Reducing Turn-Around Time for Time-Lapse Feasibility Studies

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Abstract

Time-lapse seismic technology has become one of the main tools for production monitoring in off-shore reservoirs. Simulator-to-seismic workflows have been developed to integrate 4D seismic data with the production strategy. By comparing synthetic seismic traces computed from a dynamic reservoir model with real traces, reservoir engineers can update the reservoir model in order to honor the 4D seismic data as well as the production history. The same workflows can be used in the context of feasibility studies to assess whether 4D data will detect saturation and pressure changes in the reservoir and evaluate the optimum time interval between successive seismic surveys to monitor these changes. Turn-around time for current workflows tends to be on the order of weeks, making repeat work with different simulation scenarios or rock physics sensitivity analysis difficult. As a result, production strategy does not always benefit fully from the 4D seismic data, leading to poorly predictive models and low recovery factor. Furthermore, the past decade has seen a steady increase in the number of repeat seismic surveys acquired over the same field, requiring even faster modeling and interpretation turn-around time. This trend will only increase with the development of Permanent Reservoir Monitoring (PRM) systems capable of generating surveys on demand. In this work, we present a smart simulator-to-seismic workflow implementation delivering fast turn-around time. Through better integration with geomodeling software, seismic validation of history-matched reservoir models and time-lapse feasibility studies can be run in a few days. The new workflow is also more flexible and goes beyond standard rock physics modeling in order to handle unconventional fluids and reservoirs.

Introduction

Formento et al.[1] and Hatchell et al.[2] have shown examples of the important role time-lapse seismic data can play in production monitoring. Experimental simulator-to-seismic workflows exist in the industry to calculate the seismic response of flow simulation models but, as explained by Yuh et al.[3], the creation of pre-stack seismic cubes from 3D reservoir grids including millions of cells is not an easy task. Yet, this type of workflow is routinely used for 4D feasibility work prior to shooting a 4D seismic survey as demonstrated by Toinet et al.[4]. Such workflows are also extensively used to help interpret actual 4D differences by comparison with the 4D response predicted from a reservoir simulation model as illustrated by Haverl et al.[5] and Kawar et al.[6].

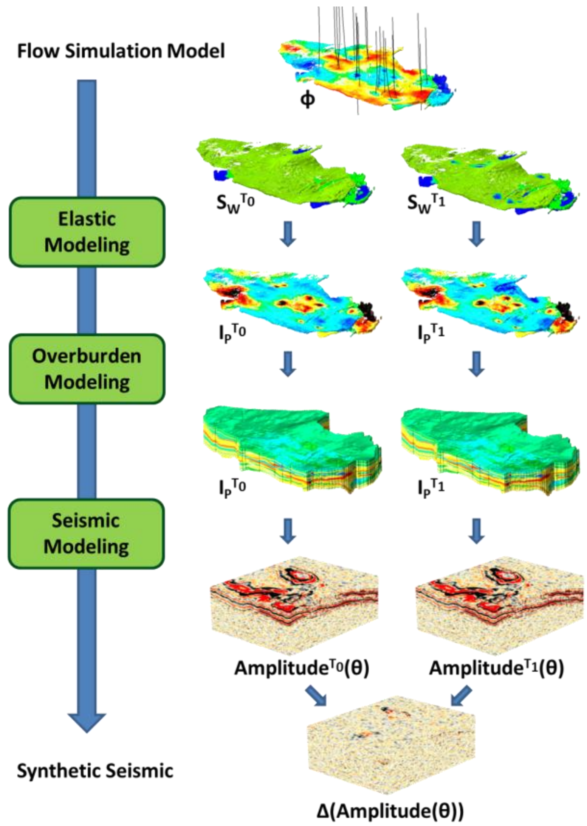


Figure 1. *Simulator-to-seismic workflow overview*. *The workflow starts from a 3D grid populated with static properties (porosity) and dynamic properties (saturations, pressure) predicted by flow simulations. First, a Petro-Elastic Model is used to link these reservoir properties with elastic attributes such as P-wave and S-wave velocities and density. Next, overburden and underburden intervals are added to the initial 3D grid in order to model the contrast of elastic attributes at the top and bottom of the reservoir interval. After resampling to the seismic bin and depth-to-time conversion, synthetic traces are computed from the extended 3D grid through a 1D wavelet convolution. Noise is eventually added to the synthetic seismic response in order to analyze the detectability of production-induced 4D effects with respect to expected repeatability of the measurements.*

