On the importance of high-fidelity 4D forward modelling, embedded in a redefined closed-loop reservoir monitoring framework: A case study

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Abstract

Forward modelling is a fundamental part of time-lapse feasibility studies and closed-loop reservoir monitoring schemes. The forward modelling workflow represents a complex interaction between multiple domains, each contributing its own set of assumptions, models, and simplifications, based on a priori information. To allow for the best use of the modelled data, the aim ought to be to keep the level of modelling-introduced noise as low as possible to allow for an optimized decision making process on the specifics of a particular time-lapse project. These considerations will have a profound impact on cost and production.

It is therefore key to keep 4D signatures subsurface-relevant, avoiding any contributions from low-fidelity forward modelling. To address this challenge, the paper at hand offers a redefined closed-loop reservoir monitoring framework that draws from and caters for a field-scale dynamic integrated Earth model and applies for various geophysical measurements. The validity of the framework and its implications are demonstrated using the purpose built Chimera model which comprises a four-way closure, faulted structure, and represents a turbidite-type reservoir with clastic depositional sequence.

Introduction

Literature produces many successful examples of time-lapse seismic case studies, with carefully analyzed 4D signatures. Calvert (2005) and Johnston (2013) offer detailed insight in this regards, by also simultaneously sketching the state-of-the-art of time-lapse seismic processing. However, quantitative and even qualitative comparisons of differences between predicted and actually measured time-lapse seismic data are much less performed and discussed in open literature, despite the obvious benefit for model reconciliation. An explanation can be found in the assumptions and methodology used for the feasibility study which can be too simplistic to warrant for a meaningful comparison. When examining 4D signatures, it often turns out that the observed 4D signal is considerably bigger, smaller or different in shape than what was expected from the preceding feasibility study, producing an ε term. Given the level of uncertainty within a 4D feasibility study performed, such a mismatch is even expected and the ε term can be further decomposed into three chief elements:

$$\varepsilon = \varepsilon P + \varepsilon G + \varepsilon M$$

εG refers to a mismatch between the actual geology and the model geology, εP refers to a mismatch between the actual physical properties and the model properties, whereas εM refers to the mismatch introduced by not taking the full complexity and interactions into account when forward modelling the data. Hence, εM can also be considered as a modelling noise term.

A structural model is built on the a priori information available within the area of interest. This can be guided by a range of geophysical measurements. These measurements are typically calibrated against rock physical properties from coring or logging to fully populate reservoir dynamic and geomechanical models. A time-lapse seismic campaign can help to reduce remaining uncertainties εG and εP inherent to the shared Earth model, as part of reservoir characterization, by also providing much needed lateral resolution away from the wells. Decoupling observed ε term, the mismatch between forecasted and measured time-lapse difference, into its individual contributions can prove difficult: A pragmatic approach would be to attribute amplitude differences to εP whereas the lateral correlation term can be attributed to structural differences, governed by εG. Clearly, reality is much more complex and these two terms are intertwined. In any case, the εM term has to be kept at a minimum.

4D feasibility studies pave the road ahead for a time-lapse seismic project on one hand, with a poor feasibility study likely to incur additional cost - should it be of missed 4D opportunities or of suboptimal repeat survey timings for reservoir monitoring. On the other hand, closed loop seismic reservoir monitoring schemes also take forward modelling into account, generated for a number of possible reservoir scenarios and to be compared with observed seismic. This allows to better constrain Earth model updates rather than solely relying on history matching that is limited to sparse well data (Hatchell et al., 2002). Hence, whatever modelling noise εM is being present in the data, this is also going to be wrapped into the structural and physical re-evaluation of the dynamic integrated Earth model. Therefore, a high-fidelity forward modelling process is required. In the following, a redefined closed-loop reservoir monitoring framework, with an emphasis on seismic, is going to be introduced which allows to minimize εM and therefore optimize the use of forward modelled data.

