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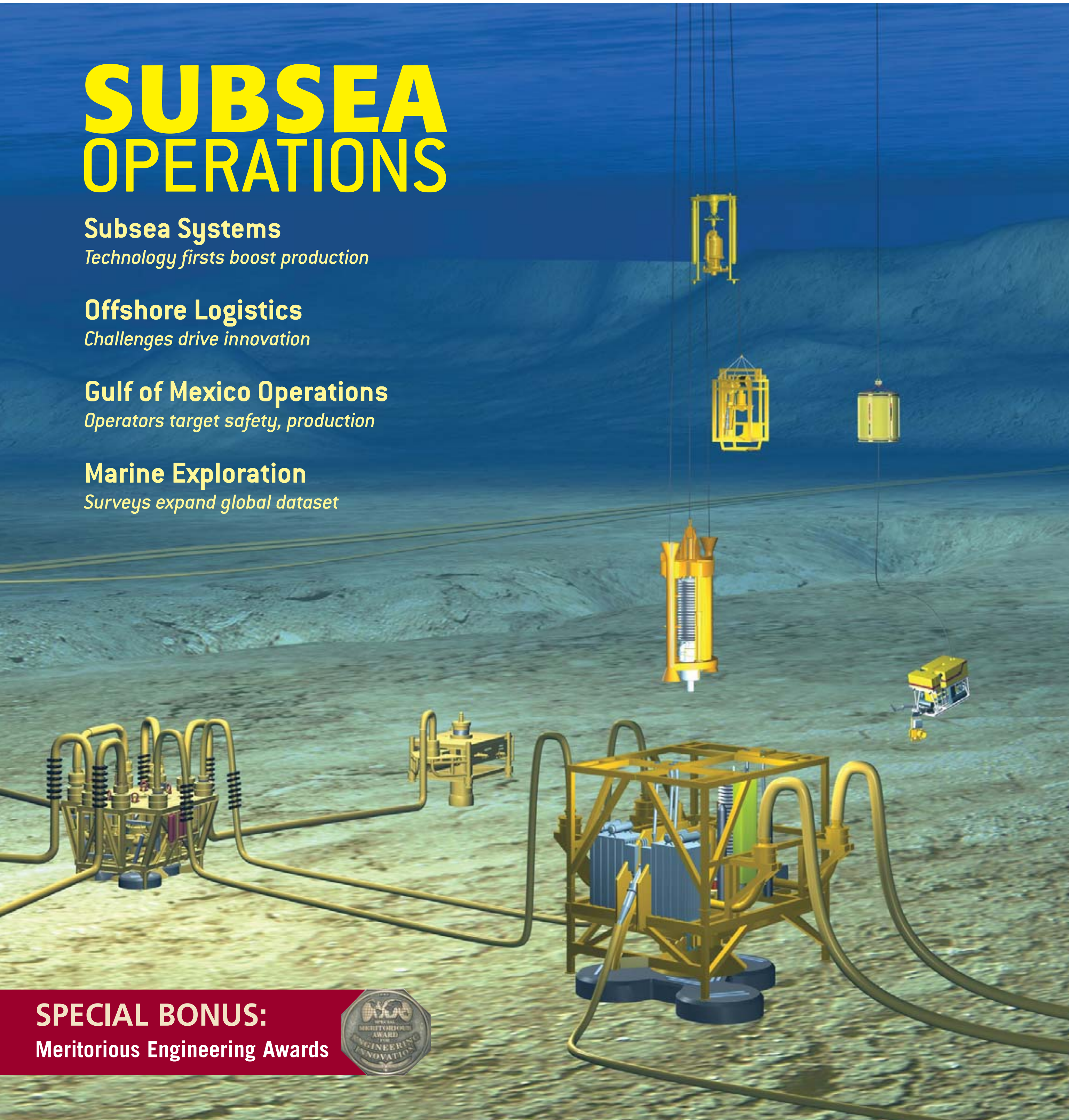

SUBSEA OPERATIONS

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Integrated geomechanics

Hess, WesternGeco and Schlumberger apply a multidisciplinary technique to resolve complex challenges affecting future reservoir development in the Danish North Sea.

AUTHORS

***Christian Rau Schiøtt**, Hess; **Anders Bruun**, Schlumberger, **Henrik Juhl Hansen**, Schlumberger and **Ed Palmer**, WesternGeco*

Time-lapse seismic techniques have been particularly successful in many places around the world. Not only do they benchmark changes that have taken place in the reservoir over a specific time period, but most often they provide clues to the root cause of the changes. This valuable information allows operators to predict with some accuracy future production dynamics. It also provides data to support subsequent decisions concerning production optimization and improved ultimate hydrocarbon recovery.

