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Sedimentological reservoir characteristics of the Paleocene fluvial/lacustrine Yabus Sandstone, Melut Basin, Sudan

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ABSTRACT

Melut Basin in Sudan is regionally linked to the Mesozoic-Cenozoic Central and Western African Rift System (CWARS). The Paleocene Yabus Formation is the main oil producing reservoir in the basin. It is dominated by channel sandstone and shales deposited in fluvial/lacustrine environment during the third phase of rifting in the basin. Different scales of sedimentological heterogeneities influenced reservoir quality and architecture. The cores and well logs analyses revealed seven lithofacies representing fluvial, deltaic and lacustrine depositional environments. The sandstone is medium to coarse-grained, poorly to moderately-sorted and sub-angular to sub-rounded, arkosic-subarkosic to sublitharenite. On the basin scale, the Yabus Formation showed variation in sandstone bodies, thickness, geometry and architecture. On macro-scale, reservoir quality varies vertically and laterally within Yabus Sandstone where it shows progressive fining upward tendencies with different degrees of connectivity. The lower part of the reservoir showed well-connected and amalgamated sandstone bodies, the middle to the upper parts, however, have moderate to low sandstone bodies' connectivity and amalgamation. On micro-scale, sandstone reservoir quality is directly affected by textures and diagenetic changes such as compaction, cementation, alteration, dissolution and kaolinite clays pore fill and coat all have significantly reduced the reservoir porosity and permeability. The estimated porosity in Yabus Formation ranges from 2 to 20% with an average of 12%; while permeability varies from 200 to 500 mD and up to 1 Darcy. The understanding of different scales of sedimentological reservoir heterogeneities might contribute to better reservoir quality prediction, architecture, consequently enhancing development and productivity.

1. Introduction

Fluvial and lacustrine sequencesare among the most complex and heterogeneous sedimentary systems with potential reservoir units below seismic resolution. However, they are of great interest forming potential hydrocarbon plays. Complexity of the depositional stacking pattern, structural framework and barriers are poorly understood which necessitates further detailed reservoir characterization efforts.

Melut Basin is one of the graben structures of the interior Sudan. It is Late Cretaceous to Tertiary rift basin representing the south-eastern extension of the White Nile rift basin (Fig. 1). The sedimentary infill of the basin is dominated by lacustrine mudstones, sandstones and local volcanics of Late Cretaceous to Quaternary age (Schull, 1988). Distribution of sedimentary facies is likely to have been controlled by pulses of extensional faults as well as thermo-tectonic subsidence. The thickness of the sedimentary infill the basin is related to erosion and configuration of the underlying Basement complex. The stratigraphic column in the Melut Basin can be divided into foursequences separated by unconformities (Fig. 2). These are: Lower Cretaceous, Upper Cretaceous, Tertiary and Quaternary (Dou et al., 2007).

Depositional setting of Melut Basin demonstrates a significant degree of heterogeneity in various scales. Understanding the reservoir rocks quality, geometry and structural barriers is the main challenge demanding detailed studies. Fundamental studies and information addressing the aspects of petroleum exploration of Sudan rift basins were published by Schull (1988) and Genik (1993). Studies concerning reservoir heterogeneity and characteristics in

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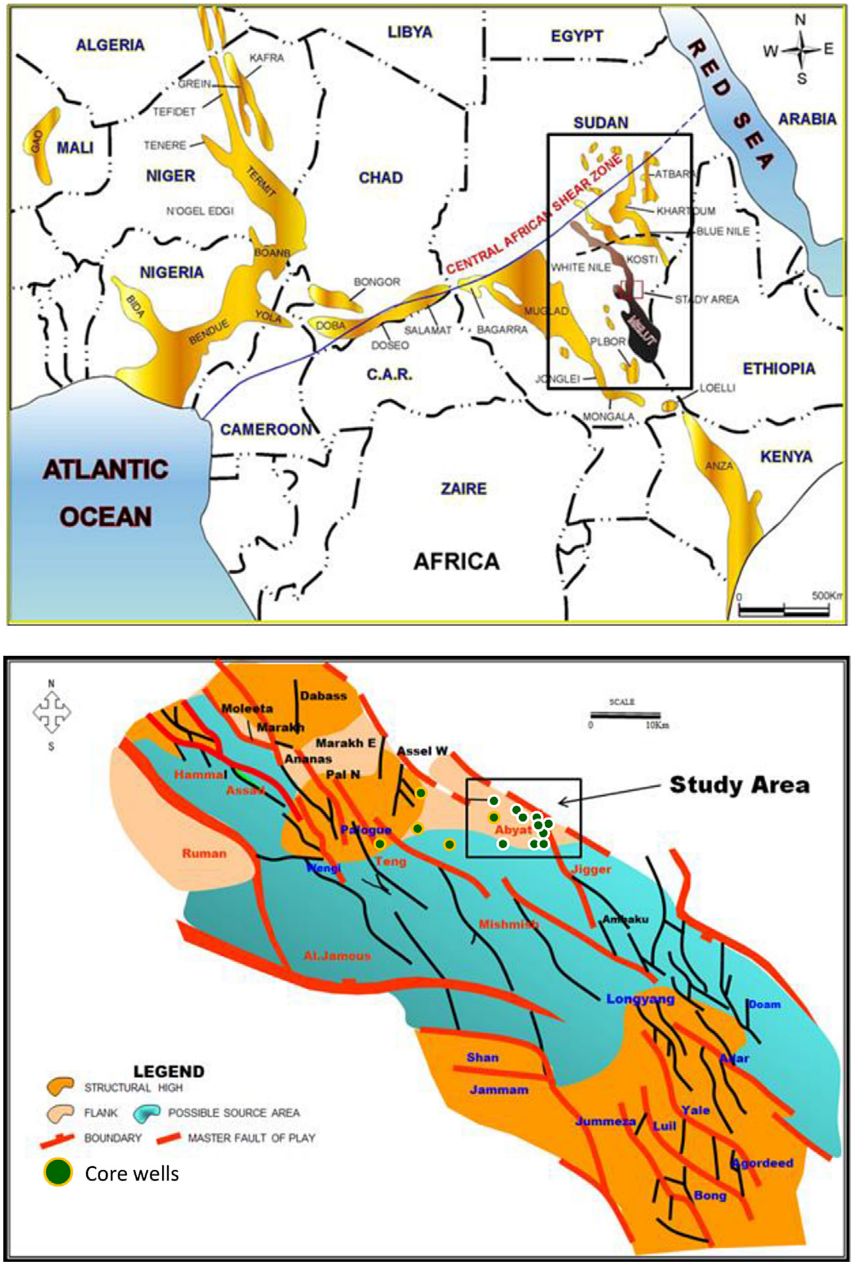


Fig. 1. Location Map of Sudan showing the study area in Melut Basin and well locations.

Melut Basin are very limited (Badi et al., 2006, 2010; 2012; Hussein, 2012). The most recent reservoir characterization and modeling study in Muglad basin was carried out by Kheiralla et al. (2012). This study indicated high degree of lateral and vertical facies heterogeneity which required higher seismic resolution data to be resolved. Petroleum geology of the Melut Basin has also been studied by Dou et al., 2007, 2008.

The current paper is intended to integrate the available core, well logs and seismic data for detailed sedimentary facies analysis, stratigraphic analysis and depositional models. The prime interest is to reveal the reservoir heterogeneity in different scales and relate it to the reservoir quality and productivity.

2. Methodology

The available data in this study consists of nine conventional cores from four wells (about 65 m of core samples), and wireline well logs from 15 wells distributed in the study area. The core data is limited in Melut Basin, therefore, the studied cores were taken from many fields in the basin (Abyat, Palogue) The methods used in this study include subsurface facies analysis from core and wireline logs, petrographic analyses, and depositional environments with implications to reservoir quality.

Sedimentologic interpretation aimed to determine the sedimentary facies and facies associations in different scales of heterogeneity based on core and well logs. Conceptual depositional models were constructed and interpreted based on facies interpretation in Yabus Sandstone. The reservoir quality analysis was carried out through petrographic analysis of thin sections prepared from cored samples of Yabus Formation. SEM and XRD were carried out to support the thin section observation, identify of clay minerals, diagenesis and mineral compositions.

