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Research Article

Modeling of Littoral Sandstones Reveal Variance in Reservoir Flow Patterns: An Example from Nyalau Formation, East Malaysia

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Abstract: Modeling of littoral sandstone reservoirs are challenging due to different scales of heterogeneities. This study introduces an improved understanding of internal structures of sandstone and the way heterogeneities in facies distribution can affect variance in reservoir flow pattern. The methodology presented in this study is based on outcrop study of the Nyalau Formation from Sarawak, East Malaysia and modeling; from selection and data collection, to facies distribution, bedding and gridding, assigning permeability to each cell within the grid in order to obtain a flow pattern utilizing PetroMod® software at reservoir depth condition. The final model were analyzed both statically and dynamically. Static examination involved visual inspection and extraction of quantitative data on different sandstone facies, including lateral and vertical distribution of sandstone and mudstone. Dynamic investigation involves simulating fluid flow through different sets of facies to understand how it behaves in terms of reservoir condition. The model also designates that more homogeneous cross-stratified sandstone facies show persistent spatial correlation of permeability and porosity that align with the cross-bedded orientation or straight. Whereas, in more heterolithic sandstone, lateral variations in permeability show spatially non-correlated patterns over centimeters to tens of meters. These variations reflect the lateral juxtaposition of flow behavior. This can improve the general reservoir modeling processes by using accurate spatial data with minimizing the error sources at each processing stages.

Keywords: Facies modeling, flow patterns, heterogeneities, littoral sandstone

INTRODUCTION

Characterization and modeling of siliciclastic shallow-marine sandstone reservoirs are challenging because of the various scales of heterogeneity that exist between and within shallow-marine deposits (Abd Rahman *et al*., 2014; Ainsworth *et al*., 2008; Howell *et al*., 2008a; Matthews *et al*., 2008; Stephen *et al*., 2008). Outcrop analogs are more commonly used to improve understanding of the geological system that has controlled production and are used as a quality check on dynamic models which reveal variance in reservoir flow behavior (Enge *et al*., 2007; Pranter *et al*., 2007). Sedimentary rocks usually have complex internal architecture caused by genetic depositional processes and alteration during burial and diagenesis (Alpay, 1972; Hamilton, 1991; Meyer and Krause, 2006; Morad *et al*., 2010; Pranter *et al*., 2007; Willis and White, 2000; Wilson and Stanton, 1994). Where heterogeneities are complex and occur at multiple scales, it is difficult to discern a priori which features exert the greatest influence on reservoir flow behavior or to define averaging rules for flow properties (Willis and White, 2000). Flow simulations of high-resolution outcrop data quantify effects and interactions of different types and scales of heterogeneity (White *et al*., 2004). A variety of both commercial and freely available software can be used to visualize the virtual outcrop. Visual inspection of the data allows improved understanding of bedforms and bedform geometries, the correlation of key surfaces (depending upon resolution), improved understanding of facies geometries and transitions. In addition to qualitative visual inspection, a key utility of the virtual outcrop is the ability to extract quantitative spatial data either manually or in an automated fashion (Pringle *et al*., 2006). In this regards,

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outcrops can provide direct inputs for property modeling (e.g., shale bed length, width versus thicknesses, connectivity) and can be modelled to understand the behavior of a particular type of system. In the studied outcrops, the variance in flow pattern were analysis in different sets of sandstone facies of Nyalau Formation, Sarawak East Malaysia. The final models was analyzed both quantitatively and