Setting the scene

The westernmost corner of the Danish North Sea is a prolific area of the Central Graben, containing more than a dozen oil fields and half a dozen gas fields. Generally defined by massive faults trending northwest to southeast, the play is bounded on the east by the Coffee Soil Fault that defines the western edge of the East North Sea High (Figure 1). Hess operates the **South Arne** oil field, located in **Block 7/89**. Discovered in 1969, South Arne was not produced until 1999 with initial development planning largely based on information provided by a conventional 3-D seismic survey executed in 1995.

With a significant part of the production coming from a small number of the producers, each well plays a critical role in field profitability. The challenge is to develop the field using a dynamic earth model that takes into account changes in the reservoir over time. More importantly, it is critical to be able to anticipate sudden changes to the field production environment so action can be taken to mitigate any adverse effects. The company does not want to drill one well too many because of the cost and the risk, but at the same time it does not want to drill one well too few and miss valuable reserves.

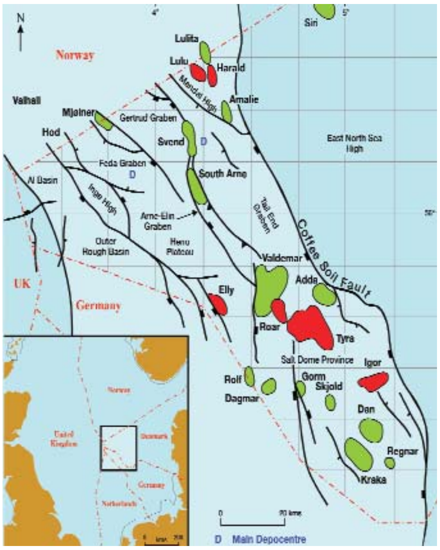

Figure 1. South Arne field lies in the center of a prolific area of the Danish North Sea. (Images courtesy of WesternGeco)

Not just a typical 4-D scenario

In 2004, Hess initiated a detailed technical and economic study to address the application of geophysical technology in future reservoir development. The study indicated that acquisition of modern 3-D seismic images could improve understanding of all the factors presently affecting production. In fact, the economic analysis indicated that an expected increase in seismic imaging quality would improve well planning and drilling enough to pay for the seismic on the basis of three development wells. Properly designed, it could mimic the original 1995 survey and provide valuable time-lapse data as well as form a new high-quality base survey upon which future decisions could be predicated. The final plan consisted of seismic acquisition using Q-Marine technology, followed by 4-D seismic visualization and analysis, rock physics, and integration into a dynamic reservoir model comprising both geomechanical and petrophysical components.

Often 4-D seismic identifies and tracks the artifacts of fluid movement within reservoir compartments as a result of production. However, at South Arne the challenge was complicated due to geomechanical changes affecting the structure itself. These had to be thoroughly understood before drainage patterns could be addressed. Quantifying the changes in reservoir compaction was a key factor in Hess' ability to predict future reservoir behavior and plan infill drilling with confidence.

Capitalizing on a proven technique

Geomechanical data has been used extensively in hydraulic fracturing design as well as in prediction of sanding or anticipation of wellbore stability problems facing drillers, including blowouts caused by geopressured zones. But in reservoir development, geomechanical applications are not as mature. Production of some reservoirs has been shown to affect the status of the structural stress field. Early manifestations of these phenomena include compaction leading to subsidence, particularly prevalent in chalk reservoirs, as experience from analog chalk fields indicates. A notable North Sea case was the **Ekofisk** field subsidence,

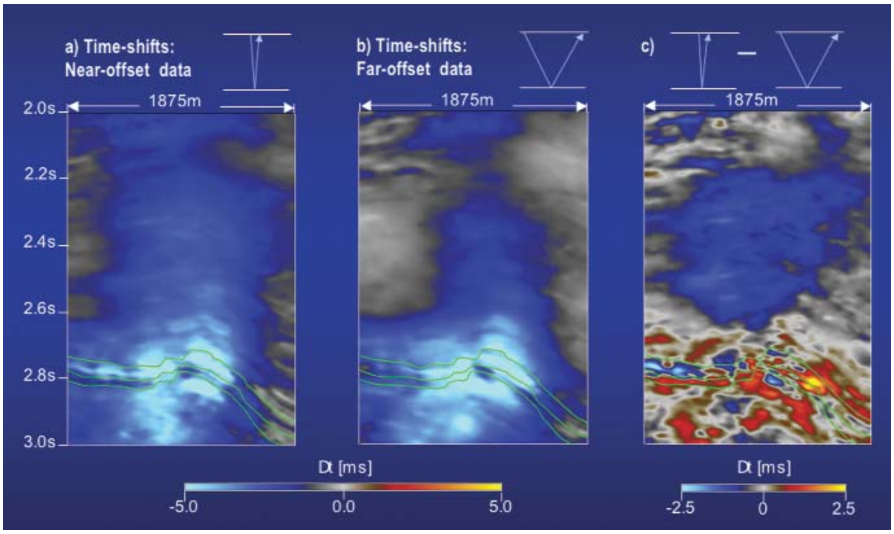

Figure 2. Time shifts due to dynamic compaction of the overburden are depicted in this analysis, which shows anisotropic changes in velocity between near-offset and far-offset data (panel c). Green lines indicate top-, intra- and bottom reservoir interpretations.