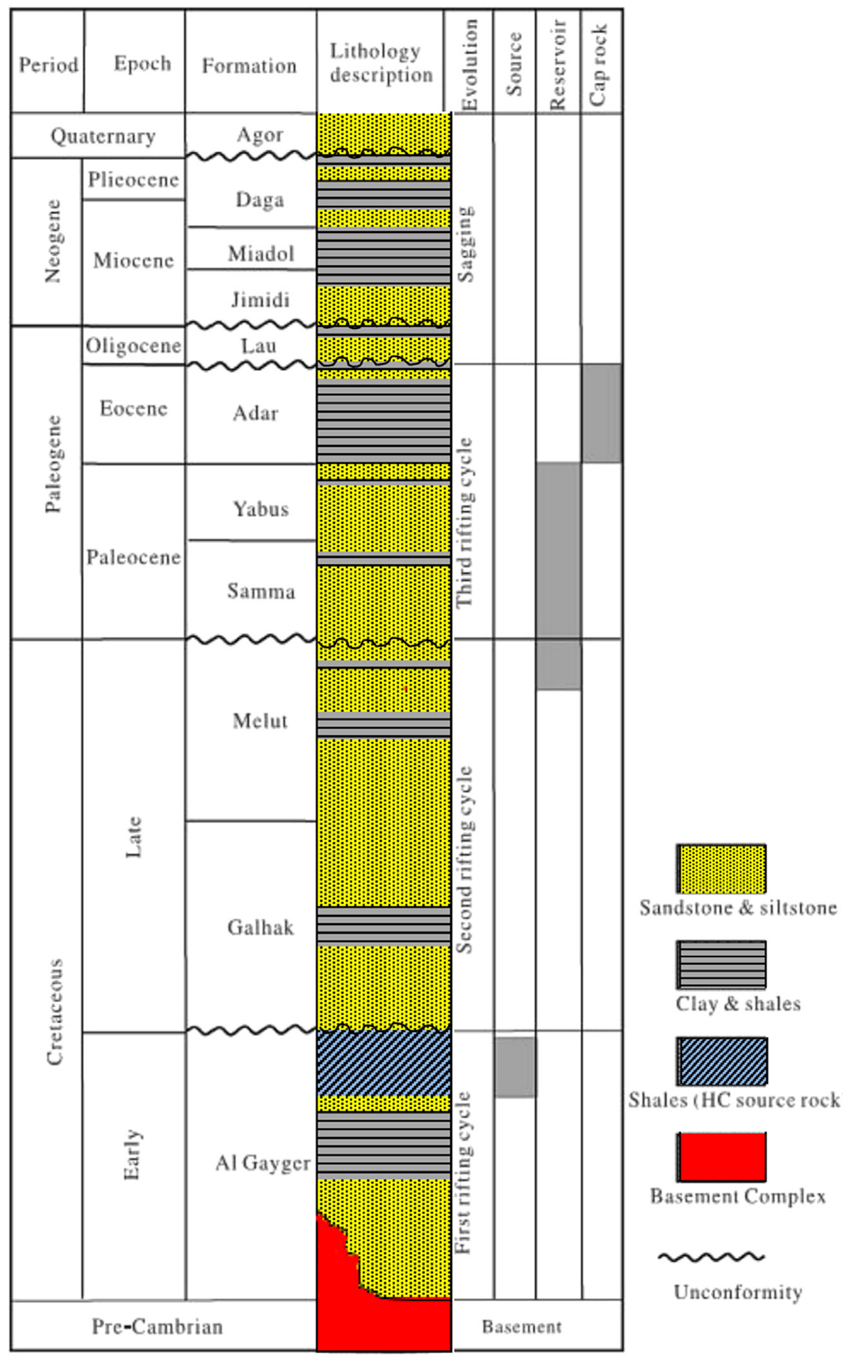


Fig. 2. Generalized stratigraphic column of Melut Basin showing the position of producing reservoirs, source rocks, and seals. The main source rock was deposited during the first synrift stage. Oils have been found in the Paleogene and Upper Cretaceous formations (modified after Dou et al., 2007).

3. Results

3.1. Subsurface facies analysis from conventional core

Detailed sedimentary facies analysis using core description revealed seven sedimentary facies in the Yabus Formation. It comprises mainly continental-derived clastics (sandy, silty lithofacies). Based on the composition and vertical distribution, the identified facies can be grouped into three main facies groups. These are; the coarse-grained sandstone group, fine-grained and argillaceous sandstone group and silty facies group. Each facies group is described below in terms of its main characteristics, association, vertical distribution and depositional environment. Table 1 summarizes the facies description in the Yabus Formation and possible interpretation.

3.1.1. Coarse-grained sandstone facies group (Lf1, Lf2 and Lf3)

3.1.1.1. Description. The coarse-grained sandstone facies group is the main constituent of the cored interval displaying vertically stacked fining-up trend. Individual fining-up sequences display pebbly and erosive base and relatively finer grained and gradational top. Three lithofacies have been identified in this group; trough

Table 1
Summary of the lithofacies in the Yabus formation.

Code	Lithofacies	Lithology	Sedimentary structures	Interpretation
Lf1	Planar cross-bedded sandstone	Sand, fine to very coarse, pebbly	Planar cross-beds	Transverse and linguoids bedforms (2-D dunes) – channel or point bar
Lf2	Trough cross-bedded sandstone	Sand, fine to very coarse, pebbly	Trough cross-beds	Sinuous-crested and linguoid (3-D dunes) – distributary channel
Lf3	Massive sandstone	Sand, fine to coarse	Massive or faint lamination	Sediment-gravity flow deposits (meandering river)
Lf4	Ripple cross-laminated sandstone	Sand, very fine to coarse	Ripple cross-lamination	Ripples (lower flow regime) – levee or floodplain
Lf5	Fine-laminated sandy siltstone to silt and mudstone	Sand, silt, mud	Fine lamination, very small ripples	Overbank, abandoned channel, or waning flood deposits
Lf6	Massive to desiccated mudstone and claystone	Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
Lf7	Siltstone, claystone	Silts, mud	Massive	Prodelta or lacustrine deposits

cross-bedded sandstone (Lf1), planar cross-bedded sandstone (Lf2) and massive sandstone (Lf3) (Fig. 3).

The lithofacies of this group are characterized by white to dark grey sandstone, with some oil stain, medium to coarse-grained, pebbly along bedding plains, moderately to well-sorted, massive (Lf3) to cross-bedded/laminated (Lf1 and Lf2). Kaolinite is occasionally common as a patches and lamination. Locally they are dominated by argillaceous and carbonaceous lamination, with rare conglomeratic and pebbly thin-beds.

3.1.1.2. Interpretation. The coarse-to-medium grained sandstone deposits indicated a fluvial system. The trough cross-bedded sandstone (Lf1) represents a meandering channel and point bar deposits. However, the planar cross-bedded sandstone facies (Lf2)

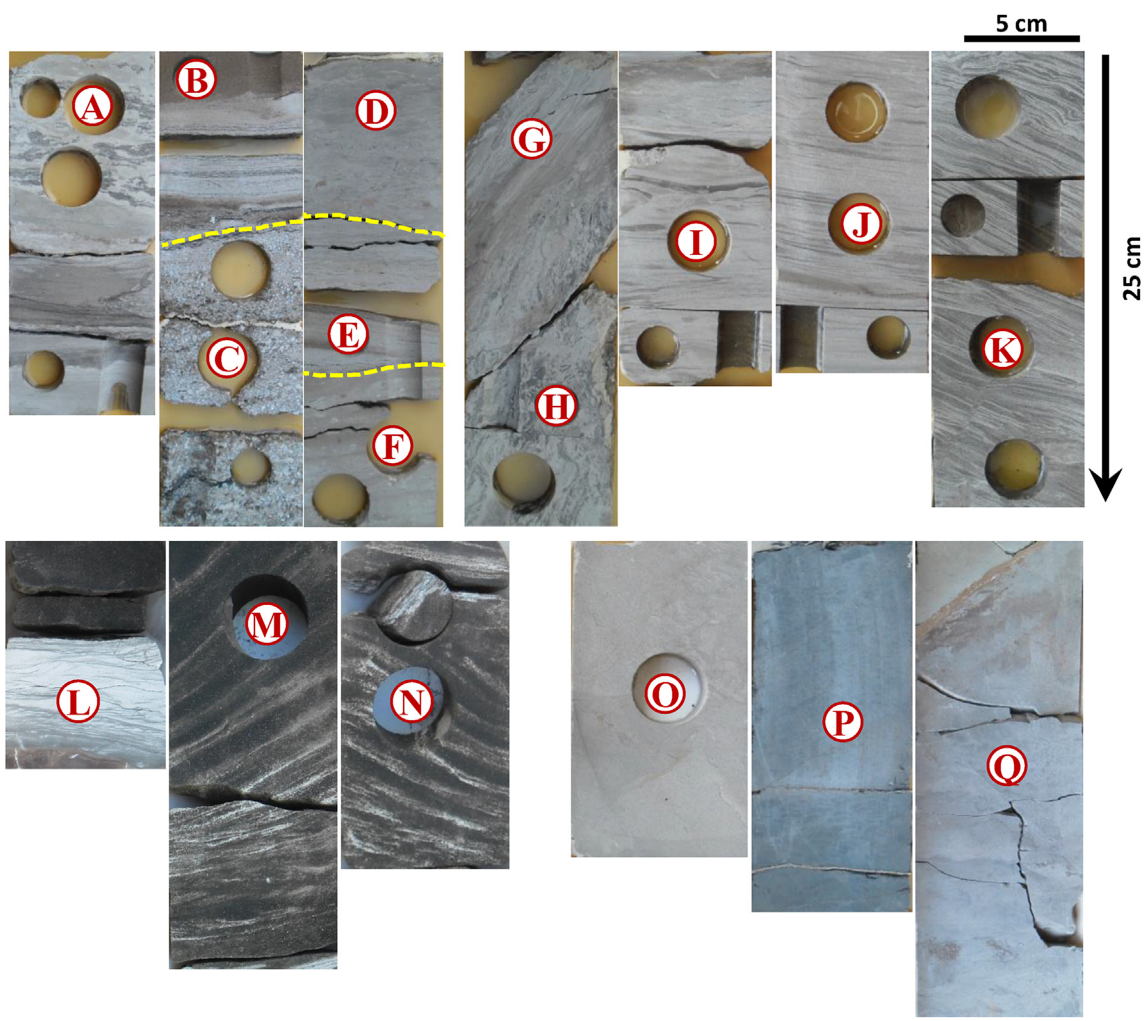


Fig. 3. Examples of the lithofacies identified in Yabus Formation. (A) Trough cross-bedded sandstone (B) Ripple cross-laminated sandstone (C) Very coarse-pebbly sandstone (D) Massive sandstone (E) Planar cross-bedded sandstone (F) Silty sandstone (G) Cross-laminated sandstone (H) Bioturbated sandstone (I) Cross-laminated sandstone (J) Fine-laminated sandstone (K) Ripple cross-laminated sandstone (L) Rippled siltstone with kaolinite cement (M) Low angle planar cross-bedded sandstone (N) Minor scale trough cross-bedded sandstone (O) Sandy claystone (P) Dark grey prodelta shale (Q) Massive claystone.

is indicating a braided distributary channel deposits. Lf3 of massive sandstone could be interpreted as a floodplain deposits within a meandering river.

