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Time lapse (4D) Seismic for Reservoir Fluid Saturation and Monitoring: Application in Malaysian Basin

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Abstract

Time lapse (4D) seismic is a valuable technology that provides vital information for field development plans and reservoir management. 4D seismic is extensively being used by oil and gas companies as a reservoir surveillance tool for better estimation of reservoir dynamic properties and reducing uncertainties of simulation models. As a result of production and enhance oil recovery activities (EOR) reservoir dynamic properties such as fluid saturation, pressure and temperature are being subjected to change which can occur independently or a combination of changes may happen in a reservoir. In this article 4D seismic technology is used to qualitatively monitor fluid saturation distribution and remaining oil using repeated 3D seismic surveys of base and monitor which are acquired in 1995 and 2006 respectively. This study integrates seismic data (base and monitor) and well log data from a mature field in the Malay basin with six years of water injection history. To predict water saturation post-stack seismic inversion is performed to extract acoustic impedance of base and monitor surveys and used them as an input for artificial neural network (ANN). 4D seismic data analysis enabled us to qualitatively interpret and identify areas of bypassed oil, generate maps of water movement pattern and guide the infill drilling activities. This methodology has the potential to further extend the life of the field and improving the recovery factor.

Keywords: *Time lapse (4D) seismic; Reservoir monitoring; Water saturation prediction; seismic inversion; Artificial Neural Network.*

1. Introduction

Time-lapse seismic technology has proven its potential for improving reservoir management and has become popular among oil and gas companies as it is a powerful tool for reservoir monitoring and detecting remaining oil and gas in reservoirs [1]. Duri field in Indonesia, North Sea fields including Gullfaks and Fulmar field are examples of successful case studies of time lapse method [2]. Properly interpretation of 4D seismic data provides updated information about production and injection activities and reservoir behavior in the subsurface. Hence, it is important to take into consideration that seismic survey quality plays an important role in the reliability of seismic interpretation and only after a careful acquisition and processing 4D seismic analysis can begin.

The 4D seismic signal contains valuable information which helps to estimate dynamic reservoir changes beyond well location and decreases uncertainties. It helps reservoir engineers and geoscientists to better understand reservoir performance and improve recovery factor by determining areas of swept and unswept, finding bypassed oil, optimizing infill drilling and imaging reservoir compartmentalization [3]. To achieve an accurate interpretation of dynamic property changes such as water saturation, pressure, etc., different seismic attributes analysis (seismic amplitude and acoustic impedance) are needed to monitor and detect anomalies through a picture of subsurface and at each domain fluid flow model can be updated [4-6]. To do so, first 4D seismic volumes (base and monitor) are transformed to post-stack or pre-stack seismic volumes, followed by applying attribute analysis and at last 4D seismic interpretation relates the detected anomalies to saturation and pressure changes.

Qualitative interpretation of 4D seismic data enable us to identify bypassed oil, swept and upswept zone, fluid contact and flood front and in case of pressure changes it helps to identify compartmentalization and fluid flow pathways [7]. Qualitative 4D seismic interpretation is more effective when changes in amplitude is mostly related to one reservoir parameter, fluid saturation or pressure. In this case, qualitative interpretation is a helpful tool for identifying zones where pressure and saturation have evolved and locating new wells for enhance oil recovery purposes [8].

In this article, qualitative 4D seismic analysis is done for a field located to the southwest of Malay basin which was discovered in 1974. 4D seismic analysis is done using two seismic surveys which are acquired in 1995 (base) and in 2006 (monitor) respectively. Water injection activity with the objective of maintaining pressure started from early stages of production. Therefore, in this study detected amplitude changes are being related to water saturation only. It is believed qualitative interpretation of 4D seismic data will result in the generation of water saturation distribution map and identification of bypassed oil areas for enhancing recovery factor.