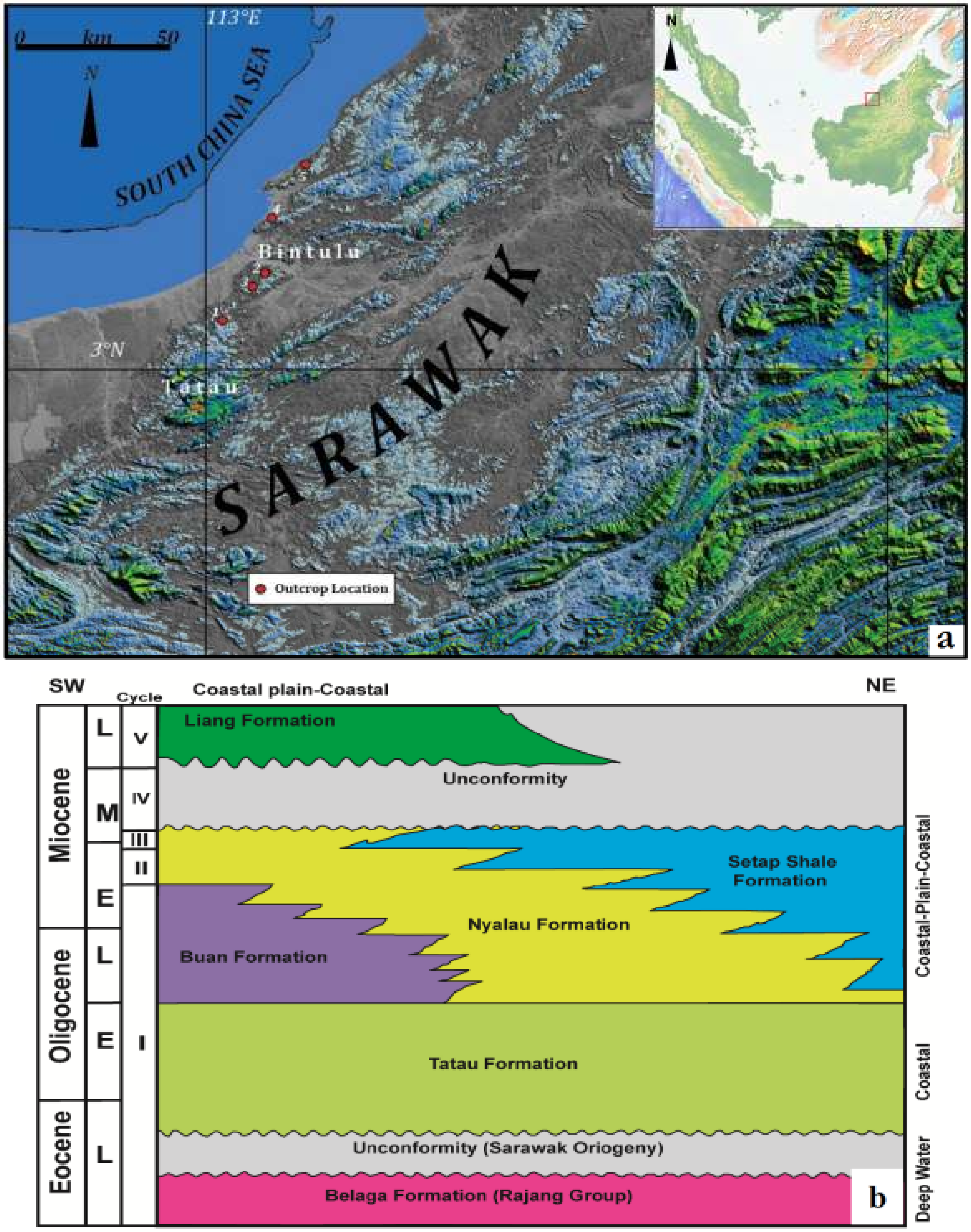

Fig. 1: a) Showing the location map of studied outcrops of the Nyalau Formation near Bintulu, Sarawak, East Malaysia with geological and structural features (Siddiqui *et al*., 2014), b) Stratigraphic framework for the onshore northwest coast of Sarawak, which belongs to the Nyalau Formation, from (Hassan *et al*., 2013)

qualitatively to understand how the different littoral sandstone facies behave in terms of flow pattern.

STUDY AREA

This work study the outcrops in the Bintulu area, Sarawak, East Malaysia bounded by latitudes 03° 20' N to 03° 15' N and longitudes 113° 10' to 113° 05' E belonging to the Nyalau Formation of Upper Oligocene to Middle Miocene. They are exposed along the shoreline and coastal areas, (Fig. 1a). The oldest rocks in the Bintulu area are the Biban Sandstone, member of the Nyalau Formation which is equivalent to Cycle II and III of the offshore hydrocarbon bearing formation of Late Oligocene-Middle Miocene age (Almond *et al*., 1990). The Nyalau Formation consists predominantly of soft to moderately hard, thinly to thickly cross-bedded sandstones alternating with mud and sandy with coal seams (Liechti *et al*., 1960). All the sandstone-bearing stratigraphy units are interfingering with coal seams and gradually pinch out northeast ward into mudstone-dominated, deep water marine deposits of the Setap Formation (Fig. 1b). The common facies types include hummocky cross-stratified sandstones, flaser, wavy to lenticular bedded facies, herring-bone cross-bedded facies and tabular-to-low angle cross-bedded sandstones. These features are indicative of wave and tidal influence within a shallow-marine setting (Hassan *et al*., 2013).

