Introduction

From a practical perspective, simulator to seismic modelling is one of the most difficult and potentially erroneous tasks facing a reservoir engineer engaged in a seismic history matching (SHM) project (Alvarez and MacBeth 2014). It requires selection and calibration of a petro-elastic model (PEM), building of a seismic geo-model of impedances, followed by seismic wave propagation modelling (Roggero et al. 2007). Finally, the key geological events for the reservoir must be identified and picked on the synthetic data and the requisite attributes evaluated. The simulator to seismic modelling workflow still presents a considerable bottleneck to making full use of seismic data in the final quantitative update of a simulation model. In particular, the PEM and seismic modelling steps are time-consuming, carry considerable uncertainty due mainly to the stress sensitivity component (MacBeth 2004; Furre et al. 2008), and require extensive calibration which is non-trivial (Amini 2014). In an attempt to circumvent the difficulties outlined above, this current work implements a proxy for these latter two steps of the calculation. This approach speeds up the workflow considerably and allows a reservoir engineer with no prior knowledge of seismic data or modelling to gain immediate access to 4D seismic data as a matching tool, with no associated loss of accuracy.

The seismic modelling proxy

We aim to provide a quick and robust prediction of the 4D seismic data from the pressure, water and gas saturation changes output from the fluid-flow simulator. To do this we limit ourselves to only mapped seismic attributes, where the attribute has been evaluated with respect to a stable and interpretable seismic horizon such as the top of the producing reservoir clearly identified in the seismic volume. The use of mapped seismic quantities is justifiable as many of the reservoirs we have interpreted are generally thinner than a fraction of a seismic wavelength, and the seismic response provides an average of the fluid saturation and pressure for the entire producing depth interval. Maps for time-lapse seismic analysis are created by differencing the individual monitor and the baseline survey maps. The challenge is to calculate this time-lapse seismic map from the depth-averaged pressure and saturation changes obtained via the fluid-flow simulation.

Our formulation is derived from the empirical observation of multiple monitor surveys across many North Sea fields (see for example Floricich et al. 2016). Inspection of the sequences for an extensive range of both observed and synthetic data indicates that both baseline and monitor images are visually similar. This is what we might expect, as the baseline response 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 component and pressure perturbed due to well production and recovery. Key to our understanding is that 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. If $A_0(x,y)$ represents the seismic response at the pre-production baseline time and ΔR the effect of subsequent fluid saturation and pressure changes in the reservoir, the time-lapse seismic map $\Delta A(x,y)$ can be constructed

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

where f is a function of the production-related changes and the geology, G, which depends on the petroelastic and seismic modelling. By involving the observed pre-production baseline survey in the time-lapse seismic calculation, we account for known (or unknown) lateral variations of the static reservoir properties such as thickness, porosity and net-to-gross, as well as destructive and constructive wavelet interference effects such as tuning in the 3D dataset. An additional benefit is that ΔA is already calculated in the attribute 'currency' of the seismic data. The form of the proxy function *f* can be considered from analogy with successful proxy modelling elsewhere (He et al. 2015). In our case, as we are dealing with relatively small changes, one obvious form for $f(\Delta R, G)$ is a quadratic in pressure and saturation changes (MacBeth et al. 2006). The relationship amplifies or diminishes the baseline seismic response according to the depth-averaged pressure ΔP and saturation (ΔS_w, ΔS_g) changes obtained from simulator predictions (they already obey material balance, and so too will the 4D seismic data), to yield the mapped time-lapse response ΔA. The accuracy and robustness of the proxy for history matching purposes is tested in the next section.

