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Closing the Loop Using Engineering-consistent 4D Seismic Inversion

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SUMMARY

An updating strategy is designed to iteratively close the loop (CtL) between the fluid flow simulation predictions and measured production history, predicted and observed 4D seismic data, and finally predicted and inverted impedance/impedance changes. The central ingredient in this scheme is the computation of elastic property changes that are inverted from the seismic in an engineering-consistent (EC) manner. The geometry, volumetrics and transmissibility multipliers for the reservoir model are updated in three successive stages by sequential comparison between the seismic and fluid flow domains. The EC-CtL workflow is implemented on a West African field, where reservoir model improvements are obtained in combination with a consistency between model, impedance and seismic domains.

Introduction

Closing the loop between the flow simulation model and the observed seismic data must honour the structural and stratigraphic interpretation of the reservoir derived from the 3D seismic (Moyen and Doyen, 2009). But there must also be a quantitative match to the production history and the areal pattern of changes observed by the 4D seismic (Staples et al. 2005). Our paper proposes a practical scheme to solve for this suggested model updating, and uses data from a Western African field to illustrate a complete close-the-loop workflow. In this process, engineering-consistent (EC) 4D seismic inversion is employed as a key driver to generating 3D volumes of impedance changes (Tian et al. 2012).

Workflow for closing the loop

In practice, most closing-the-loop workflows for 4D seismic analysis are carried out by seismic history matching (SHM) however from this process the updates may not make geological sense. In addition, such workflows typically limit perturbations to the initial geological or fluid-flow simulation model, and thus might not capture larger-scale three-dimensional heterogeneities that can have a significant impact on the production history. As a result, 4D model updates typically utilise a combination of manual interpretation and computer-aided techniques. The EC 4D inversion scheme provides a chance to convert the seismic reflectivity into volumetric impedance data that are more suited to cross-domain comparison. A particular feature is that the inversion of the 4D data is constrained by reservoir engineering predictions, which reduce the non-uniquenesses involved and maintain consistency with the physics of flow. Therefore the solutions tend to converge to those that make sense in both domains. In addition, the baseline seismic, which is interpreted to characterise the static reservoir framework, is coupled with the monitor survey when inverting for 4D differences. Driven by the EC inversion, the workflow addresses reservoir geometry, volumetrics and transmissibility updating in three successive stages (see Figure 1).

It is common practice for the geological framework and property distributions of the reservoir to be defined by the 3D seismic. However, mismatch between the presence/absence of a reservoir sand detected from 3D seismic and the observed 4D seismic response cannot allow the loop to close between the observed and predicted 4D seismic. To address this, in our stage one update the 3D and 4D signals are combined together to capture a common reservoir. Thus, for example, a reservoir signal in the 3D seismic but no 4D seismic signal indicates either a by-passed reservoir zone or an

