Practical example of data integration in a PRM environment, BC-10, Brazil

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Introduction

Deepwater developments always represent a huge capital investment, and this is especially true when the field in question is instrumented with Permanent Reservoir Monitoring (PRM). These massive financial outlays demand optimum efficiency to maximize the return on investment. This means taking full advantage of the value in the large volumes of time-lapse seismic data collected. In this paper, we examine enhanced workflows and solutions for optimizing the utility of Permanent Reservoir Monitoring data in a deepwater setting. We do this by fully integrating these data into our subsurface models and decision making in a rapid, thorough, and quantitative fashion.

Parque das Conchas (BC-10) represents a major milestone in the development and commercialization of Brazil's deep water. The project consists of several distinct small-to-medium-sized fields in the Campos Basin that allow for phasing. The fields have been developed using subsea wells and manifolds, all of which are connected to a centrally located floating production, storage and off-loading (FPSO) vessel, the *Espírito Santo* (Figure 1). The *Espírito Santo* FPSO, which has a processing capacity of 100,000 barrels of oil equivalent per day (BOE/d), was built by SBM in Singapore and delivered to Brazil in late 2008 being moored in around 1800 m of

water. The double-hulled FPSO's design required significant power and heat delivery systems to drive the seabed lift equipment and process the heavy crudes. This development is the first of its kind based on full subsea oil and gas separation and subsea pumping. This system uses 1500-horsepower underwater pumps – each equivalent to a Formula One engine – to drive oil and a small quantity of gas to the surface.

Phased development

The first phase of the Parque das Conchas project included the development of three fields (Abalone, Ostra and Argonauta B-West) connected to the FPSO via subsea wells and manifolds (Figure 1). The development wells were drilled by Global Santa Fe's Arctic 1 drilling rig, and the fields came on stream in July 2009. This first phase involved nine producing wells and one gas injector well. By July 2013 the project had produced more than 70 million BOE.

Phase two of the project, to tie-in the Argonauta O-North field, came on stream in October 2013. In phase two an additional 11 wells were drilled (including water injection), as well as adding subsea boosting equipment and brownfield topsides upgrades on the FPSO. The estimated peak production is 35,000 BOE/d. A Permanent Reservoir Monitoring (PRM) system was installed during this phase of the project, and it is this field and PRM which are the primary focus of the present work.

Phase three came on stream in March 2016. It comprises five producing wells in two fields (Massa and O-South), and two water injection wells in Massa. The fields are tied back to the FPSO. Daily production of the phase three wells is expected to total up to 20,000 barrels of oil equivalent per day at peak annual production. The success of this phased development is attributed to rigorous standardization, rapidly applied learnings, and strategic deployment of new technologies (LeBlanc et al., 2015).

Permanent Reservoir Monitoring

The Argonauta O-North field is located approximately 120 km (75 miles) southeast of the coastal city of Vitoria, in the state of Espírito Santo, Brazil (Figure 2) where water depths range from 1600 to 1700 m (4920-5272 ft). Phase two field development at BC-10 – which included Argonauta O-North – started in 2013, and water injection commenced late February 2014. The PRM system was put in place shortly after production start-up in the

Figure 1 Schematic of the Parque das Conchas (BC-10) infrastructure showing the three phases of development and tie-back to the centrally located floating production, storage and offloading (FPSO) vessel, the *Espírito Santo.*

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Figure 2 Location of the BC-10 development (left). Detailed map shows the layout of LoFS array (right) and the locations of 11 horizontal wells including 7 producers (red) and 4 injectors (blue) around Argonauta O-North field within BC-10.

Figure 3 A schematic montage, illustrating the diversity and complexity of the Data Integration Challenge.

second quarter of 2013. Ocean bottom cable technology was used for this field to monitor water flood and the general movement of injected and produced fluids. Overburden integrity monitoring via time-lapse seismic was also an objective (Farmer et al., 2013). At the time of the installation, this was the deepest deployment of PRM technology anywhere in the world (1600-1700 m water depth) with trenching of the cables into the seabed deemed unnecessary owing to the extreme depth. The Life of Field Seismic (LoFS) monitoring system is composed of 99 km of ocean-bottom cables (OBC) in 14 lines spaced 400 m cross-line, and 986 four-component sensors spaced 100 m in-line (Buksh et al., 2015).

