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# Seismic History Matching Using a Fast-Track Simulator to Seismic Proxy

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## Abstract

In this paper we propose a proxy model based seismic history matching (SHM), and apply it to time-lapse (4D) seismic data from a Norwegian Sea field. A stable proxy model is developed for generating 4D seismic attributes by using only the original baseline seismic data and dynamic pressure and saturation predictions from reservoir flow simulation. This method (MacBeth et al., 2016) circumvents the petro-elastic modelling with its associated uncertainties and also the need to choose a seismic full-wave or convolutional modelling solution, which are used in conventional simulator to seismic (sim2seis) modelling. The method is tested on an offshore field case study from the Norwegian Sea.

In this study we firstly perform a check on the validity and accuracy of the proxy approach following the methodology of (Falahat et al. 2013) as a guide. The results confirm linear superposition between the pressure and saturation effects controlling the seismic data. Next a quasi-history matching is set up - here simulation model realisations are selected by random assignation of the key parameters to define a walk through solution space. After this, both the sim2seis and proxy modelling approach are compared for each realisation against a known reference case. The results show a mean seismic error of lower than 5%, which indicates the possibility to utilise a fixed proxy to model the 4D seismic. Finally, the full seismic history matching loop is implemented, where the sim2seis and the proxy-driven SHM are launched to find the optimal solution for our field. A particle swarm optimization (PSO) algorithm is applied as the optimisation tool, and only seismic data are used in the objective function. In both cases the algorithm converged after 30 iterations, and the optimal solutions of the two schemes are comparable. It is observed that the full sim2seis and proxy-driven SHMs are only marginally different, implying that solution space is similar in both cases. We also observe that in either case, matching to seismic data only can improve the production match. A unique feature of this study is the application of a seismic modelling proxy in the SHM scheme. Despite its relative simplicity, the approach is found not to bias the optimal solution of the more conventional SHM where the full physics of seismic modelling is applied. Meanwhile, this approach can save over 60% of the total computing time compared with the normal procedure, and this helps significantly to achieve a rapid and effective seismic history matching and better define uncertainty with a larger number of realisations.

## Introduction

History matching is a common used practice which continuously assess the simulation model's performance against the historical data to decrease the uncertainty of the model and then improve the forecast reliability.

The more constraints a history matching scheme includes, the less uncertain will its outputs be (Landa and Roland, 1997, Wang and Kovscek, 2002, Katterbauer et al., 2015). Compared with the well production historical data (oil/gas/water rate, bottom hole pressure) which has been mainly used for history matching, time-lapse seismic (or 4D seismic) has a better areal coverage of the reservoir, and is thus potential useful as a further constraint (Oliver and Yan, 2011, Katterbauer et al., 2015, Stephen et al., 2014, Tolstukhin et al., 2012). Combining 1D well production data as high resolution vertical constraint and 4D seismic data as spatial constraint, seismic history matching (SHM) has been proven to provide more reliable model realisations in past decades (Huang et al., 1998, Gosselin, et al., Jin et al., 2011, Yin et al., 2016).

However, unlike simulated production prediction which can be directly compared with observation, the 4D seismic is not a direct output of fluid flow simulation (Amini 2014). Bringing the simulation and the seismic into a same domain is referred as closing the loop (Figure 1), and simulator to seismic (sim2seis) modelling is indispensable for this procedure. It requires calibration of a petro-elastic model to obtain impedance, building of a geo-model of impedance and seismic wave propagation modelling. This process is multidisciplinary, case dependent, contains high uncertainty and can be the most difficult task facing a reservoir engineer engaged in SHM (MacBeth et al., 2016, Santos et al., 2016).

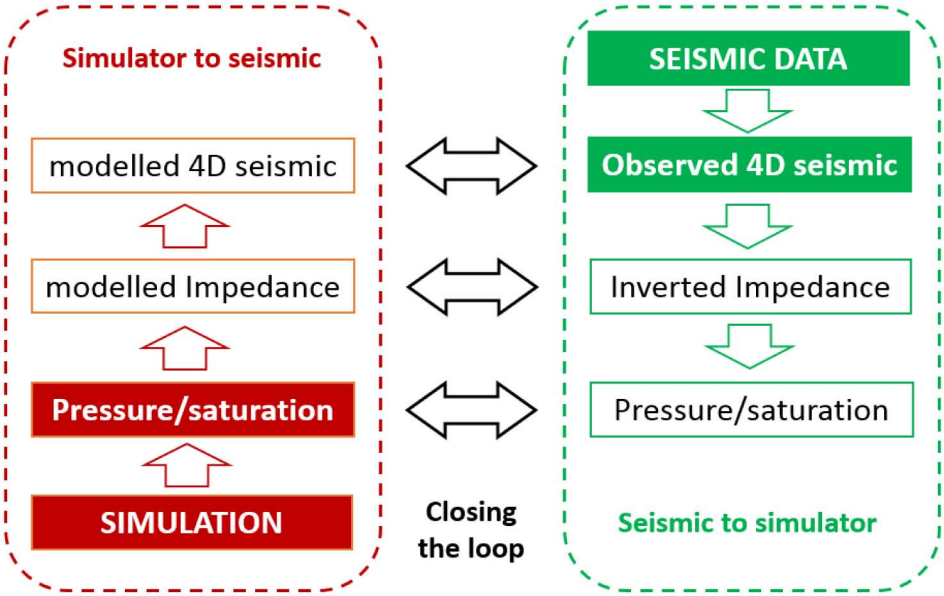


**Figure 1—Different domains of closing the loop between the simulation model and the seismic data.**

Figure 1 illustrates the different domain of comparison between seismic and simulation. Specifically, if the comparison is performed in the seismic domain, hence the petro-elastic modelling and seismic modelling will be applied to generate the simulated 4Dseismic data. A main drawback of this forward modelling procedure is to be able to deal with the associated uncertainty in the model parameters. It could be a huge challenge for the cases where a reliable petro-elastic model is hard to build. Moreover, forward modelling requires intensive computation which can be unaffordable for large size models. Examples of SHM in seismic domain can be given by Davolio (2011) on a Gulf of Mexico turbidite reservoir, and Rwechungura (2012) on a Norwegian Sea turbidite reservoir.

