Evaluation of inter-well connectivity using well fluctuations and 4D seismic data

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An integrated methodology is proposed to quantitatively evaluate interwell connectivity by uniting available data from the production and seismic domains, while simultaneously honouring reservoir geology. The Capacitance Model approach for interwell evaluation is selected initially to obtain prior understanding using well production and injection fluctuations. Then, to make proper use of 4D seismic data, we extend the newly developed “well2seis” technique to further predict the well-to-reservoir connectivity by correlating multiple seismic monitor surveys to the well behaviour data. Based on the prior information provided by the Capacitance Model, appropriate wells are selected to provide robust 4D seismic correlation. The final result is generated as a 3D attribute volume, which directly reveals spatial patterns of reservoir connectivity. The proposed methodology is firstly tested on a synthetic case, where it is shown that the well2seis correlation attribute can correctly identify key reservoir flow barriers and conduits. When applied to observed data from the Norne field, the pressure diffusion and fluid flow pathways from injectors to producers are detected, which are consistent with bottom-hole pressure measurements and observed sea water production breakthrough. We also discover a key fault barrier which was not considered in the reservoir model previously and successfully improves the history matching quality. The understanding of the reservoir connectivity is significantly improved compared to using conventional methods or the 4D seismic method independently.

1. Introduction

Accurate interpretation of reservoir connectivity, especially the pattern of fluid communication from injectors to producers, is crucial to the success of improved oil recovery (IOR). This interwell evaluation will guide the decision made for reservoir management, such as water injection optimisation, maintenance of oil production, and identification of infill well locations. Such interwell evaluation can be quite challenging because of geological heterogeneity and structural complexity. A reservoir simulation model is commonly used to capture and explore the necessary interwell communication. However, this modelling and simulation is usually complex and time consuming, and the reservoir model needs to be frequently updated via History Matching throughout the field life, in order to maintain reliable future predictions. To complement this approach, a number of methods have been suggested as alternates (Fig. 1). Most of these methods make use of the observed well injection and production fluctuations to build a direct relationship between injector and producers, and are defined here as “conventional methods”. For example, the Spearman Rank Correlation (SRC) method (Heffer et al., 1997) links the injection and production rates to create a correlation parameter that can quantify the connectivity between wells. Albertoni and Lake (2003) proposed a multivariate linear regression (MLR) based method to estimate production rate from the injection rate of surrounding injectors. Weighting coefficients in this linear model are computed to evaluate the communication between producer and injectors. Instead of using rate, Tiab and Dinh (2008 and 2013) used bottom hole pressure (BHP) responses to determine interwell connectivity coefficients via the MLR linear model. The most recent and widely used method is called Capacitance Model (CM) developed by Yousef et al. (2006), which integrates both flow rate and BHP data in a nonlinear signal-processing model to quantify the interwell connectivity. It is also called the Capacity Resistance Model (CRM) (Champenoy and Fleming, 2015). A number of published references (Sayarpour et al., 2009; Kaviani et al., 2012; Soroursh, 2014) concluded that the CM method can accurately predict well performances and interwell connectivity. Apart from the three major methods mentioned above, there are several other conventional approaches to assess the interwell connectivity but they are not so commonly applied (see Fig. 1 for details).

With more than twenty years of industrial application, 4D...
Seismic monitoring has now been widely recognized as an effective tool for reservoir evaluation and management and EOR maintaining. It can accurately detect reservoir dynamic changes caused by fluid substitutions and pressure variations due to the well production activities across the field (Johnston, 2013). By imaging the dynamic changes in the reservoir volume, the 4D seismic signal can also identify interactions between injector and producer wells during production such as waterfront encroachment and pressure depletion. These data differ from the well performance data which are sparsely distributed, as the 4D seismic provides a 3D volume of traces that can assess information between wells. 4D seismic data do, however, carry a higher uncertainty than the well data due principally to seismic noise and non-repeatability, but also inherent non-uniqueness in interpretation. To capture more detailed changes during reservoir life, as well as to enhance the quality and repeatability, multiple repeated seismic monitors can also be utilized. These are widely delivered through towed streamer acquisition offshore or in particular in fields with seabed permanent reservoir monitoring (Eriksrud, 2014). Despite the benefits, it is rare to use 4D seismic to investigate the communication pathways in the reservoir and between the wells. Previous work indicates that Huang and Ling (2006) used 4D seismic maps to optimize the interwell connectivity coefficients obtained from the MLR method in a mature field undergoing water flooding. The optimized coefficients were consistent with the 4D seismic observations and successfully helped to improve the IOR strategy. Huseby et al. (2008) combined 4D seismic with tracer data in the Snorre field. The tracer travel times between injectors and producers are used to estimate the degree of interwell connectivity throughout the reservoir and also to validate the interpretation from 4D seismic, however the analysis was still largely qualitative. Finally, Benguigui et al. (2014) showed an empirical method to quantitatively derive the fault transmissibility from 4D seismic data from a compartmentalized Norwegian Sea field.