which required the entire production facility be raised some 20 ft (6 m). In conjunction with compaction and changes in the reservoir stress field is the change in fracture permeability within and surrounding the reservoir as well as the possible creation of high-conductivity stress faults that may alter reservoir connectivity significantly through field life.

Clearly, an integrated approach comprising elements of geomechanics, 4-D seismic and rock physics was required to resolve the complexities of South Arne. But the key to success lay in planning. To achieve the desired objectives, the seismic acquisition had to be designed with the processing plan in mind. To ensure high-quality seismic images, high repeatability versus the 1995 base-line survey and an ideal baseline for potential future 4-D acquisitions, the decision was made to use Q-Marine technology. This included the use of advanced acoustic techniques and steerable streamers, which resulted in the 2005 monitor survey matching the original survey to within 3° of feather and with monitor lines centered around zero feather. In addition, low noise acquisition is likely to have enabled improved 4-D repeatability. The high degree of 4-D repeatability is manifested in an normal root mean square of 0.1 across the reservoir, which is believed to be world-class for a towed-streamer 4-D survey.

New technology yields fast turnaround

A Q-Express processing flow was designed ahead of the 2005 acquisition using the 1995 seismic survey as a basis. The design and execution of the processing flow allowed WesternGeco to supply Hess with 4-D data volumes within three weeks of firing the final shot at sea. This allowed Hess to work out the compaction corrections. Whereas dynamic simulation modeling predicted compaction around 13 ft (4 m) in the best parts of the reservoir, seismic showed compaction to be around 3 ft (1 m).

The seismically derived compaction value is confirmed by a separate geomechanical model of the reservoir which was constructed using a geomechanical simulation tool (VISAGE). This tool independently was able to verify the magnitude and distribution of the seismically derived compaction estimate.

A major concern was the risk of the processing introducing artifacts into the results, thus creating false apparent 4-D effects. This concern was alleviated by performing detailed 4-D parallel processing of both monitor and base datasets to fine-tune all parameters and create a workflow that provided the information needed to refine recovery estimates.

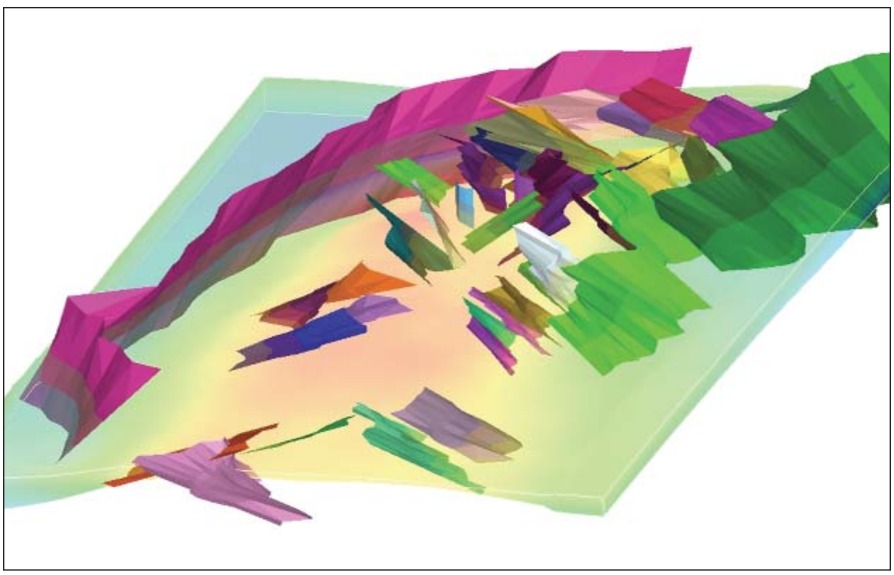

Figure 3. Complex fault geometry is revealed. Most of the smaller faults are the result of compaction-induced stress and occurred contemporaneously with production. Determining which of these are affecting production helps create an accurate dynamic earth model.