In another way, if bringing the seismic into saturation/pressure domain to bypass forward modelling in SHM, the petro-elastic model is still necessary and the inversion is a non-unique procedure. The literature examples of SHM in simulation domain are often conducted on a synthetic model (Landa et al., 1997, Davolio et al., 2011), and the non-uniqueness is usually treated inappropriately, or not treated at all (Jin et al., 2011, Osdal, 2012).

Furthermore, the intermediate domain of seismic impedance can also be used to compare simulation and real data. This approach appears to be the most popular choice in SHM literatures (Gosselin et al., 2003, Reiso et al., 2005, Roggero et al., 2007, Emerick et al., 2007), however, it has the disadvantages of the previous two: although the seismic modelling can be avoided, an extra suitable rock physics model should be applied to convert the seismic into impedance (Fursov 2015, MacBeth, et al 2016).

All the above approaches cannot totally avoid the petro-elastic modelling or seismic modelling route and all carry considerable uncertainty, increasing the difficulty of undertaking a rapid and effective SHM. In attempt to circumvent the abovementioned challenges, a proxy model based SHM approach is proposed in this paper. Despite its relative simplicity, the approach is found to perform equally as the conventional SHM where the physics of seismic modelling is applied. Above all, it speeds up the SHM workflow considerably and allows a reservoir engineer to gain immediate access to the SHM.

## Methodology

4D seismic is created by differencing the monitor seismic survey from the baseline survey, in theory it can be 3D cube or 2D maps. Considering the relatively lower vertical resolution, in literature it is more likely to use mapped seismic attributes (Brown 2014, Obidegwu et al. 2015, Rwechungura, 2012), where the attribute has been evaluated with respect to a clear, stable and interpretable seismic horizon such as the top of the producing reservoir that has been clearly identified in the seismic volume. For thin sheet-like reservoirs which are generally thinner than a fraction of a seismic wavelength, the top/bottom reservoir horizons can be used as the window to generalise seismic map (Obidegwu 2016); for thick reservoirs or ones containing major shale layers, multiple maps can be generated for each formation separately (Yin 2016). In this paper we limit our research to mapped 4D seismic, and the role of our proxy model is to calculate the time-lapse seismic maps from the depth-averaged pressure and saturation maps, which have been obtained from reservoir flow simulation.

Figure 2 (a) shows observed maps of the root mean square (RMS) amplitude of the top reservoir event for a North Sea clastic field (MacBeth 2016). Figure 2 (b) gives an identical sequence of maps, but all are derived from sim2seis using a well-log calibrated petro-elastic model (see Amini and MacBeth (2010) for details of the modelling). Both observed and synthetic data indicates that baseline and monitor images look visually similar. This is because the baseline map reflects the geological imprint of the reservoir's depositional architecture, together with the initial fluid saturations and pressure. The monitors represent the same geology but with the fluid saturation and pressure changed due to well production and injection (MacBeth 2016). These saturation and pressure signals only modify the seismic amplitudes in the regions bounded by reservoir, and thus the regions defined by the initial amplitude distribution (a similar concept is described by Shams and MacBeth 2008 or Lin 2011).

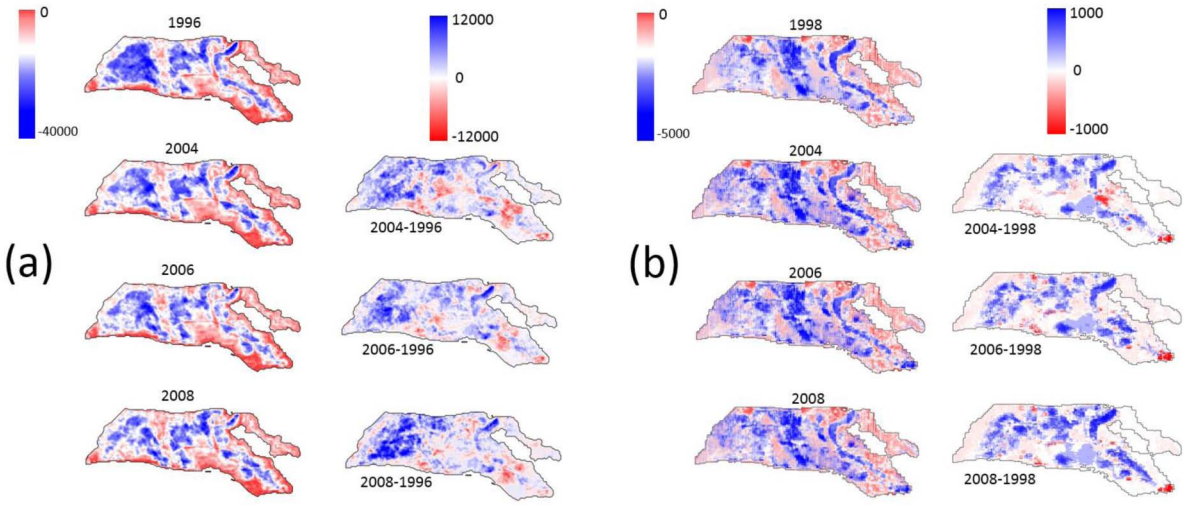


**Figure 2—(a) Comparison between the observed mapped seismic amplitudes for multiple 3D seismic surveys (left); and the corresponding mapped 4D seismic responses (right); (b) Comparison between the simulated mapped seismic amplitudes for multiple 3D seismic surveys (left); and the corresponding mapped 4D seismic responses (right).**

Analysis of above modelling and data suggests that the time-lapse seismic map $\Delta A(x, y)$ can be constructed as the product

$$\Delta A(x,y) = f(\Delta R, G) * A_0 \tag{1}$$

Where $A_0$ $(x, y)$ represents the seismic response (any particular seismic attribute such as impedance, RMS amplitude, instantaneous frequency, time-shift etc.) at the pre-production baseline time and $\Delta R(x, y)$ represents the effect of subsequent fluid saturation and pressure changes in the reservoir. f is a function of the production-related changes and the geology, $G$, which depends on the petro-elastic and seismic modelling. By involving the baseline map $A_0(x, y)$ in the 4D seismic calculation, we account for variations of the static reservoir properties such as thickness, porosity and net-to-gross etc.. Although the 'proxy' relationship in (1) is empirical in origin, the utility of the dynamic part of this equation has been established in past inversion studies (for example, Alvarez and MacBeth 2014).

