Abstract

In the present study, two methodologies to integrate 4D seismic and reservoir simulation data were compared. The first one, named quadratic difference (QD), follows the traditional way, using deterministic seismic information. In such method, the 4D seismic information is considered an additional observed dynamic data that the simulation models must honor. The second method, called overlapping (OVL) methodology, considers the seismic information obtained from a probabilistic inversion; instead of using the 4D seismic as an observed accurate data, their uncertainties are also considered.

This study was performed in a synthetic reservoir, with intermediate complexity and several uncertainties. Maps of pressure and water saturation changes from reservoir simulation models and 4D seismic data were the information considered.

The methodologies were used to select the most representative pressure and saturation changes maps from simulation models. After the selection of simulation models using both methodologies separately, the differences between them were analyzed. In the pressure analysis, the most pronounced difference was in the pressure change maps: OVL methodology showed to be more statically consistent than QD in incorporating seismic information, since OVL only used the seismic data in locations where it were more precise than simulation data. In addition, comparing the tendencies of the values for transmissibility of the faults, we found that OVL was more accurate than QD to select the simulation models.

In saturation analysis, the same tendency was noticed, but as such analysis was performed locally, the results were less pronounced than the results from pressure change maps. Moreover, instead of comparing the transmissibility of the faults, we compared the difference between the porosity and permeability images from selected models from QD and OVL. We found relevant differences in selected permeability and porosity maps from both methodologies, highlighting locations where OVL and QD are showing different tendencies that should be considered in an optimization process.

1. Introduction

History matching is a procedure that integrates dynamic information in the reservoir modelling workflow, aiming to match simulation and observed data, to obtain reliable models to manage the reservoir performance and provide more realistic production forecast. This dynamic information is usually obtained from wells, e.g. production and pressure data. However, wells are located in specific reservoir regions; therefore, there is a lack of spatial information, which can generate limited and inaccurate calibrations. Thus, new sources have been studied and integrated into the calibration process of the simulation models, notably the 4D seismic (S4D) data.

4D seismic is the repetition of 3D (or 2D) seismic surveys at different times in the reservoir. When comparing the difference between these surveys, it is possible to obtain a spatial view of the fluids displacement as well as the pressure changes in regions that are not covered by the wells.

Traditionally, the history matching process is performed deterministically, i.e., the forecast and production strategies are based on a single model. In this situation, the S4D information (as changes in impedance maps, or saturation and pressure) is integrated as observed data that the simulation model must honor. Risso and Schiozer (2008) show an example of such integration.

Nevertheless, the history matching procedure is an inverse problem and should have multiple possible responses. Combinations of different values of the parameters that characterize the reservoir can generate the observed data, which requires probabilistic approaches to handle these non-uniqueness responses (Xavier et al., 2013; Maschio and Schiozer, 2014; Emerick, 2016). However, even when the history matching is performed probabilistically, 4D...
seismic is still integrated deterministically, so it is considered as a unique observed data that multiple simulation models must honor (Fahimudin et al., 2010; Riazi et al., 2013; Almeida et al., 2014).

Although uncertainties in seismic data are not usually considered, the acquisition, processing and interpretation of seismic has several limitations that should be taking into account. Using 4D seismic as observed data (deterministic) may not generate consistent and accurate results, since the impact of the seismic errors are neglected. Castro (2007) and Bosh et al. (2010) present some drawbacks of deterministic seismic inversion. In the present scenario, it is remarkable the lack of studies that integrate, probabilistically, both data: simulation models and 4D seismic. Stephen et al. (2005), Landro and Kumar (2011) and Assunção et al. (2016) present some of the few examples found in the literature.

The idea of this work is to compare the information acquired from two methodologies and evaluate the possible differences between them. The first uses the 4D seismic information in a deterministic way (classical approach), while the second uses 4D seismic probabilistically, considering its uncertainties.

2. Objective

The objective of this study is to evaluate the differences between two methodologies that incorporate the 4D seismic data within the history matching workflow. The first methodology, called quadratic difference (QD), uses 4D seismic deterministically following the traditional history matching practices such as the one proposed by Almeida et al. (2014). The second methodology, named OVL, considers an approach that handles probabilistic estimates from 4D seismic data and reservoir simulation models.

3. Methodology

In the present study we used a synthetic 4D seismic data that are represented by maps of pressure and saturation changes. Thus, the available 4D seismic is \( n \) maps of \( \Delta S_w \) and \( \Delta p \), yielded from a probabilistic synthetic seismic inversion and transferred to the scale of the simulation models. The information from simulation models are \( m \) maps of \( \Delta S_w \) and \( \Delta p \), which are the dynamic changes estimated from \( m \) simulation models generated from the combination of mapped uncertainties (defined in section 4.2).

