Direct correlation of 4D seismic and well activity for dynamic reservoir interpretation

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Summary

A method is proposed which identifies areas in the 4D seismic response which directly correlate with well activity, and hence are consistent with the reservoir engineer's understanding of the field. This approach makes use of the essential requirement for a causal relationship between the seismic difference signatures and the cumulative produced or injected volumes. The method relies upon the use of multiple and frequently shot seismic surveys over a common reservoir area. It is applied to data from the Schiehallion field, West of the Shetland Islands, and the resultant signals are observed to be robust, with a much reduced noise level and to enhance particularly weak 4D seismic signatures. The results may be indicative of regions of connectivity associated with each well.

Introduction

A common objective in the workflow of many time-lapse projects is the need to establish a relationship between the processed 4D seismic product and fluid flow simulation predictions. This objective is typically met by matching observed and predicted 4D seismic (from simulator-to-seismic calculations), either at a qualitative level or quantitatively via a seismic history match (Stephen and MacBeth 2006). Of importance in this procedure is the presence of noise in the 4D seismic arising from the inter-vintage non-repeatability of acquisition and processing procedures. Such noise may lead to possible ambiguities when interpreting the seismic for a reservoir signal. Whilst simulator-to-seismic computations give some understanding of what the true reservoir 4D seismic signature may look like, observed data are generally not yet sufficiently calibrated to warrant detailed quantitative inspection. Indeed, inversion of 4D seismic to pressure and saturation changes (Landrø, 2001; MacBeth et al. 2005), have revealed that there are still many inconsistencies between the seismic and engineering domains.

We believe the key to bridging these two domains is the understanding that the 4D seismic signatures must respond directly to changes in well production and injection during the time periods over which the 4D surveys are shot. It is shown below that the time-lapse seismic can be correlated to the cumulative well activity. Thus, knowledge of the well activity permits us to filter out extraneous signals or noise, and focus only on reservoir-related amplitudes. Well data used predominantly for history matching in the reservoir domain can now also be used to constrain the 4D seismic response and help control noise levels. To implement this understanding requires multiple seismic surveys shot at frequent intervals over the same reservoir. There are now many fields for which such datasets have become available.

Method

In a non-compacting reservoir the 4D signature is driven by changes of pressure and saturation due to the production and injection activity. Thus, at any particular location in the reservoir, the 4D signature is a direct function of the nearby well activity. More specifically, by modifying the proposed pressure-saturation equation of MacBeth et al. (2005) to involve only well activity, the 4D signature ΔA at location (x_i,y_i) and between a fixed time period ΔT can be written as the summation of a number of functions $f(\Delta V_j)$ of the cumulative injected or produced volumes ΔV_j from each of the N wells (j=1, N) in the field

$$\Delta A(x_i, y_i) = \psi(x_i, y_i) \sum_{j=1,N} G_{ij}\, f(\Delta V_j). \qquad (1)$$

The functions $f(\Delta V_j)$ incorporate the effects of both pressure and saturation changes. The coefficient $\psi(x_i,y_i)$ determines the strength of the response and is related to local geological conditions (the petroelastic model) whilst G_{ij} relates to the strength of the connected pathways in the geology between the well and the location (x_i,y_i) (Figure 1). The pressure change caused by the well of interest, for example, is balanced by the injecting wells (negative ΔV for producers and positive ΔV for injectors).

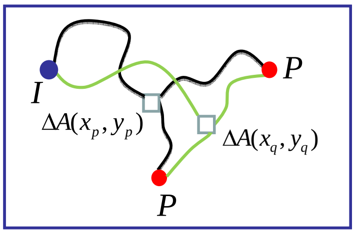

Figure 1 The 4D signature and connectivities for two generalised locations (x_p,y_p) and (x_q,y_q) are given by differently weighted sums of the cumulative volumes from the producing ($-\Delta V$) and injecting ($+\Delta V$) wells.

