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Joint Interpretation of Interwell Connectivity by Integrating 4D Seismic with Injection and Production Fluctuations

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Abstract

A technique is proposed to quantitatively measure interwell connectivity by correlating multiple 4D seismic monitors to historical well production data. We make use of multiple 4D seismic surveys shot over the same reservoir to generate an array of 4D seismic differences. Then a causative relationship is defined between the 4D seismic signals and changes of reservoir fluid volumes caused by injection and production behavior. This allows us to correlate seismic data directly to well data to generate a "well2seis" volume. It is found that the distribution of the "well2seis" correlation attributes reveals key reservoir connectivity features, such as the seal of faults, inter-reservoir shale and fluid flow pathways between wells, and can therefore enhance our interpretation on interwell connectivity. Combining with conventional interwell methods that are based on injection and production rate variations, this multiple 4D seismic method is found to support the conventional interwell approaches and can provide more reliable and detailed interpretation.

Our methodology is tested on a synthetic model extracted from full-field data for a Norwegian Sea reservoir, the fluid flow of which is controlled by fault compartmentalization and inter-reservoir shale. The full structural details and reservoir properties are preserved but three scenarios with different degrees of reservoir connectivity are created. It is found that proposed technique successfully detects the flow paths of the injected fluids in all reservoir scenarios. A volumetric attribute is created that accurately identifies the distinctive types of key flow barriers and conduits for each scenario that are known to be major factors influencing the reservoir dynamics. This proves that the well2seis attribute agrees with geological interpretations better than conventional well connectivity factors based on engineering data only. Additionally, the combination of the two types of methods provides a more robust tool for characterization of the reservoir connectivity by providing both quantitative degree and physical pattern of interwell communication.

Introduction

Accurate evaluation of the connectivity between injectors and producers is essentially important for improving water sweep efficiency and hence increasing the degree of oil recovery in water flooding projects. This interwell connectivity interpretation can provide critical information for reservoir management, such as optimizing water injection rate, maintaining high oil production, and identifying infill well locations. However, due to the reservoir geology complexity and heterogeneity, the evaluation of interwell connectivity can be quite challenging and difficult. In industry, reservoir simulation model is most commonly used to characterize the interwell communication. The modeling process is normally very complex and extremely data intensive, as the reservoir model has to be constantly updated through the whole field life in order to maintain the model reliability, which is also a very time consuming procedure. Therefore a number of other methods have been developed (Figure 1), working as alternatives to reservoir simulation, to effectively evaluate the interwell connectivity. Most of these methods simply make use of injection and production rate data to directly build a relationship between injector and producers for estimating the interwell communication. The Spearman Rank Correlation (SRC) method (Heffer et al., 1997; Fedenczuk and Hoffmann, 1998; Soeriawinata and Kelkar, 1999) compresses injection and production rates series into a single parameter to quantify the connectivity between wells. Albertoni and Lake (2003) proposed a multivariate linear regression (MLR) based method to estimate production rate using injection rate from surrounding injectors. The weight coefficients in the linear model are used to evaluate the communication between producer and injectors. Instead of using rate, Tiab and Dinh (2007, 2008, 2009 and 2013) used bottomhole pressure (BHP) responses of injectors and producers to determine the interwell connectivity coefficient in the MLR model in water flooding system. The most recently used method is called Capacitance-Resistance Model (CRM) (or Capacitance Model (CM) in some references) developed by Yousef et al. (2006), which integrates both flow rate and BHP in a nonlinear signal-processing model to provide a more robust interpretation result of the interwell connectivity. From a number of published references (Lake et al., 2007; Sayarpour et al., 2009; Yousef et al., 2009; Kaviani and Jensen, 2010; Soroush, 2010; Kaviani et al., 2012; Soroush et al., 2013; Moreno and Lake, 2014; Soroush, 2014), it is shown that the CRM method can accurately predict well performances and determine the connectivity distribution between wells. Apart from the above three major methods, there are also several other approaches to assess the interwell connectivity but they are not very commonly applied as shown from Figure 1.

