Permanent Reservoir Monitoring - 4D Quantitative Interpretation

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Abstract

In late 2012, Petrobras and PGS installed the first deep-water optical permanent reservoir monitoring (PRM) system (Thedy 2013 and Dariva 2016) over a pilot area of the Jubarte oilfield. The primary objective of the installation was to validate the fiber-optic sensing technology to detect very subtle (less than 2%) 4D elastic attribute changes in the post-salt reservoir. The goal was achieved. The high quality 3D/4D images provided by the permanent system enabled improvement in the understanding of flow patterns and allowed updating of the geological model.

Introduction

The Jubarte Field, discovered in 2001, is located 70km offshore Espírito Santo in a water depth of 1,300m in the northern Campos Basin, Brazil. The post-salt reservoir comprises of Upper Maastrichtian turbidite facies where the arenite has moderate to poor consolidation.

Given the usual turbidite complexity / heterogeneity and chaotic stacking of reservoir and non reservoir intervals, it was crucial to use a very sensitive seismic system such as PRM. Its high repeatability allowed acquiring the base survey and subsequent monitoring with the ability to record subtle production related changes.

Basic characteristics of the PRM system

The pilot fiberoptic 4-component (4C) PRM array comprises of 11 receiver-lines separated by 300 m (9 sq. km in total (Figure 1)) at 1.3 km water depth. There are 712 4C optical sensor stations positioned every 50 m along the cable, totaling 2,848 channels of accelerometer and hydrophone data. As demonstrated on the Figure 2 the PRM system provides an excelent repeatability with the NRMS below 3%, where

$$\mathrm{NRMS} = 2\mathrm{x}\mathrm{RMS}_{\mathrm{monitor\text{-}base}} / (\mathrm{RMS}_{\mathrm{monitor2}}+\mathrm{RMS}_{\mathrm{base}})$$

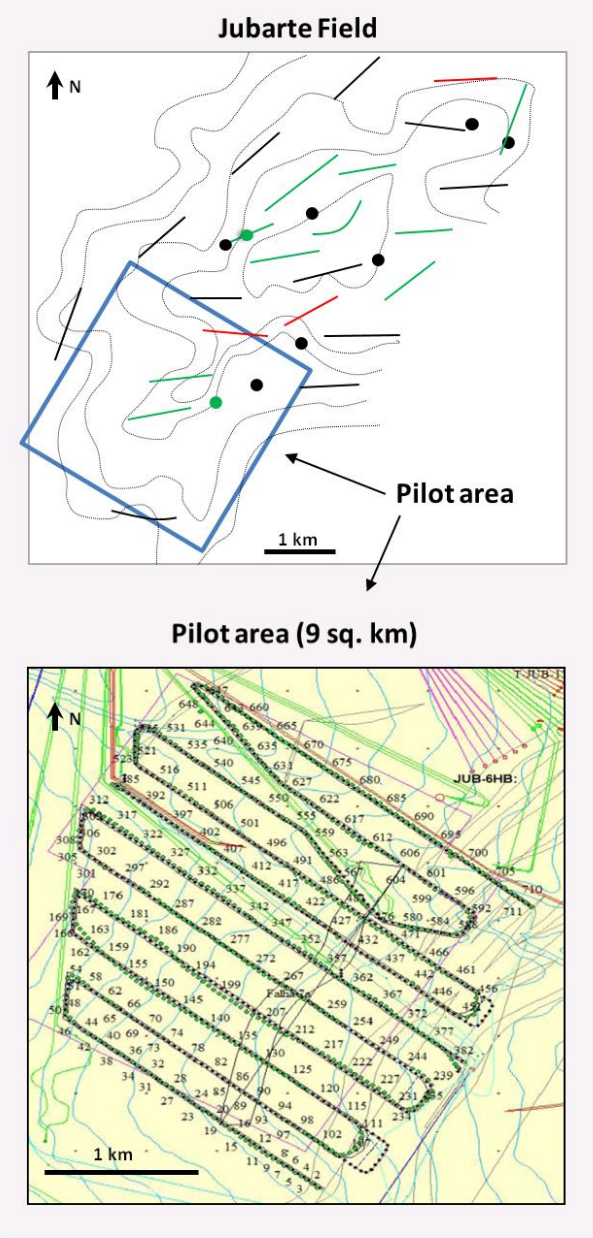


***Figure 1** Jubarte PRM schematic layout. The picture above is a schematic :structural map for Jubarte field. The PRM was installed in the southeast portion of the field, in a water depth of 1.300m.*

These subsea cables are connected to the P-57 FPSO through a dedicated optical umbilical riser to a 4D room which controls and records the optical system.

