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Simulation Model Updating with Multiple 4D Seismic in a Fault-compartmentalized Norwegian Sea Field

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SUMMARY

A new approach is proposed to effectively update fault transmissibility multipliers in a compartmentalized reservoir using many repeated 4D seismic monitors and historic well production data. Our philosophy avoids a time-consuming seismic history matching loop by directly updating the reservoir model using semi-quantitative information extracted from the 4D seismic to drive down the overall misfit. Two methodologies, applied in sequence, are proposed for our workflow using 4D signatures dominated by saturation changes. The first method detects the location of fault barriers and also confirms openly conducting faults. The second estimates transmissibility values for those open faults identified from the first method. Application of our proposed workflow proves that it can help to close the loop between predicted and observed data from both 4D seismic and well history.

Introduction

Reservoir model updating using 4D seismic has become de rigueur in the history matching of reservoir models. Conventionally, 4D seismic attributes are used in an iterative updating workflow to minimize the misfit between simulated results and observed data. Despite the research in seismic history matching, there are still a number of challenges that have yet to be overcome, including time consuming iterations, unsatisfactory convergence, and a complicated solution space. To overcome some of these difficulties, we propose a workflow that makes use of multiple seismic monitor surveys. This work extends our previous approach which establishes a correlation between frequently repeated seismic surveys and selected historic production data (Huang et al. 2010). Our current approach uses saturation change-dominated 4D signatures to locate fault barriers, quantify fault transmissibility and finally to directly update the reservoir simulation model.

The well2seis technique

4D seismic signals cannot be unambiguously interpreted without a full understanding of production activity. To develop this understanding in a quantifiable way we make use of multiple surveys shot over the same reservoir, and generate a number of 4D seismic difference maps for all paired combinations of the surveys. The cumulative volumes of a specific fluid (oil, water, gas) produced over these time intervals from a selected well group constitute a parallel time sequence. The distribution of the correlation coefficients between these two sequences across the reservoir indicates the spatial connectivity of the reservoir (Huang and MacBeth 2012). In our case we calculate the normalized cross correlation coefficient, $R(x, y)$, between produced fluid volumes and multiple 4D signatures for reservoirs in which the 4D signal is dominated by water or gas saturation changes. For water saturation change-dominated 4D signals, the cumulative volumes of produced oil are used in the calculation of $R(x, y)$, while produced gas is used for gas saturation change-dominated 4D responses.

Quantifying fault transmissibility using 4D seismic signatures

To understand how to apply the well2seis technique to fault transmissibility, consider two segments divided by a fault in a simulation model. Here, we assume that the geology, fluid properties, and boundary conditions for the two segments are the same. The main factor of influence on the simulation model is the fault transmissibility. Firstly, on the condition that the fault is totally open, the water front passes through to the second segment and reaches a steady state - it is easy to determine that this fault is openly communicating from the saturation distributions on either side of the fault. When the fault transmissibility is partially sealing, the saturation changes caused by the reduction of fault transmissibility will be quite evident. As the 4D signal is mainly sensitive to saturation changes, this phenomenon can, in principle, be used to detect the behaviour of faults on fluid flow. Furthermore, using the work of Falahat et al. (2013) to connect 4D signatures to water saturation change, and the definition of the fault transmissibility multiplier (Manzocchi et al., 1999), we show that it is possible to use the 4D seismic difference either side of the fault to quantify the values of transmissibility multiplies and hence update the simulation model.

Application to a Norwegian Sea reservoir

The above two methodologies are tested on data from a fault compartmentalized field. This field is a heavily faulted horst block and the presence of faults is the main factor that effects field depletion. The main objective of our work is to update fault transmissibility from the original simulation model (the “base case”). In this field, good quality time-lapse seismic surveys are acquired five years before the first oil in 1995, and then in 2001, 2004, 2006, 2008 and 2011. The 4D signals for this field are strongly dominated by saturation changes and the influence of water and gas saturations is readily observed. Water saturation dominates the 4D signal in the oil leg due to water flooding (a hardening zone); in the gas gap, gas saturation is the most dominant signal (a softening zone).

Applying our proposed two-step direct updating workflow, the first step is to re-evaluate the fault sealing properties and barrier locations in the base case using the *well2seis* technique. Correlation maps (Figure 1) are generated using the well group P4, P5 and P6 in both the hardening zone and softening zone by application of equation (1).

