

Poro-perm evolution in Oligo-Miocene coastal sandstones: Constraining the relative influence of sedimentary facies, mineralogy, and diagenesis on analogue reservoir quality of the Nyalau Formation, Borneo

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ABSTRACT

The application of enhanced recovery techniques to improve oil recovery requires a critical understanding of the depositional and post-depositional factors that impact fluid flow in sandstone reservoirs. This study combined facies, petrographic, mineralogical, and helium porosimetry analyses to examine the quality and producibility of the subsurface reservoir equivalents (Cycles I-III) of the Nyalau Formation in the underexplored Onshore Central Sarawak, Borneo. The Nyalau Formation consists of medium-to fine-grained, moderate-to well-sorted, and sub-rounded to sub-angular sublitharenite to lithic subarkose sandstones. Three facies associations and eight reservoir facies interpreted to have been deposited within a coast-to-coastal barrier depositional environment were delineated. The sandstones have undergone a wide range of diagenetic alterations, with the primary and secondary pore spaces predominantly occluded by authigenic quartz overgrowths and clay mineral cement. The helium porosity (ϕ_H) and Klinkenberg permeability (K_K) in the reservoir facies widely vary, ranging from 3.0 to 22.14% and 0.003 to 8.283 mD, respectively. However, the weak correlation between ϕ_H and K_K ($R^2 = 0.35$) and petrographic datasets indicate limited diagenetic and mineralogical controls on the porosity-permeability (poro-perm) parameters, consistent with relatively high heterogeneous reservoirs. We inferred that the heterogeneous reservoir properties and fluid flow in the studied analogue reservoir sandstones are dominantly influenced by depositional processes, as shoreface sandstones typically yield better reservoir quality than those deposited within the intertidal reaches. Our data indicate that diagenetic modification and bioturbation exerted lesser control on fluid-flow quality. Nevertheless, the disparity of poro-perm values in samples of the same facies suggest that localised post-depositional modifications can disproportionately affect reservoir quality, regardless of uniformity or variations in depositional conditions.

1. Introduction

The development and production of economic hydrocarbon deposits in clastic sedimentary systems depends on sandstone reservoir quality, which is mainly controlled by important geological processes (e.g., sediment deposition, provenance, diagenesis, bioturbation etc.) that exert varying influences on sandstone's fluid retention capacity and transmissivity, porosity and permeability, and hydrocarbon saturation etc. (e.g., Pittman, 1992; Guillen et al., 2008; Adepehin, 2014; Jiang et al., 2017). These petrophysical properties that are critical for fluid flow and recovery of petroleum in sandstone reservoirs are controlled by the interplay of provenance, depositional environments, primary

mineralogical composition, and post-depositional diagenetic processes at any given burial depth (Ajdukiewicz and Lander, 2010; Morad et al., 2010; Lai et al., 2016).

At shallow depth, these properties are predominantly controlled by textural parameters (e.g., grain size, degree of sorting), bioturbation, and mineralogy, whereas alteration in post-depositional parameters such as temperature, fluid chemistry, cementation, and compaction dominate during burial (e.g., Bjorlykke, 2014; Ola and Adepehin, 2017; Ahfaf et al., 2021a,b). For instance, the porosity and permeability in unlithified sands with limited textural and mineralogical variability (e.g., Gulf of Mexico deep-water Tertiary turbidites) typically decrease with increasing depth due to compactional effect (e.g., Ostermeier,

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1995). Consequently, the porosity-depth trend has been commonly used in hydrocarbon exploration across several basins (e.g., Houseknecht, 1987; Worden and Morad, 2000; Bjorlykke, 2014; Saiag et al., 2016). However, anomalously low porosities (<10%) at very shallow depth (e.g., <0.5 km) have been documented in Borneo (Adepehin et al., 2020), while contrastingly high porosity values at deeper depth (e.g., >3.5 km) have been reported in the North Sea (Ehrenberg, 1993). These deviations of reservoir petrophysical properties from the typical depth

trend in sedimentary basins can be attributed to the complex and variable interplay of depositional and post-depositional geological factors, including mineral composition, grain texture, bioturbation, cementation, compaction, effective stress (pressure), dissolution of primary grains or cement, clay fillings, and fluid chemistry (e.g., Hubbard et al., 1979; Dalrymple et al., 1992; Ta et al., 2002; Plink-Björklund et al., 2008; Legler et al., 2014; Collins et al., 2018).

