4D Seismic

– Status and Future Challenges

PART II: Future Challenges

Seismic monitoring is an important technology in the effective exploitation of reservoirs in existing fields. The successful further uptake of 4D technology requires extensive training of dedicated personnel, while the biggest challenge in 4D technology development is to produce high vertical resolution 4D images of production.

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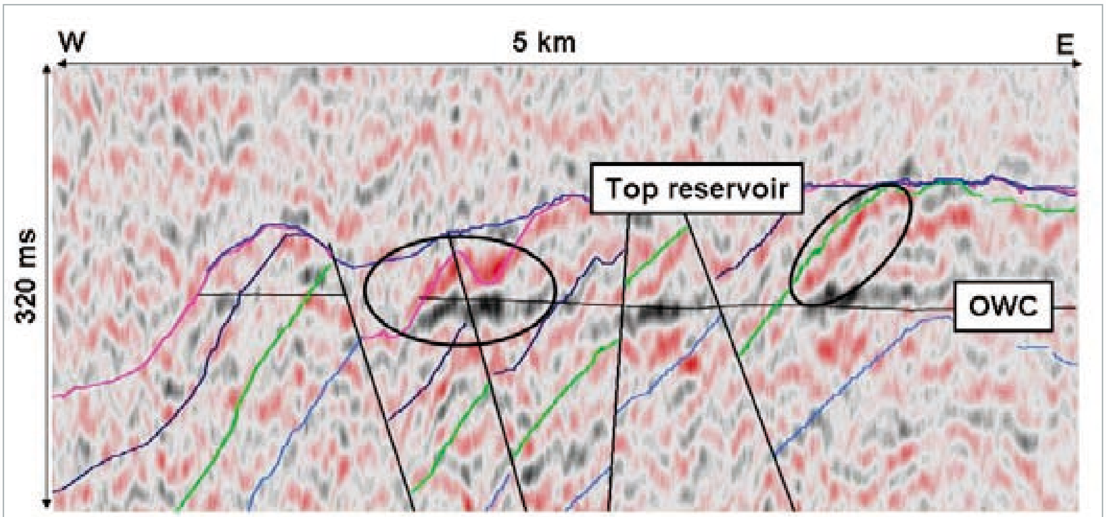
Both the potential and the challenge of using 4D is illustrated by the seismic example from the Gullfaks oil field in the North Sea. At the flank of the field, the 4D anomaly is strong and prominent, even though the original oil-filled reservoir section is pinching out (left ellipse on figure).

Prior to production, the presence of oil in the pore space generates amplitude brightening. This brightening is increased by tuning effects as the thickness of the oil column approaches zero. When water replaces oil, this effect is much weaker, and hence a strong 4D anomaly is observed, even for reservoir thicknesses down to as little as 10m. However, this does not necessarily mean that 4D vertical resolution is 10m for other parts of the reservoir. For instance, if we study other 4D anomalies for the same profile, we observe a single dipping anomaly (right ellipse).

Since this anomaly is between the top reservoir and the original oil water contact, we are not able to quantify whether it indicates that 5, 10, 30 or even 40 m of the reservoir have undergone changes due to production. Therefore, a major challenge for 4D seismic is to increase the vertical resolution in such a section, so that we are able to identify thin formations being drained within a thicker reservoir section. At the moment, high resolution 4D is only feasible where the reservoir thickness is thin.



4D difference section from the Gullfaks Field: Notice the strong amplitude changes (black color) associated with the original oil-water contact. The red-black difference anomaly within the left ellipse is interpreted as a tuning effect caused by water replacing oil in a very thin oil-zone. The right ellipse shows an intra-reservoir 4D anomaly, where it is much harder to estimate the vertical extent of the 4D effects, due to lack of vertical 4D resolution.