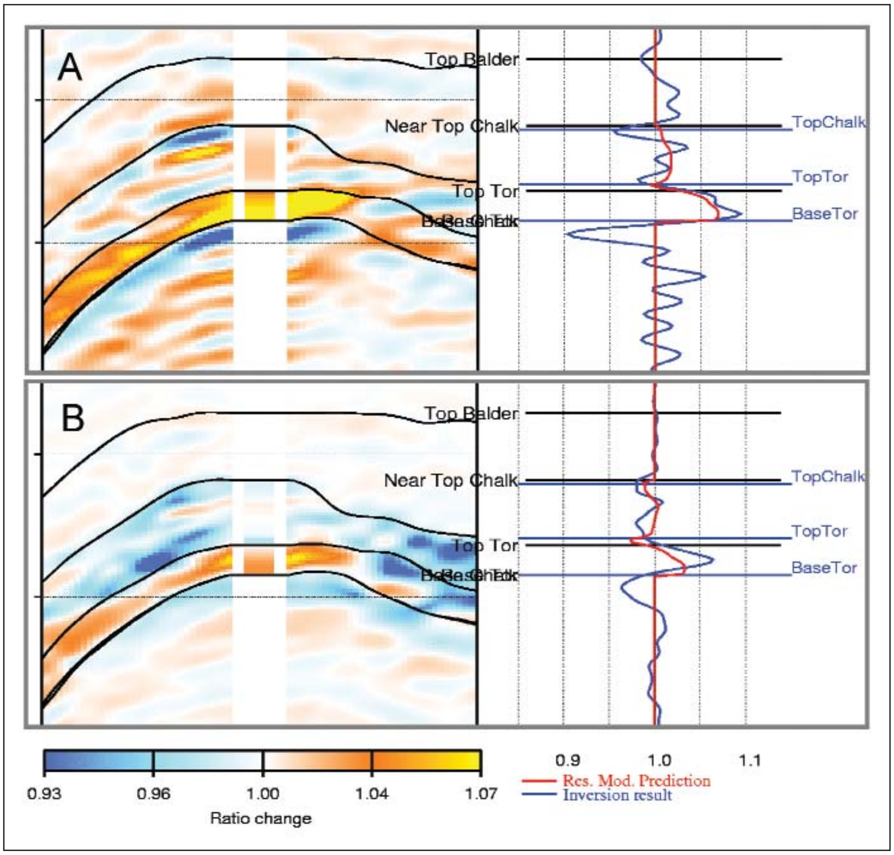

Figure 4. Changes in acoustic impedance (A) and Poisson's ratio (B) from the ISIS simultaneous 4-D AVO inversion at a key well location. The orange to yellow colors show increases in acoustic impedance and Poisson's ratio from 1995 to 2005 in the main reservoir interval, indicating a reduction in porosity and an increase in water saturation.

The seismic processing was followed by an ISIS simultaneous 4-D amplitude versus offset inversion to derive acoustic impedance, Poisson's ratio and related 4-D changes. These parameters allowed Hess to map the subtle changes in the elastic properties induced by reservoir production effects. Additionally, shifts in the timing of seismic events from 1995 to 2005 enabled a calculation of porosity changes resulting from alteration in the reservoir's geomechnical properties. To improve understanding of the production's effect on the elastic properties, an ISIS rock physics model was established. The modeling approach aims to be field-adaptive by the use of well log and core measurements while honoring theoretically defined bounds. It proved to be more accurate and efficient than existing rock physics models for the chalk reservoir, primarily because it is driven by well log data as much as possible.

This revelation meant that the company had to change its dynamic simulation model. In doing so, if one parameter changes, others must also change, or the history-matching is jeopardized. Some of the implemented changes involved accounting for direct connectivity between injectors and producers as well as the realization that some of the injection water had leaked out of the system. By carefully considering possibilities, the history match was actually improved, which in turn enhanced the ability to make accurate predictions. A brief test case was run using actual production data obtained between January and October of 2007, which confirmed an improvement in the predictive capability of the dynamic reservoir model.

Myriad changes analyzed

Hess actually did a detailed job of looking at the baseline dataset and creating a robust processing and interpretation workflow. So as soon as the monitoring dataset was obtained, it was processed to provide a quick look at the results. The relevant parameters, like velocities, had already been picked, so in three weeks, the compaction corrections were calculated. Management was informed that the compaction in the South Arne field was different than expected and how this change affected the dynamic behavior. Lastly, the project proved that an initial 4-D result can be obtained within less than a month of the last shot with careful planning and execution.

Future plans

While the full impact of this work will take time to digest, it can be said that the improvements to the dynamic simulation model will be valuable. They have reduced the risk in placing injector wells, which should optimize recovery. In one specific case the relationship between a producer-injector pair was revised as it was recognized that the history match could no longer be achieved by allowing for a high degree of reservoir compaction in the reservoir. The observed complexities of the South Arne reservoir have given impetus to the consideration of application of more geophysical reservoir monitoring technology. This provides analysis that indicates technical feasibility and that the economics are favorable. E&P

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