Time Lapse (4D) Seismic: Some Case Studies

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Abstract

We present advances in Time Lapse 3D seismic (also known as 4D seismic) and its application in oil industry. Over the years the technique has proved its potential and now it is aggressively used in most of the oil companies. We have covered the topic from the basic 4D analysis based on data differencing to the modern inversion based separate analysis of all the time lapse volumes. The paper covers all the aspects of 4D seismic data analysis including feasibility study, acquisition, and processing issues. Further, we present several successful case studies of 4D seismic.

Introduction

Time Lapse (TL) Seismic, popularly known as 4D seismic is relatively new technology used in petroleum industry. This is known concept which has been borrowed from other branch of sciences, wherein repeat surveys are conducted at some time interval to monitor the changes. 4D seismic is misnomer of the time lapse seismic, because time lapse 2D is also known as 4D survey in petroleum industry.

Advent of time lapse seismic revolutionized the petroleum industry mainly because it serves as partial substitute to the drilling. 4D seismic provides an opportunity to image the fluid flow in volumetric region not sampled by the wells. Fluid flow is thus directly mapped by the seismic data rather than solely predicted by the fluid simulation (Lumley, 2001). Well logs being very expensive, 4D seismic proved to be the cheap and reliable solution for reservoir monitoring. Now 4D seismic is a proven technology with multi-million returns in several developed oilfields having clastic reservoirs. However, the 4D response in case of carbonate reservoirs is not encouraging.

Following are the main aspects of 4D seismic, which we will cover in the following sections:

1. Definition of time lapse seismic
2. Feasibility study of 4D seismic for a given oil field
3. 4D turnaround time
4. Acquisition and processing issues of 4D seismic data
5. 4D seismic data analysis methods
6. Applications
7. Some case histories
Definition of time lapse seismic

Time-lapse seismic or 4D seismic is a repeated 2D/3D conventional seismic data or repeated 4C seismic at different time intervals (4th dimension is calendar time, which means that a repeated 2D-survey is not 3D but 4D!). In 4D seismic, the difference between two seismic vintages acquired at different time intervals under same acquisition conditions gives information on the variation of geophysical properties due to the hydrocarbon production. However the subtraction process exhibits spurious residual energy, which is not related to the time-lapse signal such as random noise, acquisition related noise and signal bandwidth variation. This energy often limits the resolution of the 4D signal.

Most successful time-lapse seismic studies are obtained from high porosity, sand reservoirs (Landrø et al., 1999, Koster et al., 2000, Landrø et al., 2001). The main cause for this is that expected relative velocity and density changes due to production are significant in sand reservoirs. However, in high velocity reservoirs (carbonates) the relative change in velocity and density is very small. Therefore, there is a need for high precision estimates of velocity changes, and time-lapse refraction seismic might be a solution.

The time lapse seismic has following advantages:
1. This is a complementary tool for infill drilling of both producers and injectors.
2. Terminate marginal wells and prevent wells from being drilled into flushed areas.
3. 4D surveys give improved drainage understanding and help to increase the total recovery rate.
4. It helps in monitoring contacts and detects partially flushed zones.

Refraction time lapse seismic:

Time lapse refraction seismic (Landrø et al., 2004) has potential for accurate estimation of the reservoir velocity changes. Careful processing using FK filters followed by RMS amplitude analysis versus offset are useful to extract the signal. Linear Move Out (LMO) correction helps to pick the corresponding events more accurately. It is observed that typically the RMS amplitude level peaks at an offset values slightly larger than the critical offset. By measuring the shift in the peaks between the base and monitor survey, it is possible to estimate the velocity change in the reservoir layer.

A high velocity overburden layer reduces the amount of post-critical energy that is refracted back from the top reservoir interface, which is used to monitor reservoir changes. If this amount of energy exceeds the noise level that depends on the thickness and velocity of this high velocity overburden then the monitoring of the reservoir velocity changes is possible.

