Submission code: BNA8K5ADJX

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Planning Life-of-Field Seismic Monitoring Strategies for Brazilian Pre-Salt Oilfields: From Acquisition Parameters to Value of Information Analysis

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Abstract

Following a 4D seismic pilot test using Ocean Bottom Nodes (OBN) acquisitions over a small portion of the Tupi field (pre-salt carbonate in Santos basin) between 2015 base and 2017 monitor surveys, the industry has recognized the capability of seismic technology to recover 4D signals in such a complex environment. This realization has prompted a significant question: how to define the optimal life-of-field seismic (LoFS) monitoring strategy for these fields? In this work, we present a methodological flow, illustrated with a case study, where we first discuss the Monitoring Area of Interest (MAoI) for a Brazilian pre-salt carbonate field, utilizing what we have called a Fluid Movement Map (FMM). We then detail the process of defining the areas for seismic receivers and shots. Finally, we conducted a Value of Information (VoI) analysis comparing two distinct monitoring strategies: OBN survey and Permanent Reservoir Monitoring (PRM) for supporting the decision-making process regarding the LoFS monitoring strategy.

Introduction

4D (or time-lapse) seismic is a well-established tool for monitoring oil and gas fields (Calvert, 2005). However, dealing with stiff rocks like carbonates, as opposed to siliciclastic reservoirs, presents additional challenges. Moving to a pre-salt environment, with its inherent seismic imaging difficulties, further complicates the process of fluid (and pressure) monitoring during reservoir production. Despite these challenges, well-planned and advanced seismic acquisitions with good repeatability, such as OBN acquisitions, followed by state-of-the-art processing techniques and multidisciplinary interpretation work, successfully recovered valuable 4D signals over the Tupi field in the 2015-2017 pilot experiment (Cruz *et al*., 2021).

In the Santos and Campos basins, Brazil, many oilfields face similar monitoring challenges. Several of these fields have already undergone 3D OBN (base survey) acquisitions. For the majority, an OBN monitoring strategy might be the best choice in the following years, adding value to field development and production management with reasonable cost and flexibility. For others, however, a PRM solution could be more suitable, offering a faster, less intrusive and potentially clearer 4D response. The question then arises: how to decide between these (and potentially other) seismic monitoring solutions? Strategy costs and data output may differ significantly.

In this work, we share the main steps we have taken to support the best LoFS monitoring strategy for one of our operated pre-salt fields in the Santos basin: i) defining the MAoI based on a flow simulator and a novel attribute, the Fluid Movement Map (FMM), which is adapted from Falahat et al. (2013) concept of thickness adaptive scaled changes measurement; ii) using an internal developed optimization algorithm based on seismic modeling to design the optimized areas for receivers and shots; and iii) conducting a VoI analysis (as per Dias *et al*., 2024), comparing the pros and cons of both OBN and PRM strategies in the context of uncertainties and decision-making support capabilities of seismic data for this particular field.

Method

To evaluate operational feasibility and estimate seismic acquisition costs, the **first step** is to define the MAoI. For a 4D acquisition, this area should address two questions: i) is there a possibility and/or expectation of a 4D signal detection there? ii) Do we have field production decisions to be supported by 4D seismic data there? The MAoI is then the intersection of these two answers.

For a first approach in the MAoI definition, we have created the FMM concept. The idea is to isolate the causes, i.e., the flow simulator effects we wish to detect. We did not want to look for a simplified map, showing the maximum (or minimum) effect for each (x,y) position, as this could be misleading. For instance, a single cell, even a very thin one, with a high effect, would mark the map with a strong anomaly. Neither do we want to use average maps, as it could be misleading as well, we would rather like to include every fluid change effects among water, gas and oil. The solution found was to adapt Falahat's (2013) approach, created to support interpretation. The main idea of the FMM is to adapt the usual $H.\phi.So$ concept, which gives a static view of where the oil is, to a dynamic (4D) case, considering every fluid. Our definition stands as in **Equation 1**. For each position (x,y,z) we compute the expected fluid saturation change (in modulus) of oil, water and gas, take the maximum, and then multiply by the porosity. After that, we integrate in the vertical (z) axis. The result is a map, measured in meters, enhancing positions where fluid saturation changes are happening. For pore pressure effects, we can derive a similar map, modifying the saturation term for an equivalent pore pressure variation.

$$FMM_{(x,y)} = \int_z \max\{|\Delta Sat_{(x,y,z)}|\}_{(gas,oil,water)} . \phi_{(x,y,z)}. dz \qquad \textbf{(Eq. 1)}$$

In the **second step** (designing the optimized shots and receivers' area to capture the 4D signal), the idea is to use the 3D (or base) OBN dataset (or a synthetic one) and reduce shots and receivers' area, computing its impact in the seismic imaging process along the way. The objective is to restrict/reduce those areas, keeping (within a safety margin) just the part that would contribute within the MAoI. This could also be done at different reservoir depths and imaging criteria (i.e.: Born modeling for conventional RTM image and/or FWI velocity model impact). For our study case, as we started the analysis prior to having the first 3D OBN field results, we had to use synthetic data all the way. The plan is to refine the results once the field data is ready.