METHODOLOGY

The manual data extraction involves the manually digitizing points along a surface such as a bed or facies boundary in Reservoir Modeling Package PetroMod®, which is a commercial reservoir-modeling package from Schlumberger that is widely used in the oil industry for the visualization and simulation of subsurface oil-field data. The points can then be stored and exported as individual points or polylines. In the latter, a polyline representing the trace was highlighted on the virtual outcrop. Points along the line that represent bed boundaries are picked and used to generate an outcrop major boundaries. The structural properties of the beds within the major boundaries are interpreted from the photographs and, ideally, calibrated to true field data. Such outcrop data can also be digitized and loaded into the reservoir modeling system as a reservoir (Falivene *et al*., 2006). Building the models involves a series of stages, which are broadly similar to the procedure for modeling a subsurface data set. These are discussed below.

Surfaces: When working with surface data (outcrop), the first stage of workflow is to import outcrop image with scale refinement (e.g., depth = 2000 m) to move the surfaces (and thus the model) into a typical depth regime for a reservoir. Then images were visually checked and tied with field sedimentology for accuracy to mark the major surfaces. The imported data were then used to build a facies, surface-based framework for the modeling. Surfaces form the framework and zone boundaries of the outcrop model represent limits where changes in lithology and petrographical properties occur.

Grids and grid population: After the surfaces are generated and adjusted, they are then used to create modeling zones. The 2D grid was created within each of the zones. The 2D grid is the cellular framework in which all of the facies and property modeling were took place. Grid scale and design was based upon the scale and nature of the geology that was being modeled and there was a degree of flexibility in the way in which a grid can be built. To create a modeling grid, it was necessary to define the grid type, the horizontal and vertical layout and the cell truncation. The resolution selected was usually a compromise between necessary resolution and computer memory limitation. The grids need to be populated with properties; in model, these were facies based. In virtual outcrop models, properties at the outcrop were interpreted and placed directly into appropriate grid cells or added from the sedimentary logs. Each cell in the grid only contains one property, either high, moderate or low quality sandstone. There are a number of different ways that this can be achieved. Grids are normally designed to specifically follow the key geological heterogeneities because they control fluid flow behavior in different sets of sandstone facies. Current limitations of computer hardware and software restrict the number of cells. The grids were often designed with a very large X and Y spacing (e.g., 50 m×50 m = 1 cm×1cm). For example, a model covering 300×42 m (surface scale), may contain as little as 10000 cells. The permeability data to each grid were bilinear interpolated to account for projection and resolution in homogeneities.

RESULTS AND DISCUSSION

The model were analyzed both statically and dynamically. Static examination involved the visual inspection and extraction of quantitative data on different sandstone facies, including the porosity and permeability. Dynamic investigation involves simulating the flow of fluids through different sets of facies to understand how it would behave as a reservoir. For dynamic simulation, we assign the petrophysical properties to the grid cells to populate the model on a facies-based approach. Using petrophysical numbers from outcrops does not necessarily give the desired analog values and sometimes can be difficult to collect correctly due to weathering or accessibility issues. On the other hand, petrophysical data from outcrops can

