4D Seismic Interpretation and Analysis of Quantitative Attributes: Applications on Marlim Revitalization Project

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Abstract

Marlim Revitalization Project (REVIT) aims to extend productive life of Marlim Field. As part of this effort, the project will include drilling new producer wells on pos-salt reservoir (turbidite lobes). In order to assist with the implementation project, various sources of information have been sought, with 4D seismic being singled out as a crucial tool for identify unswept areas and adjust those new well locations.

well locations from 4D seismic is a task that requires integrating information from several work areas such as geophysics, geology, and engineer. In a mature field like Marlim, additional information on wells construction and submarine facilities is also required. These analyses take a considerable amount of time that can impact the schedule of project. To reduce this impact, a proposal has been made to calculate water saturation from 4D seismic to speed up the needed analysis. This estimated attribute has simplified the search for new areas to adjust the originals well location.

Furthermore, the 4D seismic data has revealed a reservoir with a higher complexity than initially anticipated. Although this presents a challenge, it also can open up possibilities for new opportunities.

Introduction

The Marlim reservoir, located in the Marlim field, is comprised by turbidites of excellent permeability and porosity features. Its production began in 1991. In 1997 it was acquired the base vintage for futures 4Ds surveys. In 1994 was started water injection on reservoir and since then it has been pursuit the mass balance between liquid product and injected.

In the next decades, precisely in 2005 and 2010, were acquired two new 4D survey which provided information to several 4D applications on Marlim reservoir, as presented by Oliveira et. al., 2007, for instance. In April 2022 was finished the most recent 4D seismic acquisition on Marlim. Therefore, there are three different time intervals (1997-2005, 2005-2010 and 2010-2022) for 4D analysis, as presented in Figure 1.

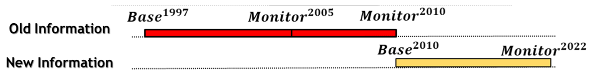

Figure 1 – *Available 4D seismic data on Marlim.*

To initiate 4D interpretation, it was performed a 4D inversion which resulted in a 4D Delta Impedance. This attribute helped us to separate hardening and softening 4D signals from each other. To speed up the analysis, in the first moment, the 4D data was interpreted using the whole-time interval, in other words, the differences observed between 2022 and 1997. Once identified unswept areas in reservoir at this time interval (2022-1997), the other intervals were analyzed to confirm or discard them. Figure 2 shows a schematic illustration of 4D Delta Impedance for each available time interval.

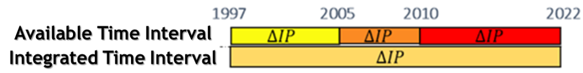

Figure 2 – *Available 4D seismic processing on Marlim.*

Despite this single volume (2022-1997), analyze each separated vintage is still needed, but look for new potential areas become easier, once the first step can be evaluated from a single data instead three.

Last, the analysis of potential areas has been performed by a multidisciplinary team. However, elastic information, extracted from 4D seismic, is not a usual kind of information. Attempt to enhance the communication between work areas was proposed an estimative of water saturation from 4D seismic using Gassmann's equation.

The results achieved have provide enough information to possibility the needed adjust for the well locations with good matching of project's schedule.

Method

Gassmann (1951) elaborated a way to calculate a saturated rock bulk modulus. Gassmann's equation combined with Reus average, Voight average and Batzle and Wang' equations (1992) allow us to obtain a saturated rock bulk modulus with a mixture of fluids.

Figure 3 presents a saturated rock bulk modulus as a function of oil and water saturation levels. To calculate this curve, it was used the average reservoir properties presented in table 1. Fluid properties used to build the curve was calculated by Batzle and Wang, as mentioned.

