At the time of the 2005 seismic acquisition water had already replaced oil along the length of the wellbore. Consequently, from 2005 to 2012 there has been little to no change in acoustic impedance close to the wellbore due to fluid replacement. However, a hardening response can be observed away from the wellbore where water has replaced oil since 2005. The location of the water flood front observed in 2012 is highlighted in Figure 7. This pattern is repeated throughout the field for injectors that had been injecting water into the Tor reservoir prior to 2005 and provides additional evidence that the FAST process has been successful. The realignment of the stress field creating the fractures along the wellbores has led to water sweeping the oil laterally away from the injectors towards the producers and preventing premature water breakthrough.

The strongest predicted hardening responses are associated with injectors that were producing in 2005 and converted to injection after the 2005 3D seismic was acquired and are highlighted in black (Figure 6). The production at the time of the 2005 seismic survey had already led to a decrease in reservoir pressure and subsequent gas break out causing a decrease in acoustic impedance in the area. Thus, the reservoir acoustic impedance was already lower than the surrounding area when water injection began, yielding a significant increase in acoustic impedance surrounding these wells compared to injection in undepleted areas. Two additional wells were drilled immediately after the 2005 seismic acquisition and are highlighted with dashed black lines.

In the northeastern part of the field, polygon A, where the conversion of a producer to an injector had been delayed, strong softening is caused by gas breakout due to the decrease in reservoir pressure. At the time of seismic acquisition in 2012, there were three wells in a row producing since late 2009-early 2010 as the middle well had yet to be converted from production to injection. One of these wells in the northeastern part of the field is the longest producer in the field and was drilled in early 2010. A slight hardening can be seen along part of the outer half of the well. This is the only well with a decrease in reservoir pressure significant enough to counter the softening from the gas breakout to generate an overall hardening response. The outer section of the well is the only part of the well that has been producing as the remaining zones have been closed and thus the largest reservoir pressure depletion occurs only in this section.

The long producer also crosses over an abandoned exploration well. There is a strong softening response along the length of the abandoned exploration well which indicates that this well is producing via a connection to the overlying long production well. This 2012-2005 4D difference data was the first indication that the long producer was connected to the abandoned well and draining from a larger area. However, this is supported by the fact that the long well has produced above expectations and could not be history matched with the reservoir model. The reservoir model is now being updated and will include this connection with the abandoned exploration well to better understand the lateral sweep at this edge of the field.

In the 4D seismic there is an area of strong hardening crossing several wells highlighted by polygon B which is associated with an area of known connections created during the FAST process (Figure 6). These fractures connected the injector with neighbouring producers causing premature water breakthrough in these wells. These connections are not in the current reservoir model which explains the lack of hardening in this area in the modelled AI change.

In area C, both the modelled and acquired 4D seismic show an area of slight softening-to no 4D AI change (Figure 6). In this area, the injectors have been blocked off to prevent any connections with a legacy well placed slightly deeper in the Tor. These injectors do not provide pressure support to this limited area so the slight softening response in the model is caused by gas breakout along the producers as the reservoir pressure drops. This response is very clear in the modelled AI change, however, in the 4D seismic data the injectors do exhibit areas of hardening. This hardening is more restricted to the injector wellbores showing water has replaced oil near the wellbores since 2005 but the water flood front has not moved far away from the wellbores. This is in contrast to the surrounding hardening responses outside of the blocked off section where the water flood front has moved farther away from the injectors. A zone isolation review and work plan is currently underway to better understand the potential sweep from these injectors.

