Technology Options for Low-Cost On-Demand Seismic Monitoring in Deepwater Brazil

J. L. Lopez, B.E. Cox, P.J. Hatchell, K. Wang, Shell International Exploration & Production, Inc.

Abstract

We present an overview of new low-cost seismic monitoring technologies that may be applied in deepwater Brazil, in particular in the prolific pre-salt province. We start with an estimate of the "size of the prize" that such a monitoring program may deliver in a field undergoing WAG recovery, followed by a survey of geophysical and geodetic areal monitoring technologies that have been deployed or are under development in other deepwater areas, including ocean bottom nodes and cables, small sources, high resolution 4D, DAS VSP, and seabed subsidence. We discuss their advantages, limitations, and their applicability to deepwater Brazil. We also discuss how these technologies need to be integrated to enable Well and Reservoir Management decisions and the trade-offs between value and cost of application. We conclude the paper with a vision for the future of low-cost, on-demand, reservoir monitoring.

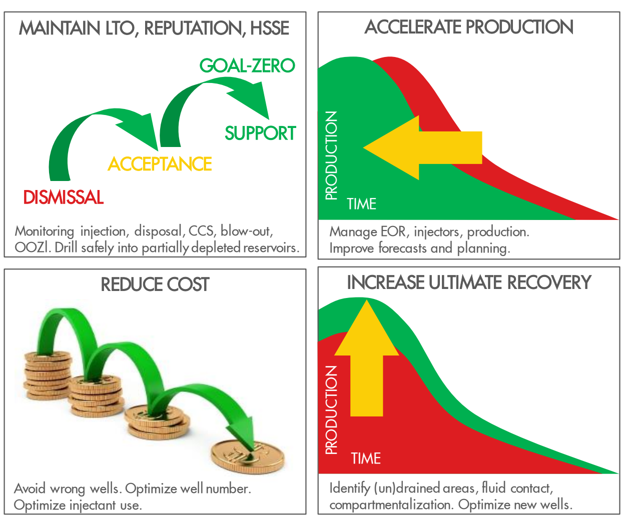

Figure 1: *Benefits attributed to a seismic monitoring program, including increased recovery, accelerated production, reduced cost, and reputation management.*

Introduction

The role of geophysics has traditionally been central in exploration, where seismic has been used as an effective method to discover and appraise new oil and gas fields. However, in today's industry the emphasis is changing from finding new fields to efficiently and effectively developing and producing existing fields. Time-lapse (4D) seismic has had a growing role in this space, with systematic application in the North Sea and the Gulf of Mexico for more than 15 years. In contrast, 4D seismic in deepwater Brazil has had a much shorter history, with important application in the post-salt at Jubarte [1] and BC-10 [2], but still no application in the pre-salt, where many large carbonate fields are under production, some for several years. A big challenge in this area is the estimated small size of the 4D effects. First demonstration of value is expected within the next few years [3].

Traditionally, 4D seismic has been acquired every 3-5 years or more to monitor how fields produce and to better plan development activities, such as drilling of infill wells (see Fig. 1). Over the last few years, however, there has been a tendency for more frequent monitoring to impact Well and Reservoir Management (WRM) decisions, such as adjustment of injection or production rates to optimize recovery or accelerate production. Such frequent 4D seismic could be used to better place development wells which are already in the Field Development Plan but whose precise location can be better informed by knowledge of fluid movements up to that point in field life.

Although seismic monitoring can provide many benefits to pre-salt assets, it needs to overcome several challenges:

- **Business case**: Demonstrate feasibility and value of information in untested areas;
- **High cost**: Manage the additional cost due to market immaturity and remoteness, contractual and regulatory complexities, high technical requirements (to detect small signals), and frequent repetition;
- **Intrusiveness**: Reduce the impact of frequent monitoring on the environment and conversely the impact of installations on seismic operations;
- **Value realization**: Ensure that benefits can be derived by translating monitoring data into actions.

To overcome these challenges there is a need to clearly specify the manner in which seismic monitoring data will be used so that one can estimate the corresponding value. This value will be eroded if seismic monitoring remains costly and intrusive. In this paper we present an overview of the advancements that Shell and industry have made in recent years to address these challenges and share a vision for the future.

