Core Driven Hierarchical Facies Modeling of Shoreface Environments: A Case Study from Offshore Sabah, Malaysia*

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Abstract

A novel approach focused on core driven hierarchical facies association for static modeling has been pioneered in the Samarang Field, offshore Sabah, Northern Borneo, Malaysia. Hierarchical facies modeling defines a broad facies association that represents the large scale heterogeneity as well as variations within depositional units. This provides the framework to control the fluid flow behavior during dynamic simulation by determining the distribution of porosity, permeability, and initial water saturation constrained to lithofacies. In a shoreface environment, additional challenges are involved in the characterization of lateral facies variation within apparently sheet-like continuous depositional units. Though these depositional units are correlatable over a large distance, the variation within the units is the key to understanding the dynamic behavior of the reservoir and deploying that to build a representative dynamic model.

Methodology

Lithofacies associations (sands, shales) and their vertical and lateral distribution within each depositional unit (upper, middle, lower shoreface, and offshore) were the main focus of this workflow. It was a classic example of utilizing the input from core description and integrating it using supervised classification based on principle component analysis (PCA) and thus capturing the depositional facies and lithofacies in a hierarchical approach both in the static and dynamic models. The workflow presented next can be divided into three parts:

1) Geological Core Description

The first part of the workflow was based on the building of a depositional model based on geological core description of deposition and lithofacies with detailed documentation on facies types, primary sedimentary structures, bedding contacts, grain size variations, sorting, bed thickness, and bioturbation (ichnofacies) and supplement it further with in-depth petrographic studies on core plugs by using scanning electron microscopy (SEM), energy dispersive X-ray analysis (Edax), and X-ray diffraction analysis (XRD) to determine the actual 3D disposition of the framework grains, clay mineralogy, distribution of clays and their distribution in relation to the pore. This type of investigation is the foundation of the reservoir assessment in the cored wells where lithofacies need to be properly identified with the correct sedimentological parameters and used as benchmarks that need to be calibrated in terms of petrophysical parameters to tie to electro-facies. Lastly, unique porosity-permeability transforms and initial water saturation models were calibrated for each of the lithofacies.

2) **Supervised Classification of Facies in Non-Cored Wells**

To propagate facies information to non-cored wells, a supervised PCA based approach was employed first in cored wells with supervised relationship based on eigenvectors built between available core descriptions, open hole well logs and interpreted well logs for clay, silt and sand volume to make systematic use of the core description and enable geological application of conventional well logs (Basu et al., 2004). The model was fine-tuned over multiple iterations to reduce the training and prediction error. Integrated log patterns of these inputs were used to characterize five lithofacies in the cored wells (high quality sand, laminated sand, bioturbated sands, heterolithics, and shale). This characterization provided a basic framework for a multi-well electro-facies classification scheme that used the final calibrated PCA model to estimate lithofacies in the non-cored wells.

3) **Building Hierarchical Facies Model using Truncated Gaussian with Trends (TGT) and Truncated Gaussian Simulation (TGS)**

A two-step facies modeling approach was developed for this study involving the building of the depositional facies model and then lithofacies model constrained to it to honor the hierarchical facies relationship from depositional facies to lithofacies. The depositional facies model is built using TGT to define a broader facies association that represents the large scale heterogeneity. Truncated Gaussian with trends has an advantage in building depositional systems where there is a natural transition through a sequence of facies. Typical examples include carbonate environments, shoreface deposits and progradational sequences. The method involves a choice of facies codes to be included in a certain ordered sequence. It honors the global fractions as well as the underlying probability field to model the transition between varying facies for each of the facies, defined along a trend in which the facies codes are expected to change. Residuals between the trend and the up-scaled well log data are then distributed, using the Sequential Gaussian algorithm, the defined variogram, variance and trend. Finally the values are converted back to the original facies codes. The association of lithofacies in a particular order and stacking defines individual depositional environments or facies. In order to honor this particular order, TGS is used to model lithofacies constrained by the depositional facies, hierarchically above. Local vertical proportion curves (VPC) of the lithofacies were generated using the depositional facies as spatial discriminators. The global VPC gives the proportion of each lithofacies per level integrated laterally over the whole field. It reflects the vertical variations of the proportions, and confirms the depositional process that governed the facies distribution. The shoreface depositional environments have distinct proportions of lithofacies. The spatial correlation lengths of each of the five lithofacies were derived from variogram analysis. This provided a robust framework to propagate facies/porosity, and the porosity model was used next to create permeability and initial water saturation models based on the core-calibrated function for each lithofacies.

