4D analysis, combining shallow hydrophone and multi-component streamer: the Cinguvu Field Offshore Angola example

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Summary

Efficiently and accurately estimating fluid-flow movement information from time-lapse data is a prime deliverable of any 4D acquisition and analysis. The key to success in this depends on a few factors including optimum 4D seismic acquisition, the seismic frequency bandwidth at the reservoir level and being able to deliver the 4D analysis or results in a very rapid and efficient manner. Maximum value of 4D is derived not from the data quality alone but also from the efficiency of delivering a 4D image and analysis. The value of the 4D decreases significantly with time, as results and analysis need to be delivered promptly to make an impact on the in-fill well program as well as on the reservoir development.

From the 4D seismic image analysis (based on a calibrated broadband PSDM seismic processing), a dynamic warping algorithm was implemented for estimation of time-shift and delta velocity on this non-conventional typical "broadband" 4D seismic i.e. new multi-component over a conventional streamer legacy survey. The 4D analysis results were then compared with the 4D rock physics analysis at the available wells over the survey and related to the production-injection mechanism. This paper will review the project results and their impact in term of reservoir management understanding.

Introduction

Time-lapse ("4D) seismic is one of the key techniques used for mapping of fluid movements in a reservoir resulting from injection-production operations. As such, it is significantly important for effective reservoir management.

With 4D, the value of information of any deliverables lie primarily in the turnaround time to delivery to make maximum impact on the infill program and reservoir management. Time-shift or time difference estimation between the surveys is one of the key attribute used for an efficient 4D interpretation. Various algorithms have been developed: from cross-correlation techniques (Rickett and Lumley, 2001), non-linear inversion (for example Hatchell, Bourne., 2006), non-linear inverse problem for deriving relative velocity change (Williamson et al., 2007). More recently, a dynamic warping or dynamic image warping was introduced by Hale in 2013 (Hale, 2013) by extending the dynamic time warping for speech recognition.

The dynamic warping implemented here in the current project provides a fast and efficient means of estimating time shifts by minimizing the NRMS (Normalised Root Mean Square) of the difference and with the constrains of the dominant frequency.

The dataset used in the present project (offshore Angola) is not a true 4D seismic *sensu-stricto* as various differences exist between the base and the repeat ('monitor') seismic. The 2011 "baseline" data is a 3D shallow towed single hydrophone streamer seismic, while the 2016 "monitor" data (part of a larger 3D acquisition) is a deep towed multi-component streamer seismic with almost the same azimuth but not the same shot pre-plot.

A 4D broadband depth processing project was carried out with the strategy of calibrating an operator-deghosted single hydrophone (shallow towed) with a re-datumed up-going wavefield. Some analysis of the recovered 4D effect include the dynamic warping (time shift and delta velocity analysis) and inversion products.

Below we go through the various steps involved in the project and will concentrate on the use of the derivative attributes, primarily the time-shift / delta-V derivatives and its impact on the reservoir understanding.

Field presentation and geological setting.

The Cinguvu Field is located offshore Angola, in the North Western part of Block 15/06, in water depth of about 1,320 m (Figure 1). The reservoir depth ranges between 2,500 and 3,000 m (TVDSS). The block is under a Production Sharing Agreement (PSA) with Eni as Operator. The Cinguvu-1 discovery well was drilled in 2009 following the discoveries of Sangos-1 and Ngoma-1 in 2008 and Nzanza in 2009. This initial exploration well went through the entire Lower Miocene reservoir section, which was found to be oil bearing in the upper part.

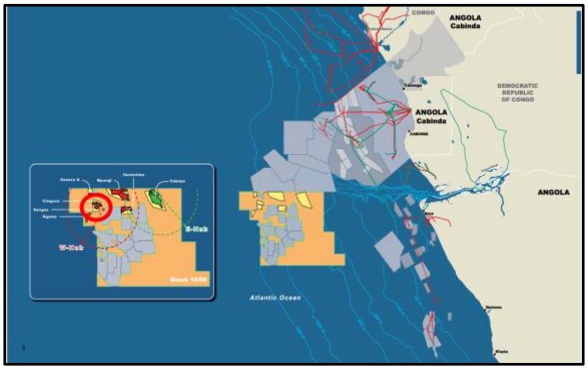

Figure 1: *West Hub in block 15/06 encompassing the Cinguvu Field (red circle)*

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The Lower Miocene reservoir comprises terrigenous sediments (i.e. sands, silts and shales) deposited during Lower Miocene within a turbiditic channel complex. This depositional environment is present in the whole of Block 15 and Block 15/06. The trapping mechanism is mixed structural/stratigraphic. The channel system has a general ESE-WNW trend and forms a flat structure closed by a fault to the east and trapped in the saddle between the Nzanza (north) and the Sangos (south) salt diapirs. Stratigraphic closure is formed to the south and north by the facies variation of the channel margins. Sealing is provided by the encasing deepwater shales.

