4D simultaneous pre-stack inversion in an offshore carbonate reservoir

Florine Villaudy*[1], Marcos H. Grochau[2], Pedro M. Benac[2], Nathalie Lucet[1], Carlos E. B. S. Abreu[2]
[1]Beicip-Franlab, [2]Petrobras

Abstract

This paper emphasizes the added value of a 4D joint elastic inversion for a multi-disciplinary interpretation of a carbonate reservoir, aiming at delineating and better understanding reservoir changes induced by the production. Although well developed in the oil industry to optimize production in siliciclastics reservoirs, monitoring seismic changes induced by hydrocarbon production in carbonate reservoirs still remains a challenging task. A 4D joint elastic inversion methodology is described and applied on seismic data recorded in 1987, 2002 and 2010, 4D processed in pairs, over an Albian carbonate reservoir in the Campos Basin, offshore Brazil. Directly inspired from the single dataset pre-stack inversion methodology, the 4D joint inversion process provides as final result optimal models of P- and S-wave impedances consistent with all input data and expressed in the reference time basis. In order to initiate a multi-disciplinary interpretation involving geologists, geophysicists and reservoir engineers, P- and S-impedance variations (ΔIP and ΔIS) attributes are generated to highlight 4D seismic anomalies, likely due to production. Despite the moderate acquisition repeatability and the presence of three siliciclastic reservoirs under production above the targeted carbonate reservoir, results above expectations are obtained. The case study presented in this paper demonstrates the adequacy of the proposed methodology for this carbonate reservoir, opening the perspective of applying time-lapse seismic inversion to even stiffer carbonates (e.g. Aptians "pre-salt").

Introduction

In the present work, the methodology of 4D simultaneous pre-stack inversion is applied to seismic data recorded in 1987 (streamer), 2002 (streamer) and 2010 (ocean bottom cable) 4D processed in pairs, over an Albian carbonate reservoir located in the Campos Basin, offshore Brazil.

Under production since 1982, the targeted carbonate reservoir is located at around 2500m depth and is characterized by an average porosity of 20% and an average permeability of 5mD. Three main layers can be distinguished: the uppermost reservoir, with better porosity and permeability; an intermediate region, almost impermeable; and the lowermost reservoir, with intermediate permo-porosity characteristics.

Preliminary to the present work, a large feasibility study based on modeling at different scales was conducted, and concluded that Gassmann equations are valid for estimating fluid substitution effects on elastic parameters in these Albian carbonates (Vasquez et al., 2007). Relative acoustic impedance variations (ΔIP) predicted from both core and log based modeling are, in average, of 3 and 6% respectively, with variations up to 20% in response to fluid changes. Considering the potentiality of detecting such levels of impedance changes, it was decided to invest in a 4D project.

A crucial part of the project, and the main focus of this paper, is to conduct a 4D simultaneous pre-stack seismic inversion to support time lapse interpretation. Based on optimal models of P- and S-wave impedances and derived attributes, the case study presented here emphasizes the added-value of the 4D joint elastic inversion to provide valuable insight to saturation and pressure changes in this carbonate reservoir.

A challenging carbonate reservoir

Applying a 4D joint inversion methodology on the targeted reservoir was challenging in different aspects. Firstly, the three acquisitions performed in 1987 (streamer), 2002 (streamer) and 2010 (ocean bottom cable), 4D processed in pairs, lead to two datasets (1987-2002 and 2002-2010) with a different surface area (Figure 1). The input seismic data for both seismic datasets are time migrated and partially stacked according to four incident angle classes: 5–18°, 15°–27°, 20–32° and 25–35°. Secondly, despite careful cross-equalizations, both datasets still differ in both frequency contents and optimal wavelet phases. The 1987-2002 dataset is indeed characterized by an optimal phase of 70° while the 2002-2010 dataset is characterized by a 0°-phase wavelet.

Thirdly, this carbonate reservoir has the specificity to be located underneath three siliciclastic producer reservoirs. These reservoirs also generate a 4D response that needs to be taken into account during the interpretation of the results.

Finally, the usual low sensitivity to pressure and saturation variations of carbonate reservoir due to carbonate high incompressibility is known to reduce the chances of detecting 4D seismic anomalies. Nonetheless, the feasibility studies give some hopes to move on in this 4D project.

