Accelerating insights from 4D seismic data with new multi-dimensional data structures

Bill Shea[1]*, Jorg Herwanger[1] and Peter Harris[1] demonstrate the work efficiency gains that are achieved by taking a 'multi-dimensional' computational approach to time-lapse analysis.

Motivation/abstract

4D seismic reservoir monitoring is routinely used to interpret the temporal changes in seismic response in terms of hydrocarbon saturation and phase, pressure, and temperature. Processing, repeatability quality control (QC), and difference analysis are typically carried out between vintage pairs, with the effort growing significantly as the number of monitoring surveys grows. The objective of this work is to demonstrate the work efficiency gains that are achieved by taking a 'multi-dimensional' computational approach to time-lapse analysis. Partial angle stacks (or angle gathers) from all seismic vintages are assembled in a single 'pseudo pre-stack' matrix of traces, to automate and accelerate the calculation of quality control (QC) attributes and production-induced time shifts. The new data structure also simplifies visualisation of 4D differences for any monitored time-step, to better understand the effects of production and injection from specific wells. For illustrative purposes, the article describes application of the method to a time-lapse dataset containing nine seismic vintages, with nine sets of pre-stack gathers and full-stack volumes, as well as 27 angle stacks.

Introduction

4D time-lapse seismic reservoir monitoring is now commonplace in large oil and gas fields and plays an important role in decisions regarding reservoir management, including the placement of new infill wells and interventions in existing wells. With frequent monitoring, it becomes possible to capture transient effects in the reservoir that would otherwise be missed with fewer monitors (Figure 1).

However, this often places increased pressure on interpreters to shorten analysis cycle time. Interpretation of the seismic changes must be shared with reservoir engineers and used to history match the reservoir simulation. The process typically involves updating the 3D geologic model, and upscaling to create a modified reservoir flow model, which is then used to simulate the seismic response again until there is a closer match.

In fields with active drilling campaigns, decisions on the placement of new infill wells or interventions on existing wells frequently must be made before a comprehensive multi-disciplinary analysis can be completed. Without full visibility, these activities are generally viewed as being somewhat high-risk. Significant value can be realised by automating time-intensive tasks, including calculation of QC attributes and production-induced time shifts, and simulating the effects of pressure and saturations using simple rock physics to make predictions with greater precision. By doing so, the cross-disciplinary loop can be closed quicker and a step-change improvement in 4D seismic analyses can be achieved. With modern quantitative interpretation (QI) software tools that utilise scalable high-performance computing (HPC) and automated multi-dimensional seismic analysis, this capability is now possible.

Building a modern 4D seismic analysis tool

Sharp Reflections originally developed its PreStack Pro software to meet the growing industry demands for viewing, processing and analysing pre-stack seismic datasets. However, through

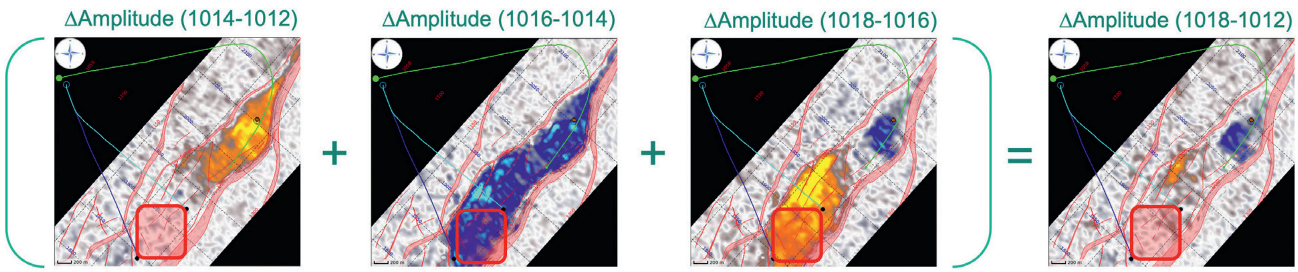

Figure 1 Incremental seismic changes from three successive monitor pairs compared to the overall effect observed over the total cumulative time interval. Frequent repeat surveys show that time-lapse signals can vary rapidly in calendar time. Effects from specific production processes (e.g. gas exsolution, transient pressures) may be captured if surveys are acquired with higher frequency.