3.1.2. Fine-grained and argillaceous sandstone facies group (Lf4 and Lf5)

3.1.2.1. Description. Two lithofacies have been identified under this group; the ripple cross-laminated sandstone (Lf4) and fine-laminated sandy siltstone to silt and mudstone (Lf5) (Fig. 3). They are recognized as a white-light grey to light brown sandstone (variably oil stained), fine to medium-grained, locally pebbly and conglomeratic with sharp and erosive bed contacts, well sorted, ripple cross-laminated, locally argillaceous and carbonaceous laminated, with rare to locally significant mottling due to bioturbation, and rarely patchy kaolinitic and micro deformation. Usually they occupy the top part of coarser and sandy facies with an overall fining-up vertical trend.

3.1.2.2. Interpretation. This lithofacies is relatively common in the studied cores from Yabus Sandstone. It usually overlies the coarse-grained sandstone facies on top of fining-up sequence. Repeated fining-upward cycles were noticed in several wells, as the stacked patterns shown in different scales. The lithofacies of this group could be interpreted as a levee or floodplain of a fluvial environment.

3.1.3. Silty facies group (Lf6 and Lf7)

3.1.3.1. Description. The silty facies group is common and representing almost one third of the cored intervals grading upward from the coarser and sandy intervals at the base. It comprises two lithofacies; the massive to desiccated mudstone and claystone (Lf6) and siltstone, calystone (Lf7).

They are mainly characterized by siltstone with color variation from light grey, yellowish brown to reddish brown, massive appearance, mottled, rooted, common oxidized yellowish/reddish brown. Occasionally coarse to fine-grained sand occurs as plugs (Fig. 3).

3.1.3.2. Interpretation. This lithofacies are mainly deposited in overbank or abandoned channels in the fluvial system. The siltstone, claystone lithofacies may indicate a prodelta to shallow lacustrine deposits.

The vertical core profiles were described and interpreted for each well as presented in subsequent section. In these vertical profiles, lithology and sedimentary structures for each facies were categorized by symbols as illustrated in the legend (Fig. 4). An example of the core description and interpretation from one well is presented in Fig. 4.

3.2. Subsurface facies analysis from wire line logs

A combination of log curves were used for facies analysis including gamma ray, sonic, neutron-density and resistivity. Gamma logs of wells were analyzed for the purpose of detecting a clean interval (indication of more sandy) and a dirty interval indicating a muddy interval, given the fact that gamma value is high at muddy units and low at sandy units. Three log motifs were recognized and each motif was assigned to a certain type of lithofacies association. Following is a brief description for log curve trends identified in this study and their possible facies interpretation.

3.2.1. Coarsening-up trend

This trend also known as a funnel shape or cleaning-up trend; it shows an upward decreasing in gamma log reading indicating an upward gradual change of clay content. This trend has been observed in Samma Formation. It is indicating a braided channel deposits underlain the meandering channel of Yabus Formation. (Fig. 5).

3.2.2. Fining-up trend

This trend is also called a bell shape or dirtying-up; it represents an upward increasing in gamma log reading due to an upward gradual change of clay content. Yabus Sandstone showed stacked upward-fining pattern from sand to shale in thin layers due to decrease in depositional energy (Fig. 5). Upward-fining predominates within meandering channel or fluvial point bar deposits, where it represents an upward decrease in energy within the channel.

3.2.3. Irregular log trends

The irregular or serrated trends show a mixed of clean and shaly that have no systematic change. They represent aggradation of shaly or silty lithology, and may be typical of floodplain, lacustrine succession, or muddy alluvial overbank facies. The uppermost Yabus Formation and Adar Formation are indicated this type of irregular trend (Fig. 5).

The core measurements of gamma ray, porosity and permeability were available in some wells in the study. These core measurements were compared to wireline logs to enable facies determination and validation (Fig. 6). It demonstrates the wireline gamma log calibrated with gamma log measured from core; and similarly the core porosity and core permeability curves. In this figure, the gamma log response is clearly identified the lithofacies in Yabus Formation. There are staked pattern of finning upward sequences started by coarse-grained sandstone (low gamma, high porosity and permeability) followed by shaly sandstone and dark shale of (high gamma, low porosity and permeability). This staked pattern is typically indicating a meandering point bar overlain by overbank shale. The estimated porosity in Yabus Formation ranges from 2 to 20% with an average of 12%; while permeability varies from 200 to 500 mD and up to 1 Darcy.

3.3. Sedimentary facies associations

Three main sedimentary facies associations have been identified in the studied succession based on wire-line log characters and core data. These are fluvial, deltaic, and lacustrine facies associations. They are reflecting the major components of depositional systems and indicating a fluvio-deltaic and lacustrine depositional regime. The following part includes a description and interpretation for the main facies association and their components.

3.3.1. Fluvial facies association

Fluvial facies association is the most dominant facies in the studied succession and constitutes up to 80%. It comprises three sedimentary facies; each one is characterized by its sedimentary features and specific depositional setting.

3.3.1.1. Channel fills. Consists of light grey, medium to coarse-grained, unconsolidated to poorly consolidated, sub-rounded to sub-angular sandstones. Fluvial channel fills in Melut Basin are massive (Lf3), parallel-laminated and planar (Lf1) to trough (Lf2) cross-bedded sandstone (Fig. 3). Argillaceous matrix and clay cement are common.

The sandstone bodies range in thickness between 2 and 10 m and are occasionally vertically stacked up to 25 m thick. The channel fill facies are dominant in Samma Formation (Fig. 5). The relatively coarse-grained sediments represent high energy and relatively high sediment supply exceeding the available

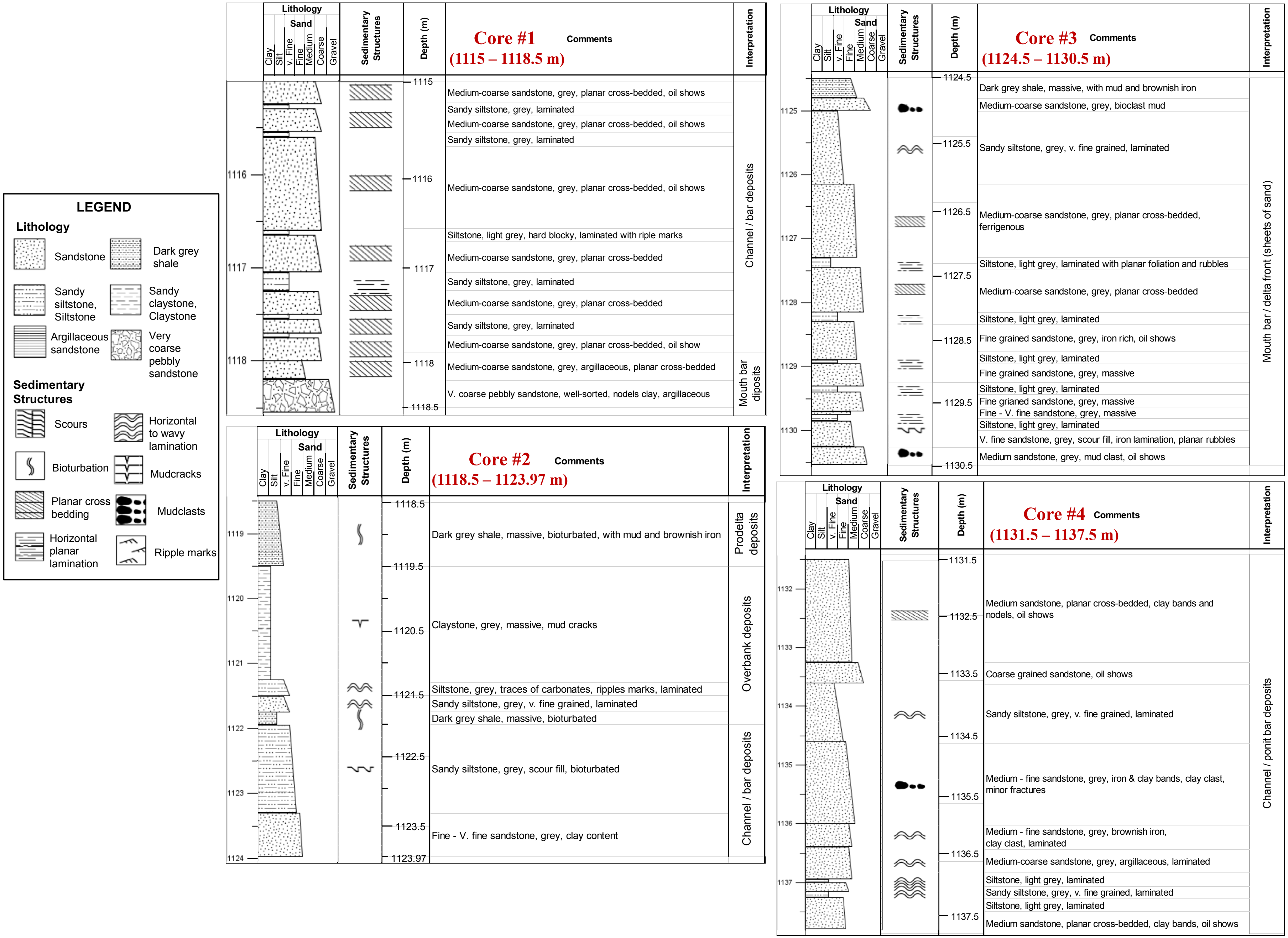


Fig. 4. Example of the core profile description and interpretation for W-1. Symbols used to describe lithology and sedimentary structures are shown in legend.

