Time-lapse helps site new Ekofisk wells

Reservoir drainage and injection patterns in Norway's largest oil field are mapped using high-resolution time-lapse seismic technology.

AUTHORS

Rob Ross, Ed Palmer, *and* ***Andy Thompson***, *WesternGeco; and* ***Haakon Haugvaldstad***, *ConocoPhillips Skandinavia AS*

Much has been written about the Ekofisk field since its discovery in 1969. Lying in the Norwegian North Sea Blocks 2/4 and 2/7, about 200 miles (320 km) southwest of Stavanger in approximately 230 ft (70 m) of water, the field has produced continuously since 1971. The field comprises a vast complex of platforms and structures.

Approximately 300 wells have been drilled on the field to date, of which about 100 wells are still active. The majority of the active wells are either oil producing wells or water injector wells. A small number of observation wells exist, as do wells devoted to injection and disposal of drill cuttings. Several of the structures have been decommissioned and are awaiting removal and disposal.

According to the Norwegian Petroleum Directorate, from an estimated 6.7 billion bbl original-oil-in-place, total field recoverable reserves are estimated at 3.32 billion bbl of oil. By the end of 2008, remaining reserves are estimated to 790.6 million bbl of oil.

A checkered career

To fully appreciate the technical challenges at Ekofisk, it is useful to understand a little of the history of the field. Production has been from the prolific Tor and Ekofisk chalk formations of early Paleocene and late Cretaceous ages. Reservoir depth ranges from 9,500 to 10,660 ft (2,900 to 3,250 m) below sea level. The reservoir rocks are high-porosity, low-permeability fractured chalk. Originally a depletion drive, production was converted to water injection in 1987.

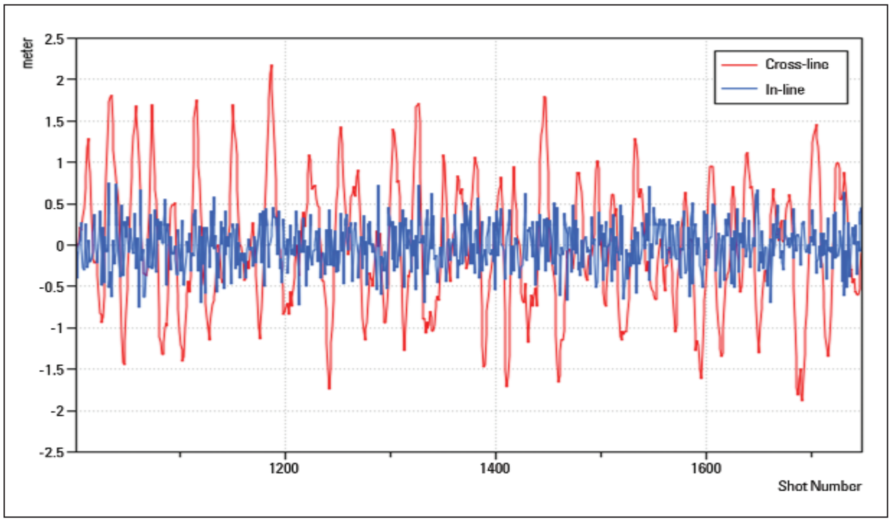

Figure 1. *Source position relative to navigation plan. (Images courtesy of WesternGeco)*

The initial pressure depletion, as well as water weakening of the chalk due to the water injection, caused the reservoir rock to compact, causing subsidence, first at reservoir level but later propagating through the overburden to the surface. The seabed in the center of the field has subsided approximately 30 ft (9 m). This led to the entire Ekofisk surface complex, at the time consisting of seven structures, to be jacked up about 20 ft (6 m). Since then, subsidence has been controlled somewhat by an injection scheme where an equivalent amount of water is injected for each barrel of liquid produced. Nevertheless, although subsidence has been slowed by water injection, wells in the field have a finite life due to collapse of their casings from the subsidence forces. This creates a continual need to drill new wells to sustain production.