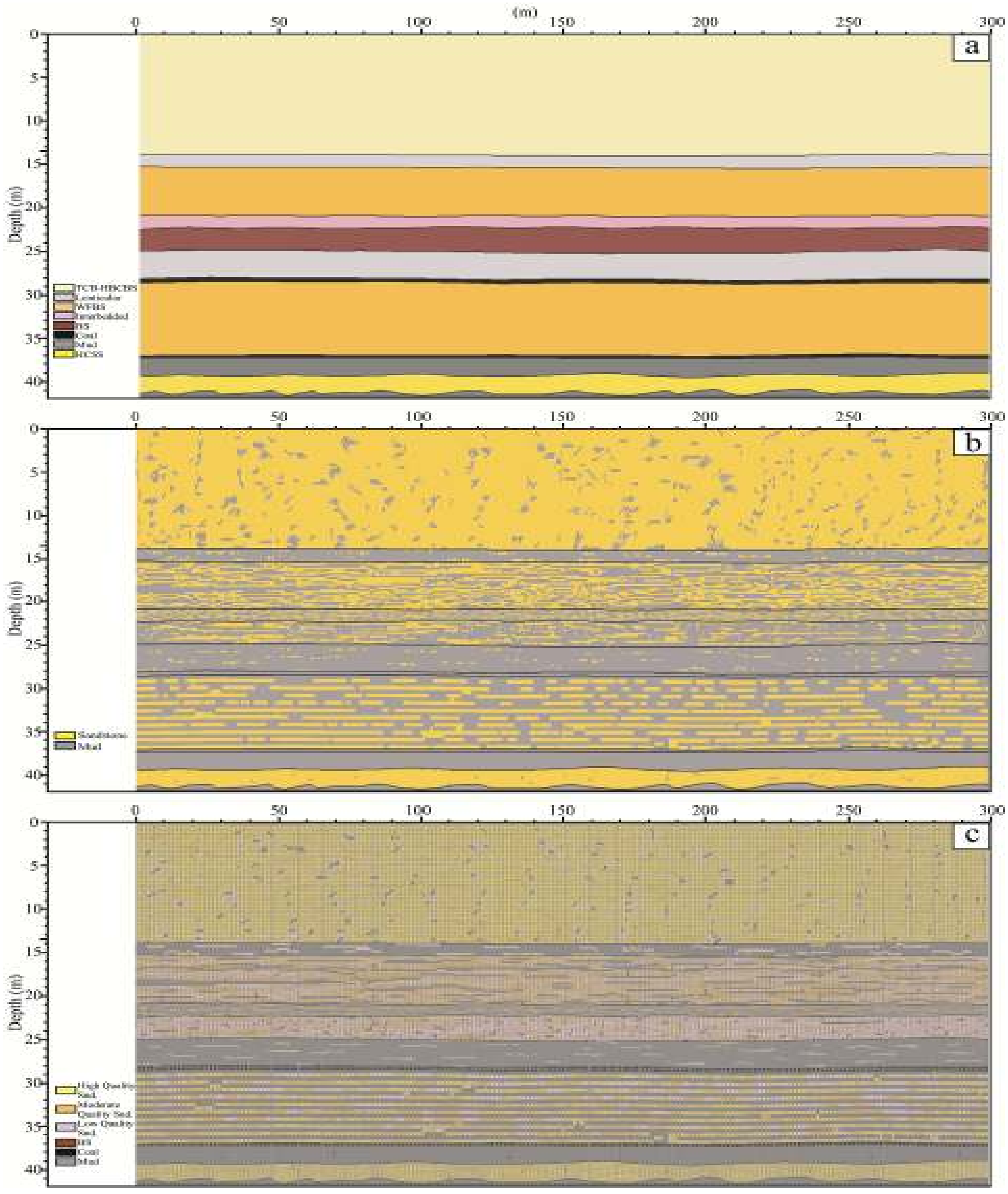

Fig. 2: Different scenarios can be possible to build a flow model; (a): different sandstone facies boundaries with no internal lithologic variability within the facies. Boundaries between each facies represent the most significant stratigraphic features that could act as flow baffles or barriers; (b): distribution of sandstone and mudstone, either continuous shale drapes on lateral-accretion surfaces that could potentially compartmentalize the reservoir into separate hydraulic flow units or discontinuous shale drapes that could create tortuous paths for fluid movement; (c): compartmentalization of lithology, facies, sandstone quality in terms of porosity and permeability and grids and grid population in the cellular framework

give a higher sample resolution and better control, if collected in a systematic manner, e.g., by a facies approach (Forster *et al*., 2004).