Example

We present a case study from the Samarang Field located in a structurally complex Sabah Basin, where the aforementioned methodology was used to build the static model for a shoreface environment. The area of interest was the Late Miocene shallow marine section, which showed repeated progradation and retrogradation within a major regressive clastic wedge that was building towards the northwest. Individual Samarang reservoirs were interpreted to portray wave/storm dominated sand bodies forming in upper to middle to lower shoreface and offshore transitional environments, accumulating in a coastal to inner shelf (Figure 1). The upper to middle shoreface sandstones typically were good reservoir quality massive to laminated sands, whereas the lower shoreface to offshore transitional environments were characterized by poor-quality, bioturbated to heterolithic sands that were formed as event beds during storms. The shales were typically formed in the offshore inner neritic shelfal environment (Forrest et al., 2009).

Three shoreface depositional facies, Upper/Middle Shoreface (UMSF), Lower Shoreface (LSF) and Offshore, were identified and modeled using the TGT to a provide depositional framework to further propagate lithofacies within it. The following lithofacies were identified in the cored interval: Massive Sandstone 1 (Sm1), Massive Sandstone 2 (Sm2), Laminated sandstone (Sl/c), Bioturbated sandstone (Sb1), Intensely bioturbated sandstone (Sb2), Heterolithic sandstone (Sm/Ms), Bioturbated shale (Mb) and Stratified shale (Ms) (Figure 1). The sedimentary characteristics of each facies are given in Figure 2 and the hierarchical facies relationships between depositional and lithofacies are shown in Table 1.

This was followed by the supervised PCA approach to propagate the lithofacies information obtained from the cored wells to ~140 non-cored wells (Figure 3). The lithofacies were then modeled using TGS constrained to depositional facies based on the relationship between depositional and lithofacies as shown in Table 1. The final lithofacies model was then used to constrain the porosity propagation using the Sequential Gaussian Simulation (SGS) (Figure 4). The permeability and water saturation models were built using the porosity model constrained to lithofacies using the core calibrated functions.

Conclusions

The methodology described above provides a robust integration in facies modeling workflow whereby core-driven facies association in a shoreface environment have been captured, characterized, and represented in static and dynamic models, including calibrated petrophysical parameters. The new models were validated in a recent infill drilling campaign where model predictions of sand quality and net pay proved to be robust. In addition, new cores were taken during the campaign that further validated the control data provided by electro-facies based facies prediction at wells and propagation based on Truncated Gaussian methods.

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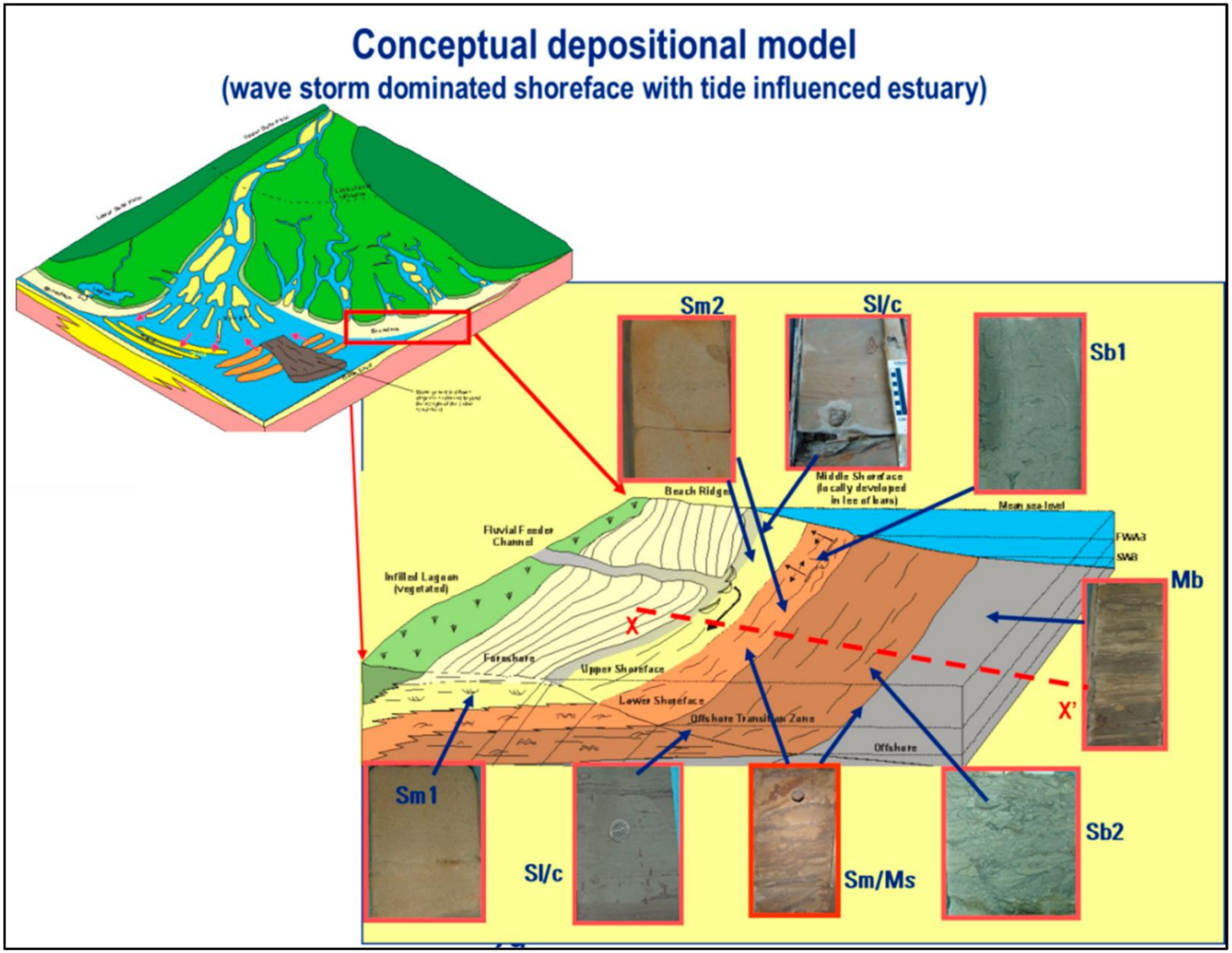

