Ekofisk time-lapse seismic – a continuous process of improvement

Håkon Haugvaldstad,[1] Bjarne Lyngnes,[1] Patrick Smith[2] and Andrew Thompson[3] describe the seismic acquisition and processing techniques that have steadily enhanced the quality and reliability of the time-lapse data on the Ekofisk field, offshore Norway, and anticipate further improvements in the future.

The Ekofisk field was the first commercial hydrocarbon discovery offshore Norway, and has been in production since 1971. It's a giant, challenging oilfield, and given its age, it is not surprising that the techniques used to produce it have evolved over the years. ConocoPhillips' objectives are to produce the field more efficiently, attain higher recovery factors and maximize the safety of their operations. The time-lapse seismic campaign described here is just one of the technologies being used to achieve these goals.

Ekofisk field

The Ekofisk oilfield (Figure 1) is located about 300 km southwest of Stavanger in blocks 2/4 and 2/7 of the Norwegian North Sea, where the water depth is about 70 m. It is a late Cretaceous/early Palaeocene anticlinal chalk structure at about 2900–3500 m depth, with a total reservoir thickness of approximately 200 m. There are two reservoirs, the Tor formation and the overlying Ekofisk formation, separated by an impermeable tight zone. The Ekofisk formation contains about two-thirds of the original reserves. Both reservoirs have high porosity (25–45%), but low matrix permeability (0.1–10 mD), and the permeability that exists is largely related to pervasive fracturing.

Figure 2 compares the Ekofisk reserves, as of December 2009, with other fields on the Norwegian continental shelf. It shows that the giant sandstone reservoirs such as Statfjord, Oseberg and Gullfaks, which were brought into production much later than Ekofisk, have been produced at faster rates. This is because Ekofisk is not straightforward to produce, and so techniques that help improve production efficiency are very valuable. The projected recovery factor compares well with other fields, but the chart shows that this will still leave significant resources in the ground. A small increase in recovery factor on Ekofisk can have a large resource and financial benefit.

Ekofisk is produced via an extensive infrastructure. A central complex, comprising several interconnected platforms, is supplemented by the Alpha and Kilo-Bravo complexes to the south and north respectively. These significantly obstruct seismic surveying. Some 90 production wells and 25 injector wells are active at any given time.

Reservoir challenges

The main reservoir challenge is the soft nature of the chalk reservoirs, which compact as the pressure depletes. A water injection programme was started in 1987 to stabilize the reservoir pressure, but the initial effect was to weaken the chalk still further, causing additional compaction. Subsidence above the compacting reservoir extends all the way to the sea bottom, which by 2008, had sunk by up to 9 m in the centre of the field. Wells drilled through the subsiding overburden tend to be deformed and eventually severed. Even though the injection programme has now slowed the rate of subsidence,