A redefined closed-loop seismic reservoir monitoring framework

The history of closed-loop seismic reservoir monitoring dates back to early 2000's. Gosselin et al., (2003), as part of the history matching using time-lapse seismic project, produce a schematic flow depicted in Figure 1. It is noted that proposed forward modelling step is too costly and hence, they reconcile the workflow by comparing elastic parameters.

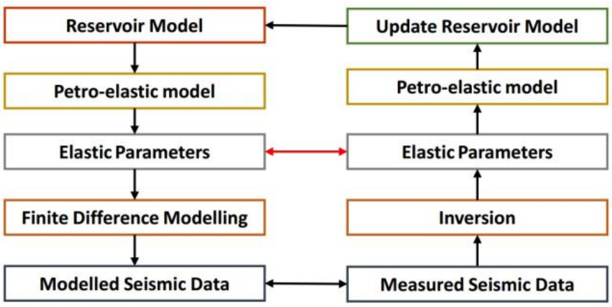

Figure 1: Closed-loop seismic reservoir monitoring workflow as sketched by Gosselin et al. (2003).

Over the next decade the technologies used in the forward modelling step of the closed-loop seismic reservoir monitoring workflow grew in line with the availability of compute resources. Two groups of methods commonly used were, and still are: a) variations on well log based fluid-substitution and petro-physical modelling, which are typically 1D and neglect realistic noise, overburden and acquisition configuration effects, and b) simulation-to-seismic modelling: Gjøystdal et al. (2007) model noise free seismic data attributes, incorporating overburden and acquisition configuration effects via ray-tracing, but still neglect realistic noise, whereas Allo et al. (2013) use 1D convolutional modelling to compute a synthetic seismic cube for each angle of incidence and each vintage. In all cases the modelling is largely confined to the reservoir interval. Even though these methods are known for its inaccuracy in describing wave propagation in complex media and its inability to describe the entire acoustic or elastic wavefield compared with full-wave methods (Thore, 2005), they still occupy a primary position in 4D forward modelling studies. The reasons are probably that these methods are generally very fast (Sahin et al., 2011).

In parallel, research increasingly indicated that the 4D seismic signal associated with production was not limited to the reservoir but that the 4D signal radiates into the over-burden, side-burden, and underburden, driven by geomechanical effects. Consequently, and to accurately predict a 4D response related to production, modelling can't be limited to the reservoir only and has to be extended to the full field and its geomechanical effects (Herwanger and Horne, 2009; Minkoff et al., 2004), describing the acoustic and elastic response to both reservoir and field-wide changes. This complex interaction incorporates the reservoir dynamics component, which encompasses fluid properties, fluid flow characteristics, field performance history and pressure distributions and profiles over time, but also the changes in stress induced by the pressure changes during production. It is the stress changes that induce strains and deformations not only within the reservoir but also around it. Hence, understanding the reservoir dynamics is not possible from studying the individual geologic, reservoir simulation, and reservoir geomechanical models in isolation but it requires them to be integrated into a full-field coupled dynamic integrated Earth model. In addition advances in computer hardware and software increasingly enable large-scale, field-wide 3D finite-difference acoustic and elastic modelling, which in conjunction with the necessary elastic properties derived from the dynamic integrated Earth model, allow to redefine the closed-loop seismic reservoir monitoring framework in Figure 2.