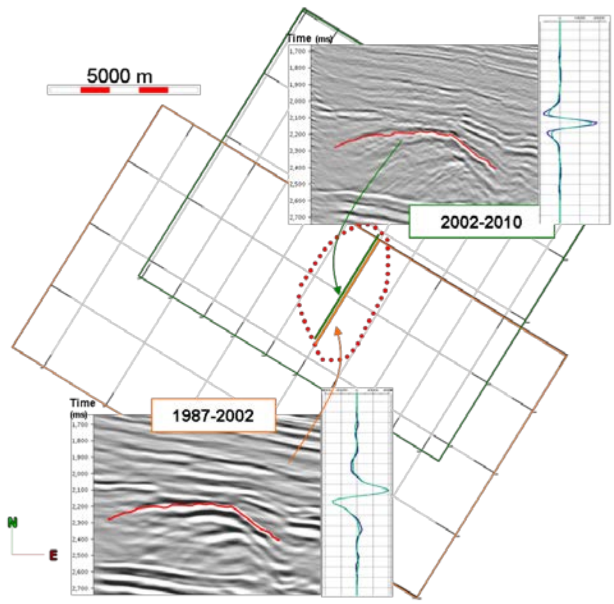

***Figure 1** – Illustration of available 4D seismic surveys (1987-2002 and 2002-2010, orange and green respectively), together with inlines sections and the optimal wavelets representative of 20-32° stack volumes (base as light blue and monitor as dark blue lines). Reservoir area is also displayed in red dotted line in the map and as a continuous line in seismic sections.*

4D joint pre-stack inversion

The 4D joint pre-stack inversion, detailed on the Sleipner case in Labat et al (2012), was applied in parallel on both available seismic datasets for a better coherency of the results. Once all data quality controls and preconditioning are performed, the methodology is composed of three main steps, as illustrated in Figure 2:

(1) Sequential pre-stack inversions: each vintage is inverted separately, in its own time basis, according to the following steps:

- A careful well-to-seismic calibration is performed for every angle class using wells with available P- and S-wave sonic and density logs, resulting in four optimal wavelets for each vintage of each dataset. For each 4D seismic dataset, the frequency content of base and monitor data turned out to be very similar.
- A unique a priori elastic model (parameterized by IP, IS and density) is then generated, based on five geological units. The same low-frequency a priori model is considered for both vintages in order not to introduce any biases in the results. As a consequence, final impedance changes between vintages after inversion would likely be assigned to seismic amplitude changes.
- Base and monitor data are finally inverted independently (Tonellot et al., 2001) using the optimal wavelets and initiated by the a priori model previously introduced. Due to the production of the above reservoir levels, time-shifts are clearly observable on optimized P-impedance volumes expressed in their own time basis (Figure 2, first track).

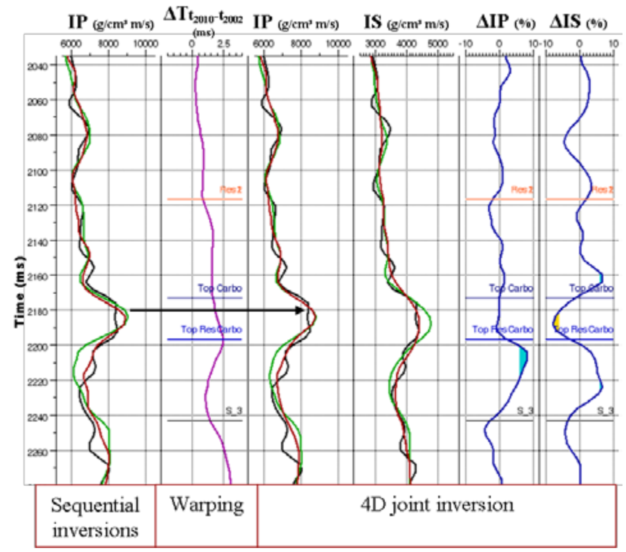

***Figure 2** – 3-steps methodology of the 4D joint pre-stack inversion (2002-2010) illustrated by results extracted along a representative producer well. Black, green and red impedance curves represent well log data, inverted base and monitor results, respectively. The marker "Top Res Carbo" corresponds to the top carbonate reservoir.*

(2) Warping procedure: an optimal time shift volume is estimated to best match the impedance distributions between the vintages. Formulated as a differential equation that links time shifts and velocity changes (Tonellot et al., 2010), it reveals to be crucial to perform the final step, that is the joint inversion of all available seismic vintages. As warping process input, an initial time scaling law designed to compensate remaining time differences due to the distinct acquisition parameters between base and monitor is estimated using a semblance algorithm. This law also compensates for the accumulated time-shifts due to the above reservoirs under production. The warping process, accounting for the fine changes in travel time, then updates the initial law into the seismic frequency bandwidth.

