4D Seismic Inversion Challenges, a Case Study on the Mature Albacora Leste field, Campos Basin, Brazil

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Summary

The study addresses the challenges of 4D seismic inversion in the mature Albacora Leste field, Campos Basin, Brazil, a complex deepwater reservoir with stacked turbiditic deposits. Using a 2005 baseline dataset and a 2022 monitor survey, the study overcomes challenges in data alignment, signal processing, and bandwidth optimization to enhance inversion accuracy. Key steps include 3D/4D matching, wavelet temporal/spatial stationarity adjustments, and dynamic warping. Results highlight fluid flow dynamics, revealing compartmentalization effects, production-induced changes, and water injection impacts. The 4D seismic study significantly improved understanding of the reservoir, identifying new infill opportunities and supporting optimized reservoir management.

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Introduction

Time-lapse (4D) reservoir monitoring studies provide seismic images of hydrocarbon reservoirs at distinct stages of the field development. Studying the images evolution and elastic properties differences through time, helps the reservoir management to better understand production fluid flow and reservoir pressure distribution. This paper describes results and challenges of the initial 4D elastic inversion on Albacora Leste field.

At the central part of Campos basin, the Albacora Leste field has an approximate area of 500 sq.km, and a varying water depth ranging from 1000 to 2000m. The Albacora Leste oil field was discovered in 1986, but it was only in 2005 that the field commercially started production. In January 2023, PRIO officially became operator of the field and managed its production.

Albacora Leste, one of the largest Campos Basin deepwater oil fields, consist of Miocene sandstones, Net thickness ranges from 5 to 35 m with high porosity and permeability. After the deposition stage, erosive channels introduced flow barriers that generated different reservoir compartments (Lemos *et al.,* 2006). Usually, reservoirs show low impedance in the seismic cubes and are clearly distinct from the surrounding hemipelagic shales that show higher impedance. In Albacora Leste, presence of low-impedance shale and interlaminated rocks (very thin shale/sandstone stacked sequences) causes negative amplitude seismic responses, comparable to the best reservoir responses. Usually, the low impedance shale and the interlaminated rocks can be identified by amplitude variation-with-offset (AVO) analysis and elastic inversion, but in the case of Albacora Leste, this does not solve the problem because of the low seismic data resolution. Models indicate the manifestation of the small gas thicknesses observed in the drilled wells. Because of seismic interference effects, such thin gas presence would not have been detected in AVO 3D study.

In 2005, a HD3D seismic, using high density of reflection points, has been acquired providing improved lateral resolution and AVO response of the reservoirs. This high-resolution seismic serves as a baseline for this reservoir monitoring case study. At the time, 2005 seismic data has brought significant improvements for Albacora Leste geological model. The hope is that 4D study with monitor survey acquired in 2022 will provide extra information which was difficult to understand with 3D analysis.

Albacora Leste seismic monitoring project

In 2022, an “opportunistic” monitor survey has been acquired over the Albacora Leste field. The term opportunistic is used, in opposite of 4D dedicated surveys, because acquisition set up of the baseline survey was not fully repeated in 2022 acquisition. The 2005 Baseline was part of a multi-client library (TGS) and the 2022 Monitor survey has been acquired using a different streamer configuration. Even if the 2005 acquisition azimuth (Figure 1), sail lines and dual source configuration has been replicated in the best possible manner for the 2022 survey, the shot positions have not been repeated. On the receiver side, the number of streamers is the same for both surveys, however the baseline data has been recorded using shallow streamer (7 m) with single hydrophone while for the 2022 Monitor acquisition deep towed multisensor cable (20 m depth) was used, providing broadband seismic signal.

Deeper towed streamers deliver useful low frequencies and improved signal-to-noise ratio. Importantly for 4D, multisensor recording provides receiver ghost-free up-going wavefield data, insensitive to the sea state.

One of the 4D seismic processing challenges was to combine a conventional baseline dataset (hydrophone only) and a broadband monitor dataset. The processing approach intends to extend the bandwidth of the 4D signal and consequently to improve the resolution of the 4D inversion. That means the data recorded with the conventional shallow streamer was deghosted with a deterministic operator using the nominal source and receiver depth. With this process, the baseline data can be directly calibrated with the ghost-free data produced by the multisensor monitor survey. Similar approach was previously applied in west Africa 4D seismic monitoring projects as described by Reiser *et al.*, (2018).