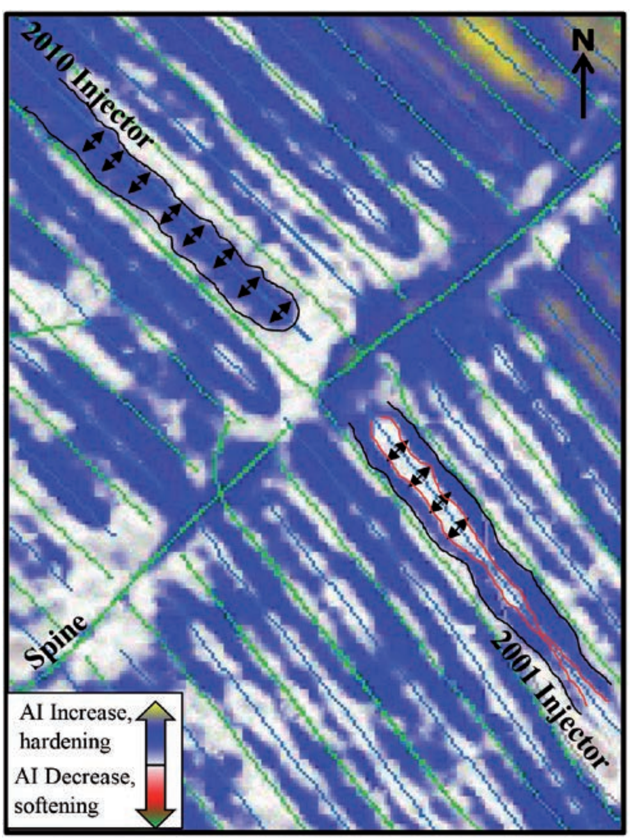


Figure 7 Zoom into center part of the field showing hardening responses for two injectors. Producers are in green, injectors in blue. One well began injecting in 2010 and the other in 2001. The hardening response for the 2010 well is centered along the wellbore with arrows indicating direction of the water flood front and the black line showing the 2012 water flood front. Arrows in the 2001 injector show where water had already replaced oil in 2005. The 2005 water flood front is shown in red and the 2012 water flood front is shown in black.

Comparison of 2012 4D data with 2005 4D data

The baseline seismic survey was acquired in 1992/1993 prior to field production which began in 1999. The first 4D seismic survey covering the Halfdan oil field was acquired in 2005. Comparing the previously calculated 2005-1992/1993 relative acoustic impedance difference with the new 2012-2005 acoustic impedance difference revealed significant changes in the lateral and vertical sweep (Figure 8). In Figure 8, the 2005-1992/1993 4D data shows hardening due to water replacing oil along the length of most injectors, with softening occurring at the producers due to gas breakout associated with reservoir depletion. By 2012 the water flood has generally moved farther away from the injectors, with some injectors showing a more efficient lateral sweep than others. The softening from gas breakout in wells with no pressure support in 2005 has been replaced with a hardening response due to the water injection post-2005. The 2012 softening response in the northeast is caused by gas breakout due to no pressure support of the newer wells drilled from 2009 to 2010. The softening along the abandoned exploration well discussed in the previous section is only seen in the 2012 4D data because the overlying Tor producer was drilled post-2005.

The 2005-1992/1993 4D seismic survey results revealed limited vertical sweep in the deeper part of the Tor reservoir (Figure 9). The hardening response associated with water replacing oil in the 2005-1992/1993 4D difference was mostly in the uppermost part of the Tor reservoir, above the wellbore. However, the 2012-2005 4D difference now shows the deeper Tor reservoir being swept (Figure 9). In the 2012-2005 4D difference the water flood front had moved farther away laterally from the injector in the upper Tor compared with the lower Tor, which produced a v-shaped hardening response similar to what was seen in the modelled acoustic impedance change from the reservoir model (Figures 5 and 9). A minimal 4D response along the injector itself occurred when the area was already flooded in 2005. Any softening directly along the injector can be associated with an increase in pressure due to continued water injection from 2005 until 2012. This hardening response associated with the progression of the water flood is in agreement with the application of the FAST technique. With well placement being high in the reservoir section, the FAST fracture is expected to propagate up to the top Tor hardground and a distance down into the oil leg. The top Tor hardground provides a barrier against vertical flood front migration, diverting the flood horizontally along the wellbore and assisting oil sweep in the upper section. The slower advancement of the lower section flood front is likely to be due to a combination of the FAST fracture not penetrating through the full net section, reduced water