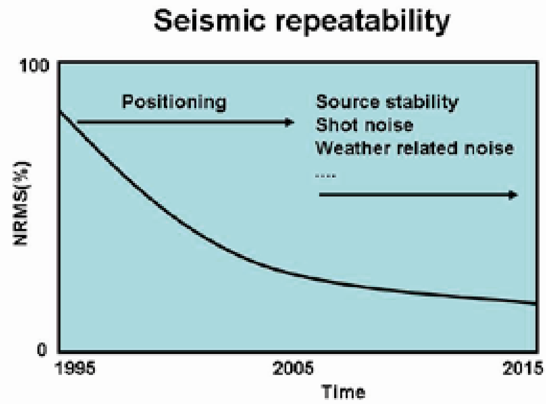
Improved repeatability

The recent major improvement in 4D repeatability, as sketched in the figure to the right, is mainly due to improved processing and better positioning of sources and receivers. Permanent 4D seismic installations and steerable or dense streamer configuration have both been significant in achieving this high accuracy 4D acquisition.

The best known example of a permanent 4D system is the Life of Field Seismic (LOFS, GEO ExPro 02/2004) project at the Valhall Field. More than 120 km of 4C cables were deployed in 2003, and so far 9 surveys have been acquired over the field. The repeatability of these data is excellent, mostly due to the fact that the receivers are fixed. Based on the experience from the Valhall Field, BP is planning similar permanent installations at the Clair Field (West of Shetland) and at the Azeri Chirag Field in the Caspian Sea. However, to date industry take-up of permanent systems has been slow. Technological improvements and reduced system cost, such as those provided by fibre-optic sensors may change this picture (Thompson et al 2006).

To improve the repeatability level further, issues like source positioning, source stability, shot time interval, rig noise, weather effects, environmental noise, and distant seismic activity have to be addressed. Other ways to increase the 4D repeatability include the use of "overlapping" or steerable streamers (Eiken et al., 2002) to ensure that the receivers are located at the same position for two separate 3D seismic surveys. This technology has shown good results for several field examples, and should be regarded as an alternative to permanent 4D installations.

Looking towards the future we expect more sophisticated 4D acquisition techniques to be developed to improve repeatability. One concept could be to tow a super dense grid of sensors to achieve a high fidelity sampling of the seismic wavefield. Such a technique will allow significant improvements in data processing, delivering high quality 4D images.

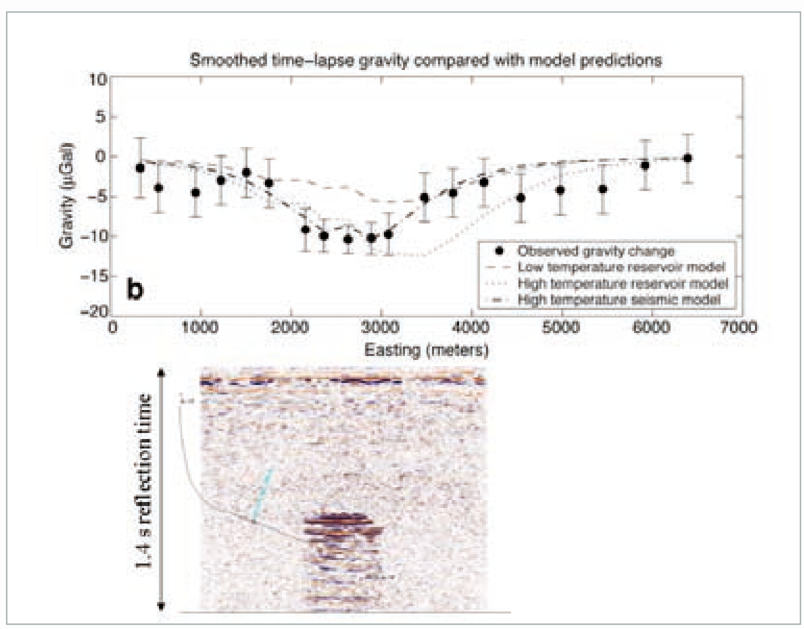


A cartoon showing how the 4D repeatability has improved from 1995 to date. The improvement is attributed to accurate 4D processing and improvement in 4D acquisition.