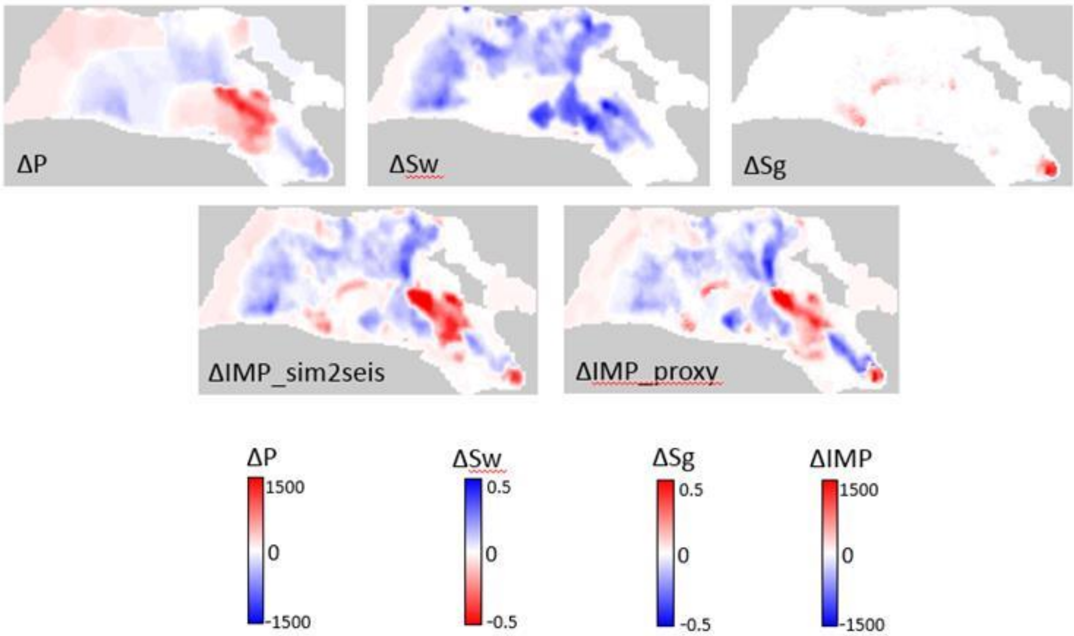

Figure 1 *Comparison of pressure and saturation change output from the simulator with changes of impedance calculated using a calibrated petroelastic model and the proposed proxy.*

Seismic history matching using the proxy

The key to using (1) effectively in modelling as part of history matching is the rapid evaluation of the proxy coefficients without recourse to the time-consuming calibration and modelling steps that we are trying to avoid. For any given simulation model run (and thus output pressures and saturations), the coefficients are determined by least squares regression to the observed time-lapse seismic data. As there are only, at maximum, nine coefficients for the proxy and typically thousands of data points, this matching procedure is over-determined and quite satisfactory. Despite being overdetermined, an important feature of the matching algorithm, to ensure robustness and accuracy, is the introduction of physical constraints or inequality rules to the coefficients. This is necessary, as the relative magnitudes of the individual terms should behave according to predictable physical laws (Alvarez and MacBeth 2016). Figure 1 shows the result of this procedure for a North Sea field. The overall pattern of the mapped response is captured well, and the proxy is observed to fit to within a mean error of a few percent. Variations between the quadratic and the linear proxy are also seen to be slight in this case: 3.2% error versus 4.5% respectively.

For seismic history matching the most important question is whether the multi-linear regression could compensate for a bad model choice with equally bad simulation predictions, and can influence estimation of the optimum and thus bias the selection of the best models. To test the impact of our approach on the performance of the SHM procedure, synthetic tests are initially performed on the reservoir model for our North Sea field dataset. A full simulator to seismic modelling (sim2seis) is performed with an extensively calibrated petroelastic model as a reference. A proxy model is created that matches the chosen reservoir model and its predictions to the reference case seismic data. Next, an ensemble of model scenarios are generated by stochastic variation of the controlling parameters (fault, geobody transmissibility multipliers and vertical permeability). For each model in the ensemble, the L2 norm objective function is used to assess the difference between the reference 4D seismic response and the proxy response, and also between the reference case and the full simulator to seismic modelling. Patricle swarm optimization is utlised in the updating strategy for the pool of solutions. The results for thirty realisations are shown in Figure 2. Two tests are performed: in the first, the original proxy coefficients are fixed after one iteration; in the second the coefficients are re-evaluated after every iteration. Importantly, the behaviour in the solution space for the objective function appears to well defined by the proxy, both in fixed and adaptive mode, and in good agreement with the full seismic modelling. Figure 3 shows that the solution space near to and including the optimal point for parameter selection may not be distorted by the use of the proxy.

Discussion and conclusions

We have developed a fast-track seismic modelling procedure that helps to simplify seismic history matching and avoids the need for a petro-elastic model or full seismic modelling. The procedure relies on a data-driven relationship between the 4D seismic data and the reservoir dynamic properties. The procedure has been tested in a full seismic history matching workflow for several North Sea