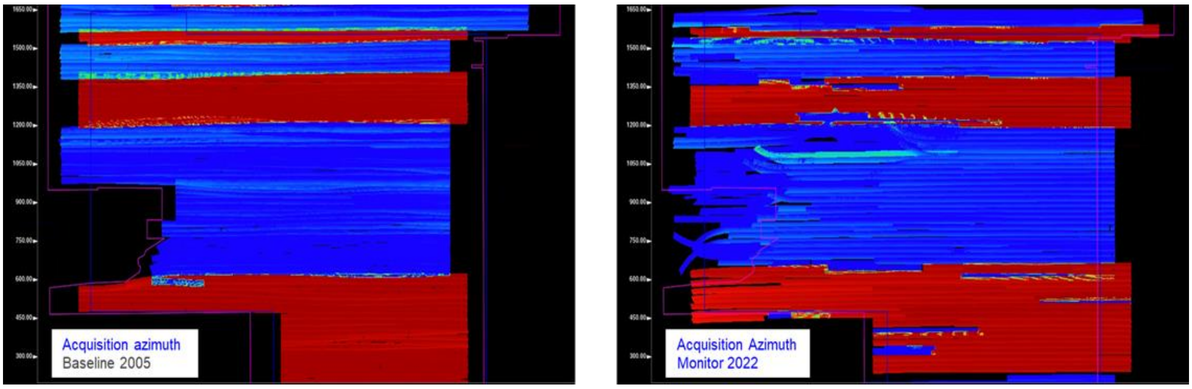

Figure 1 *Acquisition azimuth maps, for the 2005 Baseline (left) and for the 2022 Monitor (right). Red 90° and Blue 270°.*

In our 4D case, it was important to broaden both data, as much as the frequency signal-to-noise spectrum would allow, to optimise the resolution of seismic inversion of the stacked heterogeneous reservoirs.

Data post-processing challenges for 4D inversion

For an optimum 4D inversion results, the input seismic data must be preconditioned in a specific way to guaranty an optimal bandwidth of the 4D signal and to limit the effect of the 4D noise.

We summarise the key seismic data pre-conditioning stages as follow:

- **3D/4D Matching**: In addition to the conventional global data cross-equalization, a specific residual matching procedure was designed for optimizing signal repeatability along the full stack bandwidth as well as for the various angle stacks. Because broadband data provides large variation of wavelength, a signal-only matching operator must be designed using a frequency adaptive time length, meaning using longer operator for low frequencies and shorter operator for the high frequencies.
- **Wavelet temporal and spatial stationarity**: Since the overburden varies laterally in terms of thicknesses, water depths and geological characteristics, some amplitude and frequency compensation must be applied locally to the various angle stacks. The process insures a homogeneous seismic amplitude over the full reservoir area in 3D and 4D sense. The spatially variable correction, the same for both vintages, can be associated to a local absorption effect in the overburden which is compensated for at the reservoir level (Figure 2).
- **Dynamic 4D warping**: Prior to 4D pre-stack simultaneous inversion, all angle stacks of both vintages are dynamically time(/depth) aligned to extract the seismic reflectivity changes due to the reservoir production. The resolution of the calculated time-shifts is around 1/20th of the sample rate. It is a critical step, especially in our case study, as 20 years of production may create large time-shift interfering with 4D amplitude changes of stacked reservoirs. The Figure 3 illustrates the effect of the dynamic warping for recovering the genuine 4D signal due to the reservoir production. The correlations between kinematic variations and reflectivity changes are analyzed in a second step using the inverted 4D Ip.

