Two decades of 4D geophysical developments – experiences, value creation and future trends

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SUMMARY

Since the introduction of the marine seismic 4D technology in the early 90's, StatoilHydro has been piloting a large spectrum of novel technology developments, and applied these to solve a variety of reservoir challenges. In addition, we have successfully developed and implemented high resolution 4D marine gravimetric. Geophysical reservoir monitoring helps maximizing recovery from producing reservoirs using seismic, gravity and electromagnetic based methods for reservoir imaging, characterization and monitoring. Building on our ongoing IOR research efforts, StatoilHydro aims to be a leading company in quantitative integration of 4D data in reservoir modelling, and lead in tailor-made data acquisition and processing for seismic imaging and reservoir characterisation so that we can meet the challenges of the most complex reservoirs. This presentation summarizes our experience and value creation from a large number of time-lapse projects and offers our view on the future trends for 4D in reservoir management projects.

Introduction

Towed streamer seismic time-lapse technology is still - 20 years after the first ever 4D pilot run by StatoilHydro on the Oseberg field followed by the full-field investigation and application on the Gullfaks field - the dominant geophysical reservoir monitoring method. The technology has proven to be an excellent enabler for improved reservoir management and hence an important source for value creation in the petroleum industry. Today, approximately 75 % of the StatoilHydro operated fields employ time-lapse seismic technology, and seismic monitoring is an integral part of our reservoir management. Cooperation with the contractors and service industry has been of vital importance to produce the best technology solutions.

Since 1998, StatoilHydro has successfully applied gravimetric monitoring of gas production from a number of its fields. In addition, we have applied 4D gravity to monitor CO_2 sequestration.

In this presentation, we first review our experiences from a broad spectrum of applications of 4D technology. Based on these experiences we predict possible future trends for the technology in reservoir management.

Technology developments & value creation

4D seismic technology has a number of applications, including, among others: Identifying drained areas, locating undrained reservoir compartments, optimizing well placement, reducing uncertainty in reservoir development and production decisions, discriminating between reservoir fluid and pressure changes, discriminating between compacted stretching and stress changes in overburden, and monitoring CO_2-sequestration.

4D seismic started in the early 1980's, but only became commercial in the late 1990's. In the North Sea, 4D seismic was investigated on a full field scale in about 1995 in a joint Statoil-Schlumberger project at the Gullfaks field. Detectable time-lapse signals were measured, and proved to be of economic value in identifying drained and undrained areas. Soon after this, 4D surveys were acquired over several Norwegian and UK North Sea fields, including Schiehallion, Foinaven, Draugen, Troll, Oseberg, Norne, Statfjord, Forties and Gannet.

In 1996 StatoilHydro started a research project to investigate the potential of 4D gravity to monitor gas production and seafloor subsidence, realizing that gravity is sensitive to height changes as subsidence. The 4D gravity method was proved over the Troll field, with benchmark deployment in 1997 and a repeat surveys in 1998, 2000 and 2002. We are currently running gravity monitoring projects on five Norwegian offshore fields: Sleipner, Troll, Mikkel, Midgard and Snøhvit, and a trial at Ormen Lange.

In the following, we address present monitoring results from the Gullfaks and Oseberg fields, the Troll field, and the Sleipner field.

The Gullfaks field

On the Gullfaks field, time lapse (4D) seismic data play a significant role in management of the tail production (El Ouair et al 2006, Williams 2008). 4D seismic data have increased our understanding of both the static properties and dynamic behaviour of the field, challenging the production strategy and driving the reservoir management decision process. The data have identified bypassed volumes in unswept reservoir compartments, improved the estimate of remaining reserves and the associated uncertainties, and helped to identify drilling hazards that have evolved over the life time of the field. Since the first repeat seismic survey in 1996, 4D seismic data have been integrated into a multi-disciplinary increased oil recovery (IOR) effort that aims to recover 70% of the in-place reserves from a structurally complex and heterogeneous reservoir sequence.

4D seismic has contributed directly with more than 15 successful infill wells and generated a net present value of around US$1 billion while the total cost of the 4D seismic is estimated to be US$60 million.