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DOI: 10.3997/1365-2397.fb2023073

a combination of customer feedback and collaboration, and industry-funded research and development projects aimed at advancing 4D seismic interpretation, the platform has moved far beyond pre-stack analysis.

Geophysicists from Equinor began using the PreStack Pro software on 4D projects several years ago. Initially it was used for visualising time-lapse changes directly on pre-stack gathers. It was also used to apply identical pre-stack seismic conditioning workflows to each 4D survey. In certain cases, this helped to reduce noise, improve survey repeatability, and aided in identifying more subtle seismic changes.

With direct support from Equinor, the software's azimuthal data model was then adapted to work with time-lapse data, which helped with the visual comparison of time-lapse volumes and made it possible to run equivalent gather conditioning workflows on all vintages.

Over the years, additional features and functionality have been incorporated to automate and accelerate post-migration processing, repeatability QC, and quantitative time shift, time-strain and amplitude analysis of multiple time-lapse seismic vintages. At each stage of delivery, pre-stack gathers and angle stack seismic data are stored in 5-dimensional trace 'ensembles', which were initially developed to ingest and analyse migrated Offset Vector Tiles (OVT) containing offsets and azimuths.

We've adapted the OVT file structure to create a new pseudo-gather format for multi-vintage seismic computations. The 'offset x' axis is used to store traces that vary as a function of offset or angle, while the 'offset y' direction is utilised for time-lapse vintage. Traditional 'pairwise' computations between successive surveys have been replaced with a matrix approach, which permits more automated looping over all vintages. This method greatly reduces computational complexity, and at the same time permits interactive comparison of repeatability QCs, as well as time shift and amplitude differences between any pair of volumes in the ensemble. Data management is also simplified, as far fewer multi-dimensional data volumes are required to store each set of results.

Angle stacks, attributes, and maps are now treated as multi-vintage objects. Viewers display these multi-vintage datasets and show changes between volumes without pre-computing difference volumes. Overall, the extension of the 5D concept has established a brand-new way for interpreters to organise and analyse data by providing the ability to scroll through all vintages interactively and pinpoint changes that are often difficult to detect on static displays.

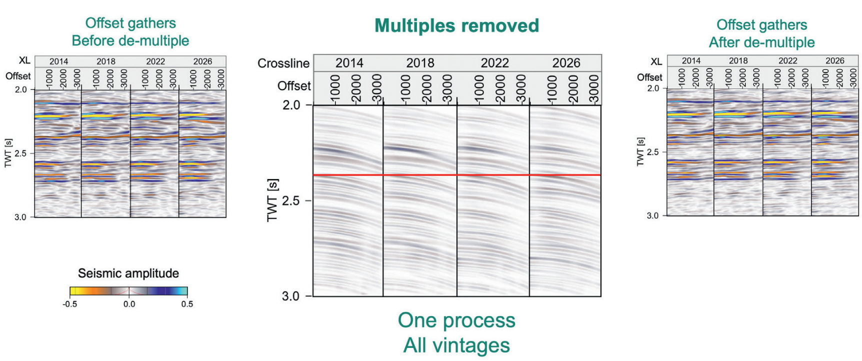

Figure 2 Effect of applying Radon demultiple on migrated offset gathers.