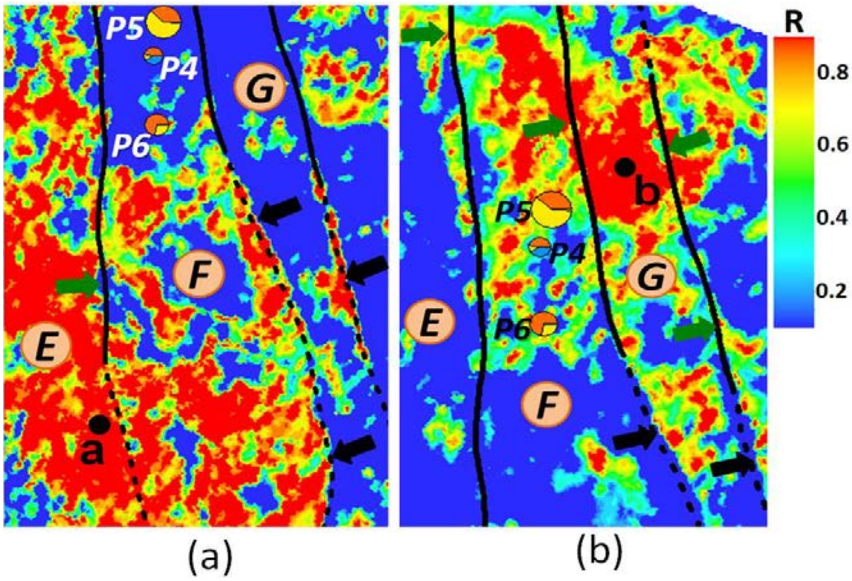

Figure 1 *(a) Well2seis correlation map for the hardening zone of the reservoir; (b) well2seis correlation map for the softening zone. In these maps, well locations are represented by bubbles, in which produced gas, oil and water are displayed by different colours (brown–oil, yellow–gas, and blue–water) in proportional to their cumulative production. Faults are displayed using black lines, where solid line means closed fault and a dashed line indicates an open fault from the base case .*

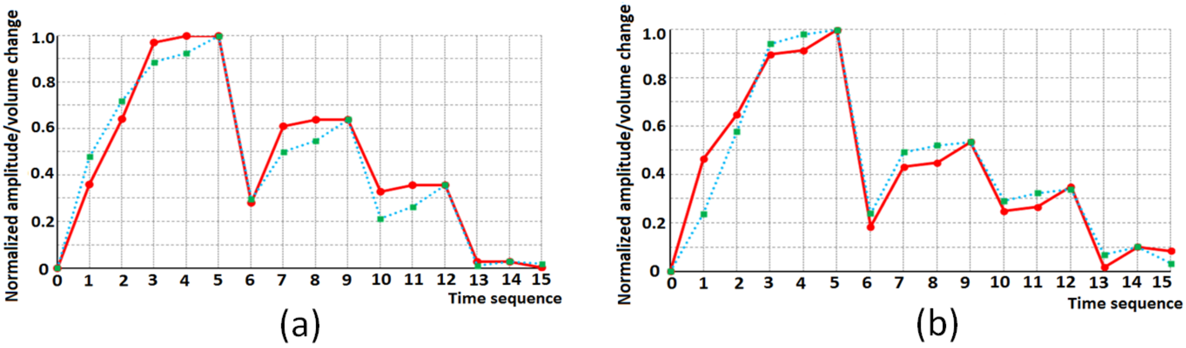

Figure 2 *(a) Profile of correlation coefficients for location* ***a*** *from the well2seis map of Figure 1(a), showing how the 4D amplitude changes at that point are highly correlated with the cumulative well production in compartment F; (b) correlation profile for location* ***b*** *from the softening zone in the well2seis map Figure1(b). Red line – 4D seismic signal differences, dashed green line – fluid volume changes at the wells.*

From the maps, the fault locations in the simulation model are observed to be quite consistent with the correlation coefficient distributions. By randomly choosing one location in each map (points *a*, *b* in Figure 1), two correlation panels (Figure 2) are created to evaluate how the multiple 4D changes are correlated with well production in compartment F. For example, even though location *a* is separated from compartment F by a fault, the 4D changes are still strongly correlated with the well activities in F (Figure 2(a)), which means the fault segment between E and F near location *a* should be open. This phenomenon can also be observed in the softening zone by referring to the second correlation panel (Figure2 (b)). The faults in Figure 1 indicated by black arrows are originally open in the base case, however the contrast of the correlation coefficient values on either side of the faults indicates that they should in fact be closed. On the other hand, the faults indicated by the green arrows should be open due to strong correlation across them. After re-interpreting the fault communication based on this *well2seis* information, a new configuration of open and sealing faults is obtained for the simulation model. These are introduced initially into the model as the location of a barrier or lack of barrier