In our case, as we are dealing with relatively small changes, one obvious form for $f(\Delta R, G)$ can be obtained by a linear polynomial (Falahat et al. 2013)

$$\Delta A(x,y) = (a_1 \Delta P + a_2 \Delta S_w + a_3 \Delta S_g) * A_0 \tag{2}$$

The relationship in (2) amplifies or diminishes the baseline seismic response according to the depth-averaged pressure $\Delta P$ and water and gas saturation changes ($\Delta S_w$, $\Delta S_g$) obtained from fluid flow simulator, to yield the mapped time-lapse response $\Delta A$. The coefficients $a_i$ with $i$ = 1:3 are derivatives of the seismic attribute with respect to the individual pressure and saturation changes. The coefficients are functions of the reservoir geology, rock properties and fluid properties. As the main reservoir variability is supplied by the baseline amplitude, the weighting coefficients $a_i$ can be assumed fixed across the reservoir (Falahat et al., 2013).

This equation is valid in practice provided the seismic survey configurations are reasonably repeatable (Fursov, 2015), and it should be noted that in the literature some debate has arisen as to whether the polynomial in (2) should be expanded as a quadratic (MacBeth et al. 2006). Arguments in favour of quadratic terms for pressure and saturation change have been provided by Meadows (2001), Cole et al. (2001) and Meadows and Lumley (2002). At a practical level, the linear version of this proxy is found to be useful for the purposes of directly inverting to pressure and saturation changes (Landro 2001, Falahat et al., 2013;

Floricich et al., 2006; MacBeth et al., 2006), thus in this study we applied the linear version, the accuracy and robustness of this proxy for history matching purposes will be tested in the next section.

## Application

The methodology described in laste section is tested on a Norwegian Sea field. This is a rotated fault block field (Figure 3), and block C, D, E contain over 97% of the initial oil in place. In vertical, most of the hydrocarbon is stored in Ile and Tofte sand formations. Therefore the 4D RMS seismic map (Figure 3) of Ile formation in block E and D is used as the objective for SHM. In this formation, there is a set of carbonate layers which are partially sealing and have variable lateral extensions. These layers, together with some local faults and barriers, influence the flow in the reservoir and lead to high uncertainty in the simulation model. Thus the multipliers of faults transmissibility, vertical permeability and local barriers transsimissibility are applied as the uncertain parameters for the following history matching.