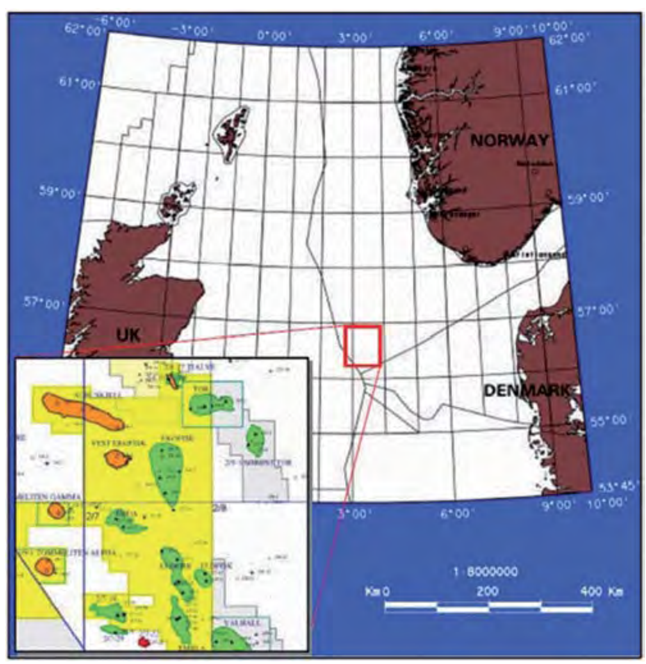

***Figure 1** A map showing the location of the Ekofisk field.*

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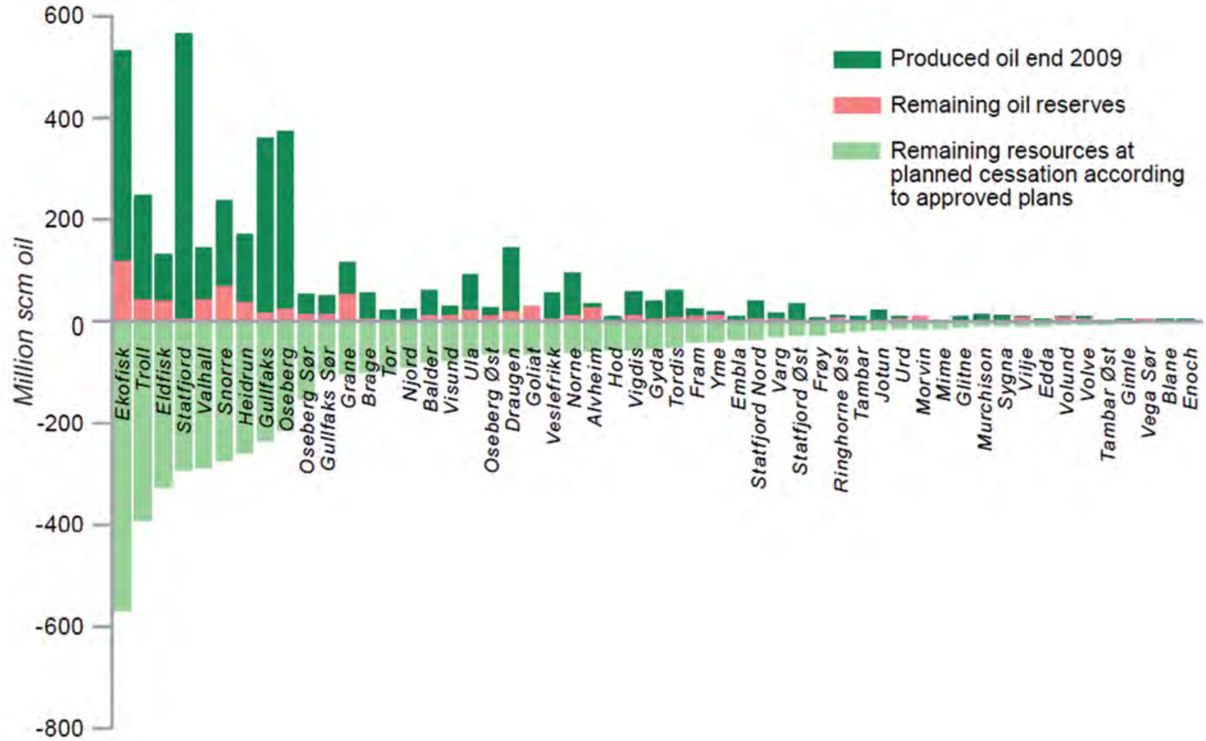

***Figure 2** Ekofisk reserves, as of 2009, compared with those of other oilfields offshore Norway (Source: NPD).*

the sheer number of producing wells means that replacements are continually required.

The low and rather variable permeability of the reservoir causes several challenges:

- Existing wells do not drain the reservoir evenly, therefore additional wells are needed to access undepleted areas.
- Production rates along a given horizontal well can vary dramatically, reducing production efficiency.
- Pore pressure variations exist between depleted and undepleted areas of the reservoir, complicating the drilling of new wells.

Geomechanical modelling is extensively used to ensure that new wells are sited such that their lifetime is maximized, and that pore-pressure variations are handled appropriately when drilling. Time-lapse seismic is an obvious tool to help identify undepleted and unswept areas and to assist the development of geomechanical models, and ConocoPhillips was an early adopter of this technology.

Seismic challenges

Unfortunately application of time-lapse seismic to Ekofisk is also challenging. About one third of the field is obscured for P-wave imaging by gas-charged intervals and pore pressure variations in the overburden (Figure 3). Also the production-related compaction causes stress relaxation in the overburden that reduces P-wave velocity. This, together with compaction-related depth changes, gives timing delays from one time-lapse survey to the next that cover a substantial fraction of the seismic survey area and hamper the application of statistical analysis and matching procedures. Deterministic time-lapse processing flows are desirable and this, in turn, requires special care during acquisition.