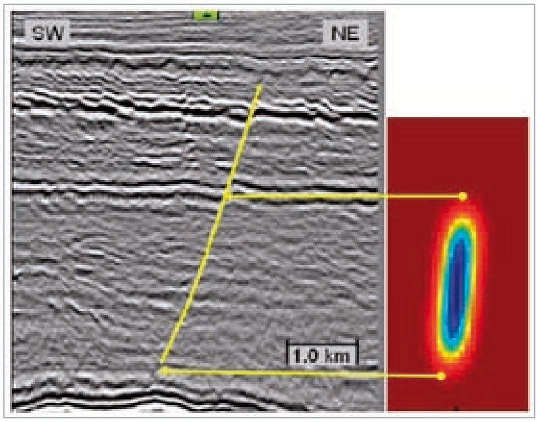
Innovative combinations

The most promising and rapidly growing methods that can be used to complement 4D seismic are 4D gravity and 4D CSEM (Controlled Source ElectroMagnetics). High accuracy time lapse gravimetric measurements have been successfully acquired over gas fields like the StatoilHydro operated Troll and Sleipner fields in the North Sea. Gravimetric monitoring works best where there is a big mass change (water influx) due to production, and therefore monitoring of huge

Time-lapse gravity changes (above) and 4D seismic changes (below) across the Sleipner CO_2 plume in the North Sea. The CO_2 injection well is shown on the seismic profile. Notice the correspondence between observed gravity changes and the time-lapse seismic data.



Courtesy of Statoil



4D estimated velocity changes in the overburden at Valhall: The estimated velocity changes (right) are 25 m/s (dark blue color corresponds to 25 m/s velocity change). The vertical seismic profile (left) shows the overburden fault (yellow solid line).

gas fields is a good application.

A successful example of combining gravity and seismic measurements is the monitoring of the $CO2$ storage in the Utsira formation at the Sleipner field (see figure on previous page).

The promise of 4D electromagnetic methods is that EM resistivity response is sensitive to saturation changes only. For seismic data, it is well known that the 4D response is more multi-causal, as saturation, pressure, and temperature changes all impact the 4D seismic. 4D EM is not sensitive to alterations in reservoir pressure, however, and hence the combined use of 4D seismic and 4D EM might offer a way to discriminate between pressure and saturation changes.

Looking into the future we expect to see permanent systems that include both acoustic sensors to monitor seismic changes and electromagnetic sensors to monitor changes in resistivity. Fibre optic sensors are the ultimate technology in this respect.

However, both gravimetric and EM are low-resolution methods, meaning that for complex reservoirs, the added value may be somewhat limited due to lack of resolution. Combined with the higher frequency 4D seismic information, one can assume that both these emerging technologies will contribute to reservoir monitoring in the years to come.

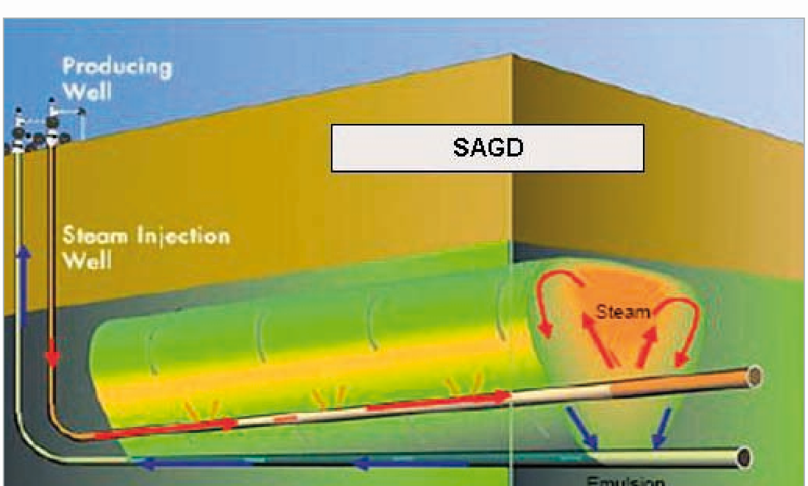
Time lapse refraction analysis has been suggested as a potential tool for determining small changes in P-wave velocities within a high velocity subsurface layer (Landrø et al., 2004). This method has not been applied to any field yet, but if it turns out successful, it could represent a potential tool for monitoring carbonate fields. So far, there have been very few successful 4D seismic case studies from carbonate fields, as the bulk strength of most carbonate rocks is higher than most sandstones, resulting in a relatively weak time-lapse signal.