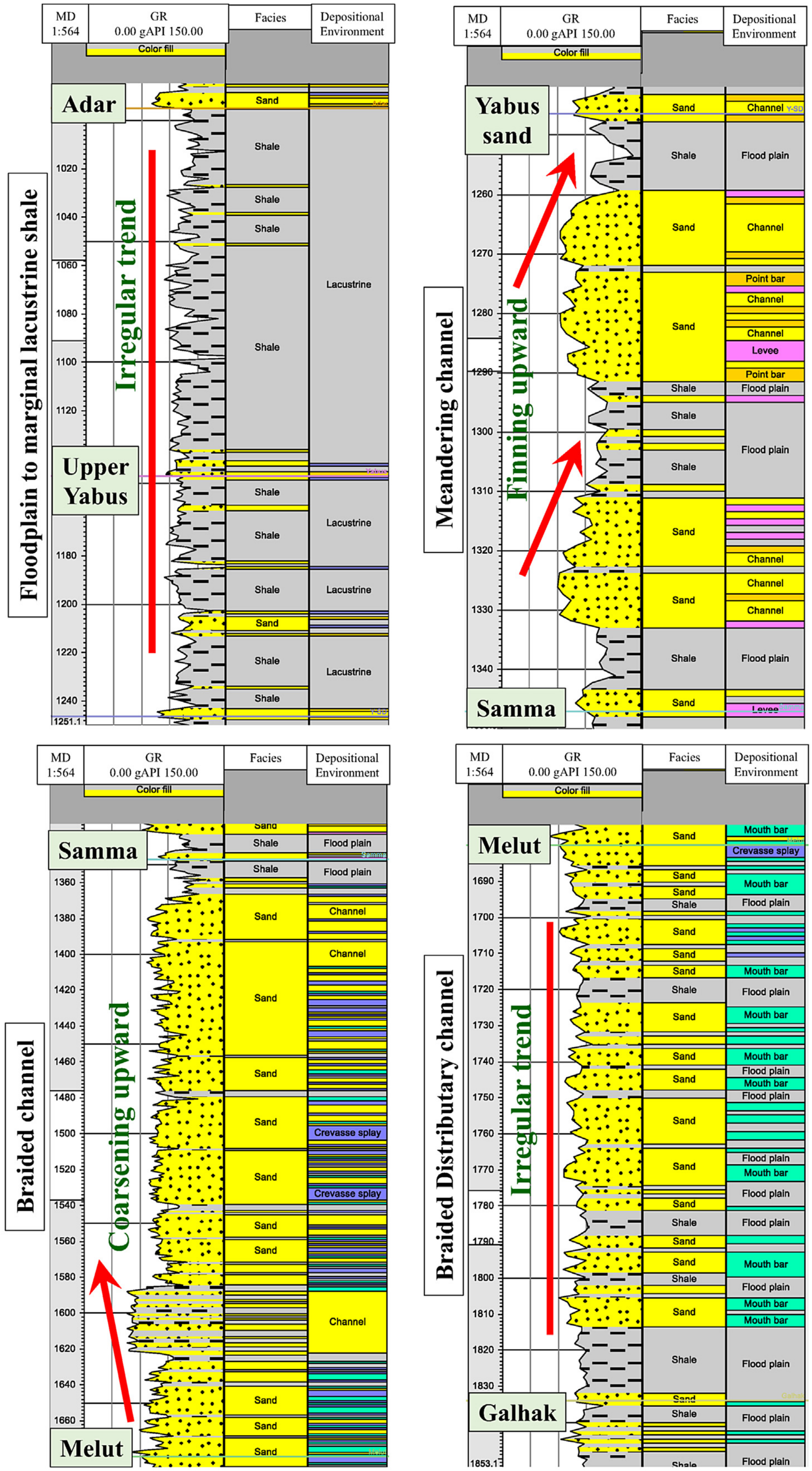


Fig. 5. Gamma ray response to different formations. Irregular trend of floodplain to marginal lacustrine shale observed in upper Yabus and Adar formations. Fining upward staked pattern of meandering deposits observed in Yabus Sandstone; the coarsening upward trends indicating point bar. Coarsening upward of braided channels observed in top Samma Formation. Irregular trend of distributary channels and fine to muddy sandstone facies observed in Melut Formation.

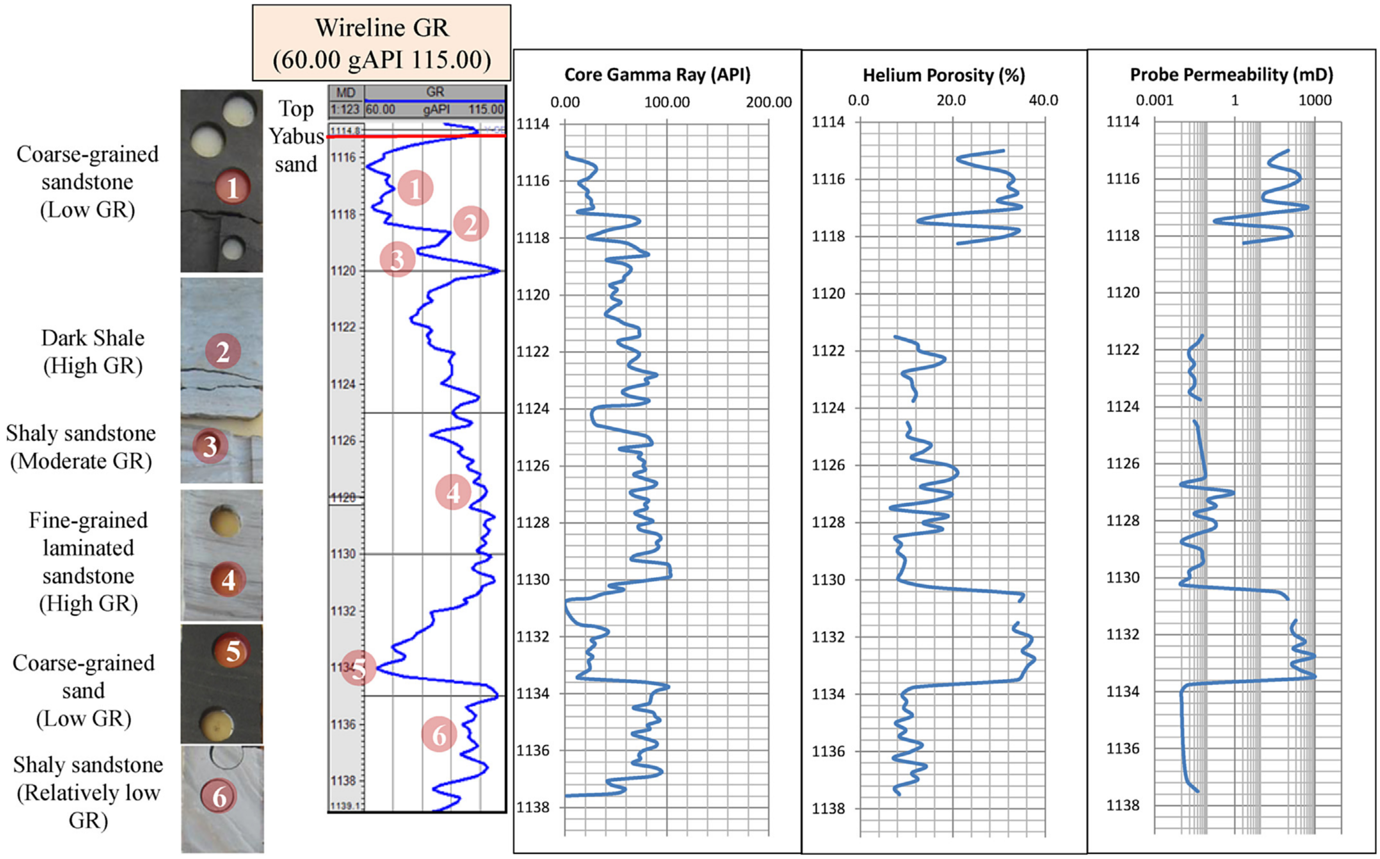


Fig. 6. Demonstration of gamma ray log (from wireline) with gamma ray, porosity and permeability measurements (from core). The lithofacies analysis is achieved based on gamma ray reading.

accommodation space leading to high degree of amalgamation (sheet-like deposits).