The sensor cables are connected via 11 km of backbone to an umbilical termination assembly which supplies power to the sub-sea LoFS system. The whole system is linked back to computers and storage on the FPSO, and can be operated from

the FPSO, or from Houston via satellite link. During the surveys, source points are 50 m in-line and 50 m cross-line, provided by a low-cost fit-for-purpose seismic vessel (Farmer et al., 2015). The nominal shooting area to monitor the field is approximately 135 km^2 (Chen et al., 2015).

The Argonauta-O North field produces from stratigraphically and structurally trapped unconsolidated turbidite sands about 1250 m below mudline. The prevailing geology makes this an ideal candidate for 4D seismic monitoring. *A priori* fluid substitution modelling shows the likelihood of a strong acoustic impedance reduction caused by gas breakout, and potentially some softening where aquifer waters are replaced by injected water. Conversely, a robust 3-5% acoustic impedance increase (hardening signature) was predicted where injection and aquifer water displaces oil.

With the PRM system installed, four seismic surveys have been acquired providing high-quality time-lapse observations for reservoir surveillance. The base survey was completed in November 2013, shortly after start of production, but before injection started; and the first monitor survey was obtained during June 2014, only three months after first water injection. Even after only three months, clear 4D signals were visible, underlining the suitability of PRM in this environment. The second monitor survey was acquired in February 2015 and the third monitor survey was acquired in 2016.

Shell's Upstream Americas Geophysics – Marine Imaging Team provides complete processing services for the BC10 LoFS data; this includes all processing from reformatting the raw SEG-D field data through final 4D volumes. Optimizations of the processing workflow have allowed for fast-track volumes within an impressive seven days of the cessation of acquisition for these surveys. The processing flow developed and applied to the LoFS data has proven to be very effective and has resulted in NRMSD values at reservoir level of 5% for the down-going wavefield per the description of 4D attributes by Stammeijer and Hatchell (2014). With these high-quality repeat monitor surveys, and rapidly delivered interpretable products, comes the significant challenge of abundant and frequent data requiring integration to leverage the broader interpretation.

Data integration challenge

Fields with PRM are still relatively uncommon, especially in deep-water settings, even though the value of these data for reservoir surveillance is well-proven. Galarraga et al. (2015) detailed the first results from PRM at BC-10, and the considerable value added by time-lapse seismic data. Naturally, one of the challenges

of PRM is how to smoothly and repeatedly accommodate and interpret the large volumes of incoming monitor data: Figure 3 shows a montage of the diverse and detailed types of subsurface data requiring integration. This could include point data (e.g. pressure measurements, production data), line data (e.g. well logs, streamlines, tracers), horizon data (e.g. interpretations, attributes, bathymetry) and volumetric data (e.g. seismic volumes, dynamic flow models).

Moreover, many of these datasets are collected repeatedly through time, hence they have a dynamic component that also needs integration. Newer technologies such as continuous data streams from optical well log data (DAS/DTS), passive seismic monitoring, and surface deformation monitoring via InSAR, tilt meters, or bathymetric pressure sensors bring new urgency to the requirements for temporal data integration. Pressure Inverted Echo Sounder (PIES) instruments were deployed at BC-10. Although primarily used for water velocity and tidal depth data for deepwater statics in processing, PIES also offer potential insights into overburden integrity and geomechanics that need to be considered in a broader environmental context. Robust quantitative integration is a challenge for analysis of newly acquired time-lapse seismic data (for example for seismic assisted history matching, water flood monitoring, etc.) as well as for feasibility studies (i.e. a forward-modelling of the expected 4D seismic response to determine when the most value can be gained from acquiring a new monitor survey). Overall it is widely appreciated that the true value of 4D seismic data comes when the data are fully integrated and analysed alongside all other available subsurface data – well data and logs, completion locations, fluid rates, static geologic models, dynamic flow models, and so on (Calvert, 2005).