Therefore new technologies like 4D EM, 4D gravimetry and highly repeated 4D seismic (or combinations of these methods) might represent a potential breakthrough for the challenges related to successful monitoring of carbonate fields.

As the technology for downhole measurements and effective transmission of such measurements improve, the use of frequently sampled well data will improve 4D seismic analysis. For instance, if frequent saturation logs can be measured in several wells, together with downhole pressure measurements, such data will enable us to constrain the 4D seismic interpretation process significantly. Therefore, it is likely that the improvement in downhole measurements will have a big impact on 4D seismic in the years to come.

Other emerging monitoring technologies include permanent in-well VSPs and passive seismic.

The principle of steam-assisted gravity drainage (SAGD). Horizontal wells are drilled in stacked pairs. Steam injected into the upper well melts surrounding oil. Gravity causes the mobilised oil to flow downward to the lower well for production.



Pushing the limits

In 2002 Guilbot and Smith showed that the reservoir compaction caused by production at the Ekofisk Field can be monitored by time lapse seismic. In addition to pressure changes, the so-called water weakening effect (a chemical reaction between water and chalk) is the most probable cause for this compaction. For the Ekofisk Field the measured compaction is more than 10 m and as a result a stretching of the overburden rocks is observed.

A recent innovative way of 4D mapping of reservoir compaction at the Valhall field was presented by Hatchell et al., 2007.

The crest of the Valhall Field is not properly imaged by conventional seismic data, due to the presence of a "gas chimney" above the reservoir. Therefore, it is hard to map reservoir compaction at Valhall in areas where the top reservoir is hardly visible. However, if the overburden rocks are stretched due to compaction, the coupled overburden stretch will lead to decreased seismic velocity, and by measuring these subtle changes in overburden velocities, Hatchell et al. were able to indirectly map the reservoir compartments that were most likely to have been compacted.

Another example of determining subtle changes from accurate time-lapse seismic data is the 4D detection of a reactivated overburden fault system at Valhall. Based on the high accuracy time lapse seismic data from this field, Røste et al., 2007, estimated a velocity change of 30 m/s close to an exist ing fault. This is interpreted as a reactivation of the fault caused by reservoir compaction approximately 200 m below the fault zone. Reservoir compaction has also been observed for sand reservoirs, and corresponding 4D overburden changes have been reported. Overburden reservoir changes are also important for well planning and in order to reduce drilling risks.

Heavy oil

The recent upward trend in the price of crude oil has spurred interest in extra heavy oils and tar sands. The number of barrels of oil in place attributed to the heaviest hydrocarbons is estimated to be as much as six or seven trillion barrels, two to three times more than the world's reserves of conventional oil and gas.

Unfortunately, there's a problem: the recovery rate for heavy oil is only in the ten to twenty percent range. One of the key questions is then whether this miserably low recovery rate can be improved. We believe that reservoir monitoring by seismic, electromagnetic or gravity could be the key to improved recovery.

During the last few years the Canadian tar sand industry has moved from surface mining into extracting oil by drilling into the extra heavy oil sands some hundred metres below the surface. Steam assisted gravity drainage (SAGD), a leading in-situ technique, already accounts for one third of the oil recovered from the tar sands.