(Figures 3 and 5). In the second step of our workflow, we estimate fault transmissibility multipliers for the open faults by our second methodology. Both observed and simulated 4D differences on either side of the faults are firstly extracted, and their ratio provides the required multiplier to update the fault transmissibility for the base case. Multiple 4D surveys enable us to calculate a series of 4D differences and thus to generate different fault transmissibility multiplier configurations, which can be combined to update the simulation model.

Figures 3, 4 and 5 show how the 4D seismic and well production matching qualities improve after applying our updating workflow. For example, in the hardening zone, after placing a new barrier between F and G near the dashed red line marked *Area 1* (Figure 3), the simulated water front becomes more consistent with the 4D observations in that area (Figure 3(c)). The improvement of seismic matching quality can also be observed from *Area 2* in Figure 3(c) near well P9. Meanwhile, the water cut history matching at well P8 (Figure 4(a)) is further improved after quantifying the transmissibility multipliers of the nearby open fault. Looking into the history matching results in the softening zone, the seismic (apart from *Areas 2 and 4* in Figure 5(c)) and well match (Figure 4(b)) are only slightly changed in the first updating step. However, after quantitatively updating the fault transmissibility in this zone, the seismic matching qualities are significantly enhanced (*Areas 1* and *3* in Figure 5(d)). The gas to oil ratio of well P9 (Figure 4(b)) is also history matched.

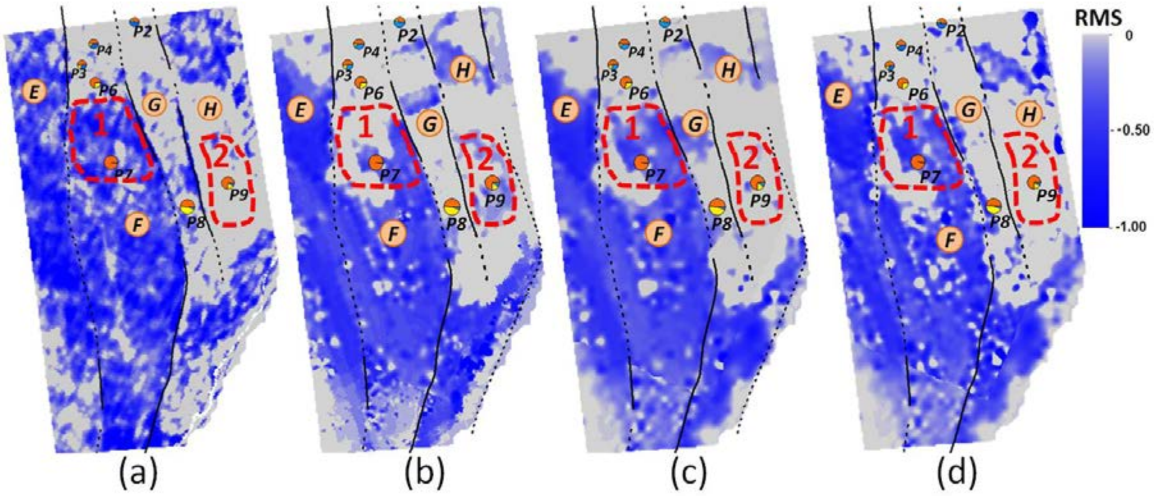

Figure 3 *Comparison between observed and predicted 4D differences from the simulation model (4D seismic amplitude RMS difference between baseline and monitor 2011) in the hardening zone: (a) observed 4D difference, (b) simulated 4D differences from the base case, (c) simulated 4D difference after the first updating step, (d) simulated 4D difference after the second updating step. The dashed red lines mark out the areas where seismic matching quality is improved.*