Data integration solution

Presented here, we discuss a solution for integrating all available reservoir data in a single interactive platform, thus allowing multi-disciplinary team members the benefit of rapid access to relevant datasets. Such an environment encourages the different geoscience and engineering disciplines to challenge or confirm each other's ideas, assumptions, and conclusions through direct qualitative and quantitative comparisons. This quickly generates the highest possible value from the 4D seismic data, and hence the best reservoir surveillance decisions. The integration of all available data and models can have a direct impact on infill drilling, wells reservoir facility management (WRFM), future seismic activities, and overall cost reduction and revenue maximization.

Figure 4 illustrates the diverse data types commonly integrated in this system. In onshore situations, well data are typically more plentiful, and surface infrastructure and lease positions can be a key constraint requiring careful spatial consideration. This contrasts with offshore fields where seismic data are often more abundant, including the possibility of 4D seismic data. In any event, during the development of this tool considerable effort has been expended on minimizing the barriers-to-entry, both in terms of data import and ease-of-use. Where possible, loading data into the tool has been made as easy as drag-and-drop, with the minimum of data reformatting. Usage is streamlined
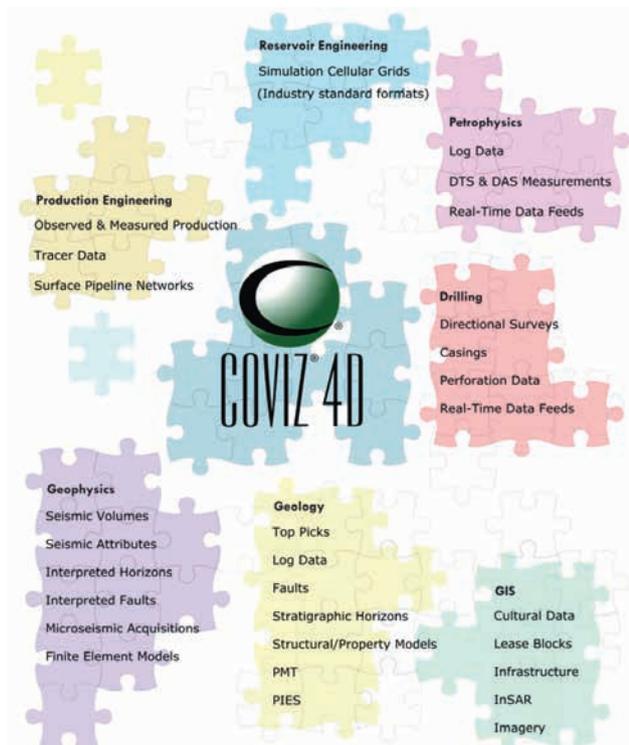

Figure 4 An overview of the types and variety of data incorporated in the data integration workflow.

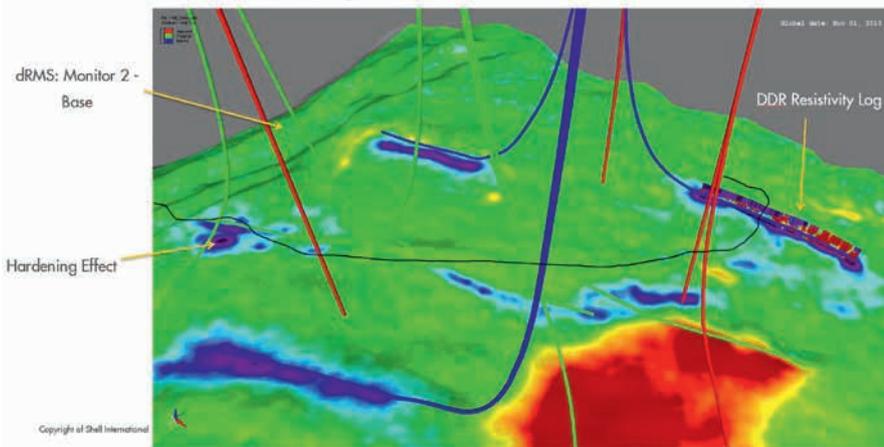## Static Model and 4D Integration

Figure 5 A deep resistivity image log (DDR6) was acquired for Injector 1 (blue) while geosteering the well; the image log is indicative of sand content (net-to-gross). The hardening signal associated with the injector well (blue/purple colours in the seismic attribute) indicates that the 4D anomaly is well distributed along a high net-to-gross sand present throughout the well. Note also the lesser hardening signals around the producing wells (green) as formation water replaces oil. The large red anomaly in the 4D seismic signature is caused by gas coming out of solution.