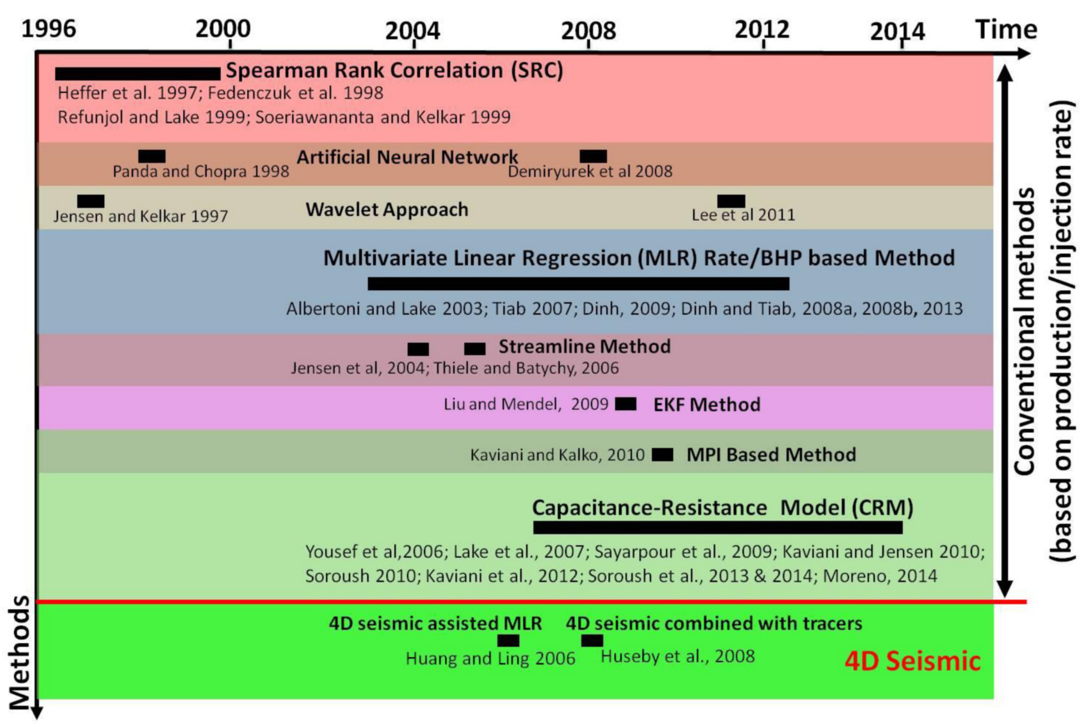

Figure 1—State of "art" to date of the interwell connectivity study methods

With more than twenty years of application in industry, 4D seismic monitoring has been recognized as an effective technology for reservoir evaluation and management. It is proven that 4D seismic can detect changes in reservoir pressure and saturation, due to fluid displacements and distributions between wells and across the field. By imaging the fluid changes in the interwell volume, the 4D seismic signal can identify the interactions between injector and producers such as the movement of waterfront. 4D seismic is different from well historical data which are sparsely distributed, as it provides a volume of spatially distributed data containing more information for characterizing the connectivity of the reservoir. But the 4D seismic data normally have a higher uncertainty than well data due to seismic noise and non-repeatability. To enhance data quality and seismic repeatability, multiple repeated seismic monitors and even seabed permanent reservoir monitoring (PRM) are more widely available (Eriksrud, 2014). These high quality 4D seismic surveys contain invaluable information for determining the interwell connectivity, as they can capture much more detailed evidences about the interaction between wells. Only a few studies address the use of 4D seismic to investigate the communication between wells. Huang and Ling (2006) used 4D seismic to optimize the interwell connectivity coefficients obtained from the MLR method in a mature water flooding field. The newly optimized coefficients were consistent with 4D seismic observations and successfully helped to improve the water flooding strategy of the field. Huseby et al. (2008) combined 4D seismic with tracer data in the Snorre field. The tracer travel time between injector and producers are used to estimate the degree of connectivity between the wells and also to validate the interwell interpretation from 4D seismic. The analysis was mainly qualitative.

Our study proposes a new technique to mathematically correlate well behavior data to 4D seismic response through a linear causative relationship. The generated correlation attributes are measured within a 3D volume which can provide a better volumetric understanding of the communication between wells. The technique is applied to a synthetic simulation model from a Norwegian Sea field data. By testing on three scenarios with different patterns of reservoir structure and connectivity, it proves that this "well2seis" technique can accurately interpret fluid flow paths from injectors to producers, indentifying key reservoir connectivity features such as barriers and conduits. To further validate the understanding, conventional interwell study techniques including SRC, MLR and CRM methods are used joint with our "well2seis" application.

The well2seis technique for interwell study

It is generally understandable that 4D seismic surveys acquired across a field can capture reservoir changes spatially between wells, such as pressure and saturation changes during the production period. There is no doubt that all these changes are caused by fluid extraction or injection from the wells. In another words, the 4D seismic signals should contain important information about the interwell communication. On the other hand, as 4D seismic signature is caused by these well activities, it cannot be unambiguously interpreted without a clear understanding of the production and injection history of the wells. If there is an indicator that can quantitatively link 4D seismic change at a specific reservoir location to its corresponding well behavior, the spatial distribution of this indicator will be able to clarify how the reservoir changes at any location are related to the well activities. It will then enable interpretation of the well interaction with the reservoir fluids at each point of the field. Therefore it will evaluate the status of communication between the wells.