2. Geological setting

Figure 1. Malay Basin location map between Peninsular Malaysia and Vietnam [9]

Malay basin is located to the east of peninsular Malaysia (Figure 1) and exploration of petroleum in this basin started in 1968. Structurally, this field is asymmetrical elongated in a northwest-southeast direction and it is about 500 km long. Malay basin comprises different stratigraphic groups which starts from A group (youngest) to M group (oldest). The study area is in southwest of Malay basin and has an asymmetrical structure. The reservoir of interest is in I stratigraphic unit form lower-upper Miocene age and the depositional environment reservoir is interpreted as fluvial-deltaic to estuarine channel [9]. Core analysis of reservoir of interest has shown combination of parallel laminated to cross-bedded sandstones with frequent intervals rich in mud clasts which indicates a high energy shore-face environment. Hydrocarbon production started in 2001 and water injection is implemented in early stage of production for reservoir pressure management. Hence, 4D seismic is an important source of information for understanding the movement of injected water in this reservoir. Based on AVO classification the reservoir under study is in class III category as it shows bright spots for far angles [10].

3. Methodology

4D seismic interpretation workflow for this study is divided into two main parts. First, post-stack seismic inversion is implemented to invert the base and monitor 3D seismic surveys using Hampson-Russell Software. Second, fluid saturation was predicted from inverted seismic attributes (acoustic impedance) using an artificial neural network (ANN). The 4D seismic qualitative interpretation was based on fluid saturation and acoustic impedance anomalies or changes. The workflow used in this study is illustrated in Figure 2.

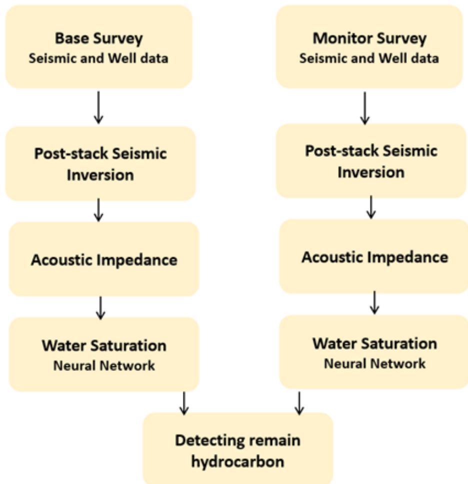

Figure 2. Overall workflow of qualitative 4D seismic study for water saturation prediction

Synthetic seismogram was used to provide a 'tie' between changes in rock properties in a borehole and seismic reflection data at the same location. In order to do that, two logs namely sonic and density log were employed. These logs provide information which are of great significance in determining the acoustic impedance as well as the reflection coefficients of the rock layers. Furthermore, prior to seismic interpretation and inversion a good tie with a high correlation coefficient was attained using proper wavelet. This process followed by implementing post-stack seismic inversion to generate acoustic impedance which is a physical property of the rock by integration of well data and seismic data. Post-stack inversion itself is divided into different types such as model-based and spares-spike and bandlimited inversion. As discussed by Russel and Hampson for model based inversion, an initial earth model is built and is altered until getting the best match between synthetic seismic and observed seismic data [11].

In this regards, three wells (W1, W2, and W3) and two seismic surveys (base and monitor) have been employed to create an initial model of P-wave, density and acoustic impedance using Hampson-Russel software. The extracted acoustic impedance model is the input for obtaining volume of derived acoustic impedance. At last, the neural network model was used to predict water saturation using acoustic impedance and well data. The artificial neural network concept was implemented due to its good capacity of extracting nonlinear correlations between acoustic impedance and water saturation as well as the low impact of noise in data.

3.1. Artificial neural network

Neural network or artificial neural network (ANN) is developed since the 1980's and is inspired by the human brain function. ANN has nonlinear and parallel processing approach and the process includes receiving raw data as an input, training the data and solving the unseen problems, and give out estimation of the nonlinear problem [12-13]. Neural network can be divided into supervised and unsupervised. In a supervised neural network, a set of particular inputs are used to generate particular output and neural network is responsible to figure out the relationship between input and output set of data. While in unsupervised a series of input are introduced and neural network is responsible to identify pattern itself. There is no specific output for unsupervised neural network and this make it difficult to interpret the output. The theory of neural network in Hampson Russel software follows four main steps:

1. Using Seismic data and well log data as an input
2. Calibrating well logs to seismic data
3. Training seismic attributes for prediction of reservoir parameter of interest
4. Applying the train results to whole seismic volume

Hampson *et al.* demonstrated the application of neural network for P-wave log prediction which was based on multiple seismic attributes. The research concluded that neural network helps to predict different logs such as acoustic impedance, porosity, and water saturation, Seismic forward modelling and wavelet extraction is not needed, Resolution greatly increases and Cross-validation can be used to measure the success of neural network in predicting reservoir properties [14].

