Seismic time-lapse in a maastrichtian turbidite field in Campos Basin/Brazil, with support of elastic inversion and seismic modelling studies.

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Abstract

Seismic time-lapse studies (S4D) in sandstone reservoirs have been successfully carried out in various fields of Campos Basin, Brazil, over the last years (example in Johann et al. [1]). Very frequently, it was proven as an excellent tool of reservoir characterization, mainly when it is integrated with geological and engineering data. The main goal of time-lapse seismic interpretation generally is to identify effects of pressure and saturation variations, focusing in management and projecting of oil and gas fields. In many cases it has been possible to get this interpretation purpose. In this offshore maastrichtian turbidite field, in central part of Campos Basin, we can see a good example of a seismic time-lapse's application for achieving the objectives mentioned above. This paper shows how an integrated 4D study could help us to provide useful information to better understand the reservoir changes and to provide insights for the field management. Basically, we could highlight areas on reservoir with high probability of pressure/saturation changes (dynamic information) and consequently infer about porosity/permeability distribution qualitatively and structural features (static information). And we judge that both required information were satisfactorily achieved since all available data, like geological/engineering model, hard dynamic, production/injection history and seismic data, converged to a better understanding of this reservoir. We must add in seismic data all set of processing data, including mainly the 4D simultaneous elastic inversion that it was an excellent tool of investigations by providing dynamic elastic properties. A key element was also the input from the Forward modelling study to translate dynamic simulator properties into elastic attributes and synthetic 4D signal. These steps of the workflow are described as well as the main results of this 4D study.

Introduction

The turbidite field studied consists of two main zones which are vertically separated, probably without fluid communication, with high levels of porosity (25%) and permeability (1000 MD) and containing heavy oil (19-21API). The field has been producing oil and water was injected since 2007. Gas cap was not observed nor expected as the fluid pressure has always been significantly higher than the bubble pressure. The water injection rates have always been controlled to avoid excessive overpressure. From the second quarter of 2008 it was observed a water breakthrough in both main zones (Figure1).

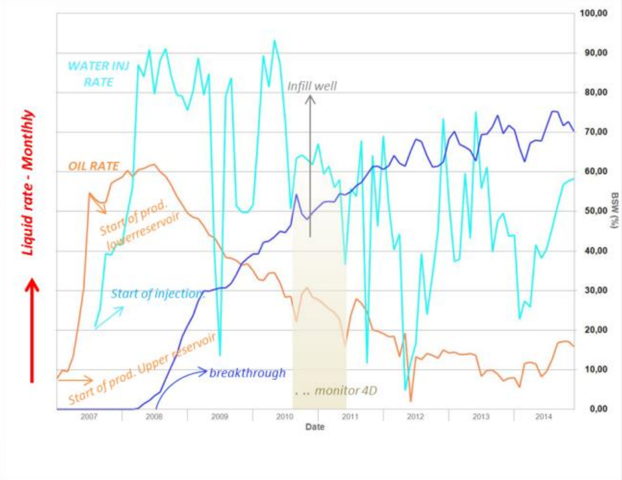

Figure 1: Field's Production History

The field's development started with an extensive campaign of drilling of producers and injectors, when in the end of 2010 an infill producing well was drilled seeking new opportunities of not drained oil. At the same period, a monitor seismic was acquired composing with the base seismic acquired in 1995, long before the beginning of production, and designed with the objective to perform a time-lapse study. Knowledge about some of the flow processes, such as water saturation increase with breakthrough and depletion/overpressure, had been gathered from measured well logs and production/injection history. The objective for this 4D dataset is to further investigate the changes in flow properties occurring between 2007 (beginning of production) and 2010 (infill well).

The seismic time-lapse interpretation was supported by 4D simultaneous elastic inversion applied on partial-stacks, which were the outputs of a dedicated 4D seismic processing. During this processing, an important aspect was the involvement of the asset, checking the suitability of the data for 4D inversion and interpretation purposes: progressive increase of repeatability, maintenance of AVO's relationships, real seismic difference vs. expected using 4D seismic modeling. Although there was significant difference between the acquisition parameters of the two datasets, it was possible to provide an excellent result from processing. The subsequent 4D Elastic Inversion was indispensable for this study. In addition to help with the interpretation, the use of flow classification and quantification of elastic attributes, it has brought the possibility to discriminate pressure and saturation changes. Petro-elastic modeling has supported the 4D seismic inversion and seismic interpretations.