The QD methodology, fully presented in section 3.1, is used to select the simulation models using deterministic 4D seismic data (section 3.1.1). Section 3.2 presents the OVL methodology, which also uses the 4D seismic information to select the most representative simulation models. However, the OVL methodology uses probabilistic 4D seismic information (section 3.2.1). The last section of the methodology, section 3.3, present details about the differences evaluated between both methodologies. We emphasize that, due to the characteristics of the data sets, the analysis of \( \Delta p \) and \( \Delta S_w \) maps are performed separately.

3.1. Quadratic difference (QD) methodology

This methodology incorporates the seismic information deterministically, calculating the quadratic difference between the single map of \( \Delta p \) (or \( \Delta S_w \)) obtained from the observed 4D seismic information and the \( m \) maps of \( \Delta p \) (or \( \Delta S_w \)) generated from simulation of \( m \) models. There are multiple maps from simulation models that must be compared with the observed (deterministic) map obtained from 4D seismic inversion.

The discrepancy between the \( m \) maps of \( \Delta p \) from simulation and the single \( \Delta p \) map from 4D seismic is measured by the quadratic difference in every grid block, according to Equation (1).

\[
QD_p(s) = \sum_{k=1}^{K} \sum_{n=1}^{N} (\Delta p_{SIM}^{k,n} - \Delta p_{SEIS}^{k,n})^2 \quad \text{for} \ s = 1, 2...m
\]

(1)

Where \( N \) is the number of blocks in every layer and \( K \) is the number of layers of the models. Variable \( s \) represents the simulation model studied. SIM is the estimate from the simulation model and SEIS the estimate yielded from 4D seismic inversion.

In the \( \Delta S_w \) analysis, due to the data variability in depth, the models comparison is made for each layer separately, as shown Equation (2). Thus, at layer 1 the selected models can be different of the selected models from layer \( k \). For the pressure analysis, on the other hand, the selected models are the same concerning all layers.

\[
QD_{SW}(s,k) = \sum_{n=1}^{N} (\Delta S_w_{SIM}^{k,n} - \Delta S_w_{SEIS}^{k,n})^2 \quad \text{for} \ k = 1, 2...K \quad \text{for} \ s = 1, 2...m
\]

(2)

3.1.1. Selecting simulation models using QD

After calculating the quadratic difference values, \( QD_p(s) \) and \( QD_{SW}(s,k) \) the simulation models are placed in ascending order and the ones which presented the lowest values of \( QD_p(s) \) are selected. The same procedure is performed for \( QD_{SW}(s,k) \).

2
3.2. Overlapping (OVL) methodology

In this methodology, the $n$ maps of $\Delta p$ (or $\Delta S_w$) from seismic are compared, simultaneously, with the $m$ maps of $\Delta p$ (or $\Delta S_w$) from simulation. The methodology consists in computing the overlapping coefficient (OVL) that shows the percentage of overlapping between the probability density functions (PDFs) generated with the $\Delta p$ (or $\Delta S_w$) estimates from simulation and seismic data. The PDF are generated using the kernel density estimator proposed by Botev et al. (2010) and the OVL is calculated for every grid block independently. From the OVL comparison it is possible to identify four different regions: (1) both dynamic changes estimates from seismic and simulation are similar, (2) simulation estimates are more precise than 4D seismic, (3) the data sets indicate divergent estimates and (4) 4D seismic estimates are more precise than simulation. Figure 1 illustrates the methodology and the “4 Regions Map” that can be obtained gathering the information of every grid block. The methodology can be used as a diagnostic tool (for instance, define the agreement/disagreement of the two data sets and define which data is more precise) or/and to select the most representative models. This second application is explained in section 3.2.1.

3.2.1. Selecting simulation models using OVL

The selection step is presented at the bottom of Figure 1. The idea is to select only the simulation models that present the same dynamic change estimates of the seismic, using only the reservoir locations where seismic is more precise than simulation (Region 4). The selection of the simulation models is performed for every grid block and in the end of the procedure, the most frequently selected models considering all blocks are filtered as good models. The selection here is performed separately, for $\Delta S_w$ and $\Delta p$, thus selected simulation models from $\Delta p$ analysis are not the same of $\Delta S_w$. Assunção et al. (2016) provide further details about this methodology.

3.3. Evaluating differences between QD and OVL methodology

After the selection of simulation models using both methodologies separately, the differences between them are analyzed. In the pressure analysis, we compared the average map of $\Delta p$ maps selected by each methodology with the reference (true) map, to observe the improvements. We also compared the 4 Regions Map of the selected maps to observe how each methodology used the 4D seismic information available. Differences in some of the uncertain reservoir parameters such as faults transmissibility were also observed in this analysis.

