Enhancing dynamic interpretation at the Valhall Field by correlating well activity to 4D seismic signatures

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Abstract

Sequences of 4D seismic changes extracted over different time intervals from multiply repeated seismic surveys are correlated with the identical time sequences of cumulative fluid volumes produced from or injected into wells. Maps of these cross-correlations have previously been shown to produce a localized signal in the connected neighbourhood of individual wells. The technique is applied to the frequently repeated seismic surveys from the life of field seismic project in the Valhall Field, for which the 4D seismic signature is dominated by compaction-assisted pressure depletion. For these data, both acoustic impedance and time-shift attributes are found to have a remarkably consistent correlation with the well activity from selected groups of wells. Furthermore, maps of these results have sufficient fine scale detail to resolve interfering seismic responses generated by closely spaced wells and discrete zones of gas breakout along long horizontal producers. We conclude that uniting well data and 4D seismic data using our proposed method provides a new attribute for dynamic interpretation of the producing reservoir.

Introduction

A 4D seismic signature cannot be unambiguously interpreted without a clear understanding of the historical production data for the field of interest. Thus, for example, reservoir hardening (impedance increase) around a producer can be linked to pore pressure decrease, or softening (impedance decrease) around an injector to a pore pressure increase. Putting the seismic signal into the context of the well activity resolves the ambiguity of the hardening being predominantly caused by the alternative explanation of water encroachment, or the softening by gas coming out of solution.

Another way in which 4D seismic signatures may be understood is by their timing with respect to well activity. An increased pressure signal from activation of an injector may be identified some distance from the well as a pressure effect before the waterfront arrives. In general, we may expect that the evolution of seismic signatures from repeat seismic surveys should be related to the well activity over the corresponding time intervals. Well activity is defined here as the variation in the measured volumes produced or injected into the formation over time from the wells in the field (Huang and MacBeth, 2009; Huang et al., 2010).

As more 4D surveys are acquired at shorter time intervals, the correlation between cause (saturaton and pressure variations induced by the well activity) and effect (the 4D seismic signature) can be utilized practically. Implementation of this well-centric approach requires multiple seismic surveys shot at frequent intervals over the same reservoir. In this respect, one important trend in the development of 4D seismic acquisition in the past decade has been the more common use of frequently acquired seismic surveys. There are now many fields in the North Sea for which such datasets have become available. For example, life of field seismic (LoFS) projects have been implemented on the Valhall Field which have so far delivered 12 or more 3D seismic surveys shot at time intervals of 2–10 months apart. Similar projects have been initiated on the Clair Field (Foster et al., 2008), the Snorre Field (Morton et al., 2009), and the Ekofisk Field (Haugvaldstad et al., 2010). In the wider context, many fields such as Norne (Osdal and Alsos, 2010) and Schiehallion (Floricich et al., 2008) have been repeatedly shot with seven or eight towed streamer surveys at intervals of 12–24 months apart. It is the purpose of this article to demonstrate that such frequent monitoring not only fulfils the needs for depletion and water injection monitoring for improved well performance and accurate simulation model updating, but also opens up access to inter-disciplinary tools that provide a hard link between the dynamic information in both the seismic and engineering domains.

Relating well activity to the seismic response

At any particular location in the reservoir, the 4D signature is a direct function of the production and injection history

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of wells connected to that location. More specifically, by modifying the proposed pressure-saturation equation of MacBeth et al. (2006) to involve only well volumes, a pressure-dominated 4D signature evaluated over a fixed time interval can be related to the cumulative sum of the produced or injected volumes from these wells. For example, in the neighbourhood of an individual well, \( j \), such a 4D signature can be linearly correlated to the well activity when observed as a sequence at many different elapsed times. We propose that seismic data acquired from multiple repeated surveys can exploit this principle. For many surveys shot over the same location \((x,y)\) at different intervals \(\Delta T_k\) (where \(k = 1, \ldots, P\)) of calendar time, it is possible to form a time sequence of mapped 4D signatures \(\Delta A_k\) associated with a corresponding sequence of cumulative volumes \(\Delta V_k(\Delta T_k)\) from the measured production or injection data (Huang and MacBeth, 2009) such that

\[
\Delta A(x, y, \Delta T_k) = GAV_j(\Delta T_k),
\]

where the lumped term \(G\) on the right contains information about the geology, fluid properties, petroelastic model, connectivity, and degree of compartmentalization (and hence reservoir boundary conditions). Generalizing to combine the effects of a connected group of \(M\) producers and \(N\) injectors, the time-lapse seismic changes \(\Delta A(x,y)\) for each time interval may be written as

\[
\Delta A_k(x, y) = G \left[ \sum_{j=1}^{M} B_j \Delta V^o_j + \sum_{j=1}^{M} B_j \Delta V^w_j + \sum_{i=1}^{N} B_i \Delta V^w_i \right],
\]

where \(B_j\) and \(B^w_i\) are the formation volume factors for oil and water respectively, \(\Delta V^o\) the oil volume difference, and \(\Delta V^w\) the produced or injected water volume difference.