Ekofisk marine streamer time-lapse surveys

Five marine streamer surveys have been acquired over Ekofisk, as described in Table 1. The first survey was acquired in 1989 in two stages using a dual source, dual streamer configuration. The prime line data was acquired with a survey azimuth of 347^0, but additional orthogonal lines were acquired to improve coverage around the platforms and to provide additional illumination of the seismic obscured area (SOA). Streamer under-shooting was also used to acquire data beneath the infrastructure (Figure 4). In 1999 a second survey was acquired using two sources and four streamers to improve efficiency. The time-lapse seismic results were sufficiently encouraging that a third survey was acquired in 2003. As this survey was also intended to improve seismic resolution, a single source eight streamer layout was used, and the source and streamers were towed shallower. Ocean bottom cable acquisition, rather than streamer undershooting, was used to obtain coverage around the infrastructure. The first Q-Marine, point-receiver marine seismic system survey was acquired in 2006. This duplicated the 2003 acquisition configuration, but streamer under-shoot was used for coverage beneath the platforms. Rather than try to duplicate the 2003 source and receiver locations, the stream-

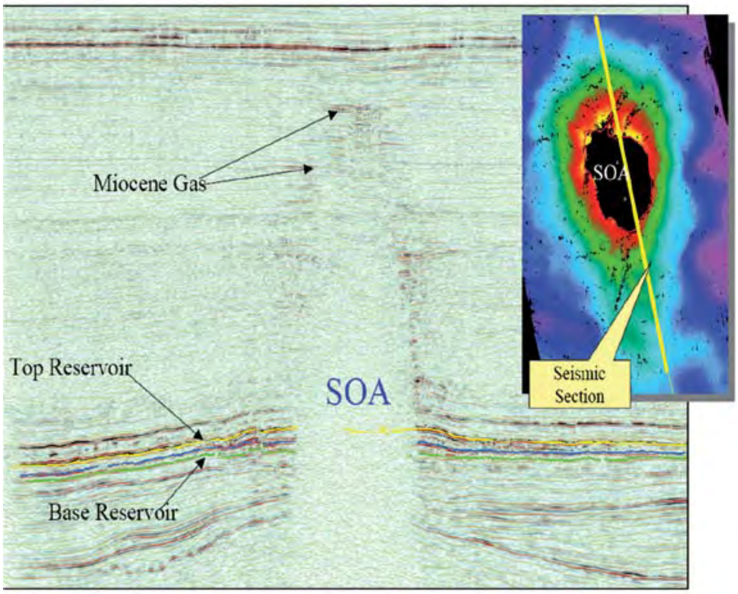

Figure 3 *A seismic section showing the seismic obscured area (SOA), plus a map showing the extent of the SOA relative to the extent of the Ekofisk 3D survey.*

Year	1989	1999	2003	2006	2008
Contractor	Geco & Prakla	Geco-Prakla	WesternGeco	WesternGeco	WesternGeco
Technology	Conventional	Conventional	Conventional	Q-Marine	Q-Marine
Configuration	2 sources / 2 streamers	2 sources / 4 streamers	1 source / 8 streamers	1 source / 8 streamers	1 source / 8 streamers
Source/streamer separation (m)	50 / 100	50 / 100	- / 50	- / 50	- / 50
Source/receiver depths (m)	6 / 8	6 / 6	5 / 6	5 / 6	5 / 6
Inline near/far offset (m)	120 / 3120	142 / 3142	160 / 3760	250 / 3850	250 / 3850
Acquisition style	Steer vessel for coverage	Steer vessel for coverage	Steer vessel for coverage	Steer vessel & streamers for coverage	Steer vessel, source and streamers to duplicate 2006 acquisition

Table 1 *The acquisition configurations of the marine streamer seismic surveys acquired over Ekofisk.*

ers were steered to maximize coverage. The second Q-Marine survey was acquired in 2008 with identical configuration to 2006 and, this time, the Dynamic Spread Control system (Paulsen and Brown (2008)) was used to automatically steer the vessel, source and streamers to duplicate the 2006 source and streamer locations. Crossline data was also acquired; this did not explicitly repeat that which was acquired in 1989 due to the inherent configuration differences and the changes in infrastructure that have occurred over the years.

The Ekofisk time-lapse seismic datasets thus give us an interesting suite of data comparisons:

1) 1989 versus 2008 – a pair of surveys with very different acquisition configurations.
2) 2003 versus 2006 – a pair of surveys with identical acquisition configurations, but not acquired in a way that duplicates source and receiver locations.
3) 2006 versus 2008 – a pair of surveys with identical acquisition configurations, and acquired to repeat source and receiver locations as accurately as possible.