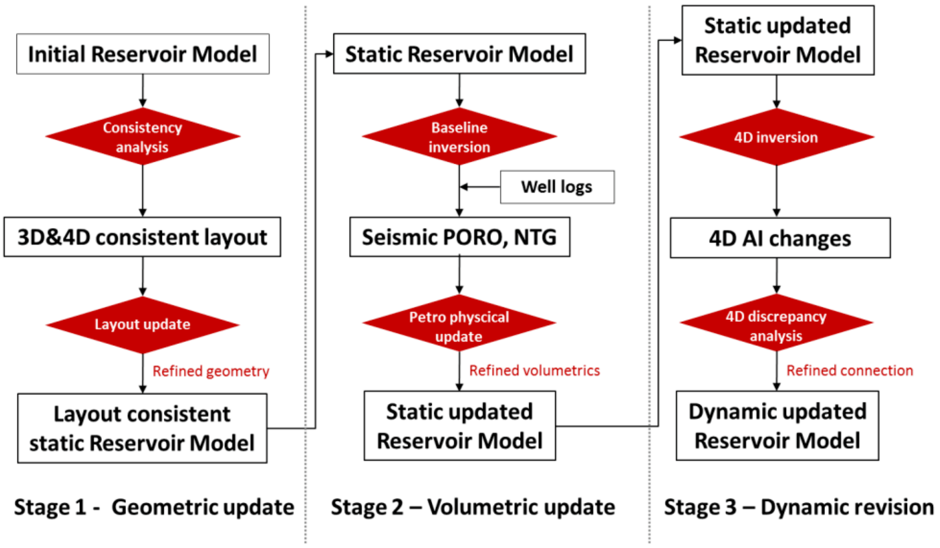


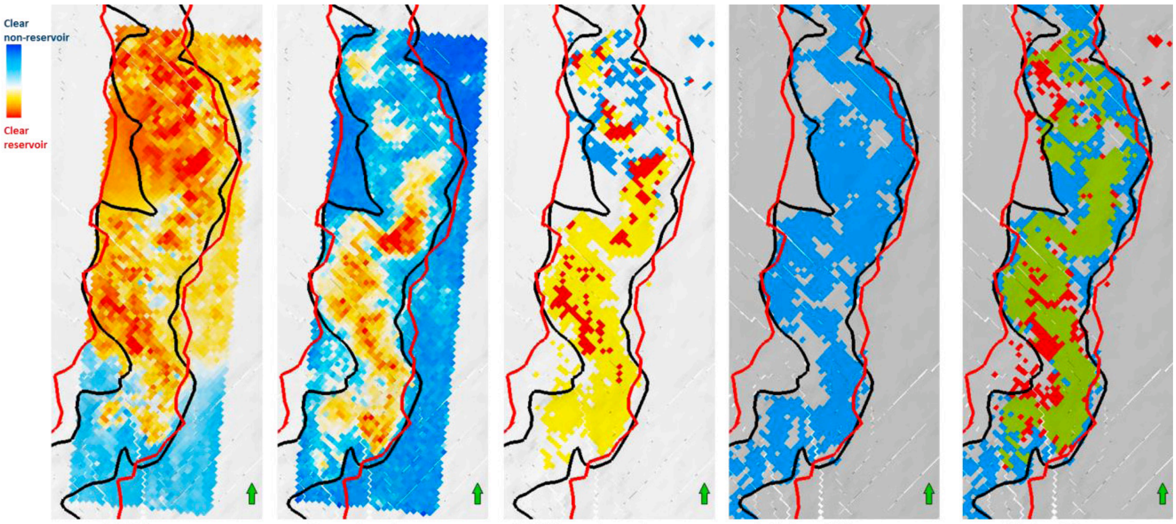
Figure 1 *Inversion-driven workflow to close the loop. Stage one takes both 3D and 4D seismic into consideration to revise the shape and distribution of the reservoir sands. Stage two revises volumetric parameters such as porosity and NTG by inverting the baseline seismic data. At stage three, the discrepancies between the predicted and inverted 4D impedance differences are used to update the simulation model and adjust fluid flow behaviour.*

isolated reservoir segment. In contrast, a 4D seismic signal but no 3D seismic signal indicates a need for a closer look at the 3D interpretation. After the necessary adjustments have been made, stage two focuses on the petrophysical parameters that are of direct impact to the reservoir volumetrics such as porosity and NTG. In order for the 3D inversion used here to be consistent with the model used, porosity and NTG are scaled to honour the observed petro-elastic relationships with impedance derived from well logs. With the new volumetrics, the impedance change predictions from the simulation model are now compared directly to the inverted 4D seismic impedance changes (inverted according to our EC constraint). Mismatch is identified and transmissibility multipliers adjusted until the match is improved.

Application to a West African field

The above updating workflow is tested on a West African field. This particular field has stacked unconsolidated turbiditic sands of several cycles. High solution gas to oil ratio and a reservoir pressure near bubble-point are reported at the exploration stage, resulting in a large amount of exsolved gas after early production. High resolution time-lapse seismic are acquired two years prior to the first oil in December 2001, and then subsequently in 2002 and 2004. During our stage one update, the V_P/V_S ratio is derived from the baseline seismic by inversion and attempts are made to validate the presence of quality reservoir sands. Petrophysical analysis of the well log data suggests a NTG cut-off of 0.40 separates reservoir sands from the surrounding non-reservoir shales. The corresponding V_P/V_S is found to have only a scattered relationship with the NTG, so this suggests the 3D interpretation by this route is uncertain. In contrast, the 4D seismic amplitudes are employed to assist the determination of the active reservoir. The thresholded envelope of the 4D seismic amplitudes illuminates the major sand packages undergoing dynamic change.

The resultant reservoir sand determinations from the joint 3D and 4D seismic analysis are shown in Figure 2. This reservoir architecture is then compared directly with the active reservoir cells in the initial simulation model. Common cells are retained whilst missing cells are added to the initial model in order to cover all the observed 3D and 4D seismic signals. These newly added cells are mainly found to lie along the edges of the original channel complex, rather than floating in an isolated fashion (which would indicate a low probability of being correct, and indicate the influence of the uncertain 3D seismic product). These additional cells are given rock permeability and fluid properties values of their neighbours so as to create a natural expansion of the reservoir. Due to the new cells, the model is now capable of matching both the observed 3D and 4D data. In stage two, the original NTG and effective porosity values of the reservoir model are re-scaled according to the 3D inversion results. This reconstructs the material balance of the field and secondly adds realistic heterogeneities into the



V_P/V_S Layout — 4D envelope layout — 3D&4D consistent Layout — Initial model layout — Updated layout