Feasibility study of 4D seismic

Feasibility study of 4D seismic experiment is essential before acquiring 4D seismic data. Lumley et al. (1997) developed a quick spreadsheet analysis technique to assess applicability of 4D seismic project. The spreadsheet requires rock physics as well as seismic data analysis. Thus, for feasibility study, log analysis, rock physics measurements and seismic modeling is essential. National Geophysical Research Institute, Hyderabad, India in collaboration with Institute of Petroleum Technology, NTNU, Norway conducted a rare 4D analysis of seismic data acquired over a heavy oil field in Cambay basin, India (Mehdizadeh et al. 2007b). The objective of this study was to monitor the fire front movement caused by in-situ combustion (a thermal enhanced oil recovery process) and its effect in a heavy oil field.
Typical feasibility analysis involves estimation of velocity and density changes due to change in reservoir state. Feasibility analysis helps to understand whether a measurable 4D signal (within seismic resolution) is possible or not. Thus, feasibility analysis is a crucial step before embarking on a 4D seismic project.

Changes in seismic response due to changes in the reservoir state can be dramatic or subtle depending on the reservoir rock, depth of burial, and changes in fluid saturation, pressure and temperature. The stiffer the rock is and the deeper the reservoir, the less the anticipated change in seismic response. Before investing in time-lapse surveys, it is always useful to estimate the change in seismic response and, then, use that estimate to evaluate the feasibility of observing the changes in the reservoir that will be useful in production decisions.

**4D turnaround time**

The value of a 4D seismic project is very much dependent on turnaround time. Further, turnaround time depends on the change in reservoir properties which can produce sufficient change in seismic signal in order to be recorded as a signal. Often it is not possible to have significant 4D signal in short period of time. Another factors affecting turnaround time are acquisition and processing. In spite of these constraints it is better to have an 80% result within 2-3 months than a 100% result within a year. To accomplish reasonable turnaround, a multidisciplinary approach is required from survey planning phase.

**Acquisition and processing issues of 4D seismic data**

Advances in seismic acquisition system have increased repeatability of multiple seismic surveys conducted at the same place. Industry has experimented permanent acquisition systems and several other advances viz. node technology and Q technology (a propriety technology of WesternGeco (Schlumberger)). High repeatability led to enhancements in 4D seismic signal-to-noise ratios. Repeatability studies have shown that small changes in tides, water table, ambient noise conditions, near-surface properties, source and receiver positioning, etc. can have significant deleterious effects on 4D seismic data (Moldoveanu et al., 1996; Beasley et al., 1997; Ebrom et al., 1997; Rennie et al., 1997; El-Emam et al., 1998; Porter-Hirsche and Hirsche, 1998). Many of these acquisition effects are reduced by minimized streamer cable feather, improved design of ocean-bottom and land positioning methods, and installation of permanently emplaced receiver arrays. Some acquisition effects, like water table variation, may not be addressed by improved acquisition design, and instead may need to be addressed in the time-lapse data processing stages. Processing of multiple 3D seismic cubes recorded at the same site has brought awareness that our 3D processing methods may not be as accurate as we once thought. Contrary to our algorithm theories, model-based and surface-consistent processing techniques that should give repeatable results on multiple 3D seismic cubes often do not.

The general objective of time lapse or 4D seismic monitoring is to look for production driven changes in the reservoir and determine areas of bypassed production. This is accomplished through the comparison of repeated 3D seismic surveys recorded over the field. The general framework of 4D seismic processing involves spatial cross equalization, temporal (or time) cross equalization of the monitor seismic volumes with the base survey. Care should be taken to cross equalize the two seismic volumes (base and monitor) in non-reservoir zones. A complete cross-equalization will nullify the effect of production related changes in the reservoir. Mehdizadeh et al. (2007a) processed the 4D data from Balol heavy oilfield, India. We carried out all the above mentioned pre-processing steps considering two pairs of data volumes at a time. Base-monitor1, base-monitor2, and monitor1-monitor2. Examples of 4D pre-processed data for inline 633 are shown in fig. 1-3.
**Fig. 1**: Cross-equalized monitor 1 data using base data as a reference volume for inline 633.