To develop the abovementioned understanding in a quantifiable way, we make use of the well2seis technique which was originally proposed by Huang and MacBeth (2010) for pressure dominant 4D seismic fields and then extended to both pressure and water saturation controlled 4D seismic by Yin and MacBeth (2014). Here, we consider a reservoir under water flooding where only oil and water phases are present and a number of n repeated time-lapse seismic surveys are acquired over the recovery period for the field. A total of $N=n*(n-1)/2$ 4D seismic differences will be created for all paired combinations of the 4D surveys to form a sequence $\{\Delta A_1, \Delta A_2, \ldots, \Delta A_N\}$, where ΔA represents the 4D difference of a seismic attribute such as amplitude or impedance. As all of these 4D seismic signals are due to well production/injection, the corresponding reservoir fluids volumes changes for the same time intervals can be derived by the combination of well production and injection data weighted by formation volume factors. This type of well data can constitute another time sequence of well behaviors $\{\Delta V_1, \Delta V_2, \ldots, \Delta V_N\}$. Putting the two time sequences together, a dimensionless normalized cross-correlation factor W2S (W2S named as the “well2seis attribute”) can be obtained for any location of the reservoir:

$$W2S(x,y,z) = \frac{cov\left(\Delta A(x,y,z), \Delta V\right)}{\sqrt{var\left[\Delta A(x,y,z)\right] var\left[\Delta V\right]}} \tag{1}$$

where *cov* stands for the covariance of the two time sequences while *var* for the variance of each sequence. The metric of $W2S(x, y, z)$ ranges from 0 for no correlation (which means the well behavior is not responsible for the 4D seismic changes), to 1 for a perfect correlation. Once the well2seis attribute W2S is calculated for every seismic bin within the reservoir, a volumetric property will be obtained to reflect the connection between the 4D signals and the well behavior, which implicitly measures the degree of reservoir connectivity to the wells of interest. Compared to the conventional interwell coefficients that are obtained using well data only, this new 3D attribute can not only quantify the degree of connectivity but also shows the pattern of communication such as the paths of fluid flow, which are essential to the interwell connectivity evaluation.

Whilst the correlation attribute W2S can work as an integrated tool to delineate the connectivity between wells, care must be taken regarding interpretation of this attribute. The major considerations are the limited number of 4D seismic monitors and the level of seismic noise, which can cause spurious correlation and provide misleading interpretation. To ensure the robustness of the correlation product and reduce ambiguities, the statistical significance of the correlation attribute is firstly calculated, which is distributed as Student’s t-distribution (Press et al., 2007). Then the *P* value test can be conducted to assess that whether the correlation result is confident enough to reject the null hypothesis (Krzywinski and Altman, 2013). We choose the most conventional significance level of 0.05 in our *P* value test, which allows up to 5% of incorrect decisions. This process enables us to obtain a threshold value to filter out spurious and unreliable correlations and to ensure the reliability of the W2S attribute.

Application

The methodology describe above is applied to a synthetic model extracted from full field data of a Norwegian Sea field. This is a heavily faulted horst block field, where the presence of faults and inter-reservoir shale are the main factors that influence fluid flow in the reservoir. The production of the field is mainly driven by water flooding since the first oil in 1995. Six time-lapse seismic surveys are considered 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 has been successfully applied to the field to update fault transmissibility of the simulation model to a satisfactory degree (Yin and MacBeth, 2014). In this study, we select two main production compartments (A and B) from the history matched simulation model to construct a synthetic model while the structural details and reservoir properties as well as fluids properties are preserved (Figure 2). The new model is built using the same grid as the original simulation model with lateral size 100m by 100m and vertical thickness varying from 3 to 11m. Three production wells (P1, P2 and P3) are preserved in the upper flank and there are 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, being approximately equal to each other. Three scenarios with different schemes of reservoir connectivity are design in order to test the general applicability of the proposed technique. Synthetic seismic cubes for the six 4D seismic surveys are acquired using simulator to seismic modeling (Amini, 2014) for each scenario of the model. Since this is a water flooding reservoir, understanding the mechanism that how the injected water reaches each active producer will be the key to evaluate the interwell communication. Therefore the total six 4D seismic surveys are correlated to water injection from the two injectors to detect the path of water flooding. According to the statistically significance, a correlation attribute above 0.44 can provide sufficient confidence to visualize communication to the wells of interest. At the same time, three major conventional interwell study methods (SCR, MLR and CRM) are also applied simultaneously with the well2seis technique in each scenario, in order to validate the well2seis interpretation result and also to provide more reliable interwell interpretation.