It was investigated that, different scenarios can be possible to build a flow model. The most simplistic facies scenario (model 1, Fig. 2a) consists of different

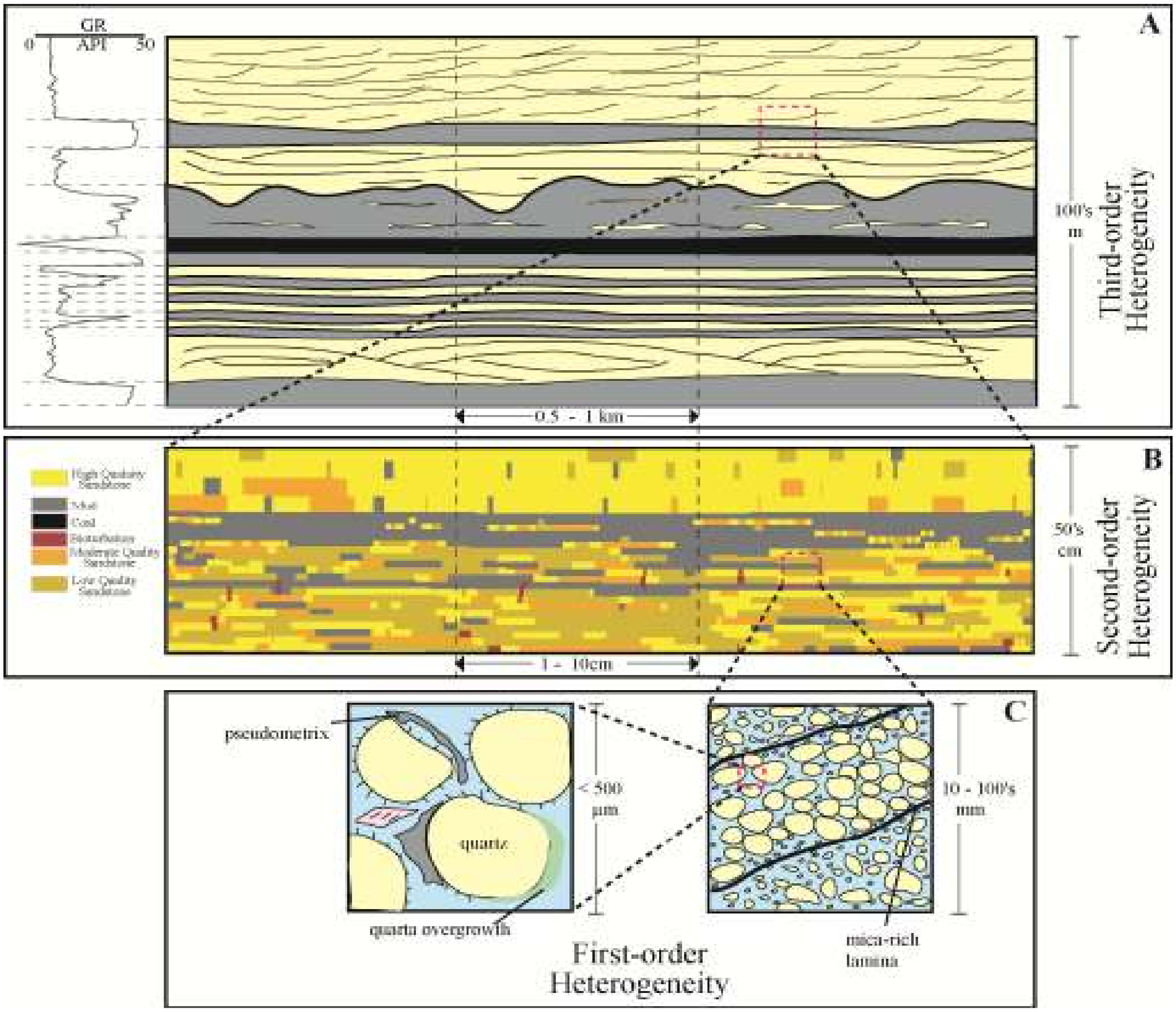

Fig. 3: Generic hierarchy in heterogeneities; A) outcrop scale, with different lithological contrast, can easily be identified through gamma ray log but limited to thin resolution beds, B) heterogeneity at the scale of distribution of quality of sandstone in terms of permeability and porosity variation and C) heterogeneities includes the pore network, grain-sizes and composition, grain packing and diagenetic alteration reveals the first-order of heterogeneities