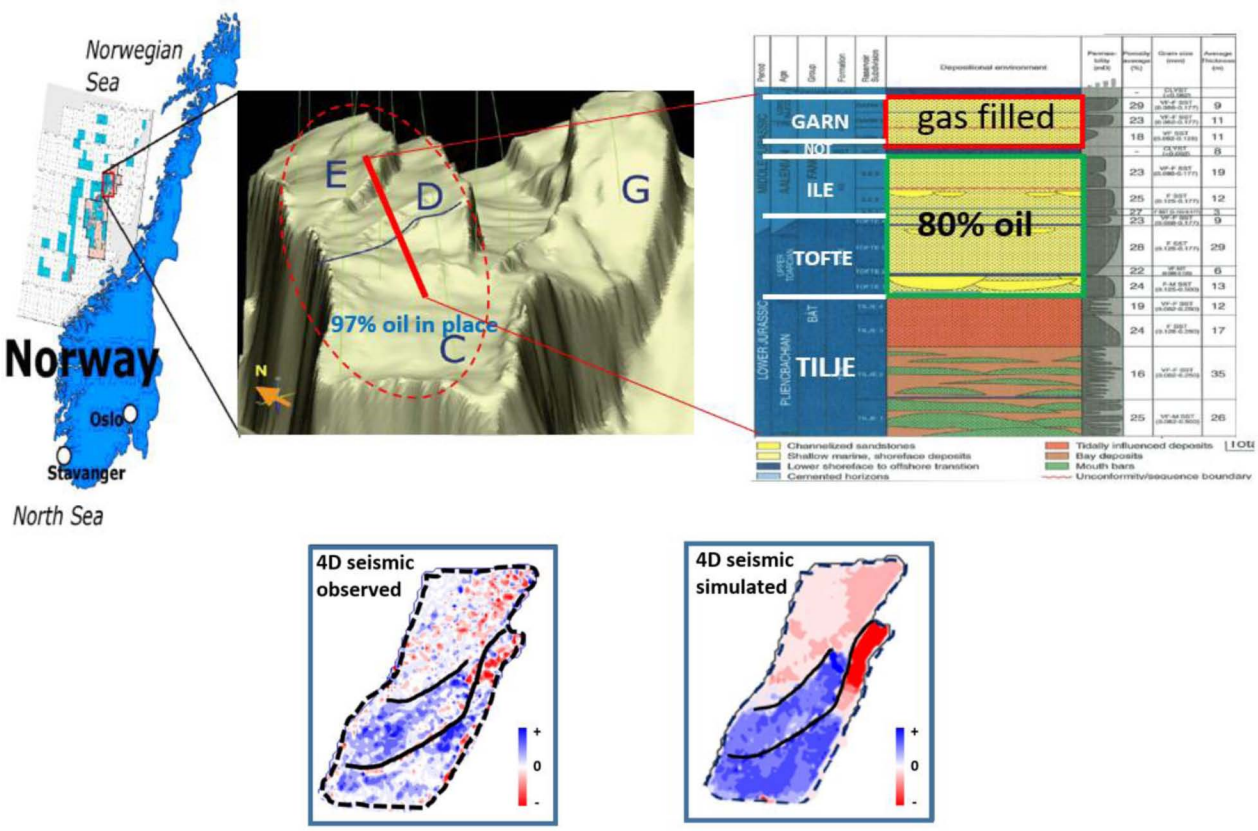


**Figure 3—location (top left), horizontal view (top middle), and vertical view (top right) of the Norwegian Sea field; bottom: observed and simulated 4D seismic of Ile formation at block E and D**

The initial simulation model is history matched using well production data, the field oil and gas production rate were perfectly matched, but the water cut was oversimulated (Figure 4). The the improvement of water cut matching is the target of the following SHM. In terms of seismic, four databases were available (2001, 2003, 2004 and 2006), the first two shots, 2001 and 2003, will be utilized in the following SHM workflow as the gap between simulation and observation developed from this period.

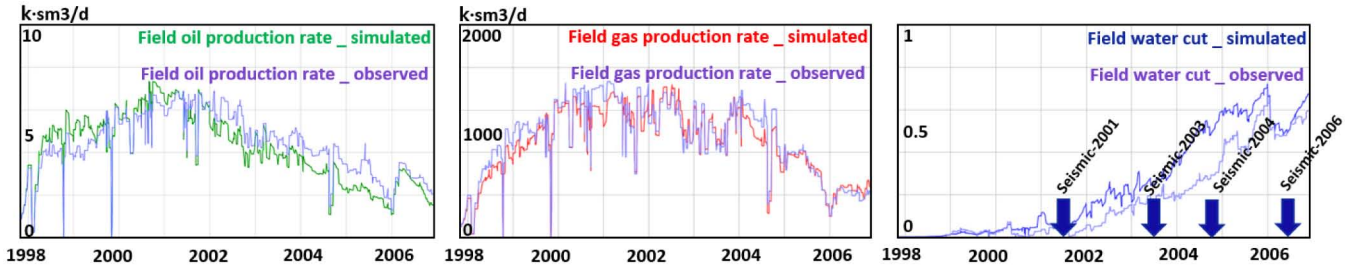


**Figure 4—simulation vs observation of the initial simulation model (production history matched)**

As mentioned in last section, before conducting SHM, a linearity evaluation of the proxy model (equation 2) need to be done first. The purpose of this process is to evaluate the accuracy and robustness of the linear proxy, in other words, to check the linear relationship between modelled 4D seismic and simulated pressure and saturation changes. Afterwards, a quasi-history matching (without optimization) is designed in order to test the numerical stability of the coefficients in equation (2): because the SHM workflow cannot afford the computational cost of running full sim2seis to update these coefficents for each model, a fixed set of coefficents is essential. Only if these coefficents does not vary too drasticaly, then a fixed proxy equation can be applied for further history matching use.

## Linearity evaluation

The main assumption behind the equation (2) is that modelled seismic response might be decomposed into effects of P/S (pressure/saturation) changes linearly. Although it is a data-driven assumption with limited physical basics, it has been proved in literature (Falahat, 2013, Fursov, 2015) to be successful on synthetic or real field data. However, considering the complexity of the seismic attribute, reservoir geometry and other considerations, this proxy (equation 2) would have different performance based on specific cases. Therefore, before the further use of this proxy in SHM, we set up this linearity evaluation to confirm whether it is suitable for our case.

Following Falahat's method (2013), we use the initial simulation model and sim2seis to conduct this study. We first run the flow simulation, afterwards the pressure, water and gas saturation changes in Ile formation during 2001-2003 are made into maps using pore volume weighted algorithm (Figure 5.a). The sim2seis (Amini, 2014) are then applied to model the independent 4D seismic signatures (2003-2001) of these three variables (Figure 5.b), three independent seismic signatureare then summed up as the mixed 4D seismic. Meanwhile, we utilise sim2seis to model the real 4D seismic, taking all three variables into consideration.