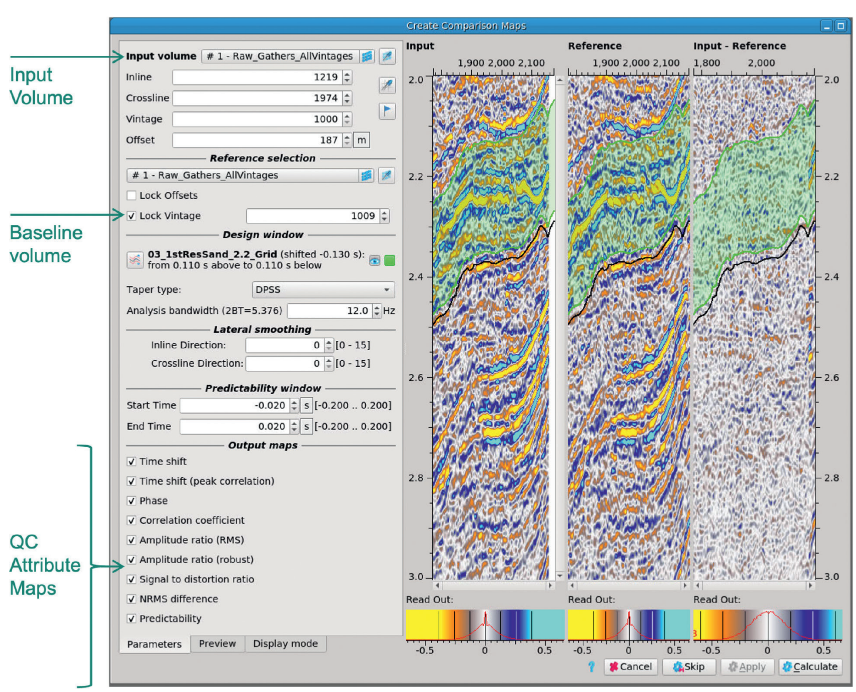

Figure 3 4D comparison maps are produced between the baseline volume and each successive monitoring survey in a single computation. The tool may be used on stacks, gathers, and on partial stacks, with one map per offset or angle.

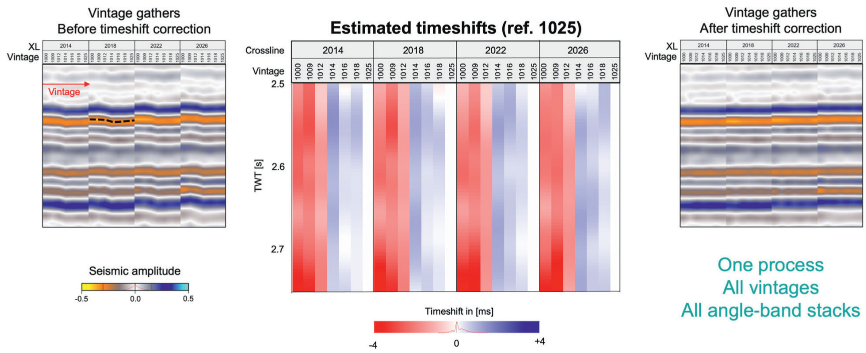

Figure 4 shows the effect of multi-vintage time shift estimation and removal for a single angle stack volume at four selected CDP locations. Input and output data are displayed as 'vintage pseudo-gathers", with survey date increasing from left to right. On the input data, subtle time shifts are observed on all strong reflections, but have been removed on the resulting output stacks. Incremental time shifts between successive vintages are shown (central display), and these time shifts have been used to align all monitor surveys to the newest survey.

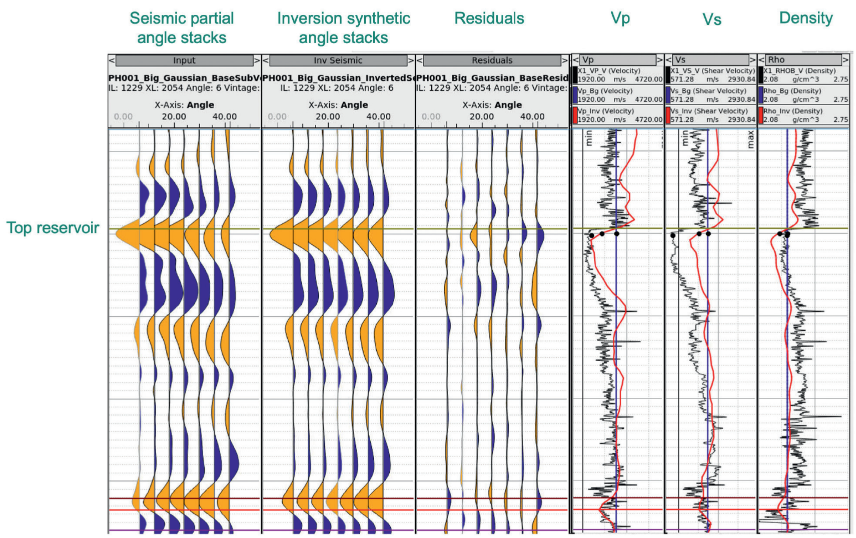

Figure 5 Results from pre-stack relative inversion at a single blind well location. Inverted Vp, Vs, and density curves closely mimic the main trends observed in well logs, although the dynamic range of the inverted data is somewhat reduced. This mismatch may be reduced by adjusting the scaling of the wavelet used for inversion but will not affect relative differences between surveys.