Based on the relations in Equations (1) and (2), Huang and MacBeth (2009, 2011) have shown that the amplitude of pressure-dominated seismic signals on the Schiehallion Field vary directly with fluctuations in the amount of fluid produced or injected into closed compartments. They also carried out flow simulation and seismic modelling studies which validate the proposed method for different seismic attributes and reservoirs.

With multiple seismic surveys, a time sequence can be created by making difference maps for all possible pairs of surveys, i.e., \(\Delta A(x,y)\) for all \(\Delta T_k\). Indeed, for \(n\) surveys, there are \(n(n - 1)/2\) combinations of differences. It is the concatenation of these different combinations that form the sequences used in this method. Thus, for the 10 repeated surveys used here for the Valhall Field, a sequence with 45 distinct difference maps can be generated. After this, the seismic attribute sequence \(\Delta A_1, \Delta A_2, \Delta A_3, \ldots, \Delta A_{45}\) for each seismic bin location \((x,y)\) is separately linked to the corresponding sequence of cumulative volumes \((\Delta V^o_1, \Delta V^o_2, \Delta V^o_3, \ldots, \Delta V^o_{45})\) for a connected well group by calculating the normalized cross-correlation (NCC) statistic (Bevington, 1975). Good correlation implies a connection to the particular well or well group via Equations (1) and (2). This measure is calculated for each seismic bin location \((x,y)\), thereby producing a map of NCC across the reservoir region of interest. When mapped, this seismic-to-well correlation measure maintains the lateral resolution of the seismic data, and is therefore usually higher than that of the flow simulation model.

More repeat surveys or alternations in well rate lead to an increasingly complicated and finer scale time sequence, hence increasing statistical robustness of the NCC measure. To ensure stability, a minimum credibility threshold is needed for the NCC maps, as for a particular size of time sequence the NCC coefficient is only statistically significant above a certain value. Below this threshold there is a chance that samples drawn at random can yield the same coefficient (Bevington, 1975). For example, for the 45 points used here, sequences with NCC coefficients greater than 0.38 are significant with a 99% confidence, whereas for 10 points this threshold becomes 0.77. Another reason for thresholding the NCC maps used in the current work is to focus on the 4D signature induced only by a particular well or group of wells, and to exclude the contributions from other wells. The correlation coefficient between the selected well group of interest and the seismic sequence must in this case be higher than the sequence correlation between the excluded wells and the selected group.

The above approach opens up the possibility of reconciling well and seismic data in the data domain rather than the model domain. Well data normally used exclusively for history matching in the reservoir engineering domain can now also be directly integrated with time-lapse seismic data. We will now apply this approach to the data from the LoFS on Valhall. The method is applied to the data after preliminary modelling tests to determine whether the compaction-assisted, pressure or saturation driven, 4D signal will respond with a similar behaviour to that described above. It will be shown from the data that this seismic does indeed provide a high degree of conformance to the predictions of Equations (1) and (2).

### Application to Valhall LoFS

The Valhall Field is located in the Central Graben, North Sea in the southernmost corner of the Norwegian continental shelf. It was discovered in 1975 and has been in production since 1982, with the majority of production under primary depletion. As is typical of chalk fields, the reservoir rock is characterized by a high porosity and low permeability. Approximately 50% of the drive mechanism has come from rock compaction and active geomechanical effects that directly affect production (van Gestel et al., 2008).

The approach outlined in the previous section is applied to three areas: the South Flank, North Flank and South Crest areas of the field (Figure 1). Across the field, the seismic response is strongly related to the pressure reduction and resulting compaction. It is thus anticipated that the method should work well with these data. A water injection programme was started in 2007 and there is a need to understand
interval are computed 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 as in Equation (2). Although strong 4D seismic changes can be observed in the three regions of interest, some challenges to dynamic 4D seismic interpretation are known to exist. It will be shown how our results can be used to enhance the interpretation in these areas, and help resolve these potential difficulties. We tackle these issues using two types of seismic attributes: the acoustic impedance (AI) difference obtained through the process of coloured inversion plus a calibration step (Connolly, 1999); and time-shift attributes that are extracted from the overburden and can be correlated to compaction using an R-factor (Hatchell and Bourne, 2005).