Figure 1. Schematic illustration of the conceptual depositional model for the Samarang Field and association of various lithofacies within hierarchical depositional facies units.

Litho-facies Character	Massive Sandstone 1 SM1	Massive Sandstone 2 SM2	Laminated Sandstone Sl/c	Poorly Bioturbated Sandstone SB1	Intensely Bioturbated Sandstone SB2	Heterolithic Sandstone SM/Ms	Bioturbated& Stratified Mudstone Mb,Ms
Grain-Size	Medium to coarse grained well sorted	Fine to medium grained well sorted	Fine upper to fine lower grained,moderately well sorted. Units separated by clay partings or mud rip up clasts lining individual amalgamated units	Fine lower to very fine upper grained, moderately poorly sorted	Fine lower to very fine upper grained, moderately poorly sorted	Medium upper to fine upper grained, well sorted for the sandstone alternating with shales or finer grained layers	Pure shales were rare. Both the shale varieties had silt introduced from either bioturbation or silty lamination
Sedimentary structure/special characters	Amalgamated units with sharp to erosional contacts	Amalgamated units with sharp to erosional contacts occasionally marked with clay partings	Hummocky cross stratified (SCS locally), tangential to tabular cross bedded, occasionally parallel to lenticular laminated, with mud drapes	Erosional contacts in between units and sometimes associated with parting lineation	Erosional contacts in between units, sometimes associated with parting lineation and broken shell hashes. Patchy distribution of cementation	Amalgamated contacts, HCS, oscillation ripples, mud drapes, occasionally with coaly rip up clasts and mm scale coaly layers	Stratified shales shows well developed parallel lamination or ripple lamination
Rate of sedimentation & Bioturbation (ichnospecies)	High sedimentation rate with rare bioturbation (mostly *Anconycnus* with some *Helminthopsis*)	High sedimentation rate with rare bioturbation (mostly *Rosselia,Ophiomorpha,Rhizocorallium*)	Moderate sedimentation rate with rare bioturbation (mostly *Ophiomorpha or Rhizocorallium*)	Low sedimentation rate with frequent bioturbation (mostly *Paleophycus,Skolithos,Planolites ,Teichichnus*)	Very low sedimentation rate with intense bioturbation obliterinq any primary sedimentary structures(mostly *Cruziana* and *Zoophycos* ichnofacies assemblage	Low to moderate sedimentation rate with moderate bioturbation showing *Asterosoma* to *Zoophycos* ichnofacies assemblage	Bioturbated shales show *Cruziana* to *Zoophycos* ichnofacies assembalge
Reservoir Quality	Good reservoir quality (por 0.22-0.24,perm 1-4D)	Good reservoir quality (por 0.22-0.24,perm 500mD-1D)	Good reservoir quality (por 0.22-0.25,perm 100mD-800mD)	Poor reservoir quality (por 0.18-0.23,perm 50-200mD)	Poor reservoir quality (por 0.11-0.18,perm 1-50mD)	Moderate reservoir quality in the sand as in laminated sandstones	Non reservoir

Figure 2. The sedimentary characteristics of each lithofacies in terms of grain size, primary sedimentary structures, sorting, bioturbation (Ichnofacies), special characters, rate of sedimentation, and reservoir quality.

