High Resolution Deterministic Inversion in the Arab-D Carbonate Reservoir of the Ghawar Field, Saudi Arabia

Costas G. Macrides * (konstantinos.makridis@aramco.com) and Ayon Dey
Saudi Aramco, Dhahran, Saudi Arabia

Summary

Despite the recent advent of sophisticated prestack inversion algorithms, poststack model based impedance inversion remains one of our most extensively tested, robust and computationally efficient tools for reservoir characterization, particularly in carbonate reservoirs where pre-stack AVO inversion remains challenging.

In this paper we show that when acoustic impedance derived from model-based inversion is used as an external attribute in a Probabilistic Neural Network (PNN) scheme with seismic attributes, superior impedance results are obtained revealing high resolution details of reservoir architecture. Examples of the application of this method on the carbonate Arab-D reservoir of the giant Ghawar field in the Arabian Peninsula are shown.

Introduction

After decades of production, the Ghawar field remains the most prolific asset in Saudi Aramco's portfolio. The key oil producer in Ghawar, especially in its northern sector, is the upper Jurassic Arab-D carbonate reservoir (Stenger et al., 2003). This paper describes our efforts to enhance the results of conventional model-based acoustic impedance inversion in the Arab-D reservoir by using a neural network approach. Of particular interest, for reservoir management purposes, was the delineation of the Arab-D reservoir zones 2A and 2B which are separated by tight calcite stringers. Such high resolution details could not be obtained by conventional inversion, which tends to underperform in the rapidly alternating sequence of thin layers in the Arab-D. The study covered an area of 400 Km^2 in northern Ghawar and made use of 32 wells for well-to-seismic calibration, initial model building and, finally, neural network training.

Method

The essence of the method is to use the result of standard model based inversion as an external attribute to obtain improved estimates of impedance using a probabilistic neural network. This involves a mapping process that uses step-wise regression to determine an optimal set of seismic attributes that can be used for training the neural network to predict impedance values.

Well-to-seismic calibration was carried out at 32 wells uniformly sampling the Fazran, 'Ain Dar, Shedgum and Uthmaniyah operational sectors in northern Ghawar. The overall quality of the calibration process was high (average correlation coefficient with the extracted full phase wavelet was 0.76) and revealed no major interference from multiples within the Jurassic sequence. The initial impedance model was low-passed filtered with corner frequencies at 12 and 17 Hz to ensure that it contributed only the low frequency part of the spectrum that is missing from the seismic. Composite traces extracted at each of the 32 wells for calibration purposes were also used for computing seismic attributes. A subset of these attributes determined via step-wise regression was used for training the probabilistic neural network, in a mapping mode, to predict acoustic impedance. The impedance result from the model based inversion was used as the principal seismic attribute to guide the above mapping process. The analysis window for the neural network was 220 ms long encompassing all four carbonate reservoirs of interest within the Jurassic sequence, including the Arab-D primary target reservoir. To safeguard the integrity of our solution against the danger of overtraining we selected the smallest possible number of attributes that minimized the cross-validation error of the multi-attribute transform (Hampson et al., 2001). To further validate the PNN results, blind tests were conducted at new well locations that were previously not included in the training set.

Examples from North Ghawar

Figure 1 shows a 3D view of the time horizon interpreted as the top of the Arab-D reservoir over the north Ghawar study area. Two north-to-south trending anticlines with sub-parallel axes, 'A' and 'B', can be observed. Notice the cross-sectional asymmetry of anticline 'A'.

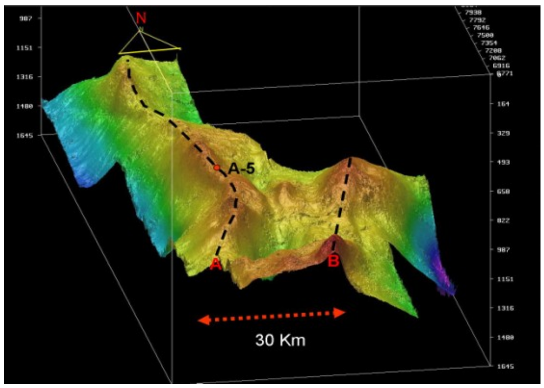

Figure 1. Structure of the Arab-D reservoir over the northern Ghawar field.

Figure 2 shows a single inline impedance section, intersecting well A-5, extracted from the model-based inversion volume. All four carbonate reservoirs in the Jurassic (Arab-D, Hanifa, Hadriya and Lower Fadhili) are clearly visible in the inverted section. However, problems with delineation of fine reservoir details are present in the inversion result.