**Fig. 2**: Cross-equalized monitor 2 data using base data as a reference volume for inline 633.
There are several processing steps after 4D pr-processing viz. amplitude balancing, frequency balancing etc. A complete 4D processing steps can be seen in 4D Promax manual (A Landmark Processing Software) and Kumar et al. (2006).

A recent advancement in 4D seismic data analysis and processing is demonstrated by Vedanti and Sen (2009) where in it is proposed to treat all the 3D volumes constituting 4D seismic data separately. This approach is significantly superior from the previous approach in the sense that cross-equalization introduces several artifacts because of noise and non-repeatability of the data.

Repeatability:

The time lapse data can be useful to observe the changes induced by production or by implementation of any enhanced oil recovery (EOR) method, if the data is repeatable. The residual differences in the repeated surveys, which are not related to the changes in the reservoir affect the applicability of time lapse surveys and act as time lapse noise. Hence, before interpreting time lapse seismic data, some repeatability issues should be addressed. One commonly used method to quantify the repeatability is to use NRMS (Normalized RMS) analysis. In this method the percentage normalized RMS difference of the two traces (say $a_t$-$b_t$) from two different surveys within a given window $t_1$-$t_2$ is computed using the formula (Kragh and Christie, 2002):

$$NRMS = 200 \frac{RMS(a-b)}{RMS(a) + RMS(b)}$$

where NRMS is measured in percent, and the RMS operator is defined as
\[ RMS(a_i) = \sqrt{\frac{\sum_{i=1}^{n} (a_i)^2}{N}} \]

where \( N \) is the number of samples in the time interval \( t_1-t_2 \).

The value of NRMS is not limited to the range 0-100%. If both the traces contain random noise, the NRMS is 141% (\( \sqrt{2} \)). If both the traces anti-correlate, the NRMS error attains its maximum value i.e. 200%. The repeatability of two time lapse surveys can be characterized by the NRMS-value. Typical NRMS-values for some of the early 4D studies, like for instance the Gullfaks 4D study (Landrø et al., 1999, Landrø, 1999b) are 60-80%. For more recent 4D studies using steerable streamer technology (Goto et al., 2004) typical NRMS-values might be between 10 to 30%. For land data the NRMS-values are often higher, due to acquisition problems and seasonal changes within the near surface layers.

**4D Seismic analysis**

Once multiple seismic volumes (baseline, and monitor surveys) are processed, an optimal 4-D seismic difference anomaly may is generated. This difference map helps to identify the zones of 4D anomaly. Once anomaly is identified, full time-lapse interpretation and analysis can begin. Analysis usually starts with a calibration step in order to tie time-lapse changes in the seismic data to time-lapse changes in other reservoir data types viz. well logs, core measurements, pressure or temperature data, production history, etc. (Ecker et al., 1999). This calibration step, which usually involves modeling seismic data from well data, builds confidence that the 4-D seismic changes are real and not an artifact of non-repeatable acquisition and processing methods. The interpretation of difference volume is qualitative in the sense that anomalies are often inferred to be changes in oil, water, or gas saturation (Anderson et al., 1997; Sonneland et al., 1997; He et al., 1998). However, the interpretation can be complicated by changes in other dynamic properties, like gas saturation, pressure, or temperature (Lumley, 1995a, b; Jenkins et al., 1997), and geologic properties like porosity or rock compressibility may change unexpectedly due to compaction (Walls et al., 1998) or fracturing (Johnston et al., 1998).