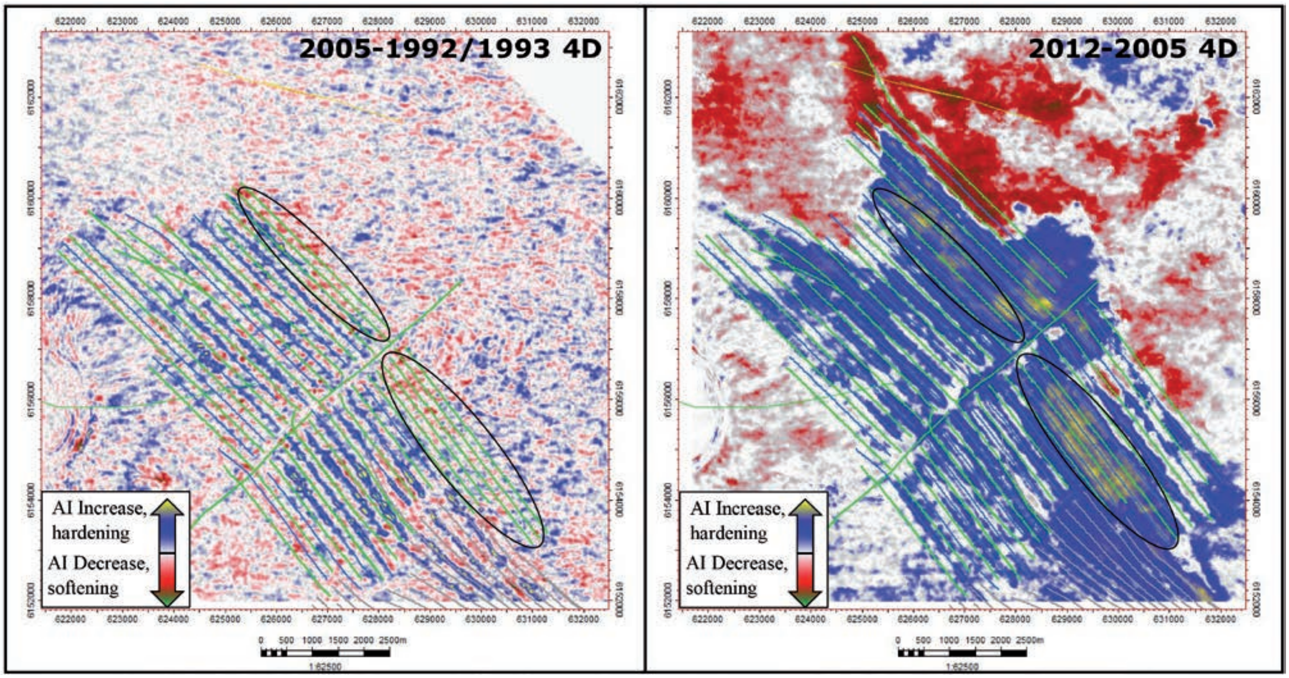


Figure 8 *Map of upper Tor relative acoustic impedance change from 1992/1993 to 2005 (left) and change in absolute acoustic impedance from 2005 to 2012 (right). Wells in polygons were converted to injection post-2005. Producers are in green and injectors are in blue. Dan wells are in grey.*

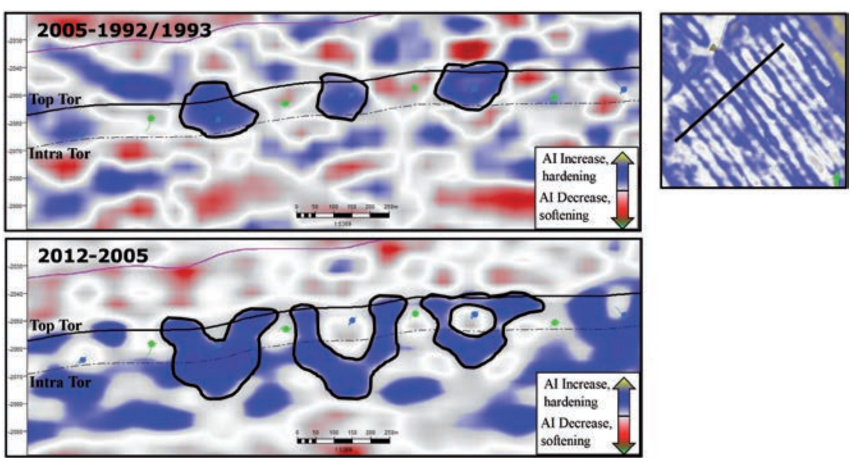


Figure 9 *Cross sections, in m/sec, through the original 2005-1993/1992 (upper) and the new 2012-2005 (lower) 4D acoustic impedance change volumes. Producers are in green, injectors in blue. In 2005, the hardening response was limited to the upper part of the Tor reservoir. In 2012, the hardening response penetrates deeper into the Tor reservoir indicating an improved vertical sweep compared with 2005.*

injection due to less reservoir pressure depletion and poorer reservoir quality.

Ekofisk oil production 4D response and iterative quality improvement

In mid-February 2012 the first Ekofisk formation oil well began producing above the main Halfdan Tor oil field. The well was placed in the high GOR oil rim area. In this area the Ekofisk Formation is characterized by porosities ranging from 27% to 37% and associated permeability of 0.5-1 mD. The new seismic was acquired in this area four months later. The first fast track 4D amplitude difference volume showed a strong softening response associated with this well (Figure 10). Insights gained from interpreting the first fast track, as well as applying multiple attenuation, led to an improved second dataset 11 weeks after the seismic acquisition completed. The 4D response is associated with gas breakout due to lack of pressure support in this high GOR oil producer. The stronger softening on the outermost section of the well is associated with the only part of the well that was stimulated. The stronger softening in the inner section of the well is where there are two open wellbores due to a sidetrack. The middle section, with the least softening, is where there is only one wellbore and no stimulation. This 4D response provides important information for future well completion and stimulation design.