"Size of the Prize" from Seismic Monitoring

We first estimate the "size of the prize" that may be claimed or shared by seismic monitoring, by quantifying the applicable benefits and the Cost involved in realizing those benefits [4]. As a generic example we consider a pre-salt carbonate field developed using a typical WAG scheme with a yearly cycle (water injection switches to gas injection, and vice versa, once a year), such that the following two 4D benefits may be realized:

Increased production by optimal adjustment of water/gas injection rates to prevent gas breakthrough and gas cycling. Reservoir engineers optimize such production parameters based on history-matched dynamic models; here we would augment the process with 4D seismic data. Dynamic model simulations suggest that an increase of 2,000 bbl/d in production is possible, or 2% incremental recovery when using a 100,000 bbl/d FPSO.

Increased ultimate recovery by better placement of development wells. These wells would not require additional CAPEX (already in plan) and take advantage of dynamic information from the frequent seismic surveys. The magnitude of this benefit will depend on the expected recovery and the degree of uncertainty in dynamic model parameters. A 3% incremental recovery due to optimized well placement informed by frequent seismic monitoring in a phased development seems reasonable to expect.

In our example we get a 5% increase in EUR. An NPV calculation needs to account for the additional costs to realize this increment (OPEX) and assume an oil price profile over time. An Adjusted NPV needs to further absorb the cost of seismic monitoring, which depends on the seismic technology, frequency of monitoring, and area covered. These calculations can be executed in detail for given fields of interest. Having established the "size of the prize" for seismic monitoring, next we review monitoring technology options that may help deliver this value.

Marine Surveillance Technologies

For marine applications we consider a range of monitoring solutions with seismic sensors on the sea surface, on the seabed, or in boreholes, which can be deployed permanently or temporarily. A visual overview of these methodologies is shown in Figure 2 and a tabular summary of their advantages, limitations, and status of deployment in deepwater Brazil is given in Table 1. In this paper we contrast pre-salt vs. post-salt applications, where in terms of seismic monitoring the relevant difference is the expected size of the 4D signals.

(1) Streamer Seismic (NAZ/MAZ)

Most seismic surveys in deepwater Brazil have been acquired with streamers, either in a single sailing direction (NAZ) or multiple directions (MAZ). Due to regulatory constraints, surveys with multiple source boats (WAZ) have not been acquired in country. Streamer surveys are very suitable for post-salt areas. In pre-salt areas they have been used to advantage for exploration and reservoir characterization (although with some limitations due to uneven illumination, especially in the pre-stack domain). Streamer surveys are unlikely to be useful for reservoir monitoring of the pre-salt carbonates, as the level of 4D noise introduced by poor repeatability would overwhelm the expected small 4D signals.