Selected example 1 – North Flank

The field is mostly produced by many long-reach horizontal wells (Barkved et al., 2009), and the 4D seismic signatures can be observed to be clearly associated with individual perforations. Figure 2 shows how the time shifts behave over this area relative to the wells. However, it is found that due to the dense positioning of the wells it is difficult to precisely resolve the individual well responses using conventional 4D seismic attributes, as the closely positioned responses overlap and interfere.

Plots for the cumulative volumes obtained from all seven wells in the North Flank are shown in Figure 3a. Comparing and correlating these well activity sequences is an important prerequisite reference step for this study, and we identify two distinct groups of wells each with similar characteristics (Table 2). In the first group are wells N-5, N-7, and N-15 (Figure 3b), with an intra-group correlation coefficient between 0.94 and 0.99. In the second group are wells N-11, N-12, and N-14 (Figure 3c), with a similar intra-group correlation, but a correlation with the first group of 0.883. It appears just possible to separate the two groups on the basis of their different behaviour.

Proceeding with the seismic-to-well correlation analysis, all wells correlate strongly with the time-lapse signatures when plotted over calendar time or sequence number defined by different combinations interval time. Figure 4 shows a map of the NCC statistic defined from the previous section,
relating the well activity of Group 1 (as characterized by well N-15) to the 4D time-shift attribute. In this case, the threshold for the map is set at 0.85 to eliminate any undesirable correlations with well Group 2. Interestingly, a major feature strongly concentrated around well N-15 is revealed, with smaller concentrations around the other Group 1 wells N-5 and N-7. The correlation process has separated the original seismic response into the discrete drainage areas influenced by the wells in Group 1. Figure 5 shows the corresponding NCC map for the correlation between Group 2 wells, as characterized by well N-14, and the time-shift attribute, with an identical threshold set. The major anomalies now concentrate on N-11, N-12, and N-14. In both maps, the boundaries of separation between the drainage areas of N-15 and N-14 are now clearly visible, and these are quite different from any interpretation that might be made on the observed seismic response in Figure 2. It should be noted, however, that although the desired separation is achieved, responses at N-12 and N-11 from Group 1 are still observed, this being an artifact of the narrow margin between intra- and inter-well correlation that exists for this particular case. Note both correlations are still higher than the statistical significance threshold of 0.38 at 99% confidence.

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<tr>
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<th>Group 1</th>
<th>Group 2</th>
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<tr>
<td></td>
<td>N-5</td>
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</tr>
<tr>
<td>Group 1</td>
<td>N-5</td>
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<tr>
<td></td>
<td>N-15</td>
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</tr>
<tr>
<td></td>
<td>N-7</td>
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<tr>
<td>Group 2</td>
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</tr>
<tr>
<td></td>
<td>N-12</td>
<td>0.875</td>
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<tr>
<td></td>
<td>N-14</td>
<td>0.835</td>
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</tbody>
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Table 2 The matrix of NCCs calculated between time sequences of cumulative produced volumes at the wells from the North Flank. The wells are divided loosely into two groups based on the magnitude of their cross-correlations. The correlations between wells in group 1 and 2 are lower than any of the intra-group correlations.
which indicates that in this case that there is a larger difference between the intra- and inter-well correlations.

Figure 7 shows the resultant seismic-to-well correlation NCC map thresholded at 0.75, generated by correlating the AI signatures with S-12, characterizing Group 1. The maps reveal two strong zones of correlation related to wells S-11 and S-12 and a weaker zone related to S-14, but also small circular regions of reduced correlation that are positioned over the well perforations. This correlation weakening is caused by the exsolved gas disrupting and reversing the systematic hardening trend established between pressure depletion and the AI attribute. These zones are not evident in the map of AI change shown in Figure 6. Indeed, a separate study (Barkved et al., 2009) has shown that it requires an attribute designed using a mix of multiple attributes to specifically illuminate these particular gas zones. These zones correspond to particularly active and competent perforations, with good connection to the formation, high reservoir quality, and hence well developed pressure depletion.

**Selected example 3 – South Crest**

Our third example is based on injector G-24 on the South Crest, surrounded by a number of producers A-2, A-3, A-11, A-16, and A-18 (van Gestel et al., 2010). G-24 starts injecting after the sixth LoFS survey and then injects at a constant rate. To detect the resultant waterflood precisely, the reservoir hardening effect caused by water influx must be identified in the AI response (Figure 8). Unfortunately, reservoir hardening of a similar magnitude can also be induced by pressure depletion from the neighbouring producers. This interference
Preliminary modelling studies support this finding and show that the pressure signal defined by NCC is lower and more spatially diffuse in comparison to the stronger and more compact saturation signal. Figure 9 shows the NCC map thresholded at 0.80, generated by correlating the G-24 well activity with the AI changes. This highlights a strong connection around G-24 possibly related to the waterflooded zone, and a variation in concentration associated with the individual perforations (perhaps related to the performance of the injector completions). The zone delineated by this approach is also in general agreement with the results of coupled fluid flow and geomechanical simulation shown in Figure 10a and the resultant NCC map in Figure 10b.