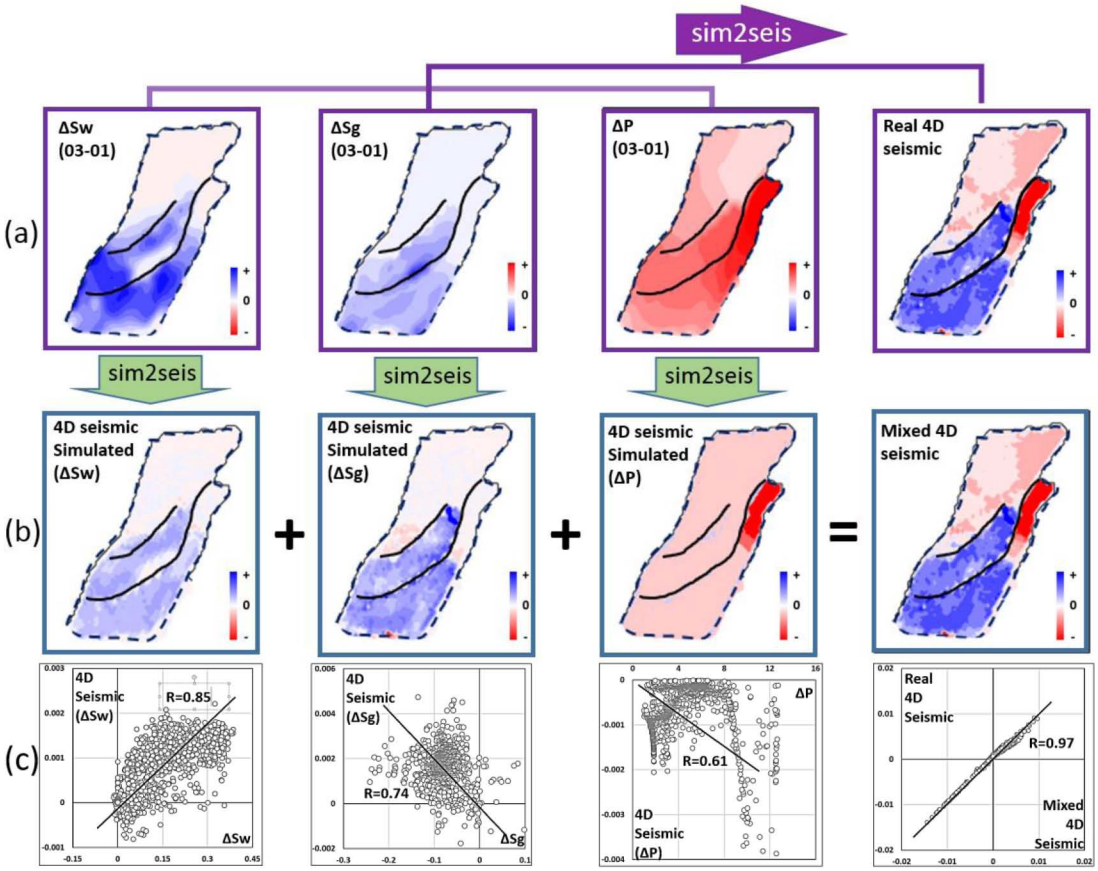


**Figure 5—(a) From left to right: water saturation, gas saturation and pressure changes of Ile formation during 2001 and 2003 from initial simulation model, rightmost: real 4D seismic modelled by sim2seis; (b) Modelled 4D seismic signatures considering independent variables above, rightmost: modelled seismic considering all three variables; (c) From left to right: crossplot of above P/S variables and corresponding independent 4D seismic signatures, rightmost: crossplot of real and mixed 4D seismic.**

We then make two test: 1) the mixed and real 4D seimic maps are compared and cross-plotted (Figure 5.c, rightmost). The correlation coefficient (R) =0.92, indicates that the real 4D seismic signature can be regarded as a mixture of independent effects of P/S changes. 2) The 4D seismic responses corresponding to each change are cross-plotted against the three independent variables suggested above (Figure 5.c, three on the left), the P/S is observed to show the strongest linear correlation with the seismic data. The results here suggest that modelled seismic can be approximated by linearly scaled P/S variables in this case.

## Quasi-history matching

The coefficents in equation (2) are calculated by linear regression: ($\Delta S_w$, $\Delta S_g$, $\Delta P$) come from the flow simulation outputs and ($\Delta A$, $A_0$) are the seismic. According to Falahat's analytic calculation, the coefficents of a proxy model are related to the static properties such as porosity, thickness and NTG of the reservoir (these properties are presented by the products of ($a_1$, $a_2$, $a_3$) and $A_0$ in our equation (2)). Thus if the static parameters of the simulation model are updated during history matching, these coefficents will result in change of the perturbation. As mentioned above, a fixed proxy with a fixed set of coefficients is necessary for an efficient history matching loop, therefore we need to quantify the variance of the coefficents for a certain SHM.

We set up a quasi-history matching procedure to achieve the above purpose. Firstly the uncertain parameters of SHM and their value ranges were determined. Then a one-at-a-time algorithm (Dehghan, et al., 2012) is applied for sensitivity analysis to screen out the top 10 sensitive parameters (Table 1).

Afterwards 30 points are randomly selected from the 10-dimension search space, each represents a possible scenario during SHM. Our quasi-history matching is finally conducted on these 30 scenarios.

**Table 1—sensitive parameters and value ranges**

| parameter | number | value range ($10^x$) |
|---|---|---|
| Barrier transmissibility multipliers | 1 | [-4, 0] |
| Faults transmissibility multipliers | 2 | [-2, 2] |
| Vertical permeability multipliers | 7 | [-3, 3] |

$$O.F. = \frac{\sum(sim_i - obs_i)^2}{\sum(obs_i)^2} \times 100\% \tag{3}$$

An objective function of SHM is defined as equation (3). $sim_i$ stands for the i-th cell of simulated (by sim2seis or proxy) seismic map, and $obs_i$ is the observed seismic at the corresponding cell. Because this study focuses on seismic proxy, only seismic mismatch is counted in the function.

The initial simulation model is launched to obtain dynamic outputs like $\Delta S_w$, $\Delta S_g$ and $\Delta P$. Based on that the seismic data ($\Delta A$, $A_0$) is then modelled by sim2seis and will be used as a reference (synthetic history data) for quasi history matching. With the data ($\Delta S_w$, $\Delta S_g$, $\Delta P$, $\Delta A$, $\Delta_0$), a linear regression of equation (2) leads to the first set of coefficents is referred to as the "fixed proxy". Analogously, all the 30 scenarios are launched and each will have an individual set of coefficents and we name them "adaptive proxies". For the 30 scenarios, we then apply both fixed and adaptive proxy on each to obtain the modelled proxy seismic. The misfit value between reference and modelled (sim2seis, fixed and adaptive proxy) seismic of each scenario is then calculated (Figure 6). The top plot gives a visual comparasion, and correlation coefficent between sim2seis and the two proxies (Figure 6.b 6.c) indicates the results of proxy and full sim2seis are very close. The crossplot Figure 6.d shows that the fixed proxy performs as well as the adaptive one in this study, thus it is effective to use the fixed proxy in our later SHM workflow.

