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Application of Time Lapse (4D) Seismic for Petroleum Reservoir Monitoring and Management-A review

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Abstract
Time lapse seismic also called 4D seismic is one of the recent techniques employed in petroleum production monitoring and management within the last two decades, it involves taking two or more 3D seismic at different calendar times over the same reservoir .Case study of 4D seismic in the USA, North sea, Indonesia and of course Nigeria have shown that the expenditure on 4D seismic is justified. Key benefits of 4D seismic include optimising injector profile management, optimising well placement, defining barriers to flow or compartments, assessing zones of undrained and bypassed oil, all of which leads to cost effective increase in oil and gas production. Onshore oil fields in Nigeria should also have 4D seismic and more publications from companies operating in Nigeria is encouraged.
Keywords: Seismic, petroleum, reservoir monitoring, 4D seismic, management

1. Introduction

Energy demand is increasing, petroleum must supply the greater part of energy demanded because of the economic, environmental and technological limitations of renewable and radioactive sources of energy. According to Mohanty (2012), energy consumption is expected to triple in this centaury; petroleum production must increase to be able to meet the demand of this energy. Technology will be the main driver of increased petroleum production and the role of physics in the development of the new technologies needed for increased petroleum production can not be over emphasized. This paper is a thorough review of one of the geophysical technique: time lapse seismic that is contributing a lot to increased petroleum production over the last ten years.

Time lapse seismic also called 4D seismic is two or more 3D seismic surveys taken at different calendar time over the same reservoir. The base survey is usually taken before production starts in the field while the monitor survey is several months or years after commencement of production. Each of the survey is first processed in the usual way and a direct difference between the base survey and monitor survey revel production related changes in pressure and saturation as shown in figure 1. The fourth dimension in 4D seismic is time. It is not geologic time but real time on the order of months and years.

Within the last decade, time lapse (4D) seismic has evolved from an academic research topic to a method of reservoir monitoring and management. Initially data of dynamic behaviour of reservoir was limited to small scale monitoring at borehole scale, now 4D seismic provides data that describe reservoir fluid behaviour between wells (Denney, 2012). Thus time lapse seismic is a sophisticated method of reservoir monitoring and management that rely on the combination of geological models, static and dynamic properties of the reservoir rock and detailed-production and pressure data. The aim of this paper is to review up to date developments in the application of time lapse seismic with emphasis on the physics of the technique and the benefits gained in case studies across the globe thereby encouraging more investment in 4D seismic.

2. History and Physics of Time Lapse (4D) Seismic

Hydrocarbon production is an alteration and movement of the pore fluid. Fluids can only move and its properties change if its pressure varies in space and time. The same way seismic reflections depend on the elastic properties of the subsurface. It is therefore necessary to understand how the pore fluid properties and its pressure affect the elastic properties of rock, so that temporal variations in a seismic response can be interpreted.

One of the first experiments that inspired the concept of time lapse seismic occurred accidentally in the laboratory. A very low (1.5 %) porosity Chelmsford granite sample was saturated with water and left between a high frequency transducer and receiver to measure the acoustic-wave velocity which steadily decreased as time passed. The only apparent variable in the experiment was the water saturation in the sample which decreased with time by drainage and evaporation. The velocity drop followed the alteration of the pore fluid as water was gradually replaced with air (Nur, 1969).

The two principal elastic parameters that affect seismic waves are: the bulk modulus and the shear (or rigidity) modulus. The bulk modulus is related to rock and fluid compressibility. Shear(S) waves are affected by bulk