Previous studies have shown that primary porosity is strongly related

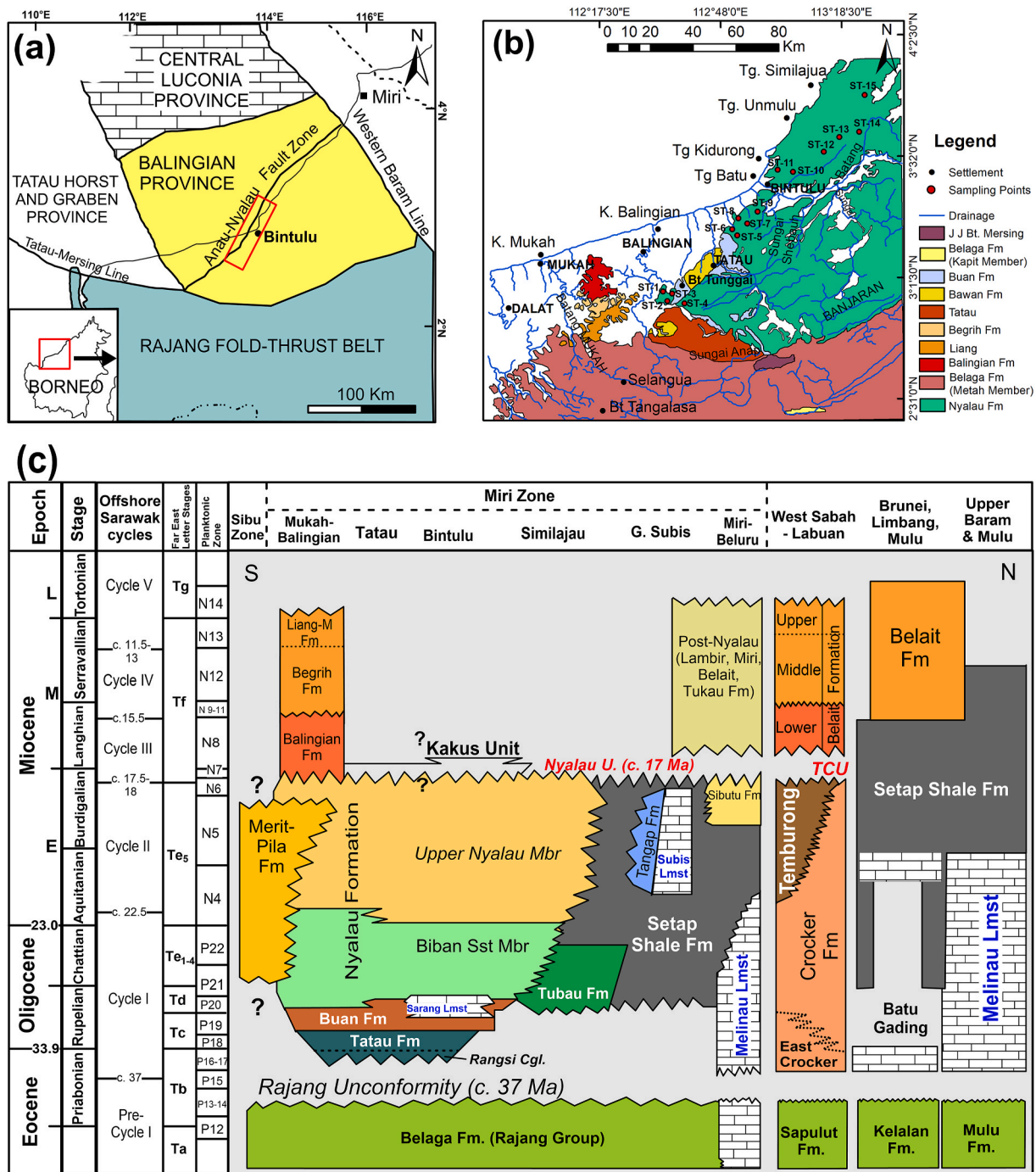


Fig. 1. Geological overview of the study area (a) Map of the Sarawak Basin, Borneo showing the Balingian and Tinjar tectonostratigraphic provinces (Modified from Amir Hassan and Johnson, 2012). The rectangle shows the study area, (b) Map showing sample collection sites and the distribution of the Nyalau Formation and other lithological units in the Onshore Sarawak Basin, Borneo (Modified from Adepehin et al., 2019a), (c) Eocene-Miocene regional stratigraphic framework of NW Borneo showing correlation of the onshore Sarawak formations to the offshore Cycles, Sabah Basin, and Brunei (modified after Liechti et al., 1960; Hutchison, 2005; Jong et al., 2017; Breitfeld et al., 2020). Note that the Sarawak Cycles was adapted from after Madon et al. (2013) and the Far East Letter Stages and Planktonic zones were obtained from BouDagher-Fadel (2015, 2018).

to the sediment's depositional environment and could reach about 40% in well-sorted siliciclastic reservoirs (e.g., Beard and Weyl, 1973; Pryor, 1973; Houseknecht, 1987; Mode et al., 2013; Lai et al., 2016). These studies showed a porosity range of 17–52% in point bar sands, 39–56% in beach sediments, 42–55% in dunes, and 40–45% in barrier island sands. Relatively, the presence of significant muds/clays that constitute reservoir fines in shoreface-subtidal-intertidal environments lowers effective porosity in coast to coastal barrier reservoir sandstones (e.g., Adepehin, 2019; Xu et al., 2021). In addition, the primary textural composition and reservoir quality of sandstones can be significantly modified by bioturbation through either (i) mixing of clay with clean sands, which may reduce the porosity and permeability of sediments, or (ii) destruction of thin clay laminae that may increase the vertical permeability (Bjørlykke and Jahren, 2012). For instance, during early diagenesis at shallow depth, burrowing worms can produce grain coatings of smectite-rich clay that may be altered to chlorite coatings, preserving porosity, and improving reservoir quality at greater depth (Worden and Burley, 2003).