Discussion and conclusions
With all time-lapse projects there is a need to establish a relationship between the processed 4D seismic products and fluid flow simulations. This objective is typically met by matching observed and predicted 4D seismic, either at a qualitative level or quantitatively via a seismic history match (Stephen and MacBeth, 2006). As observed seismic data are generally not yet sufficiently calibrated to warrant detailed quantitative inspection, we believe the key to bridging these two domains is the understanding that 4D seismic signatures must respond directly to changes in well production and injection during the time periods over which the 4D surveys are shot.

makes it very difficult to delineate the waterflooded zone using this attribute. This is particularly true in the region between G-24 and A-16 or F-17. However, the inter-well correlation coefficients between G-24 and A-16, and between G-24 and F-17 are 0.768 (Table 4), and hence separation of the response with the neighbouring producers is possible only for high NCC thresholds. Further, it is found here that the NCC attribute is predominantly affected by the waterflooded zone around G-24 and is less sensitive to pressure.

![Figure 7](a) NCC map computed using the well sequence of S-12. Low correlation regions are observed and highlighted using dashed lines. The time sequences of seismic change and cumulative volume are computed for two observation points 1 and 2, where the 4D seismic changes are dominated by (b) reservoir compaction, and (c) a combination of reservoir compaction and the gas breakout effect.

![Figure 8](a) Mapped AI change on the South Crest of the Valhall field. G-24 is an injector, the remainder of the wells are producers.

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<th>Group 1</th>
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<tbody>
<tr>
<td>S-11</td>
<td>S-12</td>
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<tr>
<td>S-12</td>
<td>0.988</td>
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<td>S-14</td>
<td>0.991</td>
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<td>S-15</td>
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<tr>
<td>S-3</td>
<td>0.516</td>
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<td>S-10</td>
<td>0.516</td>
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Table 3 NCCs calculated for cumulative volume time sequences from the South Flank.
character. The cause of this localization is probably the low permeability of the chalk and perhaps the compaction mechanism. The shape of the Valhall anomalies has been verified by comparison with results obtained from synthetic seismic for the field (not shown). Importantly, the unique well signatures on Valhall give rise to higher cross-correlation coefficients than seen with previous applications of the technique. The effectiveness of the technique, improves with the number and frequency of 4D surveys and the greater the complexity of well activity.

Well data used predominantly for history matching in the reservoir engineering domain can now also be used to constrain the 4D seismic response and help reduce noise levels. An early example of this concept showed how material balance constraints derived from the simulation can be imposed on the seismic (Huang et al., 2000). In this current article, it has been further demonstrated that it is possible to correlate mapped 4D seismic signatures from multiply acquired repeat surveys with the cumulative volumes produced at wells over these time intervals. The resultant signals identify only those areas of the seismic data which are strongly consistent with the well activity, and hence define portions of the reservoir connected to the wells. This is true regardless of whether the 4D seismic signatures are dominated by pressure or saturation. This information unites the seismic and well domains without the use of the simulation model. The signal tends to be quite robust and informative when compared to the individual 4D seismic difference signatures. The signal is not a conventional 4D seismic attribute, in the sense that it does not compare selected pairs of vintages but rather averages over multiple repeat surveys. As such, the distribution of the ‘attribute’ and its statistical significance will vary with the number of multiple surveys available and their overall time intervals. This seismic attribute can be used as a diagnostic tool for examining reservoir connectivity and constraining the simulation model.

Application of the well-to-seismic correlation method at Valhall reveals strong, localized signals around the wells. The spatially confined nature of these signals appears quite specific to the compacting chalk, as a previous application of the technique to Schiehallion has revealed a different, more extensive, character. The cause of this localization is probably the low permeability of the chalk and perhaps the compaction mechanism. The shape of the Valhall anomalies has been verified by comparison with results obtained from synthetic seismic for the field (not shown). Importantly, the unique well signatures on Valhall give rise to higher cross-correlation coefficients than seen with previous applications of the technique. The effectiveness of the technique, improves with the number and frequency of 4D surveys and the greater the complexity of well activity.

Table 4 The matrix of NCCs calculated between each pair of the time sequences of cumulative volumes derived from the production data of the wells in the South Crest area. The injector has noticeably different well activity compared to the other wells in this area.
In the future, such signatures may permit analysis of drainage patterns and conditioning of the simulation model to avoid well failure. This leads to the outrageous suggestion that, despite the practical consequences, more attempts should be made to fluctuate well production and injection during survey periods to aid in dynamic interpretation of the reservoir.

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