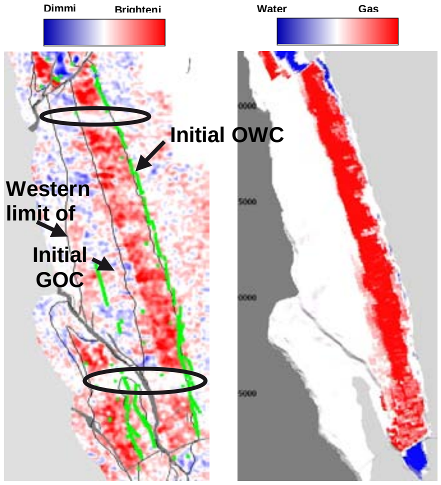

Figure 2: *4D seismi Base Reservoir of th compared to reservo (right).*

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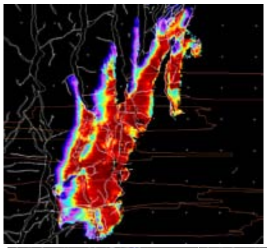
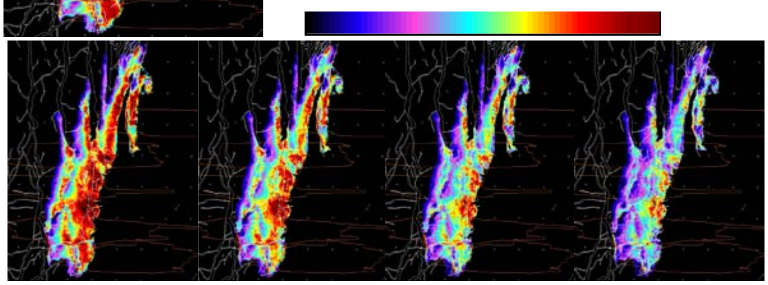


Figure 1: *Left: Oil saturation map within the Tarbert Fm from the Gullfaks reservoir model, 1985. Below: Attribute maps from 4D inversion showing the averaged Oil sat value. Extracted from 4D inversions from surveys in -96, -99, -03 and -05 respectively. Hot colors indicate highly Oil saturation*



The Oseberg field

The successful Oseberg 4D campaign is based on a feasibility pilot using repeated 3D seismic in a proper 4D setting (Johnstad et al, 1994). The initial exploration 3D was shot in 1982, but as a basis for modern 4D technology, new surveys for the pilot were shot by StatoilHydro in 1989 and 1991. These were the first surveys where the nominal parameters between the acquisitions were maintained unchanged, thus giving repeatability that even today will be considered useful for 4D work. The 4D campaign on Oseberg has been a technical and economical success – (based on surveys in -92, -99, -04 and -07) and has been used for implementation of modern quantitative 4D techniques. as elastic inversion giving estimates of Vp/Vs changes over time supporting the interpretation of pressure vs. saturation changes in the reservoir units (Andersen,T. et al, 2006).

The Troll field – tailor made solutions

Due to the very large area of the Troll East gas field, repeated full 3D surveys was not considered a feasible solution in early field development i.e. due to the high cost. As an alternative, StatoilHydro proposed and is currently running a campaign based on repeated 2D acquisitions where the vessel is towing a very dense spread of streamers. In this way, a very high degree of receiver position repeatability is obtained, giving excellent 4D signal/noise ratios. The repeated 2D lines have been used to map the pressure depletion du to gas production, and an average pressure drop of 15 bar has been detected from the seismic (Tøndel et al, 2005). Full field gravity data have been acquired to complement the 2D time-lapse seismic data and to map the water influx, and to date 4 relative gravity repeats have been acquired (Eiken et al, 2008). The gravity data have proven valuable in updating the reservoir understanding and locating remaining reserves.
Due to the encouraging results from the repeated 2D seismic lines a full field 3D seismic repeat survey was acquired in 2008 in order to map water influx and pressure depletion in greater detail.