Numerous hydrocarbon reserves have been discovered in shallow marine reservoir sandstones (e.g., Manzocchi et al., 2008; Howell et al., 2008). The shallow -coastal marine sandstone of the Nyalau Formation (Fig. 1) in the Tatau-Bintulu area of east Malaysia is a major and regionally extensive stratigraphic unit deposited by wave and tidal processes (Amir Hassan et al., 2013; Adepehin et al., 2019a, b, c, 2020). The onshore Nyalau Formation is the equivalent of the petroleum-producing siliciclastic Cycles I and II successions in Sarawak offshore in the Balingian Province and Baram Delta Province (Fui, 1978; Amir Hassan et al., 2016; Lunt and Madon, 2017). Although published geochemical datasets indicate organic-rich shales and coals in the formation, the search for commercial hydrocarbon deposits in the Nyalau Formation in the study area – the southern part of Miri in the Baram Delta Province (Fig. 1a), Onshore Central Sarawak remains unsuccessful despite decades of exploration activities (Abdullah, 1997a, b; Madon and Abolins, 1999; Togunwa et al., 2015; Adepehin et al., 2018). The organic geochemical data for the shaly and coaly source rocks of the Nyalau Formation indicate excellent type 1 and II petroleum source rocks, which are dominantly composed of vitrinite macerals that are gradually maturing into the oil kitchen (Adepehin et al., 2018). Siddiqui et al. (2016) delineated five reservoir facies (reservoir units showing inherently similar depositional origin and fluid flow parameters) in the Nyalau Formation based on porosity and permeability data from five outcrops in the Bintulu area. They identified the hummocky cross stratified sandstones and the herringbone cross-bedded sandstones facies as the best reservoir types. Porosity loss in the subsurface reservoir units of this formation is mainly controlled by compaction (Adepehin et al., 2020), whereas polyphase mineralogical and textural reservoir heterogeneities were identified in sandstone outcrops of the Central Sarawak Basin (Adepehin et al., 2019a).

Current understanding of the porosity-permeability (poro-perm) controlling factors and the evolution of reservoir facies in the Nyalau Formation remains limited and the lateral variation of the mineralogical and petrophysical parameters within and between reservoir facies remains understudied. Here, we present reservoir facies analysis, petrographic, mineralogical, and helium porosimetry data from fifteen outcrops of the nearshore-coastal shallow marine deposits of the Nyalau Formation in the onshore Sarawak Basin, Borneo, to constrain the relative influences of depositional and post-depositional processes on poro-perm development in the reservoir facies of the Nyalau Formation. The relative influences of facies characteristics and diagenetic signatures on reservoir quality were assessed, and inferences were drawn for subsurface reservoir quality in the producing offshore reaches of the basin and by implication, other reservoirs deposited in similar geologic settings.

2. Geological setting

The Sarawak Basin is in the north-western part of Borneo (Fig. 1a), which comprises three petroleum-producing provinces - Brunei in the north, Indonesia (Kalimantan) to the south, and East Malaysia (consisting of Sabah, Sarawak, and Labuan basins) to the northwest. The Sarawak Basin is situated between latitude 26 °N to 13 °S and longitude 85 °E to 135 °E (Hall, 1998), and extends for approximately 300 km offshore (Mat-Zin and Tucker, 1999). This basin ranks among the most petroliferous provinces in Southeast Asia, consisting of eight tectono-stratigraphic provinces, including the Balingian and Tinjar provinces in the Central Sarawak (Tjia, 2000). The regional geology of the Sarawak Basin has been detailed in previous studies (e.g., Reinhard and Wenk, 1951; Fui, 1978; Mat-Zin and Tucker, 1999; Madon, 1999; Zheng et al., 2016; Lunt and Madon, 2017). The complex geodynamic evolution of the basin varied between five distinct provinces – the Baram-Balabac Basin, Luconia, interior highlands, north-western Borneo trough, and South China Sea rift (Cullen, 2014). The Baram-Balabac and Luconia basins in the low coastal and offshore represent the transition of the Pan-Borneo from deep marine to shallow marine conditions after the Sarawak Orogeny (Cullen, 2014). However, the Sarawak Basin evolved after the collision of the Luconia Block with the West Borneo basement during the late Eocene (Liechti et al., 1960; Mat-Zin and Tucker, 1999). The rock units in the entire Central Sarawak were significantly affected by the Palaeocene-early Eocene Sarawak Orogeny (ca. 40–36 Ma) and thus, structurally influenced, as evident by the sub-horizontal to nearly vertical bed orientations of the rocks (Fig. 1c, Adepehin, 2019).