To address the reservoir connectivity issue, our study firstly introduces a new technique which unifies both well data and 4D seismic via a single metric for interwell connectivity evaluation. This “well2seis” technique is tested with the existing conventional technologies to investigate the pros and cons through a comparative study. An integrated workflow is developed to combine the advantages of both well2seis (spatial coverage of connected pathways) and conventional approaches (direct interwell measurement) for generating robust interwell interpretation. We show that the production data based interwell study can be used to provide the selection of well groups for the well2seis analysis. The approach is tested on both a synthetic dataset to establish validity and accuracy, and then a structurally complex field dataset from the North Sea. In both synthetic and field applications, the conventional approaches significantly enhance and complement the well2seis 4D seismic interpretation of reservoir connectivity. The integration of these techniques not only quantifies the degree of communication for each well pair, but also reveals the spatial reservoir connectivity pattern by detecting fluid flow and pressure diffusion pathways, and identifying key reservoir flow barriers and conduits.

2. Methodology

2.1. Well2well techniques

Here, the conventional interwell connectivity approaches are evaluated by selecting three of the most widely used methods based on the literature review: the Spearman rank correlation (SRC) method, Multivariate Linear Regression (MLR) method, and

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**Fig. 1.** The state of science on interwell connectivity evaluation methods. The methods are categorised into two types: conventional methods which only make use of well production and injection data, and 4D seismic methods which make use of 4D seismic data. (Demiryurek et al., 2008; Dinh, 2009; Dinh and Tiab, 2007; Dinh and Tiab, 2013; Fedenczuk and Hoffmann, 1998; Jensen et al., 2004; Kaviani and Jensen, 2010; Kaviani and Valkó, 2010; Lake et al., 2007; Lee et al., 2011; Liu et al., 2009; Panda and Chopra, 1998; Soeriawinata and Kelkar, 1999; Sorosh, et al., 2013; Tao and Bryant, 2015; Thiele and Batycky, 2006).
the Capacitance Model (CM). Heffer et al. (1997) were first to use SRC to calculate the correlation coefficients between injection and production rate fluctuations over time. They proved that the rates correlation can provide a good measure of the communication between individual wells. Next Albertoni and Lake (2003) assumed that, under reservoir conditions, the production rate can be estimated using the injection rate of surrounding injectors by a multivariate linear regression (MLR) function:

\[ \hat{q}_j(t) = \hat{q}_0 + \sum_{i=1}^{l} \lambda_{ij}w_{ij}(t) \quad (j = 1, 2, \ldots, N) \]

where \( \hat{q}_j(t) \) is the predicted liquid production rate for producer \( j \), \( l \) the number of injectors, \( w_{ij}(t) \) the observed injection rate of injector \( i \), and \( \lambda_{ij} \) represents the imbalance between production and injection. The weighting coefficient \( \lambda_{ij} \) accounts for the contribution from the injector \( i \) to the production rate of producer \( j \), and therefore immediately quantifies the required interwell connectivity. Due to the limitations of SCR including spurious correlations when correlating rate only, this MLR approach became most popular until the CM method superceded it. The CM method is a nonlinear signal-processing model derived from material balance. By solving the general differential equation of material balance in a reservoir system with injectors and producers, Yousef et al. (2006) found that each well production rate can be predicted using the injection rate and well bottom-hole pressure (BHP) data:

\[ \hat{q}_j(t) = \hat{q}(t_0)e^{-\frac{t-t_0}{\tau}} + \sum_{i=1}^{l} \lambda_{ij}w_i(t) + \sum_{k=1}^{m} v_{kj}P_{BHP}(t_0)e^{-\frac{t-t_0}{\tau}} - P_{BHP}(t) + P_{wbfk}(t) \]

where

\[ w_i(t) = \sum_{m=1}^{n} \left( e^{-\frac{t-m}{\mathcal{T}}} - e^{-\frac{t-m-1}{\mathcal{T}}} \right) w_i(t_m) \]

and

\[ P_{wbfk}(t) = \sum_{m=1}^{n} \left( e^{-\frac{t-m}{\mathcal{T}}} - e^{-\frac{t-m-1}{\mathcal{T}}} \right) P_{bfk}(t_m) \]

In (2), \( \hat{q}_j(t) \) is again the predicted production rate at time \( t \) for producer \( j \). On the right handside of the equation, \( \hat{q}(t_0)e^{-\frac{t-t_0}{\tau}} \) accounts for the initial production condition of producer \( j \) at time \( t=t_0 \). \( w_i(t) \) is calculated from the injection rate \( w_i(t) \) of injector \( i \), indicating the influence of the injector on the producer \( j \), and \( l \) is the number of injectors. The estimated interwell coefficient \( \lambda_{ij} \) still quantifies the connectivity for the injector-producer pair \( i-j \). The CM also takes BHP data into account as shown in the third term of the right hand side, where \( v_{kj} \) determines the effect of the BHP variation of producer \( k \) on the producer \( j \), and \( K \) is the number of active production wells. \( P_{BHP}(t) \) is the BHP of producer \( k \), and \( P_{wbfk}(t) \) the convolved BHP of producers \( k \) on producer \( j \). The convolved injection rate and pressure terms can be calculated from (3) and (4), where the time constant \( t_0 \) represents the dissipation of pressure between injector producer pair \( i-j \), and \( t_0 \) is the time constant between producer pair \( k-j \), and \( n \) is the number of discrete time steps by time \( t \). In summary, all the above three methods can work efficiently provided there are well production and injection data, but they lack the constraint from the reservoir geology when conducting the calculations. For fields with large number of wells, these methods will generate many interwell coefficients, which make it difficult to evaluate the spatial reservoir communication patterns effectively. This aspect is addressed by the well2seis method described below.