The slow turn-around time of the workflow is, however, a strong limitation and underlines the need for an easier integration of 4D seismic data into the loop leading to production decisions based on the reservoir model. Early implementations of simulator-to-seismic workflow are often weakly linked with geomodeling tools increasing the data transfers and potential for errors. Furthermore, they are usually not able to handle complex rock physics models, such as the ones needed for unconventional reservoirs. To alleviate these problems, CGG and Petrobras have jointly developed a flexible simulator-to-seismic workflow, fully integrated with geomodeling applications and capable of using any user-defined rock physics model. We will present the main steps of this new workflow and show how it substantially decreases the turn-around time of time-lapse feasibility studies and seismic validation of flow simulation models.

Workflow Implementation

As illustrated in Figure 1, the workflow input is a 3D stratigraphic grid populated with history-matched dynamic reservoir properties such as saturations and pressure predicted at different calendar times together with static properties like porosity and net-to-gross. A Petro-Elastic Model (PEM) is used to compute elastic attributes (e.g., P-wave and S-wave velocities and density) from these reservoirs properties for each existing or planned acquisition time. Next, overburden and underburden intervals are added to the initial 3D grid in order to model the contrast of elastic attributes at the top and bottom of the reservoir interval. Horizontal resampling to the seismic bin is followed by trace-by-trace (angle-dependent) reflectivity calculation, depth-to-time conversion and synthetic traces generation by wavelet convolution. The resulting synthetic amplitude cubes correspond to the reservoir seismic response at each survey time. Differences between surveys show the expected 4D effects due to changes in reservoir fluid saturations and pressure. Noise is added to the synthetic seismic cubes in order to analyze the detectability of production-induced 4D effects. Depending on the magnitude of the added noise, 4D effects can be partially or totally masked, indicating the necessary seismic repeatability to be achieved with the planned acquisition system.

Figure 2 shows the main workflow window. It is divided into a series of panels, each one corresponding to a given step of the workflow. In each panel, the modeling parameters are available on the left-hand side whereas the right-hand side is dedicated to data visualization and