Figure 2 *The inverted V_P/V_S ratio and the 4D envelopes used to define the 3D and 4D seismic consistent reservoir architecture, which can then compared with the original model to update the reservoir-related cells.*

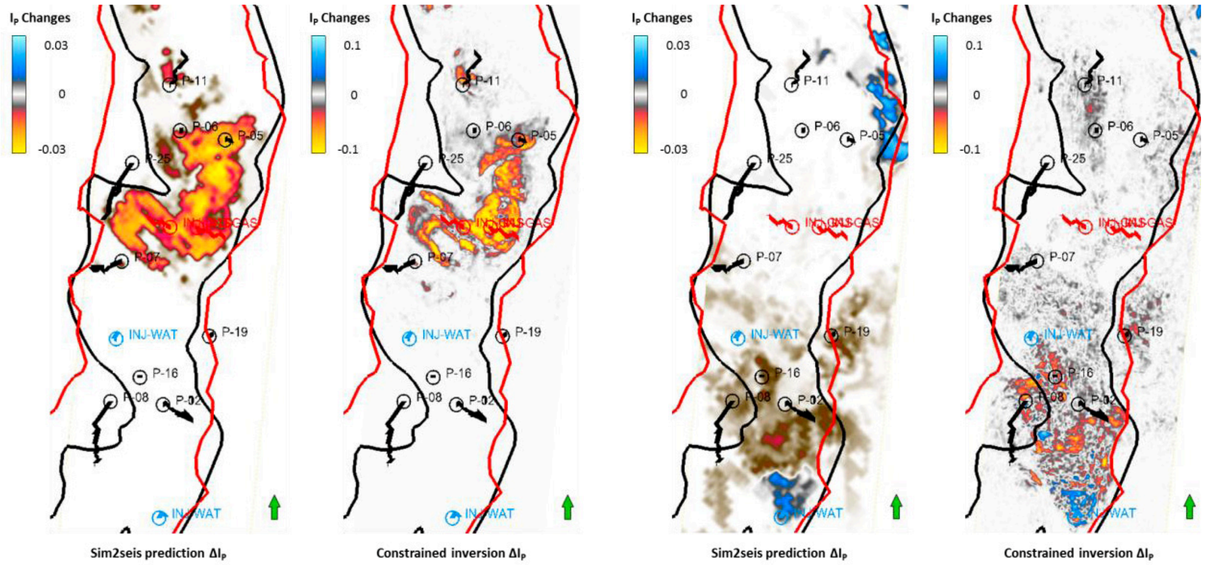


Figure 3 *Two examples of the comparison between model predictions and the EC 4D inversion. Left: a time slice of impedance changes at the level of gas injection. Decreases of impedance are related to the gas cap where the P-06 well shows a conflict; Right: a time slice at the water flood level, where the model behaviour is in agreement with the observed 4D seismic .*

model to improve the match to the observed 3D seismic. After updating, in our example it is found that the channel sands are subject to a reduction of pore volume and this cancels the pore volume increase from the new cells that are introduced in the stage one update.

The reservoir impedance differences are now calculated by inverting the 2001 and 2002 seismic surveys in a coupled inversion scheme. The predictions from the new simulation model and the inverted impedance differences now show a similar behaviour. Features such as an impedance decrease due to gas injection can be observed. A discrepancy is found at the northern producer P-06, where the reservoir model predicts that re-injected gas is directly connected to the well, while our work suggests very little presence of gas signal. Our solution appears consistent with the historic GOR at well P-06 (Figure 3(a)). A time-slice from the deeper part of the reservoir shows that there is a reasonably good match between the model and our inversion for the southern water injector (Figure 3(b)). The inversion results (4D changes of impedance) are then superimposed onto the reservoir grid and quantitatively compared with the model predictions. By subtracting inverted and model impedance changes, a discrepancy cube is obtained which is used as guidance to manually adjust the fluid flow predictions by fine-tuning the transmissibility field. This procedure shows that transmissibility in the northern area of the field should be reduced by 60%, whilst in the south it should be increased by 30%. Following from the stage three update we observe that the production match remains fairly good and does not significantly improve, whilst the match from the synthetic 4D seismic improves throughout (see Figure 4 and Figure 5).