For the **third step**, we have followed the VoI methodology presented in Dias *et al*. 2024. The (net) VoI is defined as the expected variation of the Net Present Value (NPV) of the production project, once we evaluate the seismic costs, its expected ideal gains, and the penalizations due to both signal/noise limitation and time delay between interpretation and reservoir changes.

Results

For the **first step**, as we are doing a LoFS approach in this case, we have computed the FMM in an automated way, for every pair of acquisition dates. For each (x,y) position, we took the maximum amplitude between every map (as we are in a water-alternating-gas, WAG, injection pattern, we should not look only for the first to last acquisitions changes). This final FMM supported the MAoI. This area was then optimized in terms of projects and decisions to be supported with the 4D seismic data. **Figure 1** illustrates this procedure.

For the **second step**, following a seismic modeling scheme, we have selected the receiver's positions that contribute the most for the MAoI image. A similar approach was carried to define the shooting area. **Figure 2** illustrates this selection and its expected impact on the final image.

For the **third step**, following Dias *et al*., 2024 (**Figure 3**), we have estimated the costs for the PRM and OBN strategies. We have modelled a PRM acquisition every 1.5 year with a 500m x 100m grid, and an OBN every 3 years, with a 500m x 500m one (different grids and monitoring intervals will impact costs, signal/noise and time delay penalizations in the VoI analysis). The ideal gains, i.e., the ones that we expect with perfect and on-time data, are the same for both strategies - although other gains should be considered, such as those related to passive PRM data. As the PRM cost is higher than the OBN one, this comparison could only favor a PRM strategy in cases where the net gain (ideal gain – penalization) would suppress costs differences. These penalizations were calculated following the same methodology, where the expected 4D signal is computed for each reservoir cell, and then an acquisition dependent noise level is added, followed by a statistical hypothesis test to see if the expected signal is greater than the expected noise.

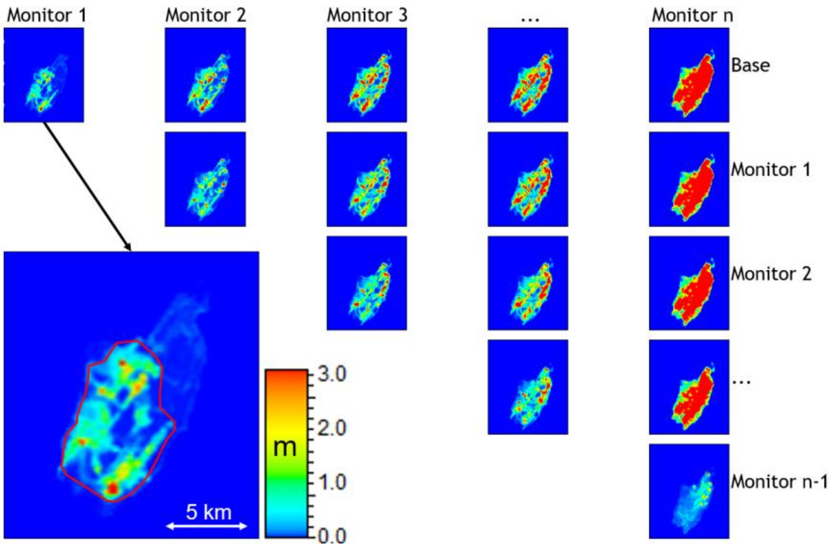

Figure 1: Fluid Movement Map for each pair (collum - line) of acquisition dates. The maps, expressed in meters, represent the (vertical) integration of fluid saturation changes in absolute value, multiplied by porous volume. The red polygon illustrates the MAoI if we were planning just a single acquisition (Monitor 1 – Base).