Figure 5 shows, for these three comparisons, bin-based maps of source positioning errors and source plus receiver positioning errors. As one might expect, the errors are uniformly large for the 1989–2008 comparison and rather variable for the 2003–2006 comparison. The results for the 2006–2008 comparison are consistently good – 95% of the shots in 2008 matched the 2006 source positions within 2.5 m, and the source plus receiver positioning errors are much less than 50 m over most of the survey area.

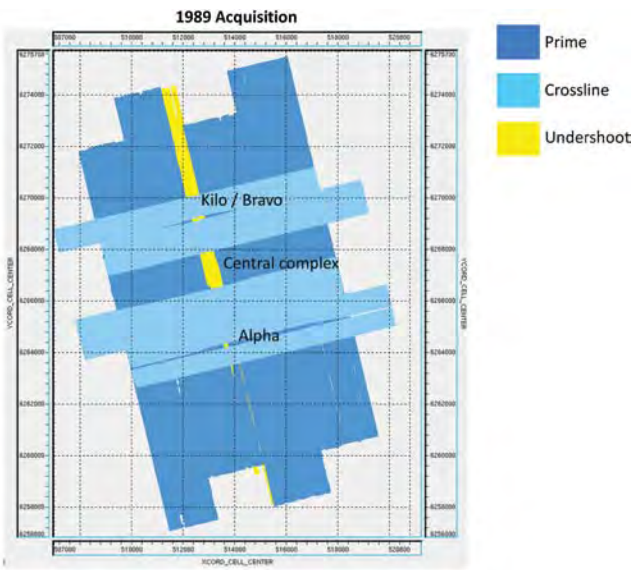

Figure 4 *A map showing the different types of coverage acquired during the 1989 acquisition.*

These improvements in survey repetition accuracy have a direct impact on the quality of the time-lapse seismic data. Figure 6 shows maps of NRMS difference (Kragh and Christie, 2001) for the three comparisons. The areas of large NRMS difference in the centre of the maps are related to production-related changes in timing and amplitude. Ignoring these areas, we see that the NRMS difference amplitude for the 1989–2008 comparison is a rather poor 30–40%, although some of this has to be attributed to the poorer quality of the 1989 dataset. Use of an identical acquisition configuration (2003 –2006) improves the NRMS figure to around 20–30%. Duplication of source and receiver locations (2006–2008) gives NRMS values of 10–20%.

The Ekofisk asset team has so far made limited use of amplitude differences between the surveys. The team has demonstrated a predictive relationship between inter-survey timing delays and reservoir depletion, and so the ability to accurately measure time shifts between surveys is of paramount importance. Figure 6 also shows Top Ekofisk timing difference maps for the three comparisons. Ignoring areas where

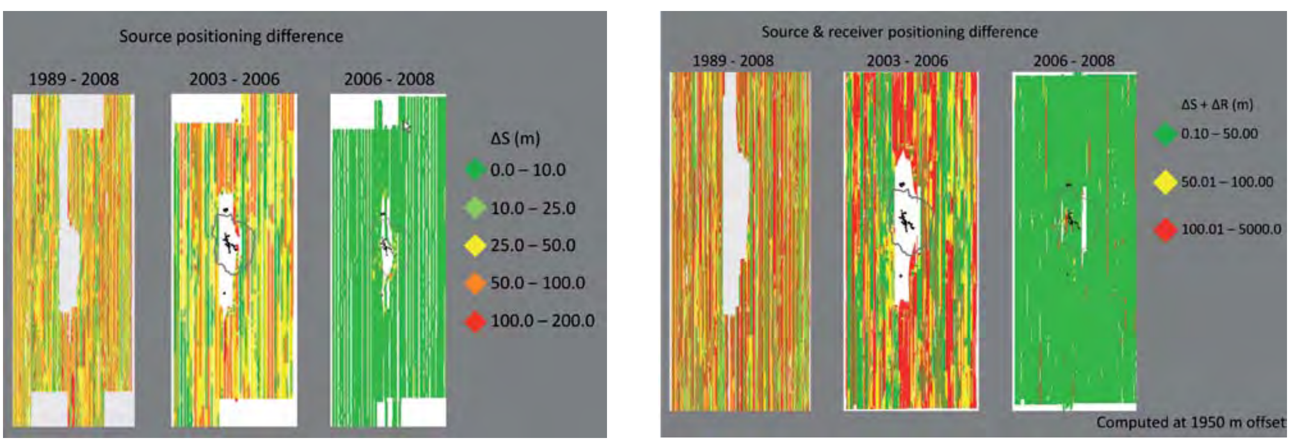

Figure 5 *Bin-based source positioning difference maps, and source and receiver positioning difference maps, for the three comparisons described in the text.*