3.3.1.2. Point bar. Dark to light grey, coarse to very fine-grained; occasionally rounded to sub-rounded; well to moderately sorted, kaolinitic sandstones. They are massive, low-angle cross-bedded and parallel laminated sandstones (Fig. 3). Locally they are bioturbated and grade into mudstone. They are varying in thickness between 3 and 10 m thick. Ripple marks are observed along with erosive and sharp bases. This facies association is observed in Yabus Formation (Fig. 5).

Stacked fining-upward successions, mud dominated and cross-bedding, with 5–20 m thickness are all evidences for the sandy meandering channels. The trough cross-bedded sandstones resulted from dunes migration, while the planar cross-bedded sandstones are resulted from sand waves migration. The horizontally-bedded sandstones indicate a depositional periods of upper flow regimes (Miall, 1996).

3.3.1.3. Floodplain fines. Comprises reddish brown, massive, parallel laminated, rooted mudstone and shale. They range in thickness between 2 and 15 m. These facies are dominant in the uppermost Yabus Formation (Figs. 3 and 5).

This facies with unconfined sheet geometry indicates distal and inaccessible depositional setting from the main channel due to distance or sedimentary barriers; where deposition accumulated by suspension flow. The high preservation of fine-grained material and upward-fining trend suggest increasing rates of base-level rise that eventually led to flooding of the area during humid climate (Miall, 1996). Increasing the base-level rise will increase the fine-grained sediments preservation upward of each story.

3.3.2. Deltaic facies association

This facies association is recognized in the uppermost Yabus Formation, it represent the distal fluvial facies of distributary channels and prodelta were upgraded to lake setting (Fig. 5).

3.3.2.1. Distributary channels. The distributary channels facies association consists of fine to medium-grained, light grey, rounded to subrounded, unconsolidated to poorly consolidated sandstones. They are built up of fine to very fine-grained, occasionally medium to coarse–grained, sandstones. They have a thickness range between 2 and 7 m. The sandstone bodies are trough to planar cross-bedded (Lf1, Lf2), massive (Lf3), parallel-laminated (Lf4, Lf5) and bioturbated dominated by argillaceous and kaolinite matrix. The base is occasionally paved by coarse intraclasts.

They represent distributary channels which were deposited by traction (high-energy) transport, resulted by uni-directional current flow (Miall, 1996). This relatively small, sinuous channels encased in alluvial plain deposits were prograded into the lake.

3.3.3. Lacustrine shale facies association

Massive to parallel laminated (Lf6, Lf7), moderately hard, sub-blocky to blocky, silty mudstone with kaolinitic matter. They are interpreted as a lacustrine deposits and recorded episodic sedimentation out of suspension in a lake. Internal organization of the lacustrine facies (abrupt boundaries, extensive pedogensis and asymmetric sequences) points to a strong response to base level changes. The lacustrine facies association was observed in upper Yabus and Adar formations (Fig. 5).

Two important assumptions are substantial for lacustrine deposits in the continental rift basins (Miall, 1996). The first assumption is that the enough water and humid climate are essential to form a large lake if topographic configuration is favorable. The second assumption is that the low rate of sediment supply across the rift shoulders relative to subsidence rate during the phase of lacustrine development.

3.4. Depositional environments

The conceptual depositional model of the studied formations is presented in (Fig. 7). The depositional regime during Samma Formation shows widening of drainage basin and increase of sediment supply filling the vertical interval. The dominance of sandy braided channels reflects high sediment supply due to base level fall and low accommodation space. The decrease of accommodation development rates results in slow aggradation and channel sandstones become increasingly amalgamated in Samma Formation. Upwards in the stratigraphic succession (i.e. during the deposition of Yabus Formation), the relative rise of base-level created a shift in the accommodation space and sediment supply. The further upward expansion in basin accommodation supplies areas of sediment supply to be restricted at the upstream. Hence, meander belt facies associations and point bar sandstones are likely to be dominated in lower part of the Yabus Formation. Amalgamated point bar sandstones were commonly observed at the lower part of the Yabus Formation. Upwards the channel sandstones become more solitary and isolated in overbank muds as a result of continuous creation of accommodation space and rise of base level. This condition was concomitant with increase potential to preserve the floodplain fines and decreasing the continuity amount of the channel sandstone.

The accommodation increases against depositional rate enables progression of marginal lacustrine and development of anastomed channels (shallow and narrower channels relative to meander channels) at the uppermost part of Yabus Formation. Anastomed channels were associated with a sedimentation move towards land due to flooding and decreasing rates of aggradation in valley comparing to channel swapping rates. However, the bodies of channel are dominantly filled by fine sandstone thinning laterally; this suggests that these were abandoned gradually because the flow has changed to a new channel (Leeder and Gawthorpe, 1987). Rapid rise of base-level results in flooding of the basin by lacustrine deposits. They show upward-coarsening succession which record progradation of lake-shore-line. This fact can be evident from abundance sandstone with increased thickness enabling deposition of mouth bar deltaic in Samma Formation (Leeder and Gawthorpe, 1987).

Coarse-grained sediments in delta-front might be periodic and swapped with quiescence times to fine-grained by suspension transport (Leeder and Mack, 2001). These fine-grained deposits resulted by a relative rise in the base level implying low-energy sediments. During base level rise, the expansion of basin, there is extension of lake, where distributary channels are developed. Mouth bar as deltaic lobes are deposited on the proximal lakes, while lacustrine deposits prevailed in the distal lake.

3.5. Facies distribution and reservoir heterogeneity

The aforementioned facies associations were interpreted at each

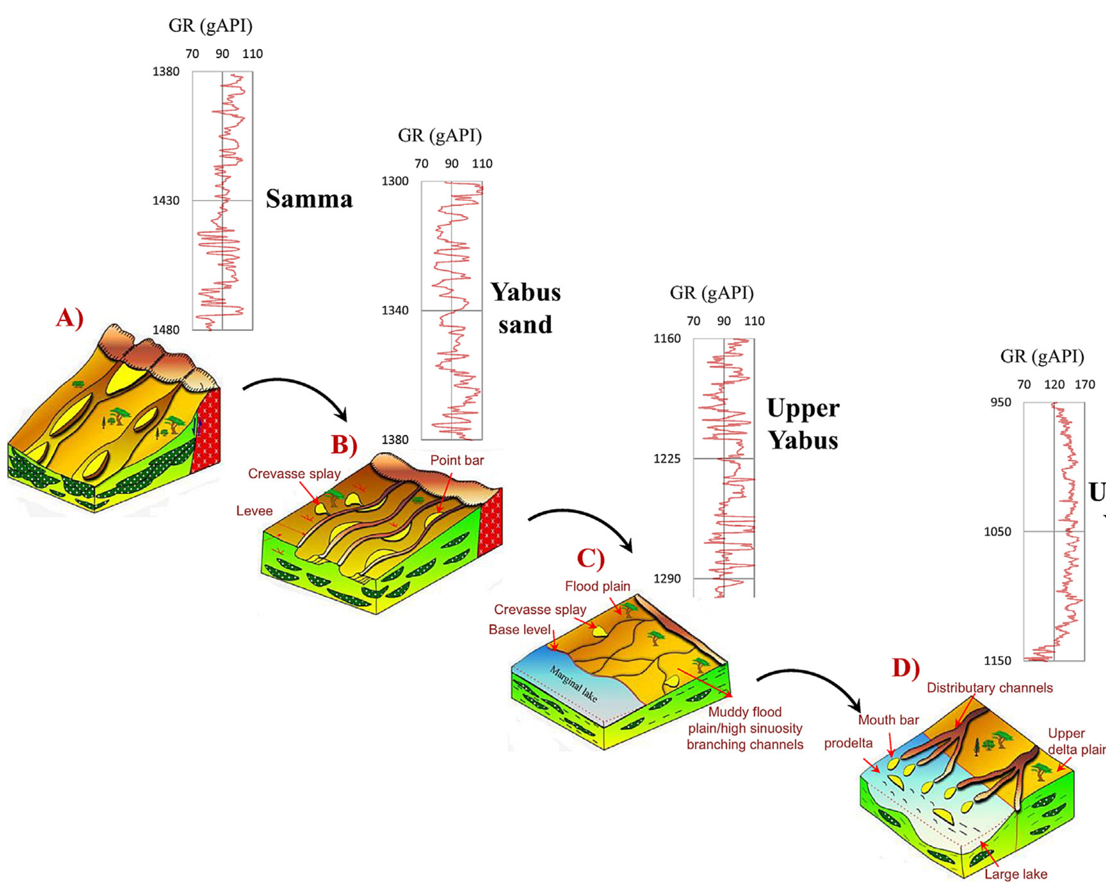


Fig. 7. Depositional models for Adar and Uppermost Yabus, Upper Yabus, Yabus sand and Samma formations.

well based on different wire-line logs and cored intervals. The spatial distributions were carried out in order to identify the lateral and vertical facies changes and to predict the main trends of grain-size variations. All these criteria supported the recognition of the main channel cores and margins, reservoir geometry, seal characters and depositional cycle's hierarchy.

In the study area, channel sandstones of the Yabus Formation are well-developed in southeastern part of the field (around W-1); where clear wedging is shown towards northern part (around W-2) as illustrated in (Fig. 8). However, the thick channel sand is developed in Yabus Formation around W-2. This vertical and lateral distribution pattern of sand bodies in the Yabus Formation provides better insight about sandstone reservoir heterogeneity in macro to meso-sale (well log resolution).