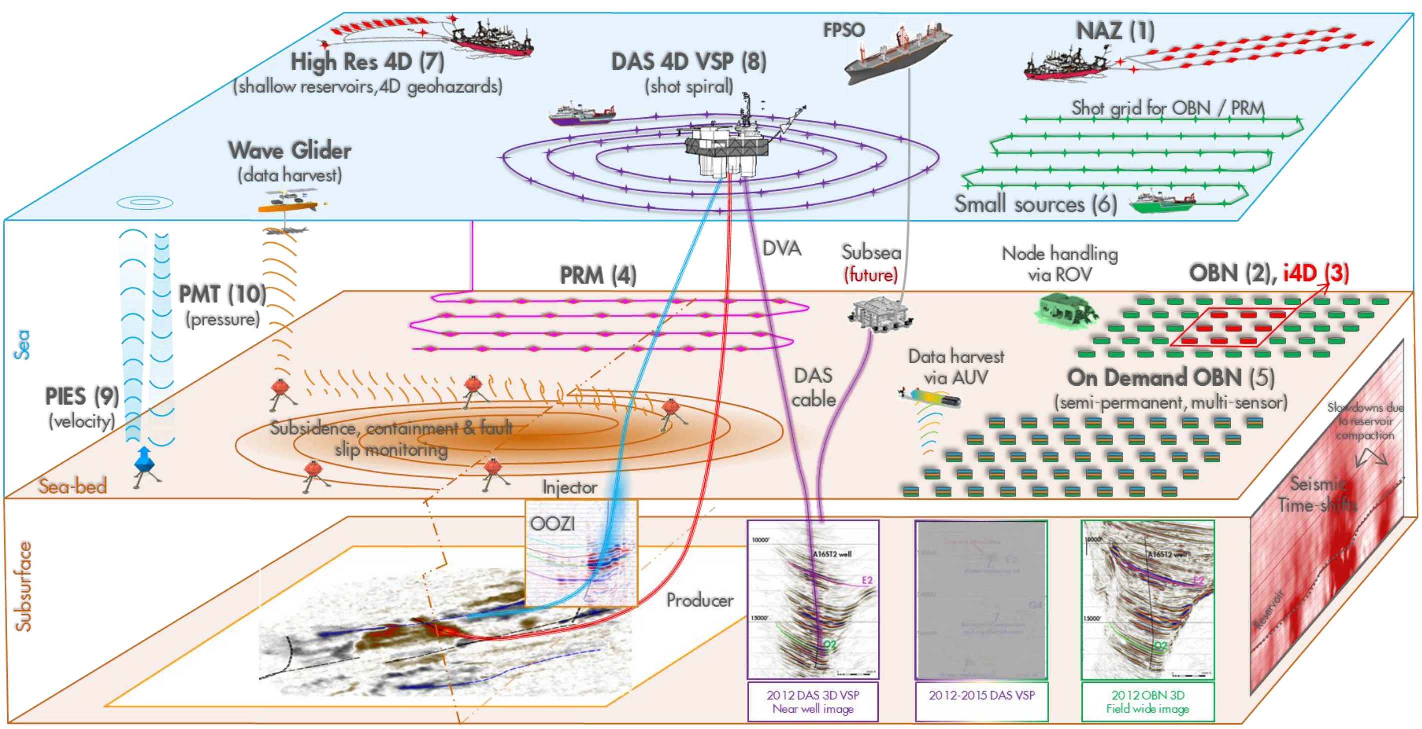

Figure 2: Seismic and geodetic surveillance technologies applicable in deepwater Brazil (numbered labels correspond to those in the text and in Table 1). Some of these technologies have been proven, others are being tested or planned to be tested, while others require further development.

#	Technology	Description	Advantages	Limitations	Status post-salt Brazil 4D	Status pre-salt Brazil 4D
1	NAZ/MAZ (Streamer seismic)	Narrow & multi-azimuth streamer	Cover large areas at low cost	SNR & 4D fidelity below salt	Proven	Not suitable
2	OBN (Ocean Bottom Nodes)	Seismic recording on retrievable nodes	High fidelity 4D, very flexible monitoring	May miss very small 4D effects	Not needed	Testing in Santos Basin
3	i4D with OBN	OBN over small areas or short durations	Lower cost, early 4D information	Limited areas	Not needed	To be tested
4	PRM (Permanent Reservoir Monitoring)	Permanent fiber optic Ocean Bottom Cables	Very high fidelity 4D, frequent monitoring	High CAPEX, long-term commitment	Proven at BC-10 & Jubarte	Developing business cases
5	OD OBN (On demand OBN)	Seismic recording on semi-permanent nodes	Very high fidelity, on-demand monitoring	Medium CAPEX, seabed endurance	Not needed	To be tested
6	Small sources	Use much smaller airgun sources	Lower cost source vessels, lower footprint	Depth of penetration	Testing at BC-10	To be tested
7	High Res 4D	Streamer surveys with many short cables	Very low-cost reservoir monitoring	Shallow reservoirs, zero offset	Testing in Gulf of Mexico	Not suitable
8	DAS VSP (fiber optic)	In-well seismic recorded using DAS	Low-cost injector & producer monitoring	Targeted areas	Waiting for fiber optic deployment in subsea wells	
9	PIES (Pressure Inverted Echo Sounder)	Measure water velocity during 4D surveys	Higher fidelity 4D seismic enabler	Average velocity (not a profile)	Proven at BC-10	Planned
10	PMTs (Pressure Monitoring Transponders)	Measure seabed deformation continuously	Compaction, fault slips, seabed infrastructure	real-time data uploading	Needs testing (subsidence signal and detectability)	