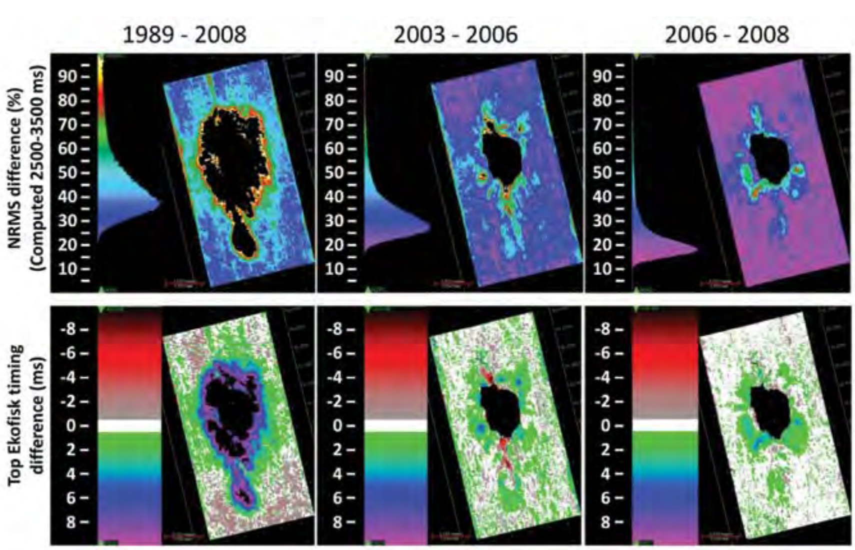

Figure 6 *NRMS difference maps, computed 2500–3500 ms, and Top Ekofisk timing maps for the three data comparisons described in the text.*

Basic	Optimized	High resolution 4D
Reformat & nav-merge	Reformat & nav-merge	Reformat & nav-merge
		First break attenuation & swell noise attenuation
		Tidal statics correction
Shot-by-shot deconvolution to consistent wavelet (2006, 2008 only)	Shot-by-shot deconvolution to consistent wavelet (2006, 2008 only)	Shot-by-shot deconvolution to consistent wavelet (2008 only)
		Platform/ship noise attenuation
		Interpolation to 25 m shotpoint interval (1989 only)
		3D rig reflection attenuation
First break attenuation & swell noise attenuation	First break attenuation & swell noise attenuation	
Temporal resample to 4 ms	Temporal resample to 4 ms	
Spatial resample to 12.5 m group spacing (2006, 2008 only)	Spatial resample to 12.5 m group spacing (2006, 2008 only)	
	Tidal statics correction	
Zero phase conversion & debubble	Zero-phase conversion & debubble	Zero-phase conversion and debubble
		Interpolation to 6.25 m group interval (1989 only)
	Receiver motion correction	Receiver motion correction
Tau-p deconvolution	Tau-p deconvolution	Deterministic Water layer Demultiple + 2D SRME
Rig reflection attenuation	Rig reflection attenuation	
Spatial resample to 25 m group spacing	Spatial resample to 25 m group interval	
Tidal statics correction		
Weghted least squares radon demultiple	Weighted least squares radon demultiple	
		Offset error correction (1989 only)
		Spatial repositioning (1989 only)
		Time shift decomposition
Surface Consistent Amplitude Correction (not 2006, 2008)	Weak trace compensation (2003 only)	Weak trace compensation (1989 only)
		Inverse Q filtering (phase only)
Sort to 30 common offset cubes at 100 m offset increment	Sort to 69 common offset cubes, at 50 m offset increment	Sort to 56 common offset cubes at 50 m offset increment
	4D binning	Expanded bin 4D binning
Infill missing traces	Regularization by azimuth moveout	Regularization by azimuth moveout
	Inverse Q filtering (phase only)	
3D Kirchhoff pre-stack time migration	3D Kirchhoff pre-stack time migration	3D Kirchhoff pre-stack time migration
Residual moveout	Residual moveout	Residual moveout
	Weighted least squares radon demultiple	Weighted least squares radon demultiple
		Global matching
Stack	Stack	Stack
3D interpolation to 12.5 X 12.5 m grid	3D interpolation to 12.5 X 12.5 m grid	3D interpolation to 12.5 X 12.5 m grid
Gun & cable static correction		
Inverse Q filter (amplitude & phase)	Deterministic spectrum whitening	Deterministic spectrum whitening
Time-variant filtering & gain	Time-variant filtering & gain	Time-variant filtering & gain
Global matching	Global matching	Global matching
	Gun & cable static correction	Gun & cable static correction