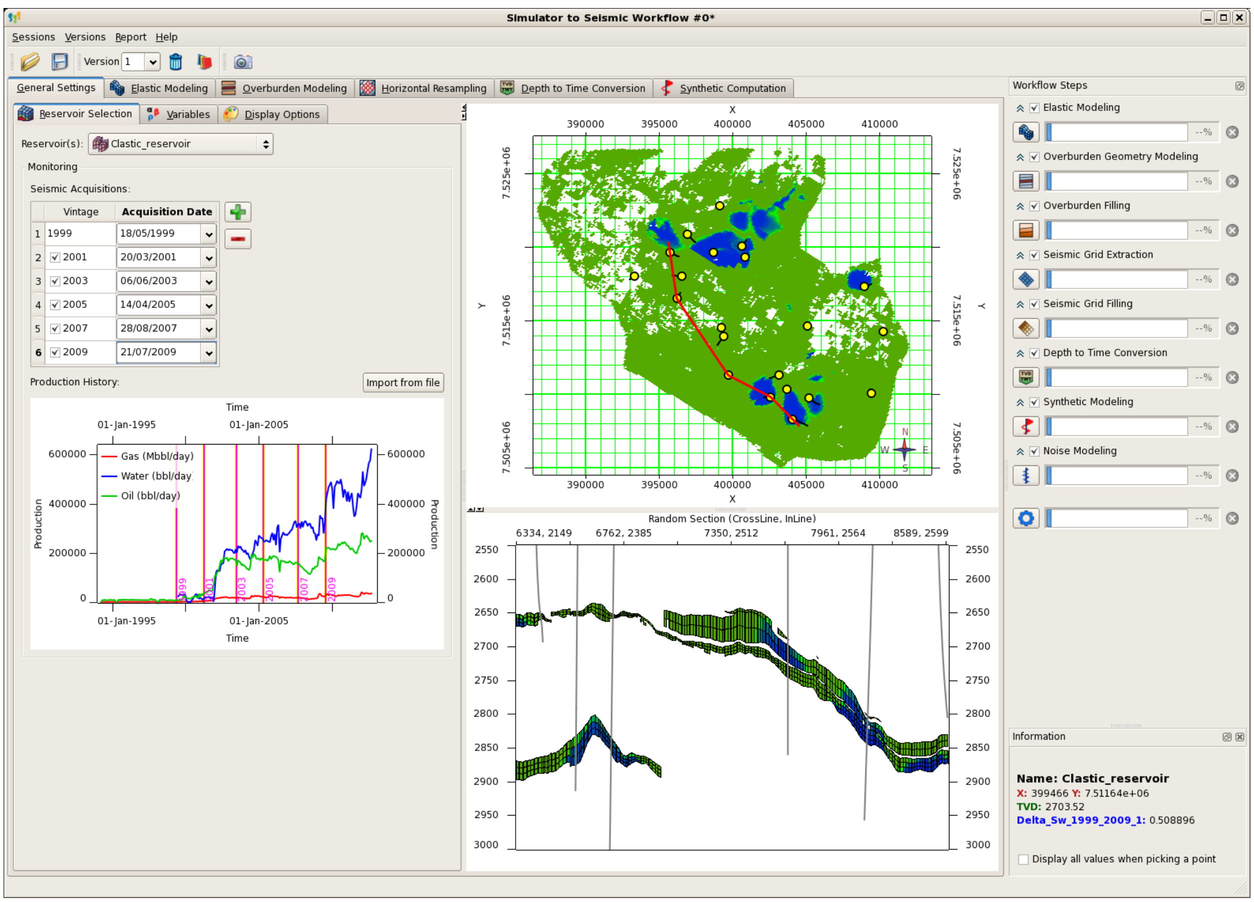


__Figure 2. Graphical user interface of the simulator-to-seismic workflow.__ The top left panel is used to select the reservoir grid and seismic acquisition dates (existing and/or planned surveys). Production curves can also be imported and visualized along with the seismic acquisition dates. In the middle, dynamically linked map and section views are used for data analysis and quality control. The buttons and associated progress bars on the right-hand side are used to launch the different workflow steps and monitor background computations.

modeling quality control. The different computations are launched through the detachable remote control located on the right-hand side of the window. The last button of the remote control runs the full workflow. This functionality is particularly useful to study the sensitivity of the reservoir seismic response to the simulation inputs or rock physics modeling parameters as repeated computations can be chained together and performed with a single click control.

With standard tools, time is often lost due to the lack of integration between the simulator-to-seismic workflow and the geomodeling applications that are used to handle the flow simulation grids and seismic cubes. In our case, the workflow has been developed in a platform-independent library and can easily be plugged into existing commercial geomodeling software. This architecture speeds up the global turn-around time of the workflow and limits the number of data transfers between applications, thus, further reducing the potential for errors. Time-consuming calculations are run in a separate thread leaving the application responsive at all time. The user can therefore set the parameters for the next modeling step or analyze the quality of the previous modeling results while waiting for a computation to finish. This also improves significantly the workflow efficiency.

Elastic Modeling

The first workflow step uses a PEM to link reservoir properties such as porosity, saturations and pore pressure with the elastic attributes. The PEM is applied cell-by-cell in the input 3D grid for all simulation cases. The static properties (porosity, mineralogy…) remain identical for all vintages but the evolution of the dynamic properties (saturations, pressure, temperature, Gas-Oil ratio…) will result in different elastic attributes for each vintage. Comparing the time-lapse changes in dynamic properties with the corresponding changes in elastic attributes gives a first idea of the expected time-lapse effects in the reservoir, as illustrated in Figure 3.