4D Feasibility

The 4D feasibility was conducted by the Eni Reservoir department team in Milan prior to the acquisition of the new 2016 broadband seismic survey. The objective of the 4D feasibility was to establish the expected variation in elastic properties due to the injection-production reservoir management scenario proposed (pressure maintained reservoir). The key conclusions of this study were (see Figure 2):

- 15% increase (positive difference) of acoustic impedance between monitor and base due to oil substituted by water
- 20% decrease (negative to weak difference) of acoustic impedance due to gas ex-solution depending of the amount of gas coming out of solution
- Seismic modelling shows strong 4D response in terms of amplitude and time (velocity) changes
- The 4D seismic response is “so strong” that even in the presence of noise or non-optimum repeatability the 4D signal will still be observable.

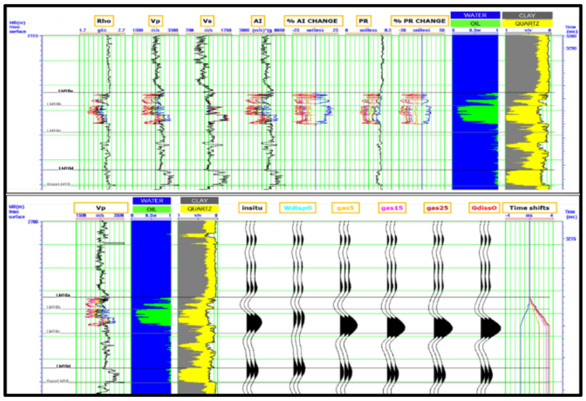

Figure 2: *Example of a 4D feasibility study over 1 well in the Cinguvu Field. The black curve corresponds to the reservoir elastic response pre-production, Blue curve corresponds to the elastic response when water is displacing oil, and orange to red when there is from 5 to 15% gas exsolved into the reservoir*

Pressure effect evaluation has not been performed, since no well samples were available for laboratory analysis. Moreover, no pressure change 4D effects are expected as the production-injection scenario for this reservoir foresee pressure maintenance.

As some amplitude/impedance changes occur with the production/injection mechanism, this will translate into some time shift between the two surveys in the order of: a speed up of the velocity in the order of + 3-3.5ms when gas comes out of solution, and slow down of -1.5ms due to water replacing oil between the base and the monitor.

4D Seismic Imaging

The “baseline” survey was acquired in 2011 by WesternGeco using a single hydrophone sensor and the “monitor” in 2016 by PGS using a dual-sensor (deep-towed multi-component streamer) technology as part of a larger (1,043 km²) 3D survey in which just 80 km2 constituted the 4D survey. Acquisition azimuths were consistent between surveys, however many other parameters were significantly different including: native bin size, disparate source location and no cable feather matching was performed during monitor acquisition.

As a result, the main objective of the “4D processing” of these overlapping surveys was to co-process in depth each vintage (processed independently up to the offset class stage regularization) with an extended signal bandwidth to produce calibrated high resolution base and monitor seismic images and differences that can be used to derive 4D attributes at the final processing stage.

One of the aim was also to preserve the phase and amplitude throughout the processing sequence to optimize any 4D signal resolution at the primary target interval (lower Miocene).

The other objective was to high-grade the conventional hydrophone dataset to as close as possible to match the broader bandwidth of the multi-component towed streamer seismic in order to gain more low and high frequencies and not the reverse (degrading the broadband data to match the previous survey). The post-migration sequence included, in addition to the usual RMO, the final Radon, and stack.

The use of a joint operator was a key process for the final local matching. This joint operator is constrained by the Signal-to-Noise Ratio and based on an adaptive time window i.e. the operator is estimated using different time windows according to the frequency. In other words, the operator will be longer for the low frequency of the signal

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and shorter for the high frequency part of the signal. This joint matching operator was implemented to maximize the seismic 4D bandwidth between the de-ghosted hydrophone and the broadband multi-component streamer i.e. upgrading the hydrophone survey (Figure 3) to match as close as possible to the new acquisition. After the joint matching operator, a shallow window dynamic warping was applied to the data to minimize the 4D differences in the overburden (see following algorithm explanation).

