# The value of 4D seismic: Has the promise been fulfilled?



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## Abstract

Time-lapse (4D) seismic is a key component of an asset's reservoir surveillance strategy. Its value lies in optimizing field developments because it enables the detection of reservoir changes due to production, and it allows for timely corrective action toward optimal field management. In producing assets, 4D seismic adds incremental economic value by providing 3D information on the dynamic performance of reservoirs. This can occur during each of the four phases of the life of a field: first, by helping extend the field's base production and injection plateau through the identification of infill target areas (bypassed hydrocarbons) or areas of inefficient injection support; second, by adjusting depletion plans and optimizing hydrocarbon recovery mechanisms and their efficiency; third, by rejuvenating the field through taking advantage of existing infrastructure to develop stranded pools and targeting poorly swept areas of the field; and fourth, by managing the life of field more effectively through monitoring saturation and pressure changes at both reservoir and well scales. The value gained from deploying 4D seismic often exceeds our expectations when compared to that derived from a value-of-information exercise prior to acquiring such data. This is due to the "known unknowns," such as flow features that occur below the seismic scale, and "unknown unknowns," such as complex reservoir connectivity. We present several field examples and show that the source of value falls under two main categories: quantifiable, such as net present value (NPV), and qualitative, such as improved field knowledge and decision making. We also discuss a case where 4D gave rise to an incremental increase in NPV that exceeded one-third of the field's total original NPV.


## Introduction

Despite their relatively poor vertical resolution compared to well-log data, 3D seismic data have enabled skilled interpreters to characterize changes in the subsurface, away from known well control points. The introduction of time-lapse (4D) methods has allowed for the detection of even smaller reservoir changes than were previously thought possible to observe. Past efforts have shown that by repeating source and receiver geometries, one can minimize noise (i.e., minimize normalized rms or NRMS, see Kragh and Christie, 2002), which helps uncover subtle changes that occur in the subsurface due to field-development processes. Recent improvements in processing techniques have relaxed the prior requirements to repeat exact prior geometries during 4D surveys, and this has opened the door to different kinds of "repeats": it is now feasible to compare new higher-end streamer data (broadband or wide azimuth) to legacy streamer data and to compare ocean-bottom seismic to legacy streamer data (Wei et al., 2016). Interpreting 4D is all about understanding the properties of the reservoirs, fluids, and pressures and deciphering the meaning of the changes observed in the repeated seismic data, all within the existing signal-to-noise constraints.

Numerous publications discuss the use of 4D seismic monitoring and its technical merits as a tool deployed during the life of field, but few of those publications address the actual value that the technology brings to a project. In this paper, we focus on the type of value, both quantitative and qualitative, that a 4D survey may bring. Our experience reflects a sizeable number of 4D surveys in multiple basins and reservoir types from around the world.

## Defining value

***Sources of value.*** There are many accepted quantitative measures of business value. One of the most commonly cited metrics is net present value (NPV). Additionally, more qualitative value measures are cited, such as competitive advantage, which can be derived by some form of proprietary knowledge or access to that knowledge, and improved decision quality. Exploration and production companies typically establish business and value metrics around the three broad categories of profitability, growth, and sustainability (Figure 1). These metrics can be and often are in tension, but all three are important for success over the long term. 4D seismic provides information that can impact all three of these business driver categories.

***What is profitable oil?*** 4D techniques enable us to identify volumes of incremental oil that may be recovered from existing fields. However, that oil is recoverable only if it is cost effective to do so. This incremental recovery of oil typically follows a law of diminishing returns and eventually must end when it becomes cost disadvantaged or exceeds operating expenses for the field. Profitable oil consists of barrels that can be exploited where the marginal cost of finding and producing the barrels is low enough to generate positive financial returns.

***Life cycle in the oil patch.*** Life-of-field seismic (LOFS) refers to the use of seismic methods throughout the life of a field to help optimize field management. The LOFS terminology has been around for a long time (Jack, 1997), but the concept is worth revisiting in the context of profitable oil. Figure 2 illustrates the life of a typical oil field. The vertical axis reflects cash flow