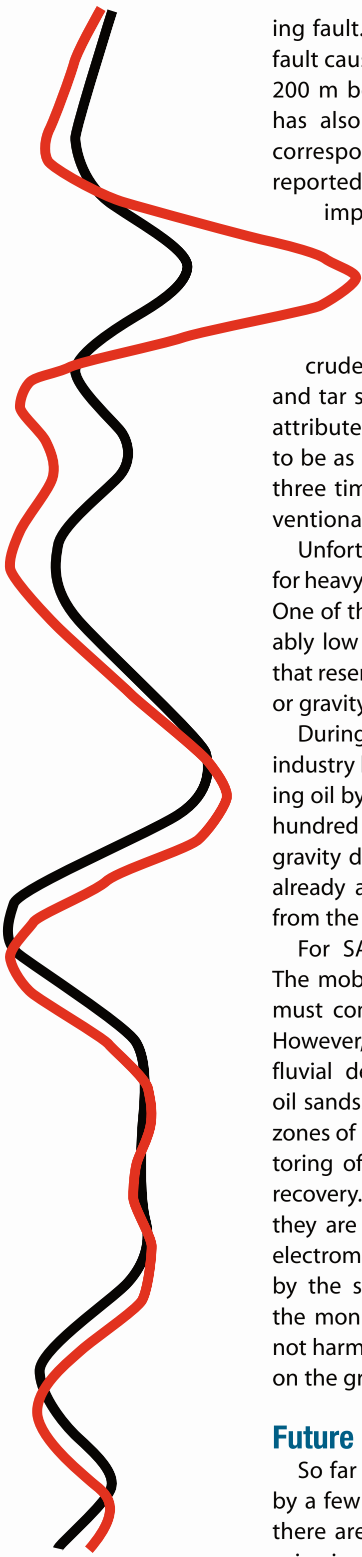
For SAGD efficiency, sand continuity is critical. The mobilized oil resulting from the injected steam must communicate with the lower producing well. However, shale layers and lenses are common in the fluvial depositional environments typical of many oil sands. Since it may be somewhat difficult to map zones of high shale content before production, monitoring of the SAGD efficiency is critical to enhance recovery. This is a challenge for geophysicists, but they are helped by the big change in acoustic and electromagnetic properties of the tar sands caused by the steam chamber development. Furthermore, the monitoring techniques that we develop should not harm the landscape or the conditions for wild life on the ground.

Future prospects for 4D seismic

So far the use of 4D seismic has been dominated by a few major oil companies. Despite the fact that there are a few dedicated software systems for 4D seismic analysis already in place, there appears to be an important gap to bridge here in order to introduce 4D to a wider user group. However, conventional interpretation systems should be sufficient to conduct a 4D study. We think that a major limitation for a wider use of 4D technology may lie in training. Although 4D seismic is not very advanced, it requires knowledge of several disciplines like geology, geophysics, rock physics and reservoir engineering. Therefore, operating companies need to train the staff in their asset teams to handle such surveys in an efficient way. The necessary services from the contractors are available, so the bottleneck is probably the training of key personnel within each company. Our impression is that 4D interpretation is often done very effectively as a cooperative effort between the asset team and a corporate research centre or technical service centre.

The size and the complexity of the field is certainly a crucial factor when permanent installations are considered, as there is no doubt that a huge field is required to finance the upfront costs for a permanent 4D acquisition system. For conventional 4D surveys, the size of the field is also important, but probably to a lesser extent. We think that the use of 4D seismic in deep marine fields will increase in the future, especially since well costs are high in such areas. The first 4D examples from such areas offshore Brazil and Angola show excellent results.

The need for some crucial step changes, as outlined in this article, may also be important for the survival of 4D technology, and we think that the need for high vertical resolution 4D images is the most important one. If a sub-seismic resolution can be achieved, the seamless integration of the data with the geological model as well as the reservoir simulation model will be realised, securing more permanent use of 4D seismic data in the future.



Typical 4D seismic response: Pre- and post-production seismic traces (black and red, respectively) showing amplitude increase at top reservoir and corresponding time shifts for proceeding seismic events. Time shifts are caused by velocity changes within the reservoir.

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