2.2. The well2seis technique

All reservoir-induced dynamic changes detected by 4D seismic data are caused by fluid extraction or injection at wells. Therefore the 4D seismic signals by their nature reflect critical information on interwell communication, especially when multiple seismic surveys are available. Seismic data also directly conforms to reservoir geology compared to the well behaviour data. However 4D seismic signatures caused by the well performance cannot be unambiguously interpreted without a clear understanding of production and injection behaviour over the survey period. The well2seis technique (Huang and MacBeth, 2012) is formed by correlating a specific seismic attribute directly to net reservoir volume changes obtained from well data when the 4D signal is pressure dominated. The results of this method can clearly map pressure communication across different geobodies. Yin et al. (2015a) extended this technique to reservoirs undergoing water flood where water saturation and pressure changes can simultaneously occur and jointly affect 4D seismic signatures. This generalised the technique to a wider range of fields.

Considering a non-compacting oil reservoir with \( n \) repeated time-lapse seismic surveys acquired during the production and water injection, a total of \( N = n(n-1)/2 \) 4D seismic differences are created for all paired combinations of surveys. They will construct a sequence \( \{ \Delta A_1, \Delta A_2, \ldots, \Delta A_N \} \), where \( \Delta A \) represents the 4D seismic difference attribute such as amplitude or impedance (map or volume). The corresponding reservoir fluid changes for the same time intervals can be derived by the combination of observed production and injection data weighted by formation volume factors. Material balance states that reservoir pressure variation is proportional to its fluid volume variation (whether with depletion or injection), while the net reservoir volume variations over time can be obtained by converting the well surface production and injection data to formation values. Therefore the obtained net reservoir volume variations from the wells can be correlated to the pressure induced 4D seismic signal. On the other hand, water saturation changes are mainly related to reservoir cumulative oil extractions, hence the cumulative oil production from the wells can be correlated to the water flood 4D seismic signals. This type of well behaviour data constitutes another time sequence \( \{ \Delta V_w, \Delta V_w, \ldots, \Delta V_w \} \). Putting the seismic and fluid volume time sequences together, the normalized cross-correlation factor W2S (named as the “well2seis attribute”) can be obtained for any location \((x, y, z)\) of the reservoir where:

\[ W2S(x, y, z) = \frac{\text{cov}(\Delta A(x, y, z), \Delta V)}{\sqrt{\text{var}(\Delta A(x, y, z)) \cdot \text{var}(\Delta V)}} \]

The metric \( W2S(x, y, z) \) ranges from 0 for no correlation (which means the well behaviour is not responsible for the 4D seismic change), to 1 for a perfect correlation. The measure of correlation can be applied to assess the degree of reservoir connectivity to the wells of interest. Compared to the well2well coefficients that are obtained using well fluctuation data only, W2S not only quantifies the individual connection but also reveals the pattern of communication between the wells. The major consideration for accurate evaluation is the number of 4D seismic monitors and the level of seismic noise, which can cause insignificant or spurious correlations. To ensure the robustness of the W2S product, a metric for statistical significance is determined with the Student’s t-distribution (Press et al., 2007). This t-distribution allows us to assess the probability to reject the null hypothesis (Krzywinski and Altman, 2013) which is no correlation with 4D seismic signal.
Therefore it helps to determine whether the correlation result is sufficiently confident so that spurious correlation can avoid being misinterpreted. For our work, we choose a significance level which permits up to 5% incorrect decisions.

2.3. Well2well versus well2seis

To fully understand the different methods describe above, we conduct a comparative study using a synthetic model. The synthetic model for this test is extracted from full field data of a Norwegian Sea field, which was used by Benguigui et al. (2014) to investigate fault connectivity. This is a heavily faulted horst block, where the presence of faults and inter-reservoir shale are the main factors that influence fluid flow. The production of the field has been driven predominantly by water flooding since first oil in 1995. Six time-lapse seismic surveys are acquired in total with the baseline obtained in 1991 and five monitors shot in 2001, 2004, 2006, 2008 and 2011. Before our study, the well2seis technique was successfully applied to the field to satisfactorily update fault transmissibilities in the simulation model (Yin and MacBeth, 2014). In our study, we select the main production compartments A and B from the history matched simulation model, preserving the original structure and model properties (Fig. 2(a)). The model grid has a lateral cell size of 100 m by 100 m and vertical thickness varying from 3 to 11 m. Three production wells (P1, P2 and P3) are preserved in the upper flank and there are also two water injectors (I1 and I2) in the lower flank of compartment A to support production. The fluid production and injection rates are kept similar to the real field development history, these being approximately equal to each other (Fig. 2(b)).