Further complications ensued due to trapped gas in the overburden. This gas is believed to have migrated up from the reservoir over geological time and created a low-velocity gas "chimney" over the center of the reservoir, which obscures the seismic image of the deeper formations. This is called a Seismically Obscured Area and is shown in Figure 4.

Seismic has value

Notwithstanding the complications caused by subsidence and gas cloud accumulation, marine seismology has emerged as the most effective way to monitor fluid movement in the reservoir. Four-D seismic measurements enable a better understanding of drainage patterns, structural deformation, and change in the reservoir distance from well locations. By using 4-D seismic measurements, a producing reservoir can be optimally managed by detection and control of fluid migration fronts and better placement of new wells. In addition, reservoir simulation models, when constrained by 4-D seismic measurements, can deliver an improved prediction of future reservoir performance.

Time-lapse seismic data can help the reservoir engineer react to unexpected well or injection program failure, to search for bypassed zones leading to better well placement, to develop reservoir production plans while validating the dynamic model, and to monitor fluid migration and injection paths. This data can also contribute to the question of whether to abandon the field or not.

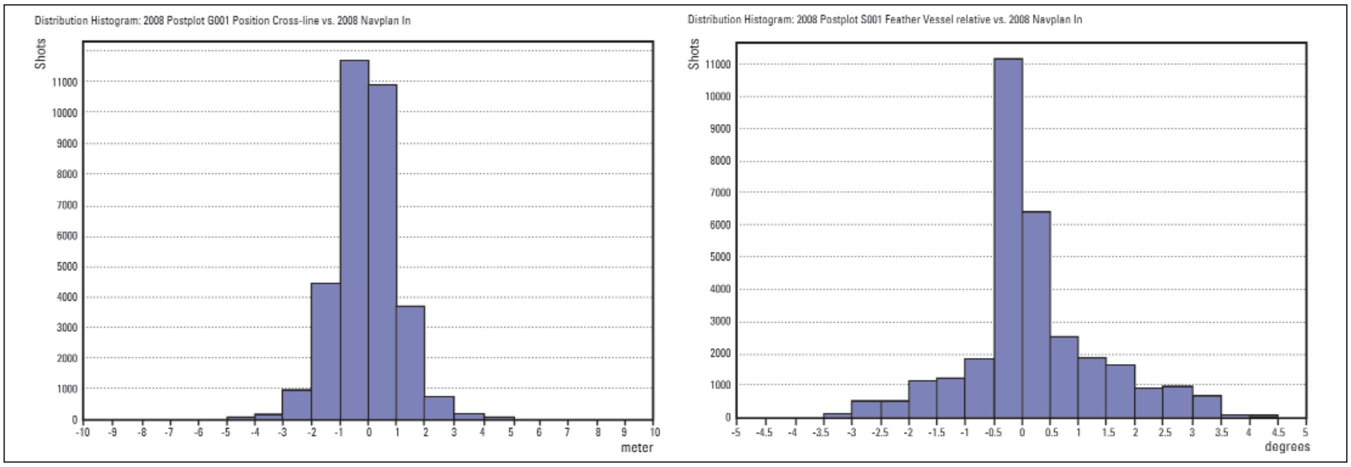

Figure 2. Source and feather repeatability.

ConocoPhillips was an early recognizer of the potential of time-lapse seismic, the first Ekofisk monitor survey being acquired in 1999 over the baseline 3-D survey from 10 years earlier. A further monitor was acquired in 2003 with the objective of relating the changes observed between the three surveys with further subsidence and/or injection water incursion. It must be noted that in processing 4-D time lapse seismic, the result is controlled by the lower quality survey within the time-lapse sequence. Even with the technology available to the component surveys of the time-lapse sequence, the 4-D results were extremely encouraging, so much so that ConocoPhillips decided on a future systematic schedule of 4-D seismic surveys to monitor injection patterns and help identify new locations and trajectories for infill well drilling.