sandstone facies boundaries with 100% sand and mud. This scenario assumes that there is no internal lithologic variability within the facies. Boundaries between each facies represent the most significant stratigraphic features that could act as flow baffles or barriers (Fabuel-Perez *et al*., 2010). The other lithology scenarios and corresponding model were built using distribution of sandstone and mudstone, either continuous shale drapes on lateral-accretion surfaces that could potentially compartmentalize the reservoir into separate hydraulic flow units (model 2, Fig. 2b) or discontinuous shale drapes that could create tortuous paths for fluid movement. The third scenario is the compartmentalization of lithology, facies, sandstone quality and grids and grid population (model 3, Fig. 3c) in the cellular framework in which all of the facies and property modeling within PetroMod® take place. Grid scale and design is based upon the scale and nature of the sandstone type that is being modeled and there is a degree of flexibility in the way in which a grid can be built. To create a modeling grid, it is necessary to define the grid type, the horizontal and vertical layout and the cell truncation. The resolution selected is usually a compromise between necessary resolution and computer memory limitation. For scenario 3, the mud drapes are restricted to the different quality sandstones (high, moderate and low quality in terms of porosity and permeability) of the accretion surfaces and sand-on-sand contacts exist near the toe of the accretion surfaces (model 3, Fig. 2c).

Reservoir heterogeneities: Siliciclastic shallow-marine sandstone reservoirs are inherently heterogeneous assemblages of different facies and commonly characteristic of sediment texture, stratification type and bedding architectures (Abd Rahman *et al*., 2014; Alpay, 1972; Howell *et al*., 2008b). Numerous investigations of reservoir heterogeneity and its characterization have been made in recent years (Higgs *et al*., 2010; Jordan and Mountney, 2010; Stephen *et al*., 2008; Uličný, 2001). Most of the methods proposed, however, either are too involved mathematically to be practical in routine applications, or require specific information on the reservoir that is not always esily available (Alpay, 1972).

Here, the sandstone quality (in terms of small scale reservoir) of the Nyalau formations display high degree of facies heterogeneity, which are the assemblage of several factors; sediment texture, stratification type, bedding, grain-size, lateral and vertical thickness variation and diagenetic alteration. These sandstones of shallow-marine deposition environment have some significance in subsurface reservoir quality evaluation (Siddiqui *et al*., 2014). Therefore, the order of heterogeneities have been classified in a variety of ways, according to their size or scale. The common categories, used here, are of three generic hierarchy (order) of heterogeneities scale (Fig. 3).

First-order heterogeneities: Elements of first-order heterogeneities includes the pore network, grain-sizes and composition, grain packing and diagenetic alteration. Analysis of all or most of these properties is essential for adequate reservoir description, because these properties provides the database and thus the formation for reservoir description at large scale (Jackson *et al*., 2003).

In the studied outcrops, there is usually a direct relationship between primary depositional lithofacies, reservoir properties and performance. For example, sandstone facies of TCBS and HBCBS become progressively thicker bedded and coarsening upward results more permeable upward. Therefore, use of grain-size analysis and petrophysical analysis provides best interpretation and variation in first-order heterogeneities.

Second-order heterogeneities: Quantitative and qualitative analysis by mercury prosiometer in terms of porosity and permeability reveals the second-order of heterogeneities. All the sandstone facies show high values of porosity and permeability by mercury prosiometer as compare to measurements by image point-count and tiny perm II measurements (Beard and Weyl, 1973). This is because of the fact that all the grain-size variation and diagenetic alteration are deactivated while measuring with mercury prosiometer and tiny perm II. These parameters (micro-scale) cannot easily identified in second-order of heterogeneity. Therefore, the quality of sandstone (in low and moderate quality sandstone) in terms of porosity and permeability show high values, although they have some diagenetic and grain-size variations (that become neglected), results in quality reduction.