Let us now consider the particular case of a pressure-dominated 4D seismic signature around a single well. Here, we can distinguish between several flow regimes. It is known that fluid flow system is in a pseudo-steady state when production or injection is in a constrained space such as a fault block or low permeability zone. Under this condition, $f(\Delta V_j)$ is linearly proportional to the cumulative produced or injected volumes, so that $f(\Delta V_j) \propto \Delta V_j$. However, if the producing wells of interest possess adequate pressure support from neighbouring injection wells or an active aquifer, then there is no pressure change (the steady state condition), and thus $f(\Delta V_j) = 0$. In the general case, when neither regime is strictly applicable, only a fraction of ΔV_j contributes to the function. To cover all cases we write $f(\Delta V_j) \approx \xi \Delta V$, where ξ is a coefficient that may be approximately constant around each well and it's neighbourhood. ξ is likely to vary across the field, and should be constant with calendar time at a particular location. It follows that ΔA at a location close to the active well $j=M$ should be proportional to the cumulative volumes produced or injected (ΔV_M) from this well (Figure 2). This specific application of (1) assumes the other wells are some distance away and do not interfere - the validity of this relationship can be judged by observing the correlations in Figure 3. The strength of this correlation is dependent on the surrounding geological conditions

$$\Delta A(x_i, y_i) = \psi_i \xi_{iM} G_{iM} \Delta V_M . \qquad (2)$$

Thus, in the neighbourhood of well $j=M$, the pressure-driven 4D signature may be linearly correlated to the cumulative fluid volumes produced or injected, when observed as a function of production time.

Extending this concept further, we postulate that seismic data acquired from multiple repeated surveys can exploit and reinforce this relationship. Thus, from many vintages of survey shot over the same location at different intervals in calendar time, it is possible to form a time sequence of mapped 4D signatures ΔA_k associated with a sequence of cumulative volumes ΔV_k (k=1,K) from the production/injection data (Figure 2).

$$\Delta A(x_i, y_i; \Delta T_k) = \{\psi_i \xi_{iM} G_{iM}\} \Delta V_M (\Delta T_k), \qquad (3)$$

where the lumped term in the righthandside brackets contain information about the geology, connectivity and compartmentalisation. Now, for each well M and a particular nearby location (x_i, y_i), the normalised cross correlation coefficient between the 4D seismic signatures and the change in well volumes can be calculated

$$R = \frac{\sum_{k=1}^{K} (\Delta A_k - \overline{\Delta A})(\Delta V_k - \overline{\Delta V})}{\sqrt{\sum_{k=1}^{K} (\Delta A_k - \overline{\Delta A})(\Delta A_k - \overline{\Delta A})} \sqrt{\sum_{k=1}^{K} (\Delta V_k - \overline{\Delta V})(\Delta V_k - \overline{\Delta V})}} . \qquad (4)$$

The thresholded, normalized correlation coefficient calculated for each seismic pixel in the area of interest defines the new 4D signal associated with the particular well of interest. This exercise is now repeated around the neighbourhood of each well in the field. The technique has particular merit for those 4D signatures that are noisy, and has the potential to enhance the interpretation by producing maps of the lumped term on the righthandside of (3).

One further step is required to ensure the correlation coefficients can be interpreted uniquely. It is known that each well possesses a radius of influence beyond which no signal can possibly have originated from that well. Calculation and application of this avoids inter-well crossover ambiguities. Here, this is implemented using a prior probability function centred on the well and superimposing this on the correlation anomalies. This relation is obtained by use of the hydraulic diffusivity equation applied to radial flow. This requires specification of the porosity, total fluid mobility, rock and fluid compressibilities, and knowledge of the well pressures. Values for the reservoir parameters are extracted as distributions from the simulation model, and then a Monte-Carlo procedure implemented to define a range of distances of influence from the well for which pressure decays below a preset cut-off of 200psi - given a specific elapsed calendar time. This stochastic approach allows us to define a probability distribution associated with the outer boundary of the area influenced by each well.

Application to the Schiehallion field

The technique is applied to data from the Schiehallion field, West of Shetlands area in the North Sea. The reservoirs in the field consist of stacked turbidite sands of Paleocene age lying between 1800 and 2064m. These sands are complex to produce, and there is known compartmentalisation from major E-W trending faults and the sand body geometry and interconnections. Connectivity has been recognised as a key factor for reservoir management (Parr et al. 2000). These data have been previously studied for connectivity by Al-Maskeri and MacBeth (2005), Stephen and MacBeth (2006) and Floricich et al. (2008). The proposed method is tested on segment 4 in the south eastern portion of the field, where the 4D signal is dominantly pressure driven. Processed seismic are available for 1996 (baseline), 1999, 2000, 2002, and 2004, relative to a production start-up of 1998. These data have been cross-equalised by the field operator and are of satisfactory repeatability. Here, we work with maps of the *RMS* amplitude generated from the picked top of the T31 producing interval. This sequence of acquisitions forms a variety of permutations of possible 4D signatures in calendar time.