density and shear modulus, while compressional (p) waves are affected by bulk density and both bulk and shear moduli. The combination of bulk and shear modulus used in the calculation of P-wave velocities is called stiffness and is a measure of the rock-frame stiffness and pore –fluid stiffness.
Reservoir elasticity is affected by lithology ,fluid content, and variations in pore pressure .Seismic velocity(V),attenuation(Q), and reflectivity measurements contain information on the fluid distribution in the reservoir .For example, the ratio of compressional to shear velocity(VP/VS)is dependent on the bulk modulus and shear modulus of the rock, which are related to porosity and fluid content in the pore space. Seismic monitoring of changes in reservoir elasticity can be linked to properties associated with the movement of fluids in the reservoir. This link yields information that can be used to improve the validity of fluid-flow models and the reservoir-management decisions that rely on flow-model forecasts. Time-lapse multicomponent seismology which is the ability to monitor both P and S-waves is a tool for volume resolution- the ability to sense changes in the bulk rock-fluid properties of the reservoir with time (Journal of Petroleum Technology, 1999). Comparisons of travel time or seismic velocity measurements, amplitudes, and frequencies of P and S-waves enable the discrimination of rock and fluid properties and their changes over time.
Seismic anisotropy is a measure of the fine scale structure in the reservoir. According to Fanchi et al (1999) multicomponent surveys can take advantage of seismic anisotropy. An anisotropic reservoir exhibits differences in properties as a function of spatial orientation .Horizontal permeability, for example, will be greater in one direction than another. In an anisotropic medium ,a shear wave split into two orthogonally polarized components(S1 andS2).The S1 wave is faster, and its velocity and attenuation are affected by lithology , porosity ,and pore saturants .By contrast, the S2 wave is slower ,and its velocity and attenuation are affected by reservoir features such as fractures. The different dependencies of the S1 and S2 waves provide information for determining dynamic reservoir properties such as permeability, porosity, and fluid saturations. Multicomponent seismic studies thus have been especially useful in the characterisation of reservoir rock properties, including lithology, porosity and fractures.

3. Case Studies

Time lapse seismic influences on reservoir management are not fully realised especially in Nigeria because the current 4D seismic reservoir-monitoring projects are in their development stages. The technical success of 4D seismic monitoring, subsequent impact on reservoir management decision, increased oil production and overall economic advantages of time lapse seismic are illustrated in the following case studies.

3.1 Gullfaks field, Norwegian North Sea

The Gullfaks field is a Statoil operated field, approximately 50 miles east of the North Shetland Platform in the Norwegian section of the North Sea. The reservoir sands are shallow marine to fluvial deposits of Jurassic age. About 80% of the reserves are found in the Brent Group and the remainder in the statfjord, Lunde and Cook formations. The original exploration seismic survey was shot in 1979, and another in 1985 when there was a production start-up. Full production began in 1986 from Jurassic offshore marine fluvial reservoir sands. In 1995 a 4D seismic study was performed over the tarbert formation, the upper-most producing unit (Soenneland et al 1997). The Tarbet formation which is a member of the Brent Group is a clean, fluvial –deltaic sandstone with an approximate thickness of 180ft and an average porosity of 34% and was being water flooded for pressure maintenance (Veire et al, 1998).Structuraly the Gullfaks field is complex, with a domino-style fault block geometry, eroded horst complex with subhorizontal layers and steep faults, and a graben system as shown in figure 3 (Landro et al, 1999).
Acoustic reservoir signature from the 1995 3D seismic survey was compared to a baseline survey taken in 1985. Differences in the acoustic reservoir signature enabled Statoil to determine saturation changes and potentially bypassed pay. Although the appearance or disappearance of gas is often more observable (Wang, 1997 and Fanchi, 1999), the replacement of oil by water in the Tarbert reservoir resulted in a detectable 9% change in seismic character (Fanchi, Pagano and Davis, 1999).
Considering that Gullfaks field is dominated by fault-blocks, and understanding of fault control on oil migration and reservoir compartmentalisation is needed to optimise field development. With the aid of 4D seismic data set, a new method for fault-seal analysis was tested, which led to a better understanding of reservoir compartmentalisation and subsequent reservoir development. As a result of the reservoir-monitoring project at Gullfaks two fault-block compartments with initial oil saturation were identified. A long horizontal well was completed through the two fault-block compartments and through a third region with slightly diminished oil saturation. The new well confirmed the oil saturation distribution predicted by the 4D seismic project. A Second well previously abandoned, was sidetracked and recompleted in areas where 4D predicted no oil drainage. Upon completion, this well produced 6,000 b/d of oil.

3.2 Duri field, Indonesia

Duri field is a Chevron operated shallow lying early Miocene sands with a 107m thick reservoir interval. The reservoir is made up of the Kedua, Lower Pertama and Upper Pertama formations having average porosity of 34% and permeability of 1.5D. Primary recovery from the field is very low due to the presence of heavy oil, thereby making it necessary to use steam flooding to mobilize the oil by heating it up and hence reducing its viscosity. Steam flooding enhances the recovery factor from 8% to an economic level of 60% recovery (Jenkins, Waite and Bee, 1997). The reservoir is heterogeneous, therefore it is often difficult to know where the steam flows; steam can be left in the ground, or channeled inefficiently along high permeability zones, thus leaving substantial parts of the reservoir unswept.

The aim of the 4D seismic survey was to track the steam flood both horizontally and vertically over time so that the injection can be optimised. Two base line and six monitor 3D seismic surveys were recorded over the same steam injection pattern between 1992 and 1995. Dynamite source and hydrophones for the receivers producing 100Hz seismic were used.