In this study, the neural network in used through Hampson-Russel software with the purpose of prediction of water saturation using wireline logs. For establishing the relationship between the log and seismic data two types of attributes are introduced to neural network including internal and external attributes. The internal attribute is the original 3D seismic volume and external attribute is inverted volumes of acoustic impedance. Then, the relationship between targeted log and seismic data are analyzed and by using the attributes that gives the highest correlation between well and seismic data water saturation volume of base and monitor is predicted.

4. Results and discussion

This section intends to discuss the result of seismic attribute analysis and detected fluid saturation anomalies based on 4D seismic data for the reservoir located in Malay basin. The qualitative 4D seismic analysis is done using acoustic impedance-resulted from seismic inversion- of base and monitor seismic surveys which follows by prediction of water saturation using seismic and well data.

4.1. Seismic inversion (acoustic impedance)

3D seismic surveys including base and monitor surveys have been used in post-stack seismic inversion and results are shown in Figure 3.

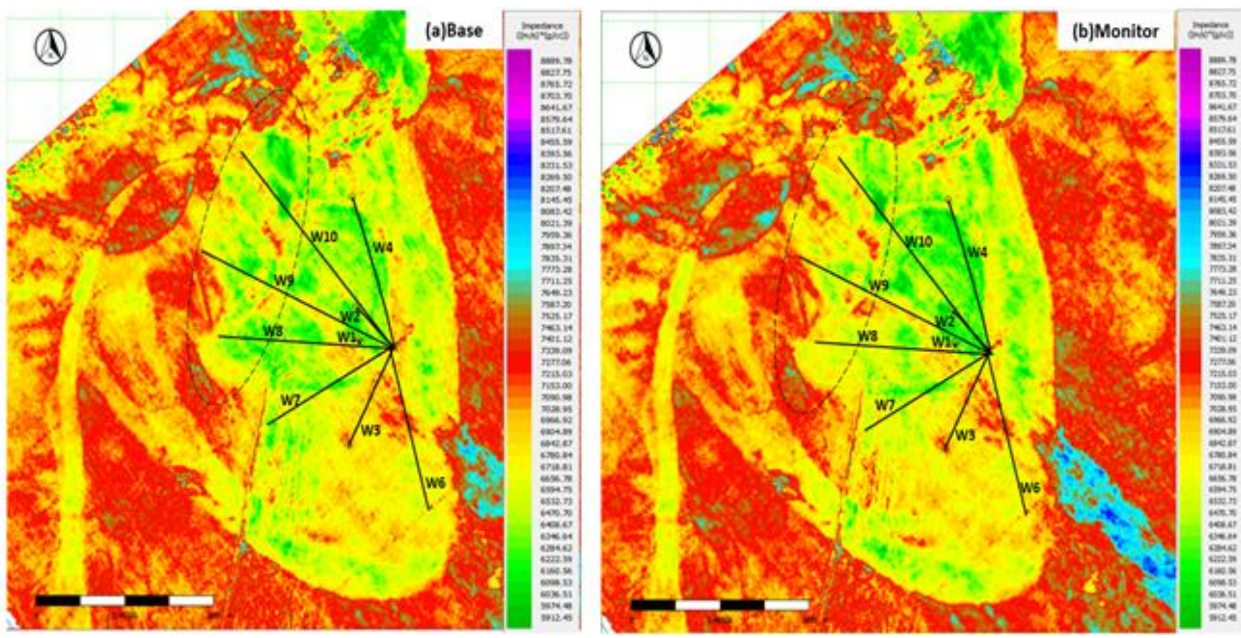

Figure 3. Acoustic impedance map of (a) base and (b) monitor survey indicates Hardening effect in reservoir after water replacing oil and Increase in acoustic Impedance in monitor survey