A library of standard PEMs has been implemented covering a wide range of reservoir settings, including unconsolidated and consolidated sandstones, carbonates as well as heavy oil reservoirs. The PEM library can be used to model a number of production or injection scenarios such as primary depletion with gas coming out of solution, water or gas injection, thermal flooding or CO2 injection. In addition to the standard library, PEMs can be customized easily. For example, a field-specific, well-calibrated PEM can be imported, added to the library and applied without software re-compilation. Furthermore, any of the PEM parameters can be modified interactively and the elastic properties can be re-computed directly. This is crucial for rock physics sensitivity analysis, as some PEM parameters have a significant impact on the computed elastic attributes. For example, cement content in granular models and pore aspect ratios in inclusion models have a large effect on computed rock stiffness and corresponding P-wave velocity. In practice, we run the entire workflow several times in order to assess and rank the effect of key PEM parameters.

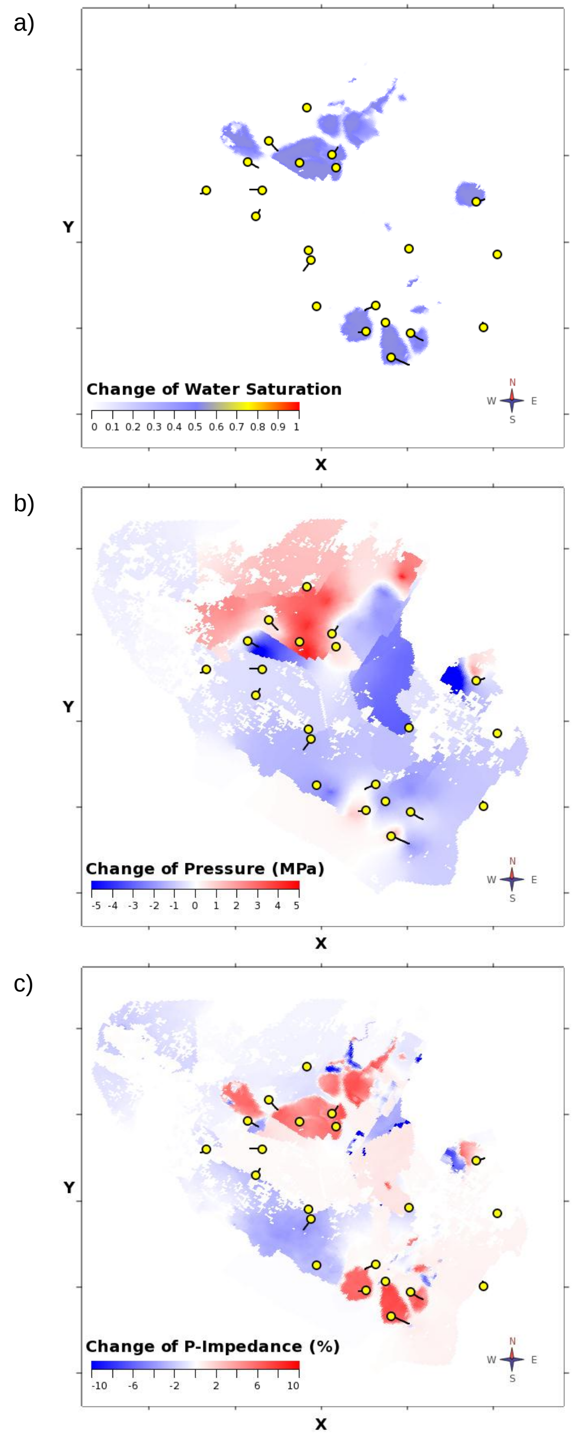


Figure 3. *Elastic modeling.* *Change of a) simulated water saturation, b) simulated pore pressure, and c) P-wave impedance computed through a PEM from the given changes of saturation and pressure for a clastic reservoir offshore Brazil. A 5% change of P-Impedance is a commonly agreed detectability threshold. With this assumption, the evolution of the water-flooded zones around the injection wells (red areas) and depleted zones around the production wells (blue areas) could be monitored with 4D seismic data.*

Overburden Modeling

At each trace location, a seismic reflectivity series is computed from the vertical acoustic impedance contrast between successive cells in the 3D simulation grid. In order to correctly model seismic reflections at the top and base of the reservoir interval, we extend the 3D grid by adding overburden and underburden intervals, as illustrated in Figure 4.