(3) 4D joint inversion: the joint stratigraphic inversion consists in inverting all pre-stack seismic data simultaneously according to the estimated scaling law. Directly inspired from the single dataset inversion methodology, the 4D joint inversion process provides as final result optimal models of P- and S-wave impedances consistent with all input data and expressed in the reference time basis. 3D constraints can be introduced in some geological units in order to obtain the same optimal earth model in the areas where the production is supposed to have no effect. In our case, as 4D changes are expected in the overburden and as the base reservoir horizon was not available, no constraint is applied to perform the 4D joint inversion.

Comparing sequential and 4D joint inversion results of the 2002-2010 dataset (Figure 2), amplitudes are slightly lower after 4D joint inversions but a better stability from base to monitor is noticeable. It is highlighted by ΔIP log, which remains close to 0 where no production is recorded while a variation higher than 6% is observed just below the entrance of the carbonate reservoir. The physical warping is granted to be part of this quality improvement. One can note that although usually not as trustable as ΔIP log, ΔIS log is also showing noticeable variations only in the reservoir interval.

4D seismic characterization: essential to initiate a multi-disciplinary interpretation

A trustworthy characterization relies above all on a robust horizon picking. Due to the phase rotation between both seismic datasets, the unique horizon interpreted preliminary on a zero-phase seismic volume could not be used anymore and needed to be refined. As presented in Figure 3 for 1987-2002 dataset, the original horizon (yellow line), located above the actual entrance of the reservoir, was refined (blue line), using the 1987 frequency enhanced mid reflectivity volume, to be further used to interpret 4D seismic anomalies. The refined horizon is indeed now corresponding to a starting point of decreasing P-impedance, as expected from log data.

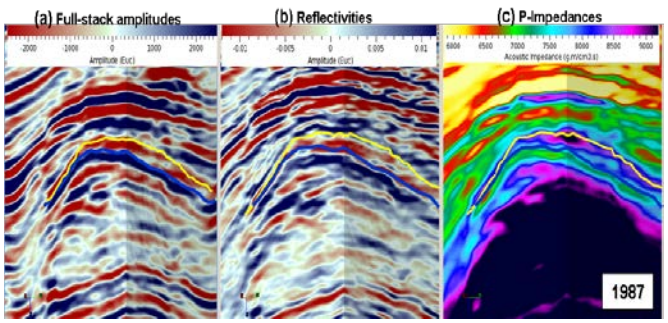

Figure 3 *– Amplitude sections from (a) 1987 full-stack volume; (b) reflectivity resulting from the 4D joint inversion and associated to mid 1987 angle-stack of the base 1987; (c) optimized P-impedance volume. Yellow and blue lines represent the original and refined reservoir horizons, respectively.*

Moreover, while the 1987-2002 dataset covers the southern part of the reservoir only, the 2002-2010 dataset allows mapping also the northern region.
An overview of changes induced by hydrocarbon production over the field is provided by average optimized P-impedance maps (Figure 4), extracted from refined horizons in a 32ms window below the top carbonate reservoir, therefore representative of the uppermost reservoir layer. Despite the known carbonate facies heterogeneities and the usual low sensitivity to pressure and saturation variations due to carbonates high incompressibility, reducing the chances of detecting 4D seismic anomalies, Albian carbonates of this particular field are clearly showing a 4D response with localized changes of P- (and S-) impedances from 1987 to 2002 as well as from 2002 to 2010.