Third-order heterogeneities: Elements of field side study interms of lithological thickness, facies boundaries and connectivity and lateral variations are of third-order heterogeneity. These parameters can easily be identified in field observation. This approach is particularly fruitful in terms of lateral and vertical dimensions of sandstone and mud, which distributes the permeable and non-permeable zones analytically at outcrop scale. Statistical methods have also been used to evaluate lateral variations in term of reservoir properties of sandstones. For example, (Stalkup, 1986) considerable lateral variability in outcrop measurements of permeability of shallow-marine sandstones were found. It was analyzed that permeability distribution also be described stochastically rather than deterministically. Therefore, third-order heterogeneity scale can be useful

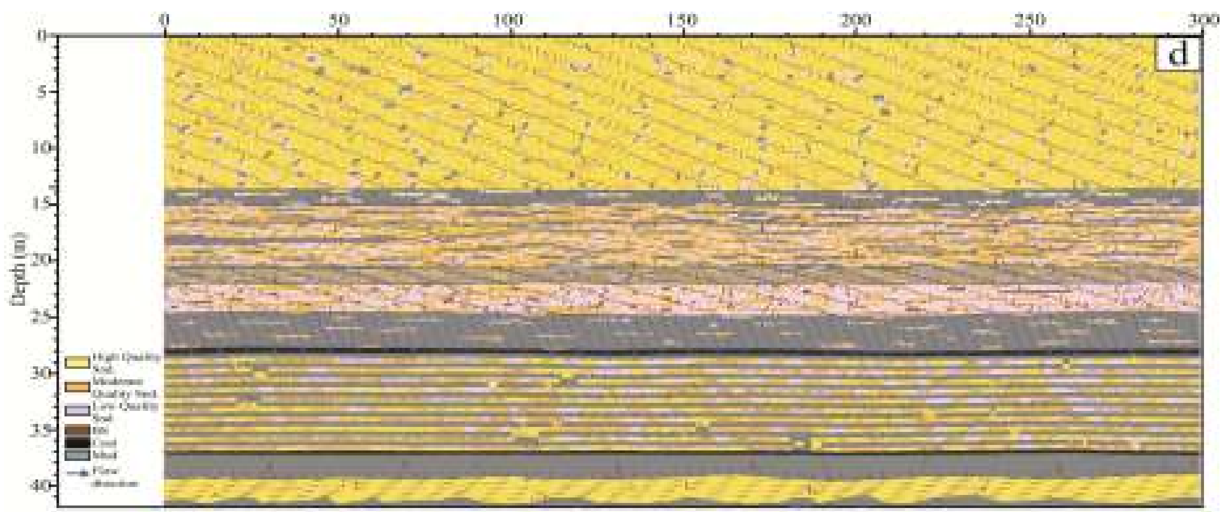

Fig. 4: Flow distribution in each sandstone types by assigning permeability to each grid block with patterns in flow behavior in sandstone facies

in delineating gross architectural elements with recent improvement in data capturing technique, which can be supportive in 2D modeling

MODELING

The final output model, after employment of all scenarios, is the flow distribution in each sandstone types by assigning permeability to each grid block resulted that, there is patterns in flow behavior in each of the sandstone facies (Fig. 4) which is dependent on sandstone quality in terms of three different scales of heterogeneities (Fig. 3). For instant, in more homogeneous cross-stratified sandstone facies e.g., Herringbone Cross-Bedded Sandstone (HBCBS), hummocky cross-bedded sandstone (HCSS)