DRMS Monitor 2 & Dynamic Model Delta Gas Saturation
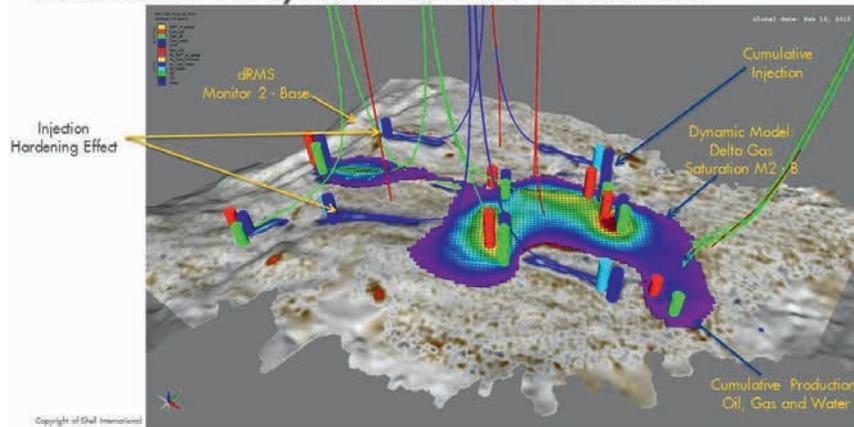
Figure 6 dRMS map and dynamic model showing the change in gas saturation between the second monitor survey and the baseline. Production and injection wells and fluid volumes are also shown.

such that the effort of the skilled interpreters is focused on valued-adding analysis, rather than on data preparation and software training.

An important element in the usage of this integration platform is assembling a 'Data Registry' which references all the key datasets that are drawn into the reservoir management decision-making process. A vital component here is involvement of the key stakeholders to ensure their buy-in and support for the process. This is typically best achieved by demonstrating value through past case histories and ease-of-use. Once involved in the process, the subject matter experts are almost always the best advisers on which datasets and interpretations to reference through the Data Registry.

With specific reference to BC-10, we incorporated all the relevant team data from the various disciplines. Figure 5 shows Deep Directional Resistivity log (DDR6) acquired for Injector 1 while geosteering the well; the image log is indicative of sand content. This is shown together with the 4D seismic signal. The acoustic hardening around the injector shows that the 4D anomaly is well distributed and uniform along a high net-to-gross sand present throughout the more than 1000 m of horizontal penetration under consideration, thus showing excellent efficiency of the completion and injection process.

Figure 6 shows another example from BC-10 illustrating the integration of a 4D dRMS map with modelled gas saturation

from the dynamic model. This process begins with largely automated/scripted workflows to import the latest versions of dynamic datasets (seismic, production data, etc.) into the dynamic visual 4D environment. Within this interactive environment, it is easy to compare, for example, the 4D seismic response alongside the dynamic model and the well data/production data. For instance, note the long, narrow hardening signals indicative of injection water replacing oil along the four injection wells. This suggests strong evidence of good effective performance of the water injection along the completed intervals. The strength and extent of the signals can be compared to the volumes of fluid injected (shown as vertical blue towers). The large red areas of acoustic impedance softening in Figure 6 are related to gas breakout, which can be observed around some producers. This softening was expected *a priori* since the initial reservoir pressure was only ~100 psi above bubble point.

Not easily illustrated here, but of critical importance, is the evolution of these signals through time. Allowing the entire team easy access to intuitive temporal animations has been established as a critical success factor: our minds are naturally tuned to assimilate and interpret such movement/temporal animations. This allows, for example, rapid and easy spatiotemporal comparisons between fluid injection volumes and movement in the 4D seismic signature.

This visual 4D appraisal is readily extended into a full, quantitative 4D comparison. In many cases this means qualitatively reconciling spatially overlapping but geometrically diverse datasets. For example, seismic data are sampled on to a highly regular, evenly spaced grid in XY and Z/T, whereas reservoir flow models have typically far more heterogeneous shapes and sampling. Likewise, well data have highly heterogeneous sampling in the three spatial dimensions and need careful consideration when quantitatively compared to a volume-filling dataset. Temporal sampling is also typically heterogenous between the datasets.