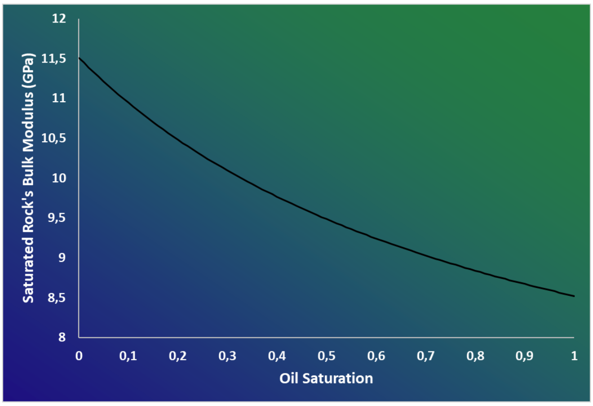

Figure 3 – *Saturated rock's bulk modulus as a function of fluid saturation.*

	Average	Standard Deviation
Dry rock bulk modulus	5.8 GPa	1.5 GPa
Shear Modulus	3.7 GPa	0.5 GPa
Porosity	0.28	0.04
Mineral bulk modulus	33.2 GPa	3 GPas

Table 1 – *Average and Standard Deviation reservoir properties in Marlim reservoir.*

As the saturated rock density can be obtained from a weighted mean; and the shear modulus is not sensible to the fluid, thus it is possible obtain, from saturated rock bulk modulus, the P-impedance as a function of fluid saturation as presented in Figure 4.

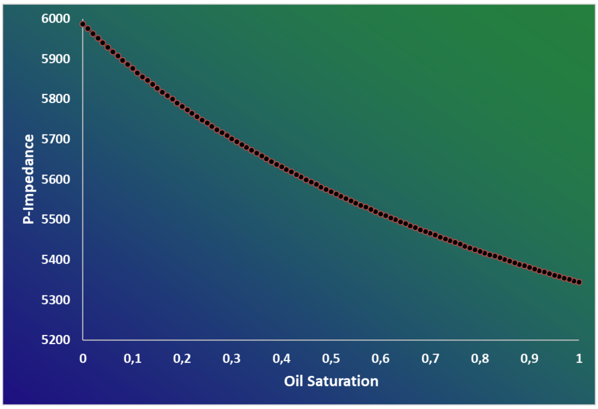

Figure 4 – *P-Impedance as a function of fluid saturation.*

If one point in x-axis (like 15%, for instance) it tokens as the initial water saturation, then it is possible calculate how the impedance varies as a function of water volume variation from that initial point. Besides that, if we swap x-axis for the y-axis, then it is possible to obtain a curve of water saturation variation as a function of P-impedance variation, as presented in Figure 5.

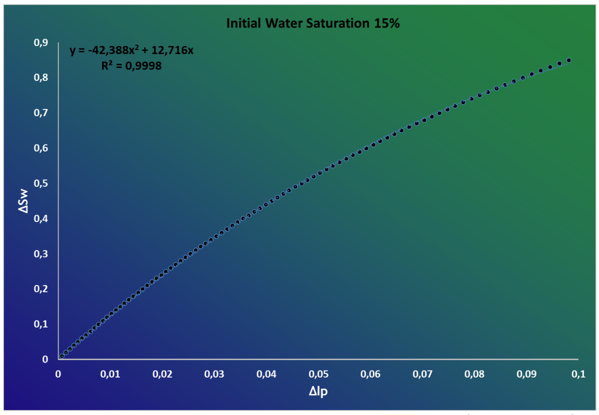

Figure 5 – *Water saturation variation as a function of P-impedance variation.*

As 4D inversion allow us to calculate impedance variation, therefore, we can use the regression presented in Figure 5 to obtain an estimative of 4D water saturation volume.

<u>Assumptions</u>

The curve that adjusts the points presented in Figure 5 represents an inversion function of the simplest petroelastical model that could be built from the average properties. Thus, the water saturation values calculated will be correct only if the simplest model used is adequate to represent the reservoir. In other words, apply this inversion function, to estimate 4D volumetric data, involves some assumptions, once the reservoir has features that vary spatially.

However, as will be seen, despite the values estimated are not perfectly corrected, they could represent valid values and works as a powerful tool to identify unswept areas.

1. *Initial Water Saturation*

As seen in Figure 5, the curve is not linear, implying that a same impedance variation can lead to different estimated saturation values, depends only the initial saturation conditions. Therefore, it is important to have an estimate of the initial saturation level to ensure the best possible confidence to the curve. For sure, the saturations will vary regionally which implies that the result will not be the correct, but how much closer the initial used value is of the real saturation, closer of the correct answer the result will be.