These extra intervals can be delimited using a picked horizon or simply a shifted ghost of the top or bottom interface of the input grid. The pillars in the extended intervals can be vertical or follow the orientation of the input grid pillars in order to extend faults beyond the reservoir interval. The added geological layers can follow different stratigraphic styles such as proportional and parallel to top or bottom interface. The input 3D grid may contain thick layers in non-reservoir intervals. These layers can be sub-divided in the extended reservoir grid in order to refine the reflectivity series and get more realistic synthetics. If gaps exist between layers of the input grid, new layers are automatically added ensuring no holes remain in the extended grid. For the same reason dead cells, i.e., non-reservoir cells not used by the flow simulator, are also activated.

In all non-reservoir intervals, elastic attributes can be populated by kriging log data or resampling an existing grid attribute such as an inverted impedance field. If required, S-wave velocity is computed using an empirical law such as the Greenberg-Castagna relationship or a constant V_P/V_S model. Similarly, saturated rock density can be computed using Gardner's law. The activated dead cells in the reservoir interval are populated using the same options.

Outside the reservoir interval, we assume that the geometry and elastic attributes remain the same with time. Nevertheless, the flexibility of the workflow means that porosity and thickness could easily be defined as additional dynamic inputs. Geomechanical effects such as porosity reduction due to compaction or porosity augmentation due to dissolution could therefore be handled within the workflow.

Seismic Modeling

After horizontal resampling to the desired seismic bin, the extended reservoir grid is converted from depth to time using the P-wave velocity attribute stored in the 3D grid. As an option, several reference horizons known in both domains can be used to constrain the depth to time conversion. Once the grid is defined in the time domain, reflectivity series are computed using the Zoeppritz equations or their Aki & Richards approximation. Next, a 1D convolution with specified wavelets is applied to compute a synthetic cube for each incidence angle and each vintage. Synthetic time-lapse effects are also automatically calculated from the difference between successive synthetic seismic amplitude cubes. If real seismic data are available, residual cubes corresponding to the difference between synthetic and real traces can also be generated automatically. They can be used as a criterion for seismic validation of the reservoir model. 1D convolution modeling has the advantage of being quick but has limitations that need to be kept in mind when analyzing 4D synthetics. Illumination is not taken into account; this can make the comparison with real seismic data difficult in case of complex geometry, like salt diapirs. This type of convolution is also blind to vertical faults.