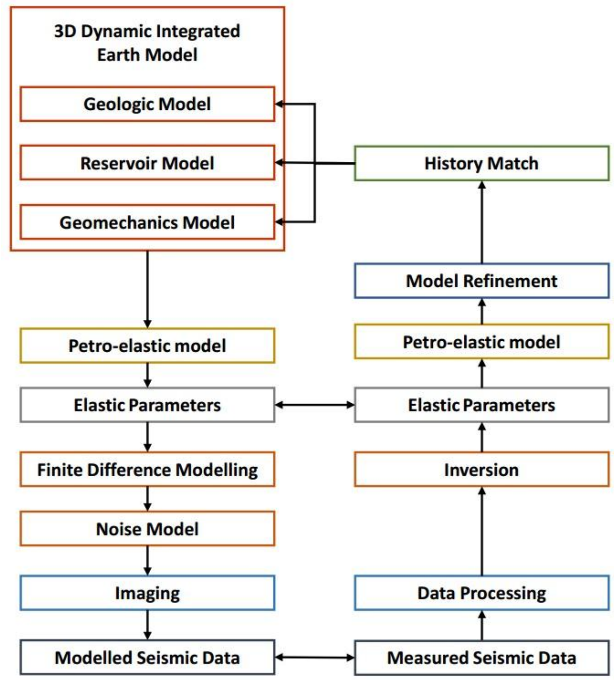

Figure 2: Redefined closed-loop seismic reservoir monitoring workflow, catering for a 3D dynamic integrated Earth model.

The benefits of a 4D feasibility study as a component in a closed-loop seismic reservoir monitoring workflow are maximised when the forward modelled 3D data corresponding to the base-line date are compared with the recorded and processed base-line 3D data to assist with static model reconciliation (Ullman de Brito et al., 2011; Rabani et al., 2014). Subsequently, the forward-modelled 4D data corresponding to the monitor date or dates are compared with the corresponding recorded and processed 4D monitor data to assist with dynamic model reconciliation (Stephen and Kazemi, 2014; Rey et al., 2012). Comparing high-fidelity forward modelled 3D and 4D data and appropriately processed 3D and 4D time-lapse seismic data can offer detailed insight into coupled reservoir fluid flow and geomechanical processes, allowing the operator to update and calibrate the dynamic integrated Earth model, facilitating higher fidelity predictions of future reservoir behaviour as part of a closed-loop seismic reservoir monitoring framework (Ali et al., 2008; Hurren et al., 2012, Pluchery et al., 2013).

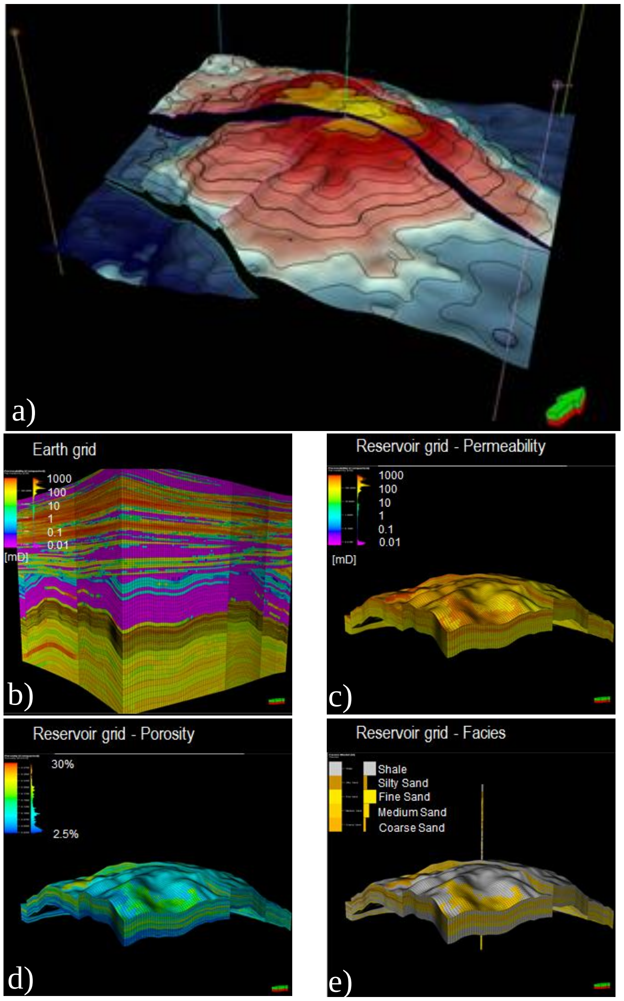

Figure 3: Chimera reservoir model, representing a faulted dome structure in a clastic environment governed by shale and sand. a) top reservoir, b) full-field permeability model on the Earth grid, c) permeability model on the reservoir grid, d) porosity model, e) facies model.