With the aid of a major software development consortium over the past year, we have added more 4D functionality, including:

- Launch of PCube+ 4D, which simultaneously inverts a baseline and monitoring survey to identify fluid front movements,
- New functionality to automate pre-stack and multi horizon attributes, which is especially useful to track 4D differences in multiple producing zones or fields with stacked pay,
- A new 1D non-linear inversion algorithm developed by the Edinburgh Time-lapse Project (ETLP) for time shift estimation and removal,
- A major upgrade to the parametric gather modeller, which now allows interpreters to model seismic changes as a function of both saturation and pressure.

The new capabilities aim to further speed up users' understanding of reservoir characteristics, for confident well targeting in field development.

Real-world use case

4D studies typically begin by comparing observed seismic changes to known changes in pressure, saturation, and other reservoir properties that occur during production. Baseline and monitoring surveys are first co-processed, with significant attention paid to ensuring detectability and optimising repeatability. Time-shift correction methods are then used to align each monitoring survey to the baseline, to remove two-way travel time differences that result from production-induced velocity changes in the reservoir. Finally, amplitude differences are computed on reservoir horizons, or inverted attributes are used to identify differences in key elastic rock properties.

While a quicker full-stack approach enables easy detection of 4D changes (i.e., hardening or softening), it is not sufficient to attribute the observations to specific changes in fluid saturation, pressure, temperature, or possibly even seismic acquisition and processing artifacts. Pre-stack seismic attribute methods offer the advantage of helping to separate effects due to pressure and fluid saturation changes but require more effort to apply. Pre-stack methods require many more individual volumes and generate multiple difference volumes for each vintage pair. In short, every analysis becomes multi-dimensional.

Pre-stack inversion is often used to estimate acoustic impedance (AI) and P to S wave velocity ratio (Vp/Vs), which both vary as a function of pressure, fluid phase, and saturation. With the aid of a rock physics model, it is possible to interpret these changes directly using the inverted attributes, and without generating intermediate pre-stack seismic attributes in the process.

Examples from a mature field with over a decade of time-lapse seismic monitoring serve to illustrate the complexities of working with many 4D vintages, and the significant efficiency benefits that accrue from our new multi-dimensional approach. In this case, the field operator has acquired nine surveys over the course of the field life, with a baseline survey and eight monitors.