***Table 1:** Advantages, limitations, and status of seismic monitoring technologies applicable in deepwater Brazil. Colors indicate proven or likely to succeed (green), being tested or prospective (yellow), not suitable (red), and not needed (grey).*

(2) <u>Ocean Bottom Nodes (OBN)</u>
Time-lapse surveys using ROV-planted seismic nodes have been in use in the Gulf of Mexico since 2006, resulting in high-fidelity images even for reservoirs below salt. Due to cost and complexity, surveys in water-flooded areas are repeated about every three years. In pre-salt Brazil there is an ongoing 4D OBN pilot at Lula [3] with nodes covering a 111 km^2 area. For the purposes of reservoir characterization larger surveys are preferred, as recently reported in the press for Libra (735 km^2) and Buzios (1,600 km^2) to be acquired in 2017.

(3) <u>i4D with OBN</u>
A cost-efficient option for OBN is to design node patches to illuminate specific areas of interest, for example around key injector or producer wells. When such patches are used to monitor change over short time intervals (e.g., weeks to months), the technique goes by the name of "instantaneous 4D (i4D)". The "i" also stands for inexpensive, innovative, and intelligent. This method enables monitoring of fast reservoir changes such as those occurring in the vicinity of water injection wells.

Examples of i4D results are shown in Figures 3 and 4, demonstrating use for out-of-zone injection [5] and sub-salt monitoring [6]. The i4D application in Fig. 3 can be used during an OBN baseline survey to measure the level of 4D noise and to obtain early 4D data if a subset of the survey is repeated at the end of the months-long campaign over wells that may be active during that time.

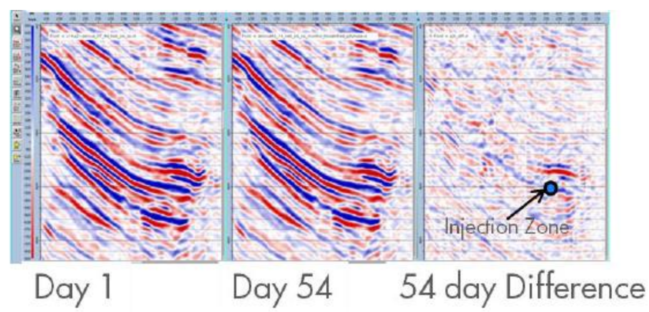

***Figure 3:** 4D seismic acquired over a water injector at Mars in the Gulf of Mexico over the span of 54 days [5].*

(4) <u>Permanent Reservoir Monitoring (PRM)</u>
4D seismic repeatability can be maximized by placing permanent seismic receivers on the seabed, as systems using Ocean Bottom Cables (OBC) enable. Such systems have been deployed in shallow water in the North Sea (Valhall, Clair, Ekofisk, and most recently at Snorre and Grane [7]) and in deep water in post-salt Brazil (Jubarte [1], BC-10 [2]). The Snorre application shows that frequent (twice-a-year) seismic is critical to proper monitoring of WAG cycles [8].

The BC-10 application (Figure 5) has demonstrated that 4D interpretation results are directly indicative of water flood containment and the movement of different fluids in the reservoir. As such they provided critical information to optimize well rates in both injectors and producers during early field life [2] and gave new insights into detailed reservoir architecture and aquifer support. The very high sensitivity of the PRM system enables detection of reservoir changes after only a few months of water injection. The down-side of PRM systems is the long planning cycle and significant upfront capital, and therefore such systems are only cost-effective if many repeat surveys are acquired. Cost could also creep up over time if parts fail over the very long deployment time.

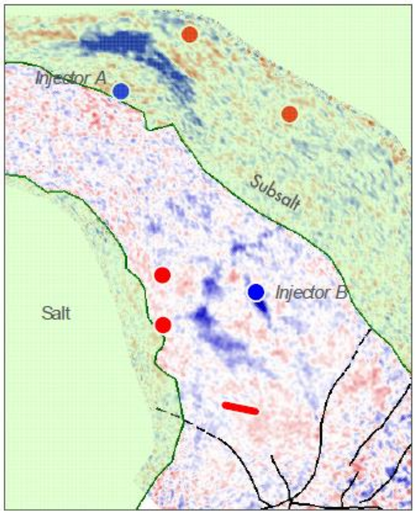

Figure 4: *4D seismic acquired in the Ursa field in the Gulf of Mexico showing clear signals even below salt [6].*