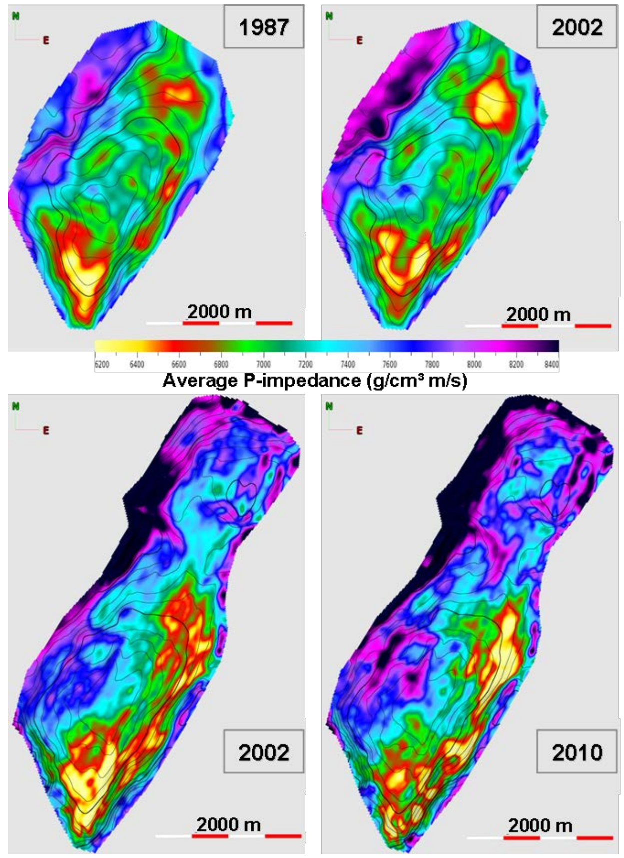

Figure 4 *– Average P-impedance maps extracted from refined horizons for each vintage of both datasets.*

In the perspective of a multi-disciplinary interpretation, relative impedance variations (ΔIP and ΔIS) are generated from P- and S- optimized impedance volumes.

Examples of meaningful saturation and pressure anomalies

Among many meaningful anomalies where 4D inversion results bring crucial information in the comprehension of the production effects, two case-studies are developed in this paper. While the first one deals with water saturation effects induced by an injector well, the second case-study focuses on a depleted area that induced gas generation.

Aiming at guiding a revitalization study, an injector well paired to a close producer well (referred respectively as IW and PW in Figures 5 and 6, both wells are multi-fractured horizontal) was drilled during the period 2002-2010. Its impact on the producer well and its vicinity is presented on average P-impedance variation maps, extracted from 1987-2002 (Figure 5a) and 2002-2010 (Figure 5b) 4D joint inversions. Indeed mostly affected by fluid saturation changes, positive P-impedance anomalies are expected. Between 1987 and 2002, except for two localized 4D anomalies in the vicinity of the wells W1 and W2, likely due to depletion, no significant 4D anomalies are observed along the pair IW-PW. Positive P-impedance anomalies are however registered in the 2002-2010 period, at the exact positions of the perforations, represented as green plain circles.

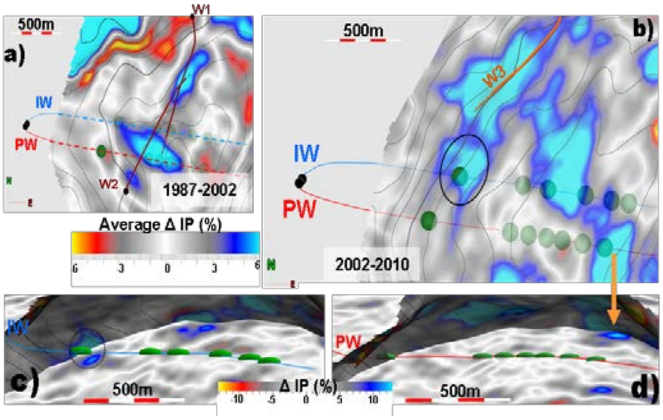

***Figure 5** – Average P-impedance variation maps extracted from: (a) 1987-2002 and (b) 2002-2010. Vertical ΔIP 2002-2010 sections along: (c) injector and (d) producer wells. Positive variations are displayed in blue and negative variations in yellow. Plain green circles represent the perforated intervals.*

Vertical ΔIP sections along both injector and producer wells (Figure 5c and d) are then illustrating that while the wells were drilled in the intermediate reservoir layer, almost impermeable, 4D anomalies are observed along the top of the carbonate reservoir, in the uppermost layer. This analysis permitted to point out preferential regions in which water is injected.