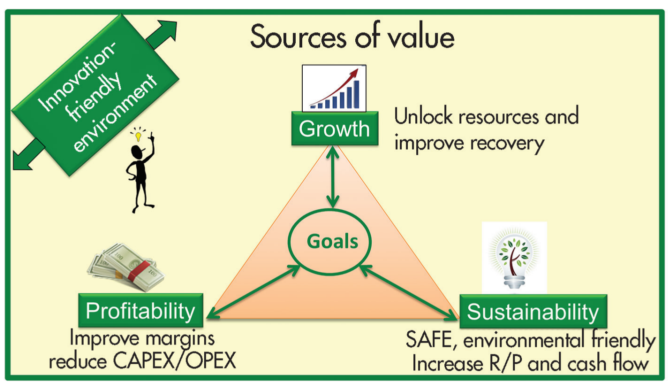


**Figure 1.** Common measures of value in the oil patch, including growth, profitability, and sustainability.

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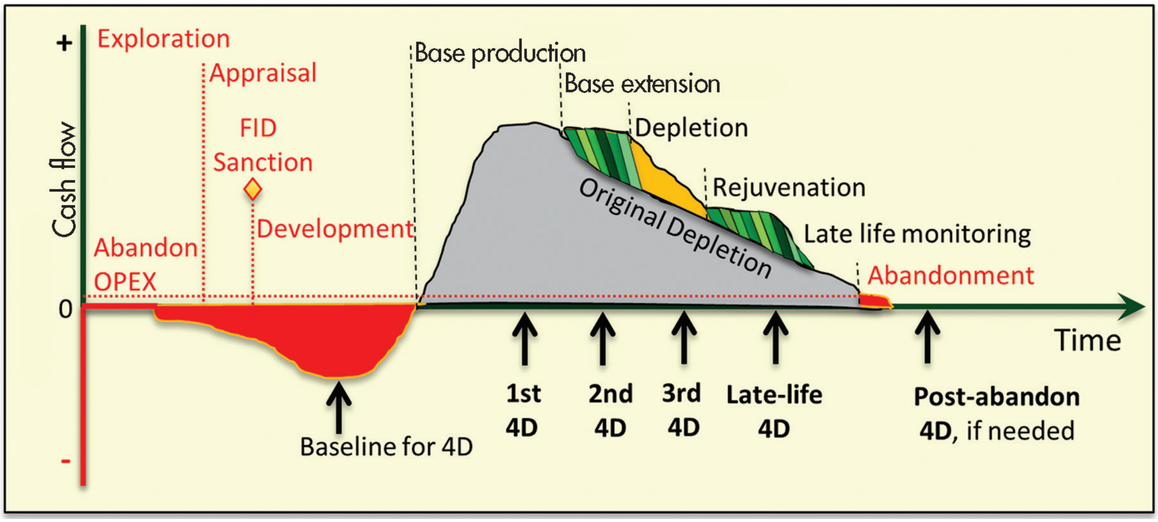



**Figure 2.** The life cycle of an oil field. Note the four main phases: (1) base production/injection and its extension, (2) depletion, (3) rejuvenation, and (4) late-life/pre-abandonment. For each phase, a prudent operator will assess the viability of acquiring a new (4D) seismic data set.

as a function of time, and the areas shaded in red are times of negative cash flow. The field produces until cash flow falls below operating expense, at which point the field is abandoned. There are in general four overlapping phases where 4D seismic, as part of an integrated reservoir surveillance program, can bring value throughout the life-of-field development:

***Base production.*** In the first phase, 4D is used to help manage or extend base production and injection by identifying areas of stranded hydrocarbons (bypassed areas), inefficient injection support, and infill targets. The main goal of this phase is to hold a production plateau (which is usually matched to the size of the production facilities) as long as possible and to arrest the field's initial decline in production. Each onion-skin-like layer shown in green in the base production plateau of Figure 2 represents new barrels brought about by a new production or injection well enabled by the 4D.

***Depletion.*** In the second phase, 4D is used to adjust depletion plans and help achieve the optimal recovery of hydrocarbons. 4D helps recognize areas of partial or inefficient sweep as well as areas of better-than-expected enhanced oil recovery, thus potentially saving the drilling of an injection well for example. There are many examples in the literature in which 4D provides vertical sweep characterization. It all depends on reservoir thickness and seismic resolution. 4D seismic is particularly well suited to estimate the quality of lateral sweep, away from wells. Later in this paper, we show examples of vertical and horizontal sweep characterizations. During the depletion phase, it is possible to make key reservoir decisions by matching 4D-calculated oil saturation volumes with results from reservoir simulations.

***Rejuvenation.*** In the third phase, operators are looking to "rejuvenate the field" and target areas of the reservoir that are more difficult to reach. 4D is used to define optimal well trajectories through overburden characterization, as this overburden is also responding to changes over time. In this sense, 4D can help assess the feasibility of new extended-reach wells and minimize their cost as the asset team continually tests the reservoir limits. In this phase, it is common for previously unidentified tie-back wells to be brought into the main production facility and for deeper reservoirs to be tested. In rejuvenation, "new oil" is found near "old reservoirs," the access of which is impacted by information obtained by the 4D. This is illustrated once again by the onion-skin-like layers shown in green in the rejuvenation portion of Figure 2, in which each layer represents wells that either accelerate production or contribute new barrels, all enabled by 4D.

***Monitoring mature fields.*** In the fourth and last phase, production declines rapidly, and fields approach the end of their economic life, so it becomes more critical to monitor individual reservoir segments through time. This includes the monitoring of completions and/or well work and planning for abandonment of the field. Here, 4D is used as a tool for integrated surveillance of the overburden and the reservoir sections. At the reservoir level, it is used to monitor subsidence, to assess the effectiveness of individual well completions through time, and to recommend potential well interventions. In the near surface, 4D is incorporated with site monitoring for environmental changes, or it is used as a forensic tool to investigate unexpected events, such as well failures or early gas/water breakthrough. Such examples have been published for North Sea chalk reservoirs (Haavik et al., 2014).

In summary, when integrated as part of an overall surveillance program, 4D seismic data can help identify new, previously unrecognized production targets and help assess sweep efficiency for improved oil recovery. 4D data is also used to "protect" reserves, to reduce the risk and uncertainty associated with a changing overburden, and to help provide the best possible trajectories for new wells. All of these activities are central to effective reservoir management.

## Drivers of value

During field management, adding value is best described in the context of making favorable changes to the economics of the field. This can be achieved through making the wells safer, incrementing production (rates and/or reserves), or decreasing costs (diminishing the well count, improving the completions design, or changing the well type).

When developing a field, operators create a field-development plan (FDP) which will be sanctioned and executed over time. The FDP is optimized during sanction (preproduction) by using all of the data available at that time. The FDP fixes the basis for the field development with all associated capital spending and associated schedule. It is important to recognize that there are many unknowns when the FDP is initially created. Borrowing from terminology used in the U.S. military (Rumsfeld, 2002), there are "known unknowns," such as subseismic-scale flow features, and "unknown unknowns," such as complex reservoir connectivity, that exist at the time of the initial reservoir development plan. Such unknowns are difficult to quantify and model prior to commencing field development. With new production data and a renewed understanding of the subsurface, the FDP can later be modified and optimized. 4D technology plays an important part in providing new data to update our understanding of the field's evolution and to impact revisions to the FDP.

The concept of value incorporates the important element of time. 4D seismic technologies have been proven to bring about positive changes to field developments because they can provide feedback about subsurface unknowns in a short and actionable amount of time. A 4D survey's value tends to decline over time, so there is often a need to acquire multiple repeat surveys to be able to keep providing new information in pertinent time.