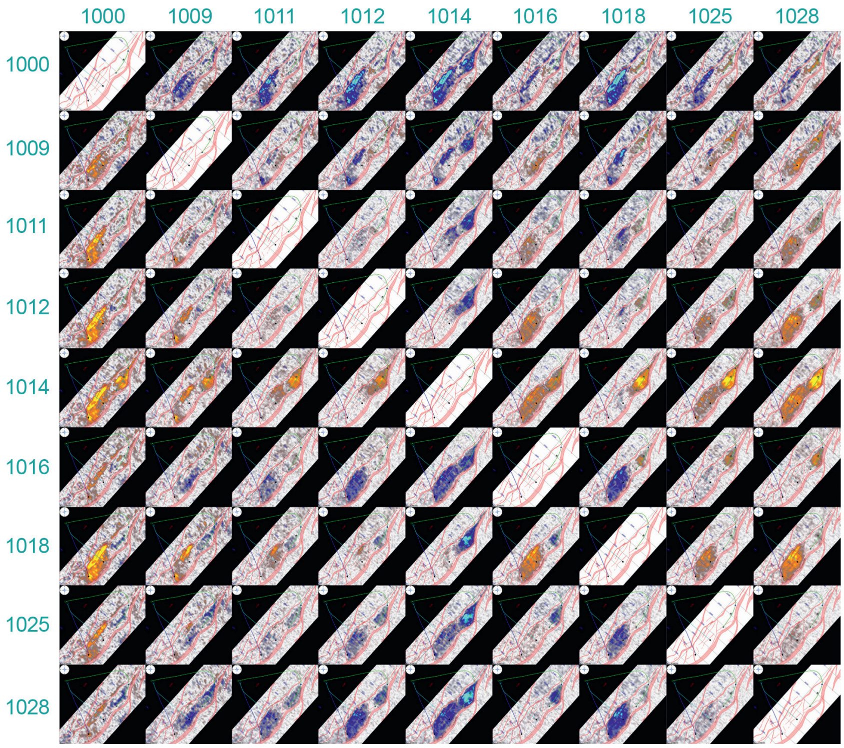

Figure 6 Full-stack amplitude differences (calculated consistently as newer vintage amplitude minus older vintage amplitude) at the top reservoir horizon. Nine vintages generate 81 possible difference pairs, with 36 unique 'non-diagonal' combinations (zero difference along the matrix diagonal). Blue colours indicate a hardening response and orange indicates a softening response.

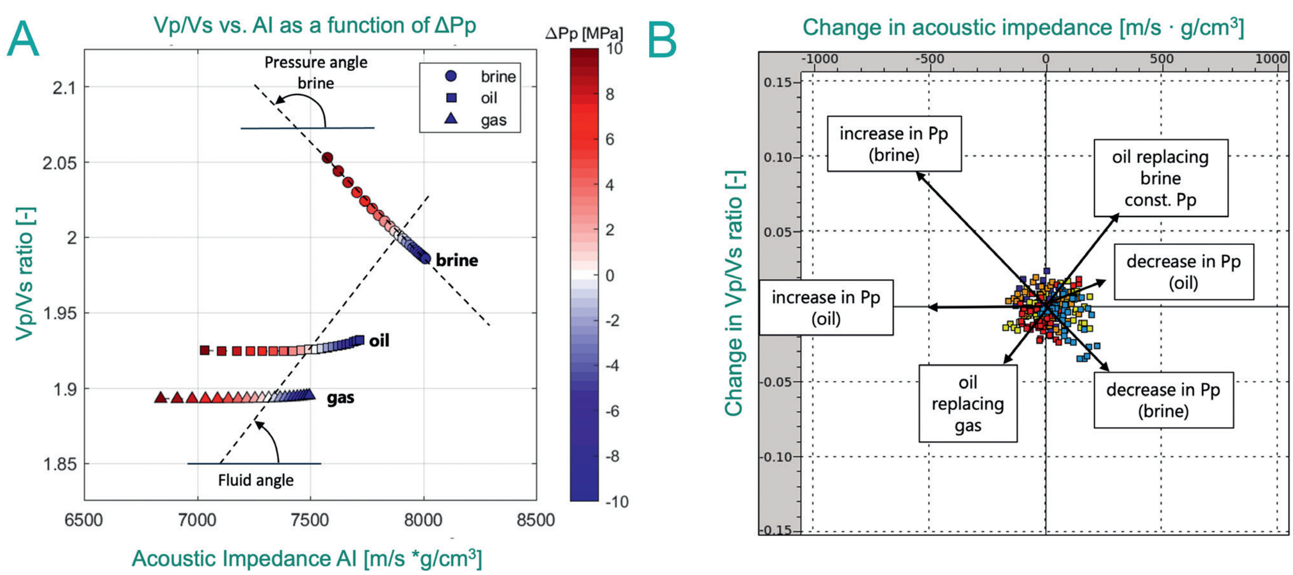

Figure 7 (a) Predicted AI and Vp/Vs due to changes in pressure and saturation, from rock physics model. (b) Cross-plot of differences in AI and Vp/Vs, with arrows showing expected directional movement due to changes in pressure and fluid phase. Actual inverted seismic data points (coloured by vintage pairs) are shown in an area where no production effects are expected. The scatter in this plot indicates the expected uncertainty in the inversion results.

The seismic database consists of nine sets of pre-stack gathers and full-stack volumes, and 27 angle stacks (three per vintage), plus a multitude of derived volumes.

After arranging these data in multi-vintage sets, any pre-stack processing, matching, or QC algorithm can be applied to the nine sets of pre-stack gathers in a single automated run. This results in the generation of a single multi-dimensional output volume. Figure 2 above shows the effect of applying Radon demultiple on migrated offset gathers from one of the monitor surveys; at four CDP locations. The figure also shows the removed multiples, i.e.,the difference between the left image an the right image.

