4D Seismic

– Status and Future Challenges

PART I: Status

Time-lapse seismic is now a proven technology for monitoring fluid movements and identifying undrained compartments in thick offshore clastic reservoirs. Several challenges still exist, however, in particular the use of the technology for carbonate and thin-bedded clastic reservoirs.

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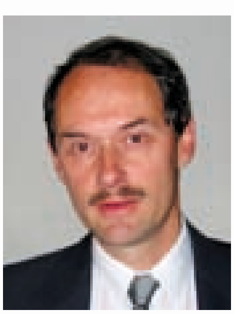

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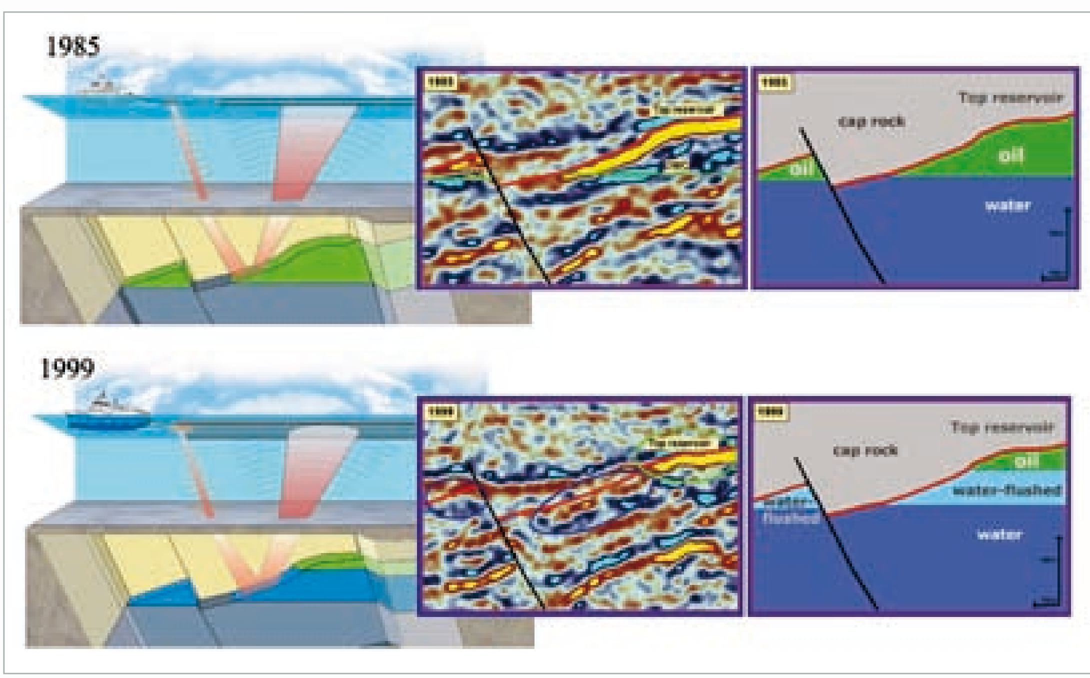
Seismic reservoir monitoring - known both as 4D and time-lapse seismic - consists of repeating 3D seismic surveys in order to make snapshots of the fluid and pressure fronts in a hydrocarbon reservoir during production. Time is the extra dimension over standard 3D seismic acquisition – hence the poplar name 4D. This technique is increasingly accepted as a valuable reservoir management tool, and a global expansion in activity has been seen.

4D seismic technology has a number of applications, including, among others: Identifying drained areas, locating undrained reservoir compartments,



A celebrated 4D example from the North Sea Gullfaks field, discovered in 1978 and still producing. The changes in seismic reflection amplitude between the two surveys in 1985 and 1999 result from a significant depletion of the oil due to production. The difference in the reflection strength of the top of the reservoir is related not only to reduction in oil saturation, but also to the original oil-column height. Where water replaces oil, the reflection strength is diminished, causing a dimming effect on what was a strong response from the top of the reservoir. The strong seismic response from the oil-water-contact (OWC) in 1985 has also been dimmed, owing to production of oil. The smaller oil accumulation, to the left of the fault, was drained by 1999, whereas much of the oil was still to be recovered from the larger trap, to the right of the fault.

Geographical areas with the most 4D seismic activity

optimising well placement, reducing uncertainty in reservoir development and production decisions, discriminating between reservoir fluid and pressure changes, discriminating between compacted and non-compacted reservoir compartments, identifying stretching and stress changes in overburden, and monitoring CO_2-sequestration.