## Progress in 4D techniques and workflows

In the early days of seismic monitoring, 4D was applied in a semiquantitative manner to identify areas in the subsurface where differences in seismic reflectivity occur as a function of production. Many 4D surveys are still interpreted in a relatively qualitative manner with a fast turnaround, but they suffer some limitations if they are based solely on changes in acoustic impedance (AI). For example, a decrease in AI can be due to an increase in reservoir pressure, to a decrease in water saturation, or to gas coming out of solution. Conversely, an increase in AI can be caused by a decrease in reservoir pressure or an increase in water saturation. However, prestack analysis of 4D data can differentiate between the two effects of pressure and saturation by using seismically computed elastic rock properties (Lumley et al., 2003). As a recent example, Nasser et al. (2016) presented results of a modern rock-physics-inversion (RPI) technique that allowed for a detailed reservoir characterization and that discriminated pressure effects from saturation changes. We can increase our level of sophistication in 4D analysis techniques when the data is robust enough to do so. The industry is moving from analyzing time shifts and changes in reflectivity over time to the interpretation of changes in elastic impedance space and, ultimately, to the world of direct and joint prestack inversion for reservoir properties such as pressure and fluid saturation, through a calibrated rock-physics inversion, as described by Ball et al. (2014).

The 4D interpretation can be made quantitative when calibrated with other disciplines through a shared earth model. For example, Figure 3 shows an RPI prognosis for a blind well and compares that prediction to what was encountered when the well was drilled. Figure 3a shows a prediction of static reservoir properties: it shows a prediction of net sand thickness (pseudo-GR curve) and porosity (porosity curve) on the left-hand side, while the right-hand side shows what was encountered. Figure 3b, compares a prediction of dynamic reservoir properties (oil saturation) on the left-hand side, with the actual measured oil saturation on the right-hand side.

For many reservoirs, changes in fluid saturation obey established rules of fluid substitution. However, the elastic responses due to changes in pressure are less understood and more difficult to predict. They often require calibration to core in order to measure changes in the frame moduli of the reservoir rocks as a function of pressure.

In this paper, we present a number of seismic examples from several fields located offshore Equatorial Guinea (Figure 4, after Clechenko et al., 2014). For geologic context, all fields are combination structural-stratigraphic traps that were deposited during Campanian times as part of deepwater turbidite systems. There are two main deepwater sediment feeder systems that incised into a mid- to upper-slope depositional environment toward the basin center to the west. The northern canyon system exhibits a deeply eroded and confined part in the Elon area and feeds reservoir

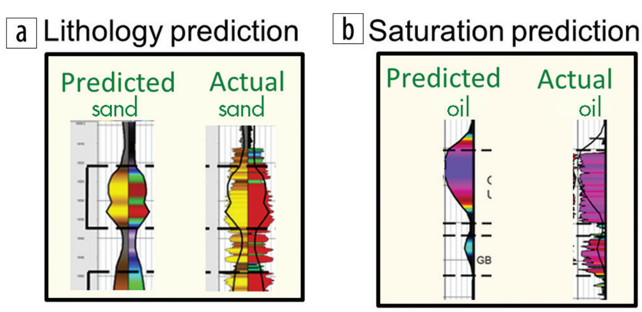



**Figure 3.** Seismic predictions of static and dynamic reservoir properties, using RPI and a blind well. (a) Static properties. The curves displayed on the left represent RPI-based predictions of lithology, thickness, and porosity, while the curves on the right depict what was encountered in the well. (b) Dynamic properties. RPI-based predictions of oil saturation (curve on the left) as compared to what the actual oil saturation encountered in the well (curve on the right). Figure modified, after Blangy et al. (2014).

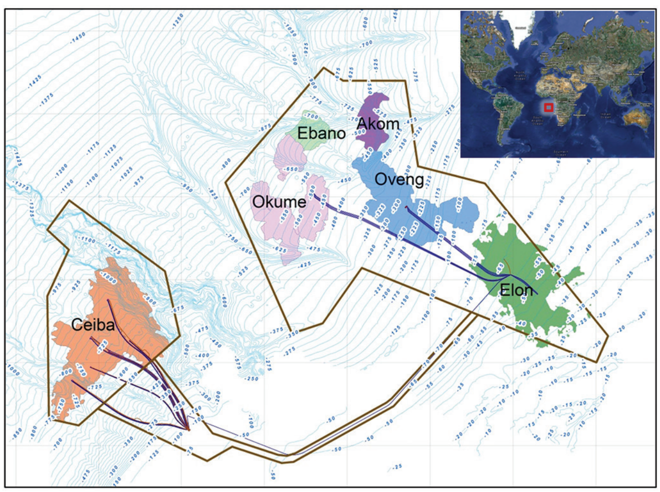



**Figure 4.** Location map of the fields in the Ceiba and Okume area, offshore Equatorial Guinea. Figure modified, after Clechenko et al. (2014).

sands to the Elon, Oveng, Akom, and Ebano fields before spilling into the Okume Field. The sands in the first four fields exhibit a high degree of confinement with multiple stack pay intervals, while the Okume sands are weakly confined and exhibit lateral stacking. The Ceiba Field is a structural trap with weakly confined turbidite sands having been fed from a separate canyon system. The reservoir sands are of high porosity. Geophysically, when the sands are hydrocarbon filled, they exhibit a lower AI and a lower $V_P/V_S$ ratio as compared to the bounding reservoir shales. As such, the seismic behavior of the oil reservoirs is a class 3 AVO response (Rutherford and Williams, 1989).

As an industry, we have generally obtained good results using RPI. For example, Figure 5 shows a 79% reliability using RPI techniques for one of our fields. In Figure 5a, true positives (green) and true negatives (blue) occur when we encountered what we predicted (i.e., the reservoir and pay being present or not) in a 14-well drilling campaign. As shown in Figures 5b and 5c, approximately 21% of the blind tests were unsuccessful (i.e., pay was found where we did not expect it, and no pay was found where we did expect it). These false anomalies were due to seismic resolution issues and seismic interference with "hard streaks" (thin carbonate stringers). With further research and calibration to the local knowledge of the area, we can improve on those statistics.