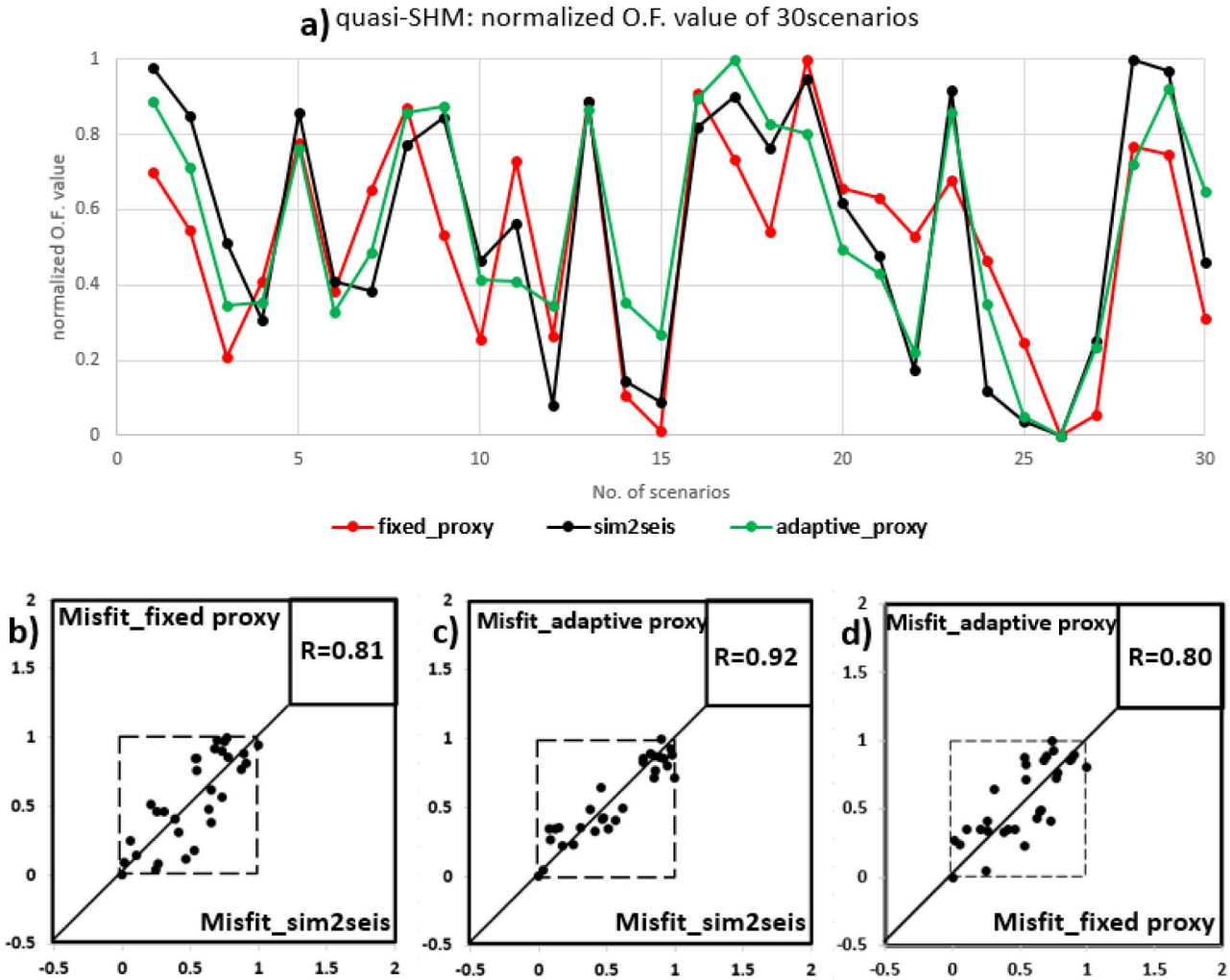


**Figure 6—a) result of quasi-SHM, three set of normalized objective function values; b) crossplot of sim2seis and fixed proxy; c) crossplot of sim2seis and adaptive proxy; d) crossplot of adaptive and fixed proxy**

## Seismic history matching

Following the above two steps, a seismic history matching is eventually conducted. As mentioned earlier, the uncertain parameters and their value ranges are screened by a sensitivity analysis (Dehghan, et al., 2012), and the same objective function (equation 3) is applied for this SHM loop. The optimization algorithm is an ensemble based Particle Swarm Optimization (PSO, Omran, et al., 2005) and the configuration parameters are listed in Table 2.

**Table 2—configuration parameters of PSO algorithm**

| parameters | value |
|---|---|
| Dynamic inertial weight $\omega$ | 0.4-0.9 |
| Weights $c_p$_*best* | 2 |
| Weights $c_g$_*best* | 2 |
| Boundary condition | reflecting strategy |
| Swarm size | 10 |
| Max iteration | 30 |

The first iteration contains 10 randomly selected scenarios the specific values are plotted in Figure 8a. Then sim2seis and the fixed proxy work respectively as the seismic modelling part in the SHM loop (Figure 7). After 30 iterations, both SHM loops converge to a certain resolution (Figure 8.b, 8.c). The grey dashed broken lines mark the maximum and minimum value for each parameter of the last swarm, as the window is quite narrow we take the mean value of the window as a reference for the two optimal resolutions. In Figure 8d the two optimal solutions are plotted by a black line which stands for the initial simulation model. The solution of the full sim2seis and proxy-driven SHMs are only marginally different (only tiny difference around well P1) and it is similar from the comparison of 4D seismic maps (Figure 9). In both cases, compared with the initial model, the optimal solutions show lower value of transmissibility/permeability multipliers, which means after SHM, the flow resistance inside the region increases.