Conclusion

Quick seismic processing turnaround of the new 4D time lapse survey over the Halfdan oil field and greater DUC allowed for interpretation and integration of the new 4D results seven weeks after completion of the seismic acquisition.

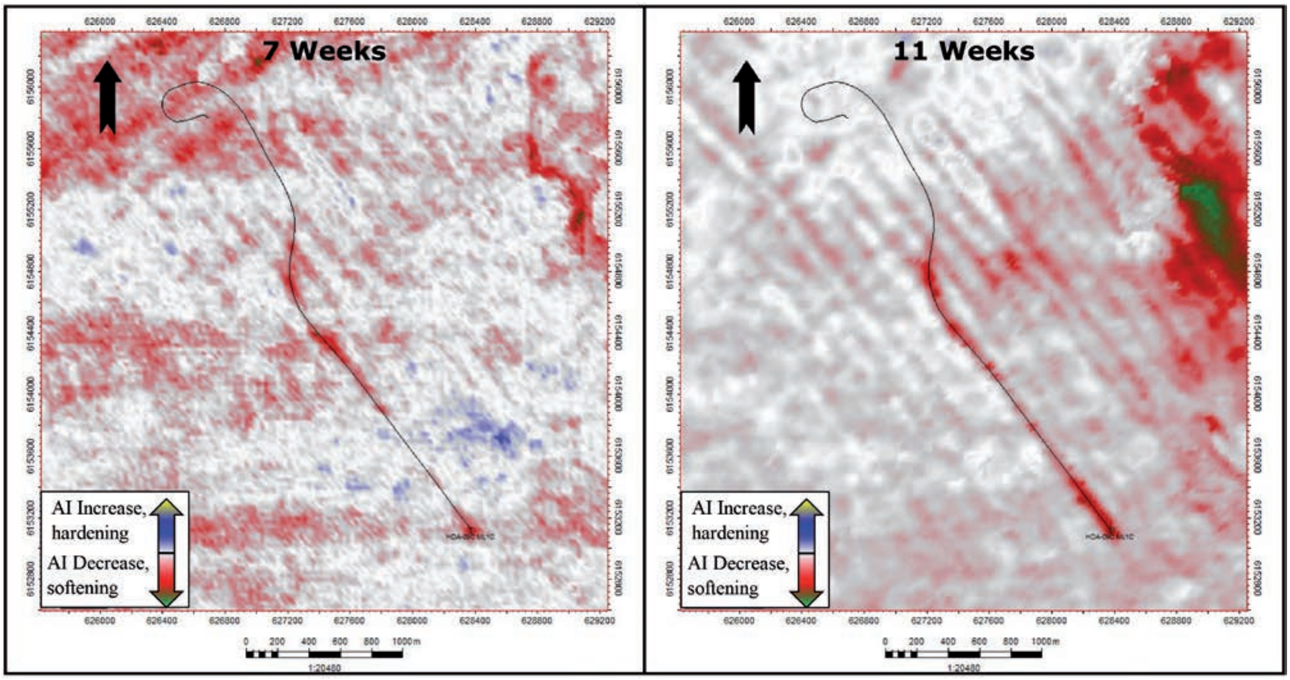


Figure 10 *Comparison of first fast track acoustic impedance difference (left) and second fast track acoustic impedance difference in the Ekofisk (right). Ekofisk oil well displayed.*

Interpretation of the first fast track provided information for continuous improvement during the processing flow and an improved fast track dataset was received 11 weeks after the seismic acquisition completed. The rock physics model shows that increased water saturation due to the water flooding along the injectors in the Tor oil-bearing reservoir dominates the 4D change in acoustic impedance yielding a hardening response. In areas where reservoir pressure has dropped below the bubble point, softening occurs due to a decrease in acoustic impedance from the gas coming out of solution. However, if the reservoir pressure drop is significant, hardening can be seen along a producing well. The observed softening along the length of an abandoned exploration well reveals the well is serving as a conduit into the overlying production well. The new 2012-2005 4D seismic survey shows the vertical sweep moving deeper into the reservoir compared with the previous 2005-1992/1993 4D. The v-shaped hardening response within the Tor reservoir clearly shows the lateral sweep is progressing more quickly in the upper, higher porosity part of the reservoir compared to the lower part of the reservoir. The reservoir model is currently being updated with the 4D seismic data. These new insights into the lateral and vertical sweep progression since 2005 have been used to justify several well interventions and workovers to improve the oil recovery within the Tor reservoir.

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