The Nyalau Formation (Fig. 1c) is composed of soft-to-moderately hard and particoloured, alternating medium-to fine-grained sandstone, and thin shale lamina in the lower part, while the upper part is characterised by early Miocene coal seams, thick shales, and sand-shale heterolithics towards the top (e.g., Liechti et al., 1960; Peng et al., 2004; Amir Hassan et al., 2013). The succession of the Nyalau Formation is subdivided into two end members: the Biban Sandstone (Lower Nyalau) Member and the Upper Nyalau Member, although the uppermost section has lately been proposed as the Kakus Unit (see, Breitfeld et al., 2020). The sandstone beds are gently folded, generally a few centimetres to <2 m thick on outcrops (Adepehin et al., 2019a), and conformably overlying the Buan Formation in the study area (Fig. 1c). The basal component of the Nyalau Formation is predominantly composed of hard and well-bedded Biban Member, which is mainly sandstones with minor intercalations of argillaceous sediments, few limestone lenses, and abundant foraminiferal (Liechti et al., 1960). The formation shows an essentially upward fining trend with varying sedimentary and biogenic structures in outcrops (Fig. 2). The sedimentary package of the Nyalau Formation is grouped into eight facies and three facies associations that revealed an overall wave-to-tidally influenced coastal deposits (Amir Hassan et al., 2013).

3. Materials and methodology

The studied samples were collected from fifteen Nyalau Formation outcrops across the Selangau-Tatau-Bintulu Road, western flank of Batu Tunggul area south to the Tg. Semalaju area in the north (Fig. 1b). The outcrops were studied on the field, and sedimentary structures were observed and described (Table 1). Weathered surfaces were avoided during descriptions and sample collection. The sandstones were defined and classified into different reservoir facies (RF) based on differences in sedimentary and biogenic structures, textural properties, and bulk mineral compositions. Bioturbation intensity (BI in %) in each sample was calculated as the ratio of burrowed area to the total surface area of hand specimen, where BI >70% is considered intense bioturbation, BI <30% indicates minor bioturbation, and intermediate values between 30 and 70% indicate moderate bioturbation (Baniak et al., 2015; Ben-Awuah and Eswaran, 2015; Adepehin, 2019).

Twenty-four polished thin sections of representative samples (n = 3)

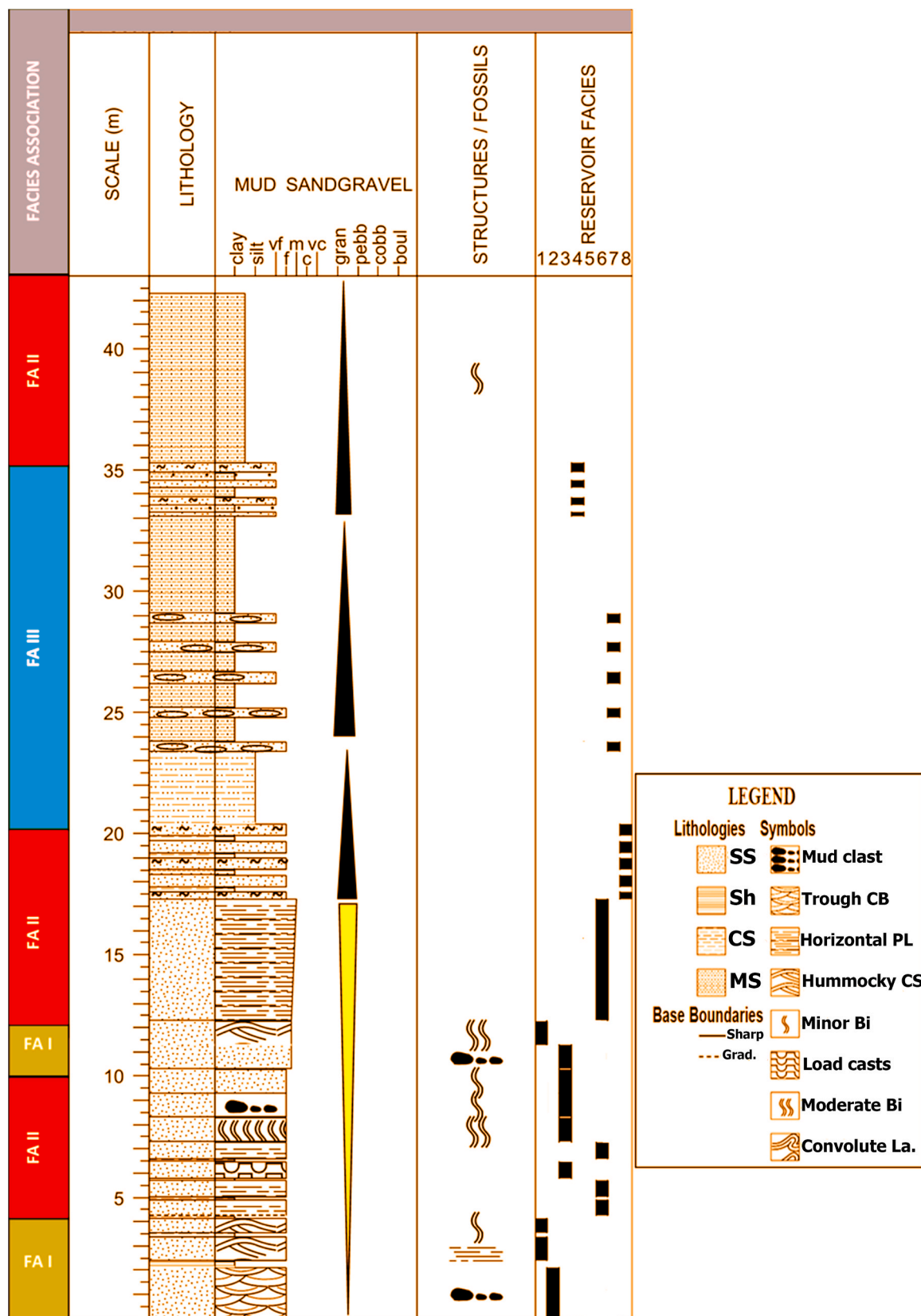


Table 1

Reservoir facies description and interpretation of the Oligo-Miocene Nyalau Formation.