On a large vertical scale of 570 m succession covering the whole formations (Yabus, Yabus sand and Samma), the depositional stratigraphic hierarchy as distinguished in the area commences with; sand-dominated thick vertically-stacked and amalgamated point bars at Samma Formation. They pass upward to thin beds of point bar sandstones with frequent mudstone and shales in Lower Yabus Formation. Then, the succession is more dominated by muddy floodplain/marginal lacustrine shales and mudstones near top Yabus and Adar formations (Fig. 9).

The stratigraphic correlation of the Yabus Formation introduced up to ten subsequences (Yabus 1 to Yabus 10) depending on their presence in each well. This correlation is based on well logs and described cores from Yabus Formation. The stratigraphic zonation indicated that these stratigraphic subunits are completely present in deeper wells such as W-1 (Fig. 10), which is located toward the basin center. However, the lower subunits are missing in the wells existing on paleo-highs. For instance, in W-2 the lowermost subsequences were missing and only Yabus 1 to Yabus 4 subsequences exist as a result of onlaping onto northern paleo-high.

3.6. Sandstone petrography

The sandstone samples from Yabus Formation are characterized by presence of ultrastable minerals such as quartz (>75%) and contain less stable grains such as feldspar, mica and rock fragments. Accordingly, they are mineralogically mature and classified as arkosic-subarkosic to sublitharenite sandstone (Fig. 11)(Folk, 1974). Some samples were classified as quartz arenite with high quartz content (up to 98%). The presence of matrix-rich sandstone in Yabus Formation suggested a high degree of lateral and vertical facies heterogeneity along Melut Basin. It is also indicated that the reservoir quality of Yabus Sandstone is a facies-dependent in the study area.

Detrital minerals are mainly quartz and K-feldspar (Fig. 12.a). Quartz (35–91%) dominates, comprising mainly monocrystalline (27–82%) and subordinate polycrystalline (4–16%) grains. Monocrystalline quartz is dominant over polycrystalline ones. Quartz grains display both straight and undulose extinction. Crystal boundaries within polycrystalline grains are commonly sharp and straight, although irregular in some grains. K-feldspars (1.3–15.3%) are typically highly etched, but trace amounts (microcline) are fresh. Feldspar is rarely found; it is less stable and alters to other minerals such as clays and micas during weathering and transportation. Detrital matrix clays (0.7–21%) have a patchy

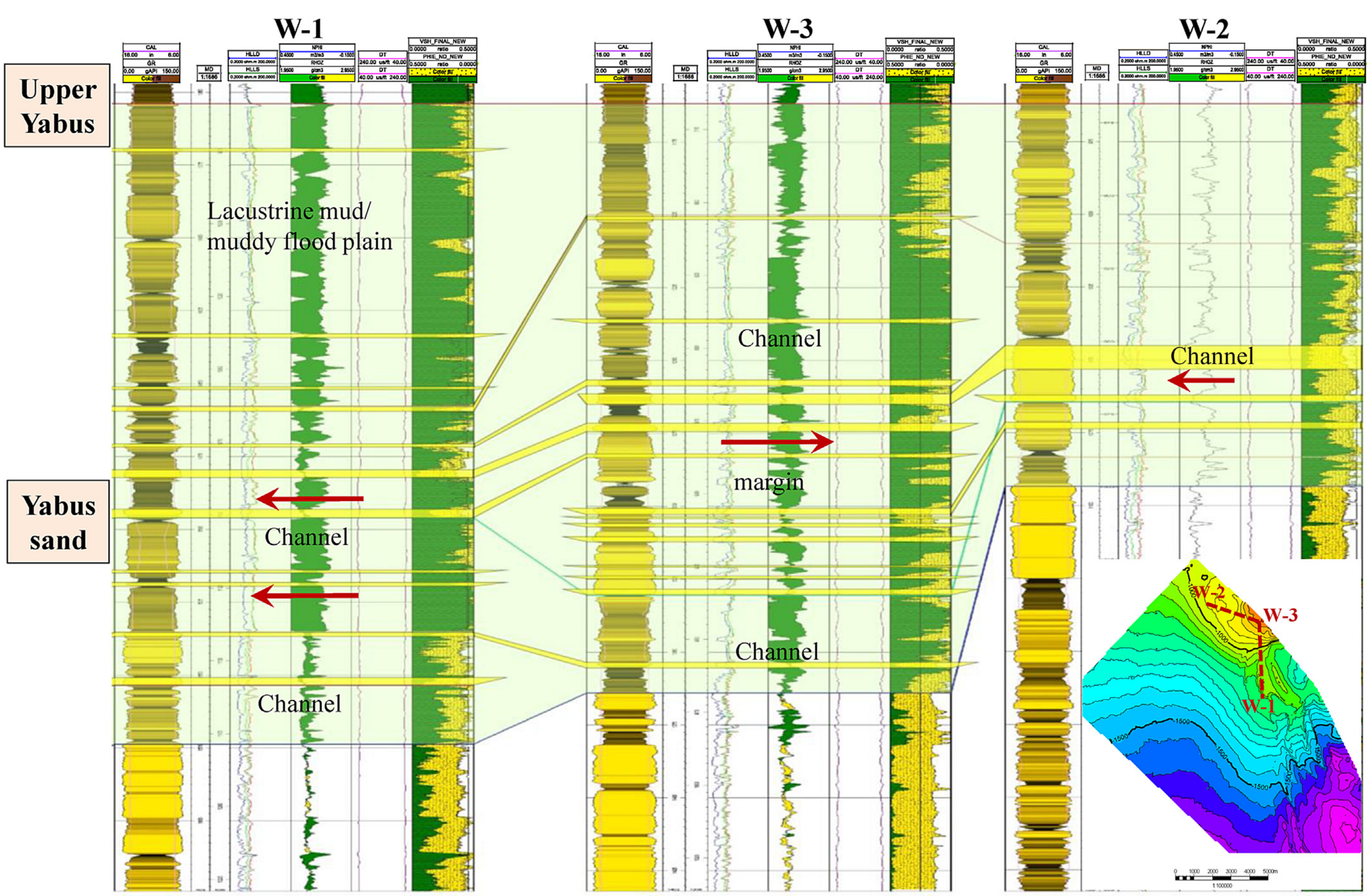


Fig. 8. Spatial distribution of sedimentary facies association and sand bodies' geometry.

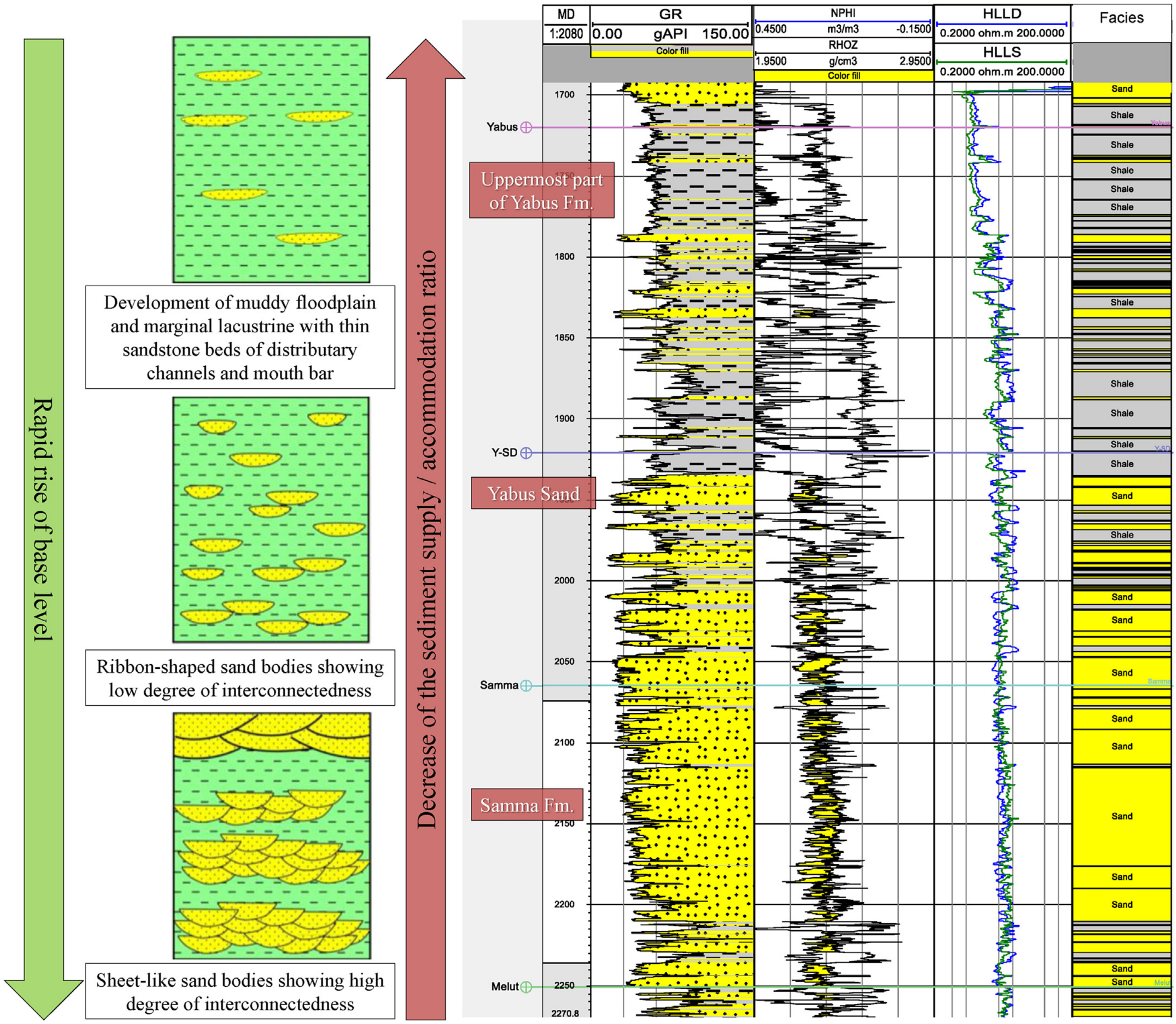


Fig. 9. The effects of changes in the ratio between sediment supply and accommodation on sand bodies' interconnectedness (modified after Curri, 1997). Samma and Lower Yabus Formation showed connected sand bodies, while Middle and Upper parts of Yabus Formation showed low connectivity of sand bodies.

distribution, and are pore filling. Minor amounts of clays adhering to grains surfaces are thought to represent matrix, rather than grain-coating clays.