After the validation of the PRM system, Petrobras and PGS tested and validated a new reservoir characterization technique - 4D Bayesian Inversion (4D BI) using the PRM seismic data. This Bayesian method allowed for further understanding of key reservoir parameters such as saturation, NTG, porosity, pressure and, importantly, provided an estimate of their uncertainties.

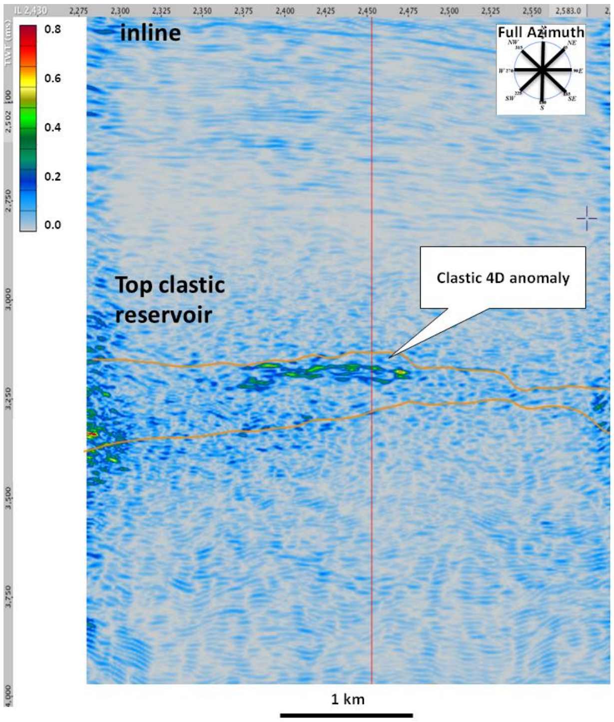


Figure 2 Repeatability between the base and monitor 2 vintages – NRMS attribute.

Brief summary on 4D Bayesian Inversion

A more in-depth theory of the method is described by Gunning and Glinsky (2004). Only a generalized overview of the method is provided in this paper.

The 4D BI is a trace by trace stratigraphic layered, multi-vintage, pre-stack Bayesian simultaneous seismic inversion engine. The initial knowledge (or prior) consists of expected elastic properties of the reservoir in the form of depth dependent rock physics trends and their respective standard deviations. The statistical depth dependent rock physics model is obtained by interpreting end-member lithologies from well log data which record the respective elastic properties and their statistics. The priors need to be, as much as possible, validated by the core sample measurements at the target depth with saturation and pressure information in order to establish a 4D rock physics model template.

Based on the priors, thousands of reflectivity traces / simultaneous MCMC realizations (P & S) are created per XY location per vintage at each target depth. The simulated traces have the absolute properties of the matrix as a stationary part and fluid properties, pressure scenarios etc. as dynamic parts.