The interesting changes in the surveys were related to the conductive heating and pressure effects. These changes were generally very large and observed in a matter of few months as shown in figure 2 (Jenkins et al, 1997). A large time structure developed from within and below the injection interval due to a combination of changes in the reservoir properties. This time structure grows in successive surveys and reached a maximum after 31 months. The benefits of the survey includes: shutting of injection in the swept zones, putting steam into cold zones and locating observation wells. After reviewing the practical benefits, the Chevron team determined that 4D seismic significantly improve injector profile management.

3.3 Eugene Island 330/338, Gulf of Mexico USA

Eugene Island block 330 in the Gulf of Mexico is operated by PennzEnergy, and Eugene Island 338 is operated by Texaco. The fields are adjacent and located approximately 50 miles south of Louisiana coast. The LF sandstone reservoir has an average porosity of 27%, permeability of 500 md, and water saturation of 35%. Cumulative production from the LF reservoir was 1.2million bbl oil equivalent during the period 1974-1988.

A 3D data set of the LF sand reservoir was collected in 1988, it was normalised and compared to an earlier data set collected in 1985.the appearance of gas due to pressure depletion changed the reservoir acoustic response and enabled the operator to identify where gas-oil ratios had increased. Also, a change in acoustic response along the reservoir boundary made it possible to identify the updip migration of the reservoir water-oil contact.

The operator identified bypassed oil and gas by recognizing regions in the 3D data set that remained constant between 1985 and 1988. This led to a 1994 completion of a 1,200 ft horizontal well in the suspected zone and initial production from this well exceeded 1,500 b/d and by 1996 had added a total of 1 million bbl to the cumulative oil production from the field. A similar technique was used on the IC sand reservoir of Eugene 330 to identify bypassed oil. It led to the completion of a successful well in 1991.

Additional 3D seismic data sets were gathered at Eugene Island 330/338 in 1992 and 1994. Each is being coupled with the two earlier data sets and currently serves as the basis for multiple, ongoing time-lapse studies. Eugene Island 330/338 demonstrates that a baseline 3D seismic survey (a survey taken before the commencement of production) is unnecessary (Fanchi et al, 1999).

3.4 Bonga field, Nigeria

Bonga field is operated by shell and located in (1000m) deep water, 120km south –west of the Niger Delta Nigeria. The field initially had 16 subsea oil production and water injection wells connected to the 2mm barrel capacity floating, production, storage and off loading (FPSO) vessel.

The base line seismic survey in the Bonga field was short in 2000 which enabled the siting and drilling of wells and relevant activities prior to start –up of production in November 2005.The 4D seismic survey was short in 2008 over a period of 76 days using 10 –streamer marine seismic acquisition vessel, source vessel and two support vessels (Detomo, 2008). This marine 4D seismic survey was Nigeria's first 4D seismic survey in deep water, was technically complex and involved several high-risk activities including operating air guns and towing long streamers with close passes to the Bonga production fixed installations.

The aim of the 4D seismic survey was to provide a much improved understanding of the ongoing reservoir drainage performance after two years of production and enable better well placements such that the Bonga field life –cycle production will be maximised .The design of this 4D acquisition was fully compatible with both the baseline survey of 2000 and future monitor 4D surveys anticipated over the Bonga area. Initial interpretation of the 4D data influenced well planning and operational performance which reduced uncertainty in the decisions that benefit all stakeholders. Improved 4D seismic products from this survey are continuing to deliver new results. A significant aspect of this survey was the involvement of Nigerians who made up 40% of the personnel on –board. The processing and interpretation of the seismic data were done within the national borders of Nigeria thereby providing Nigerian contractors and local shell staff the opportunity to gain valuable deepwater 4D seismic experience.

3.5 Meren field, Nigeria

The meren field is operated by Chevron and is located in shallow water (50 feet deep) in south east of Lagos

Nigeria about 10 miles offshore. Meren field has six fault blocks with over 40 producing sands. The total estimated original oil in place (OOIP) is 1.8 billion barrels of which 750million barrels had been produced. The field produces 85,000 barrels of oil per day, from reservoirs that are part of a set of sand –shale retrograde/ prograde near –shore depositional sequences. The oil is fairly live seismically at Meren with a solution GOR of 400scf/stb, this gives a good compressibility contrast with reservoir brine.