Figure 7 shows the 4D dRMS data numerically sampled into one realization of the dynamic flow model. Detailed examination within the tool reveals areas of high-quality match between the seismic and dynamic model. Interactive investigation also quickly identifies areas of opportunity, where further refinements may improve the predictive value of the flow model.

We can take the data integration workflow a step further by looking more closely at the relationship between dynamic model changes and amplitude changes. Figure 8a shows the Water Saturation change between baseline conditions in 2013
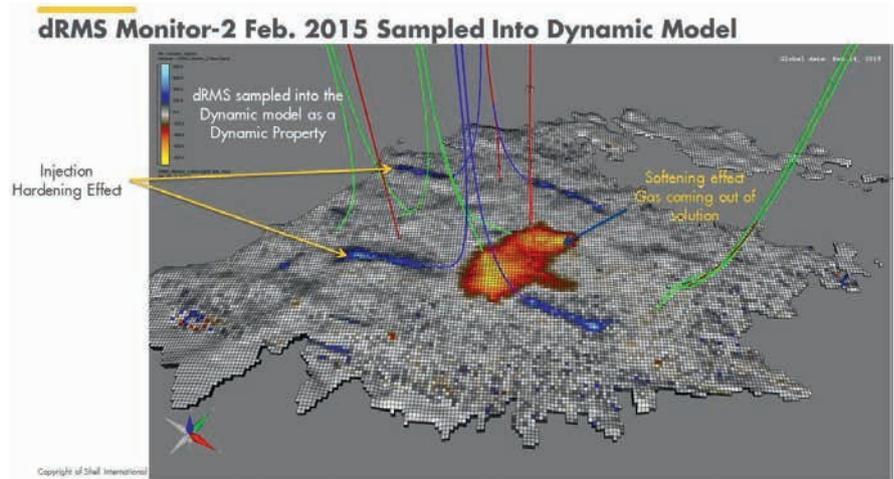

Figure 7 4D dRMS data sampled into the dynamic model for direct quantitative analysis. This cross-sampling of spatially overlapping, yet geometrically diverse, datasets allows the easy construction of interactive cross-plots and other statistical products such as those shown in Figure 8.
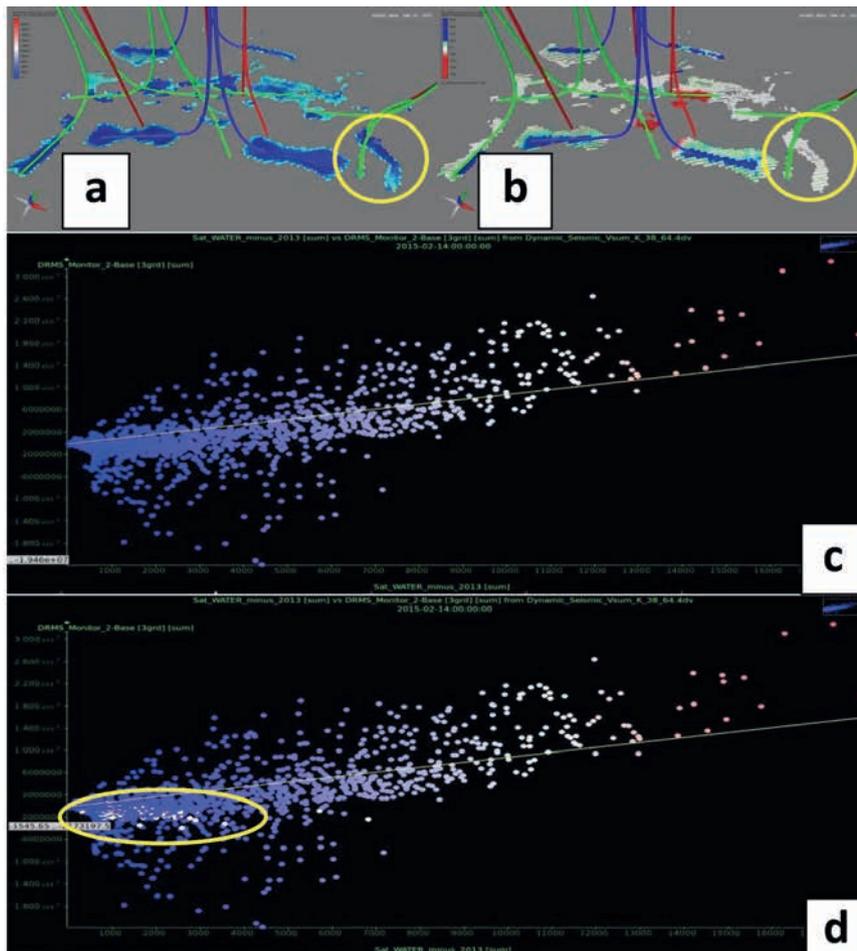