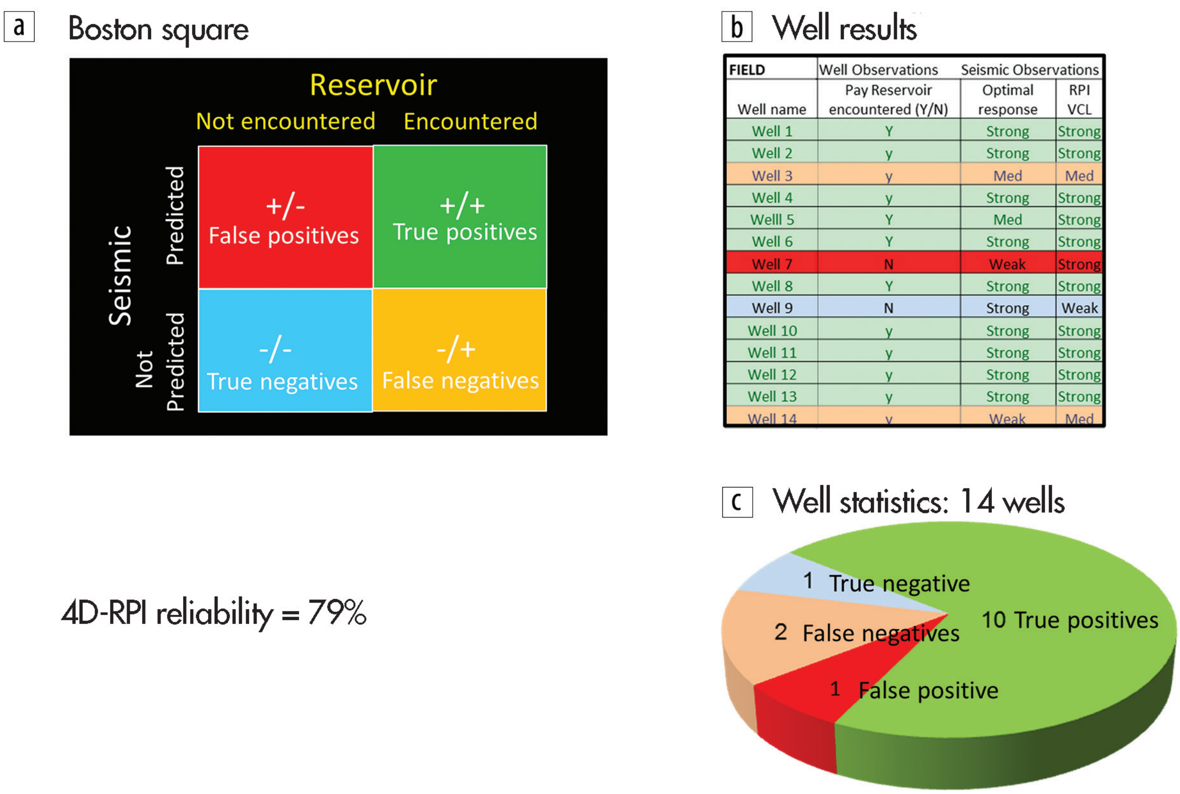
Ball et al. (2014) showed how to calculate *relative* changes of elastic properties due to changes in pressure (for example $dV_P/dP$ and $dV_S/dP$) that can be identified within the seismic bandwidth. Predicting pressure by using 4D seismic away from well control also requires an understanding of reservoir fluid properties as a function of pressure, volume, and temperature conditions as the field is produced. The combined rock-fluid elastic response of the reservoir can exhibit a complex evolution through time. We will show an example in which the reservoir pressure was allowed to drop beneath the bubble point before being repressurized by water injection.

## The 4D value proposition: Examples

We show four examples of positive impact of 4D to the life of a field project.

***Management of base production.*** The first example shows how we used 4D as a tool to help extend production and arrest inevitable production declines. At Ceiba and Okume, we have many examples of new production originating from seismically identified in-field targets. Today, that production contributes to the majority of the rate from our declining fields. These infill targets might come from virgin or undrilled compartments or from areas that have not been swept efficiently.

Figure 6a shows an RPI-based oil saturation calculation from the Ceiba Field (Figure 4), where the main channel sand is at virgin oil saturation (preproduction) in 1999. Figure 6b shows the same channel (postproduction) in 2010, with the seismically RPI remaining oil volume. The field is being produced using a water flood, and the 4D seismic is able to illuminate the nonuniform nature of the water sweep through individual reservoir sands.




| FIELD | Well Observations | Seismic Observations | |
|---|---|---|---|
| Well name | Pay Reservoir encountered (Y/N) | Optimal response | RPI VCL |
| Well 1 | Y | Strong | Strong |
| Well 2 | y | Strong | Strong |
| Well 3 | y | Med | Med |
| Well 4 | y | Strong | Strong |
| Welll 5 | Y | Med | Strong |
| Well 6 | Y | Strong | Strong |
| Well 7 | N | Weak | Strong |
| Well 8 | Y | Strong | Strong |
| Well 9 | N | Strong | Weak |
| Well 10 | y | Strong | Strong |
| Well 11 | y | Strong | Strong |
| Well 12 | y | Strong | Strong |
| Well 13 | y | Strong | Strong |
| Well 14 | y | Weak | Med |

**Figure 5.** An example of statistical analysis of the RPI results from the Ceiba drilling campaign. (a) True positives, in which the seismic predicted sand and was correct, are in green; true negatives, in which the seismic correctly predicted no reservoir, are in blue; false positives, in which the seismic wrongly predicted reservoir, are in red; and false negatives, in which the seismic wrongly predicted the absence of reservoir, are in yellow. (b) The drilling campaign involved 14 wells, color coded according to the Boston square in (a). (c) Pie-chart representation of the results of (b). Figure modified, after Blangy et al. (2014).