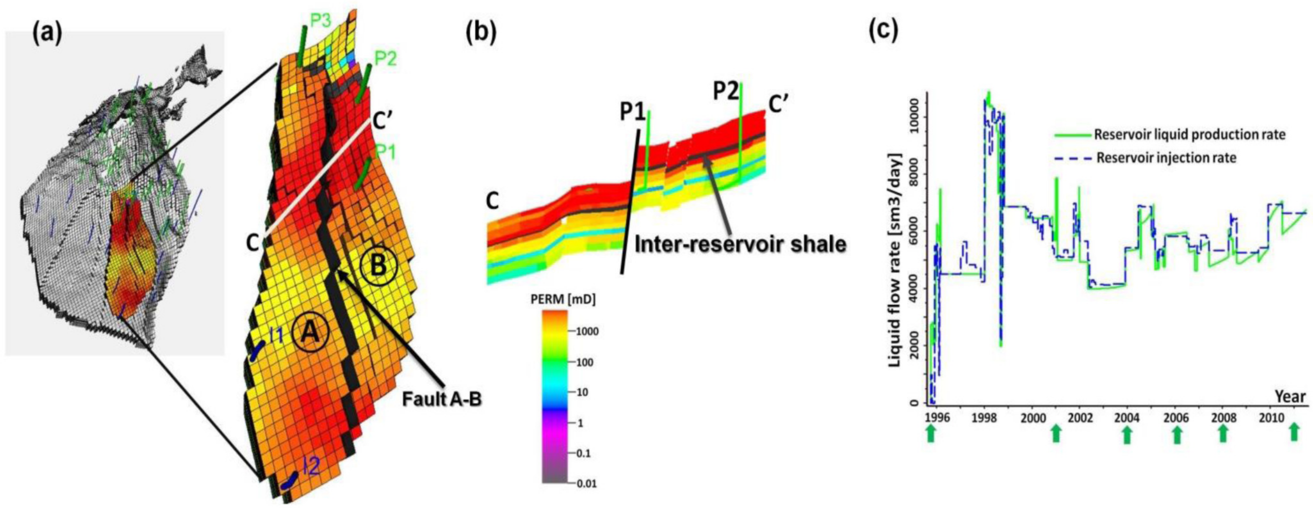

Figure 2—(a) Synthetic model extracted from the Norwegian Sea field simulation model including compartment A and B. The locations of well I1, I2, P1, P2 and P3 are marked out in the figure. Fault A-B is the major influencing fault between compartment A and B. (b) Cross-section C-C′ generated from the synthetic model. The major reservoir fault is represented by the black solid line while the inter-reservoir shale is also pointed out in the vertical section. (c) Production and injection history of the model.

Scenario one

The first scenario is to test whether the well2seis technique can detect the effect of fault barriers between wells. We set the south part of the major fault A-B as a fluid flow barrier (pointed out by the black arrows in Figure 3(a)), while the rest part of the fault is conductive (pointed out by green arrow in the figure). Correlating the sixteen years water injection history to the six 4D seismic surveys, a 3D well2seis property is created and displayed in Figure 3(b). In Figure 3(c), two vertical cross-sections A-A′ and B-B′ are generated from the well2seis property. As shown in the figures, the distribution of the thresholded W2S attribute value clearly outlines the flow path of the injected water. Both the W2S volume and vertical sections reveal that the water injection from I1 and I2 bypassed the fault barrier, traversed the open fault segment and then reached the producer P1 and P2 in compartment B. The sealing effect of the fault barrier is clearly identified by the big contrast of the W2S value across the fault. In addition, the vertical section A-A′ also suggests that the communication degree from the injectors to producer P1 is higher than P2 due to the distance between the wells.

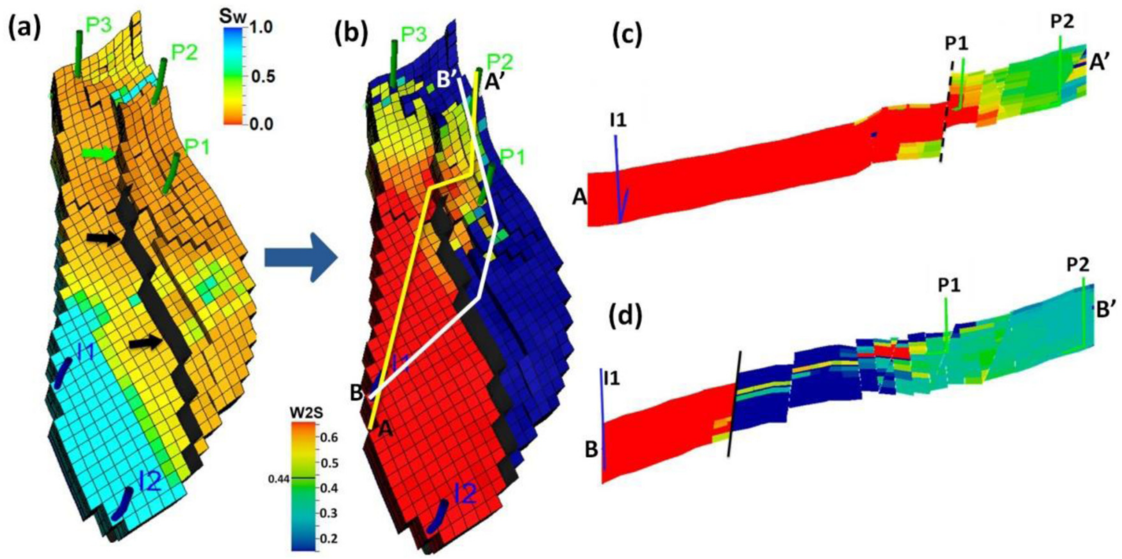

Figure 3—(a) Scenario one of the synthetic model. The black arrows point out the sealing segment of the main fault A-B while the green arrow indicates the location of the conductive part. (b) 3D well2seis property generated from correlating water injection history to multiple 4D seismic surveys for the scenario. (c)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 open fault while the black solid line means the fault barrier.