Figure 8 a) Water Saturation change between base and Monitor-2 b) dRMS between base and Monitor-2 c) Cross-plot of a versus b d) Cross-plot of a versus b with the selected area inside the circle from a and b shown highlighted in white on the cross-plot.

and Monitor 2 in 2015. Figure 8b shows the dRMS attribute for the same time period while filtered to show only the hardening effect – for easier comparison between the amplitude changes and the water saturation difference, especially around the water injector wells.

We can also easily limit this comparison to the K-layers within the dynamic model that show the formation water sweep (which is the bottom half of the dynamic model). Such filters are quickly and easily applied, to provide interactive feedback on exactly where the correlations are found, and how the correlations between the attributes evolve in time and space. The qualitative correlation observed from this fast, interactive analysis is reinforced by Figure 8c which shows a strong positive correlation as expected: With the increase in water saturation we see an increase in the strength of the 4D difference amplitude. Such cross-plotting enables quantification of water saturation changes over time and examination of the effect on 4D seismic amplitude, with a direct link back to the spatial environment. Moreover, if we consider the spatial anomaly highlighted by the yellow circles in Figures 8a and 8b, where we see changes in water saturation in the dynamic model but no related changes in seismic amplitude, this highlights an area that needs further study to match the dynamic model to the 4D seismic data. As one would expect, when the data within the yellow circle are highlighted in the cross-plot (Figure 8d) it is clear that this anomaly does not match the trend observed between the saturation changes and 4D amplitude. Work to investigate the absence of a strong 4D seismic response in this area is ongoing.

Taking this analysis even further, we can continue by performing a full forward modelling of the dynamic model (Sim2Seis). In this process the saturation/flow model is used to generate a petroelastic model, which is then used in a convolution procedure to generate synthetic seismic volumes. These synthetic volumes can then be used in thorough quantitative analysis, and seismic assisted history matching at each of the monitor time-points. Again, this workflow can be scripted/ automated, allowing for rapid sensitivity analysis of the critical input parameters to explore the relationships between the physical parameters.

But perhaps the greatest strength of this integration platform is the accessibility – allowing all members of the team to benefit from rapid access to relevant datasets in an easy-to-use and easy-to-understand environment. This encourages communication and mutual understanding across the technical disciplines, and quickly leads to extracting the most value from the 4D seismic data, and hence making the best reservoir management decisions.

Conclusions

When used in an appropriate geologic setting, a PRM system can offer tremendous insight into dynamic reservoir behaviour at a temporal frequency not easily or economically achieved by typical streamer-acquired 4D seismic data. However, with these insights comes the significant challenge and responsibility of abundant and frequent new data for integration. We should embrace this challenge as an excellent opportunity to work across traditional discipline boundaries, i.e. geophysicists need to become more familiar with dynamic flow models, and reservoir engineers should understand the meaning and value in 4D seismic data. In fact, such cross-discipline understanding is essential to maximizing value. Bringing all necessary data into a single integrated platform encourages these different disciplines to understand and challenge each other's ideas, assumptions, and conclusions. Time-lapse seismic adds significant value to our understanding of reservoir performance; integrating temporal changes adds another dimension, leading to better development decisions. Areas that can be impacted are infill drilling, WRFM and future seismic activities, and overall cost reduction and value maximization.

Acknowledgments

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