In the Troll west area, the main challenge is to monitor the production from the very thin oil column (10-20m) over a large area (770 km2). Before a full field 4D implementation was initiated, a 3D pilot was run in -98 to demonstrate the ability of towed streamer technology to detect even very minute changes in the oil column. The successful pilot triggered the current 4D campaign that is now an integrated part of the reservoir management of the field. Workflows for qualitative and quantitative interpretation are developed (Haaland et al, 2008). The applications of this ranges from identification of IOR targets, optimized well placement for infill drilling as well as well completion. As a result, every year, an average of four new targets are identified from 4D data, while all drilled wells are being optimized with respect to both well placement and well completion, yielding increased recovery of the field. Accumulated value creation approximates 100 MUSD per year.

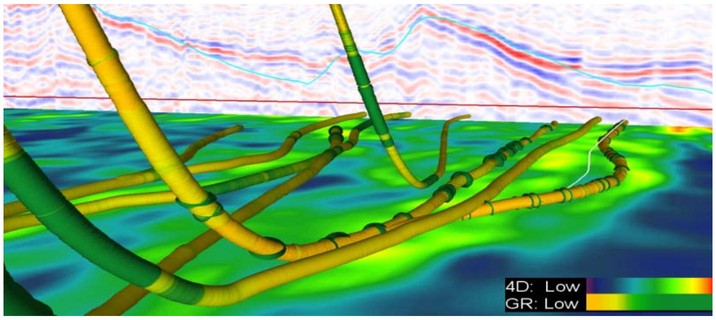
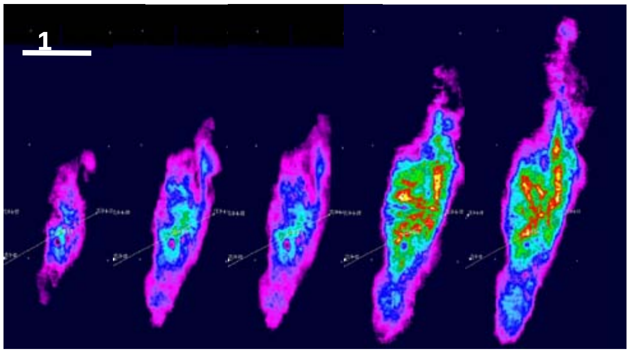


***Figure 3:** High 4D response denotes clean sand and can be correlated to low clay content. The well plan (white trajectory) was updated in the low 4D area to avoid the assumed clay-rich area. While drilling, this update proved to have increased the amount of clean sand in the well by more than 100 meters.*

The Sleipner field – Monitoring of CO_2 storage

Seismic monitoring has proved to be a powerful tool at the Sleipner site, North Sea. This is the world's first, largest and longest-running CO_2 storage project. Six repeat surveys through 12 years have revealed both an expansion and densifying of the CO_2 plume. Distribution estimates of the CO_2 saturation has been made from 4D seismic data and understanding of CO_2 flow, with reasonably accuracy.
Gravity monitoring has been tested at the Sleipner site, and a time-lapse signal from the injected CO_2 has been detected. This constrains the in-situ density, which otherwise is poorly determined, because the CO_2 has densities and temperatures close to the critical point. (Eiken, O., 2008).



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Future trends

The future holds requirements related to even shorter response times and shorter turn-around times for time-lapse geophysical data acquisition, processing, interpretation, and ultimately the model updating procedures. The challenge lies in reducing the time spent on this chain from months/year down to days/weeks.

Today much of the 4D seismic application is qualitative, or at best semi-quantitative, i.e. the time-lapse seismic data is used to identify areas of changes in saturation and pressure distributions between seismic survey times. The need for being more quantitative is already here, i.e. to estimate not only <u>what kind</u> of changes but also <u>how large</u> are these changes in saturation and pore pressure. In the rapid workflows of the future the quantitative interpretation methods will be an integral part.
Our experience indicates that time-lapse geophysical monitoring will steadily increase its importance as a reservoir management tool. In addition to proper integration of different types of geophysical measurements, we focus on development of workflows

that honour the full information content in the geophysical data for reservoir model updating.

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