The authors will first describe the techniques implemented during the study, starting with the 4D seismic modeling workflow and its application. The second section will describe the 4D inversion scheme that has been used, in the end leading to a description of the benefits gained from the whole workflow for the interpretation of the 4D data.

Use of Seismic Modeling Studies

The value of 4D seismic modeling has been demonstrated in previous studies (Dos Santos et al.[2]), as a tool for validation and calibration of the seismic 4D responses with the different fluid properties variations that are predicted by the flow simulator. The integrated simulator-to-seismic workflow and specific tool developed in collaboration between Petrobras and CGG (Allo et al.[3]) was used in the present survey, and is described in figure 2. Starting from the field's flow simulator grid in depth, synthetic seismic is generated in time after undergoing several steps. A critical first step is the calibration of the petro-elastic model (PEM), which is a set of equations that link rock and fluid properties such as porosity, fluid saturations, and pressures to elastic attributes – P- and S-velocities, density. It reconciles different static measurements (cores, logs and seismic) obtained at different scales and different domains (depth and TWTime). The PEM is based on the Rock Physics Template built by Petrobras Cenpes. Gassman equations combined with Kdry dependency on pressure (the latter based on core measurements following Mavko et al.[4] approach) were used to derive elastic attributes from dynamic-rock/fluid properties.

In order to compare the modeling results to the processed seismic 4D signal, the simulator was then re-gridded, in the depth domain, inside a seismic-oriented stratigraphic grid, where cells have similar bin size as the seismic data. The forward modeled Vp is also used to define the time-depth relationship, controlling the depth-time conversion using a reservoir horizon as anchor point. Synthetics are then computed from the reflectivity for the different years of production by 1D convolution with the appropriate wavelet.

Comparing the 4D changes obtained on the modeled seismic with the real seismic at different processing steps was a key aspect of this project. A close follow up of the processing by the asset team was set up and enabled faster decisions and better communication. The use of simulator-to-seismic workflow helped to reconcile reservoir engineer, geophysicist and 4D seismic processor points of view, by directly allowing to calibrate the observed 4D signal to the seismic anomalies predicted where saturation and/or pressure change were expected. The method significantly improved the confidence in the decisions taken during the processing of 4D seismic data.

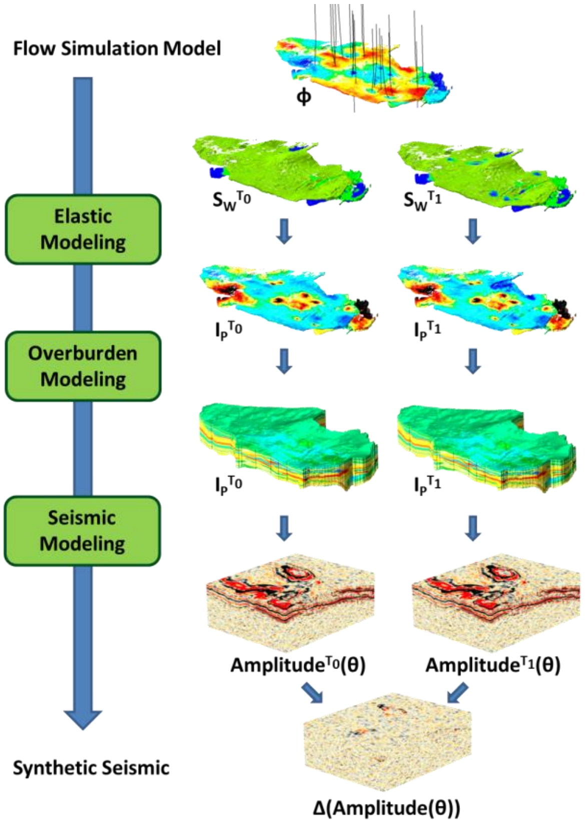

Figure 2: Simulator-to-seismic workflow

As an illustration, two steps of the 4D seismic processing are shown in figure 3. The significant change in time-lapse response observed along the processing was backed up by the information coming from the flow simulator. While seismic response differs from synthetic one, as expected, some main features are identifiable and directly linked to controlled information from the reservoir. For example the presence of an overpressure area around injector 4 in the lower reservoir is predicted by the flow simulator, in which the increase in pore pressure between base and monitor creates a softening effect and a decrease of P-impedance. The modeled 4D seismic therefore shows a decrease in amplitude at the top of the reservoir, where the through gets stronger negative values. While this signature is not obvious on the raw migrated seismic data, the final data displays a very identifiable negative difference in line with the expected pressurization of the compartment.