***Table 2** Processing flows for the Basic, Optimized, and High Resolution 4D processing routes.*

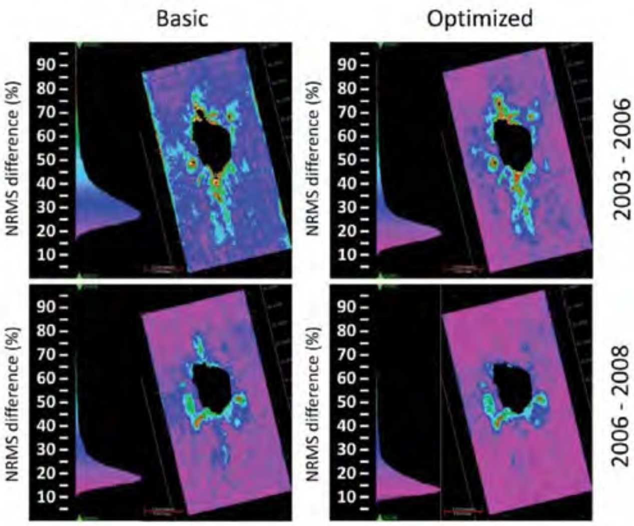

Figure 7 NRMS difference maps, computed 2500–3500 ms, for the 2003–2006 comparison, and the 2006–2008 comparison, calculated from datasets processed through the Basic and Optimized processing flows.

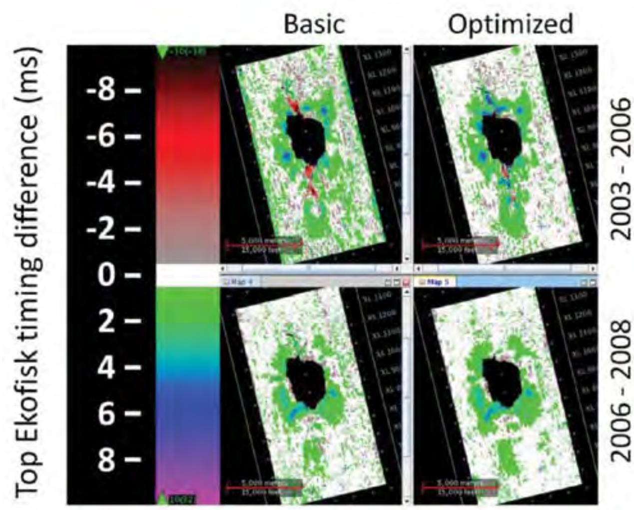

Figure 8 Top Ekofisk timing difference maps for the 2003–2006 comparison, and the 2006–2008 comparison, computed from datasets processed through the Basic and Optimized processing flows.

hydrocarbon production has caused timing differences, we see that the measured time shifts for the 1989–2008 comparison are quite noisy. Those for the 2003–2006 comparison are more stable, but still variable. The timing differences for the 2006–2008 are noticeably more consistent.

Improvements in the time-lapse processing flow

Basic route processing flow

The data acquired in 2003 was to be compared with the rather old and poor quality datasets acquired previously. The initial time-lapse seismic processing therefore 'downgraded' the 2003 data to the quality of the earlier surveys. This Basic processing flow, summarized in Table 2, has been applied to all subsequent surveys to enable 'apples-to-apples' comparisons, and the attributes shown in Figure 6 were computed from these datasets.

Optimized processing flow

In 2006, a new Optimized flow, summarized in Table 2, was developed that took advantage of the higher quality data and recent developments in time-lapse processing technology. This has been applied to the 2003, 2006, and 2008 datasets. The crossline data from the 2008 survey was not included, in order to maintain compatibility with the other surveys. Figure 7 shows that the Optimized flow improves the NRMS difference by about 10% for the 2003–2006 comparison. The NRMS difference, away from areas affected by reservoir production, for the 2006–2008 comparison is now about 8–12 %, which is a very respectable figure. The time shift maps in Figure 8 show that the timing stability of the 2003–2006 comparison is substantially improved. The stability of 2006–2008 comparison is also improved, though to a lesser degree. This is an interesting observation – it suggests that well-repeated time-lapse seismic surveys can provide useful results with rather basic processing flows that can be delivered in short time frames. The 2008 data, processed through the Basic flow, was delivered only four weeks after acquisition completion.