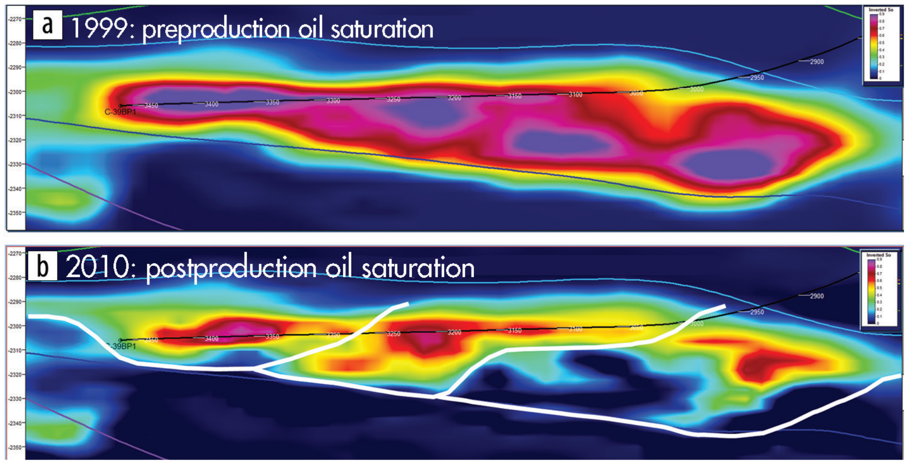



**Figure 6.** Assessment of water sweep in a reservoir under water flooding. (a) Vertical seismic section showing RPI inverted oil saturation in a channel sand (1999, preproduction). Deep blue colors represent either high water saturation or nonreservoir, while deep reds represent sand reservoirs with high hydrocarbon saturations. (b) RPI-inverted oil saturation in the same sand, postproduction in 2010. 4D changes are evident within the basal conglomeratic part of the sand, which has higher permeability. Figure modified, after Blangy et al. (2014).

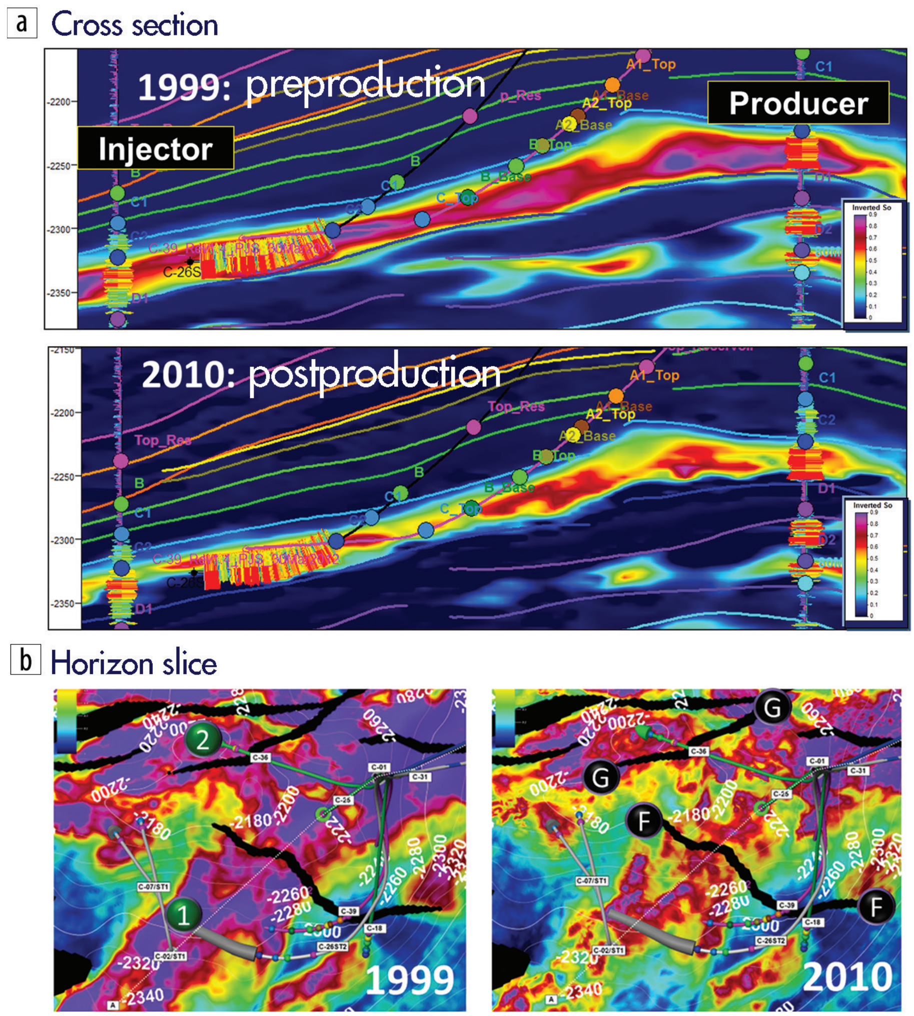



**Figure 7.** 4D data seismic RPI-calculated oil saturation volumes through time, used to evaluate the recovery efficiency from the field. (a) Cross section of seismically derived oil saturation, pre- and postproduction at Ceiba. The section is along the axis of the main channel (SW-NE). Deep blue colors represent high water saturation, while deep reds represent sand reservoirs with high hydrocarbon saturations. (b) Horizon slices extracted at the main reservoir level from seismically derived oil saturation, pre- and postproduction at Ceiba. Note faults F-F and G-G, as well as the anomalous areas labeled 1 and 2, discussed in the text. Figure modified, after Clechenko et al. (2014).

4D changes are evident within the basal part of the sand, which consists of a conglomerate of higher permeability. They indicate that this portion of the sand body has been thoroughly swept, while the upper portions of younger channel fill remain undrained. This is a 4D example characterizing vertical sweep during production. The solid white lines in Figure 6b indicate additional lateral offset surfaces — or permeability barriers — which define the internal architecture of the channel fill. It is important to note that those internal barriers were not readily identifiable in the baseline static 3D survey acquired in 1999. Through simultaneous RPI, the 4D has defined isolated and largely untapped reservoir compartments that were previously unknown. The compartments form infill targets that were subsequently confirmed by the bit. This was one of the true positive cases discussed in Figure 5.