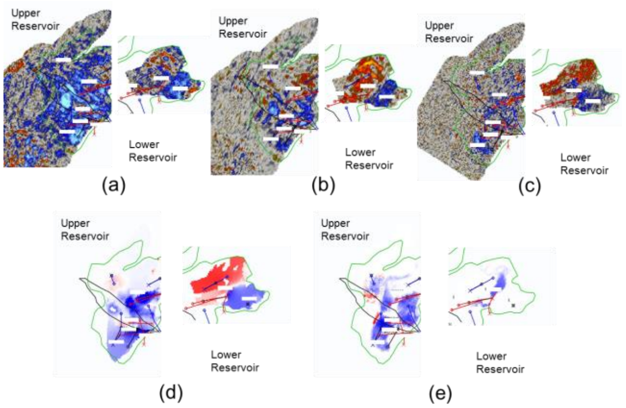

Figure 3: Modeled 4D difference compared with seismic 4D difference at two stages (a) raw post migration full stack difference at top reservoir (b) final full stack difference at top reservoir (c) modeled 4D difference from simulator-to-seismic workflow incl. 3% random noise addition (d) delta Pp in the top layers of the simulator grid (e) delta Sw in the top layers of the simulator grid

4D Seismic Inversion

Following the close monitoring of the 4D processing from a reservoir characterization point of view, a global 4D inversion was run. The 4D simultaneous elastic inversion methodology is a global time-lapse inversion scheme, where base and monitor data are jointly inverted, as described by Lafet et al.[5]. Simulated annealing is used to optimize a single objective function in which all vintages and angle stacks are combined. This ensures that the obtained time-variant elastic attributes best match all input stacks to the corresponding synthetics, which are computed by convolving wavelets to full Zoeppritz reflectivity series.

Independent wavelet extraction for each angle stack, and residual time-alignment of all data cubes were performed before base and monitor surveys were inverted simultaneously. The multi-vintage inversion starts from an initial layered model in which Vp, Vs and density are defined for base and monitor. Smoothed version of the results of a preliminary 3D elastic inversion of the base survey were used in this case, and kept identical for base and monitor. The possibility to use 4D constraint cubes for time-lapse coupling between inverted parameters exists, but was found unnecessary. In this case the seismic data quality was sufficient to obtain ranges of elastic attributes variations that matched the values predicted during the initial modeling steps. Lateral constrains in the form of 4D masks were not applied either, as within the reservoir units competing 4D effects were expected (pore pressure increase, depletion and water replacing oil) and it was decided not to input hard constrained information about their respective localizations and magnitude.

Improved imaging of the fluid variations (saturation changes as well as pressure changes) is expected from the inversion workflow (Six et al.[6]). The improved vertical resolution compared to seismic amplitude based attributes, and the use of inversion results for a better understanding of the reservoir behavior are discussed in the S4D interpretation section.

4D Seismic Interpretation

The results of the integrated 4D seismic interpretation has shown that it is possible to detected variations in saturation and pressure in upper and lower reservoirs, showing static and dynamic characteristics. 4D difference signals reveal relevant stratigraphic and structural features, as provision and transmission of zone faults and occurrence of internal sealing shales which act as barriers to vertical flow. We consider these both aspects to be the most important results coming from the application of the seismic time-lapse workflow in this maastrichtian turbite.

A good way to increase the reliability in the interpretation of 4D signals is to compare them with some hard data, like well logs, or production/injection history. In many time-lapse workflows, scenarios of fluid substitution are simulated at wells, along with other kinds of modelling. By using measurements obtained from the infill well, the pressure and saturation changes observed were confirmed and showed features of particular interest.