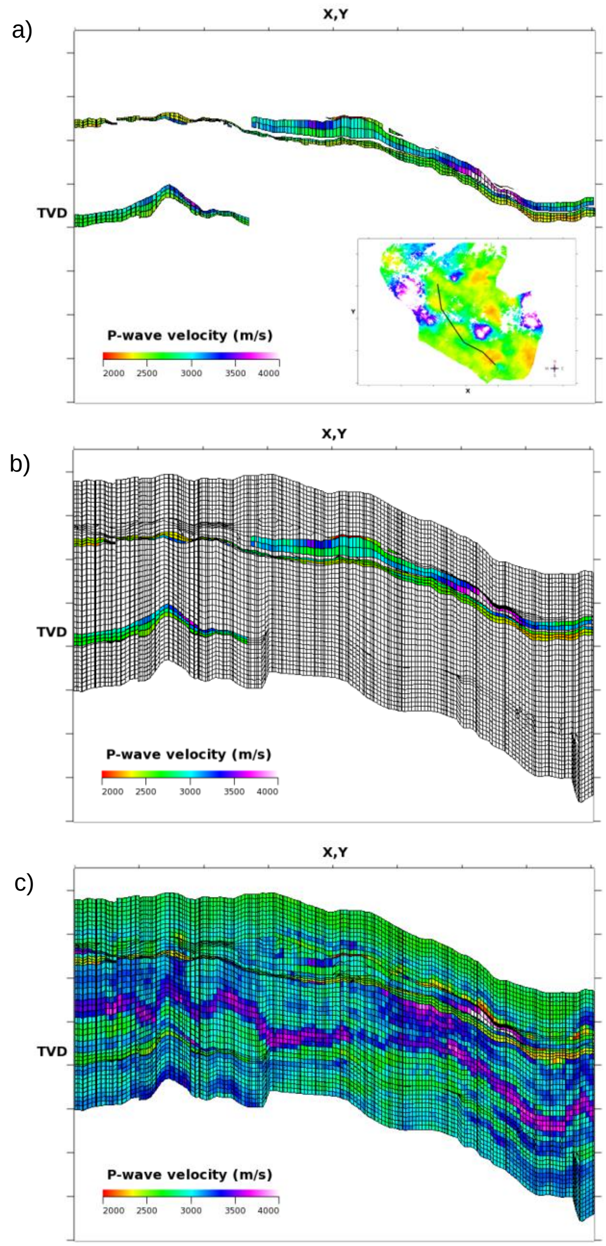
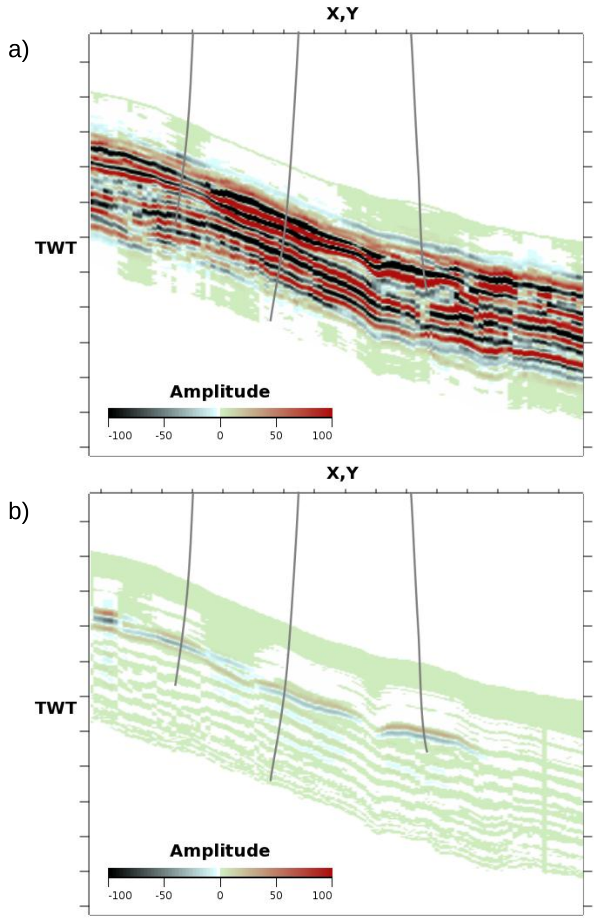


Figure 4. *Overburden modeling.* *a) Base vintage P-wave velocity section showing two disconnected reservoir intervals. The map at the bottom-right shows the position of the section; b) The extended reservoir grid after adding overburden and underburden intervals of 100 meters (10 layers parallel to the top and bottom of the input grid) and intraburden layers in-between the reservoirs; c) The same extended grid after filling of the non-reservoir cells from an existing elastic inversion result.*

The effect of noise on the 4D synthetics needs to be carefully assessed. Currently, two types of noise are considered in the synthetics calculation:

- Static time shifts which break the lateral continuity of seismic events. This option is used for example to model lateral temperature variations in the water column or tidal statics.
- Random background noise specified by a given energy level (calibrated to the synthetic seismic energy through a signal-to-noise ratio) and a given frequency bandwidth, defined by default as the bandwidth of the synthetic signal.

The critical point in this modeling step is to determine the level of background noise that will mask the production-induced time-lapse effects as shown in Figure 5. This gives a good indication of the minimum change in elastic attributes that translates into a detectable time-lapse effect. When this detectability threshold is known, the reservoir engineer can estimate the ideal time intervals between future seismic acquisitions for reservoir monitoring. In the case of seismic validation of a history matched reservoir, the discrepancy between synthetic and real 4D differences allows the reservoir engineer to identify the regions where the reservoir model needs to be updated in order to honor the real seismic data.