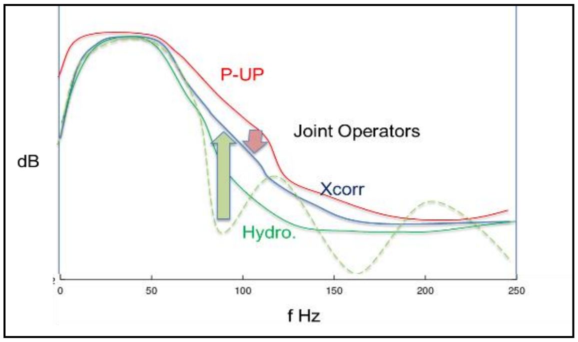

Figure 3: *Joint matching operator principle. Red amplitude spectra corresponds to amplitude spectra of broadband multi-component dataset and green represents amplitude spectra of conventional hydrophone with residual receiver ghost effect. The joint operator enhanced the frequency spectra of the conventional dataset to a common ghost-free spectra between the conventional and the multi-component seismic amplitude spectra.*

All the way along these processing steps, 4D quality controls were generated on post-stack data to assure an improvement of the repeatability (using the NRMS) and predictability. In the reservoir interval, the NRMS went down to 0.15 for this non-optimum 4D seismic survey, this is an impressive result.

Dynamic Warping Methodology

The next step was to improve the understanding of the changes in reservoir parameters such as saturation and pressure as they play a key role into the time-lapse seismic anomalies. One of the fastest and reliable attribute to derive is the amplitude difference between surveys. Amplitudes differences have two components: a pure signal amplitude element (i.e. variation of reservoir inducing a change in acoustic/elastic properties or reflectivity changes) and a time-shift element due to velocity changes. Decoupling the time-shift from the amplitude changes enables a better understanding of the 4D difference due to velocity and or density changes alone. PGS developed a robust dynamic warping tool allowing analysis of the $\Delta Vp/Vp$. This 4D dynamic warping algorithm combines the conventional 1D warping techniques which estimate image displacements (deformation) by minimizing the difference and the NRMS decomposition into 4D attributes: S/N, RMS ratio, time-shift and dominant frequency, (Lecerf et al., 2015). The L2 norm in the usual warping inversion is replaced by the formulation of the NRMS representing the normalized energy of the difference. By using this approach, the resulting time-deformation, minimizes the NRMS and can be constrained by the dominant frequency of the wavelet and the noise level. The technique allows the detection of very small 4D misalignments and avoid the calculation of the time shift in very low S/N.

Interpretation and Results

Over the area of interest, three wells are available for the calibration and understanding of the 4D response. Well CIN-101 (in the central part of the survey, see Figure 4) is a producer with a water cut of 57% at the time of the monitor survey, whereas well CIN-2-ST1 (eastern part of the area of interest) had a water-cut of 15% in 2016 and well CIN-201 was injecting water. It should be noted that, according to the geological interpretation and reservoir understanding, the depositional environment for well CIN-101 (producer) and CIN-201 (injector) are located in the main channel whereas well CIN-2-ST1 (producer) is positioned on a crevasse splay system and is in an up-dip position.

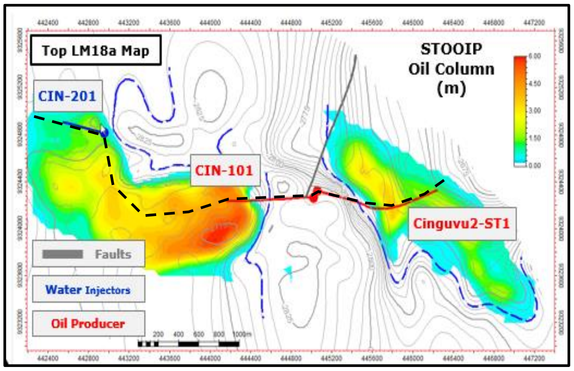

Figure 4: *Top reservoir two way time and injectors (in blue) / producers (red) wells with the random-line (dashed black line).*