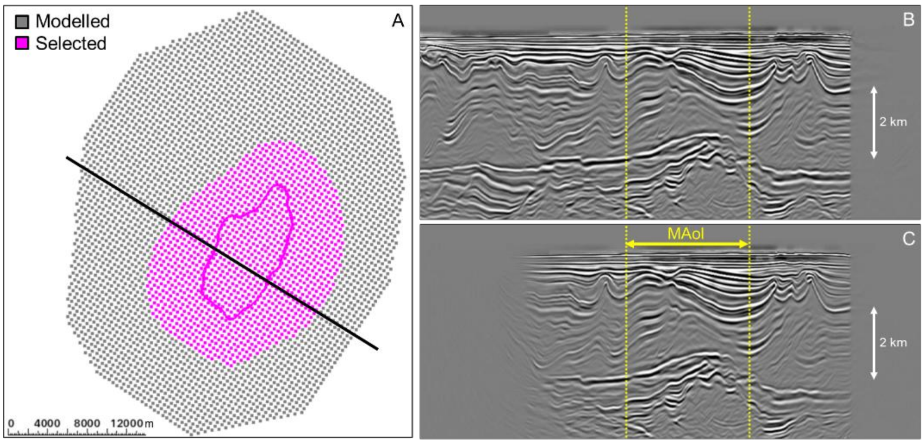

Figure 2: (A) Modelled receivers' positions (gray + pink) and selected ones (pink). (B) RTM synthetic image from the section illustrated in A, utilizing all modelled receiver data. (C) Same image as B but restricting receivers to the pink ones (after shots area optimization as well).

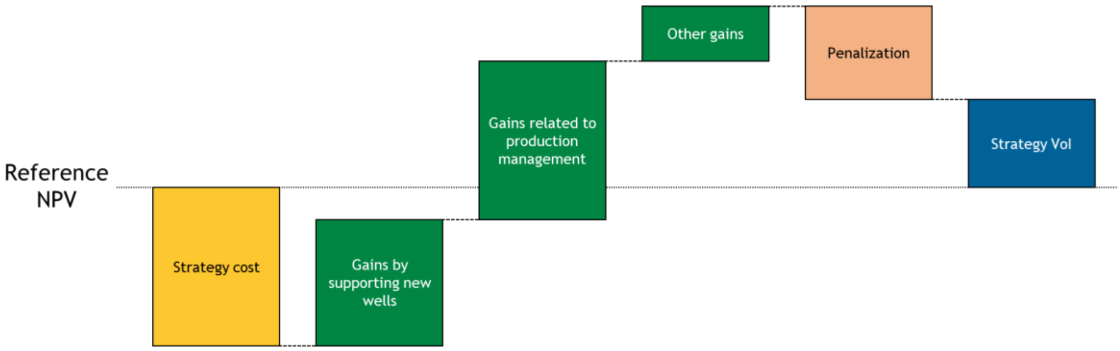

Figure 3: Illustration of the VoI methodology adopted (Dias *et al*., 2024). The net VoI of the seismic strategy corresponds to the balance between its expected costs and gains (ideal gains minus penalizations) on the project's NPV reference value.

As every input for the VoI analysis came with its own uncertainties (like the number of wells to be supported, gains per well, product management gains with intelligent completion operation, etc.), we performed a Monte Carlo simulation with 100.000 scenarios. The results, confronting both strategies, can be analyzed in a diagram as illustrated in **Figure 4**.

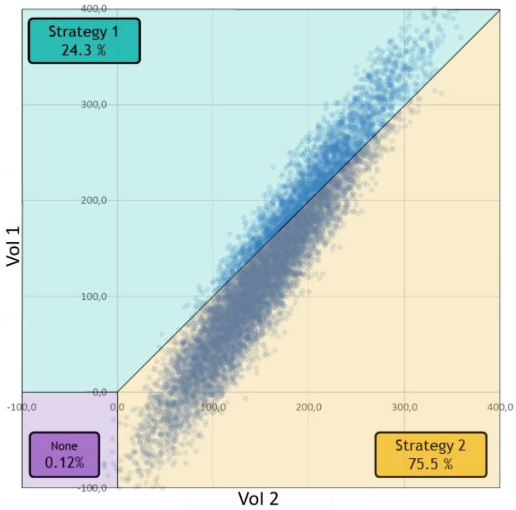

Figure 4: For every simulated scenario, we can compute the net VoI for each strategy. If both are negative (purple region), it might be better not to monitor the field, otherwise, we analyze expected net VoI, percentiles and the number of favorable cases for each strategy.

We have conducted this kind of analysis in different fields. In most of them, an OBN monitoring strategy is the one with higher VoI. For others, nonetheless, a PRM could bring more value. In those cases, we have conducted a Front-End Engineering Design (FEED) study with optical PRM providers to better access operational feasibility, improve PRM cost estimation, and ultimately support the final LoFS monitoring strategy.

Conclusions

In this paper, we share the main steps taken to support LoFS monitoring strategy, which is a complex and multi-factor decision: costs, flexibility, data quality, response time, amount and type of decisions to be supported, etc. The VoI serves as a decision-making tool to be evaluated in conjunction with other aspects, such as risks and strategic decisions. These VoI and LoFS strategies analyses are still ongoing, with the participation of the respective partners of each field.

Acknowledgments

Authors thank Petrobras and its partners, Total Energies, Qatar Energy, Petronas and Galp, for permission on publishing this work.

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