Facies Code	Reservoir Facies	Description	Interpretation
RF 1	Hummocky cross-stratified sandstones	Brownish to dirty white medium- to fine-grained sandstones with occasional whitish clay drapes. The thickness of beds ranges from 0.4 cm to ~1.1m.	Resulted from depositional processes influenced by storm energy that resulted into suspension and lateral traction in middle to upper shoreface coastal marine environment (Dott and Bourgeois, 1982).
RF 2	Trough cross-stratified sandstones	Greyish to brownish, medium- to fine-grained sandstones with varying thickness between 0.5 and 2.2m. Contains a host of rip-out clasts, which are of mud and coal lithologies and laterally discontinuous argillaceous layers.	Likely deposited through the process of saltation when shallow tidal sediment that resulted from the three-dimensional downstream migration of ripples or dunes bedforms in a flowing fluid (Wulf, 1962; Meckel, 1967).
RF3	Massive/structureless sandstones	Occurs as 0.2m–3m thick, well-sorted, sub-rounded to rounded, very fine- to fine-grained structureless sandstones, and sometimes with moderate to intense bioturbation that obscured sedimentary structure. Typified by dominant quartz, rare feldspar, and significant amounts of illite	Resulted from obliteration of initial physical sedimentary structures by burrows of <i>Skolithos ichnofacies</i> in subtidal to lower intertidal environments where sediment movement is relatively slow (Middleton, 1966; Middleton and Hampton, 1976; Dalrymple, 1992).
RF 4	Wavy- to flaser-bedded sandstones	0.5–1.5m thick, loose to partially consolidated, and moderately bioturbated fine-grained sandstones to siltstone, often characterized by internal planar laminations and dark mud drapes.	Probably formed by the actions of oscillated, mud-rich, turbulent–laminar combined flow or through the countering action of strong flood tide acting against flow jointly instigated by strong ebb tide and river action in mixed flats (intertidal zone) (Reineck and Wunderlich, 1968; Dalrymple et al., 1992; Nichols, 2009; Gugliotta et al., 2016; Collins et al., 2020).
RF 5	Silty- to clayey-sandstones	Very well-sorted to well-sorted, sub-rounded fine-grained sandstones with silty and clayey lithological modifiers and bed/laminae thickness of 15 cm - ~1.5m. Presence of white clay patches sporadically in some locations. <i>Diplocraterion</i> burrows were observed among others	Deposited by action of dwindling river flow, perhaps with some marine influence, devoid of larger grained loads. Presence of the suspension-feeding <i>diplocraterion</i> burrows suggest deposition in subtidal to intertidal environment (Mason and Christie, 1986).
RF 6	Horizontally laminated sandstones	Greyish to brownish, angular to subangular, medium- to fine-grained sandstone, typically occurring within coarsening upward sedimentary	Deposition under upper – low flow regime, plane-bed conditions in marginal marine setting (Miall, 1978), or as a sand flat deposit in the head-ward portions of macrotidal

Table 1 (continued)

Facies Code	Reservoir Facies	Description	Interpretation
		package with thickness of 0.4–~1.9m. Devoid of internal structures and typified by <i>Skolithos</i> especially <i>Ophiomopha</i> burrows.	estuaries (Dalrymple et al., 1990).
RF 7	Lenticular bedded sandstones	Sub-angular to well-rounded, low spherical, and well sorted, medium- to fine-grained sandstones. Commonly occur as sand ripples/sand lenses and are typically disconnected and/or isolated from one another by cm-scale argillaceous materials. Bed thickness ranges between 0.1 and 1.2m.	Possibly deposited in mud flats or subtidal environments through slack water by the action of mixed tidal and fluvial processes (tidal rhythm –tidal lack), which favours suspension of argillaceous materials, deposited thereafter on relatively smaller and often disjointed sand bodies (Reineck and Wunderlich, 1968; Dalrymple et al., 1992).
RF 8	Flaser bedded sandstones	Greyish to pale yellowish, moderately sorted to very well sorted, medium- to fine-grained sandstone with BI between 0 and 25. They are predominantly composed of detrital quartz grains in clay dominated matrix.	Deposited in sand flat to mixed flat areas of intertidal zone by the action of a strong flood tide counteracting flow mutually initiated by strong ebb tide and river action in low gradient meandering channel (Dalrymple et al., 1992; Nichols, 2009).