The conventional methods (SRC, MLR and CRM) are then applied to quantify the interwell connectivity. The computed interwell coefficients from these methods using well injection and production fluctuations are overlapped with the average map of the well2seis property and represented by the lengths of black bars in the map (Figure 4). Similar to the W2S correlation property, the average map reveals the fluid pathway of injected water between the well, and clearly indentifies the effects of the fault conduit and barrier. As shown from the figure, the interwell coefficients from the three methods for injector I1 tell us that the connectivity degree between I1 and the producers are relatively good and mainly related to the distance between the injector and producers. This result is consistent with our model expectation. As the location of the fault barrier does not block the fluid flow between the injector I1 and the three producers too much, the distance between injector and producer should be the main factor influencing the communication between the wells. In terms of the communication between I2 and the producers, especially the communication from I2 to P1 and P2, the fault barrier should be the dominant influencing factor. The SRC interwell coefficients (Figure 4 (a)) fail to identify the fault barrier by providing quite a large value of connectivity between I2 and P1. The results from the MLR (Figure 4 (b)) and CRM (Figure 4 (c)) method are similar to each other and both detect the effect of the fault barrier. But the barrier effect interpreted by the CRM coefficients is more recognizable than with the MLR method. Generally, the CRM provides the best results among the three methods and it is most consistent with the well2seis interwell evaluation. The combination of the CRM and well2seis techniques provides an integrated quantitative interpretation.

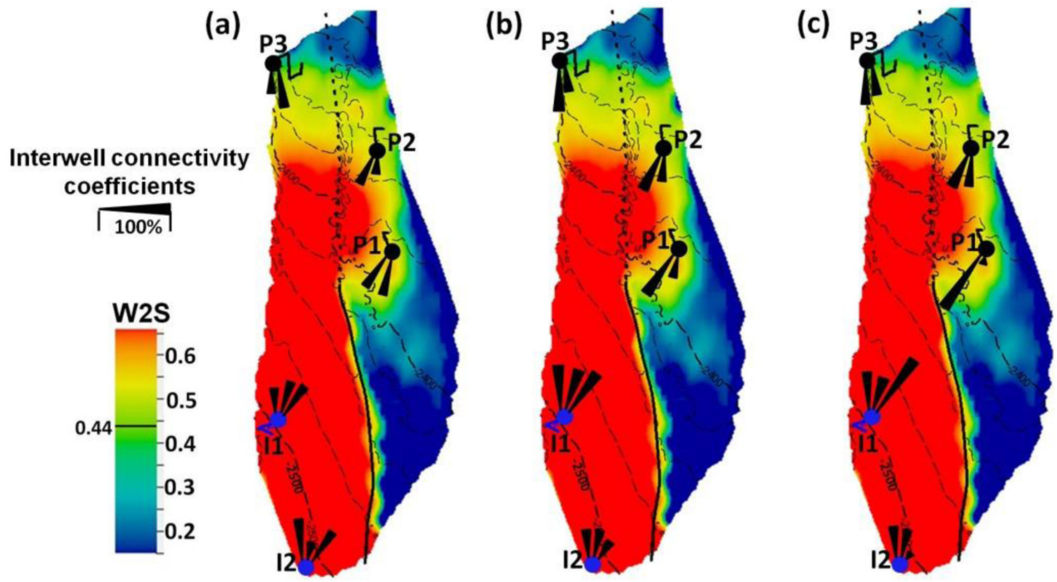

Figure 4—(a) Average map of the 3D W2S property overlapped with the interwell connectivity coefficients obtained from the SRC method. (b) Average map of the 3D W2S property overlapped with the interwell coefficients obtained from the MLR method. (c) Average map of the 3D W2S property overlapped with the interwell coefficients obtained using the CRM method. The length black bar in the maps represents the value of the conventional interwell connectivity coefficients (ranging from 0 to 100%).

Scenario two

In this scenario, the fault barrier is removed but the inter-reservoir shale is activated to be a non-transmissible formation as displayed in Figure 5. The shale formation divides the reservoir section into two formations – upper formation and lower formation. But the two formations are connected to some degree because of the fault displacements. The well perforations are also re-designed in the scenario: producer P1 is perforated in the upper formation, well P2 in the lower formation, P3 in both lower and upper formations, while the two injectors are all perforated in the lower formation. The objective of the scenario is to test whether the well2seis technique can evaluate the vertical effects from the shale formation.