By comparing base and monitor survey significant acoustic impedance anomalies is detected. Generally, discriminating between the effect of saturation and pressure on 4D seismic data through acoustic impedance is challenging if both pressure and saturation changes has the same degree of impact on seismic response. However, based on pervious sensitivity analysis on the impact of pressure changes on seismic attributes it has been concluded that the pressure effect is negligible [10,15-16].This might be due to the injection activities were initiated at earlier stage of production and it has helped to maintain the pressure within the reservoir. Therefore, in our qualitative 4D seismic analysis detected anomalies are being related to water saturation only. By analyzing the generated maps of acoustic impedance for base and monitor survey a decrease in acoustic impedance value is observed in the areas close to the injectors (W6 to W10) which is due to replacement of oil by water (higher density and velocity) and oil being swept towards production wells. Furthermore, areas with no saturation changes shows no changes in 4D acoustic impedance. Increase of acoustic impedance due to replacement of hydrocarbon by water is referred as hardening effect which is observed in reservoir.

4.2. Water saturation prediction using artificial neural network

Prediction of water saturation using neural network is based on integration of well logs and seismic data.

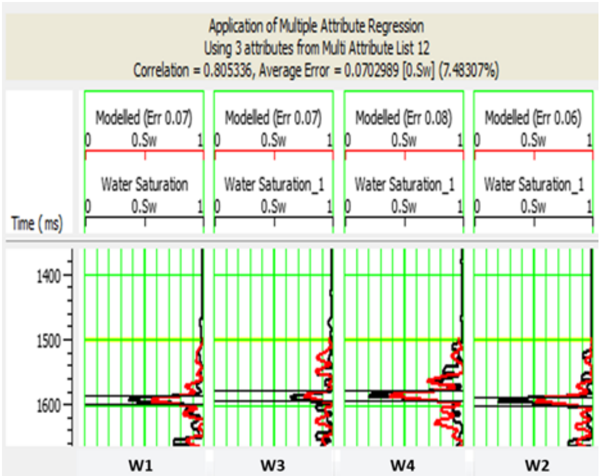

Figure 4. Modelled versus measured water saturation at the location of four wells (W1, W2, W3, W4) using multi attributes with correlation of 0.8

First, in this study four wells (W1, W2, W3 and W4) along with 3D seismic and acoustic impedance are used to analyses which attributes provides better correlation between modelled and real water saturation at the well location.Figure 4 illustrates the result of multi attributes (Amplitude envelope, raw seismic and integrated absolute amplitude (inversion result)) for prediction of water saturation at the well location. Maximum correlation is 0.80 with average error of 0.07. Next, the multi attributes will be used to run neural network model. It worth mentioning that water saturation estimation from acoustic impedance using both artificial neural networks and any other empirical functions is somehow challenging. Generally, the relationship is not so robust due to its distribution which can be fully or partially saturated. Furthermore, acoustic impedance is strong function of lithology and porosity.After training data, the developed model has been used to generate the map of water saturation for both base and monitor survey. Figure 5 illustrates water saturation distribution map of base and monitor surveys at reservoir interval.