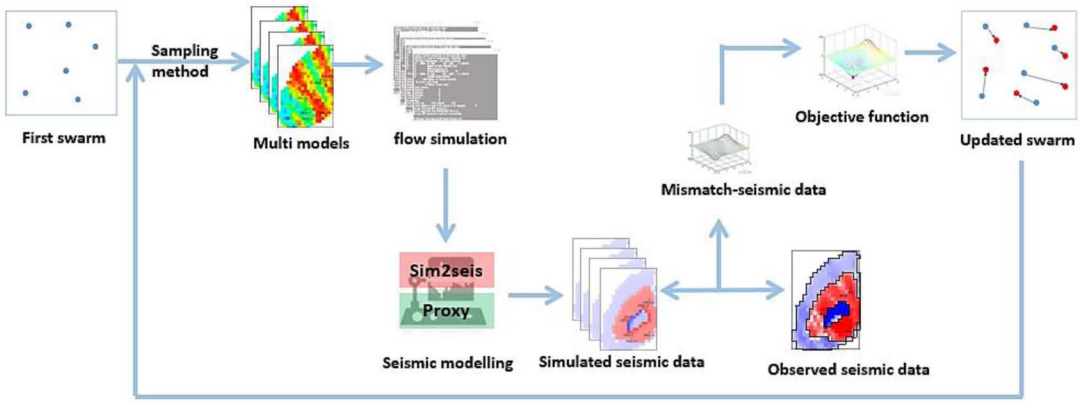


**Figure 7—the loop of SHM where sim2seis and proxy can work as seismic modelling part**

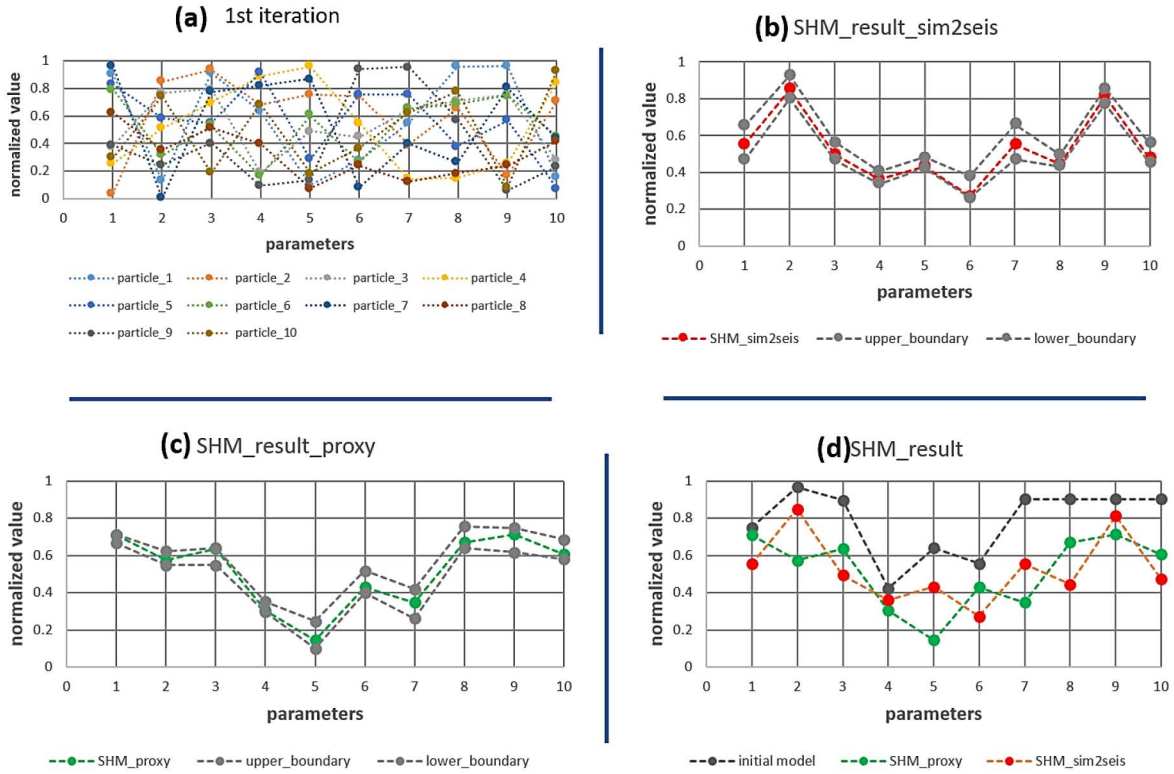


**Figure 8—a): the first iteration of PSO: each dashed line stands for a simulation model and the dots indicate the value of each parameter; b), c): optimal solution of sim2seis and proxy driven SHM. The grey dashed lines mark the maximum and minimum value for each parameter of the last swarm, red and green lines stand for the optimal solution; d): comparison of SHMs optimal solutions and the initial model**

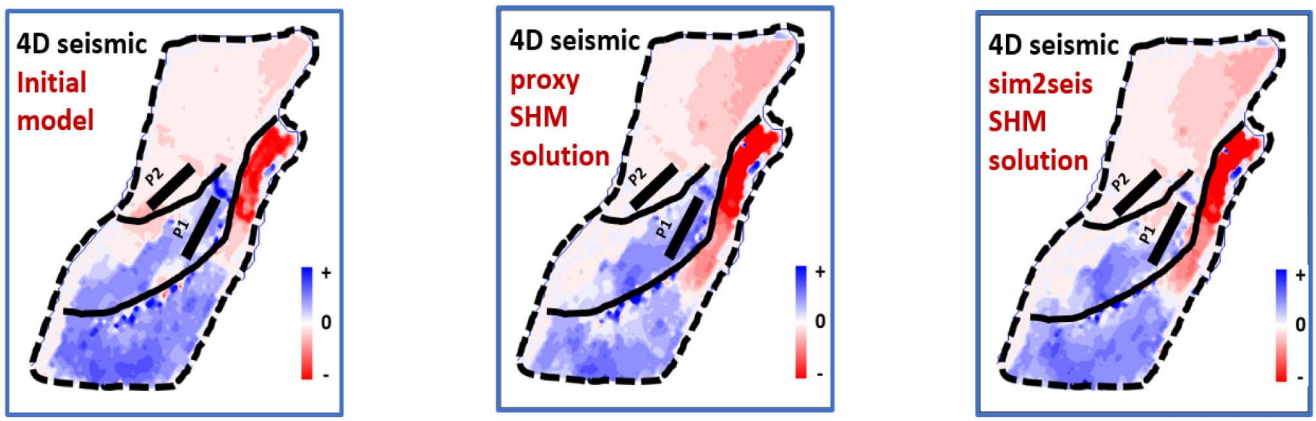


**Figure 9—left 4D (03-01) seismic map of Ile formation in block E and D of the initial simulation model; middle: from the optimal solution of proxy driven SHM, right: sim2seis optimal SHM solution**