Similarly, a complete suite of common 4D comparison maps may be generated between each monitor and the original baseline survey, for every individual trace in the pre-stack offset gathers (Figure 3). This detailed scrutiny of offset-dependent repeatability may be used to selectively remove particularly noisy traces before stacking, to lower detectability thresholds and improve confidence in the subsequent interpretation.

Time-shift computations are also dramatically simplified using the multi-vintage approach, as shifts are simultaneously computed and removed for all offsets or angles and all vintages. (Figure 4). The resulting output volumes can be quickly QC'd before proceeding to more detailed analysis.

Each vintage is inverted to Acoustic Impedance (AI) and Vp/Vs ratio using a simple Bayesian pre-stack relative inversion. This inversion is derived entirely from the seismic data, without the need for a complex prior model. With this relative approach, inverted AI and Vp/Vs values do not match the dynamic range of log measurements at well locations (Figure 5). Nonetheless, relative differences between surveys have proven to be remarkably robust, and mapped differences are very useful in mapping pressure fronts and water sweep in the main producing reservoir.

Map-based amplitude analysis of differences between baseline and monitoring surveys generates a very large number of maps for each reservoir interval. Nine surveys yield 81 maps and 72 differences for each attribute, 36 of which are unique and non-zero. Our approach automates the generation of both instantaneous and interval attributes from all vintages for each producing interval, with differences between any pair of survey vintages calculated interactively (Figure 6). Overall changes are easy to detect on the maps themselves, and respond differently to water injection, water flood, changes in gas-oil ratio, and gas exsolution.

To help separate pressure and saturation effects, we use detailed cross-plot analysis to map the change in AI and VpVs ratio as a function of time and relate to known pressure and saturation changes measured downhole in wells or estimated from 3D reservoir simulations. Our inversion-based approach simplifies the analysis, since elastic property changes to pressure, fluid fill, and water and oil saturation can be derived from a simple rock physics model (Figure 7).

The rock physics model relates ΔAI and ΔVp/Vs to changes in pore pressure and Swater, Soil, Sgas. This model can be used to analyse temporal changes in specific map locations with the aid of regionally restricted cross-plots.

Figure 8 shows temporal changes in AI and VpVs between successive vintage pairs in two different locations within the reservoir. Vintage dates have been changed to keep the field example anonymous. Production from producing well P-1 began early in the field life, before the first monitoring survey was acquired ('year' 1012). Injection well I-1 came online at the same time, to maintain reservoir pressures and prevent gas exsolution from the original oil leg. This injector was shut in year '1015' and replaced by Injection Well I-2, which started injecting water in 1016.

On cross-plots, AI and Vp/Vs differences between successive vintage pairs helps to track changes in saturation and pore pressure during production. At the I-1 injector location (Figure 8a), inverted data show observed movements only along the NW-SE diagonal. Non-zero differences are observed (- AI, +Vp/Vs) during the first years of production. The first pressure drop was observed when injection switched from well I-1 to well-I2 but was quickly reversed when the new injector came online.

Cross-plot movements follow a more complex set of trajectories at the southwest end of the P-1 production well path (Figure 8b). Early in production, pressure decreases occurred as the injected pressure front appears to have been delayed.