High resolution processing flow

One of ConocoPhillips' near term goals is to develop full field models from the surface to reservoir level for well planning. The time-lapse seismic flows described so far were designed to optimize time-lapse seismic repeatability at reservoir level. The point receiver acquisition system used in 2006 and 2008 enabled the development of a high resolution processing flow that optimized the resolution of the 2008 dataset from sea bottom down to reservoir level. The crossline data was also included in this dataset to give better illumination around the SOA. Figure 9 compares, from sea bottom to reservoir, the high resolution processing with the optimized 4D processing flow. We see a dramatic improvement in image quality and resolution.

The 1989 dataset was processed through a modified version of this flow, using interpolation to match the finer sampling of the 2008 data. Despite the deeper source and streamer, and generally poorer data quality, the shorter near offsets of this survey mean that the resolution close to the sea bottom is better than that of the 2008 data.

High Resolution 4D processing flow

The 2008 and 1989 surveys were then co-processed through a modified version of the high resolution flow (see Table 2) to provide high quality time-lapse comparisons in the overburden. The crossline data was included, where it was consistent between the two surveys, and especial

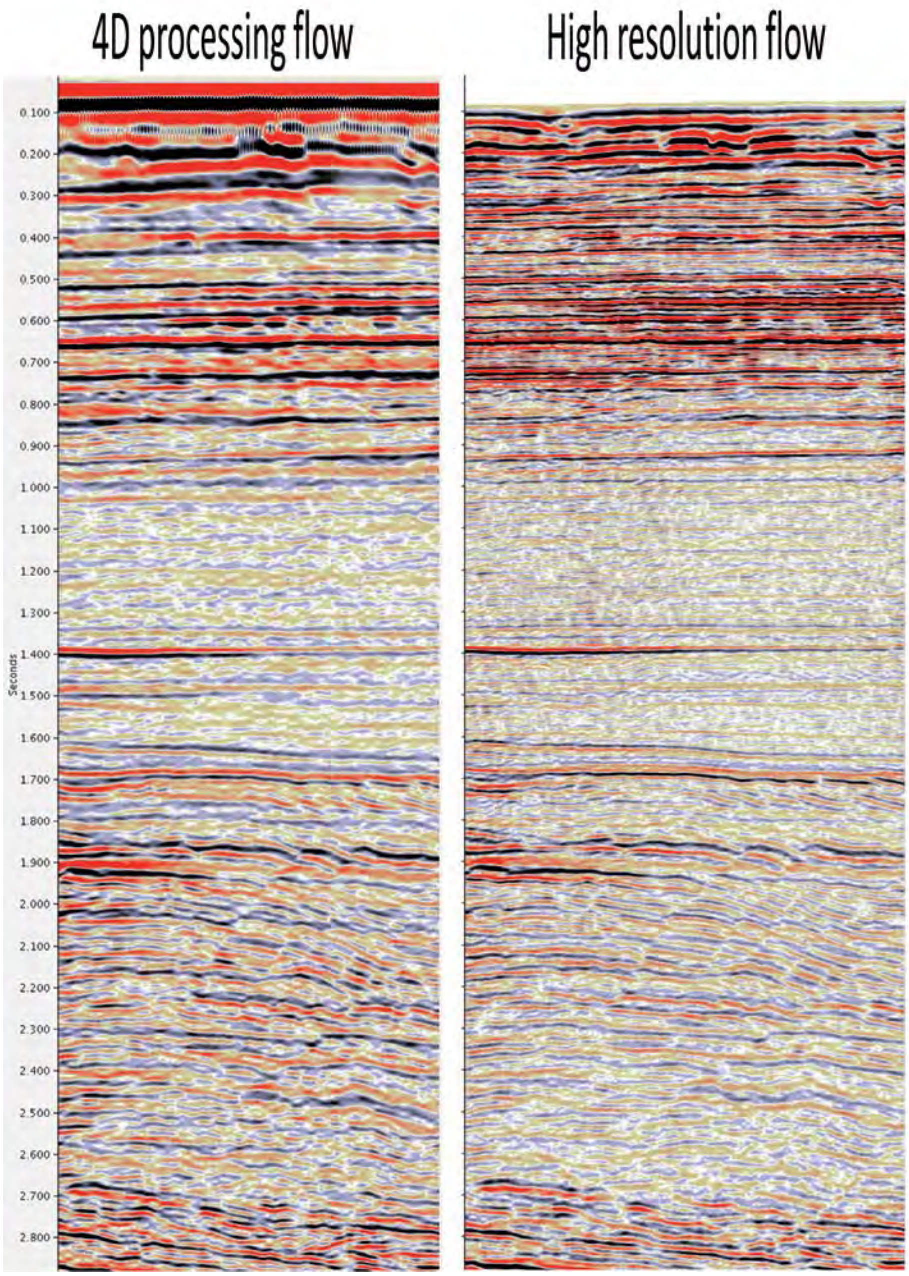

Figure 9 *Comparison of a 3D migrated inline from the 2008 survey, processed using the Optimized 4D flow and the High Resolution processing flow.*

attention was paid to minimizing the variability of the older dataset. This was not a trivial matter, given the size of the area affected by 4D signal. The results, however, showed a substantial improvement in repeatability compared with the basic processing flow. Figure 10 shows how the timing stability is improved, and Figure 11 shows that the general NRMS difference has decreased from 30–40% to around 20%.