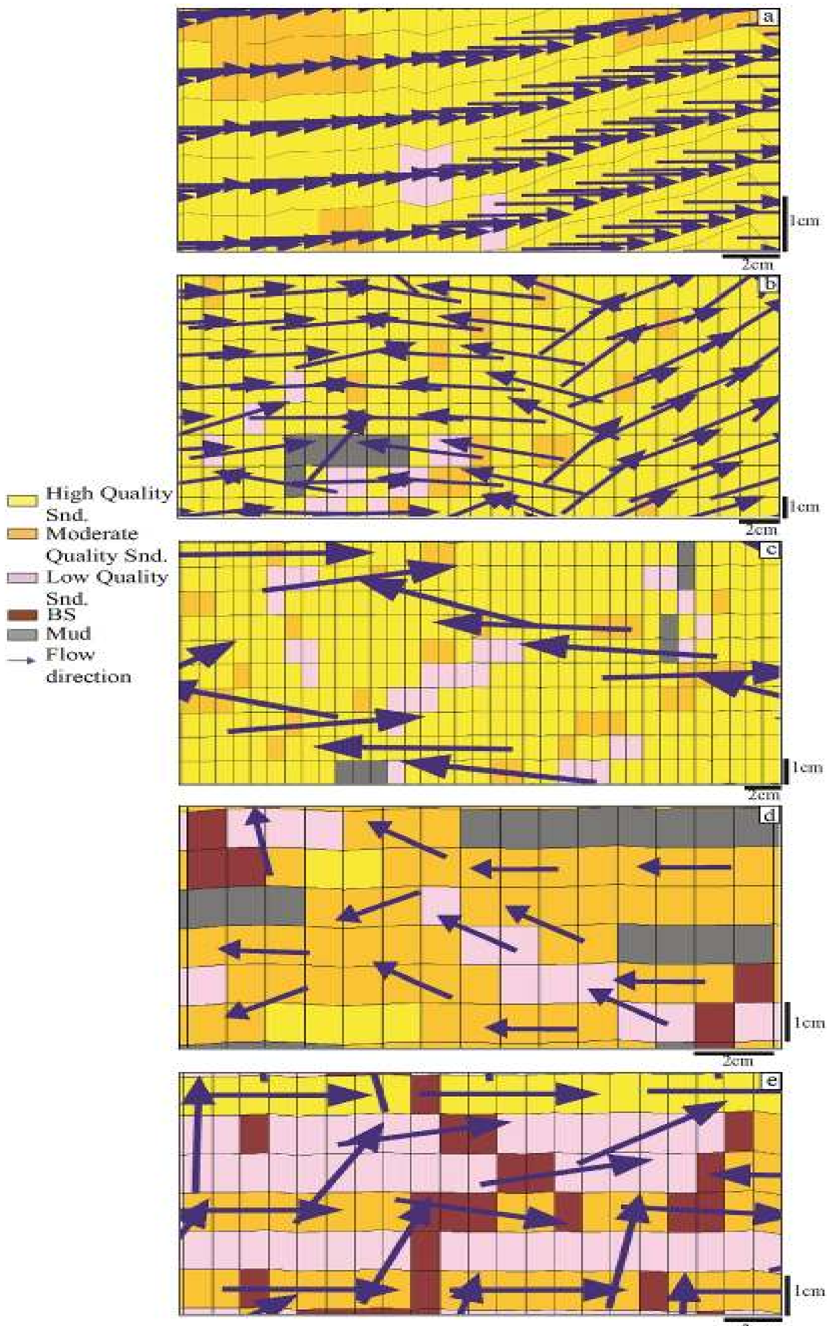

Fig. 5: Flow distribution in different sandstone types with their patterns; (a): HCSS show the distribution of high quality sandstone mostly with linear pattern fallowed by bedding; (b): distribution of sandstone and mudstone, either continuous shale drapes on lateral-accretion surfaces in HBCBS fallow the bidirectional pattern; (c): pattern in TCBS align with the bedded orientation; (d): heterogeneous pattern in WFBS and; (e): BS sandstone with no specific patter in flow due to distortion with bioturbation that my divert the flow or some time can be pervious

and Trough Cross-Bedded Sandstone (TCBS), show persistent spatial correlation of permeability that align with the cross-bedded orientation or straight (Fig. 5a to c). Whereas, in more heterolithic sandstone e.g., Wavy-to Flaser-Bedded Sandstone (WFBS) and Bioturbated Sandstone (BS), lateral variations in permeability show spatially non-correlated patterns over centimeters to tens of meters (Fig. 5d and e). These variations reflect the lateral juxtaposition of flow behavior.

CONCLUSION

The model were analyzed both statically and dynamically. Static examination involved the visual inspection and extraction of quantitative data on different sandstone facies, including the porosity and permeability. Dynamic investigation involves simulating the flow of fluids through different sets of facies to understand how it would behave as a reservoir. The more homogeneous cross-stratified sandstone facies (e.g., Herringbone cross-bedded sandstone, hummocky cross-stratified sandstone and trough cross-bedded sandstone), show persistent spatial correlation of permeability that align with the cross-bedded orientation or straight. Whereas, in more heterolithic sandstone (e.g., wavy-to flaser-bedded sandstone and bioturbated sandstone), lateral variations in permeability show spatially non-correlated patterns over centimeters to tens of meters. This will illuminates the flow behavior in reservoir rock system and can improve the general reservoir modeling processes by using accurate spatial data with minimizing the error sources at each processing stages.

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