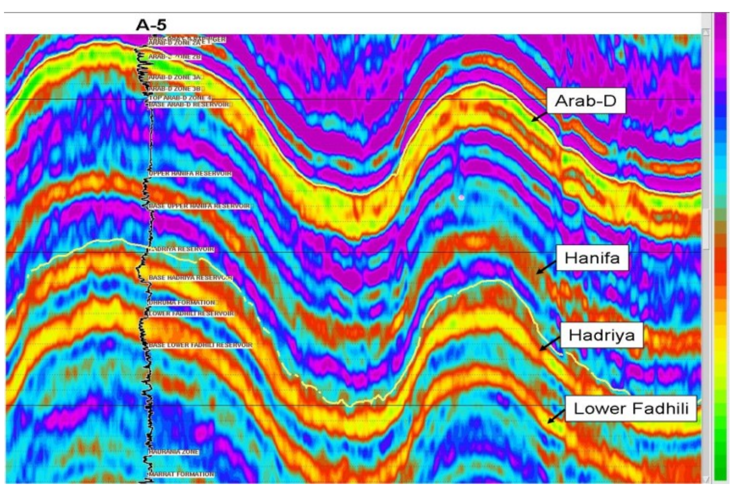

Figure 2. Inline impedance section through well A-5 extracted from model based inversion. The inserted log is the impedance log at this location. Low impedance is shown in green, high impedance in purple.

The lack of resolution can be assessed more clearly by analyzing the results of inversion tests performed at well A-5, shown in Figure 3a. Let us first focus on the upper Jurassic interval representing our primary target, the Arab-D reservoir. The inversion (red curve) identifies the reservoir with a single low impedance lobe but is unable to differentiate between reservoir zones 2A and 2B that, as the impedance log indicates, are separated by a tight 20-ft stringer. Furthermore, the inversion result seems to underestimate the net pay thickness of the Arab-D reservoir which is characterized by very sharp top and bottom boundaries.

The need to enhance the resolution of the inversion results at the Arab-D level was dictated by our reservoir development goals and led us to investigate the possibility of using a neural network approach for improving our impedance prediction. Using the impedance from the model-based inversion as an external attribute, we sought to identify the best set of additional seismic attributes that could be used to train the network, in a mapping mode, to predict acoustic impedance. All attributes were extracted from composite traces created from a cluster of seismic traces in the vicinity of each of the 32 available wells. The analysis window was 220 ms long, extending from the top of the Arab-D reservoir to the base of the Lower Fadhili. Our best impedance prediction results were obtained with a probabilistic neural network using a total of eight attributes and an 11-point (11 ms) operator. Using more than eight attributes resulted in overtraining of the network as witnessed by an increase in the cross-validation error. The most highly correlated attribute was the impedance obtained from the model-based inversion, the second in the list being a 5/10-15/20 Hz filter slice of the seismic volume. Other attributes highly ranked in the list included the quadrature trace and the instantaneous frequency. The result of our PNN prediction at well A-5 is shown in Figure 3b and is displayed side by side with the result of the model-based inversion for comparison purposes.

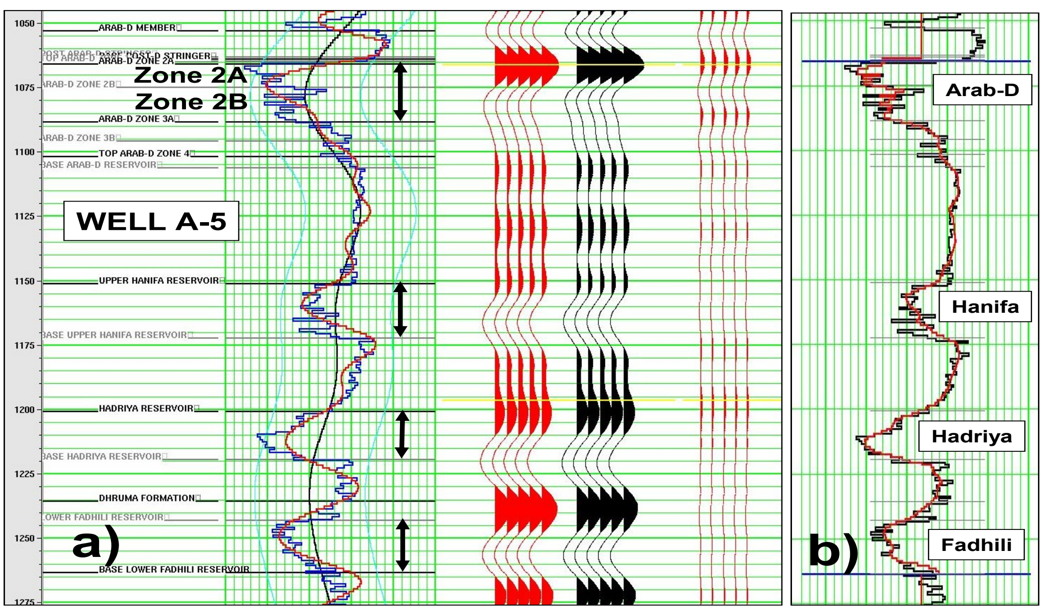

Figure 3: Inversion test at well A-5 over the Jurassic carbonate sequence (a). Model based inversion followed by probabilistic neural network impedance prediction at the same well (b).