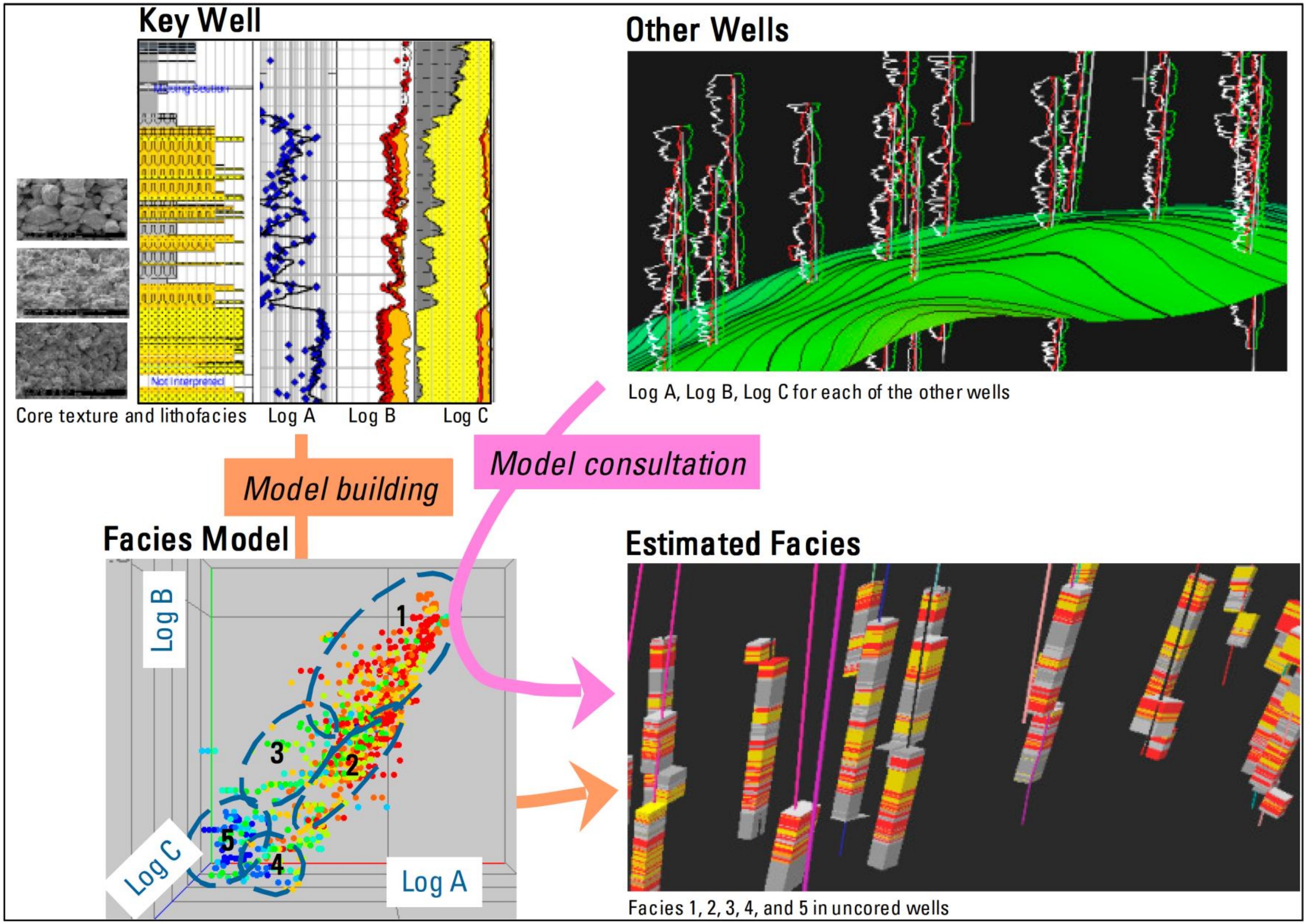

Figure 3. The workflow illustrating the propagation of lithofacies in non-cored wells using the supervised principle component analysis (PCA) approach.