The workflow sketched in Figure 2 is a two-pass process. The first pass starts from the dynamic integrated Earth model and passes through a rock physics transform to obtain a 3D elastic, full-field geophysical model to surface. The sensitivity of the 4D signal to simulated reservoir changes as a function of future-time is analysed to assess the validity, frequency and design of seismic base-line and monitor acquisition. Assuming a 4D signal is detectable, the second pass starts from the processed time-lapse seismic and progresses through the inverse process to the reservoir simulation. At each step, analysis and reconciliation takes place between the measured and modelled 4D signal, ending the process with an update of the coupled dynamic integrated earth model. In the following, the seismic feasibility and forward modelling workflow of the first pass, the left column in Figure 2, is worked in detail using the Chimera model.

Chimera model and forward modelling

The Chimera model is shown in Figure 3 and depicts the static model to surface, along with the reservoir facies, porosity and permeability. It was built to test the redefined closed-loop seismic reservoir monitoring framework introduced in Figure 2 and represents a turbidite-type reservoir with a maximum sand porosity of 25% and a maximum permeability of 200 mD in a water depth of 200m. Hydrocarbon is accumulated within a four-way closure and the structure is segmented by a number of normal faults across the field. The reservoir contains light oil supported by an aquifer from the bottom and is associated with an initial gas cap. The bubble point pressure is approximately 275 bar.

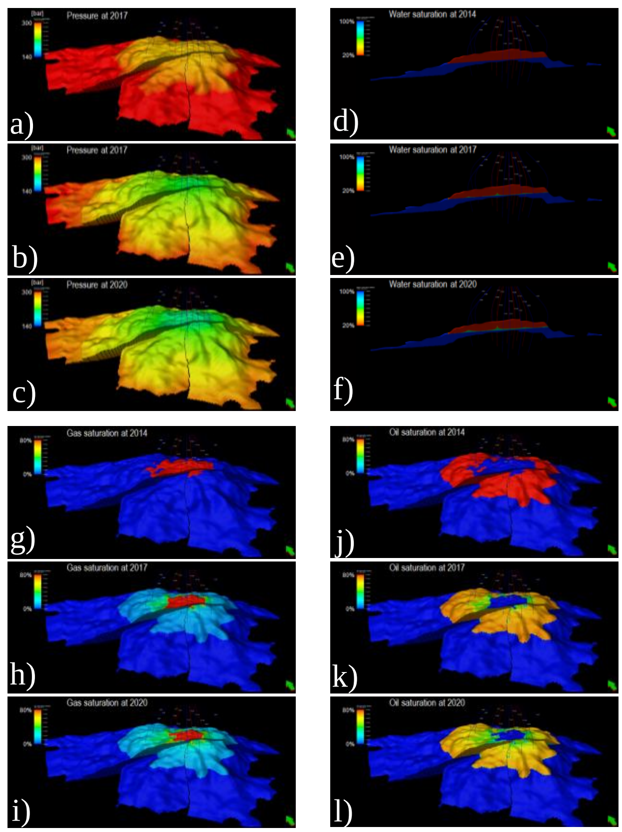

Figure 4: Dynamic reservoir simulation for two production scenarios: Primary production for the first three years, and water flooding for the next three years: a-c) pressure, d-f) water saturation, g-i) gas saturation, j-l) oil saturation.

For simulation, multiple time-stamps were generated in an interval of three years and with the monitor base-line set to 2014. The simulation consists of two main production scenarios, designed to evaluate the 4D seismic monitoring capability and its value in production history matching: primary production depletion, followed by water flooding recovery. During the first three years, the reservoir is produced using primary depletion, whereas during the following years the reservoir is produced by water injection to maintain reservoir pressure. Figure 4 depicts pressure, as well as water, gas and oil saturation of the simulation for the first six years.

To determine the changes in seismic response associated with these production scenarios, a high-fidelity 4D feasibility and modelling workflow is proposed as shown in Figure 5. Dynamic simulations are exercised as part of a dynamic integrated Earth model. Pressure changes caused by depletion or well injections generate a change in the effective stress in the rock, leading to compaction or expansion and changes in the elastic properties. These realizations are then transformed via the petro-elastic rock-physics model to obtain elastic properties for the 4D feasibility study.