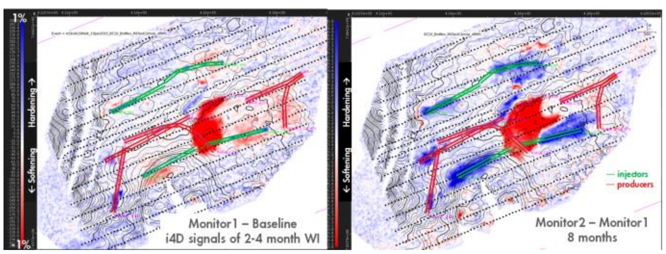

Figure 5: *PRM results at BC-10. Frequent surveys generate value through WRM decision-making [2].*

(5) <u>On-Demand OBN</u>
Semi-permanent nodes that remain on the seabed for years and can be turned on and off, such as the ZLoF [9] system from Fairfield, enable on-demand OBN surveys. The ZLoF system (commercial but not yet deployed in a field) can record data for a total of 300 days (e.g., 60-day yearly surveys over five years) with data harvesting done by ROV. Relative to PRM, such systems reduce financial exposure (CAPEX, repairs) and increase flexibility (reposition nodes as needed), while preserving high 4D fidelity, although OPEX is higher (due to ROV costs).

(6) <u>Small sources</u>
One may reduce cost by using smaller air-gun sources, which can be deployed from less expensive vessels (a step change in vessel day rate occurs in the vicinity of 500 in^3, which is in the upper range of site survey or small VSP vessel source sizes). In reservoirs under benign overburden (Figure 6), small sources can provide sufficient 4D quality to interpret large-scale features. Cheaper surveys will allow frequent monitoring commensurate with the time scale of changes in the subsurface. The corresponding decrease in 4D data quality can be partially mitigated by using permanent sensors to reduce 4D noise. An added benefit of the smaller sources is that they decrease the environmental footprint that may constrain seismic acquisition in future. Small sources may also be implemented using marine vibrators, which the industry continues to develop.

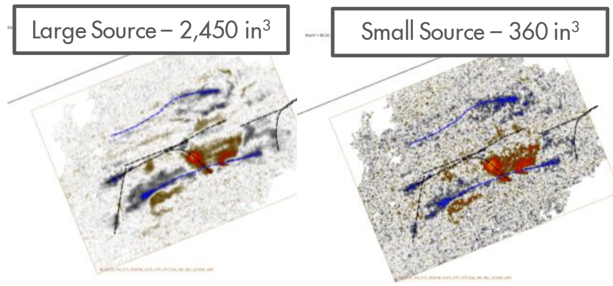

Figure 6: *PRM results at BC-10 using large (left) and small (right) sources. The small-source data have higher noise, but the 4D signals are similarly interpretable [11].*

(7) <u>High Res 4D</u>
For high resolution monitoring of reservoirs shallow relative to the seabed (such that water bottom multiples occur later in the section), an ultra-low-cost option is the use of a towed streamer system with many short (100 m) but closely spaced cables providing bin sizes of 3.125m x 6.25m. In 2016 Shell conducted a campaign over three fields in the Gulf of Mexico using the P-Cable system operated by NCS (http://pcable.com/) to mature and establish the limits of the technology for 4D applications. This technology may be applicable in Brazil post-salt.

(8) <u>4D DAS-VSP</u>
For wells with installed fiber-optic cables, VSPs using Distributed Acoustic Sensing (DAS) can provide very economic, minimally intrusive, repeatable areal coverage around injector or producer wells to monitor water front movements, horizontal injector conformance, and potential out-of-zone injection issues [12]. With no well intervention, DAS VSP enables recording along the entire length of several wells simultaneously; this would be impossible with conventional geophones. In favorable areas we believe that surveys could be acquired for $1 mln. The first 3D DAS-VSP in deepwater was acquired at Mars in 2012 (*Figure 7*) and a 4D DAS-VSP was acquired three years later. The 4D results are comparable to those obtained with 4D OBN within the illumination area of the VSP geometry. Since then DAS-VSP has been acquired using small sources, which results in a cost and footprint reduction (*Figure 8*), and simultaneously in multiple wells, which results in a larger imaged area [14].

