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Campos Basin 4D study. A Case Study Integrating Conventional Hydrophone and Multi-sensor Towed Streamer for monitoring the Albacora Leste field

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Abstract Summary

In this 4D case study, conducted in the Campos Basin, Brazil, we demonstrate that is possible to extract reliable field production information with relaxed constraints on the acquisition repeatability. We show how different streamer technology datasets can be combined to monitor the production of the Albacora Leste field. The aim is that the 4D study will provide additional reservoir production information on fluid saturation and pressure changes. This "opportunistic" Albacora Leste 4D case study combined a 2005 Multi-Client Baseline dataset, acquired with shallow towed conventional hydrophone streamer, with a 2022 Monitor dataset acquired with deep towed multi-sensor streamer. One of the 4D imaging challenges was to accommodate the two types of streamer and non-repeated shot positions for computing an accurate 4D signal. Through specific 4D processing sequences and a 4D Least-Square Kirchhoff imaging approach, we succeeded in improving the seismic signal resolution and were able to detect consistent fluid saturation and pressure changes within thin sandstone layers in the reservoirs. The 4D Albacora Leste project has enabled us to map and better understand the longstanding production of this complex and compartmentalized reservoir composed of turbiditic stacked channels with the aim of identifying new development opportunities.

Introduction

Time-lapse (4D) reservoir monitoring consists of acquiring several 3D seismic data at different stages of a field life and analyzing differences in seismic images (4D signal). To enhance the quality of the 4D signal, exclusive time-lapse marine acquisitions require similar recording sensor types and steerable navigation equipment to ensure the repeatability of sources and receiver locations. However, multi-client seismic data is often acquired with efficiency in mind and is not usually optimised for 4D monitoring purposes, as the fundamental 4D principle of "repeating acquisition design" is generally not followed.

In this 4D case study, conducted in the Campos Basin, Brazil, we demonstrate that is possible to extract reliable field production information with relaxed constraints on the acquisition repeatability. We show how conventional shallow towed single hydrophone streamer data can be combined with deep towed multi-sensor acquisition data to monitor the production of the Albacora Leste field.

The Albacora Leste field is located in the northern area of the Campos Basin about 120 km from Cabo de São Tomé with water depths ranging from 1000 to 2000 m. Discovered in 1986, the Albacora Leste oil Field began its production in 2006. The field consists of Miocene sandstones units with high porosity and permeability. After the deposition stage, erosive channels introduced flow barriers that resulted in reservoir compartmentalization (Lemos et al., 2006). In the case of Albacora Leste, the reservoir characterization using 3D AVO is challenged by the weak seismic resolution. The hope is that 4D study will provide additional reservoir production information on fluid saturation and pressure changes.

4D Albacora Leste monitoring project

For this 4D project, the baseline data consists of a conventional seismic, using high density of reflection points, acquired in 2005. In 2022, an 'opportunistic' monitor survey was conducted on the same area with the objective of gathering information of fluid and pressure changes in the reservoir targets. The term 'opportunistic' is used here, as opposed to 4D exclusive surveys, because the 2005 Baseline data was part of a multi-client library and the 2022 Monitor data was acquired using a different streamer configuration. The 2005 acquisition azimuth, sail lines, and dual source configuration were replicated as closely as possible for the 2022 survey (Figure 1). However, the shot positions were not repeated. On the receiver side, the baseline data was recorded using shallow towed (7m) hydrophone only streamers, while the monitor has been acquired with deep-towed (20m) multi-sensor cables providing a broadband seismic signal. The number of streamers and the separation distance was the same for both surveys.

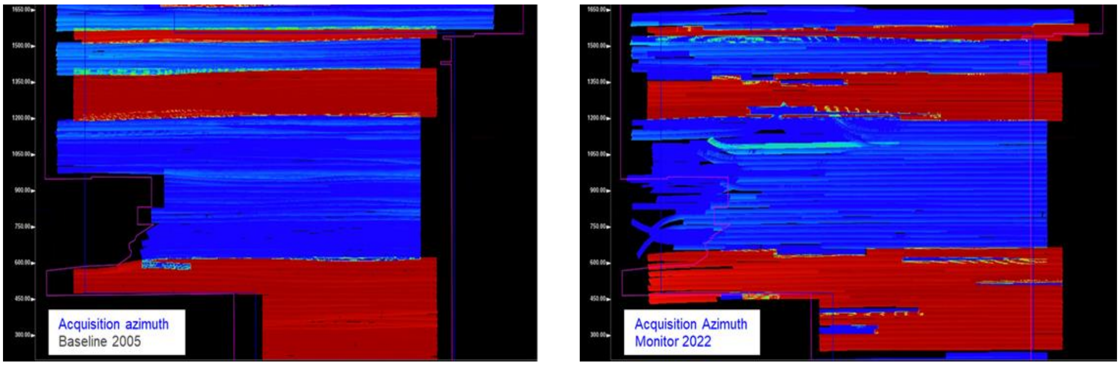

Figure 1*: Acquisition Azimuth maps for the 2005 Baseline and for the 2022 Monitor. Red and blue colours represent the direction of the acquisition.*

