Introduction

The construction of 3D geological models is extremely significant for optimum well placements and maximizing profit. For a robust geological model, the amount of input data into the model is very important, and the quality and accuracy of these data is just as important too. Such models depend on sedimentological input from cored wells through core descriptions and facies assignment.

In many cases, the number of cored wells in any given hydrocarbon field is limited. To compensate for this, facies could be predicted for the vertical uncored wells to virtually increase the number of wells with sedimentological data. However, attention should be considered in this process to produce accurate and systematic predicted facies.

The facies prediction workflow described here uses the Middle Jurassic Lower Fadhili Reservoir from Saudi Arabia as a case study. The objective of the workflow is to highlight how to predict facies accurately and more geologically realistic through sedimentology and sequence stratigraphy.

Data and Methods

The facies prediction workflow was applied on a dataset from a field in eastern Saudi Arabia from which 15 cored wells of the Lower Fadhili Reservoir were described. Detailed sedimentological analysis of more than 800 m of the Lower Fadhili was done to record mineralogy, textures, sedimentary structures, ichnofabrics, grain types and sizes, and fossils content and their abundance. Facies assignment was chiefly based on the dominant grain types and fossils abundance.

For constructing the sequence stratigraphic framework of the Lower Fadhili Reservoir, wireline logs including gamma ray, neutron porosity, and density were used to correlate the identified stratigraphic surfaces between the cored wells. This was done after placing the core descriptions with assigned facies against the logs and depth-shifting them by matching the core plug porosity with the porosity log. Through following the concepts and principles of sequence stratigraphy described in Kerans and Tinker (1997) and Catuneanu *et al.* (2009), the interpretation of the stratigraphic surfaces was based on facies offsets and proportions according to the proposed depositional model. These data were then presented in cross-sections and facies trend maps that show the distribution of the reservoir facies across the field.

Based on the framework, the stratigraphic surfaces were then populated to the uncored wells. A cutoff value of a maximum of 40^{o} inclination was determined to select uncored wells for facies prediction. The total number of wells with that criteria was 13 wells.

For facies prediction, neural network was utilized to initially train the wireline logs from the cored wells and then apply the algorithm to the uncored wells. The process started with preparing data tables for all wells that list the degree of core coverage and types of logs available in each well in order to determine key wells and exclude unreliable wells. The must-have logs for the prediction include gamma ray, density, neutron porosity, total porosity (PHIT) logs, and the calculated minerals volumetric. Other logs can be used too such as sonic, and photoelectric index (PEF) logs. This step was followed by normalization of gamma ray, sonic, and neutron porosity logs while cross-plotting density versus neutron porosity logs helped to eliminate bad data. Unsupervised prediction was then performed to generate electrofacies and group the wells according to the correlation coefficient of the electrofacies. Within each group, the key well is used to train the logs in the supervised prediction stage. Following that was the blind test where the other cored wells in each group were used to predict the facies for the key well. Once a good match of the predicted facies with actual core facies is met, the combination of logs used for that prediction was applied to the uncored wells within every group. Finally, facies trend maps based on the stratigraphic framework were used to quality control the results.

Results

On the basis of sedimentology, the Lower Fadhili Reservoir has seven distinct facies. These include from shallowest to deepest:

1. Bioturbated *Thaumatoporella* wackestone/mud-dominated packstone: The green algae *Thaumatoporella* is common to abundant in this facies along with benthic foraminifera, echinoderms, and brachiopods. The bioturbation is moderate to intense and the porosity is observed within the foraminifera and *Thaumatoporella* as intraparticle porosity.
2. Bioturbated *Thaumatoporella-Cladocoropsis* mud-dominated packstone: Along with *Thaumatoporella*, *Cladocoropsis* is common to abundant in mud-dominated packstones with other skeletal grains. The bioturbation in this facies is also moderate to intense and the dominant porosity type is intraparticle porosity within the *Cladocoropsis, Thaumatoporella*, and foraminifera.
3. Bioturbated skeletal-peloidal grain-dominated packstone/grainstone: This facies has the best porosity in the form of interparticle porosity between peloids, intraclasts, coated grains, and skeletal fragments. Also, intraparticle porosity is present within foraminifera and coated grains. The facies lack any preserved sedimentary structures due to the moderate bioturbation.
4. Bioturbated microbial coated grains mud-dominated packstone: This facies is composed of coarse to granular size microbially coated grains that display intraparticle porosity as a result of partial leaching. Other grains associated within the facies include benthic foraminifera, echinoderms, and brachiopods.
5. Bioturbated skeletal wackestone/mud-dominated packstone: Intense bioturbation characterizes this facies, which is composed of benthic foraminifera, echinoderms, and brachiopods. Porosity is observed within the foraminifera as intraparticle porosity.
6. Bioturbated spiculitic wackestone: The facies is dominated by sponge spicules that are also associated with brachiopods, echinoderms, and foraminifera. The facies is characterized by very low prosity.
7. *Bositra* wackestone/mud-dominated packstone: The dominant fossil in this facies is the species *Bositra buchi* that form wackestone and mud-dominated packstone textures along with the foraminifera *Lenticulina*, echinoderms, and brachiopods. The facies is characterized by high pyrite content and is bioturbated by the horizontal burrows *Chondrites*.

Based on the recognized Lower Fadhili facies, the depositional settings for the reservoir was middle to outer ramp under low energy, normal salinity, and open marine conditions (Figure 1). This interpretation is supported by the extensive bioturbation, presence of micrite, lack of sedimentary structures, and existence of open marine fauna such *Bositra* and echinoderms (Scholle and Ulmer-Scholle, 2003; Hughes, 2004). The sequence stratigraphic surfaces were interpreted on the basis of this proposed depositional model and enabled the construction of the Lower Fadhili stratigraphic framework. The cross-section in Figure 2 shows 10 fourth-order sequences that define the framework of the reservoir. These 10 sequences form two third-order sequences that demonstrate the overall facies lateral migration across the field. An overall progradational trend of the reservoir facies is observed from the north to the south of the study area. This is evident from the deposition of the shallow *Cladocoropsis*-dominated facies in the lower sequences before it dominates vertically and prograde southward in the upper sequences. In addition, the Lower Fadhili Reservoir is thicker with better porosity development in the north than the south. This is attributed to higher carbonate production and accumulation rates in shallower areas in the north.

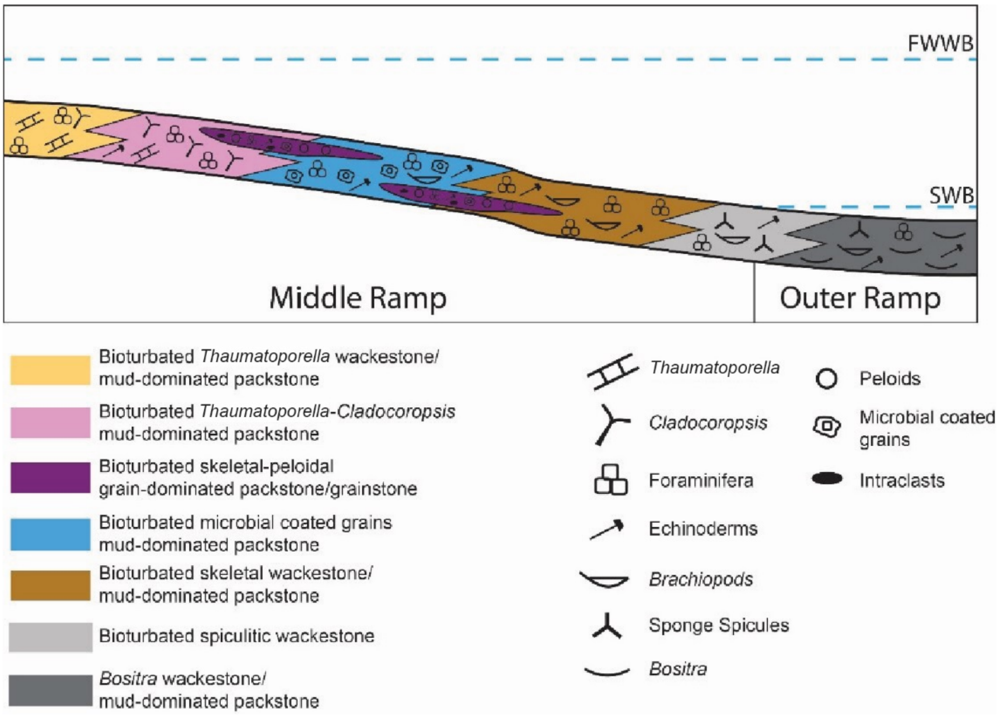

Figure 1 *Idealized depositional model of the Lower Fadhili Reservoir (not to scale).*