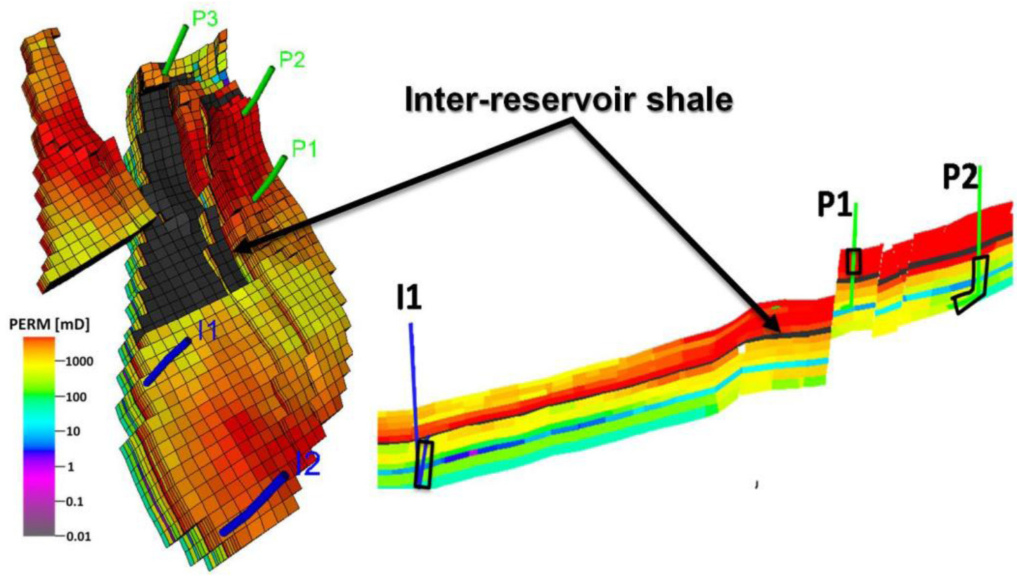

Figure 5—Scenario two of the synthetic model. The location of the inter-reservoir shale formation is pointed out by the black arrows. The black boxes on the well trajectories indicate the perforation section for well I1, P1 and P2.

In a similar way to scenario one, the well2seis attribute is firstly calculated for the reservoir and then overlapped with the conventional interwell coefficients. Figure 6 shows the average map and two vertical sections generated from the 3D W2S property. As illustrated from the vertical section in Figure 6, the water injection in the lower reservoir firstly drives the oil under the shale formation towards the producers due to the sealing effect from the shale. Once it reaches the locations where the lower and upper reservoirs are connected by a fault, the injected water passes through to the upper reservoir, and continues flowing both backwards and forwards due to the gravity and pressure gradient. Finally, the injected water reaches each producer perforated in different formations. As to the interwell coefficients in Figure 7, all three conventional interwell methods generate a similar degree of connection between the two injector and producer P3 which is perforated in both formations. For the producer P2 perforated in the lower reservoir with the injectors, the SRC method fails to predict the interwell connection by generating a negative value, while the remaining two methods provide quite reliable results. In terms of the producer P1, it is not perforated in the same formation as the injectors, but the faults make them connected. In addition, the fault displacement close to I1 is much larger than the area near I2, which provides a larger degree of communication between I1 and P1. Therefore, compared to the MLR method, which provides no indication about the communication between P1 and I2, the result from CRM is more accurate. Again, by combining the well2seis results with the most reliable interwell method CRM, a much more comprehensive interwell interpretation is obtained.

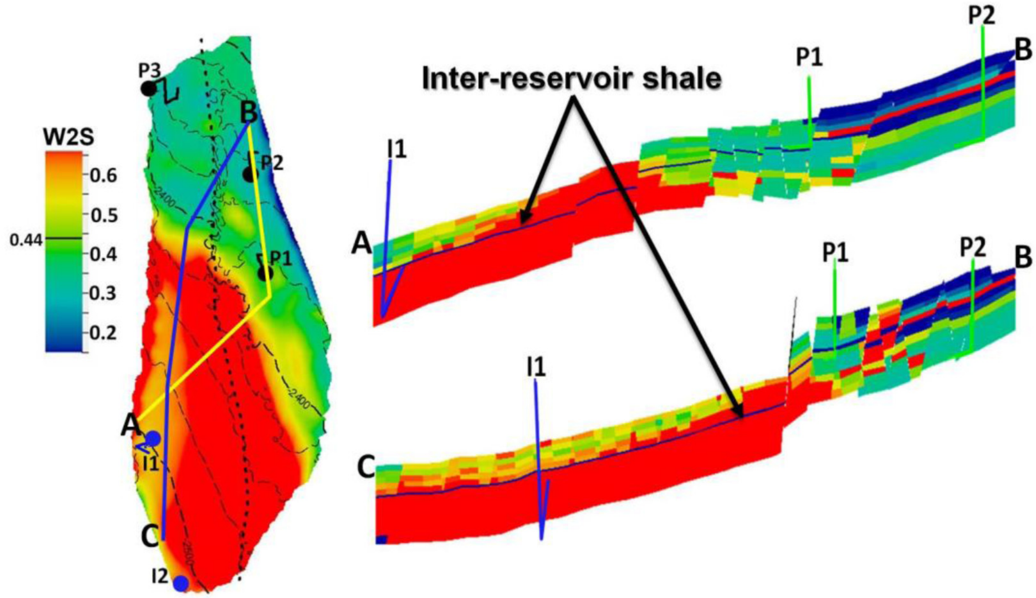

Figure 6—Average W2S map and two vertical cross-sections A-B and C-B generated from the well2seis property for scenario two.