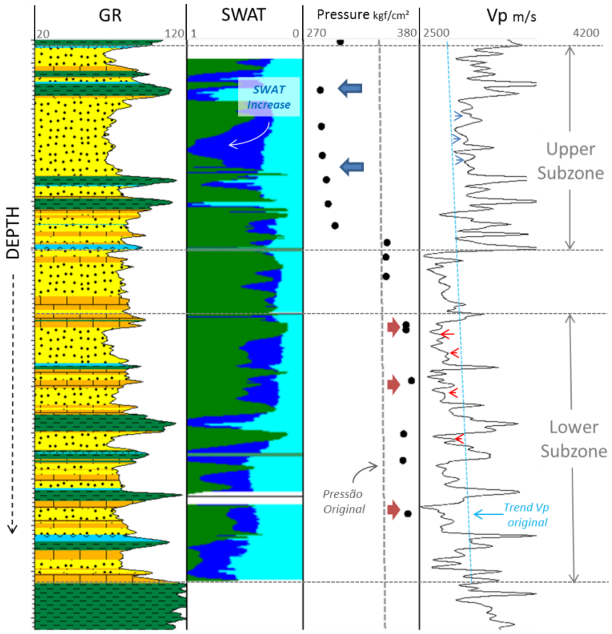

Figure 4: Logs of infill well showing depletion (blue arrows) and water saturation increase in the upper subzone and overpressure (red arrows) in the lower subzone

We can subdivide the upper reservoir in two subzones at the seismic scale. In the scale of high resolution's stratification, it is subdivided in many subzones with a strong control of sealing shales. The pressure log acquired on the infill well shows the effect of these barriers in pressure distribution. In the upper subzone it is possible to observe about 30Kgf/cm² of depletion and in the lower subzone about 20Kgf/cm² of overpressure

(Figure 4). This occurs because the production was concentrated historically in the upper subzone and the water injection was distributed in all subzones. Associated to depletion in the upper zone, the saturation log shows substitution of oil to injection water. From the rock and fluid properties modelling, we would expect a hardening signal in the upper subzone and a softening signal in the lower zone. And this is what can be identified in the ΔIP attribute coming from 4D inversion, which shows an increase of P-impedance, in the range of 4%, in line with the modeled ΔIP (Figure 5).

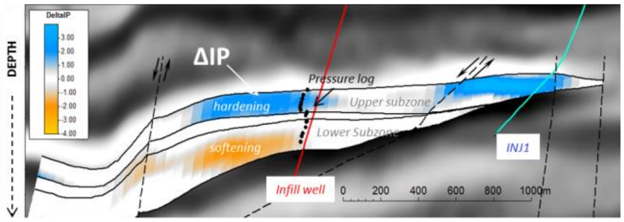

Figure 5: Well cross section along infill well and *injector1* illustrating hardening and softening effects associated to depletion/water saturation increase in the upper zone and overpressure in the lower zone

The average map of water saturation increase calculated from flow simulator, better fitted to the historical, is quite consistent with the seismic ΔIP. Also there is a good correlation of seismic ΔIP with the map of net-to-gross that it was calculated from the seismic (Figure 6). We could say that 4D map represents the distribution of water saturation increase in 2010, in depleted zones that represent the best paths, in agreement with seismic net-to-gross map. In north region the hardening 4D signal does not occur, which is explained by the structural interpretation where a hanging wall of an important normal fault is highlighted (see in figure 6). For this region, the combination between water saturation increase and an expected overpressure by the influence of injector well I3, it seems that the softening effect is more acceptable to happen.

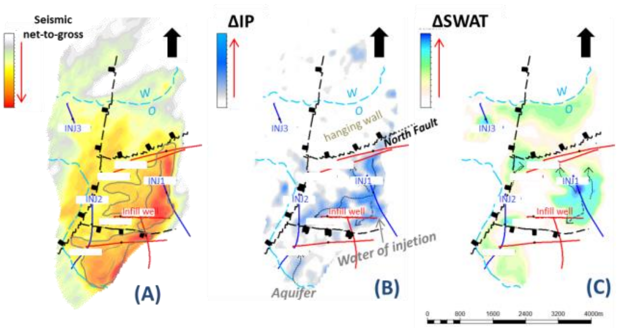

Figure 6: Map of ΔIP extracted in the upper subzone compared with seismic net-to-gross and water saturation increase (A) Map of seismic net-to-gross (B) Map of ΔIP showing hardening effects distribution rounded by north fault (C) Water saturation increase

Softening effects are more expected and observed in the lower subzone of upper reservoir as shown in the infill well. The average map of negatives ΔIP of the lower subzone shows the softening distribution (Figure 7). It is noted three great elongate shapes in the SW-NE direction associated with three injection wells. This may indicate permeability anisotropy associated with deposition directions of turbidite lobes. There is a reasonable correlation between softening shapes in the 4D map and the map of overpressure from flow simulator.