It was considered that the saturation in 1997 and 2005 was 15% and in 2010 was 35%. These values were estimated from the results observed at the flow model and the fluid balance in the reservoir.

2. *Representative Average Properties*

The second assumption considers that there isn't variation in the average values of the petrophysical properties used to build the curve presented in Figure 5. Despite the Marlim reservoir being considered quite homogeneous, some scenarios were elaborated to have a sensitivity of the uncertainties brought by the non-observance of this assumption.

The curve in Figure 5 was used as the base scenario and two other scenarios were built from the average values and standard deviation of the properties (table 1). To do that, we added or subtracted the standard deviation values to the average values. (The new scenarios also considered the relationships, usually observed, between some elastic parameters and porosity).

Figure 6 presents the result of this analysis. As expected, there is, for the same impedance variation, a deviation in the saturation estimates that increases with the intensity of the 4D response. However, it is noticed that the dispersion is not so great; if we take a Delta P-impedance of 6% as an example, it is calculated, in the base scenario, an increase in water of 59%; while if we are closer to the optimistic or pessimistic scenario, we would have a saturation of 55% or 65%, respectively. Despite the width of uncertainty range, it could be obtained a valuable information about the order of water saturation variation magnitude.

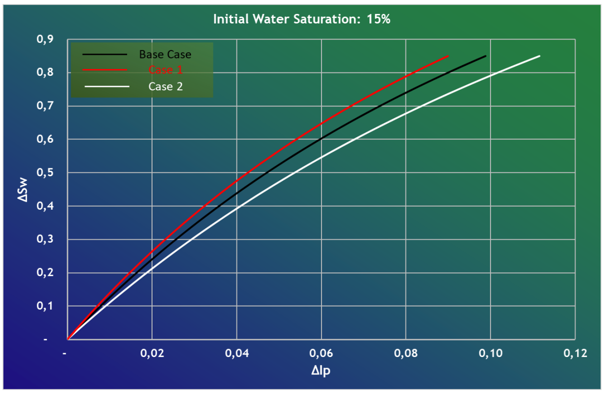

Figure 6 – *Impact of change in properties in the function to estimate saturation.*

3. No Pressure Effects

A very critical assumption is that the anomalies observed in the 4D data are exclusively due to saturation effects. It is known that pressure change influences impedance. Therefore, the application of the function will only be valid in areas where there is no change in pressure.

In Marlim reservoir, the pressure was well controlled through the injection of water into a reservoir with good hydraulic communication. Therefore, only small variations have been observed in Marilm, despite that, these variations will impact the estimative of water saturation, but the results observed indicate small interference.

In reservoirs where the change in pressure is a reality, it is necessary to estimate and remove it to calculate the saturation as proposed in this paper. One possible adjustment is to assume that changes in S-impedance variation will due only to pore pressure changes. Then estimate a regression, like presented for saturation change. From a 4D elastic inversion, we could obtain S-impedance variation and apply the regression function and estimate a pore pressure change.

Once obtained the pore pressure variation, we could model that to obtain the P-impedance effect due to pore pressure change. Now, if we remove P-impedance modeled due to pore pressure from the 4D P-impedance data, we will have a data without pore pressure effect and calculate water saturation changes. This process could be repeated iteratively until the result stabilizes.

Results

As mentioned, all the 4D seismic data together have revealed a reservoir more complex than it used to thought and Figure 7 illustrate that very well. This figure shows some geobodies extracted from the 4D P-impedance data between 2022 and 1997. Still in the figure, we have some arrows pointing out the preferential paths of fluid. We believe that these preferential paths correspond to depositional lobes and, even though Marlim reservoir is homogeneous, they control the fluid flow in the reservoir. In other words, despite the homogeneity, we observe an anisotropy control. This information has proven itself as very useful, because it allows a better understand of reservoir and has potential to reveal unswept areas.