Significant value adding

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. D etectable time-lapse signals were measured, and proved to be of economic value in identifying drained and undrained areas (compare illustration). 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.

Measured in terms of the seismic acquisition market, 4D seismic is a "little sister" compared to the 3D exploration market – its share is around 3%. Even though difficult to quantify exactly, the economic impact of 4D seismic, particularly in the North Sea, has been significant. The major oil and gas companies eagerly present their impressive technical successes, but unfortunately some are reluctant to publish their economic analysis of the benefits to production and reservoir management. We await these with interest, as they are needed to emphasise the value rather than the cost of 4D, in order to promote further uptake of the technology. Open sources, however, estimate the added value of North Sea 4D to be more than US$ 4 billion, with the added value at Gullfaks alone calculated to be close to US$ 1 billion. Furthermore, 4D is estimated to have reduced drilling costs by more than 6%, and contributed to additional reserves averaging 5% per field.

Strong European market

One way to estimate the size of the 4D seismic market is to calculate the 4D seismic expenditures of contractor and service companies for each region. This expenditure is dominated by the 4D seismic acquisition cost. A study undertaken by the French Institute of Petroleum (Lumley, 2004) showed that for the period 2000-2003, the 4D market was dominated by the North Sea (80%), offshore West Africa (7%), offshore North America (6%), and Far East (4%).

Today, the picture is almost the same. 4D seismic is a technology predominantly applied offshore Northwest Europe, in particular the North Sea and the Norwegian Sea. This market measured in terms of seismic survey expenditures is still 80% of the worldwide 4D market. Other important geographical areas are offshore West Africa (Angola and Nigeria), offshore North America (Gulf of Mexico), and offshore South America (predominantly Brazil).

The dominant player in the 4D acquisition market today is StatoilHydro. More than 20 4D streamer surveys were acquired during 2006. The other two big players are BP and Shell. BP has decided to invest strongly in permanently buried sensors for 4D, with installations at the North Sea Valhall field, the Caspian Sea Chiraz field and the US Clair field. The other main companies are ExxonMobil, ConocoPhillips, Chevron, Total and the Brazilian national company Petrobras.

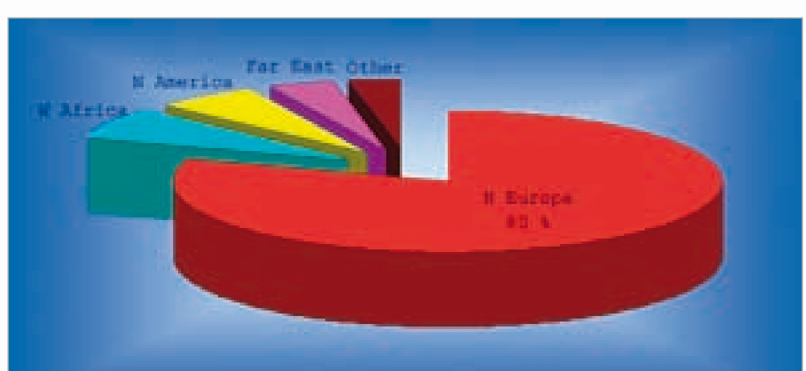
More discrimination

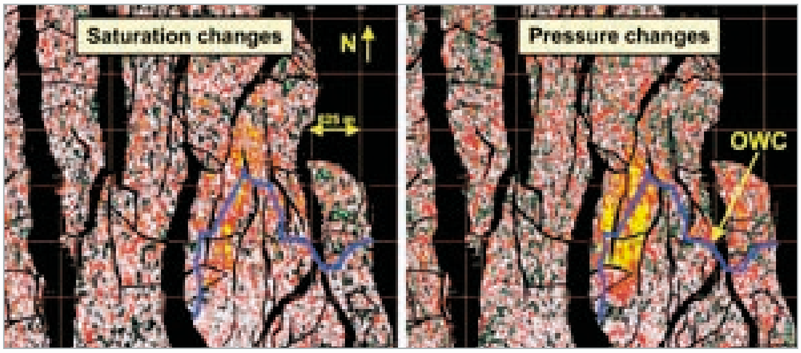
For reservoir management purposes it is important to discriminate between pore pressure changes and fluid saturation changes within various reservoir compartments.

One way to perform this separation process from 4D seismic data is to use time lapse AVO analysis, since pressure and fluid might show similar responses on stacked 4D data, but somewhat different responses on 4D AVO data. Other options are to use 4C seabed seismic data or controlled source electromagnetic data (CSEM).