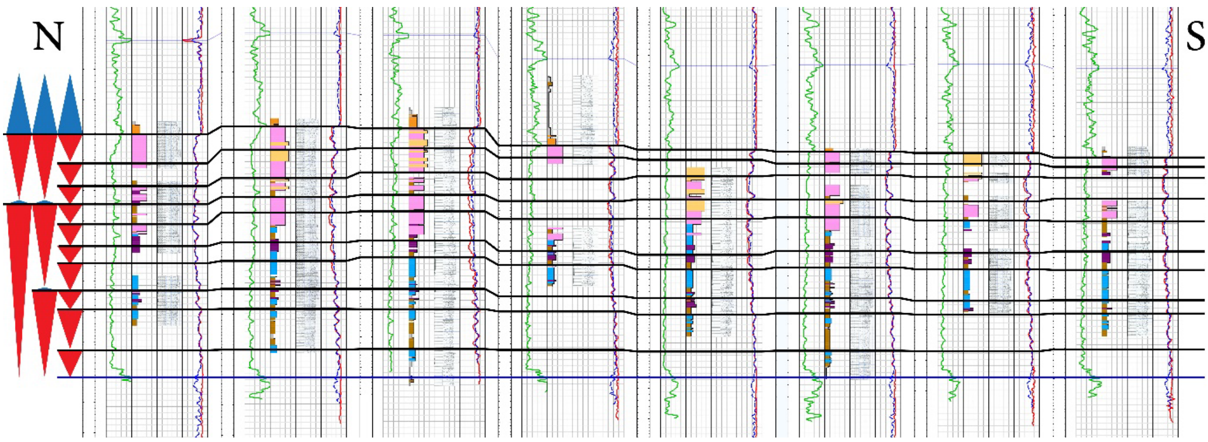

Figure 2 *Sequence stratigraphic framework of the Lower Fadhili Reservoir showing 10 fourth-order sequences.*

By utilizing the sedimentological (depositional facies) and stratigraphic (the framework) data, facies were predicted for 13 uncored wells. The use of the stratigraphic markers as bounding surfaces and the treatment of each sequence as a reservoir zone helped significantly in training the logs based on the cored wells and in predicting the facies for the uncored wells. In this instance, the prediction algorithm would match the logs signatures with only the facies present in any particular zone. As a result, the predicted facies followed the facies trend that is defined by the sequence stratigraphic framework. For example, the *Bositra*-dominated facies is only present in the basal sequence of the Lower Fadhili, and therefore, the algorithm will not predict it in the fifth sequence. If the zonation and constraints provided by the stratigraphic surfaces are not applied, then the prediction algorithm could potentially predict the *Bositra*-dominated facies in the upper part of the reservoir if it finds the same logs character as in the base, which is not realistic. Therefore, the stratigraphic framework minimizes the prediction uncertainty and provide a tool for quality control of the predicted facies.

Conclusions

The facies prediction workflow described through this study illustrates the necessity for reservoir sequence stratigraphic studies. In the case of the Lower Fadhili Reservoir, sedimentological analysis identified seven distinct facies that deciphered the depositional setting and environments of the reservoir. This information helped to establish the sequence stratigraphic framework of the Lower Fadhili with 10 fourth-order sequences. Through the integration of sedimentology and wireline logs, the logs were trained to predict the facies from the cored wells within each depositional sequence, and then the prediction algorithm was applied to the uncored wells. By this workflow, the total number of wells with sedimentological data, i.e. facies, was increased to 28 wells distributed across the field. Such data will help to construct a 3D geological model with less uncertainty in comparison to the case if only the cored wells are only used for the geological model. This will reflect into a better distribution of static and dynamic data for the 3D simulation model. Finally, facies prediction without a stratigraphic framework will produce a random distribution of facies that violates the sequence stratigraphic principles underlying such reservoirs.

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