Meren field was discovered in 1965 and first production began in 1968; and has over 80 producer and injector wells. The base line seismic survey was a 1987 Chevron legacy 3D survey while the 4D survey was short in 1996 .A detailed 4D seismic interpretation of the Meren E-50 reservoir sand in Block 2 ,based on horizon amplitude extractions from the 1987 and 1996 cross-equalised seismic cubes were consistent with well production histories at 22 of the 24 wells.

The 4D seismic interpretation suggested that water from two injectors has preferential channel –flow characteristics ,which indicated a strong stratigraphic flow –unit over print on the reservoir not previously discernible from well data alone (Lumley ,Nunns ,Delorme ,Adeogba and Bee , 2000). In addition, three areas within the E-05 that may contain major bypassed oil reserves were identified and a better definition of the leaking or sealing nature of the reservoir faults was obtained.

4. Conclusion

Time lapse seismic survey add a cost of about $1/ barrel of oil produced while its benefit far outweighs this cost. Key benefits of 4D seismic include optimising injector profile management, optimising well placement, defining barriers to flow or compartments, assessing zones of undrained and bypassed oil, all of which leads to cost effective increase in oil and gas production. Gulfaks field in Norway is a classical example of the success in the application of 4D seismic and most of the case studies are offshore. From the success, onshore fields are encouraged to benefit from this application of technology. Onshore oil fields in Nigeria should also have 4D seismic and more publications from companies operating in Nigeria is encouraged.

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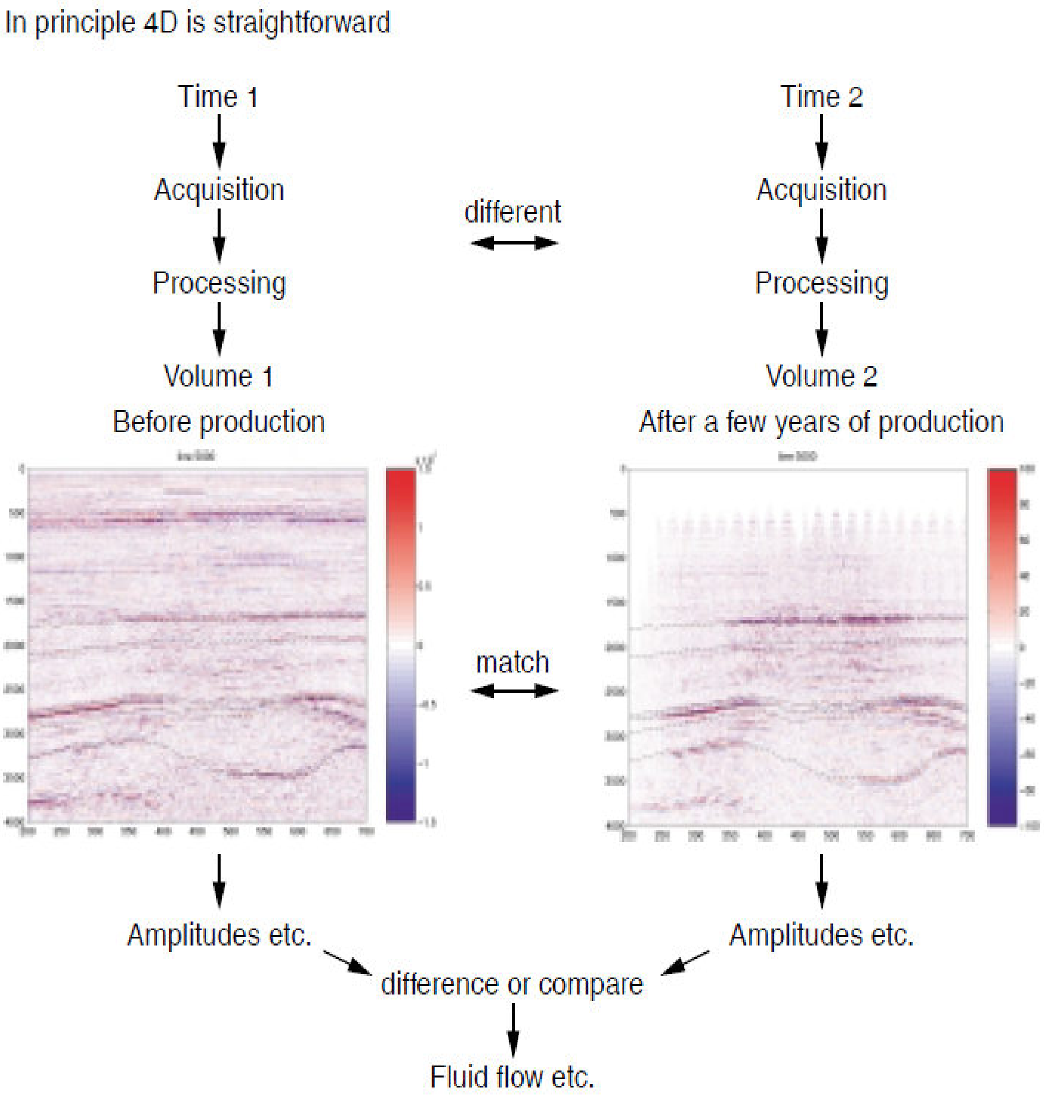