So far, most examples show that it is possible to discriminate between the two effects for increases in reservoir pore pressure, while it is hard to detect and quantify a reservoir pore pressure decrease. 4D observation of pore pressure changes has also

Cumulative expenditures on 4D seismic services during the period 2000-2003 show that the North Sea/Norwegian Sea represented 80% of the market. The market share offshore West Africa was 7%, offshore North America 6%, and Far East 4%. Today, offshore Latin America is a new region of 4D activity, but there is somewhat less activity in the Far East. (Lumley 2004).





Estimated saturation (left) and pore pressure changes (right) for the Cook Formation at the Gullfaks field. Red to yellow colours represent relative increases. Notice that the pressure anomaly terminates close to faults, and passes the original oil-water contact, while the saturation anomaly terminates close to the original oil-water contact.

lead to new insights into pressure prediction in exploration.

CO_2 sequestration

4D seismic expertise has also been put into good use in a somewhat unconventional way – to monitor and analyze the behaviour of subsurface CO_2-repositories. One example is the Statoil-operated Sleipner field, where for more than 10 years 1 million tons per year of CO_2 have been injected into the Utsira Formation, a thick, water-bearing, highly porous, very permeable, weakly consolidated sandstone 1,000m below the seabed. This is being done solely for the purpose of protecting the natural environment.

4D seismic is used to monitor the formation's behaviour. The method is particularly suitable as the velocity of sound waves can be used to differentiate easily between high-velocity water-bearing and lower-velocity gas bearing sandstones. The 1999, 2001, 2002, 2004 and 2006 seismic displays strikingly show the increase in the rock volume affected by injected CO_2.

Future challenges

Not all reservoirs are ideal candidates for 4D seismic technology. Over the last 10 years the industry has gained substantial experience through a large number of 4D seismic surveys across a large variety of reservoir situations, including clastic, carbonate and fractured reservoirs under various recovery schemes.

The oil and gas industry now regards 4D as a proven technology for monitoring fluid movements and identifying undrained compartments in thick offshore clastic reservoirs. The challenge for the geophysicists is to extend the 4D technique to thin-bedded clastic reservoirs, carbonates, onshore sedimentary basins and extra heavy oil and tar sands

Although it has been a success story so far, there are important challenges that need to be met to ensure that the technology will be a frequently used tool world wide. In our view the most crucial challenges are:

- Improved vertical 4D resolution (ideally, 1-10m);
- Improved repeatability, enabling application to carbonate reservoirs; and
- Innovative ways to combine 4D seismic with other measurements and simulation methods.

These challenges will be discussed in Part II, to appear in the next issue of GEO ExPro.

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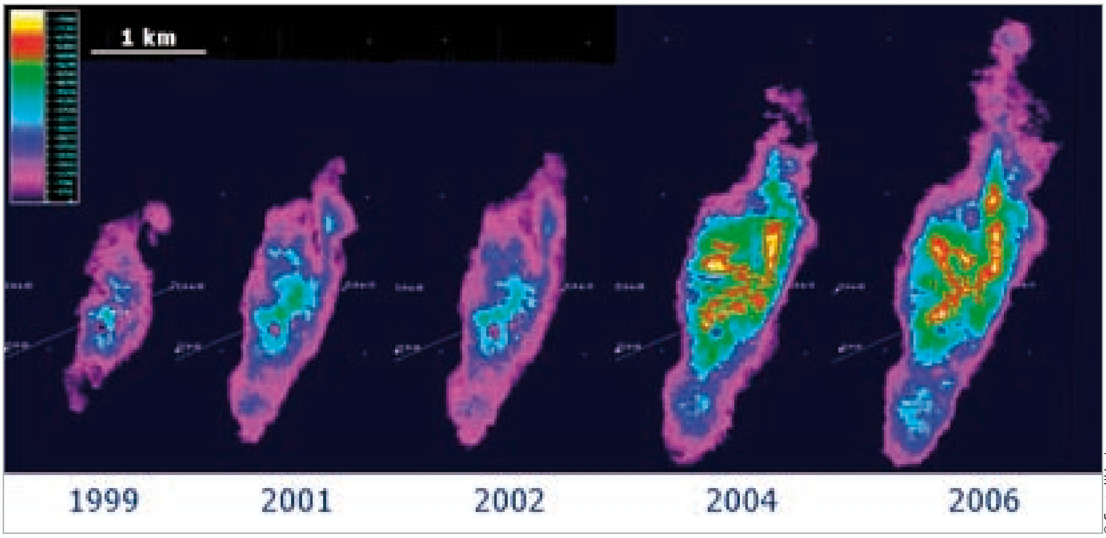

Seismic images of the development of the CO_2 plume at the Sleipner field