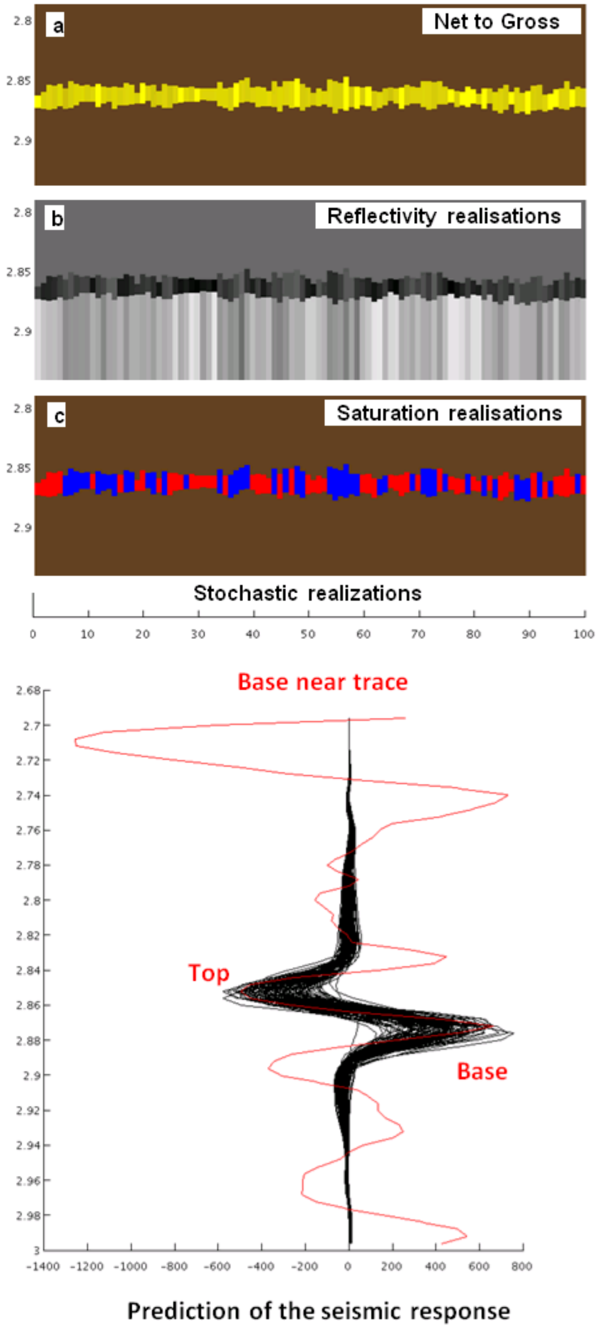
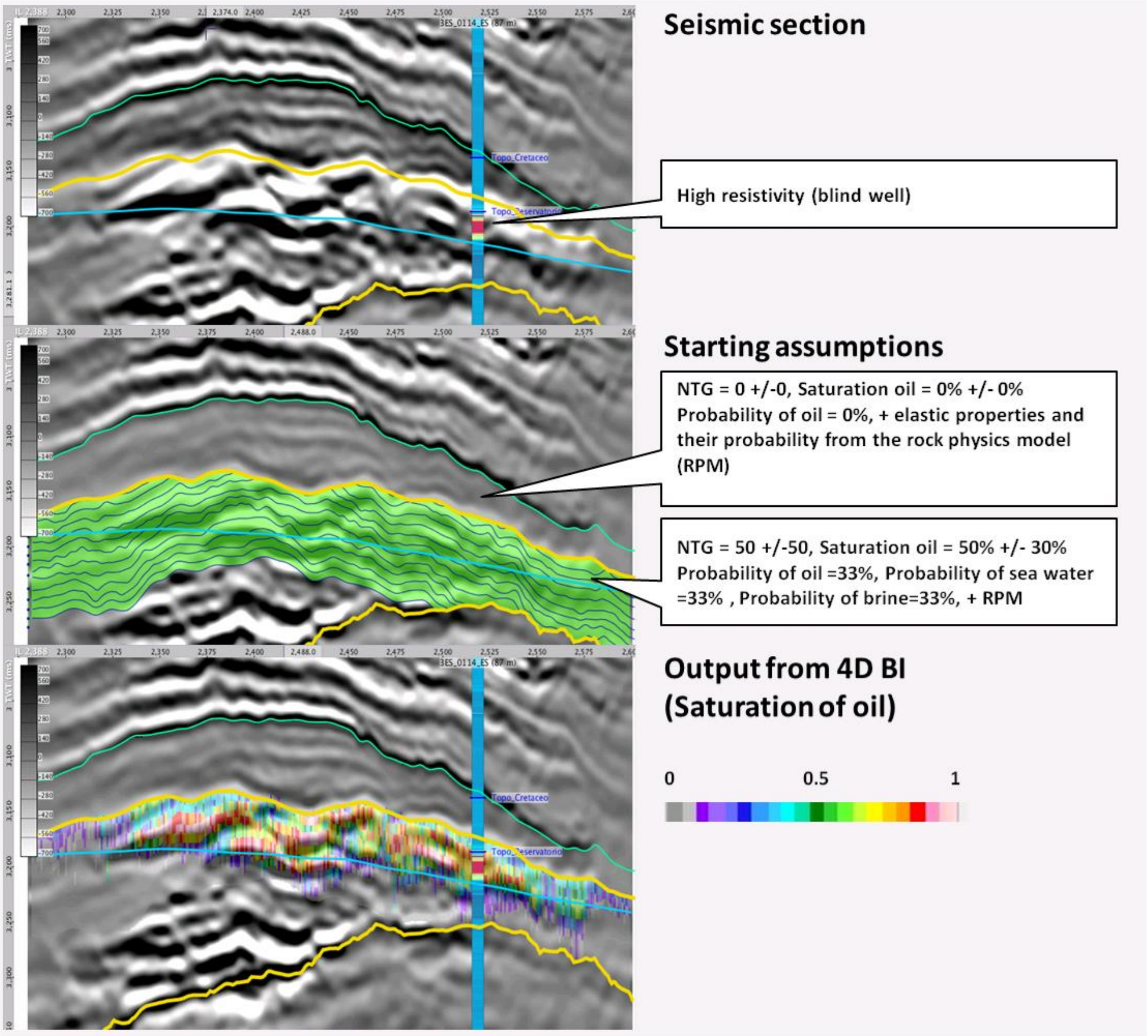