The studied samples are characterized by low to moderate proportions of authigenic phases which are dominated by kaolinite (0.5–9.5%) as shown in Fig. 12.b. The kaolinite predominantly occurs as an authigenic replacement of detrital clay patches. The kaolinite occurs as chaotic aggregates of booklets and short verms (Fig. 12.c). Minor amounts of kaolinite are replacive after mica. Minor amounts of authigenic silica (0.3–2.0%) occur as thin discontinuous syntaxial overgrowths and small euhedral projections.

Pores are mainly interparticle pore, locally secondary intraparticle pore and minor dissolution pore due to partial dissolution of feldspar (Fig. 12.d, e). Macropores are interparticle pores, moderately common and large relativity.

Because authigenic quartz takes the form of thin discontinuous overgrowths as microcrystalline quartz and the kaolinite takes the form of very finely crystalline pore-filling aggregates of books and short verms (Fig. 12.e), carbonate cementation is low, and therefore authigenic minerals have minor influence on reservoir quality. Meanwhile, the dissolution has minor contribution to the reservoir quality.

4. Discussion

4.1. Vertical and lateral distribution of facies, environments and controls

The Muglad, Melut and Blue Nile are the three major sedimentary rift basins interior Sudan. The tectonic evolution of these basins are likely to have been affected by similar tectonic events (Schull, 1988). The common tectonic and sedimentation characteristics in these basins are:

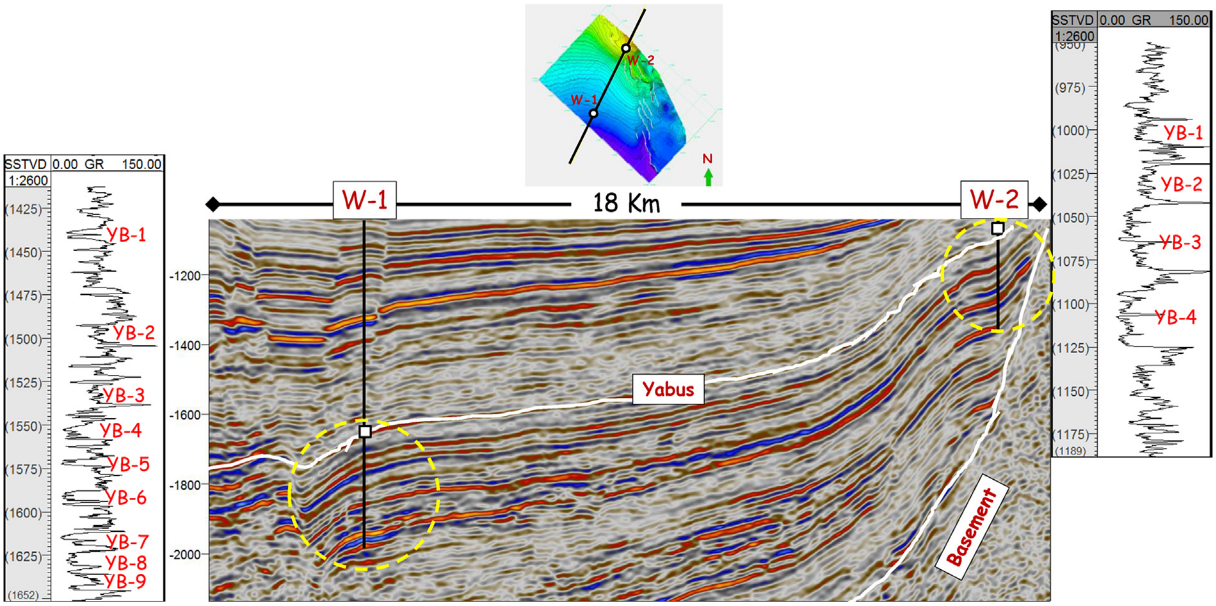


Fig. 10. 10 subsequences of Yabus Formation are completely observed in W-1 due to basin syncline, Yabus 9 is equivalent to the main reservoir Yabus-Sand (Y-SD). While the deeper subsequences are missing in W-2 due to basin palaeo-high (pinch out), Yabus 4 is equivalent to Y-SD.

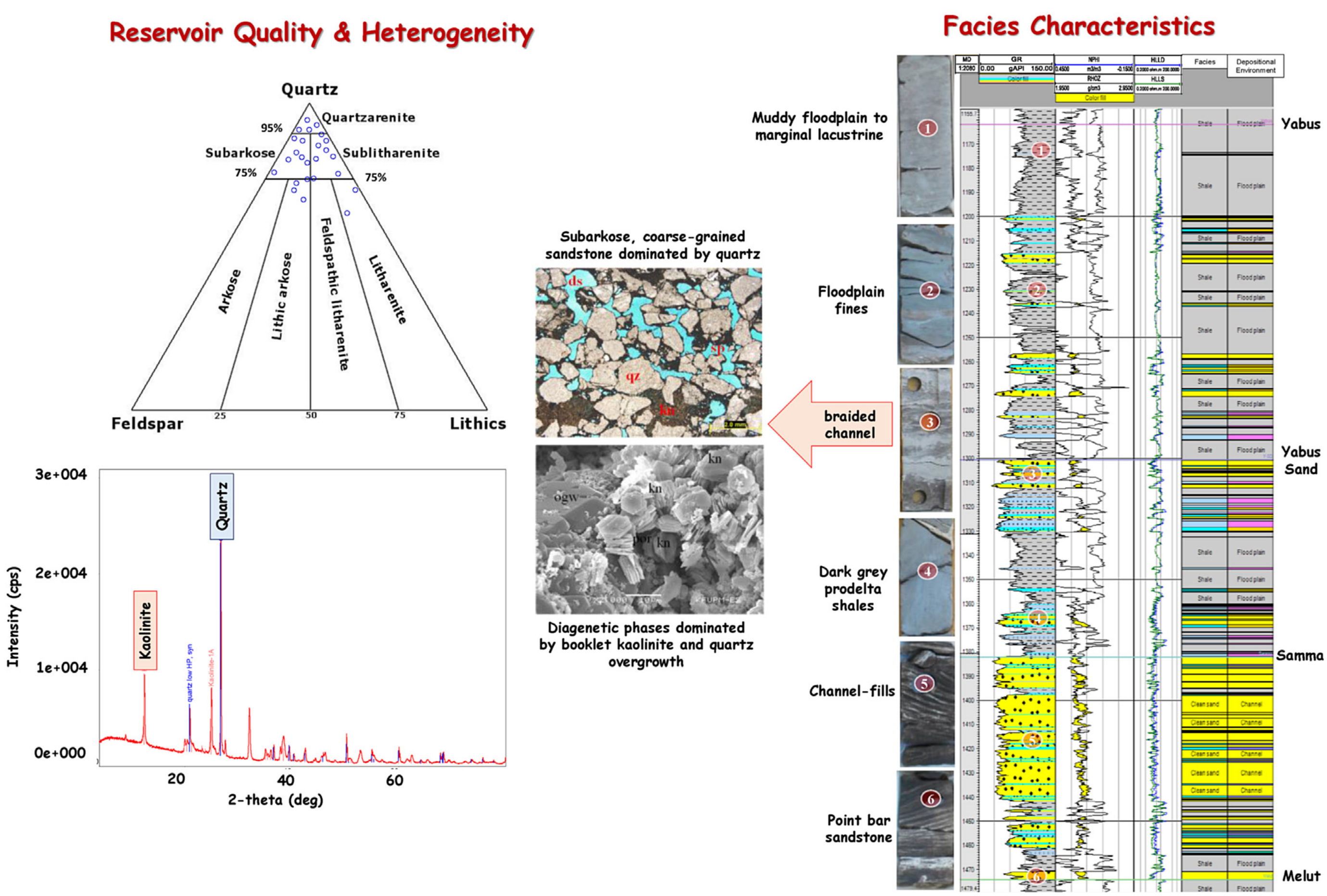
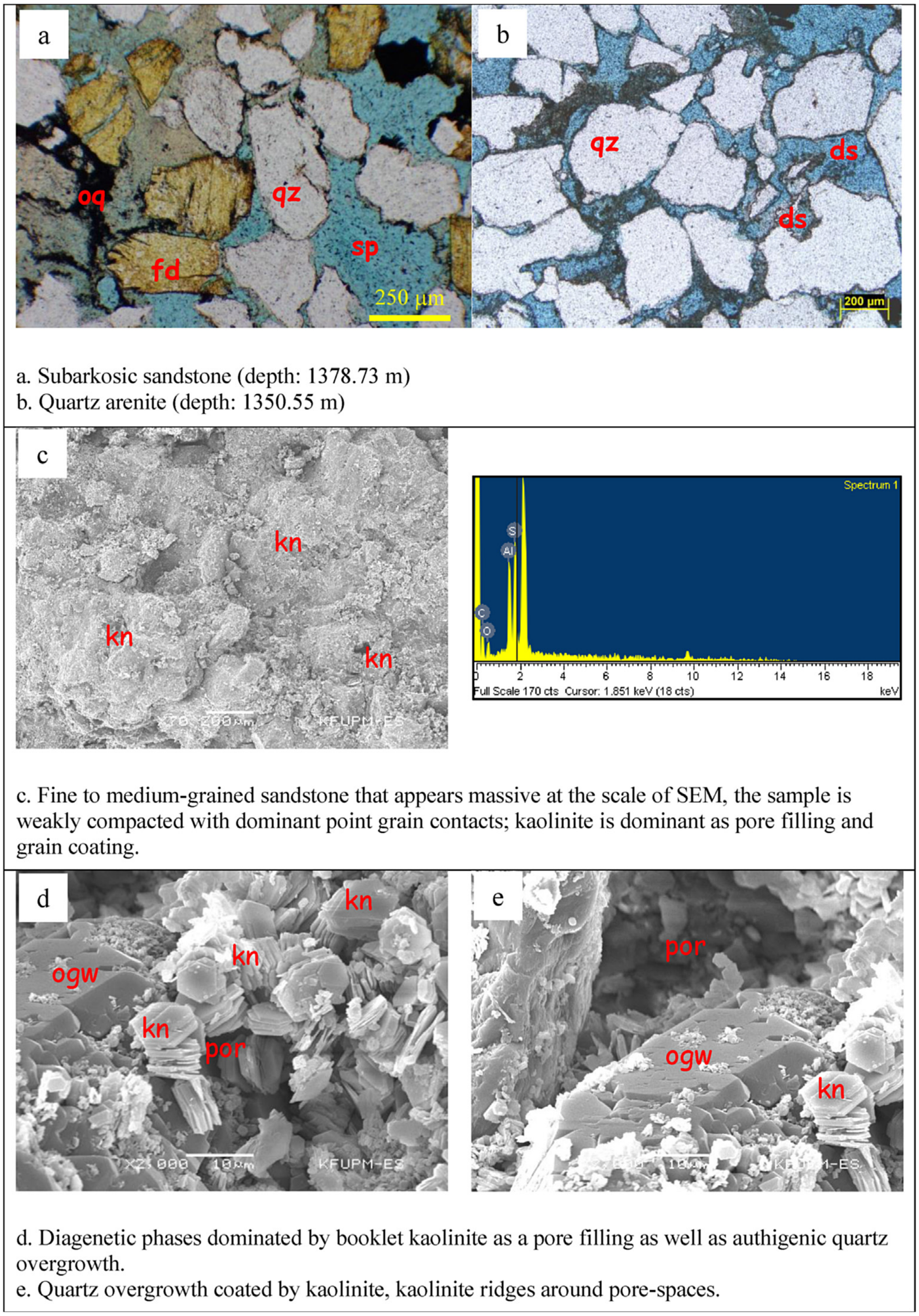