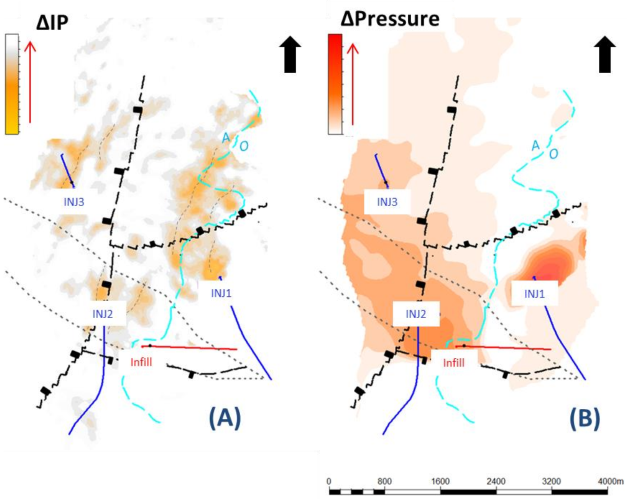

Figure 7: Map of ΔIP extracted in the lower subzone compared with fluid pressure increase (A) Map of ΔIP showing softening effects distribution (B) Fluid pressure increase

All injection wells show softening effects around this location, in both reservoirs. Also in the lower one it is observed these effects on negative ΔIS map (Figure 8). It is understood that the decrease in shear impedance at the time of monitor acquisition was around 3-4% smaller than the original, due to the increase of pore pressure exerted by the injection well I4. Their configurations are related to the distribution of better reservoir rocks bounded by faults.

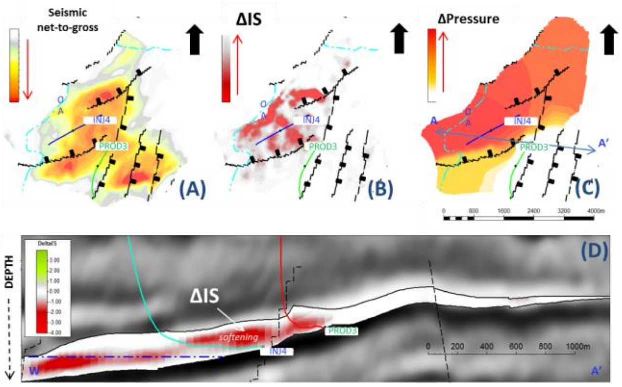

Figure 8: Softening effects in the lower reservoir (A) Seismic net-to-gross (B) ΔIS map (C) Fluid pressure increase (D) Well cross section along *injector4* and *producer*

Conclusions

The study presented in this paper showed the applicability of seismic 4D to identify elastic effects associated with pressure/saturation changes on a turbidite field in Campos Basin/Brazil, validated by production data.

This result was achieved by an integrated interpretation workflow strongly supported by a 4D elastic inversion and seismic modelling studies. Globally, as observed dynamic data was taken into account, the reliability of the proposed interpretation was improved. In this regard, both the pressure effects and water saturation increase, mainly related to injection processes, could be vertically and laterally mapped, with a good correlation to conceptual, geological and dynamic models.

The value of the seismic modeling studies was proved once again to help us in the flow of inversion and interpretation. Moreover these studies assisted us predictively to relate fluid properties to elastic/seismic effects. Finally 4D simultaneous elastic inversion provided us a very important tool of interpretation because we could work in a suitable domain of interpretation, easier to relate dynamic/seismic properties and better to interpret correlating to stratigraphic zoning of this reservoir.

Acknowledgments

The authors wish to express their gratitude to PETROBRAS and CGG, for the support and permission to publish this work, and co-workers of both companies for their valuable input.

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