Figure 3 1D TWT test of the 4D Bayesian Inversion: a) and c) are NTG and Sw realizations respectively, b) reflectivity realizations; figure below is the synthetic response (black traces) overlaid with the recorded Base seismic (red trace).

These reflectivity traces are then convolved with wavelets generated through a multi-well Bayesian wavelet extraction, (Gunning and Glinsky 2006) corresponding to each angle-stack and vintage. The resulting synthetic response is then compared to its respective vintage. The aim is to find a group of traces that best fits the seismic and production induced changes in it. This group of synthetic traces has a record of the properties used to generate them allowing therefore, not only the estimation of the absolute reservoir properties, but also their respective uncertainties. A near stack 1D example is shown in Figure 3 corresponding to a 100 realizations. The lower picture shows the original seismic trace in red and the 4D BI realizations in black. The modelled traces are based on the reflectivity realizations (top - picture b) which in turn are dependent on other properties e.g. NTG and Sw (pictures a & c). Uncertainties are captured by multiple stochastic models using Markov Chain Monte Carlo methods. The program output includes the Mean, P10, P50, P90 and STD of the thickness, NTG, Porosity, Density, Net Saturation, Pressure etc. of the group of synthetic traces that match the measured data.

Practical implementation of the 4D BI

The following results are based on joint inversion of all three vintages and correspond to the post salt reservoir. Figure 4 below shows results of the 4D BI along a key line going through the reservoir's oil bearing zone. The top section represents one of the three input seismic vintages (Base, Far). The initial assumption was set as follows: for the seal (probability of finding oil was set to 0%,



Seismic section

High resistivity (blind well)

Starting assumptions

NTG = 0 +/-0, Saturation oil = 0% +/- 0%
Probability of oil = 0%, + elastic properties and their probability from the rock physics model (RPM)

NTG = 50 +/-50, Saturation oil = 50% +/- 30%
Probability of oil =33%, Probability of sea water =33% , Probability of brine=33%, + RPM

Output from 4D BI (Saturation of oil)

Figure 4 Seismic section (Base) is shown on top. The following picture is a starting assumption for the seal (probability of finding oil 0%, saturation of oil 0%, NTG 0%) and reservoir (probability of finding oil 33%, brine 33%, sea water 33%, saturation of oil 50 +/-30%, NTG 50 +/-50%). The picture at the bottom is a posterior mean for the Base's predicted saturation of oil.

saturation of oil to 0%, NTG to 0%) and for the reservoir interval (probability of finding oil 33%, brine 33%, sea water 33%, saturation of oil 50% +/-30%, NTG 50% +/-50%). The 4D BI was able to predict the oil saturation consistent with the known OWC given the contact was not added as an initial constraint of the 4D BI. Also the HC prediction matches the blind well's resistivity log where red color means a very high resistivity associated with presence of oil

Simultaneous pre-stack 4D BI (Base and 2 Monitors) over the entire pilot area (~9 sq. km) provided an essential statistical set (Mean, P10, P50, P90 and STD) of the reservoir parameters both in TWT and Depth. The output included Thickness, Net-to-Gross, Porosity, Oil Saturations, delta pressure, net oil, delta net oil and etc. The obtained reservoir properties were conformable with the existing well data and knowledge of the reservoir behavior between the base and the monitors. Each predicted reservoir property had probability and uncertainty estimates (Figure 5) in the form of 3D layers and volumes.