The biggest enabler for the further deployment of DAS VSP will be the availability of fiber optic cables for subsea wells, expected to take place by 2020. There are and will probably be ten times more subsea wells than Direct Vertical Access (DVA) wells in deepwater fields (certainly all those in the Brazilian pre-salt).

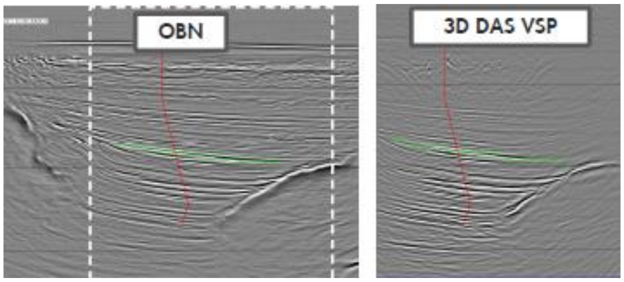

Figure 7: *3D DAS VSP image (right) compared to OBN image (left) [13].*

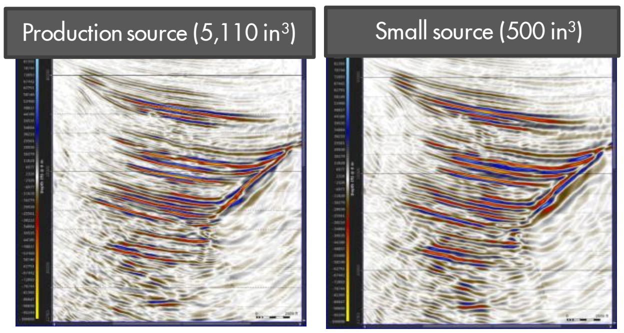

Figure 8: *3D DAS VSP image using OBN production source (left) and a much smaller source (right). The images are flanked by salt on both sides [14].*

(9) PIES (Pressure Inverted Echo Sounder)
Uncertainties in water velocity and tidal variations impact repeatability of 4D seismic in deepwater. Although processing methods attempt to solve for these uncertainties from the data, it is preferable to measure these variables directly using a few PIES seafloor devices [10] positioned across the survey area (see Figure 9). With the expected small 4D signals in the pre-salt, such data acquisition refinements may become critical to measuring 4D effects with confidence.

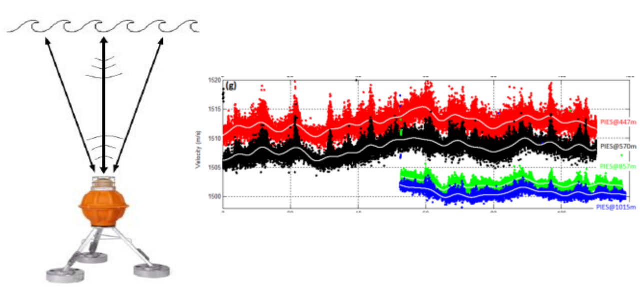

Figure 9: *A PIES unit at the seafloor provides an average vertical water velocity, as shown on the right for PIES units at different water depths [10].*

(10) PMTs (Pressure Monitoring Transponders)
The technologies described above enable reservoir monitoring using seismic methods. To get a fuller picture of the subsurface it is important to link the changes observed on seismic to the geomechanical changes in the reservoir and the over- and under-burden. A key input to this process is provided by measurements of seabed subsidence, such as those provided by a network of Pressure Monitor Transponders (PMTs) [15]. The PMTs measure seafloor state continuously and are sensitive to slowly varying deformations (subsidence) or sudden shifts (e.g., fault slips). Data harvesting is typically done remotely using autonomous Wave Gliders or vessels of opportunity equipped with acoustic modems. The magnitude of subsidence in Brazil pre-salt carbonates is modeled to be small, but estimates are uncertain and need to be validated in the field. Fault slips would result in much larger seafloor signals. Integrating geodetic and seismic data provides a more complete picture of the dynamic processes in the subsurface [16].