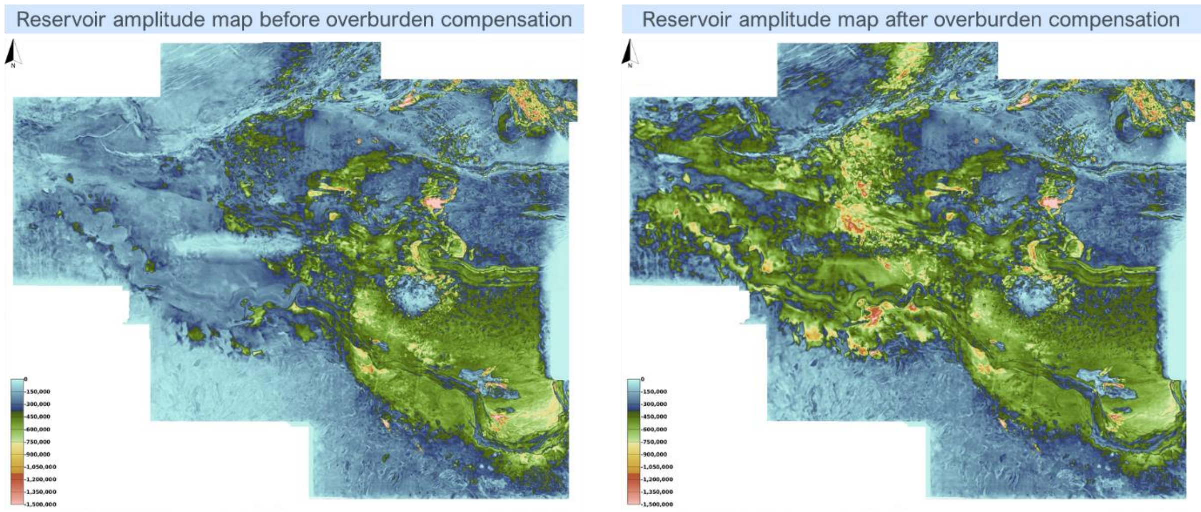

Figure 2 *Effect of the overburden compensation on amplitude response. Note the seismic energy of Western part of the reservoir is weakened due to overburden thickness. The correction process insures a consistent seismic energy over the area.*

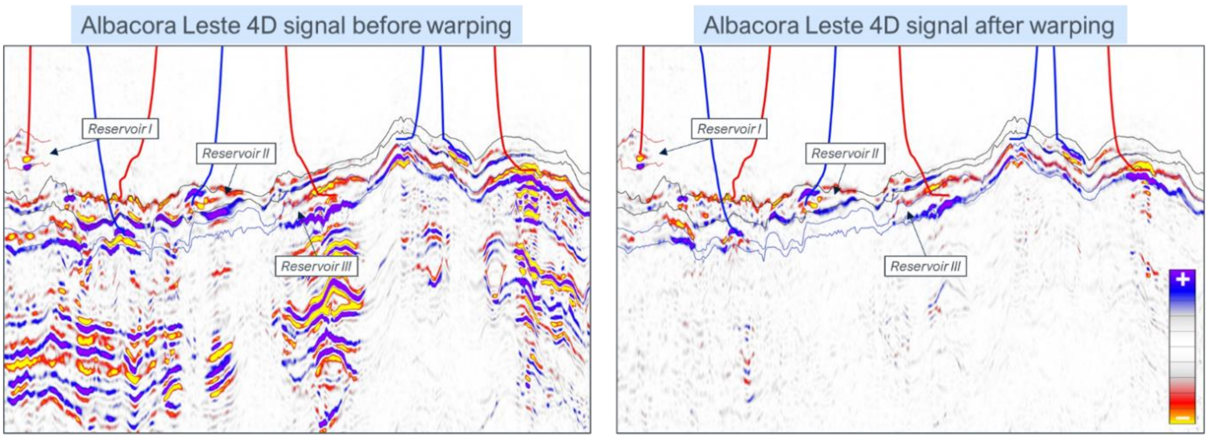

Figure 3 *4D seismic differences before (left) and after (right) dynamic 4D warping showing a series of stacked reservoirs. Red horizons show top and base of reservoir I, black horizons show top and base of reservoir II and blue horizons show top and base of reservoir III. Red well paths represent oil producers and blue well paths represent water injectors.*

Albacora Leste 4D inversion results

One of the objectives of the Albacora Leste 4D study is to understand fluid flows and pressure field evolution in a gas cap located in structural high of reservoir III. During the oil production (heavy oil) on the flank of the gas cap structure, water injection has been used to improve oil recovery and to maintain pressure in the gas cap. Effective pressure maintenance or no pressure variation should translate to weak 4D signal in the gas cap. However strong reservoir compartmentalization may influence and perturb the desired injected water path.