Changes in net oil between the Base and M2 surveys can be seen on the Figure 6. It shows the delta net oil between the base and the monitor 1 (left hand-side image) and the same for the base minus monitor 2 on the right hand side, both obtained with the 4D BI without any simulator input. The injector wells are displayed in cyan.

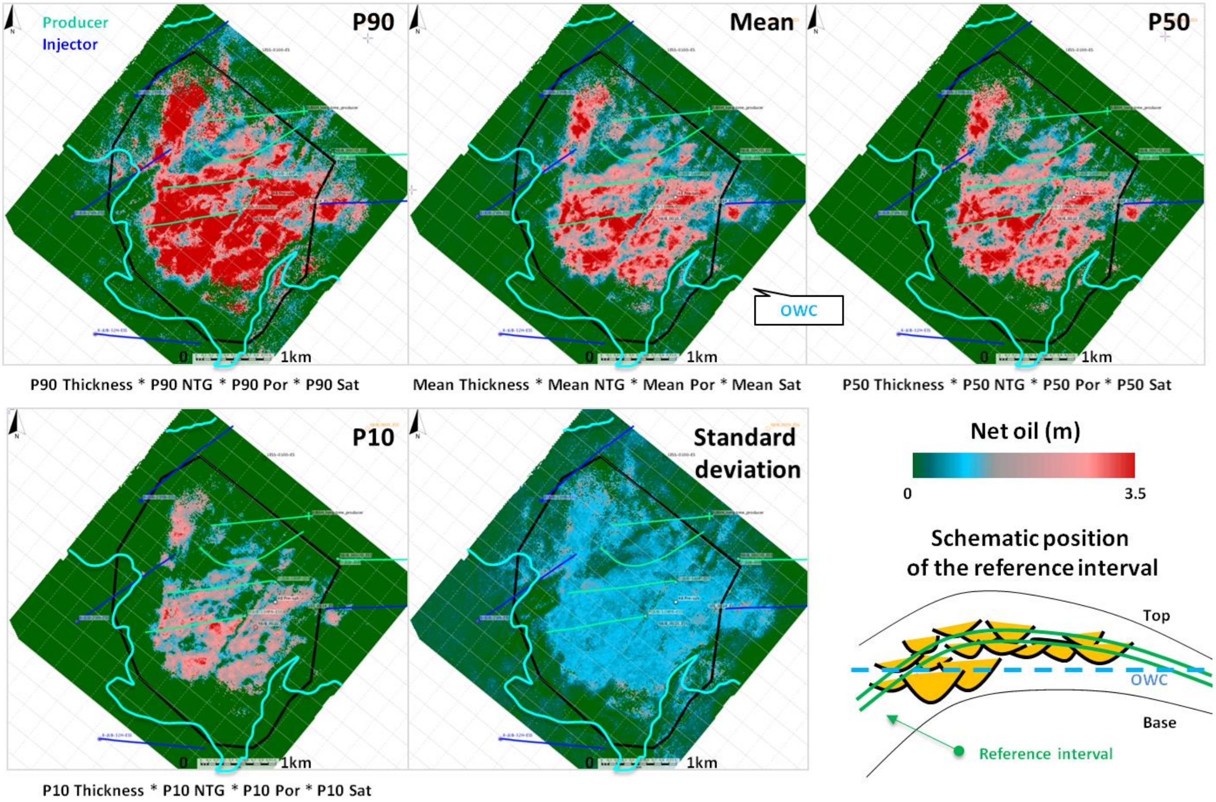


Figure 5 4D BI output of the Monitor 1 net oil probabilities and standard deviation. The reference surface is mid reservoir.