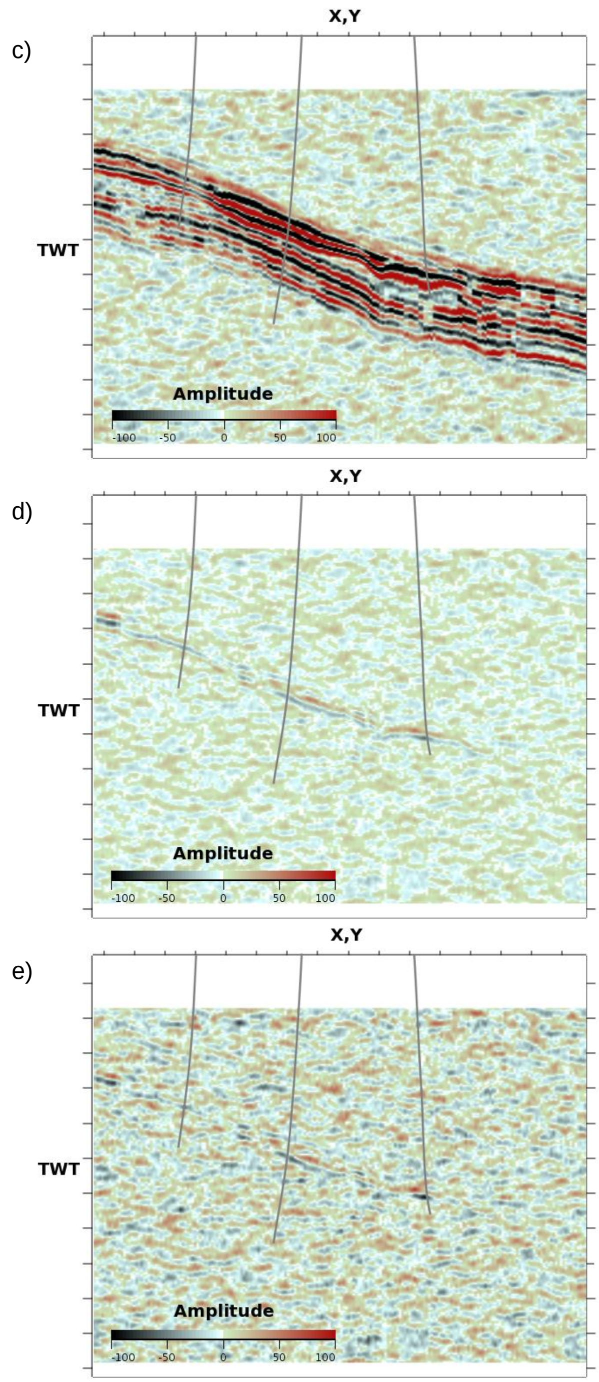


Figure 5. *Seismic modeling.* *a) Synthetic seismic section corresponding to the base vintage and an incidence angle of 30°; b) Synthetic 4D difference between base survey and last monitor survey for the same incidence angle. The effect of water injection and oil replacement is clearly visible on this section passing through three production wells; c) Synthetic seismic amplitudes after adding random noise with a signal-to-noise ratio of 4; d) and e) Synthetic 4D differences after adding random noise with a signal-to-noise ratio of 4 and 2, respectively. Detectability of production-induced effects is considerably reduced with the increased level of background noise.*

Conclusions

A fully integrated simulator-to-seismic workflow has been implemented in order to reduce the turn-around time of time-lapse feasibility studies. Starting from pressure and saturation distributions predicted by reservoir simulation, the workflow computes time-lapse changes in elastic properties using a petro-elastic model applied cell-by-cell to the 3D simulation grid. Overburden modeling is followed by the computation of 4D synthetics which can be compared with real 4D data, if available. The complete workflow can be re-run quickly using different flow simulation cases, different petro-elastic model parameter values or synthetic noise characteristics. This allows fast scenario and parameters sensitivity analysis which is important to understand the main factors affecting the 4D seismic response of the reservoir. The workflow is tightly linked with geomodeling platforms. This facilitates the integration of the 4D synthetics with the geological and flow models allowing the reservoir engineer to take into account the seismic information when taking decisions about production strategy.

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