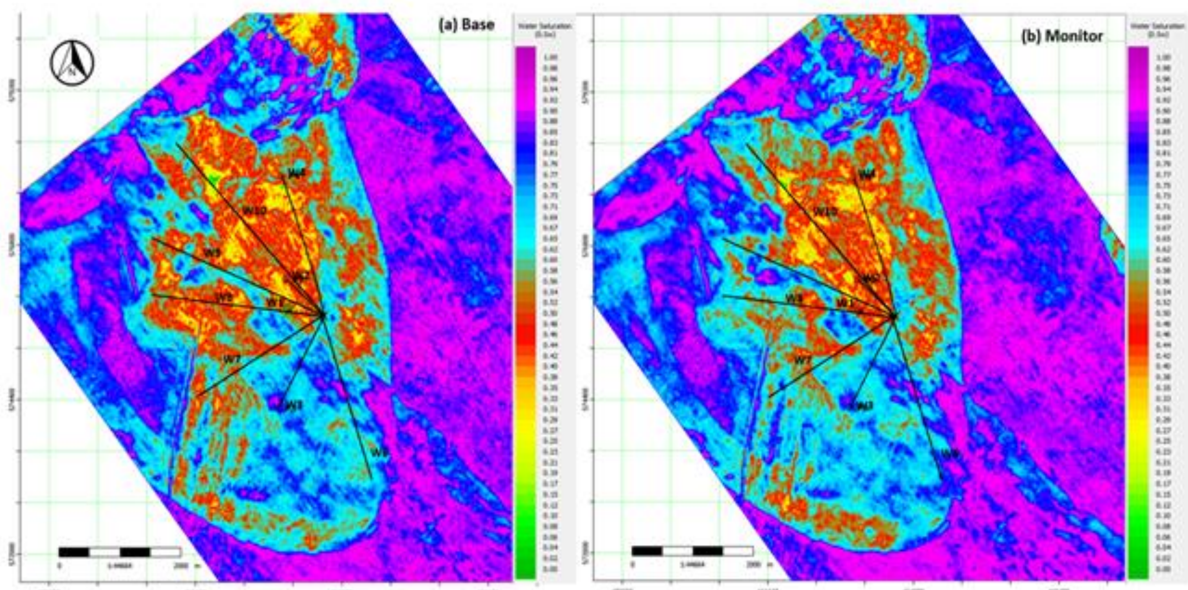

Figure 5 Predicted water saturation for (a) base and (b) monitor survey using neural network at the reservoir interval indicates replacement of oil by water at location of injection wells and distribution of water in reservoir

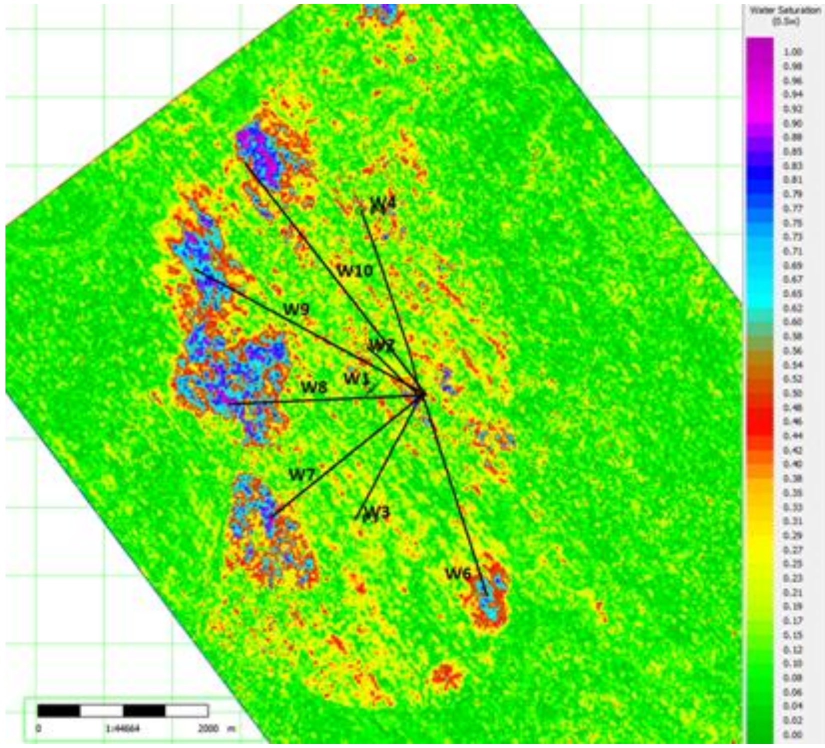

Figure 6. Difference map (monitor-base) shows higher values of water accumulation at the location of injection wells