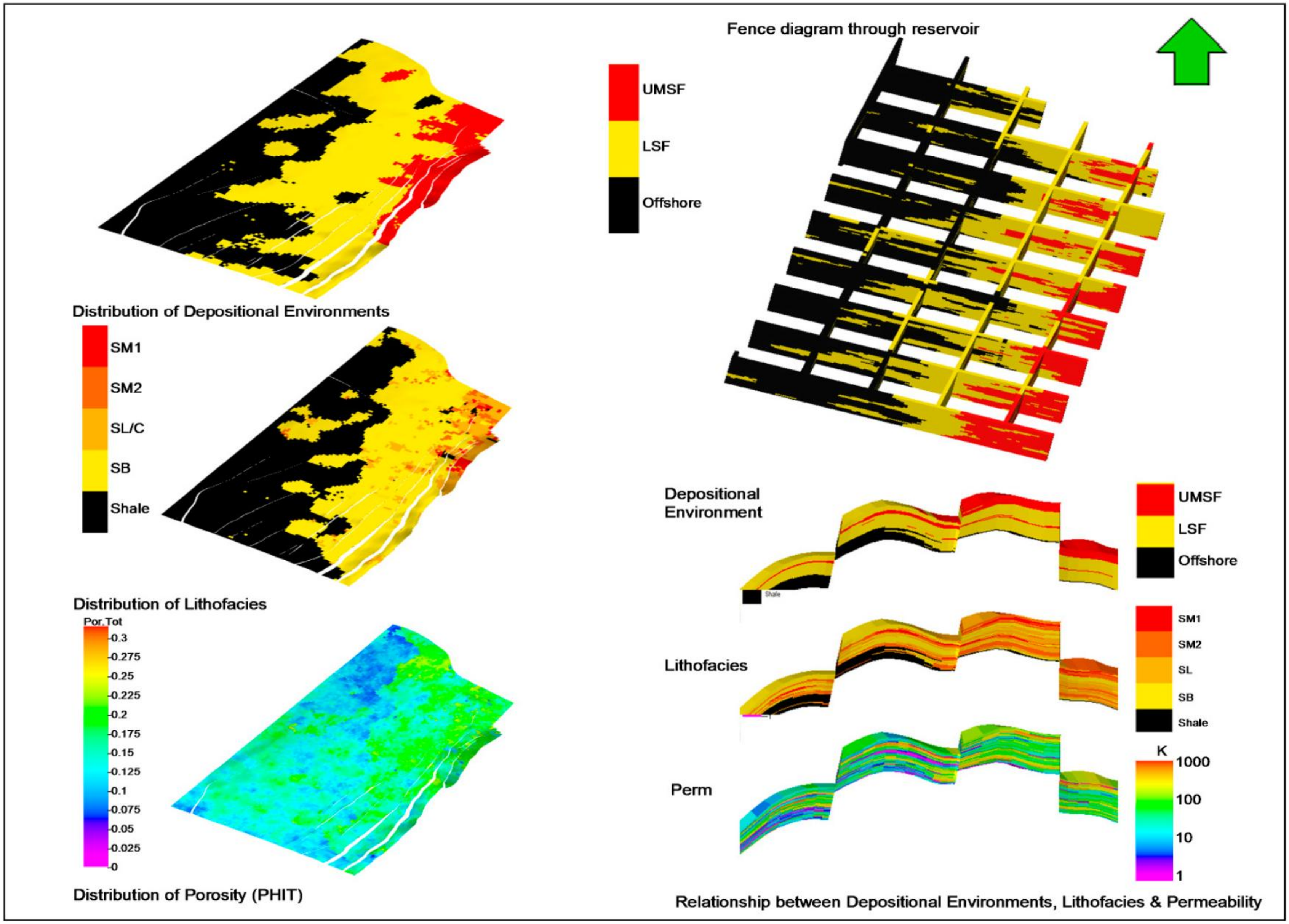

Figure 4. Illustration of the sequential model building based on depositional environments and lithofacies.

<table>
<tr><th>Depositional Facies</th><th colspan="6">Lithofacies Associations</th></tr>
<tr><td>Upper Middle Shore Face</td><td colspan="2">SM1</td><td colspan="2">SM2</td><td colspan="2">SL</td></tr>
<tr><td>Lower Shore Face</td><td colspan="2">SM2</td><td colspan="2">SL</td><td colspan="2">SB</td></tr>
<tr><td>Offshore</td><td colspan="3">Shale</td><td colspan="3">SB</td></tr>
</table>

Table 1. Depositional facies and lithofacies associations.