To reduce the interpretation ambiguity, it is preferable to make a quantitative interpretation by inverting the 4D seismic data to produce maps of the changes in the dynamic properties directly. Lumley (1995a, b) and Jenkins et al. (1997) estimated temperature and steam saturation maps from the Duri steam-injection pilot. Sonneland et al. (1997) used an attribute clustering technique to make maps of oil, water, and gas saturation from the Gullfaks project. Lumley et al. (1999) estimated oil, water, and gas saturation maps by seismic modeling transforms at the Meren field, offshore Nigeria. Tura and Lumley (1998, 1999a, b) and Landrø (1999a) present method to simultaneously estimate fluid saturation and pressure changes using time-lapse AVO inversion. Vedanti and Sen (2009) used acoustic impedance to track the in-situ combustion in Balol heavy oil field.

Conventional way of analyzing 4D seismic data is to look for the 1) time shifts 2) amplitude changes between baseline and monitor surveys. Also, based on sensitivity of seismic parameters to saturation and pressure related changes it is possible to identify whether a given 4D anomaly is due to saturation change or pressure change (Landrø and Stammeijer, 2004).
Case histories

4D seismic has been successfully used as a tool to monitor enhanced oil recovery (EOR) process in many reservoirs. Some of the good examples discussed here are: Gullfaks, Norway; Duri, Indonesia; Alberta, Canada; Fulmar, UK; Holt, USA and Balol, India. Some of these examples are taken from (Brown, 2004).

Gullfaks (Norway):

Gullfaks oil field of North Sea is the best example of success of 4D seismic monitoring. This is an oil and gas field in the Norwegian sector of the North Sea operated by StatoilHydro. It was discovered in 1979, at a water depth of 135 meters. The initial recoverable reserve is 2.1 billion barrels, and the remaining recoverable reserve in 2004 is 234 million barrels. This oil field reached peak production in 2001 at 180,000 barrels per day.

This field was covered by 3D seismic survey in 1985 before the production started and the repeat survey was done in 1995 in the same direction but the presence of production platform resulted in gaps in coverage. Second repeat survey was recorded in 1996. The error due to gap in coverage was compensated by proper processing (Sønneland, 1997). Fig. 4 demonstrates the hydrocarbon reserve before the production. Initial oil water contact (OWC) is shown in blue colour. With continuous production the OWC was rising by 13 cm per year thus in fig. 5 we can clearly see the shifting of high amplitudes from the initial OWC. Thus 4D has helped in identifying the production related changes and the unswept zones in the reservoir. In 1997 two wells were drilled into the zones, which were determined as undrained based on 4D seismic monitoring. Both of these wells encountered oil filled reservoirs, also the waterfront movement predicted in the reservoir was confirmed by the well data. Further details of 4D Gullfaks study can be found in Landrø et al., (1999).

Fig. 4: Horizon slice of top reservoir amplitude from Gullfaks field, Norwegian North Sea from 1985 survey (before production), (reproduced from Brown, 2004)
**Duri (Indonesia):**

The Duri oilfield is one of the 141 oil fields operated in Sumatra, Indonesia by PT Caltex Pacific Indonesia under a production sharing contract with the Government of Indonesia. Discovered in 1941, the Duri field is one of the world’s giant oilfields and the biggest steamflood operation located in the Rokan block with current oil production of 200,000 bpd (31,000 m³/day). The insitu formations of the Duri field are unconsolidated sands; coupled with a steam flood operation they are susceptible to producing large quantities of oily viscous fluids as a by-product from the oil production. Up to 400 m³/day (2,500 bpd) of oily viscous fluids are generated at five oil production Central Gathering Stations (CGS) in the Duri oilfield.

In order to monitor the steamflood in Duri, a baseline survey was acquired in 1992 before any steam was injected. Five monitor surveys were recorded after 2, 5, 9, 13 and 19 months to monitor the reservoir (Lumley, 1995a, b Jenkins et al., 1997, Waite and Sigit, 1997). Vertical seismic sections from baseline and monitor surveys are shown in Fig.6.