To enhance the seismic resolution, our strategy, validated in West Africa 4D cases (Reiser et al., 2018), is to extend the 4D signal bandwidth by combining the deghosted (2005 Baseline) hydrophone data and the up-going wavefield data intrinsically produced by the deep-tow multi-sensor streamer (2022 Monitor). In practice, the 2005 data recorded with the conventional streamer is deghosted with a deterministic operator using the nominal source and receiver depth. A direct 4D comparison with the ghost-free up-going data of the monitor survey can be achieved.

Data processing for 4D LSM imaging

To overcome the significant challenge of the acquisition differences, we implemented a 4D Least Squares Migration approach (LSM). This is a combination of 4D least-square imaging technology alongside specific 4D processing steps. Three key processing steps have been reviewed and adjusted to optimize the 4D LSM imaging result: 4D Binning, 4D Matching and 4D Denoise.

4D Binning

The aim of 4D binning is to ensure maximum uniformity in source-receiver location between the baseline and monitor data, without compromising the trace density needed for interpolation and regularization procedures. In our case of no-repeated source and receiver location, the 4D binning process was essential for optimally selecting trace pairs. The sum of the source pair distance and receiver pair distance (denoted as dS+dR) is commonly used as a geometrical threshold to reject non-repeatable trace pairs. Analyzing the dS+dR attributes mapped for a near and a far offset classes, it can be observed that most trace pairs fall below the limit of 100 m for the near offset, while the far offset has a larger statistical distribution. Consequently, we defined an adjustable threshold of geometry dS+dR in conjunction of a minimum of NRMS to maintain good repeatability without compromising trace-pair coverage for each offset class. This approach limits large areas with missing trace pairs, facilitating signal regularization and interpolation before data migration.

4D Matching

For the baseline data, the goal of deterministic source and receiver side deghosting was to enhance the hydrophone signal (band-limited data) to match the broader bandwidth of the monitor up-going wavefield data as closely as possible. A joint 4D matching process is designed for each angle-range to mitigate residual effects on the baseline dataset. These joint operators are constrained by frequency dependent signal-to-noise to ensure signal-only matching. In addition, operators are computed with an adaptive time window, resulting in the matching filter using different window lengths according to the given frequency band. In other words, the operator length will be larger for the low frequencies of the signal and shorter for the high frequencies. The joint matching operators cross-equalize both signals on the common signal amplitude spectrum and correct the residual phase difference between the de-ghosted hydrophone streamer data and the broadband up-going wavefield data.

4D Denoise

Despite advanced 4D matching process to handle the signal calibration, we still observed some 4D noise remaining in the seismic differences. This noise is likely due to the non-repeated shot and significant streamer feathering issues. The residual noise primarily appears at the edges of the signal bandwidth (below 8 Hz and above 60 Hz) and should be addressed as a function of a wave number. To tackle this, we performed 4D denoise in the curvelet domain which decomposes the images into wave number bands. Figure 2 shows the results of the 4D denoising application.

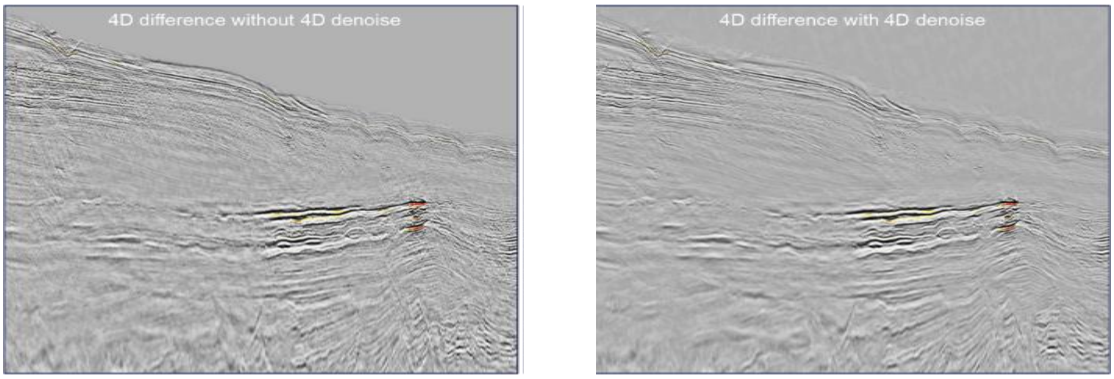

Figure 2: *4D differences without (left) and with (right) the 4D denoise in curvelet domain.*