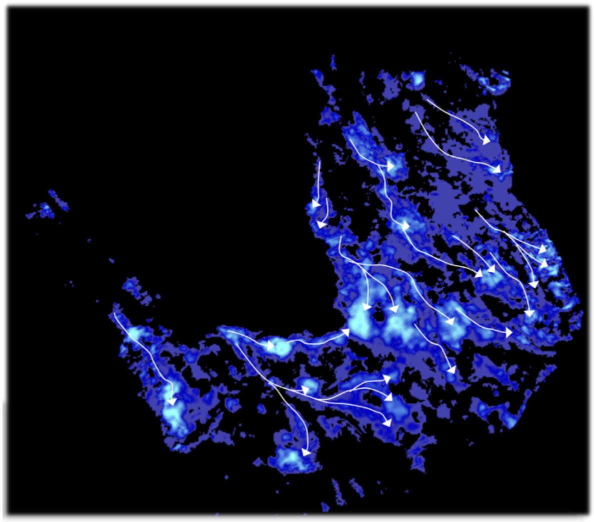

Figure 7 – *Geobodies extracted from 4D impedance data between 2022 and 1997.*

Figure 8 shows a 4D P-impedance map of the period between 2022 and 1997. And, using the methodology already described, the water saturation was estimated from this data, and it is presented in Figure 9. A quick comparison between Figure 8 and 9 allows us to conclude that the calculation operated only a scale conversion between the two properties without lose or create information.

Once it was calculated the water saturation, then, it is possible use it to estimate an oil saturation or even a residual oil map if we combine it with thickness, as presented in Figure 10.

As there isn't an active aquifer in Marlim, it is known that the entire increase in water in the reservoir was due to the difference between injected and produced water which can be measured. To evaluate the results obtained was performed a quality control that compare the water volume estimated from the 4D seismic saturation maps with that one measured. Table 2 shows this comparison.

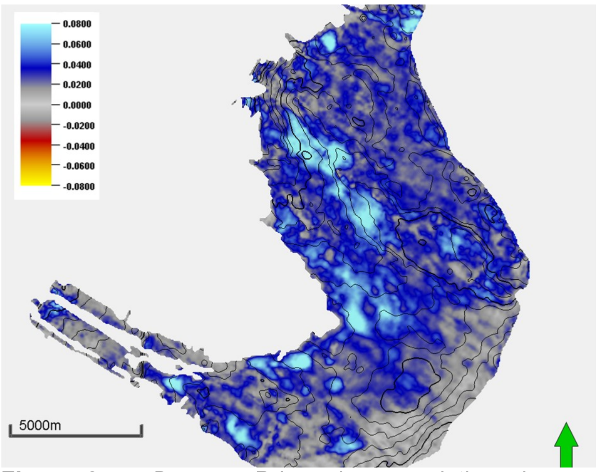

Figure 8 – *4D mean P-Impedance variation observed between 2022 and 1997.*

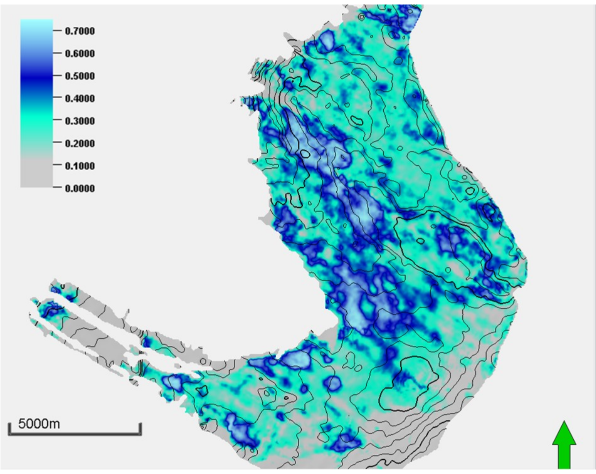

Figure 9 – *Mean water saturation variation estimated from 4D seismic between 2022 and 1997.*