**Fig. 5:** Horizon slice of top reservoir amplitude from Gullfaks field, Norwegian North Sea from 1995 survey (during production), (reproduced from Brown, 2004). Movement of high amplitudes away from initial OWC is seen

**Fig. 6:** Vertical section from six repeated seismic surveys. A synclinal shape due to gas in the reservoir is formed. (Reproduced from Jenkins et al., 1997)
The yellow lines show the top and base of the steam injection interval. A synclinal shape develops within and below this interval after 2 months, and grows to about 20 ms after at 31 months. We can also see that the data do not change above the steam zone, which clearly indicates that this is the effect of steam injection in the reservoir. The pressure and heat of steam causes progressive travel time pull ups and push downs, which are seen in figure(6). The progressive effect can also be seen as expanding circles in figure (7). In this figure the baseline survey before steam injection is on the left. The other surveys from left to right are after 2, 5, 9, 13, and 19 months of steam injection.

![Image](image_url)

**Fig. 7:** Bench-cut display from the six seismic surveys showing principally time slice views of the increasing steam effect after 0, 2, 5, 9, 13, and 19 months of steam injection. (Reproduced from Brown, 2004).

**Northern Alberta (Canada):**

Northern Alberta oil field is situated in Canada. This is one the best examples of heavy tar reservoir and thus, is a major production challenge. The steam injection is going on in the heavy oil reservoir to make the oil producible. An increase in temperature of tar of 100°C decreases its velocity by 50%. Thus good 4D anomaly was expected on time lapse data. To monitor the steam flooding, four 3D surveys were recorded. The drop in seismic velocity was observed by push-down of a deeper reflector and by increased amplitude in the tar sand section (Pullin et al., 1987). Seismic inversion was carried out to generate the impedance and velocity volumes. A slice of the velocity difference volume is shown in fig. 8. The colours indicate that the sand is affected by the heat of the steam.
Fig. 8: Inverted velocity difference depth slice at a depth of 200m between two surveys recorded several months apart. Colors indicate sand affected by the heat of the injected steam. Green dots are positions of injection and production wells. (Reproduced from Brown, 2004)

Another example from Northern Alberta is Cold Lake, which is under steam injection for recovery of heavy oil bitumen for more than 10 years. In this case also the 4D seismic monitoring has mapped the pockets of the reservoir which are affected by the steam flood, thus by suggesting locations for new wells to be drilled in non affected pockets (Eastwood et al., 1994).

Fulmar (UK):

The Fulmar oilfield is situated 312 km east of Dundee, Scotland, United Kingdom. It is operated by Talisman Energy who took over from the previous operator, Shell at the end of 1996. It was discovered in December 1975 in a water depth of 82 meters. Estimated ultimate recovery is 544 million barrels (86,500,000 m³) of oil. It is named after the fulmar, a sea bird. The oil reservoir is located at a depth of 3,050 meters. This field was covered by two 3-D legacy surveys recorded in 1977 and 1992. In this field water is displacing light oil and reservoir is thick sand. The time interval between the two 4D surveys is 10 years (Johnston et al., 1998). Thus there were good chances to observe the 4D effects. Fig. 9 shows horizon slices of top reservoir of Fulmar field for two different surveys. It is clearly seen that the top reservoir reflection amplitudes are different. Some of these differences indicate effects of production.
In this case 4D data had some serious repeatability issues, therefore the impedance inversion was carried out and the final interpretation was done on the basis of difference of inverted impedances between the two surveys. Impedance inversion difference section showed indications of water influx and pressure decline. Also, the decrease in impedances was interpreted as an effect of gas injection. Further details of this study can be found in Johnston et al. (1998).

**Holt (USA):**

A part of Holt oil field of north-central Texas, USA was under the thermal EOR (in-situ combustion). A detailed pilot study was carried out by Greaves and Fulp (1987) to detect change in seismic reflection character attributable to the combustion process, determine the direction of burnfront propagation and determine the volume of reservoir swept by the combustion process.