Furthermore, we compare the production matching improvement of two SHMs, of which the objective function only contains seismic mismatch. As introduced at the beginning of this part, the main mismatch of the initial model is water cut. Hence we selected two main producers in the region, well P1 and P2, to check the improvement of the production match (Figure 10).

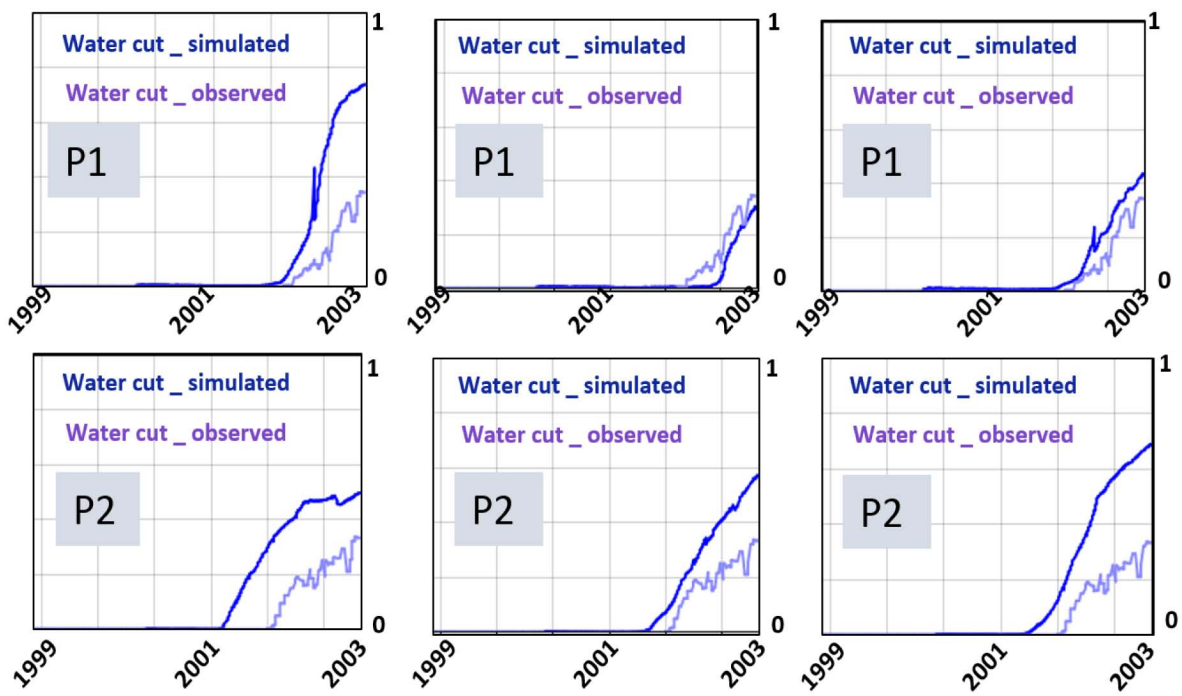


**Figure 10—left side: the well water cut data and modelled seismic (by sim2seis) of the initial model; the middle column corresponds to the optimal solution of fixed proxy-driven SHM and the right side is from the sim2seis-driven SHM optimal solution.**

In the initial case, well water cut for the two wells was over-simulated. Water breakthrough time (WBT) of P1 was well matched but cumulative water production (CWP) was over simulated. For well P2, the simulated WBT was 6 months before the observation and CWP was also over-simulated. In the optimal model of sim2seis SHM, the improvement of well P1is clear. For P2, the CWP became worse, but the WBT was improved by 50%. In the case of proxy solution, the match of two wells were both clearly improved.

In terms of the computation time, a single run of sim2seis (petro-elastic modelling, 1D convolution plus maps extraction) takes roughly 850 seconds while the proxy only needs couple of seconds. In the SHM loop where fluid flow simulation is also included, the speed could be improved by 60% by using the proxy.

## Conclusion

We have developed a proxy seismic modeling procedure that helps to simplify seismic history matching and avoids the need for a petro-elastic model or full seismic modeling. This method relies on a data-driven relationship between the 4D seismic data and the reservoir dynamic properties. It has been studied in three ways from different perspectives, firstly we verified the linearity hypothesis, then we performed a quasi-SHM and finally we integrated this proxy into a complete SHM, applied on a Norwegian Sea field. The results, conclusions and further recommendations can be drawn from this study:

1. The linear relationship between 4D seismic map and 4D pressure and saturation maps is firstly confirmed following Falahat's method, and the results of quasi-history matching indicates the possibility to utilise a fixed proxy to model the 4D seismic. At the last stage, sim2seis and proxy-driven SHMs lead to comparable optimal solutions. Even with little perturbation, the proxy method performed well in the SHM workflow as a replacement of costly sim2seis modelling.
2. In either SHM case (sim2seis or proxy-driven), matching to seismic data can simultaneously improve the production match, this proves that the spatial information contained in seismic can be a further constraint for history matching in combination with production data.
3. For further recommendations, mapped based seismic is a precondition of this procedure which can be a potential limitation for other cases. In addition, the application conditions such as the field geostructure, seismic attributes selection need to be explored exhaustively.

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