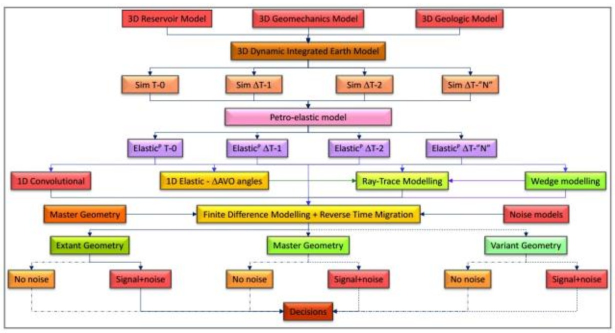

Figure 5: Proposed 4D feasibility and forward modelling workflow.

To determine the fluid sensitivity of the rock, where in most cases Gassmann's theory (Gassmann, 1951) is reliable, core measurements are often accounted for in order to quantify the stress sensitivity of the rock and MacBeth (2004) reports that accurate petro-elastic transfer functions that adequately translate the production scenarios to elastic properties are absolutely fundamental to the accuracy of the predicted 4D seismic response.

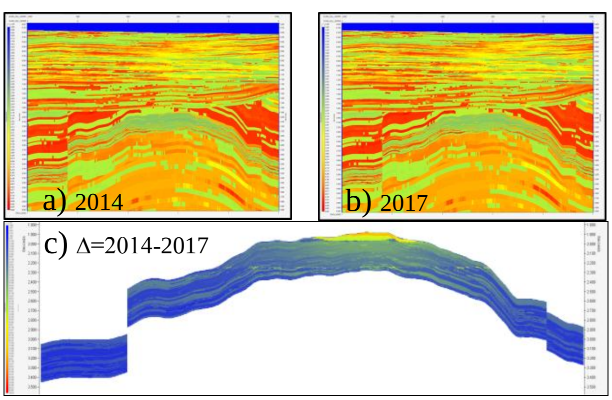

Figure 6: Elastic model obtained through rock physics transform. Vp is shown in a) for 2014 time stamp and in b) for the 2017 time stamp. Corresponding 4D difference is depicted in c).

However, rock sampling for special core analysis can be biased (MacBeth et al., 2006), for instance because of selecting competent rocks for sampling so that they don't fall apart. This will produce a biased feasibility study toward underestimating the strength of the 4D fluid or stress signal. Rasolofosaon et al. (2008) further reports that the inconsistency reported between the measurements and predicted response by Gassmann's theory seems to be tied to questionable velocity and drained moduli measurements rather than limitations by the theory itself. Nevertheless, for the synthetic study at hand, these uncertainties can be investigated in a controlled manner also by running sensitivity analyses of its impact to the predicted 4D signatures.

Having obtained elastic realizations through a rock physics conversion based on the primary depletion production scenario for the first three years (see Figure 6), ancillary modelling parameters are determined via 1D convolutional, 1D elastic, ray trace and wedge modelling before embarking upon finite-difference modelling with the derived elastic properties. The modelling effort depicted in Figure 7 shows results from a classic industry approach and simulates the final migrated image by convolution of vertical reflectivity profiles.