***Sweep efficiency of water injection.*** The second example shows the use of 4D to assess the sweep efficiency of water injection. Figure 7a shows another 4D seismic example from the Ceiba Field. The difference in the 4D data is used to evaluate the recovery efficiency from the field. Here we analyze seismically RPI-calculated oil saturation volumes through time, between 1999 and 2010. The injector is located downdip to the left of the figure, and one can readily see the preferential water sweep at the base of the sand.

To evaluate areal sweep, we do the analysis in map view or, better yet, directly in the 3D volume of calculated oil saturation. In Figure 7b, the sand channels are oriented in a northeast-southwest direction, and we compare their saturation in 1999 and 2010. One can see the horizontal sweep from southwest to northeast in the main sand. The F-F fault appears to be a minor baffle, while the G-G fault has acted as a barrier to fluid movement. The area labeled (1) has been efficiently swept, while the area labeled (2) is a candidate for redrill.

Using outcrop data, Beaubouef et al. (2011) showed the importance of identifying barriers and baffles in producing reservoirs to develop models that accurately predict reservoir performance. This level of granularity in the identification and mapping of the regions of sweep in the reservoir, as well as subtle barriers or baffles, would not be obtainable using only well-based surveillance tools (Figures 6a and 6b).

The knowledge about the large-scale plumbing and connectivity — or lack thereof — within the reservoir channel complexes has been brought about by the analysis and understanding of the 4D seismic. It was previously unexpected and therefore was an "unknown unknown."

***Monitoring reservoir pressure changes.*** The third example shows how we are using 4D to monitor reservoir pressure changes over time. Some published examples have shown successfully that 4D techniques can be used to monitor pressures as a function of time in a producing reservoir. One such example can be found in MacBeth et al. (2006).

Figure 8 shows a striking example of reservoir pressure buildup by water injection, as identified from 4D seismic RPI at the Okume Field (Figure 4). The water injector is located toward the left of the map; a new well, as shown in white on the map, was drilled along the channel axis appearing in red (Figure 8a). The seismic lines are oriented north-south along the well path. As seen on the section of RPI-calculated oil saturation (Figure 8b), two well-defined sand channels are identified within the two lines that delineate the top and base of the reservoir interval. The lower unit appears to be discontinuous based on the 2003 oil saturation, but it exhibits a large decrease on the AI difference section (deep red or softening in AI) as shown in Figure 8c. This is also accompanied by a decrease in shear impedance (SI), shown in Figure 8d. The change in elastic impedances within the sand is interpreted as water pressuring through the aquifer, rather than "pushing" oil toward the producer. Based on RPI analysis, the sands were predicted to be overpressured by approximately 1000 psi during injection, and by 500–700 psi while the injection is turned off. This prediction compared favorably to the results obtained in the field: the injector was shut-in, a production well was drilled (as shown), and actual overpressure measurements of close to 700 psi were obtained. This 4D analysis provided insights as to the large amount of overpressuring that is actually occurring within the aquifer due to water injection. Prior to the 4D analysis, this was an "unknown unknown," yet this knowledge is important to management of the water-injection program used for enhanced recovery.

Ultimately, the goal in any 4D activity is to monitor the evolution of the reservoir and to look for deviations from our understanding of how that reservoir should behave. In other words, the value of the 4D here comes from seeing a variance from the expected behavior and taking corrective action to improve field performance.

***Detailed planning at the well scale.*** Our last example shows how we used 4D to plan detailed intervention at the well scale. When fields start to age, it becomes important to understand large-scale changes in the overburden (above from the reservoir) as well as changes within the reservoir. These changes occur at the well-completion scale. Fields in their final stage of production hold smaller remaining reservoir targets that require more complex well paths, thus necessitating detailed fine-scale planning integrated with geomechanics.

Figure 9 is an example from the Okume Field, showing the very complex path taken by the water (water channeling) from the injector on the right to the producer on the left. Two paths, as indicated by the white lines, are taken by the injected water at a bifurcation point: one path leads to the overpressuring of a poor-quality low-permeability sand, as depicted by a decrease in AI shown in orange colors; the second path flows through a separate sand channel of good quality and displays water sweeping in a circular pattern

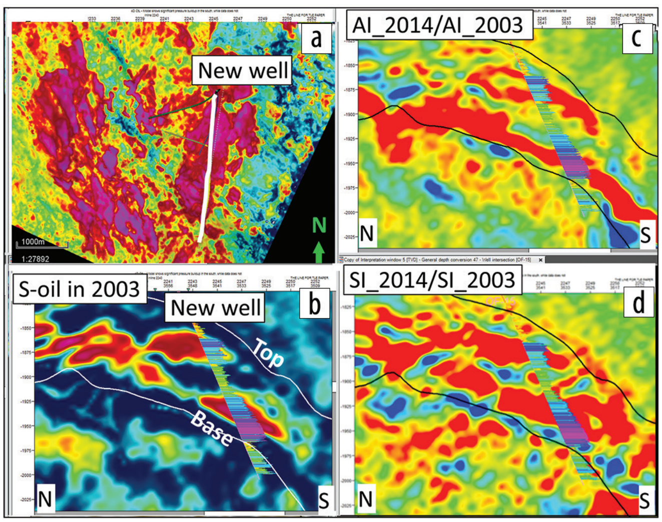



**Figure 8.** (a) Map showing the location of a new well that was drilled along the axis of a sand channel. (b) The RPI-calculated oil saturation from 2003 shows two sand channels, with the lower unit appearing to be discontinuous from north to south. (c) and (d) However, this same sand appears continuous and exhibits a large decrease on the AI and SI difference sections (deep red or softening in impedance). This indicates that the lower sand is connected and is being pressured up by water injection nearby, which was confirmed by the well.