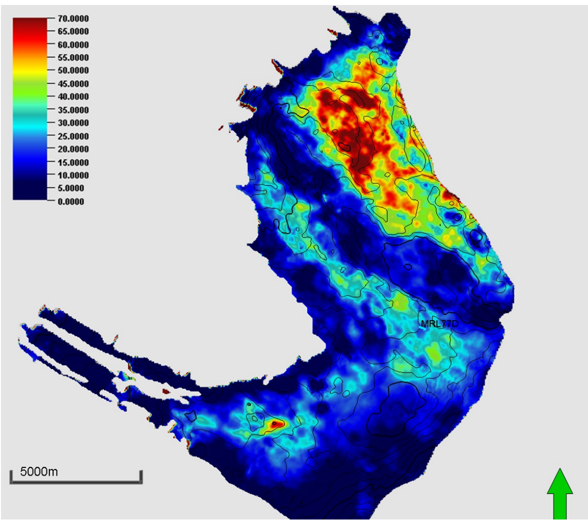

Figure 10 – *Residual oil thickness map from 4D seismic data.*

It can be seen, through Table 2, that the saturation estimative allowed the recovery of water volume values with orders of magnitude very similar to those measured. This result adds robustness to the saturation estimative, because, despite the assumptions, it was still possible to obtain values with the same order of magnitude as which was measured.

Even though the measured data is a hard kind of data, we have an uncertainty about the date that should be chose to get the measurement, because 4D seismic acquisition used to take a couple of months to be conclude, which makes comparison difficult. However, the last line in table 2 correspond to the sum of the other lines and looks like when we take account the whole time the differences are reduced.

	4D Seismic	Measured Data
2005-1997	219 MM m³	242 MM m³
2010-2005	114 MM m³	96 MM m³
2022-2010	144 MM m³	124 MM m³
2022-1997	477 MM m³	462 MM m³

Table 2 – Comparison between water volume estimated by 4D seismic and Measured Data.

In 2021 and 2022, some old wells were logged again, and it could be estimated new values of water saturation along these wells. Water saturation, in these wells, were compared with that one estimated from 4D seismic as shown in Figure 10. The penultimate track, of each well, in Figure 11, shows the measured residual oil (green) and water (purple) saturation curves; in the same track, dashed line shows the estimated water saturation from 4D seismic. It can be noticed that, despite the difference in resolution, the estimated saturation was able to capture the sweeps observed in the logs, which brought more security to the methodology applied and to the 4D seismic itself.

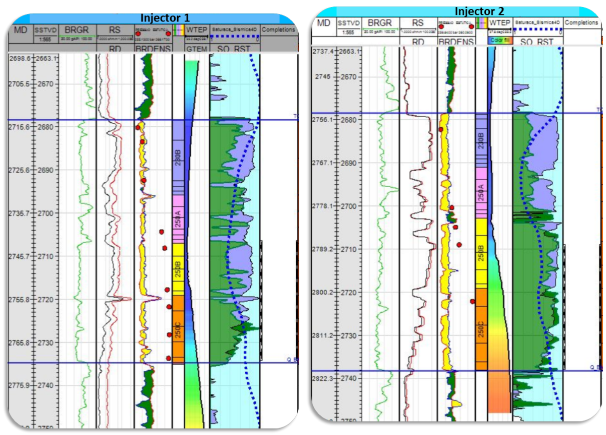

Figure 11 – *Logs of Injectors 1 and 2. 1º track presents Gamma Ray; 2º track: resistivity; 3º track: density and neutron porosity; 4º track: layering; 5º track temperature; 6º track oil saturation (green), water moved (purple), original water (cyan) and estimated water saturation from*

4D (dashed blue line); and 7° track presents the completion zone.

Both the measured and estimated water saturation in Figure 11 show an increase in water saturation at the top of the reservoir, different from completion zone (last track). By some mistake, the injection took place purely at the top, as in Injector 2, or also at the top, as in the Injector 1. The temperature log (5th track) also suggests injection in these positions.

Figure 12 presents a map of mean estimated water saturation from 4D (2020-1997) between top and base of reservoir. Still in this figure, there are 3 locations initially proposed to REVIT (Producer 1, Producer 2 and Producer 3); the map also shows the Injectors 1 and 2. Due to the proximity of these locations to the injectors, adjustments were needed in the 3 locations, because when we adjust the injection to the right observed depth in the flow model, the location curves were severely impacted.