4D Least-Square Kirchhoff Migration (LSK)

Due to the presence of thin sandstone layers in the Albacora Leste reservoir, advanced imaging technology, such as least-square migration, was evaluated to push the boundaries of the seismic resolution in both 3D and 4D context. We tested the capabilities, and constraints, of a 4D joint Least-Squares Kirchhoff migration solution, which compensates for multi-dimensional illumination variability and recovers legitimate reflectivity changes due to the reservoir production.

The 4D LSK methodology used in this study is based on image-domain reflectivity inversion using Point Spread Functions (PSFs). Our two-step imaging method recovers reflectivity by explicitly computing multi-dimensional PSFs and deconvolving accordingly the final pre-stack migrated image. We introduced a 4D formulation that is independent of geological and reservoir production constraints by incorporating the concept of cross-survey PSFs (Lecerf and Besselievre, 2018). Working in the image domain allows our solution to directly evaluate and compensate for illumination discrepancies from various data acquisition geometries at any location in the 4D image. Recovering reflectivity images involves regaining high wavenumbers of the signal, which are challenging to repeat and can introduce some extra 4D noise. It is crucial to control this recovery process in both 3D and 4D contexts simultaneously. We developed a specific quality control (QC) workflow that examines Amplitude Versus Angle (AVA) consistency between reflectivity angle gathers and 4D differences. Figure 3 shows the comparison of 3D and 4D images resolution between conventional Kirchhoff migration and the Least-Square Kirchhoff approach. We can observe how the 4D signal changes within the various thin layers present in the reservoir.

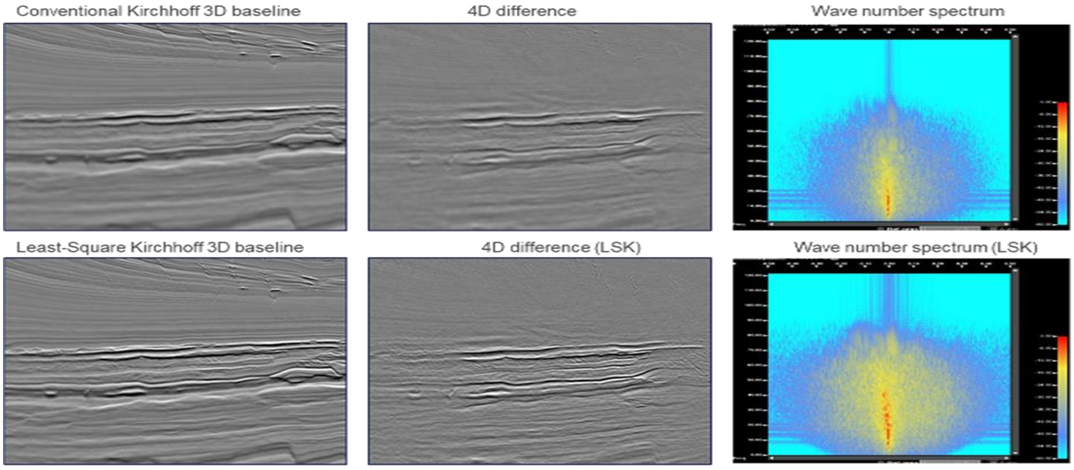

Figure 3: *Effect of the Least-Square Kirchhoff migration (LSK) on the 3D seismic images (left), on the 4D differences (central) and the corresponding wave number analyses (right).*

Conclusion

This “opportunistic” Albacora Leste 4D case study has combined a 2005 Multi-Client Baseline dataset, acquired with shallow towed conventional hydrophone streamer, with a 2022 Monitor dataset acquired with deep towed multi-sensor streamer. One of the 4D imaging challenges was to accommodate the two types of streamer and non-repeated shot positions for computing an accurate 4D signal. Through specific 4D processing sequences and a Least-Square Kirchhoff imaging approach, we succeed to improve the seismic signal resolution and be able to detect consistent fluid saturation and pressure changes within thin sandstone layers within the reservoirs. This 4D Albacora Leste project has enabled us to map and better understand the longstanding production of this complex and compartmentalized reservoir composed of turbiditic stacked channels with the aim of identifying new business opportunities.

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