Figure 1. The Principle of Time Lapse (4d) Seismic

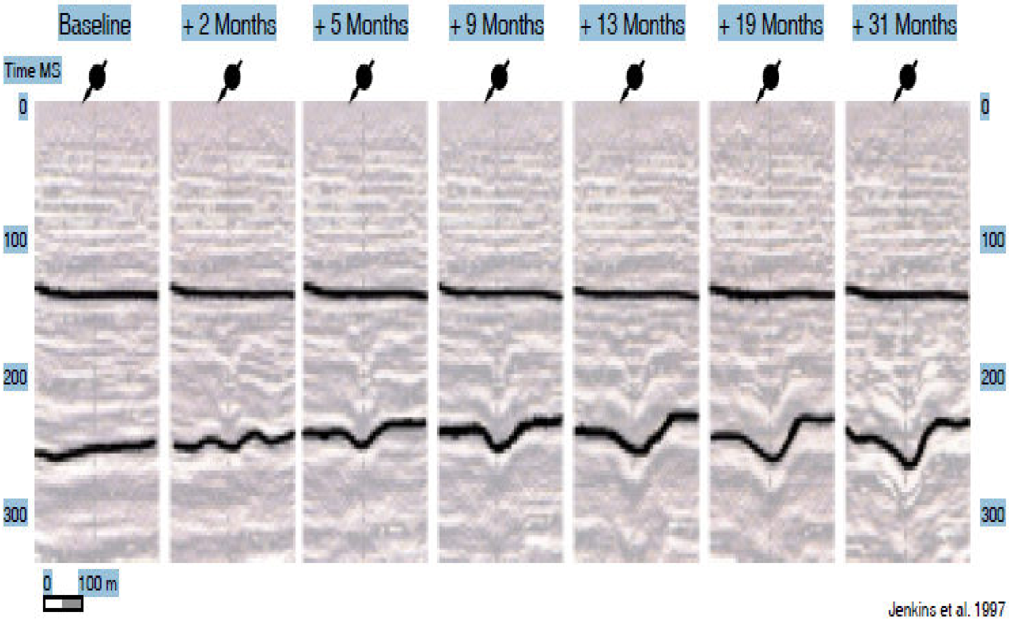

Figure 2. Seismic Sections from Baseline and Monitor Surveys,
Duri Field. (After Jekins et al 1997)

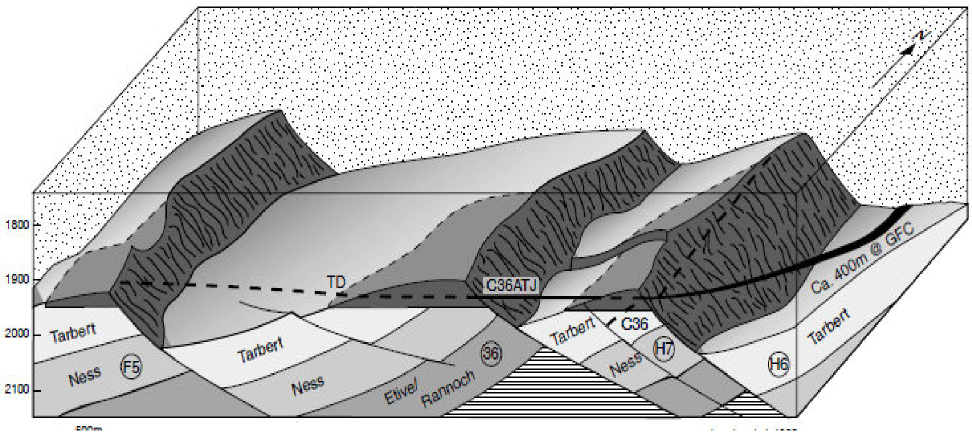

Figure 3. Gullfaks Field Geological Structure (After Landro et al 1999).