Success in time-lapse seismology lies with survey repeatability. Definitive results evolve from "apples-to-apples" comparisons of similar shot/receiver pairs from subsequent surveys. Hence, areas within the survey area that have not experienced fluid and/or structural movement over the span of the seismic 4-D experiment will not show a time-lapse signal, while areas that have experienced fluid and/or structural change will give a 4-D signal. But achieving that level of repeatability of the seismic measurement is difficult under the best of conditions. Ideally, the seismic sources and the multi-streamer array deployed behind the survey vessel must repeat the same paths through the water as the previous seismic survey. Deviation of the streamer from the survey azimuth is called feathering, and it increases with the distance from the survey vessel, exacerbated by wind, waves, and cross-currents.

From technology comes resolution?

About the time that the oil and gas sector was starting to see the benefits of time-lapse seismic, the industry was also becoming aware of its challenges, mainly centered on the repeatability of the seismic experiment. Fortunately, the evolution of time-lapse techniques coincided with technological developments that effectively removed many of the barriers impeding rapid uptake of the 4-D process.

Q-Marine technology was developed with the specific purpose of attacking the sources of noise and errors that affected quality of the seismic measurement. With the 4-D process in mind, four key developments have spurred the application of the technology by making an order of magnitude improvement in repeatability. These include:

- Calibrated sources — hardware and software to match the source signature of each component of the airgun array for maximum congruence from shot to shot and survey to survey;
- Calibrated positioning — the ability to know with considerable precision the location of each streamer component within the full seismic array;
- Calibrated single sensors — automatic calibration of each sensor in the streamer, along with 10.3-ft (3.125-m) single sensor sampling to enable noise suppression; and
- Dynamic Spread Control (DSC) — enabling the planning and automated positioning of the vessel, source, and streamers. A navigation plan is input to the 4-D position controller. The controller dynamically steers the vessel, sources, and streamers to match the 4-D navigation plan.

These key factors, along with digital group forming and massively parallel processing capabilities, have kept pace with the introduction and development of the 4-D technique. The latter have reduced the waiting time for interpreted results from months to weeks and, in some cases, days.

At Ekofisk, the first Q-Marine survey with steerable streamer technology was completed over an area of some 46 sq miles (120 sq km) in 2006. However, as with the previous surveys, the 2006 survey was acquired using a typically 3-D methodology. The emphasis was on steering to maximize fold of coverage rather than following a predefined 4-D plan.

The decision to drill new wells to sustain production requires as much foreknowledge as possible if they are to be effective. In 2008 a second Q-Marine survey was acquired to match precisely the 2006 survey. Because all the aforementioned technology enhancements were available on the 2008 survey, the positional match of source and streamer locations between these surveys was excellent. A navigation plan was created prior to the survey by a 4-D planning module. The basis of this plan was the 2006 source and streamer positions, with sail lines optimized for operational efficiency to obtain the required 4-D measurements. During acquisition, the task of the DSC was to automatically steer the vessel along the non-straight pre-plot, to laterally steer the source arrays to replicate the source positions, and to steer the streamers using remote controlled steering devices placed at intervals along the streamers to replicate the streamer feather contained in the navigation plan.

Figure 1 illustrates, for a single sail line, the degree to which the source could be positioned relative to the equivalent line from the 2006 survey. The crossline and inline deviation from the navigation plan is plotted for every shot point.

Over the entire survey, the standard deviations of the source repeatability were 3.6 and 0.98 ft (1.1 and 0.3 m) for the crossline and inline components, respectively. Overall, 95% of all shots were fired within 8.2 ft (2.5 m) of the matching 2006 source positions. The standard deviation of the feather repeatability was 1.5º. For 95% of the survey, the steerable streamers were able to control feathering within 2.8º of the base survey, which had experienced changeable varied feathering. The same accuracy was maintained in the center of the field, where seismic undershooting was performed to image beneath field structures.

Data density was maximized by the use of digitally grouped-formed data derived from the single sensor interval on the eight 11,812-ft (3,600-m) Q-Marine streamers, which were spaced 164 ft (50 m) apart. The group interval within the shot gather enabled effective sampling and removal of seismic noise. Substantial improvement in time-lapse repeatability as indicated by normalized root mean square (NRMS) values was achieved. Figure 3 shows that NRMS down to 10% was achieved over much of the Q-on-Q 4-D survey. ConocoPhillips was able to resolve differences in structural timing between the surveys of as little as 0.5 milliseconds. The impact of this level of resolution is illustrated in Figure 4, where the effect on the top Ekofisk structure of a well drilled in 2006 can clearly be seen on the time difference image.