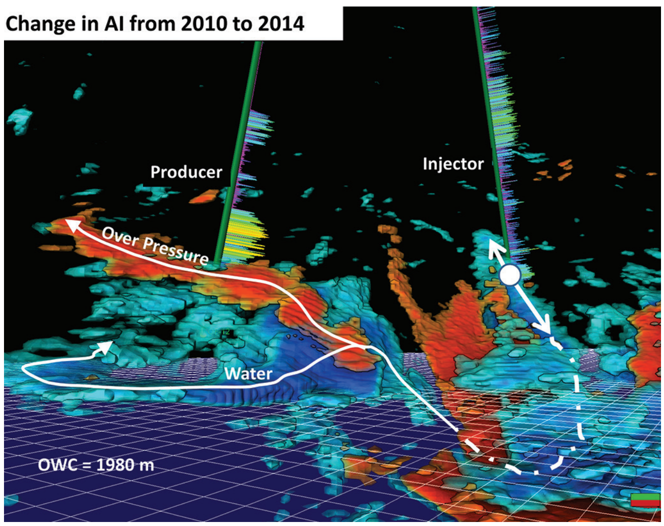



**Figure 9.** A 3D perspective at Okume, showing the complex paths taken by the injected water, which is channeling from the injector on the right to the producer on the left. Two paths, as indicated by the white lines, are taken by the injected water at a bifurcation point: one path leads to the overpressuring of a poor-quality sand (as depicted by a decrease in AI shown in orange colors corresponding to seismic softening), while the second path flows through a separate sand channel of good quality and displays water sweeping in a circular pattern from right to left (as depicted by an increase in AI shown in dark blue colors corresponding to seismic hardening).

from right to left with no overpressuring, as depicted by an increase in AI shown in dark blue. When the recently drilled producer at the left of the figure encountered the top (orange) channel on its way down to another target, it confirmed the overpressuring of that sand. This 4D example has shown the local complexity of sand-channel geometries that occur at the well scale. Clearly, these geometries were unknown prior to insights from the 4D.

Another example at the well scale is shown in Figure 10, in which a candidate well was identified for intervention. 4D seismic inversion revealed water entering the lower sand at the toe end of the well. That part of the well was shut off, and the shallower reservoir sand was completed. This recompletion resulted in a doubling of oil production and in reducing the water production by a ten-fold factor, clearly adding value to the project.

## Economic analysis of 4D

We recommend that the economic assessment of 4D's value be undertaken in a systematic manner. It is easy to estimate the cost of acquiring a 4D survey, but assessing its value is more challenging. A seismic survey does not have the same direct linkage to barrels of production as does a development well. As a result,

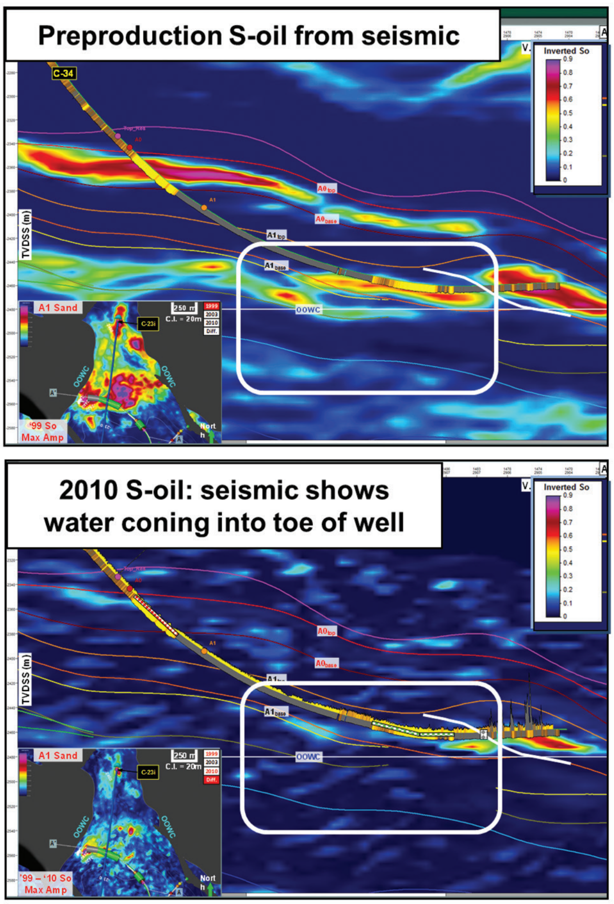



**Figure 10.** Example of RPI-calculated oil saturation used with the 4D seismic to monitor production performance at the well scale, and to guide recompletions and/or workovers. Deep blue colors represent high water saturation, while deep reds represent sand reservoirs with high hydrocarbon saturations. Water is seen entering the completed interval in the lower sand at the toe-end of the well. That part of the well was shut off, and the shallower reservoir sand was successfully recompleted as an oil producer. Figure modified, after Clechenko et al. (2014).

it is easy for decision makers to delay or not approve a seismic program because 4D appears as a separate budget line item with cost but no revenue, so striking it from the budget makes the short-term economics more attractive. Embedding the cost of seismic into a drilling program's economic analysis is a better way to estimate 4D's value impact on a field development.

There are several possible ways to capture the value creation associated with 4D seismic.

***The EMV approach.*** One way to capture this value creation is to calculate an expected monetary value through decision trees. This approach requires an estimation of Bayesian probabilities of geologic and commercial successes with and without 4D. However, it is not a trivial matter to assign probabilities to the branches describing a future well that would be planned with or without 4D seismic. By using reasonable ranges in the probabilities of the various branches, it is possible to gain intuition as to how much improvement 4D would need to create in order to materially impact overall project NPV. This technique can give an idea of whether the field would benefit from investment in a 4D survey. If posterior probabilities are little changed regardless of a 4D survey, then the value of this 4D information is low.

***The scenario approach.*** Another way to look at the incremental value of 4D is through the use of Venn diagrams, by comparing scenarios of field development with, and without, 4D seismic. If decisions around a preferred scenario are likely to be impacted by information we expect to obtain by 4D, the survey will likely improve the decision quality.