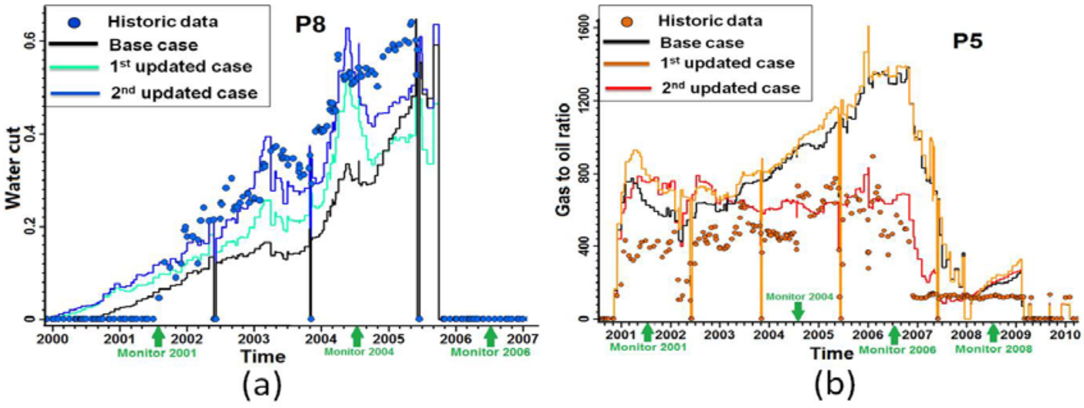

Figure 4 *Production history matching improvement after applying our workflow, (a) water cut matching results for well P8 in the hardening zone (Figure 3), (b) gas to oil ratio matching result for well P5 in the softening zone (Figure 5).*

Conclusions

Correlation of multiple 4D seismic surveys with fluid production at specific wells groups can be used effectively as a tool to determine whether the fault is sealing or conducting, and the location of fault barriers. A measure of fault transmissibility can be derived from observation of saturation changes in 4D seismic signatures in combination with these correlation maps. By applying these two methodologies to a reservoir with multiple 4D responses dominated by saturation changes, the resultant workflow enables us to directly update the reservoir model in a fast and reliable way.

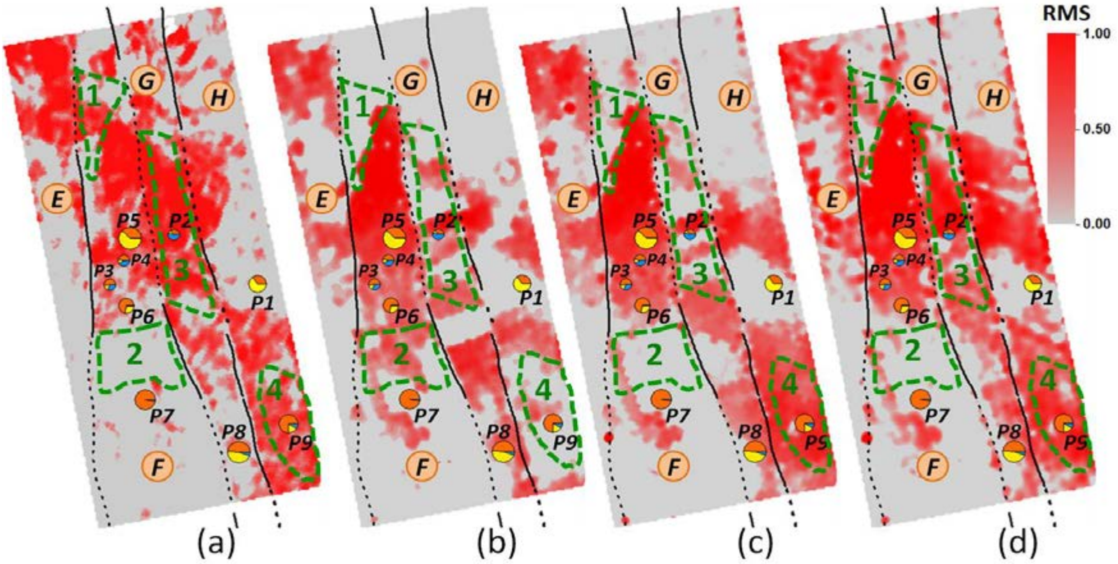

Figure 5 *Comparison between observed and simulated 4D differences from the simulation model (4D seismic amplitude RMS difference between baseline and monitor 2011) in the softening zone: (a) observed 4D difference, (b) simulated 4D differences from the base case, (c) simulated 4D difference after the first updating step, (d) simulated 4D difference after the second updating step. The dashed green lines mark out the areas where seismic matching quality is improved.*

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