In saturation analysis, the average map and 4 Regions Map were also used to compare QD and OVL, however the saturation difference was observed locally. Instead of comparing the faults transmissibility, we compared the difference between the porosity and permeability maps from selected models from QD and OVL, as these properties are more related to saturation changes.
4. Application

The present work uses a synthetic reservoir with real characteristics, named Beta. There is a reference model, which was modelled in a fine grid and represents the real reservoir response. The information usually measured in the field (production data, well logging, etc) is extracted from the reference model. The synthetic seismic response are also obtained from the reference model, through forward modelling that uses its simulation results and petrophysical properties.

Based on the information “measured in field” (acquired from the reference model), multiple simulation models were generated, in a course scale and considering the reservoir uncertainties described below. The following sections bellow presents more details about the reference model and the main uncertainties mapped, as well as the simulation and seismic data sets used.

4.1. Reference model

The reference model was created from a previous synthetic geological modelling, in a fine grid scale, 270x330 blocks and 18 layers. Its structural framework comprises four seismic faults, 13 sub-seismic sealing faults and two facies (sandstone and shaly-sandstone alternations). It has 11 vertical producers and 8 water injector wells. Figure 2 presents some characteristic of the reference model. More details can be found in Gil et al. (2016).

![Figure 2: Characteristics of the reference model: (a) Faults and sub-seismic faults (red straight lines), (b) Facies (sandstone and shaly-sandstone alternations) and (c) permeability (Gil et al., 2016).](image)

The reference model is used to validate the response from the methodologies, since it represents the true reservoir answer. The ∆p and ∆S_w maps obtained from the reference model were scale transferred to the simulation grid (90x110 blocks and 9 layers). The seismic response was also transferred to the simulation scale. Therefore, all dynamic chance maps used and compared are in the same scale. Figure 3 illustrates the pressure and water saturation changes for layer 1 from the reference model with scale transferred.

![Figure 3: ∆p and ∆S_w from reference model (layer 3 out of 9).](image)
4.2. Model uncertainties

Seven main uncertainties are considered to generate multiple simulation models: (1) relative permeability of the two facies, (2) ratio of vertical and horizontal permeabilities \( K_z / K_x \), (3) transmissibility of four (seismic?) faults, (4) facies distribution, (5) porosity, (6) absolute permeability and (7) net-to-gross (NTG). Correia et al. (2016) shows the intervals considered for each of the uncertainties listed above.

4.3. Reservoir simulation data

The simulation models are generated from the reference model information, such as well logging. It has a coursed scale, 90x110 blocks and 9 layers. The multiple simulation models were generated combining the main reservoir uncertainties mapped; being that, the true answer (reference model) is not included in the set of models.

The seven uncertainties above mentioned are combined using a sampling technique based on the Latin Hypercube, which generated 500 models. Once generated, the mismatch between the 500 models and production data was assessed and a well history matching procedure was applied. Therefore, the simulation data here used are a set of models obtained from an intermediate step of an iterative and probabilistic well history matching process. More precisely, 500 models obtained from step 2 (out of 4) presented in Almeida et al. (2014). From these 500 simulation models, we obtained 500 maps of \( \Delta p \) and \( \Delta S_w \). These maps are the information of simulation models used in this study and are presented in Figure 4.

![Figure 4: Mean of the 500 maps of \( \Delta p \) and \( \Delta S_w \) from simulation models (layer 3 out of 9).](image)

4.4. 4D seismic data

Seismic information of this work consists of IP and IS impedances, synthetically built at two different times: pre-production (T0 = 0 days) and after 5 years of production (T1 = 1800 days). This synthetic information was obtained from a petroelastic modelling, which uses the parameters of the reference model as input, such as: porosity, net-to-gross, water saturation and pressure changes at T0 and T1, etc. Further explanation about the petroelastic method used to obtain the synthetic seismic information is presented by Pazetti et al. (2015). Noise is added in these impedance values to produce more realistic synthetic seismic information. This noise addition process is shown in Davolio et al. (2014).

Impedances with added noise are the information employed in a probabilistic seismic inversion based on Latin hypercube. This probabilistic inversion generates, from IP and IS impedances, maps with estimates of changes in water saturation and pressure between T0 and T1 (Davolio and Schiozer, 2015). Thus, 500 maps of \( \Delta S_w \) and \( \Delta p \) are obtained. Figure 5 illustrates the average of the seismic data available.