***Bundling the 4D with an associated well campaign.*** A third way is to contrast the economics of a field-development program that would take place without 4D versus another program that would take place with 4D. We then display the analysis as reflecting the impact (difference) that the 4D has made on the net present value (NPV) of the field over time. We favor this third approach, and we present an example from a field development in one of our areas. In this case, the seismic cost is "bundled" with the anticipated cost/benefit analysis of all upcoming wells so as to capture the overall improvement that 4D brings to the value of an entire drilling campaign.

Figure 11 shows our analysis using the third method. First, we assume that 4D has no influence on all activities that are in the FDP. In other words, these are the economics for the field development, executed in the absence of knowledge from 4D. Individual wells, consisting of new wells that were already in the plan, work-overs, and redrills, are all credited to operations and are displayed in yellow. The total value of these wells in yellow (wells labeled "a" through "g") is illustrated by the blue baseline in Figure 11. They form the value of the field development, without benefit of 4D.

Second, we incorporate the benefits of having the insight from 4D: we either add new projects brought about through the 4D (i.e., we add new wells), or we drop planned activity (for example, we drop an injector, or we delay the conversion of a producer to an injector). The individual wells that are purely attributed to the 4D are represented in green (wells labeled "1" through "7"). Once we have prioritized the sequencing of the wells, based on an agreed rig schedule, the value for the new program point forward, including the yellow and the green wells, is represented by the red line in Figure 11. Sometimes, the attribution of value to a particular well is split between the 4D and operations. That is the case for wells 4/e, 5/g, and 6/g, where the asset team assigned a split attribution of value between the seismic and operations (wells in green and yellow in Figure 11).

Our analysis covered a drilling campaign that involved a total of 11 wells. The incremental NPV due to the 4D is the difference between the blue and red curves. The absolute monetary scale (the numbers in dollars on the vertical axis) has been removed, but one can see that in a relative sense, the 4D has enabled approximately one-third of the value of the total redevelopment program moving forward; yet the incremental cost of the 4D is a small fraction of that. This results in a very high rate of return for the 4D survey itself, given that it brings new reserves at low cost while taking advantage of existing infrastructure in the area.

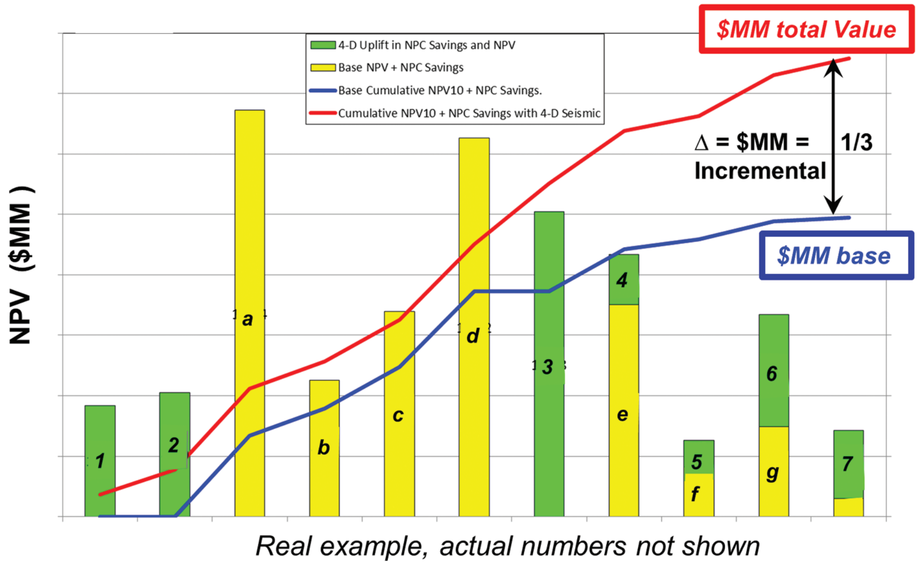



**Figure 11.** The value of 4D, measured as the incremental NPV of the field due to reservoir management activities caused by the 4D. All individual wells that were already in the plan are credited to operations and are displayed in yellow (wells labeled "a" through "g"). The total value of these wells is the blue "base" line, which forms the value of field development without benefit of the 4D. The individual wells that are purely attributed to the 4D are represented in green (wells labeled "1" through "7"). Wells 4/e, 5/g, and 6/g were assigned a split attribution of value between the seismic and operations. The incremental value of the 4D is approximately one-third of the value of the field redevelopment project. Figure modified, after Blangy et al. (2014).

The value outlined in our example does not capture the improved decision quality in the reservoir management going forward, as the 4D is integrated with other reservoir surveillance tools to inform normal field operational decisions in the future. Reservoir engineers in the team now routinely approach geophysicists when the performance of wells does not fit their expectations and ask "what do you see in the 4D?"

## Conclusions

4D seismic is a potentially high-value addition to a field's reservoir surveillance plan and should always be considered during life-of-field reservoir management planning. 4D seismic can influence the field development in many ways and at many times during the life of a field. These include:

1) extending base production, production forecasting, and holding a production plateau through identifying new infill targets;
2) monitoring field depletion and managing recovery processes through reservoir surveillance away from wells;
3) optimizing production operations through identifying problem completions and candidates for interventions at the well-scale; and
4) managing mature fields through reducing drilling-related nonproductive time and cost, optimizing complex well paths, and planning for field abandonment and environmental monitoring.

We have provided examples of these four applications and discussed ways to measure the value of 4D seismic. Value-of-information exercises are useful in attempting to capture the benefits of 4D seismic surveys. However, it is by combining the 4D with the actions that follow from it in the field, and by calculating new field development economics, that the technology's full business value can best be realized. We also found that traditional value measures often tend to underestimate the true value of 4D, because 4D seismic uncovers the "unknown unknowns" in our fields. The 4D-enabled insights of the subsurface invariably impact existing field-development plans in a timely fashion and increase the clarity of key decisions. TLE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