The five repeated seismic surveys studied produce in total ten different time sequences from the various combinations of difference maps. Using the well data provided, the cumulative produced or injected volumes for each time are computed (Figure 2). An area with gas coming out of solution is avoided in this present analysis (lower left area in map of Figure 3). Cumulative volumes are calculated based only on the produced oil and water phases, or injected water. The surface volumes are corrected to volumes at reservoir pressure using the relevant volume formation factors.

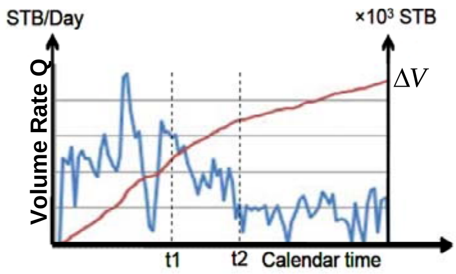

Figure 2. In this technique, cumulative volumes ΔV (red line) are generated from the rates (blue line) and summed for each well of interest.

Initial inspection of the seismic data revealed a strong underlying correlation with the well activity for regions close to each well (Figure 3). Interestingly, it is observed that when amplitudes between surveys are not satisfactorily cross-equalised, this fact is revealed in the correlation analysis and can thus be readily corrected. The resultant signals produced by the method are shown in Figure 4 for a selection of wells in the segment. The signals are observed to be quite different in character from the basic 4D seismic signatures – indeed, this may be expected as they are a composite of many 4D seismic signatures and well history. The result is considerably less noisy and more robust than a difference signature. By derivation, the signals also agree in overall area of influence and magnitude of the expected amount of production/injection (compare the results for the wells in Figure 4). Their distribution now shows the areas of the reservoir potentially active and capable of yielding a viable 4D signature, and also affected by the particular well. However it should be noted that the signals do not always appear to be spatially connected or contiguous around each well. Analysis using synthetic seismic responses and simulation predictions has shown that this character may be a manifestation of the nature of the horizon picks, particular attribute used, 3D connected pathways, and variations in the petroeleastic model.

Conclusions

It is possible to correlate mapped 4D seismic signatures from multiply acquired repeat surveys with the cumulative volumes produced or injected at wells over these time periods. This technique works provided the 4D seismic signatures are driven predominantly by pressure. The resultant signals identify only those areas of the seismic which are strongly consistent with the well activity, and hence define portions of the reservoir connected to the wells. This information unites the seismic and well domains without the use of the simulation model. The signal tends to be robust and have a much lower noise when compared to the individual 4D seismic difference signatures. The relationship to connectivity suggests it holds promise as a tool for updating the simulation model when 4D data are noisy or reservoirs are complex.

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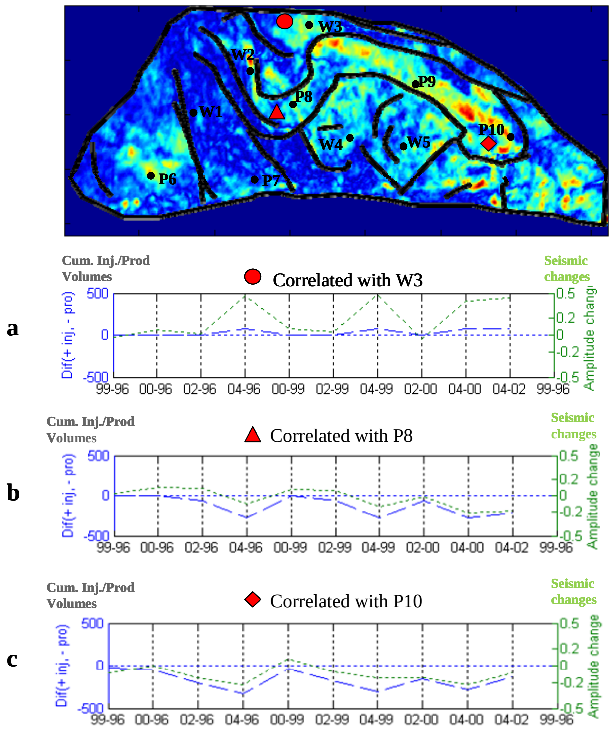

Figure 3. Examples of seismic-to-well correlations with sequences of time difference for three locations (marked by the red symbols on the top 1996 *RMS* map) near to injector W3, producer P8 and producer P10 (black filled circles).