A further benefit of the 4-D acquisition methodology proved to be the operational efficiencies that it allowed. In 2008, total infill, whereby lines are reacquired to obtain missing fold of coverage, amounted to just 11% while meeting the coverage requirements. This compared to 30% infill in 2006.

This was the first Q-on-Q 4-D marine survey commissioned by ConocoPhillips, which had 20 years of experience using seismic to map the Ekofisk field. For the first time it was able to match exactly the shot points and feathering of the previous survey using seismic streamer techniques. The end result was that the 4-D survey enabled new well locations to be pinpointed with greater precision while providing a greater fidelity in understanding reservoir management issues through injection and drainage. E&P

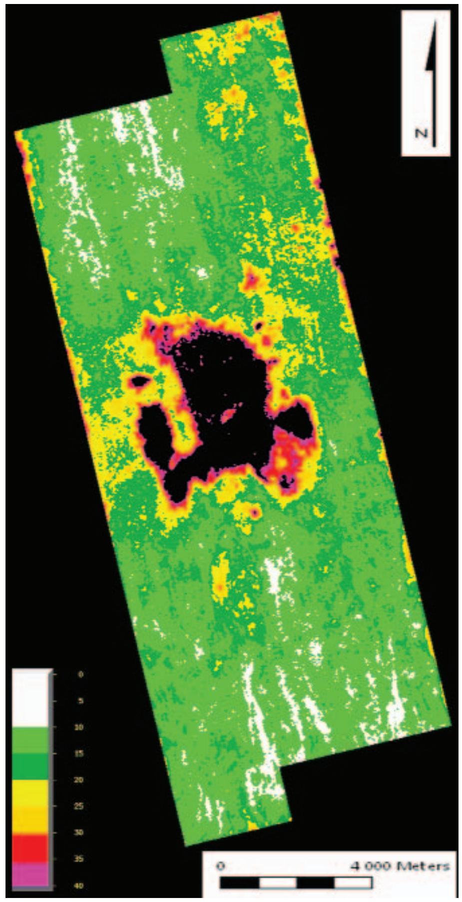

Figure 3. NRMS 2006-2008 (2.5 -3.5 sec)

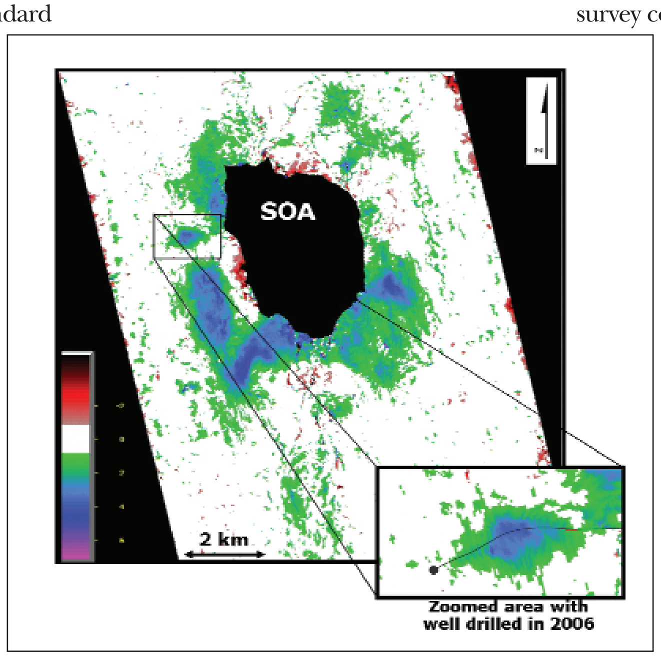

Figure 4. 4-D (2008-2006) top Ekofisk time difference (millisecond).

Acknowledgments

The authors thank ConocoPhillips Skandinavia AS and the PL018 partnership Total E&P Norge, ENI Norge, StatoilHydro, and Petoro for their permission to publish this work.