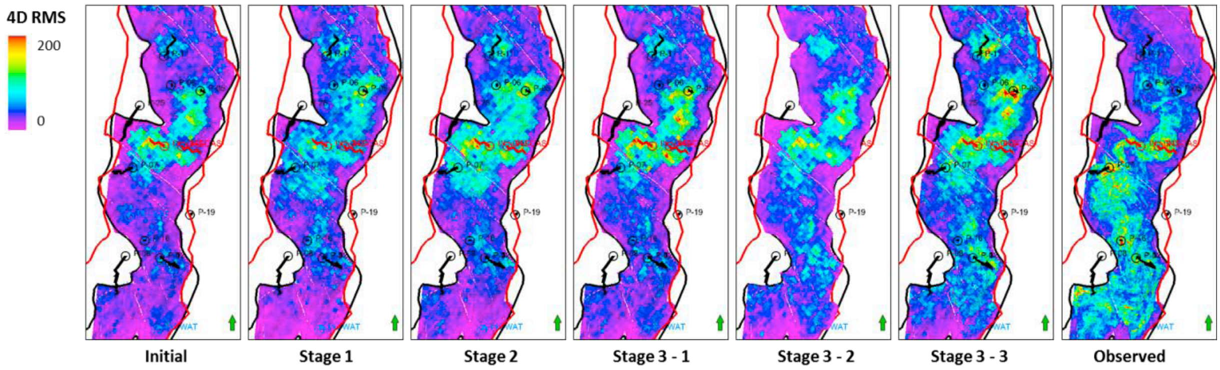


Figure 4 *A display of the evolution of the 4D seismic signals throughout our workflow. In stage 1, the synthetics add new cells to the model, and in stage 2 the volumetrics are enhanced. In stage 3, the pattern of the signal has been influenced by transmissibility.*

Conclusions

A workflow is designed and applied to reconcile 3D and 4D seismic data, together with the simulation model and historical production data. At the heart of this procedure is an engineering-consistent 4D inversion which uses prior constraints from the simulation model to influence the seismic inversion. Several stages of closing the loop are proposed. In the first and second stages 10% of the oil in place is added to the original model. The pressure profile does not change significantly, however the match to both GOR and water cut is degraded. The third stage updates the transmissibility field according to the discrepancies between the 4D inversion and the corresponding model predictions. It is believed that this particular update is more efficient than a conventional SHM, as the seismic response improves gradually towards a better match to the observed data.

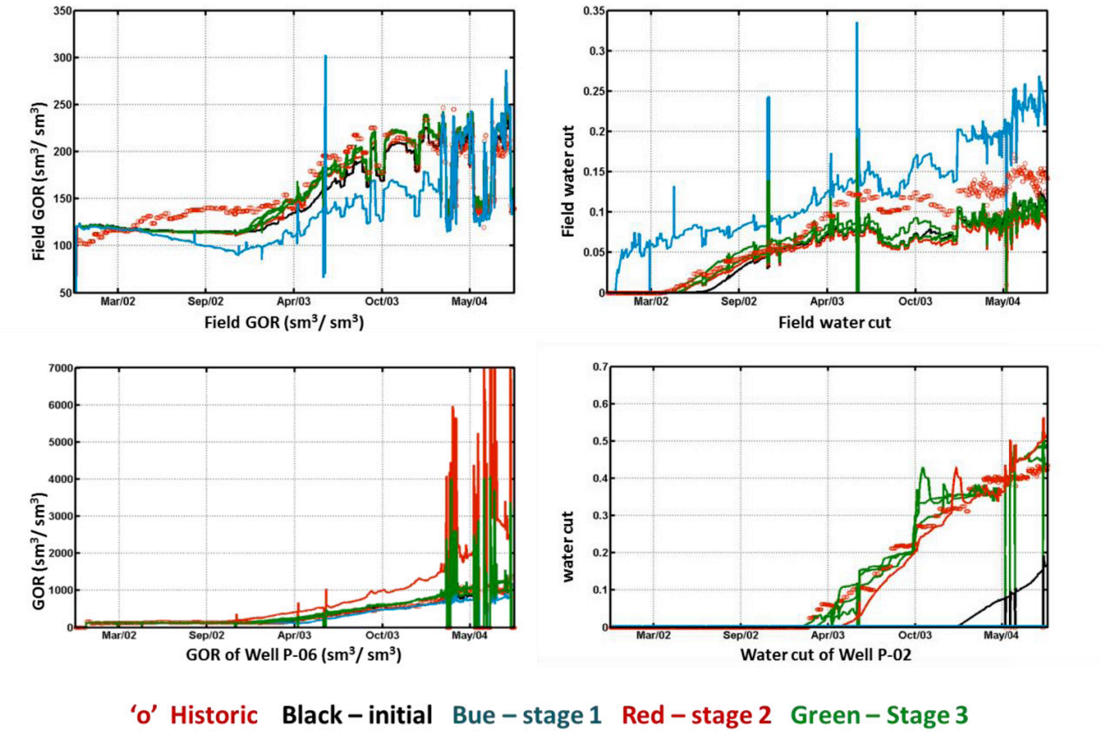


Figure 5 *The GOR and watercut profiles for a northern producer P-06 supported by gas injection and southern producer P-02 supported by water injection. Throughout the different update stages, the matches at both the local and field scales are improved.*

Acknowledgements

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