Fig. 11. Sandstone classification and integrated facies analysis from core and well logs.



a. Subarkosic sandstone (depth: 1378.73 m)
b. Quartz arenite (depth: 1350.55 m)

c. Fine to medium-grained sandstone that appears massive at the scale of SEM, the sample is weakly compacted with dominant point grain contacts; kaolinite is dominant as pore filling and grain coating.

d. Diagenetic phases dominated by booklet kaolinite as a pore filling as well as authigenic quartz overgrowth.
e. Quartz overgrowth coated by kaolinite, kaolinite ridges around pore-spaces.

Fig. 12. Examples of thin section and SEM photomicrographs Note: kn: kaolinite, qz: quartz, fd: feldspar, oq: opaque, sp: secondary porosity.

- Crustal extension, thinning & subsidence.
- Repeated three rift phases.
- Cyclic continental sedimentation.
- Three main coarsening upward cycles.
- Alluvial, fluvial and lacustrine facies.

In the Central African basins (Muglad basin), the three rift cycles are well recognized compare to Western African basins (Melut Basin). Basin extension, subsidence, sedimentation rate and accommodation all seems to be higher in Muglad basin than in Melut Basin (Schull, 1988). Consequently, this have a direct impact on the petroleum elements and productivity in these basins. The productivity appears to be higher in Muglad basin than in Melut Basin, however, the facies and depositional environments are more or less similar. Vertical and lateral facies changes and environments reflects the controls of both allocyclic and autocyclic controls (i.e., tectonic, climate and sediment supply); as well as dynamic and static controls within these environments (Miall, 2010). However, the productivity is very low in Northwestern part of Muglad basin. Missing of source rocks, discontinuity of sandstone reservoir, lacking of regional seal and thinning/thickening in middle of basin and flanks are the main challenge in Northwestern part of Muglad basin.

4.2. Implications to reservoir quality

Facies analysis indicated that Yabus Sandstone varies laterally and vertically in facies and stacking patterns (Fig. 11). Macro to micro-scale of reservoir heterogeneity suggested a deposition within a complex fluvial/lacustrine environment. This heterogeneity is one of the significant factors controlling the reservoir porosity and permeability distribution (Fig. 11).

Diagenetic changes such as compaction, cementation, alteration and dissolution are also main controls for the reservoir quality. For instance, kaolinite precipitation, presence of clay matrix and pore-filling are the main factors significantly influence the reservoir porosity and permeability (Bloch, 1991).

Reservoir quality is largely controlled by depositional texture, principally grain size, and diagenetic alterations (i.e. compaction, cementation, and leaching). The Yabus Sandstone is classified as arkosic to subarkosic and sublitharenites and thus is mineralogically mature to sub-mature. In which the macro-scale heterogeneity seems to be controlled by facies sub-environment, geometry and architecture (Miall, 2010). As well as micro-scale heterogeneity controlled by grain size and diagenetic alteration (Aigner et al., 1990). Generally, facies and depositional environments control the quality of reservoir. The facies analysis from core and log studies revealed that the depositional environments of Yabus Sandstone are mainly meandering fluvial to shallow lacustrine lake. Also the observed sandstone and mudstone bodies' thickness and widths tend to vary. Therefore, the sandstone heterogeneity and continuity as flow units within the reservoir are predicted to be varied.

The understanding of reservoir sedimentological heterogeneities might help to better prediction and assessment of reservoir quality and architecture. Consequently this might contribute to reservoir development, recovery and productivity (Slatt, 2009). This study viewed the Yabus Sandstone positively as a potential reservoir, in spite of, the high chemical reactivity and susceptibility of rapid loss of porosity and permeability after burial diagenesis (Boggs, 2009). However, secondary porosity enhancement and hydrocarbon production in such sandstone are usually predictable. Yabus Sandstone shows highly variable reservoir quality, pore-filling kaolinite, late-stage calcite, and cement, which substantially reduced porosity. Appreciable primary porosity might have preserved, however, by formation of early clay coatings and rim that retarded compaction and further cementation. Secondary porosity is present in varying degrees throughout this sandstone as a result of partial or complete dissolution of detrital grains. On balance, the range of permeability and preserved primary plus secondary dissolution porosity observed it can be illustrated that the Yabus Sandstone can contain fair-to good quality oil reservoir Melut Basin.

Integrating different source of data from cores, well logs and seismic might provide a great chance to understand the reservoir heterogeneity in different scales. This approach might be applied in other lacustrine rift basins in Sudan, consequently will enhance the oil development, recovery and production.

5. Conclusions

- Integrated facies analysis revealed seven lithofacies in Yabus reservoir of Melut Basin that deposited in fluvial, deltaic and lacustrine environments.
- The lithofacies types, association and sequences and their stacking pattern indicate that Yabus Formation deposited within meandering stream environment whereas Samma Formation was deposited within braided stream system.
- On the basin scale, the Yabus Formation showed variation in sandstone bodies, thickness, geometry and architecture.
- The stratigraphic distribution of facies and environments reflects the controls of both allocyclic and autocyclic controls, namely tectonic, climate and sediment supply; as well as dynamic and static controls within these environments.
- Different macro-to micro-scales of sedimentological heterogeneities (depositional and diagenetic) influenced and impacted the reservoir quality and architecture.
- On macro-scale, the lower Yabus reservoir shows stacked well-connected and amalgamated sandstone bodies. The middle and upper reservoirs, however, show moderate to low sandstone bodies connectivity and amalgamation.
- On micro-scale, Yabus Sandstone types, texture, composition and diagenesis such as compaction, cementation, dissolution and kaolinite clays pore fill and coat all have significantly reduced the reservoir porosity and permeability.
- The understanding of reservoir sedimentological heterogeneities might help to better prediction and assessment of reservoir quality and architecture. Consequently this might contribute to reservoir development, recovery and productivity.

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