of different reservoir facies were prepared and examined with a Leica DM 4500 P Binocular Microscope. Manual point counting (300 points) was carried out on each slide to construe the relative influence of sandstone composition on poro-perm properties. Detailed mineral textural and morphology features were observed on freshly broken, clean, and gold-coated sample surfaces under a variable pressure scanning electron microscope (VPSEM) equipped with an energy dispersive X-ray spectrometer (EDX) at the Electron Microscopy Unit of the National University of Malaysia. X-ray diffraction (XRD) of the powdered bulk mineral samples was analysed with a Bruker diffractometer using CuK α radiation operating at 40 kV and 40 mA at a step size of 0.025/s. The samples were mildly powdered with an agate mortar and a pestle, packed in cavity mount, and analysed from the angular range of 2–65° 2 θ . Sample preparation for XRD analysis and mineral identification was done after Brindley and Brown (1980) and Moore and Reynolds (1997). The X'pert High Score software was used for peak indexation, mineral identification, and background stripping. Relative mineral proportions in each sample were semi-quantitatively calculated using area ratios of distinctive peaks of individual minerals with quartz as an internal standard. Estimated mineral percentages are not empirical but are used for comparative mineral abundances. The clay minerals were identified and distinguished using the 001 d-spacing of their characteristic peaks on XRD patterns and their morphologies under SEM.

The reservoir sandstone pore systems were characterized using helium porosimetry (He-porosimetry) and Klinkenberg permeability methods. The He-porosimetry is preferred to other poro-perm determination methods because of (i) the ease with which helium molecules penetrate tiny pores owing to its relatively small size, (ii) accuracy, (iii) insensitive to mineralogy, and (iv) leaves the sample available for other usages (Kazimierz et al., 2004; Tiab and Donaldson, 2015). Core plugs of 1–1.5-inch diameter and 1 to 3-inch length of selected samples were plunged, cleaned, dried to constant weight, and kept in plug boxes in a hot oven. The grain/bulk volume of each sample was determined after cooling to ambient temperature. Care was taken to ensure ample

equilibration time in the porosimeter for the diffusion of helium into the narrow pore structures of the samples to avoid experimental errors that could result in excessive grain density and low permeability (Sondergeld et al., 2010; de Oliveira et al., 2016). Measurements were carried out at a calibration temperature of +1 °C. Authenticated results were inputted into the validation worksheet, and grain volume $\leq 0.2\%$ error was deemed satisfactory for porosity measurement. The obtained poro-perm values were plotted and petrophysically ranked as tight, fair, or good

reservoir quality (Zou et al., 2012; Adepehin et al., 2020).

4. Results

4.1. Lithological and reservoir facies descriptions

The Nyalau Formation in the studied outcrops is dominated by clastic sandstones, siltstones, shales, and mudstones with varying thicknesses