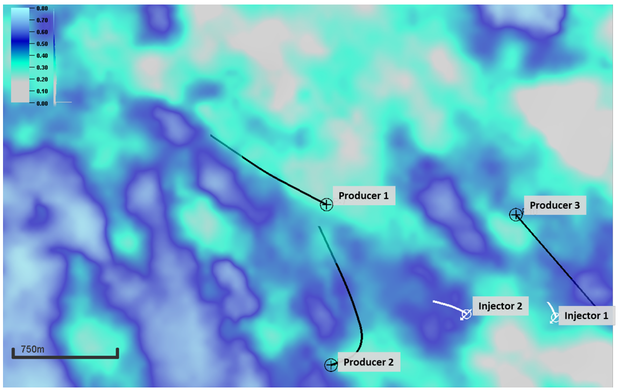

Figure 12 – *Map of mean estimated water saturation from 4D between 2022 and 1997, highlighting the proposed producers and the old injectors.*

As these proposed producers needed to be reviewed, thus, to increase the robustness in the analysis, other attributes were generated from the water saturation, such as oil saturation and residual oil thickness map (that correspond to the product between oil saturation and thickness). Figure 13 shows the residual oil thickness map with the replacement of producers 1 and 2.

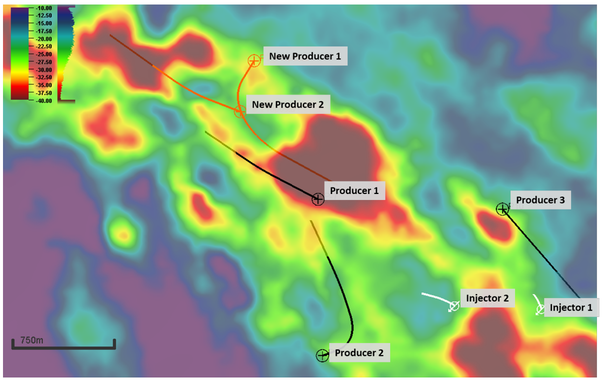

Figure 13 – Residual o*il thickness suggesting unsweept areas.*

We can see that the residual oil thickness map could indicate unswept areas that could be confirmed by the analysis of the complete 4D data set combined with geological and engineer data.

Figure 14 brings a section along the two proposed trajectories for producers 1 and 2. Due to the proximity of the new producer 1 with the injectors 1 and 2, we need navigate the well between two intervals with water (above and below).

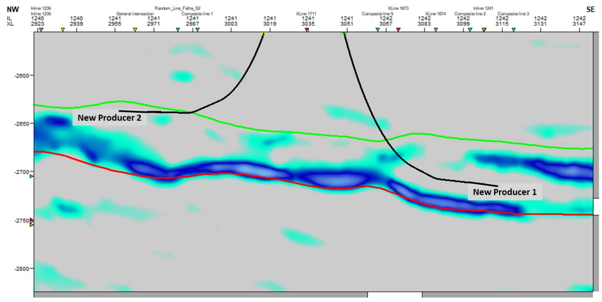

Figure 14 – *Section of 4D data across the new proposed producers 1 and 2.*

Conclusions

In Marlim, 4D seismic data has provided a better understanding of the reservoir through, for example, the identification of preferential paths. They represent important anisotropy information that reveal some complexity in geological aspects for the reservoir. Therefolre, those path reveals information that can contribute to build more robust model and, also, could reveal unswept areas.

The methodology to estimate water saturation, despite its assumptions, has shown consistent results with observed data (measurement and logs). This suggests that, although there are uncertainties, the applied baseline scenario reasonably respects the assumptions for Marlim reservoir.

The attributes obtained from estimated water saturation, like residual oil thickness, have been proved as very useful tools to identify and better boundary potential areas for location adjustments and with the potential to suggest opportunities. It must be emphasized, however, due to assumption assumed, that these attributes are useful tools, but do not replace the analysis of the original 4D seismic data (amplitude and impedance), the 3D data, the conceptual model, logs, and production data.

To resume, the 4D seismic data, and all attributes associated to it, has been proved itself, along the lifetime Marlim reservoir, as an important tool for understand reservoir and searching for, reviewing, and optimizing locations. Thus, bringing robustness and speed to revisions of well locations in Marlim revitalization project.

Acknowledgments

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