Synthetic seismic signals are calculated using simulator to seismic modelling (Amini, 2014) (Fig. 2(c)) with an identical acquisition time to the field surveys. We set the southern portion of the fault as a flow barrier (indicated by the black arrows between compartments A and B in Fig. 3(a)), while the remainder indicated by green arrow is defined as a conduit. For a water flood in the reservoir, understanding how the injected water reaches each active producer will be the key in evaluating the communication. According to the well2seis approach, the impedance volumes from six 4D seismic surveys are directly correlated to the cumulative volume of water injected from the two injectors. A W2S correlation attribute above 0.44 is recommended as providing sufficient confidence to visualize the communication between the wells in this segment. This generated W2S volume in Fig. 3(b) outlines the 4D seismic signatures caused by the injectors, indicating that the injected water reaches the three producers through the conducting pathways and bypasses the barrier. In Fig. 3(c) and (d), two vertical cross-sections A-A’ and B-B’ are generated from the well2seis property. More details of the injection induced 4D signals can be observed in these vertical sections, which also indicates the way that the injected fluid passes across the conducting fault (see Fig. 3(c)), and the blockage by the barrier in its southern flank (see Fig. 3(d)). The sealing effect of the fault barrier is identified by the high contrast in W2S across the fault location. In addition, both Fig. 3(b) and section A-A’ show that the degree of correlation becomes higher when getting closer to the injectors, suggesting a high degree of communication near the wells. This is similar to the conventional interwell studies, where, under the same geological settings, high interwell coefficients are normally obtained for well pairs with short distance. More importantly, this interpretation result directly helps to accurately place fault barriers in reservoir simulation model to improve the future predictions.

The SCR, MLR and CM well2well methods are also applied to the field data. The interwell coefficients computed from these methods are overlapped with the W2S property map in Fig. 4. The interwell coefficients indicate that the degree of connectivity between injector I1 and each producer depends on the distance between the wells. This result is consistent with our expectations from the reservoir model, as the fault barrier does not prevent fluid flow between the injector I1 and the three producers. For the communication between I2 and the producers, the SRC interwell coefficient (Fig. 4(a)) fails to identify the fault barrier by giving a high connectivity level for well pair I2-P1. However, the MLR (Fig. 4(b)) and CM (Fig. 4(c)) results are similar to each other and both detect the effect of the fault barrier. The MLR method provides a large connectivity coefficient between I2 and P1 that may misleadingly interpret a barrier as a conduit, while the CM coefficients provide more definition. Comparing all the three figures, it shows that the CM result is more consistent with the reservoir geological structures than the other two well2well methods, while the well2seis provides more detailed spatial information that can accurately locate the open and sealing segment of the fault by assimilating the 4D seismic data.

Despite the benefits of using all injection and production history, we found that shows that even the CM method has limitation.

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Fig. 2. (a) Synthetic model extracted from the Norwegian Sea field dataset. The locations of well I1, I2, P1, P2 and P3 are marked. Fault A-B is a major fault between compartment A and B. (b) Predicted historical production and injection rate fluctuations during the development stages. (c) Seismic impedance and amplitude generated for the synthetic reservoir. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
when reservoir geology patterns becomes complex. More details of this comparative study can be found from Yin et al., (2015b). The well2seis technique provides a supplement for those methods by "stacking" all the available 4D seismic into one single attribute using production data, especially when seismic noise is present. Because the results can be generated in either 2D map or 3D volumetric domain, much more relevant geological features can be characterized. However, finding the optimal well combination responsible for the 4D seismic changes is key to the success of achieving a good correlation. This can be very challenging for a field with many active wells.

To select proper wells for correlating to the 4D seismic signatures, well rate and bottom-hole pressure fluctuations are firstly used to quantify the interwell communication via the CM

Fig. 3. (a) Initial water saturation distribution and communication pattern of the synthetic reservoir. The black arrows point out the flow barrier of the main fault A-B while the green arrow indicates the location of the conductive segment. (b) 3D well2seis property generated from correlating water injection history to multiple 4D seismic surveys for the synthetic case. (c) & (d) Two vertical cross-sections A-A' and B-B' from the well2seis property. The locations of the vertical sections are displayed in (b). On the sections, the black dashed line represents the conducting fault while the black solid line identifies the flow barrier. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Map of the 3D W2S property overlapped with the interwell connectivity coefficients obtained from (a) SRC method, (b) the MLR method and (c) the CM method. The length of the black bars in the maps represents the value of the conventional interwell connectivity coefficients (ranging from 0 to 100%). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
The well2well coefficients will help us to determine if wells are in communication in a certain area of the reservoir such as a reservoir geobody, but only using the coefficients is still not enough to spatially delineate the connected pathways. For the connected and disconnected wells, they should contribute to the 4D seismic responses in a different way. Therefore the net reservoir volume changes or cumulative oil production volumes from these wells can be extracted separately to correlate to the multiple repeated 4D seismic surveys via well2seis. In this way, a new W2S attribute will be created to reflect the reservoir communication pathways spatially across the wells and indicate the interwell connectivity by applying the threshold value.