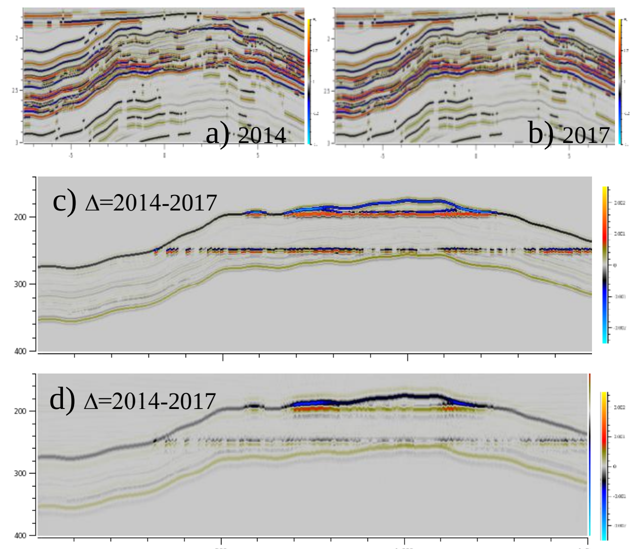

Figure 7: Reflectivity modelling using a 20Hz, zero-phase Ricker wavelet for a) 2014, and b) 2017. Corresponding 4D difference is shown in c). The 4D difference shown in d) stems from 2D ray-traced point-spread functions for base-line and monitor line.

Drawing benefit from its simplicity, the modelling however only describes wave behaviour in a layer-cake Earth with no lateral velocity variations. Therefore, when the objective is to model more complicated Earth models such as heterogeneous media, other modelling methods have to be employed. Stepping up the complexity of modelling, point-spread functions, defined as being the impulse system of an imaging system, can be employed to act as 3D pre-stack, true amplitude convolution method. Corresponding 4D difference is shown in Figure 7d, being in direct comparison with Figure 7c. It becomes evident that the two approaches yield considerably different 4D signatures, relating to a modelling error term εM.

In addition to the ancillary modelling parameters a master geometry definition is required together with a representative noise model. In order to determine if the base-line acquisition geometry will measure the 4D signal and if not what acquisition geometry will, a master geometry definition needs to be determined that is a super-set of the base-line geometry, such that the master-geometry can be decimated back to the base-line geometry and multiple other geometries of interest.

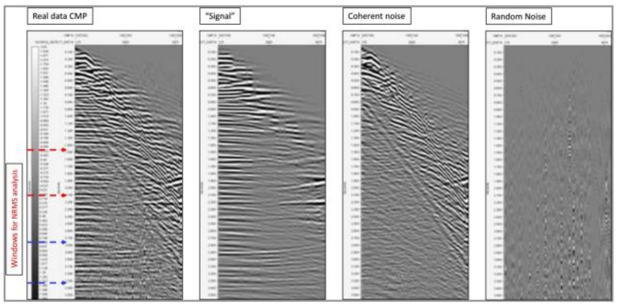

Figure 8: From left to right: Seismic gather decomposed into its individual components of signal, coherent noise, and random noise.

The representative noise model is built from the base-line seismic data by taking the processed data prior to prestack imaging and separating it into signal, coherent noise and random noise (Figure 8). The coherent and random noise models are then scaled appropriately and added to the finite-difference modelled shot gathers. To verify that the modelled gathers plus noise models accurately represent the recorded data they are calibrated via common mid-point variogram analysis (Calvert 2005). An example of such a variogram analysis is given in Figure 9, derived from the real data (blue), modelled data (red), the coherent noise model (green) and the random noise model (purple) within the red window indicated in Figure 8. Additionally, a variogram from the modelled data plus the appropriately scaled noise models is shown in orange. The variograms of the real data and modelled data plus noise models are not a perfect match. This is to be expected however, as the dynamic integrated Earth model is highly unlikely to ever capture all of the detail in the subsurface.

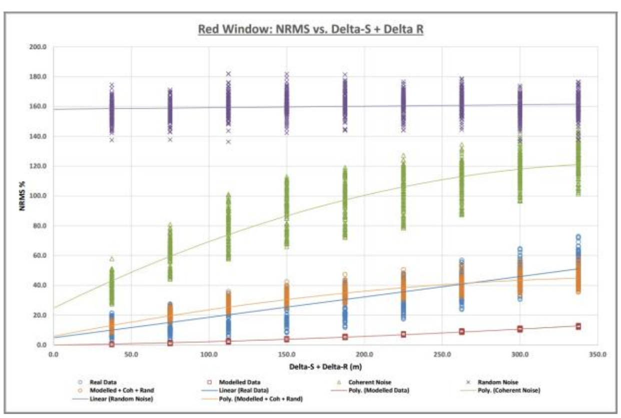

Figure 9: CMP variograms of real data, modelled data, noise models and modelled data + noise models.