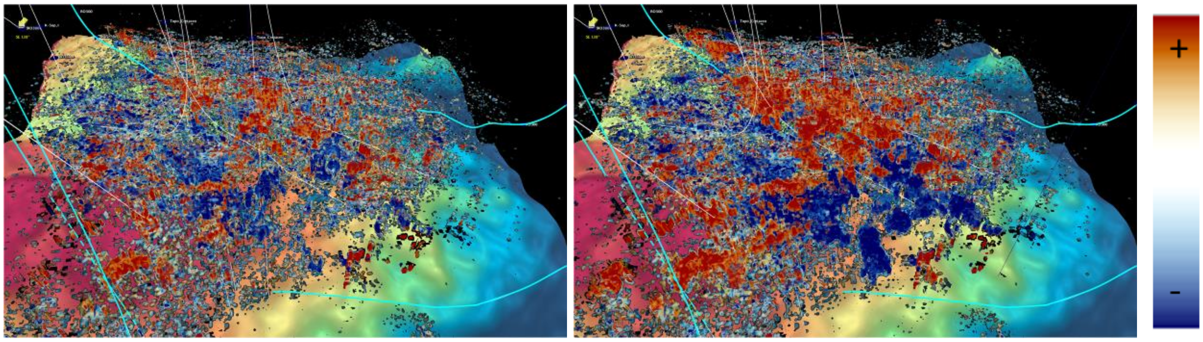
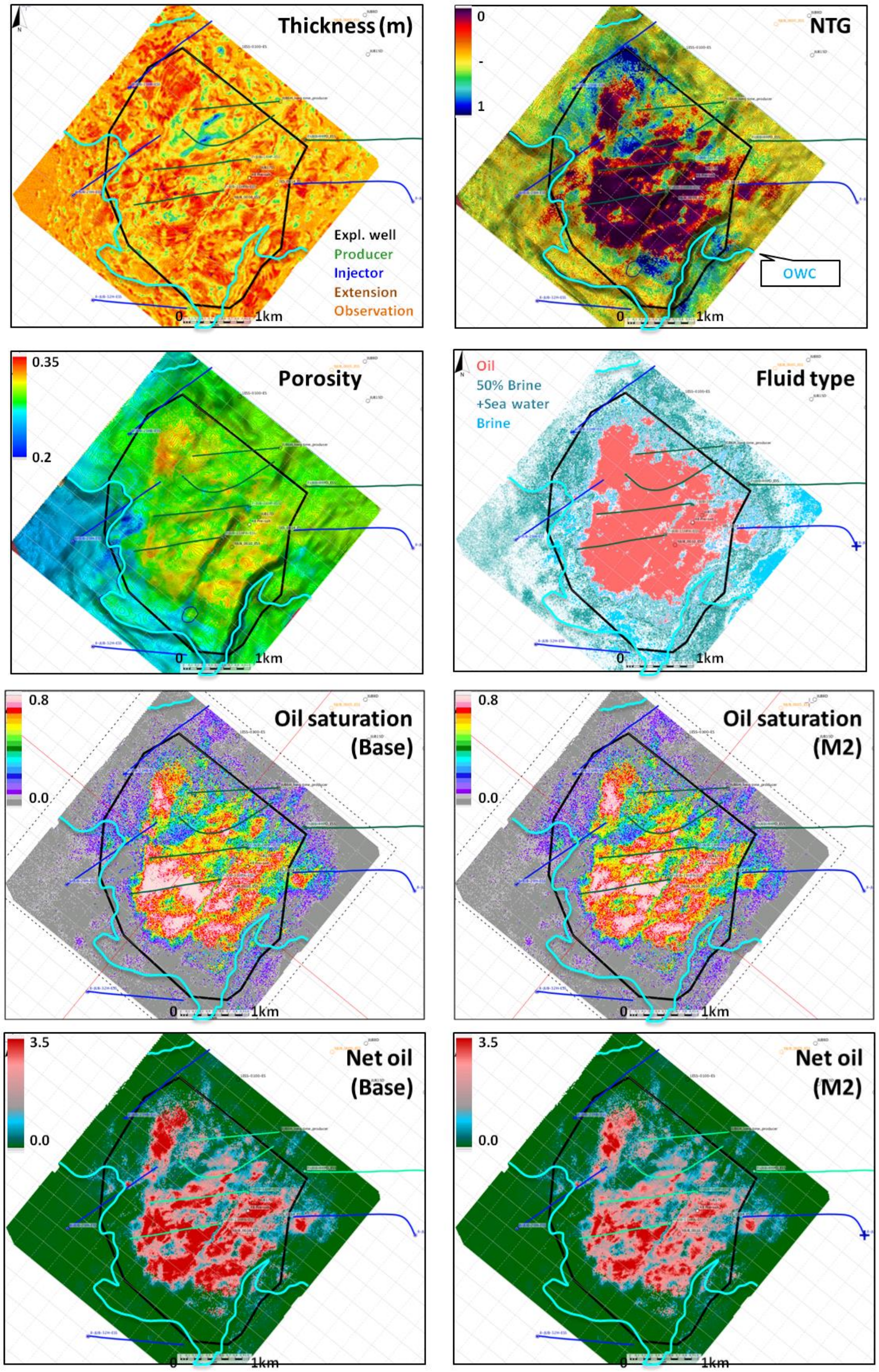