To test the above proposed methodology, we further complicate the synthetic model above by adding one more compartment and three more active wells (see Fig. 5(a)). The new synthetic model consists of three major geological compartments A, B and C, which are separated by two major faults (Fig. 5(a)). In this new model, a portion of each fault is designed as barriers and the remaining fault segments are set to be conduits. Three injectors I1, I2 and I3 are chosen to drive oil toward five active producers P1 to P5 located up flank of the reservoir. Fig. 5(b) shows an example of the injection/production rate fluctuations for wells I1, I2 and P4. It highlights the fact that the injection rates of I1 and I2 change in a similar fashion to P4’s production rate during its production period, indicating the production of P4 influences that injection behaviour of I1 and I2. This is consistent with the geological model since all the three wells are in the same compartment. Based on the workflow, the CM well2well method is applied, and the calculated coefficients for all the injector-producer pairs are plotted in Fig. 5(c). These coefficients show a good degree of communication for well pairs I2–P4 (73%) and I1–P4 (27%) that are in the same compartment. It also shows a relatively high degree of connectivity between injectors I1 and I2 to producers P3 and P5, as the fault between compartments A and B is open in the up flank direction. But for the communication between compartment A injectors (I1 and I2) and producers in compartment C (P1 and P3), they are separated by the two fault barriers, and the well2well coefficients are generally low and mostly fall below 10%. Connectivity from I3 to P1 and P2 is strong according to the well2well results, because the fault between these three wells is a flow conduit. This histogram of the well2well coefficients in Fig. 5(c) suggests that the production of P1 and P2 is mainly supported by injector I3, while producers P4 and P5 are supported by I1 and I2. Producer P3 is well supported by all the injectors due to its location in the centre between all the compartments. Based on this analysis, we can roughly divide the wells into two groups: group A includes wells I1, I2, P3, P4, and P5; group B has I3, P1, P2 and P3. Well P3 belongs to both groups due to its location and also because its production is influenced by all injectors.

Repeated seismic data are modelled using the same petroelastic model settings the previous model, and also at the same time intervals. To test if the well2well coefficients can improve the well2seis to detect the spatial connectivity pathways, a comparative study is conducted between W2S attributes calculated using the wells selected with and without the guidance from the CM coefficients. The synthetic multiple 4D seismic is firstly correlated to wells simply selected only according to the visual geological compartmentalization. The wells I1, I2 and P4 are chosen from compartment A, and then the historical cumulative reservoir fluid volume injected and produced are calculated for these wells. By correlating these fluid volume changes to 4D seismic, the W2S attribute in Fig. 6(a) is created. This attribute shows strong communication between P4 and injectors I1 and I2 in compartment A, and a certain degree of communication from compartment A to the producers P3 and P5 in compartment B. The barrier and conduit in fault A–B are accurately identified by the distinct contrast or spatial continuity of the W2S attribute across the fault. However, spurious high correlations are observed around the producer P2 in compartment C, which are somehow misleading the interpretation of the fault barrier between compartment B and C. This is because the production sequence of well P2 is similar to the well behaviour sequence derived from the wells in compartment A. The
4D seismic data is then correlated to the changes in net fluid volume derived from correct well group A, and the resulting W2S volume is displayed in Fig. 6(b). Now the W2S clearly shows a strong correlation signal between injectors I1, I2 and producers P3, P4 and P5 and the connected pathways in the model. However, no correlations are observed on the other side of the fault barriers, correctly indicating the sealing effect. Compared to the pattern in Fig. 6(a), the W2S attribute derived from well Group A has improved spatial definition of the barriers and conduits. This improved interpretation result can also be critical to reservoir model updating in terms of correctly placing the barriers, which is difficult to be achieved only using the well2well coefficients.

3. Application to the Norne field

3.1. Description of the field

The proposed methodology is now applied to data from the Norne field. This field lies offshore mid Norway (Fig. 7(a)), and is located on a horst block with an approximate size of 9 km × 3 km in the southern part of Nordland II in the Norwegian Sea. The reservoir contains mainly Lower-Middle Jurassic sandstones that are divided into four major formations – Not, Ile, Tofte and Tilje, with hydrocarbons found in the Not, Ile and Tofte (Fig. 7(b)) (Statoil, 2004). The porosity and permeability of the Jurassic sandstones range from 25 to 30% and 20–2500 mD respectively. There are a
number of major faults developed in the horst block, which divide the field into several compartments as shown from Fig. 7(b). The reservoirs consist of two separate oil compartments: the Norne Main Structure (compartment C, D, and E) which contains 97% of the oil reserves, and the remaining reserves in compartment G of the Northeast Segment (Statoil, 2004). Since first oil in November 1997, both water injection and water-alternating-gas (WAG) injection are performed to maintain the reservoir pressure as well as to improve and enhance the oil recovery. Fig. 7(b) shows the drainage pattern of the field. As Norne has entered its late production life with a recovery factor of 56% (Huang et al., 2013), finding an effective way to improve the oil recovery is crucial to extending the field life. To achieve this goal, understanding the reservoir interwell connectivity as well as the communication patterns between injector and producers will be critical. This is also important to save the costs for field IOR and EOR operations. Our study here will focus on the evaluation of interwell connectivity of the Norne Main Structure, which is the major production unit under current field development.