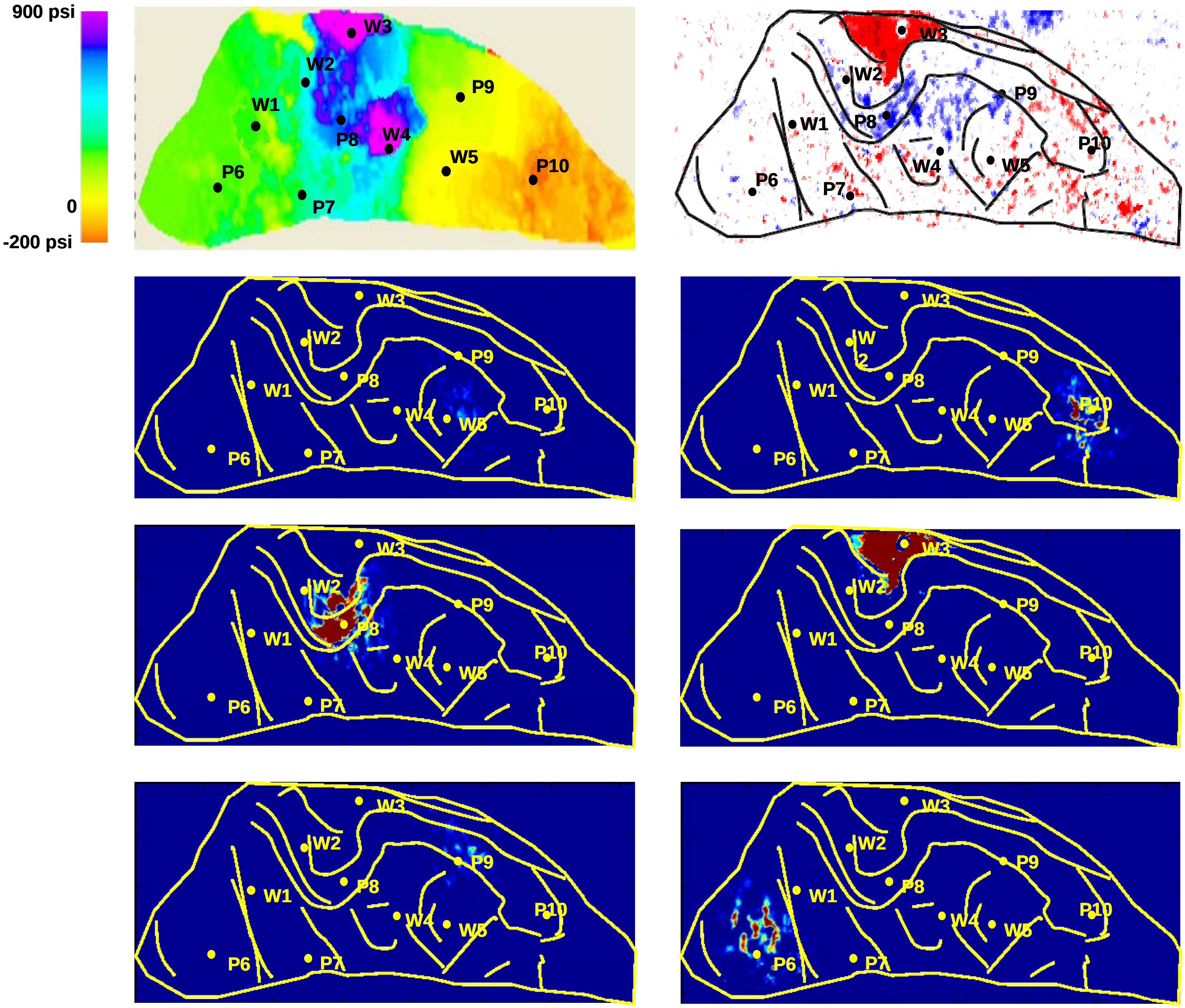

Figure 4. Top left: predicted pressure change between 2004 and 2002; top right: 4D difference between 2004 and 2002. Bottom: selection of diagrams showing results for wells W5, P10, P8, W3, P9 and P6. There are strong signals around wells W3 and P8, which have been enhanced using this technique. The signal around P6 is weak and noisy on the original 4D difference maps. Around the strongly active injector W5, there is a weak correlation between the seismic and the well activity as the pressure influence is balanced by the neighboring wells. Here, also, the conventional 4D difference is observed to possess a very weak signal. The yellow lines outline major channels and are drawn for reference.

EDITED REFERENCES

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