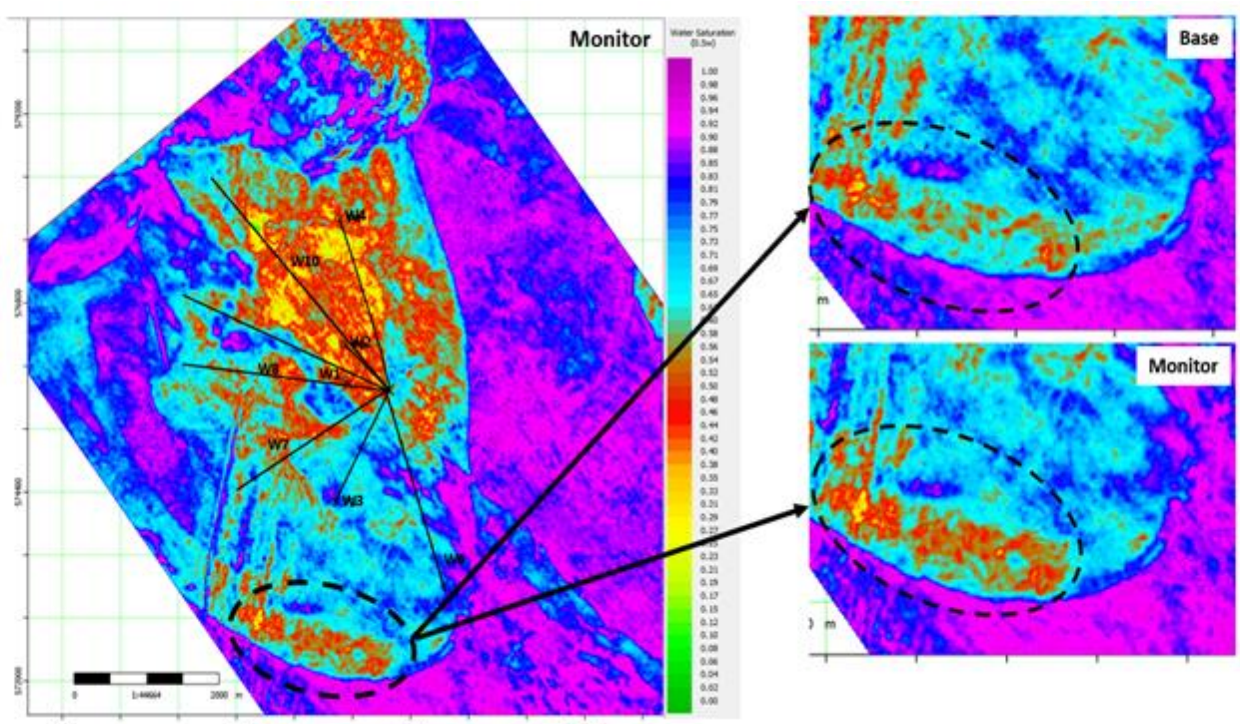

Figure 7. Water saturation map of monitor survey indicates detecting remain oil in regions that oil swept as a result of water injection. Lower values of water saturation compare to base survey

4.3. Detecting areas of remain hydrocarbon

In addition to monitoring water saturation changes, Figure 7 helps to detect remain oil in reservoir. Water injection technique is used with the purpose of maintaining pressure of reservoir and also helps to displace and sweep oil for improving recovery factor. Hence, 4D seismic analysis helps to detect the areas that oil has been swept as a result of injection activity. Figure 7 indicates detection of areas with higher oil accumulation after six years. This information is noteworthy for future drilling plans and enhancing oil recovery factor.

The most significant contribution of this work is that the remaining hydrocarbon areas were located by using 4D seismic data. In addition. The remaining oil causes decrease in acoustic impedance that can be seen from acoustic map as well. The difference map (monitor-base) illustrates distribution pattern of water in the areas close to the injectors and remain oil in reservoir.

5. Conclusion

A strong acoustic impedance were observed in the areas close to the injectors and locations where water replaced oil in reservoir. This is for the reason that water possess high density and velocity over oil. Furthermore, areas with no saturation changes show no changes in 4D acoustic impedance. As a result of water injection, oil has been displaced and accumulated in locations where can be detected through monitor survey and it shows lower water saturation values compare to base survey. The generated maps also helps to guide the infill drilling process. This study has potential to improve oil recovery factors which is essential for oil and gas industry to maximize recovery of hydrocarbon with low cost of operation.

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