The deterministic 4D seismic information used in this study is represented by the mean of the \( \Delta S_w \) and \( \Delta p \) maps as shown in Figure 5.

![Figure 5: Mean of the 500 maps of \( \Delta p \) and \( \Delta S_w \) from 4D seismic data (layer 3 out of 9).](image)
5. Results and Discussion

This section introduces the main results obtained. In section 5.1 pressure change maps are studied: we show estimates of the 500 simulation models and then estimates from the selected models from QD and OVL, respectively. The difference between the faults transmissibility are also shown in this section. Section 5.2 presents the results obtained in saturation analysis: saturation changes from the 500 simulation models and the differences between QD and OVL. In addition, in saturation analysis, selected porosity and permeability images from both methodologies are compared.

5.1. Pressure analysis

Figure 6 shows an analysis to access the quality of the 500 simulation models data. In Figure 6a, we can observe the difference between the mean of the 500 ∆p maps (Figure 4a) and the reference value of ∆p (Figure 3a). There are three critical zones: the first one located in the northwest (wells P1, P2, P9, P11, I1 and I2), the second between the faults B and C and the third between faults C and D. The first and second zones have a difference greater than -9 MPa relatively to the reference value, while the last one shows a discrepancy of more than 3 MPa. This figure also shows the great influence of the faults in the reservoir pressure change, since there is a notable difference in pressure change estimates among the four faults.

By using the OVL methodology as a diagnostic tool, we can compare ∆p estimates from the 500 simulation models with the pressure change estimates obtained from the probabilistic 4D seismic. As shown in Figure 6b, there is a huge region in the south of the reservoir where 4D seismic is more precise than simulation, therefore, seismic information can be used and might bring valuable information for the reservoir modelling. In the northwest, there is a predominance of Region 3, that is, seismic and simulation are presenting estimates totally different, therefore this region might be reevaluated. Between faults A and B there are some grid blocks at Region 1, thus, seismic and simulation shows the same tendencies and are significantly adjusted.

5.1.1. QD methodology

Performing the quadratic difference methodology to select the most representative simulation models, we obtained the data illustrated in Figure 7. It is important to highlight that this methodology uses deterministic 4D seismic and the 10% most representative models (50 out of 500 simulation models) were selected. This percentage can change depending of the study carried out. Figure 7a shows the average map of these 50 selected models.

The selection using the QD methodology presented good results. The additional dynamic information from 4D seismic reduced considerably the difference between the ∆p estimates from simulation models (selected models) and the reference value (compare Figure 6a and Figure 7a). Close to wells P5 and I8 the selected models match the expected value and the three critical zones above described presented considerable improvement: into the first and second zones it has observed a reduction from approximately -9 MPa to around -2 MPa (gain of 78%) and into third zone, between the faults C and D, a reduction from 3 MPa to less than 1 MPa.

Observing the 4 Regions Map (Figure 7b) generated with the 50 models selected, it is noticeable an increase in the number of grid block at Region 1, which indicates other improvement. However, the 4 Regions Map still exhibit regions where 4D seismic is more precise, therefore, could still be used. Moreover, several grid blocks at northwest that initially were indicating Region 3(Figure 6b) are now showing Region 2. This situation could happen, but we are
incorporating 4D seismic data and we expect that the regions where seismic is more precise than simulation (Region 4) change more significantly and not the regions where seismic and simulation were previously indicating to have divergent values.

Figure 7: (a) Difference between the mean of the selected ∆p maps using the QD methodology and the reference value.  (b) 4 regions map obtained from OVL methodology (layer 3 out of 9).

5.1.2. OVL methodology

The second methodology, which is based on the OVL methodology, was used to select the simulation models using probabilistic 4D seismic. It is important to distinguish the two roles of the OVL methodology in present work: the first is the diagnostic tool (where the output of OVL methodology, the 4 Regions Map, is used to compare seismic and simulation data) and the second is the models selection tool (bottom of Figure 1).

Figure 8 presents the results obtained from the 10% most representative selected models from OVL methodology. Comparing Figure 8a and 9a, the OVL methodology shown to be more efficient to incorporate seismic data than QD, mainly in the reservoir locations between faults A and B. Both methodologies presented similar values between faults B and C and in drained area of production wells P1, P2, P9, P11. Close to wells P5, P10, I4 and I8, different tendencies were observed: OVL presents values between 0 and -1 MPa, while the QD methodology showed values between 0 and 1 MPa in the same region.

The 4 Regions Map (Figure 8b) highlights more differences between both methodologies. We observe that almost all the blocks classified as Region 4 turned to Region 1. Another interesting feature is that reservoir locations that initially were Region 3 (Figure 6b) remained in the same region, showing a more consistent use of the seismic information than the quadratic difference methodology, since just the regions where 4D seismic could be useful changed significantly, while the others, where seismic indicates no valuable information, did not change.