Figure 6: Delta net oil over the pilot area for the period 2015 and 2012. Dark blue color indicates a decrease of net oil between the 3 surveys (M1-Base (left), M2-Base (right)) matching the water front created by the injector wells. The increase in the net oil is shown with red color. The horizon shown on both images is the base reservoir.

Dark blue color drape indicates a decrease of net oil between the 3 surveys matching the injection and production strategy. The red color drape indicates an increase in the net oil due to the induced oil displacement.

Figure 7 shows a few of the many predicted properties of the reservoir interval. This information, as well as variation estimates between surveys, can be very useful for updating reservoir models, or computing important economic parameters e.g. the total oil in place (STOIIP).



+ P10, P50, P90 and Standard deviation volumes for each attribute

Figure 7 Results of the 4D Bayesian Inversion include lots of reservoir properties, some key ones are shown on this figure: thickness, NTG, porosity, fluid type, oil saturation (Base and Mon2), net oil (Base and Mon2). The reference interval is ≈mid reservoir.

Thus with this workflow, it was possible to identify different production and injection effects allowing the Jubarte team to improve understanding of the water front and reservoir connectivity in the post-salt interval. Given the heterogeneity of the turbidite reservoir and the production scenario, it was very critical to ensure high quality, high signal-to-noise ratio (S/N), high repeatability data was input into the 4D BI process. The PRM system most certainly met this requirement.

Conclusions

All three vintages of seismic (base, monitor 1 and 2) were processed by PGS, with close participation of the Jubarte asset team. The resulting 4D seismic difference showed excellent results with NRMS below 3%. The observed 4D anomalies were due to production/injection effects (Dariva 2016). More 4D BI results will be shown from the Jubarte and other fields in the future. In the present case the 4D Bayesian Inversion is demonstrated to be a useful reservoir management tool. It allows a stronger link to be built between the subsurface disciplines of geology, geophysics and reservoir engineering and can deliver essential information for the production life of a field. It has the potential to provide more detailed results in the areas with limited well control and ensures the result will be consistent with the previous reservoir knowledge. In addition the given resulting estimate of the Mean, P10, P50, P90 and standard deviation volumes can be useful for the subsequent estimation of the remaining hydrocarbon and economic uncertainties. The 4D BI workflow and technology should prove useful to reservoir engineers working with the problem of 4D seismic data integration.

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References

Gunning, J. and E. Glinsky, M. [2004] Delivery: an open–source model–based Bayesian seismic inversion program, - USA. Computers & Geosciences 30 (2004).

Gunning, J. and E. Glinsky, M. [2006] Bayesian seismic wavelet extraction Computers & Geosciences (2006).

Balabekov, Y., da Silva, E., Coelho, F., Sebastio, M., Reiser, C., Johann, P., [2016] Validating of the 4D Bayesian Rock Physical Inversion in the clastic settings, Campos Basin, Brazil., *Rio Oil & Gas Expo and Conference 2016*

Dariva, P., Ramos Filho, W.L., Born, C.C., Falcone, C.M.O., Zorzanelli, I.B. [2016]. Monitoramento Sísmico 4D no Campo de Jubarte, Bacia de Campos – Brasil. *Anais do 48^{o} Congresso Brasileiro de Geologia.*

Thedy, E.A, Ramos Filho, W.L., Johann, P.R.S., Seth, S.N., Souza, S.C., Murray, P.E. [2013]. Jubarte Permanent Reservoir Monitoring – Installation and First Results. *13th International Geophysical Society, de Janeiro, Brazil*