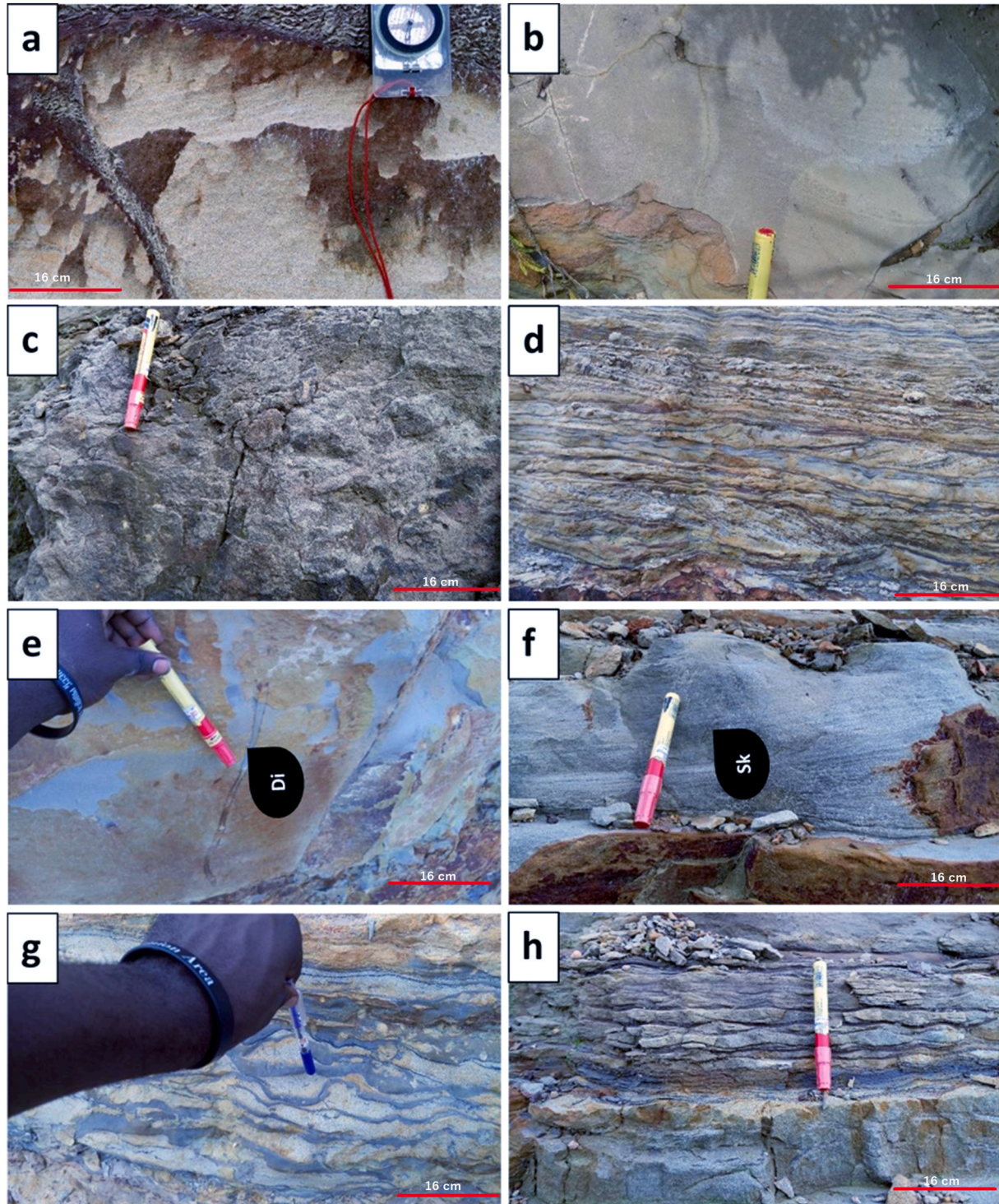


Fig. 3. Siliciclastic reservoir facies of the Nyalau Formation (a) RF1- hummocky cross stratified sandstones facies, (b) RF2- trough cross-bedded sandstone facies, (c) RF3- Massive to structureless sandstones facies, (d) RF4- wavy to flaser bedded sandstones, (e) RF5- silty-to clayey sandstones, (f) RF6- Horizontally laminated sandstone facies, (g) RF7- Lenticular bedded sandstone facies, (h) RF8- Flaser bedded sandstone facies. *Di* = *Diplocraterion* burrows, *Sk* = *Skolithos*.

between ~7.1 and 45.5 m. The lithostratigraphy of the ~42.4 m thick roadcut exposure along Coastal Road Bintulu represents the Nyalau Formation in the study area (Fig. 2). The basal ~17.5 m thick strata are composed of fine-to medium-grained sandstones in an upward-coarsening sequence. The sandstones consist of distinct beds corresponding to four different reservoir facies (Fig. 2), and lithological units, which are composed of thirteen distinctive beds with minor interlayered very thin (≤ 10 cm) argillaceous (shale and claystone) laminae. These sandstones are variably characterised by trough cross-stratification, hummocky cross-stratification, and horizontal planar lamination sedimentary structures with occasional mud clasts (Figs. 2–3). They exhibit minor to moderate bioturbation, with BI ranging from 5 to 30%. The basal sandstones are directly overlain by a ~2.5 m thick and non-bioturbated very fine-to fine-grained flaser bedded sandstone units with interbedded claystones and mudstones in a fining upward sequence (Fig. 2). They are followed by ~3 m thick siltstones that are in turn overlain by ~4 m thick lenticular bedded fine-grained sandstones with alternating mudstones in a fining upward succession. The overlying ~4 m thick mudstone is overlain by ~2 m thick wavy-to-flaser heterolithic fine-grained sandstones and mudstones. This lithological sequence is capped by ~7 m thick argillaceous siltstones.

Based on sedimentary structures, textures and bioturbation imprints (Figs. 2–4), the sandstones of the Nyalau Formation in the study area are divided into eight reservoir facies (RF) (Table 1). These include 1 hummocky cross-stratified sandstones, 2: trough cross-stratified sandstones, 3 massive/structureless sandstones, 4 wavy-to flaser bedded sandstones, 5 silty - to clayey sandstones, 6 horizontally laminated sandstones, 7 lenticular bedded sandstone, and 8 flaser bedded sandstones. The description and interpretation of these facies are summarised in Table 1.

4.2. Facies associations and interpretation of depositional conditions

Reservoir facies that show genetic relationships interpretable as the result of deposition within the same sedimentary sub-environment were

grouped into the same facies association. Thus, three facies associations (FA) were identified, which are, (i) shoreface deposits, (ii) sand flat-to-mixed flat complex, and (iii) mudflat deposits (Table 2). Statistical distributions of the FAs in the studied outcrops are estimated as 26.30% FA 1, 68.00% FA 2, and 5.70% (FA 3).

The FA 1 comprises continuous vertical sequences of RF 1 (hummocky cross-stratified sandstones) and RF 2 (trough cross-stratified sandstone) that are sometimes separated by thin argillaceous beds. It is made up of fine-to medium-grained sandstones arranged in a typical upward coarsening facies succession (Fig. 2; Tables 1 and 2). The RF 2 (trough cross-stratified sandstone) was mainly observed below the RFI, with both reservoir facies commonly separated by very thin mud lamina. These rarely bioturbated sandstones with few intraclasts are interpreted as shoreface complex deposits (Kumar and Sanders, 1976; Dalrymple et al., 1992) that transitioned from the lower to upper shoreface, favouring the development of trough-cross stratification (Fig. 4) that corresponds to zones of breaking waves and wave swash (Fig. 2; Kumar and Sanders, 1976). The presence of hummocky cross-stratification indicates the influence of depositional storms in the shoreface.