As can be seen, the results at the secondary Hanifa and Lower Fadhili target reservoirs are quite comparable between the two methods. However, within the Arab-D reservoir the impedance prediction from the PNN inversion represents a marked improvement over the result of the conventional inversion: zones 2A and 2B are now fully resolved and the 20-ft thick calcite stringer that separates them is clearly delineated. Layers of thickness less than 20 ft could not be resolved in the PNN result shown in Figure 3b. It is interesting to note that a layer thickness of 20 ft is close to the theoretical detectability limit of $\lambda/16$, given an Arab-D velocity of 11,000 ft/s and a dominant frequency of 32 Hz. Another observation that can be made in Figure 3b regarding the Arab-D is that the PNN result more precisely captures the full net pay thickness of the reservoir. Finally, within the Hadriya interval, it can be seen that the model based inversion underestimates the quality of the reservoir by predicting a minimum impedance of 34,000 ft/*g/cc while the PNN result places the minimum at 30,000 ft/s*g/cc, providing a better match with the actual log impedance and thereby predicting reservoir quality more accurately.

The optimized PNN training was applied to the entire seismic volume. An extracted impedance section is shown in Figure 4, for the same inline used in Figure 2 for comparison purposes. Notice the improved resolution of the PNN inversion at the Arab-D, the sharper definition of the base of the reservoir which can now be easily tracked across the section and also the improved lateral continuity of the Hanifa reservoir. Finally, a general observation is that the overall PNN result in Figure 4 is less 'noisy' compared to the inversion in Figure 2. A good example of this difference in character is the interval between the base of the Arab-D and the top Hanifa. This is a zone of nearly constant high impedance, as the logs at well A-5 indicate, but exhibiting significant impedance variations in the conventional inversion shown in Figure 2, unlike the PNN result.

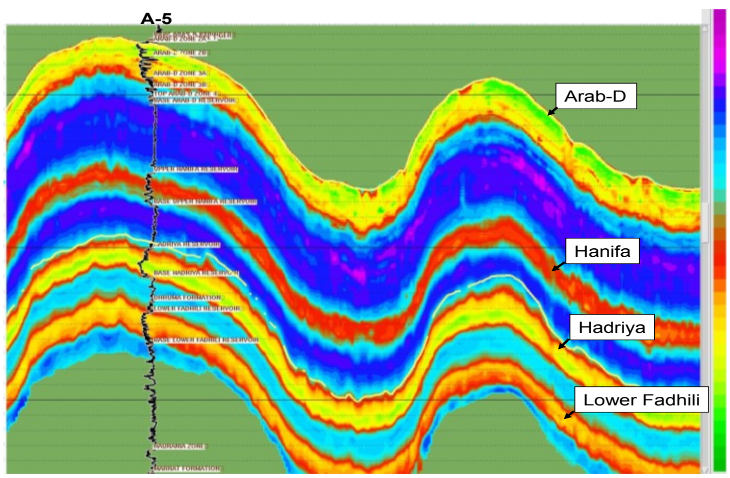

Figure 4. Model-based inversion followed by PNN impedance prediction. Compare with Figure 2.

Conclusions

Model-based inversion followed by impedance prediction using a probabilistic neural network was successfully applied over the Jurassic carbonate reservoir sequence in the northern portion of the Ghawar field, in Saudi Arabia. Significant benefits gained from applying this methodology included: a) Improved resolution and delineation of reservoir internal architecture in the upper Jurassic Arab-D reservoir, b) More accurate estimation of the net pay thickness in the Arab-D, c) Enhanced lateral continuity of the Hanifa reservoir, and d) More accurate estimation of reservoir quality and net pay thickness in the Hadriya reservoir.

Acknowledgements

We thank the management of Saudi Aramco for supporting this project and for granting permission to publish. We also thank Dr. P.G. Kelamis for critically reviewing the manuscript.

References

Stenger, B., T. Pham, N. Al-Afaleg, and P. Lawrence, 2003, Tilted original oil/water contact in the Arab-D reservoir, Ghawar field, Saudi Arabia, GeoArabia, Vol. 8, No. 1, p. 9-39.

Hampson, D., J.S. Schuelke, and J.A. Quirein, 2001, Use of multiattribute transforms to predict log properties from seismic data, Geophysics, Vol. 66, No. 1, p. 220-236.