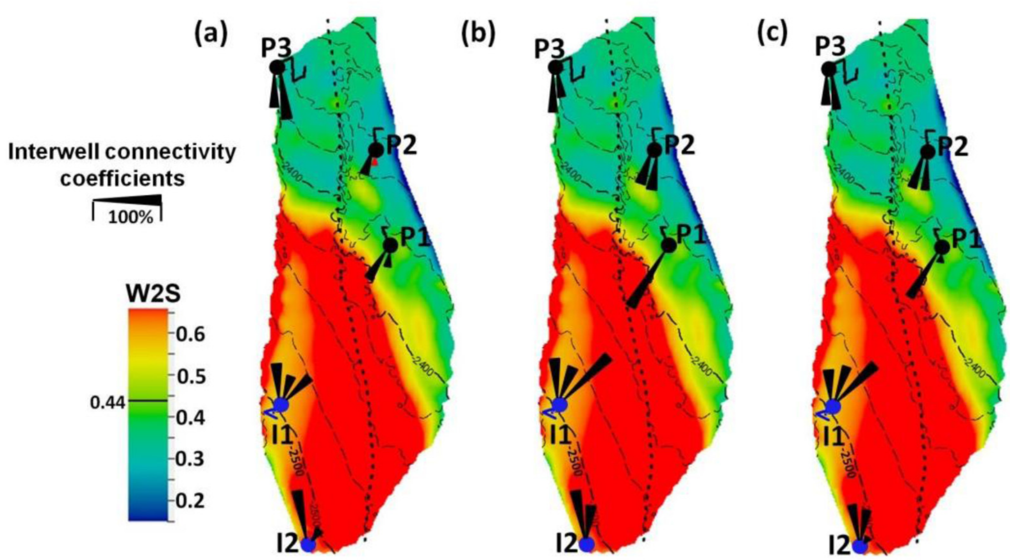

Figure 7—Average map of the 3D W2S property overlapped with the interwell connectivity coefficients obtained from the traditional inter well method SRC (a), MLR (b) and CRM (c) for scenario two.

Scenario three

Scenario three is a combination of scenario one and two with the existence of fault barriers, conduits and the inter-reservoir shale formation. The well2seis attribute generated for this scenario is displayed in Figure 8. Compared to the well2seis results from the scenario one and two, it is shown that the increase of reservoir complexity does not reduce the quality of the well2seis interpretation. Indeed, the Figure 8 shows that the W2S attribute generated for this scenario more clearly detects the locations and effects of the faults and inter-reservoir shale than the other two scenarios. The distribution of the W2S attribute suggests that the injected water is first constrained in the lower reservoir and then passes through the shale formation at the location where the upper and lower reservoirs are connected by faults, and finally the water injection reaches all the producers perforated at different layers. However, when referring to the conventional interwell coefficients for this scenario in Figure 9, the SCR method fails to identify either the shale or fault effect. The MLR and CRM methods evaluate the communication between I1 and the producers relatively well, while the CRM method is relatively more reliable since it provides a higher connectivity coefficient for I1 and P2 which are perforated in the same formation and also have relatively short distance. Neither of the two methods accurately measures the degree of connectivity between I2 and the three producers. None of the results from the three conventional interwell methods are as good as the well2seis interpretation. This suggests that the well2seis interpretation results have great potential to work as effective constraints for optimizing the interwell coefficients from the conventional methods such as the CRM.