Time-Shift Analysis: A random-line (Figure 5) passing through the injector and the producers (Figure 4) illustrates the results of dynamic warping extraction of time-shifts. It highlights distinctive differences in polarities of the time shift between the response at the injector and producers, and a very different intensity of time shift between the injector CIN-201 (weak) and the CIN-101 producer (strong), see Figure 5. When the time shift is applied to re-align the monitor seismic, it can be observed that the 4D signal in the CIN-101 producer well, for instance, more or less disappears, suggesting that the 4D signal in this area is primarily due to amplitude response rather than a time-shift or velocity changes. This type of response could be due to pressure and saturation interacting at the same time and cancelling the two effects. An encouraging validation is that the values of the maximum time-shift observed with the dynamic warping are in the same order as the one modelled at the well (i.e. a maximum of 3.5ms max in the gas ex-solution scenario).

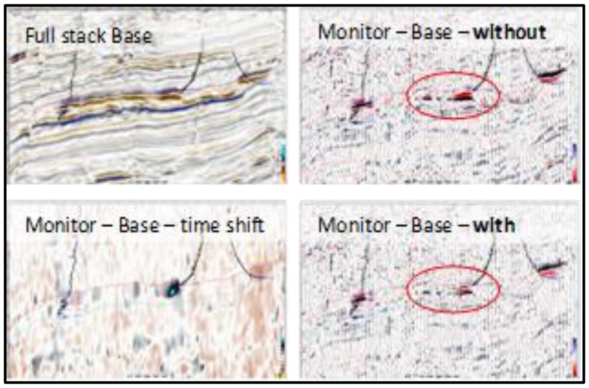

Figure 5: *Random line (dash line on the Figure 4) along the injector and producers showing a slow down at the CIN-2-ST1 due to water replacing oil and speed-up at the CIN-101 due to gas ex-solution.*

Delta Velocity Analysis: following-up the time shift analysis, the ΔV (delta-velocity) was derived. The analysis was performed by combining the DV and the RMS ratio between the monitor and the base (Figure 6), as it has been observed that for instance at CIN-101, the amplitude difference observed prior to warping was mainly due to a time shift difference and not an amplitude difference.

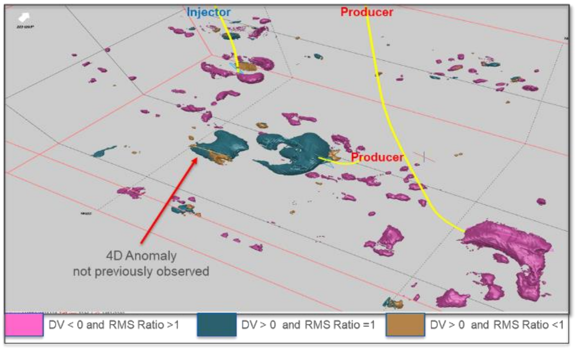

Figure 6: Geobody detection based on the DV and RMS Ratio computation between the monitor and the baseline seismic surveys.

This might suggest either a geomechanical effect and / or a pressure-saturation effect reacting in the opposite direction or a density effect. Further analysis is on-going to understand this effect. More importantly, the outcome of this is that an additional feature similar to the CIN-101is observed on the west side of the producer.

Conclusions

Assessing the injection-production effect that can be detected on repeat seismic is a key element in 4D analysis. In the present case study it has been possible to extract valuable 4D information at the reservoir interval, even though it is not based on the perfect 4D seismic from an acquisition point of view. The results are found to be in line with the well predictions from 4D modelling thanks to three key factors:

a) State-of-the-art seismic processing ensuring the optimum use of the maximum bandwidth of the “monitor” broadband multi-component streamer without having to “degrade” this seismic to be compatible with a high-graded “baseline” conventional streamer,

b) Carefully and appropriately handling the different bands of the seismic frequency spectrum.

c) Implementation of a dynamic warping based on the NRMS minimisation, which runs efficiently while providing accurate results and is timely enough to impact infill well placement and active reservoir management

The 4D seismic shows some very good repeatability and has allowed estimation of post-stack time shifts matching the well predictions and the well injection-production history. The angle stacks used for the zero-angle time-shift estimate provided a more accurate and more reliable time shift estimate. Maximising the broadband frequency of repeat 3D/4D datasets, rather than reducing to the least common denominator, improves time-shift estimates, and provide a more accurate 4D amplitude responses. As an added benefit, the broader bandwidth derivatives can be used for the low frequency model in a subsequent seismic inversion.

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