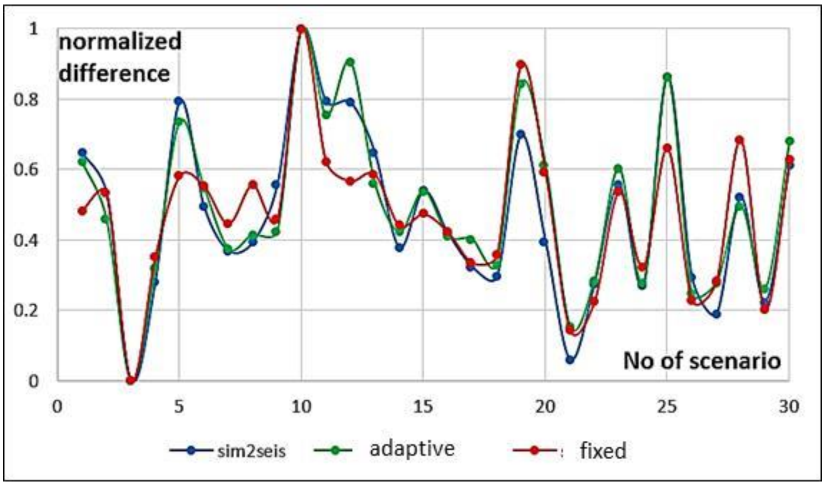

Figure 2 *Normalised misfits between predicted sim2seis solutions for thirty realisations of the simulation model and a pre-selected reference model. Blue line – full sim2seis calculation; Green line – adaptive proxy result; Red line – fixed proxy result.*

fields and found to work well. The optimal SHM solution can still be found using the proxy, and solution space appears to have a similar character to that defined by full modelling. Whilst a perfect fit is not of course completely possible with a proxy, as the relationship between the depth-averaged pressure and saturation changes and the seismic data is in reality quite complex, it does appear that by working with mapped seismic attributes the response simplifies to the level where a good practical comparison is possible. The approximate result appears good enough to run a comprehensive seismic history matching, without recourse to the petroelastic model or seismic modelling tools that may not be readily available by an asset team engineer.

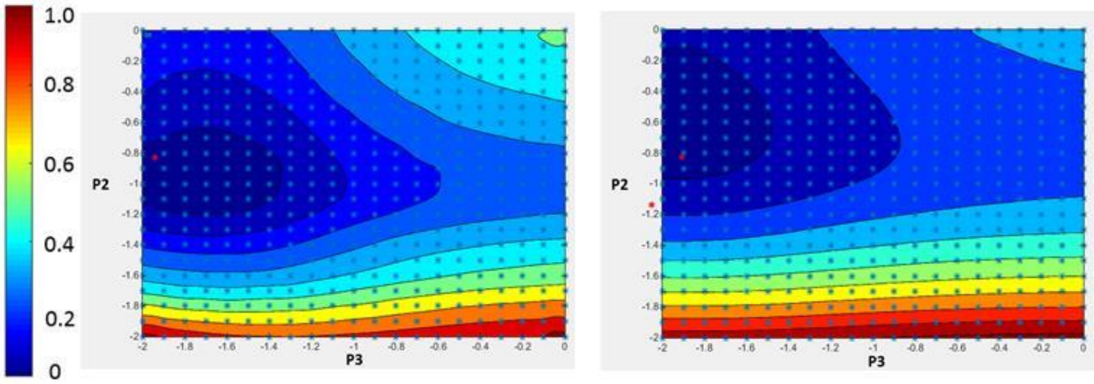

Figure 3 *Misfit surfaces for two parameters (P2 and P3) in our history match. (a) surface using sim2seis procedure; (b) surface using the fixed proxy. The red dot indicates the true solution.*

Acknowledgements

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References

Alvarez, E., and MacBeth, C. [2014] An insightful parametrization for the flatlander's interpretation of time-lapsed seismic data: Geophysical Prospecting, **62**, 75-96.

Amini, H. [2014] A pragmatic approach to simulator to seismic modelling for 4D seismic interpretation: PhD thesis, Heriot-Watt University.

Furre, A-K., Andersen, M. Moen A.S. and Tønnessen, R.K. [2008] Deriving effects of pressure depletion on elastic framework moduli from sonic logs: Geophysical Prospecting, **57**, 427–437.

Floricich, M., MacBeth, C. Stammeijer, J. Staples, R. Evans A. and Dijksman, C. [2006] A new technique for pressure - saturation separation from time-lapse seismic - Schiehallion case study: 68th Conference and Exhibition, EAGE, Extended Abstracts, DOI: 10.3997/2214-4609.201402389

He, J., Xie, J. Wen X-H. and Chen, W. [2015] Improved proxy for history matching using proxy-for-data approach and reduced order modelling: SPE Journal, doi:10.2118/174055-MS.

MacBeth, C. [2004] A classification for the pressure sensitivity properties of a sandstone rockframe: Geophysics, **69**, 497-510.

MacBeth, C., Floricich M. and Soldo, J. [2006] Going quantitative with 4D seismic analysis: Geophysical Prospecting, **54**, 303-317.

Roggero, F., Ding, D.Y., Berthet, P., Lerat, O., Cap J. and Schreiber, P-E. [2007] Matching of Production History and 4D Seismic Data - Application to the Girassol Field, Offshore Angola: SPE Annual Technical Conference and Exhibition, SPE-109929-MS.