The 4D inversion results (Figure 4) is showing acoustic impedance 4D difference at reservoir level III where strong hardening effect (blue/purple) is observed at the base of gas cap probably due to the variation of water injection effect. We observe a thin extension of the hardening effect to the north as water outflow on the side of the gas cap.

The softening (red/yellow) effect is related to the oil production and is consistent with the location of the oil producers. However, the 4D effect is clearly surrounding the gas cap and extends to areas away from producing wells (yellow arrows). The softening patch in the north may be related to the producer well on the side of the structure. This interpretation corroborates with results of dynamic flow simulations.

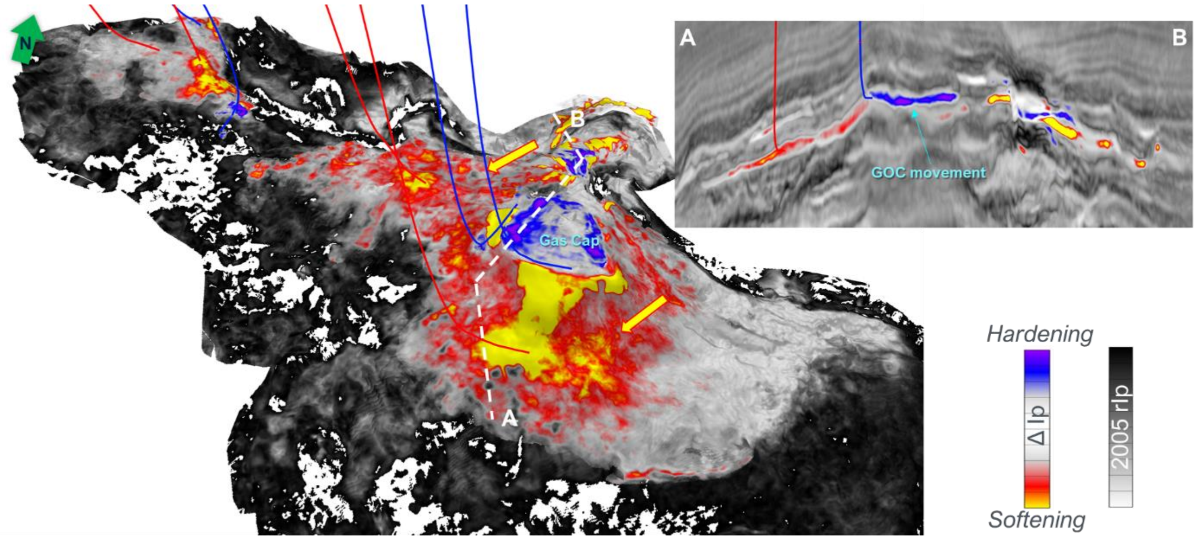

Figure 4 Delta acoustic impedance mapping softening (red/yellow) and hardening (purple/blue) effects around gas cap for reservoir level III. Well paths shown in red correspond to oil producers and well paths shown in blue correspond to water injectors.

Conclusions

The Albacora Leste 4D case study has combined a 2005 multi-client Baseline dataset, acquired with shallow towed conventional hydrophone only streamer, with a 2022 Monitor dataset acquired with deep towed multisensor streamer. Handling two types of recording streamer systems and non-repeated shot positions was one of the 4D processing challenge, which was performed by applying the preconditioning key steps such as 3D/4D matching, spatial amplitude balancing and 4D dynamic warping.

The results of this monitoring project reveal that 4D seismic data was a fundamental tool to map and understand 20 years of production of this complex compartmentalized reservoir composed of stacked turbiditic deposits. Through specific 4D post-processing techniques, the pre-stack data have been optimized for 4D inversion. The 4D study has provided a better understanding of the reservoir fluid dynamics hence allowing to identify new infill opportunities.

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