Cost vs Value Trade-offs

Next we estimate the cost of the seismic monitoring methods that can be more properly compared, namely OBN (2), PRM (4), and OD OBN (5). In Figure 10 (left panel) we show our high and low estimates of the present-value cumulative cost for yearly surveys. For OBN and PRM, the “Low” cost estimates are typical of the Gulf of Mexico, while the “High” estimates apply in less mature areas, such as deepwater Brazil. We can see that a PRM solution would be preferred on a cost basis over OBN if we commit to acquire six (twelve) or more surveys in the Low (High) cost scenario. For the OD OBN case (green curves), the Low estimate incorporates an aspirational CAPEX reduction and a subsea-resident AUV for data harvesting, resulting in much lower OPEX.

A proper comparison between monitoring solutions needs to also include Value [4]. The Risked Value is obtained by first adjusting the incremental NPV for the cost of seismic monitoring. The Adjusted NPV is multiplied by a fraction expressing the part of the estimated Value that can be realized by seismic monitoring (the “Business Scope”, assumed to be 50%) and by the Technical Efficiency of the chosen seismic solution, to give the Risked NPV. The Technical Efficiency depends on the frequency of monitoring and the Quality of 4D data. We assign a 4D data quality of 50% for OBN and 60% for PRM (because of permanent receivers plus ability to record passive seismic). In Figure 10 (right panel) we show the same six systems, plotted in the Risked Value vs. Cost space (the constant-slope lines represent VIR of 1.0, 1.5, 3.0). We can see that the Low OD OBN case is the most favourable one if it can be realized in practice.

From Figure 10 (right panel) we can see that a key unknown is where along the lines connecting the high-cost and low-cost estimates for each technology would the respective technology land in the Brazilian cost environment, once a competitive market develops in country. We note that OBN is a mature technology but cost reductions may be possible with ongoing innovation. PRM is also mature but with little market penetration, so deployment seems hindered in practice. This leaves our Low OD OBN solution with limited competition if realizable, at least partially, in Brazil.

A vision for the future

We have presented an overview of new technologies to enable low-cost, on-demand monitoring that may be applied in deepwater Brazil. Future steps to further reduce cost and increase benefit of surveillance include:

- An On-Demand OBN system that combines seismic and subsidence monitoring in an integrated node to reduce cost and provide synergistic measurements;
- Node activation and data harvesting using a subsea-resident AUV (Figure 11), thereby reducing OPEX significantly (no ROV vessel needed) [17].
- Cable deployment in subsea wells to enable low-cost DAS VSP recording, including in multiple wells simultaneously. Currently no wells are amenable to such monitoring in deepwater Brazil.
- Rigorous business cases for reservoir monitoring based on clearly actionable value of information [18] and well location optimization techniques [19].

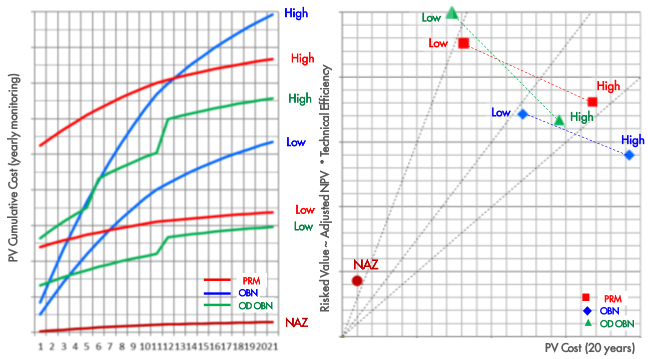

Figure 10: *Estimated costs for yearly monitoring using PRM, OBN, or OD OBN solutions (left) and corresponding Risked Value vs. Cost trade-offs (right).*

.