3.2. Multiple repeated 4D seismic on the Norne field

4D seismic monitoring has played a key role in reservoir characterization, well planning, evaluation and management on Norne to improve the oil recovery. Therefore, multiple repeated 4D seismic surveys have been acquired on Norne at different stages of the field life. Following the baseline survey shot in 1992 with conventional towed streamer technology, four highly repeatable 4D seismic surveys were acquired over the whole field in 2001, 2003, 2004 and 2006 (see Fig. 8) using a Q-Marine system. The average non-repeatability NRMS metric for the Q-marine seismic surveys is low (20%) compared to the NRMS (40%) for Q-marine versus the conventional streamer acquired baseline surveys (Rwechungura et al., 2010). Due to the data availability, the four Q-marine 4D seismic surveys are selected for this study. When referred to the field historical production performance shown in Fig. 8, it is believed that the four seismic surveys should be able to capture the reservoir changes with time during water breakthrough in 2001. This is quite critical for the timing of the 4D seismic surveys, as it enables the detection of the pathways of the injected water towards the producers via a combination of distributed hardening (water flooding, or pressure depletion) and softening (pressure increase, or gas expansion) signatures.

To evaluate the 4D seismic signatures, the seismic amplitude RMS (root-mean-square) maps are generated within the ile major production formation. 4D seismic difference maps are then calculated using the RMS maps of 2003, 2004 and 2006 by subtracting the map of 2001 (the results are displayed in Fig. 9). These maps indicate the areas of water flooding, pressure depletion caused hardening 4D responses (coloured as blue), or pressure and gas saturation increase related softening 4D responses (coloured as red). Also the volumes of production and injection during this period are displayed on the maps to link with their induced 4D seismic signals. For the 4D seismic 2003–2001 difference in Fig. 9(a), the seismic signal is relatively weak and quite scattered in the main production units (C, D and E). There is strong pressure up signal observed around the injector in compartment G caused by the water injection, but the G compartment is the area of interest. For the 4D seismic difference between 2004 and 2001 (Fig. 9(b)), the signal becomes clearer in the Norne Main Structure. An obvious pressure increase is observed around the injectors in compartment E, while hardening is also detected in compartment D related to water flooding from the surrounding injectors. After two more years of field development, the latest 4D seismic difference is obtained between 2006 and 2001 (Fig. 9(c)). This 4D seismic signature shows slightly weaker pressure signal in compartment E and a stronger water flooding signal in compartment E and central area of compartment C. This is also quite consistent with the observation in Fig. 8. The injection rate reduced continuously while the produced water cut significantly increased to almost 60% from 2004 to 2006, which slows down the pressure build up but amplifies the water flooding effect. A vertical cross-section A-B is generated from the 4D seismic difference cube between 2006 and 2001 (see Fig. 10). From this 4D seismic vertical section, significant seismic changes can be observed between the injectors and producers, which are also believed to be caused by the well behaviour.

![Field injection rate](Image)

**Fig. 8.** Historical injection and production fluctuations in Norne during the 4D seismic coverage period. In this Figs., the green line represents field oil production rate, light blue line indicates field injection rate while deep blue represents the field water cut. On the upper right corner, a reservoir compartmentalization map is shown with the yellow lines indicating the coverage area for the available 4D seismic surveys. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
during this time interval. Because the reservoir is quite thick (more than 100ms in average), polarity and side lobe effects are inevitable and these contribute to a difficult interpretation of the seismic data. Generally, all the 4D seismic effects observed in Figs. 9 and 10 reflect in the same way the interaction between the injectors and producers in Norne, since these changes are directly caused by the production and injection activities. Nevertheless, it is also observed that the existing challenges such as seismic noise, polarity changes, constructive and destructive interference of the seismic wavelet side lobes make it difficult to evaluate the inter-well interactions directly using the 4D seismic signatures. In order to address these problems, we will apply our integrated workflow developed in the previous section, as the link to well data helps to suppress the seismic noise and bring out additional information.

3.3. Integrated interpretation of interwell connectivity

There are twenty four producers, four water injectors and four WAG injectors in the study area of the Norne Main Structure by the time of the latest seismic survey in 2006 (Fig. 11(a)). In order to make effective use of all the available well data, the producers in each compartment are grouped together while injectors in each compartment are treated as a whole. This is because the reservoir properties in each compartment are relatively homogeneous, but the connectivity of the major faults between the compartments is the main uncertainty. In addition, this procedure can also make the application more efficient than working with large amount of individual wells. Fig. 11(b) shows the well2well coefficients for the three compartments. According to these, the production from compartment C (67%) is supported by the injector (including WAG injection) in its own compartment, while production from compartment D (70%) is mainly supported by the injector from compartment E. Forty eight percent of production in compartment E is from its own segment while forty three percent is supported by the injection in compartment C, which indicates that the production in E obtained similar supports from C and the

Fig. 9. Seismic amplitude RMS map differences on Norne: (a) 2003–2001, (b) 2004–2001 and (c) 2006–2001. The grey lines indicate the major faults. Active injectors and producers are represented by bubbles. As major producers are mostly located in compartment C, they are represented by a single bubble in the centre of the compartment. The size of the bubbles is proportional to the cumulative injection/production volumes. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Fig. 10. Vertical cross-section A-B of the seismic amplitude difference 2006–2001 at the location marked by yellow line on Fig. 9(c). On the section, red color indicates decrease of seismic amplitude, and blue means amplitude increase. The blue solid lines indicate water injectors, green lines are for oil producers and red line for WAG injectors. The black lines are the intersections with faults in the reservoir model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
compartment itself. However, the injection in compartment D only contributes to a very small portion (9%) of the production in its neighbouring compartment E, and it does not support the production in C and not even in its own compartment. This well2well histogram in Fig. 11(b) suggests that nearly all the production of the main reservoir is strongly supported by the well injection from compartments C and E. Based on these findings, the multiply-repeated 4D seismic surveys are correlated to all the active injectors and producers in the study area but without the injector in compartment D.