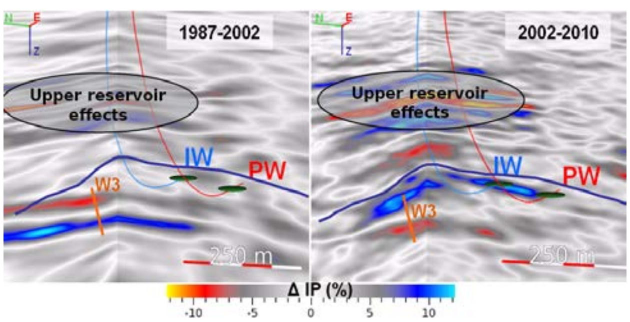

***Figure 6** – Vertical ΔIP sections illustrating a preferential way of the injected water around the wells IW and PW and an upward progression of the OWC around the well W3 between 1987-2002 and 2002-2010*

Among these preferential regions, the one located above the first perforated interval (circled in Figure 5b and c), also associated to the well W3, reveals interesting in two aspects illustrated in Figure 6:

- As explained above, no anomaly is observed around injector and producer wells in the 1987-2002 period, but then the water injected between 2002 and 2010 seems to be moving predominantly toward the well W3;
- The flat positive anomaly that is observed in the period 1987-2002 below the well W3, close to known OWC and interpreted as an up-rise of the OWC, suggests an upward progression of the water in the 2002-2010 period. This evolution appears consistent with the geological reservoir model.

The second case-study, involving both P- and S-impedance attributes, focuses in the northern region of the field, where a generation of gas associated to depletion is observed. During the production time, this mature carbonate oil field strongly depleted, which led to gas coming out of solution once fluid pressure drops below bubble point. In terms of impedances, while saturation variations are expected to impact mostly P-impedances, pressure variations are however expected to modify both P- and S- impedances. Therefore local strong positive variations of both P- and S-impedance, circled on average relative P- and S-impedance variation maps (Figure 7), are likely to be representative of depleted areas induced by the production of the wells W4 and W5, initiated in 2002. Along the W4 well path a strong localized negative variation is also observed, especially on the P-impedance variation map, interpreted as a gas cap formation. To a smaller degree, gas can also be noticed from another negative anomaly at the end of the W5 well path. These interpretations are consistent with the recorded production data.

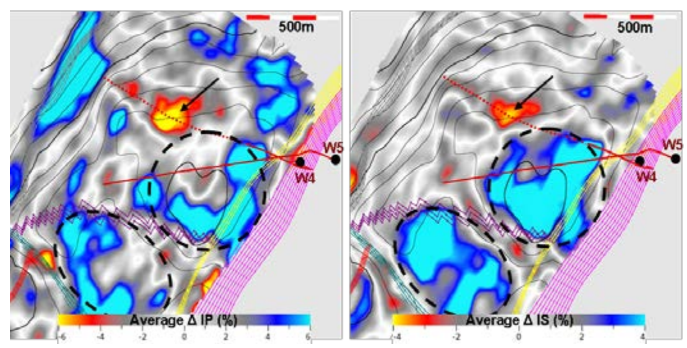

***Figure 7** – Average P-(left) and S-(right) impedance variation maps extracted within the uppermost reservoir layer for the period 2002-2010. Depleted areas are circled with the gas generated pointed out by the black arrow.*

The expansion of the areas affected by the production of both wells W4 and W5 finally seems to be directly linked to the fault distribution.

Conclusions

Well known and applied with success on siliciclastic reservoirs, we propose in this paper to perform a 4D joint pre-stack inversion on a specific Albian carbonate reservoir, expected from feasibility studies to provide a detectable time-lapse response. Considering that obtaining 4D signal in carbonates is still a challenge worldwide, the main purpose of this work is to evaluate the potential of applying such technology to support a time-lapse interpretation on Brazilian carbonate reservoirs.

Despite the moderate acquisition repeatability and the presence of three siliciclastic reservoirs under production above the targeted carbonate reservoir, the 4D joint inversion of pre-stack seismic data successfully delivers

P- and S-wave impedances for two 4D seismic datasets, satisfactorily matching the input seismic data, geological knowledge and well log data. Thanks to the warping procedure and subsequent 4D joint inversions, relative P- and S- impedance differences can be directly computed, in order to be analyzed and interpreted in terms of reservoir changes. Being able to detect strong localized anomalies, it provides a valuable insight to pressure and saturation distribution inside the reservoir.

Finally, this work conducted with success in this Albian carbonate reservoir brings hope and opens large perspectives. The 4D simultaneous pre-stack inversion methodology can be extended to other similar Albian carbonates and to even stiffer Aptian Pre-salt carbonates.

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