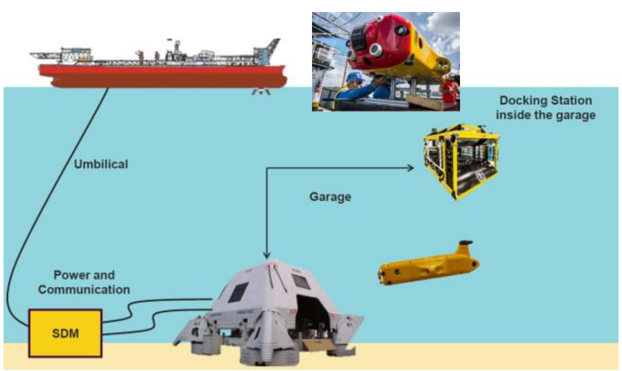

Figure 11: *Data harvesting from seabed nodes using a subsea-resident FlatFish AUV [17] would cut OPEX costs.*

Conclusions

Deepwater Brazil holds very large reserves in several prolific basins which are being exploited using complex recovery methods. Seismic monitoring in the pre-salt, even after ten years of production, remains unproven, although several ongoing efforts should provide clarity on the magnitude, detectability, and usefulness of the 4D effects by 2020. In the success case we need to be prepared to deploy low-cost and high-value solutions, as we outline in this paper.

Acknowledgments

We thank our colleagues D. Chalenski, M. Tatanova, A. Mateeva, S. Grandi, J. Przybysz-Jarnut, K. Rattansingh, D. Clarke, A. Geisslinger, P. Wang, R. Zagatti, F. Abbots, M. Araujo, P. Puccini, H. Potters.

References

[1] Thedy, E., et. al., Initial Results on Permanent Reservoir Monitoring in Jubarte, Offshore Brazil, 14th International Congress of the Brazilian Geophysical Society, 2015, p. 838-841.
[2] Galarraga, M., et al., 2015, Results of 4D monitoring from the Deepwater BC-10 life of field seismic (LoFS) in Brazil", 85th SEG Annual International Meeting.
[3] Johann, P. and Monteiro, R., Geophysical Reservoir Characterization and Monitoring at Brazilian Pre-Salt Oil Fields, 2016 Offshore Technology Conference, OTC-27246.
[4] Lopez, J., et. al., 2017, Valuation of Marine Seismic Monitoring Technologies, First EAGE Workshop on Practical Reservoir Monitoring.
[5] Hatchell, P., et al, 2013, Instantaneous 4D seismic (i4D) for water injection monitoring: 75th EAGE Conference and Exhibition.
[6] Barker, T., et al, 2015, Subsalt Time-lapse Seismic for Reservoir Monitoring using i4D in Deepwater, 77th EAGE Conference and Exhibition.
[7] Thompson, M., et. al, 2015, The startup of PRM at Snorre and Grane, 77th EAGE Conference and Exhibition.
[8] Thompson, M., et. al, 2016, Time-lapse observations from PRM at Snorre, 78th EAGE Conference and Exhibition.
[9] ZLoF = Z Life of Field; http://fairfieldnodal.com/data-acquisition/reservoir-monitoring
[10] Wang, K. et al, 2012, Direct Measurement of Water Velocity and Tidal Variations in Marine Seismic Acquisition, 82rd SEG Annual International Meeting.
[11] Chalenski, D. et al, 2016, Small acoustic sources for low-cost reservoir monitoring offshore, The Leading Edge, 35, 860–866.
[12] Mateeva, A., et al, 2013, Distributed acoustic sensing for reservoir monitoring with VSP: The Leading Edge, **32**, 1278–1283.
[13] Wu, H., et al., 2015, Dual-well 3D vertical seismic profile enabled by distributed acoustic sensing in deepwater Gulf of Mexico, Interpretation, 3(3), SW11-SW25.
[14] Chalenski, D. et al, 2016, Climbing the staircase of ultralow-cost 4D monitoring of deepwater fields using DAS-VSP, 86th SEG Annual International Meeting.
[15] Dunn, S., et al., 2016, A long-term seafloor deformation monitoring campaign at Ormen Lange gas field, First Break, pp 55-64.
[16] Riley, C., 2016, Perdido – A Five Year Look at the Technologies that have enabled Ultra-Deepwater Success, SPE ACTE, Dubai, SPE-181442.
[17] Albiez, J., et al., 2015, FlatFish – a compact subsea-resident inspection AUV", in Proceedings of OCEANS 2015.
[18] Ferreira, C. and D. Schiozer, 2014, Methodology to estimate the chance of success of a time-lapse seismic project using reservoir simulation, SPE ACTE, Amsterdam, SPE-170674.
[19] Ramirez, B., et al., 2017, Model-based Well Location Optimization – A Robust Approach, SPE Reservoir Simulation Conference, SPE-182632.