Before correlating to the performance of the selected wells, the seismic amplitude data is inverted to acoustic impedance (AI) in order to remove the polarity and side lobe effects. Fig. 12(a) shows a map view of the inverted 4D seismic impedance between 2006 and 2001. Compared to the original amplitude difference in Fig. 9, the inverted result shows much a cleaner 4D seismic signal. Pressure up caused softening effects (coloured as "brown") in the map of Fig. 12(a)) are observed around the water injectors in compartments D and E. Based on these findings, the multiply-repeated 4D seismic surveys are correlated to all the active injectors and producers in the study area but without the injector in compartment D.

To further investigate the vertical communication between wells, the cross-section of the W2S attribute is created (in Fig. 13(a)), at the same location A-B as the 4D seismic section of Fig. 10. From the thresholded W2S on this vertical section, we observe a continuous high correlation pathway across the injectors and producers which can be related to pressure diffusions, indicating that the injection from both the water and WAG injectors reached the active producers by passing the major faults between compartments (mainly from compartment D) passed mainly through the major faults between E and D, but was blocked by a fault between well P1 and E2. It then bypassed this fault barrier to form a communication channel near well B3 to reach and support the major producers in compartment C. However, the raw 4D seismic signatures in Fig. 12(a) are quite different from the W2S attribute in Fig. 12(b) especially in the compartment of well E2 (pointed out by the yellow arrow in the figures). In this area, the 4D seismic signature indicates a very strong hardening signal caused by water flooding from the injectors, whilst the W2S attribute indicates significant pressure fluctuations in the compartment which may also be caused by water injections. The observed BHP fluctuations of the well E2 in Fig. 12(c) is then referred, and the observed pressure at E2 shows that the pressure in that area dramatically increased by almost 50% (100 bars) during the 4D period, thus confirming the reliability of our W2S interpretation result. But in the 4D seismic signature, the water flooding signal is so strong that the seismic signal of pressure increase is counteracted by the seismic signal of water flooding in that compartment.
pressure increased considerably at the well locations, with more than 40% (80 bars) of pressure increment for each well during the period of the 4D seismic surveys. This is highly consistent with the W2S observations.

The region that links the major injectors in compartments E and D with the major producers in compartments C and D is also selected for a more detailed local analysis. The resultant W2S attribute in this region (Fig. 14(a)) indicates that the injection from both the major injector F1 and F2 entered the compartment of well E2, and then followed the channel in this compartment down to producer B3. It then flowed into the major production compartment C, while the major producer P1 in compartment D was not supported by any of these injectors. However, the individual 4D seismic signatures in Fig. 14(b) show a very strong waterflooding signal in compartment of E2. This leads to the conclusion that the production at well E2 is strongly supported by injector F2 in the same compartment (which was the original purpose for drilling F2 at that location). To accurately determine the communication pattern of injector F2, two cross-sections of the W2S attribute are created from F2 to E2 and P1 respectively in Fig. 15(a). The section F2-E2 detects water injected at F2 traversing the major fault to reach producer E2, identifying the fault as a fluid conduit. However, the discontinuity of the W2S attribute in section F2-P1 suggests the existence of a flow barrier marked in the section that does not exist in the reservoir model. We refer to the seismic surveys of 2001 by generating a seismic section in Fig. 15(b) at the same location of F2-P1. A very clear sub-seismic fault is observed at the same location as the W2S section in Fig. 15(a). It shows a clear collapsed normal fault between F2 and P1, thus it confirms the existence of the proposed fault.

The sealing effect of this newly detected fault can also be measured from the observed well production data (Fig. 16). In particular, natural tracers are used to estimate the seawater fraction in the produced water. Natural tracers are also commonly known as produced water chemistry (PWC), which consists of the concentration of a number of ions, including among others...
Chloride, Barium, Calcium and Sulphate, against time and producing well. The conservative ions such as Chloride are used to monitor the seawater fraction in the produced water. Since the Norne reservoir has been under seawater flooding for pressure support, it is clear that seawater fraction can be used to estimate communication between producers and injectors. Fig. 16(a) shows that although water production in well P1 consistently grew to 90% until 2007, the observed seawater fraction ceased very early by the time when the injector C4 stopped injection in 2003 (Fig. 16(b)). However, injection rate in well F2 was kept high until 2007, as
Fig. 15. (a) Vertical cross-sections of the W2S attribute at the locations F2-E2 and F2-P1, which are marked out by yellow lines in Fig. 14(a). The dashed black line on section F2-E2 indicates the conducting property of major fault between compartment E and F, while the solid line on section F2-P1 indicates a potential fault barrier. (b) Cross-section F2-P1 of the seismic survey 2001. The solid black line identifies the location of the fault barrier between F2 and P1, which does not exist in the original reservoir model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 16. (a) Observed production water cut and sea water fractions for well P1. (b) Historical (sea) water injection rate for injector C4. (c) Historical (sea) water injection rate for injector F2. The black arrows mark out the year of 2003 when P1 stopped producing sea water. (d) History matching result of the well P1 before and after placing the newly detected fault barrier into the numerical reservoir simulation model. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
shown in Fig. 16(c). The data suggests the seawater produced in well P1 is from well C4, supporting the existence of the newly detected fault, which prevents the communication from well F2 to well P1. By adding this newly detected fault barrier into the simulation model, the history matching is significantly improved for well P1 as shown in Fig. 16(d).