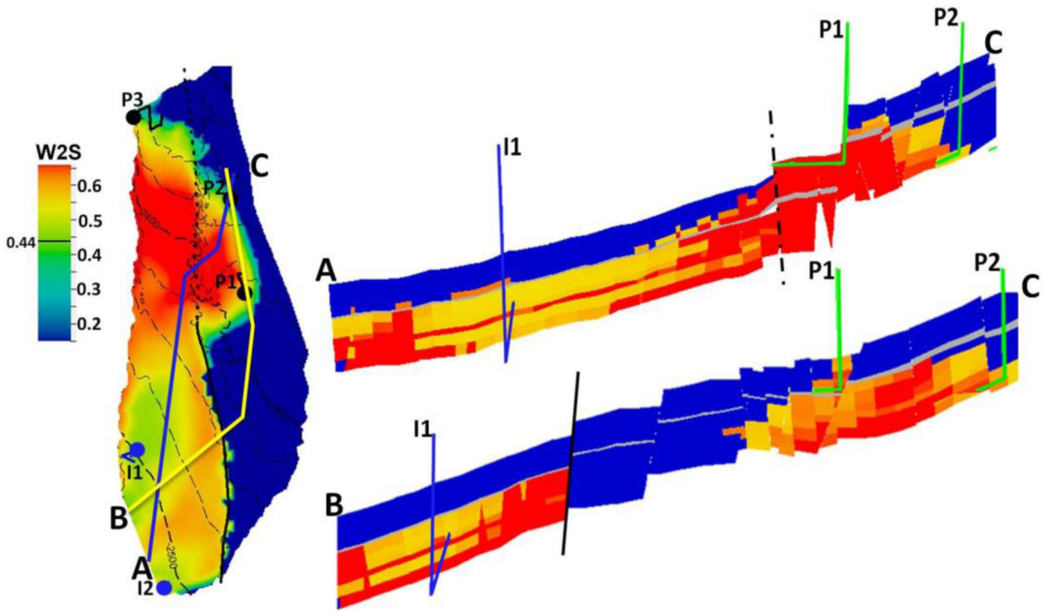

Figure 8—Average map of the 3D W2S property and two vertical cross-sections A-C and B-C from the well2seis property for scenario three.

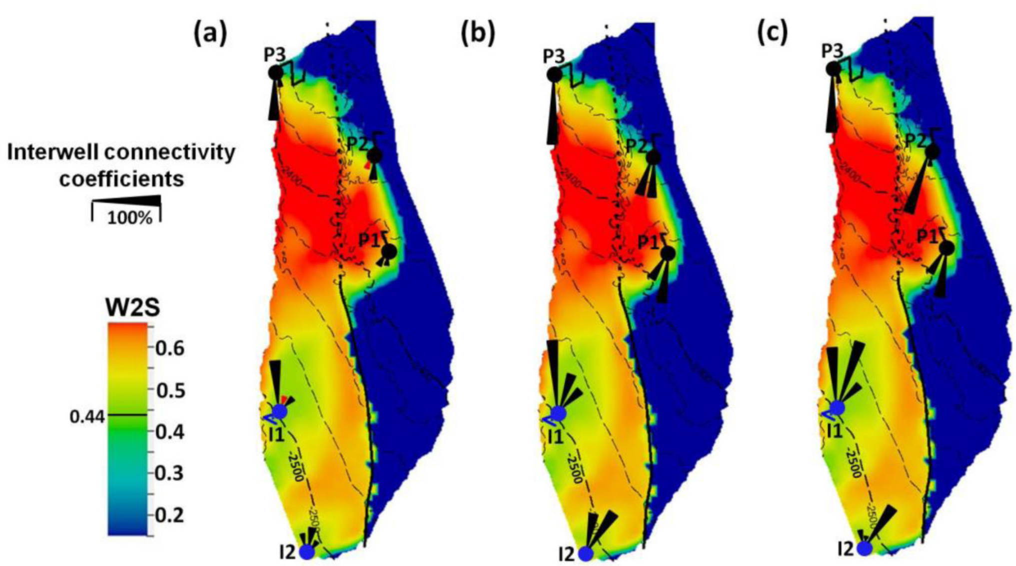

Figure 9—Average map of the 3D W2S property overlapped with the interwell connectivity coefficients obtained from the traditional inter well method SRC (a), MLR (b) and CRM (c) for scenario three.

Conclusions

This study further develops the well2seis technique to evaluate the connectivity between injector and producers. By combining the 4D seismic technique with conventional interwell study methods which use engineering data only, a more robust interpretation of the reservoir interwell connectivity is achieved. Conclusions and further recommendations can be drawn from this study:

1. The conventional interwell techniques based on engineering data can practically quantify the connectivity between injector and producers. But they show limitations when detecting the communication patterns or working on reservoirs with complex geological features. Applications to the three scenarios in this study also suggest that the CRM method provides the most reliable interwell coefficients among the three selected methods.
2. By correlating to corresponding well behaviour data, 4D seismic data show great potential to compensate for the deficiencies in the conventional techniques. The proposed well2seis technique reflects the pathways of the injected fluids and provides a volumetric attribute for measuring the connectivity between wells. By applying to reservoirs with different degree and type of connectivity, the well2seis technique also proves its general applicability in complex reservoirs.
3. Integration of the conventional interwell method with the well2seis technique can provide a more reliable and comprehensive interpretation of reservoir interwell connectivity. In addition, the well2seis interpretation result also shows potential as an effective tool to optimize the conventional interwell connectivity coefficients.

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Nomenclature

ΔA = 4D difference of a seismic attribute.
ΔV = reservoir fluids volumes obtained from wells and corresponding to 4D seismic differences.
N = number of 4D seismic surveys acquired for a field
n = total number of the 4D seismic differences generate for a field.
cov = covariance of the 4D seismic and well behavior sequences.
var = variance of 4D seismic or well behavior sequence.
W2S = well2seis correlation attribute.

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