Figure 8: (a) Difference between the mean of the selected ∆p maps using probabilistic 4D seismic incorporation and the reference value for ∆p, (b) 4 regions map obtained from OVL methodology (layer 3 out of 9).

Figure 9 shows the histograms of the values of transmissibility of the four faults extracted from the simulation models selected by applying both methodologies, QD and OVL. Faults B and C presented similar results for both methodologies. However, the statistical tendencies of the transmissibility of the faults A and D are different. The most probable level according to the OVL methodology is closer to the reference value than the one pointed by the QD methodology. The difference here observed was not so remarkably because no optimization process was performed. We expect a more pronounced difference if both methodologies were performed jointly within an optimization process.
5.2. Saturation analysis

The same analysis of the pressure change was performed to water saturation change; nonetheless, the $\Delta S_w$ analysis was performed locally, since it brings more local information than global. The idea of the local analysis is to try to get information from 4D seismic to better quantify and understand the water front displacement.

Figure 10a shows the reservoir location considered in the present analysis, nearby production wells P2 and P11 and water injector I1. Such location was chosen because there are a considerable difference between the $\Delta S_w$ estimated from the 500 simulation models and the reference value. Moreover, there is no influence of any other injector, than I1, in the water saturation change on this region. Figure 10b presents the difference between the mean of $\Delta S_w$ estimated from the 500 models and the reference value. We can see a discrepancy between the expected water front and the estimated one, with some grid blocks having a difference in saturation greater than 0.3.

5.2.1. QD and OVL methodologies

The selection performed brought better results when the methodologies were applied, as presented by Figure 11. The most pronounced improvement is found in selected models from OVL methodology (Figure 11c), which presented more grid blocks with the difference between estimated and reference close to zero than the selected models from QD methodology (Figure 11a). The black arrows in Figure 11a and Figure 11c highlight the main differences obtained between QD and OVL. In addition, comparing the 4 Regions Map (Figure 11b and Figure 11d), we can notice that OVL used more consistently 4D seismic information (Region 4) than QD, following the same tendency shown in pressure analysis (number of grid blocks in Region 4 after the selection using OVL is lower than QD).

We also compared differences between the porosity and permeability images of the selected models from both methodologies and found some locations where the differences are significant. It is calculated the difference between porosity and permeability from the 50 selected maps from OVL and the 50 selected maps from QD (e.g, for porosity analysis, we calculated $\overline{POR_{OVL}} - \overline{POR_{QD}}$). In order to normalize the results, we divided such difference by the maximum value (among selected maps using OVL and QD) of each parameter studied: porosity, permeability direction I and J and permeability direction k. The values in Figure 12 are shown in percentage and for layer 3. The most pronounced normalized difference was found in images from permeability at direction k, with normalized differences greater than 20% between the selected models from OVL and QD, indicating locations where each methodology showed different tendencies that could results in pronounced differences if an optimization process had been performed.
Figure 10: (a) Local region where the analysis was performed, (b) Mean of the 500 $\Delta S_w$ maps - reference value, (c) 4 Regions Map of the 500 models (layer 3 out of 9).

Figure 11: (a) 50 selected $\Delta S_w$ maps using from QD - reference value of $\Delta S_w$, (b) 4 Regions Map of the 50 selected models using QD, (c) 50 selected $\Delta S_w$ maps using from OVL - reference value of $\Delta S_w$, (b) 4 Regions Map of the 50 selected models using OVL (layer 3 out of 9).

Figure 12: Porosity and permeability maps showing the normalized difference between OVL and QD (layer 3 out of 9).
6. Conclusions

This work presented a comparison of two methodologies that used different 4D seismic information (deterministic and probabilistic) as a constraint to select simulation models.

The methodologies were applied in the selection of the simulation models yielding different results. Regarding $\Delta p$ maps, the selected models using OVL methodology used more efficiently 4D seismic data available than QD, yielding models properly calibrated in regions where seismic is more precise. The $\Delta S_w$ maps were analyzed locally: both methodologies showed valuable improvements to monitor the water front, however, the OVL methodology presented slightly better results.

It is interesting to highlight that QD and OVL methodologies had similar computational cost, even the OVL, which has a bigger data (once the uncertainties are considered). A future work will be conducted to compare the results from both methodologies when they are integrated in a history matching procedure. We expected more remarkable differences between QD and OVL, mainly regarding discretization levels of fault transmissibility and the porosity and permeability values.

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8. References