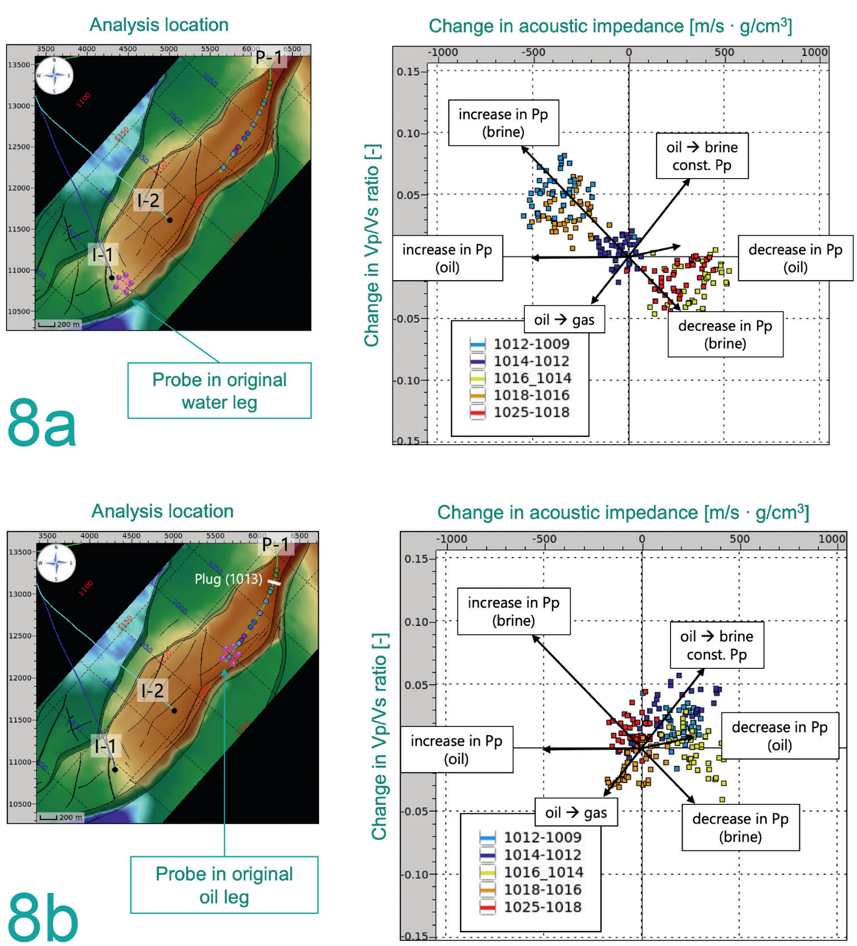

Figure 8 shows differences in inverted relative AI and Vp/Vs for successive vintage pairs at two different map locations in an isolated producing fault block. Incremental differences are colour coded by survey vintage pairs. Near the I-1 injection well location (8a) points move along the NW-SE diagonal, as expected for pressure changes in the brine leg. Differences are consistent with known pressure trends in the field. Near the toe of the P-1 injection well (8b) difference pairs move in directions suggesting combined pressure and saturation effects, with clear indications of hardening due to water replacing oil as early as year '1014'.

Pressures stabilised by 1014, and AI and Vp/Vs differences suggest that water had already reached the well location by that time. There are hints that some gas exsolution may have occurred in the interval 1016-1018, but was quickly reversed once injection resumed in injector well I-2.

The above analysis shows that semi-quantitative conclusions about competing pressure and saturation effects can be drawn from the inverted data and related directly to the production and injection timelines for wells. This analysis can only be conducted after all key processing, cross-equalisation, and inversion work is complete, and highlights the benefits of a fast, efficient, and multi-dimensional approach. The results were achieved in a small fraction of the time that is required for pairwise analysis. The study also highlighted the need to develop multi-dimensional cross-plotting capability and to extend the data model to even higher dimensions to handle multiple producing intervals, more attributes, and possibly azimuth-sectored seismic volumes.

Conclusion: The need to evolve

4D seismic is an increasingly important tool for pinpointing remaining drilling opportunities in producing fields, and acquisition technology advances have made it possible to monitor more frequently. As a result, there is a growing demand for interpretation and analysis software that efficiently analyses the breadth of data that is available, with very fast turnaround.

Operators who leverage the multi-dimensional data model and adopt a more automated multi-vintage analysis approach described here have led to efficiency gains and substantial reductions in interpretation cycle times. However, as its adoption has accelerated, a new set of challenges has emerged, particularly around integration with other key subsurface software tools, including those for simulation, geologic modelling, etc.

Many of the leading subsurface integration platforms utilise models that do not recognise multi-dimensional data structures (i.e., matrices). This creates the need for deconstruction and introduces constraints around reservoir management, which may lead to lost revenue and reduced recoverable reserves. It would be prudent for all subsurface software vendors to recognise the need to also embrace 'vintage-aware' data structures and foster seamless integration with modern pre-stack QI tools. Doing so would accelerate the industry's digital transformation and unlock further efficiency gains and cost reductions.

Acknowledgements

The data examples in this article were made available by Equinor and its partners in the field. Permission to use the data is gratefully acknowledged.