The future of Ekofisk time-lapse seismic

Given the importance of time-lapse seismic technology to the production of Ekofisk, ConocoPhillips determined that a six monthly survey interval would be desirable and

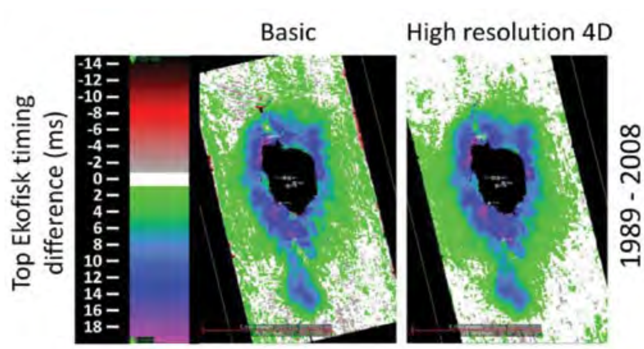

Figure 10 *Top Ekofisk timing difference 1989–2008, measured on full offset stack data from the Basic processing flow and the High Resolution 4D flow.*

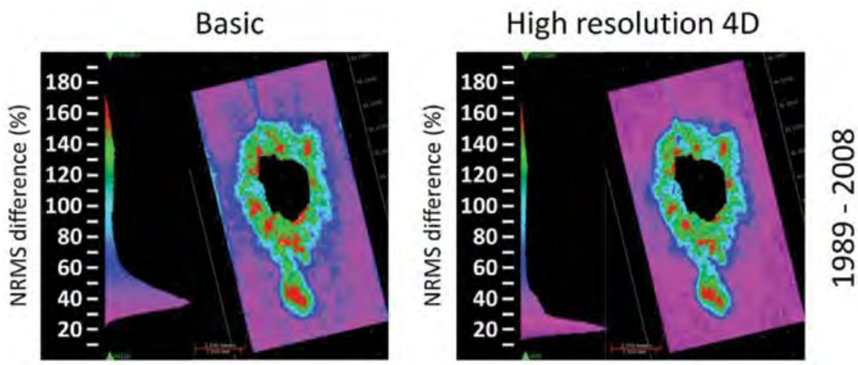

***Figure 11** NRMS difference maps, computed 2500–3500 ms for the 1989–2008 comparison, measured on full offset stack data from the Basic processing flow and the High Resolution 4D flow.*

that, given the expected lifetime of the field, a permanent monitoring system could deliver these surveys at lower total cost than marine streamer acquisition. Therefore they have installed a large permanent seismic monitoring array, and the first survey was acquired in late 2010. This system will provide full azimuth seismic data with high repeat positioning accuracy and the resulting time-lapse data is expected to have excellent timing and amplitude stability. Four-component data is recorded, giving the possibility of converted-wave imaging through the SOA.

Summary

Time-lapse seismic data is an important component of the Ekofisk reservoir management strategy, leading to greater operational efficiency, higher recovery factors, and safer operations. From the initial time-lapse comparisons, made in 1999, the time-lapse seismic data quality has steadily improved. This is not only due to better acquisition technology, but also the result of continual improvements in time-lapse data processing techniques, as new applications for the time-lapse data are defined. Further applications are expected to be identified when the first time-lapse data from the permanent monitoring array are received.

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