To monitor the movement of thermal front, three 3D seismic surveys were shot over a period of 15 months. The first preburn survey was recorded several months previous to ignition of the combustion process. The second midburn survey was recorded four months after the ignition, and the final postburn survey was shot ten months after ignition. Seismic attributes were calculated for each CDP data set and the preburn attribute were subtracted from the postburn and midburn to see the changes due to combustion. The resulting difference volumes show clear 4D anomalies in form of initiation and development of a bright spot at the top reservoir and a dim spot below it. Fig. 10 demonstrates difference in envelope amplitude at the top of the Holt sandstone. The bright spot was formed by the increased gas saturation along the top reservoir boundary. A burn volume distribution map was prepared by using postburn data. It was concluded that the injection and combustion gases had propagated ahead of the actual combustion zone.
Balol (India):

Balol oil field is located in the heavy-oil belt of Mehsana, which is a part of Cambay basin, western India. OWC in the field varies from 990 through 1025 m. The Balol reservoir is clastic and 32 m thick. The average pay thickness varies from 5 through 15 m. The porosity of the reservoir is about 28% with permeability values of 3–8 darcys, but because of high mobility contrast between oil and water, primary recovery is 10%–12% (Kumar and Mohan, 2004). Thus the heavy-oil field, Balol of Cambay basin, is a major production challenge. To enhance recovery of heavy oil in this field, the most energy-efficient method of in situ combustion was adopted (Kumar and Mohan, 2004; Mukherjee et al., 2006). The baseline 3D seismic data, representing the pre-combustion stage, were acquired by Oil and Natural Gas Corporation (ONGC), India, during November 2003. Soon after the baseline data acquisition, four wells, numbered 1, 2, 3, and 4 (fig. 11), were put on in-situ combustion successively from north to south. Since then, continuous air injection is ongoing in all of these wells (A. Saha and A. Kumar (ONGC), personal communication, 2005). The fault FF’ shown in fig. 11 is reported to be a sealing fault (Mukherjee et al., 2006), and therefore, it is likely that the injectors located on the western side of the fault have no significant effect on production. Thus, it was expected that the thermal front would move primarily toward producers in an eastward direction from the injectors. Black solid lines represent the depth contours of the major pay zone KS-1 sand within the reservoir (fig. 11). The producers are drilled at a downdip position, and the four injectors are located at updip positions. Thus, the first injector well 1 is at the shallowest level.
The two monitor 3D surveys representing post-combustion cases were recorded at an interval of one year, i.e., in December 2004 and November 2005, respectively, keeping the acquisition parameters the same. However, in an earlier study (Mehdizadeh et al., 2007a, 2007b), it was reported that the repeatability level of the two monitor surveys as compared to the baseline survey was relatively low also, the top reservoir was not seen as a clear event. Therefore, it was preferred to interpret results at the level of seismic derived rock properties such as acoustic impedance and Vp/Vs ratio obtained by partial stack inversion of seismic data. To take care of non-repeatability of seismic data, three angle dependent wavelets were used during the inversion and to avoid 4D noise, difference sections were not generated. Results of the partial stack inversion of seismic data are shown in fig. 12 and fig. 13.

![Figure 11: Location of injectors and producers in the Balol reservoir. Sealing fault FF' is seen. (Reproduced from Vedanti and Sen, 2009)](image-url)
Fig. 12: Inverted impedance time slices of top reservoir corresponding to base, monitor1 and monitor2 surveys. (Reproduced from Vedanti and Sen, 2009)
Fig. 13: Vp/Vs ratio time slices of top reservoir corresponding to base, monitor1 and monitor2 surveys. (Reproduced from Vedanti and Sen, 2009)
Both the quantitative and qualitative analyses indicate a clear drop in impedance at injectors in the reservoir zone in both monitor cases, which was indicative of combustion. Further, it was noticed that the vaporized gases were not moving towards the production well of Balol as the prominent 4D anomaly was seen as moving towards the northwest direction, i.e. towards the adjacent oil field Lanwa (fig. 14).

**Fig. 14:** Location of heavy oil fields in Mehsana, India. (Reproduced from Vedanti and Sen, 2009)

The oil production data of two wells from Lanwa field have confirmed this finding. Further details of this study can be found in (Vedanti and Sen, 2009).

**References**


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