4. Discussions and conclusions

We propose a unique multi-disciplinary workflow and attribute W2S which has not been used before for investigating the reservoir interwell connectivity. It reduces the interpretation workload by avoiding working on many individual 4D differences separately, which is nowadays common practice for multiple and repeated 4D seismic surveys. In the methodology, available reservoir data from both seismic and well production domain is fully considered through the cross-correlation to prevent a biased reservoir interpretation and provide spatial interwell understanding. It also extends the well2seis technique proposed by Huang and MacBeth, (2012); Yin et al., (2015a). We exploit the conventional interwell methods to assist in the selection of proper well groups for correlating to their corresponding 4D seismic signatures. This helps us to reduce pitfalls in the well2seis interpretation such as spurious correlations and reduce the time in well group selection. The W2S attribute is clearly defined by using statistical significance to obtain a threshold. The thresholded volumetric W2S property provides a high resolution spatial image of the reservoir, which simplifies the interwell analysis to determine the patterns and degrees of dynamic reservoir communication. For future development, the newly introduced interwell attribute W2S can also feedback information to the conventional methods, working as a constraint to optimize the well2well coefficients. Once reliable interwell coefficients are obtained, the CM method can fast calculate the production performances at a specific injection rate. In a sense, this will enable us to optimize the productivity by perturbing different injection scenarios more efficiently than using time-costing reservoir simulation models. Therefore it has the potential to improve the sweep efficiency and oil recovery of the reservoir, which is crucial for prolonging the life of fields that are in their tail end of production, especially for the current low oil price stage.

Despite the promising results from the proposed methodology, there are still a number of challenges which should be addressed for the future development. One of the challenges is from the conventional well2well methods. Since not all the wells have gauged BHP data available, this incompleteness of well data can reduce the reliability of the interwell coefficients. However, other sources of well data such as PWC and artificial tracers are more widely used to determine the seawater fraction in the produced water, which can be used to estimate reservoir connectivity. Another major challenge comes from the inadequate number of 4D seismic monitors. According to this study and our previously study (Huang et al., 2011; Huang and MacBeth, 2012; Yin and MacBeth, 2014; Yin et al., 2015a), a minimum of four repeated seismic surveys are required in order to provide reliable interpretation results with properly determined well2seis threshold value. Due to relatively high cost of seismic surveys, most of the fields by far still do not have so many repeated 4D seismic surveys to meet the requirement of well2seis. But it’s been a trend nowadays that more and more 4D seismic surveys are acquired, with the values content in the 4D seismic are more widely recognized. This technique will be readily available to enhance the reservoir connectivity interpretation once the multiple repeated seismic surveys become available in a field. The uncertainty from the 4D seismic data (the non-repeatability noise is main uncertainty source) should be concerned when applying the well2seis technique to evaluate the interwell connectivity. However, as the 4D seismic noises are not caused by the well production activities, they do not, in principle, correlate to the well production behaviours. This suggests that, via the well2seis technique, the uncertainty level from the 4D seismic caused by the non-repeatability noise can be reduced when constrained by the production data. To further investigate this, the quantitative level of the well2seis correlation error caused by the input data uncertainties (from both the 4D seismic and production data) have been discussed and quantified in the work of Yin et al. (2015a). Seismic resolution for the reservoir can also affect our methodology, especially the vertical seismic resolution for understanding the vertical communication patterns for thin-bed reservoirs. The seismic vertical resolution commonly is regarded as one quarter of the wavelength (~ 40 m), while the thickness of thin-bed reservoir is normally around 10–15 m. In order to solve this problem, it is recommended not to work on 4D seismic traces directly, but to work with seismic amplitude maps or inversion product, and multiple realizations can be considered to represent the uncertainty.

To summarize the conclusions, we find that the CM approach provides the most reliable interwell evaluation among the conventional well2well methods. It is found to be consistent with the well2seis 4D seismic interpretations, while the well2seis attribute reveals additional detail about the reservoir connectivity pattern. However, this study shows that the well data selected simply according to geological structure is insufficient in providing input to the well2seis method. With the support from CM method, the interpretation can be significantly enhanced. Application of the integrated method to a real field data derived synthetic case and the Norne field data successfully identifies the barriers and conduits between injectors and producers, and reveals the pathways of injected water and pressure diffusions. More importantly, the interpretations results agree well with the available reservoir measurements from different domains including well bottom-hole pressure, produced water chemistry and geological interpretations. We detect a critical new fault barrier on the Norne field which was not considered when planning the injectors. After adding it to the reservoir simulation model, the history matching quality is found to be improved. This suggests that the technique can be used as an efficient tool to update reservoir models for enhancing the reservoir predictivity. It demonstrates that this cross-disciplinary workflow can work efficiently to improve the understanding of reservoir connectivity for effective reservoir evaluation and management.

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