High-fidelity forward modelling results are finally shown in Figure 10. Shots were modelled on a 25m interval, with receivers every 12.5m. The maximum offset modelled is 4000m. A 5085in^3 Delta Source signature was used, together with an anelastic full waveform finite difference implementation, using a Q value of 80. Realistically modelled noise was added to the modelled shot records which were migrated and stacked subsequently. Furthermore, different acquisition geometries were chosen to explore the robustness of the 4D signature and to optimize the acquisition.

The comparison to lower fidelity seismic modelling as illustrated in Figure 7 allows framing the characteristics of the modelling error term εM. Similar comparisons can be performed for reservoir scale versus full-field scale studies by taking into account the geomechanical effects, exercising all permutations of high-fidelity modelling elements to investigate the individual contributions to εM.

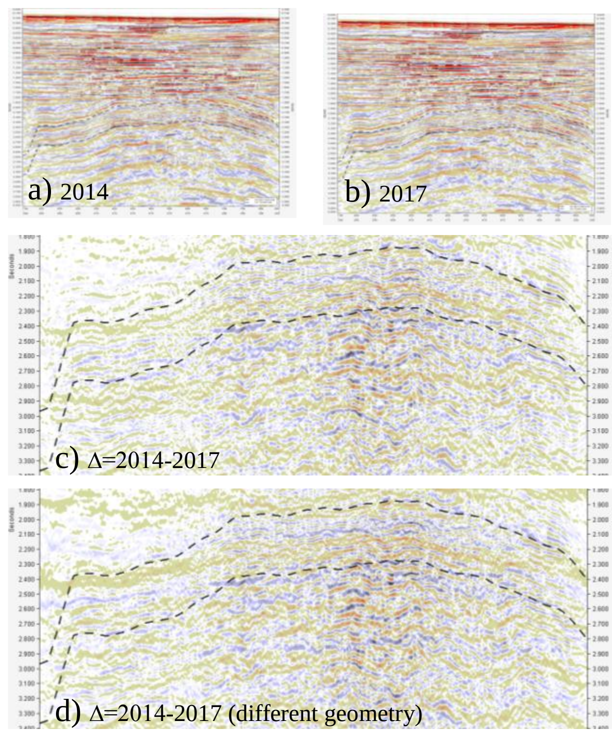

Figure 10: Finite difference modelled and imaged data with noise added for a) the 2014 base-line survey and b) the 2017 monitor survey. Corresponding 4D difference (x4) is shown in c). The 4D difference (x4) shown in d) corresponds to a different acquisition geometry.

Conclusions

The closed-loop reservoir monitoring framework has been redefined to incorporate the geologic, reservoir simulation, and reservoir geomechanical models into an integrated full-field coupled dynamic integrated Earth model to surface. The framework applies for various geophysical measurements. Given a range of reservoir simulations, high quality elastic parameters are derived via the petro-elastic rock-physics model for input into the forward modelling. In addition, the modelling step of the closed-loop reservoir monitoring workflow, illustrated by the seismic example now, comprises finite-difference modelling with realistic calibrated noise, imaged to produce a high-fidelity prediction of the 4D signal that will keep the modelling error to a minimum.

Having modelled such a high-fidelity 4D signal it can be determined if the base-line acquisition geometry will measure the 4D signal at the required time interval and if not what acquisition geometry will. In addition, reservoir monitoring can take use of the high-fidelity forward modelled data that goes beyond the traditional feasibility and survey design study, with the objective to reconcile modelled with actual measured data. Base-line data can be compared with the recorded and processed base-line 3D data to increase the fidelity of the static-model reconciliation. And the forward-modelled 4D data corresponding to the monitor date or dates can be compared with the corresponding recorded and processed 4D monitor data to increase the fidelity of the dynamic-model reconciliation facilitating higher fidelity predictions of future reservoir behaviour as part of a closed-loop reservoir monitoring framework based on a dynamic integrated Earth model and finite-difference modelling.

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