The FA 2 consists of massive structureless sandstone (RF 3), wavy-to flaser bedded sandstone (RF 4), silty-to clayey sandstone (RF 5), horizontally laminated sandstone (RF 6), and flaser bedded sandstone (RF 8) (Fig. 2; Tables 1 and 2). These sediments typically comprise horizontal laminated fine-grained sandstone beds (Fig. 3f), often overlain by flaser bedded sandstones (RF 8; Fig. 3h), and grades into lenticular bedded signatures (FA 3). The flaser bedded units from the FA 2 sandstones are often disconnected by thick to thin shale units, and the sequence is commonly overlain by wavy-to flaser bedded sandstone facies. The RF 3 of the FA 2 are well burrowed (B.I. = 40–75) and shows indications of the *Skolithos* ichnogenera (Tables 2 and 3), while *Diplocraterion* characterises the RF 5 components. Though not exclusive, flaser and wavy-flaser bedding are typical characteristics of sandstones deposited in the sand flat to mixed flat (Dalrymple et al., 1992). High BI in the FA 2 sediments is dominantly orchestrated by the *Skolithos* family, indicating subtidal to lower intertidal settings where sediment transportation is

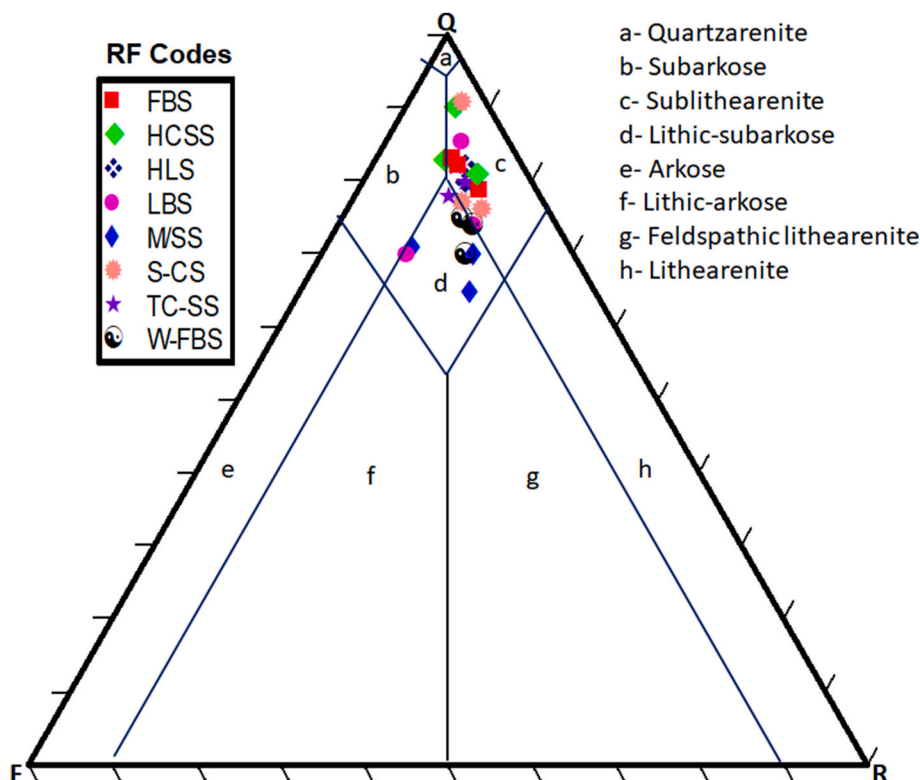


Fig. 4. QFR diagram showing framework composition of twenty-four sandstone samples of the Nyalau Formation (Folk, 1968). Plotted points represent three samples of each of the defined reservoir facies. Note that samples of the W-FBS and M/SS are mainly lithic subarkose, while other samples cluster within the sublitharenite field. Note that HCSS, TC-SS, M/SS, W-FBS, S-CS, HLS, LBS, and FBS denote hummocky cross-stratified sandstones, trough cross-stratified sandstone, massive/structureless sandstone, wavy-to flaser bedded sandstones, silty - to clayey sandstones, horizontally laminated sandstones, lenticular bedded sandstone and flaser bedded sandstones, respectively.

Table 2

Summarised description and interpretation of facies associations with corresponding fluid-flow values and analogue units.

Facies Association	Reservoir Facies	Characteristics	Process interpretation	Comparison to published studies	Mean Poro-perm
Shoreface Deposits (FA 1)	Hummocky cross-stratified sandstone (RF 1) Trough cross-stratified sandstone (RF 2)	Fine - to medium grained sandstones in a typical upward coarsening succession. Typically composed of continuous vertical succession (though sometimes separated) of hummocky cross-stratified beds/bedsets (0.4–1.1 cm) that are overlain by coarser trough cross-stratified beds (0.5–2.2 cm) that are sometimes characterised by clay drapes and argillaceous interbeds, which disconnects it from horizontal planar laminated beds of the RF 6 in FA 2.	Wave and storm influenced suspension sediment deposited between the lower and upper shoreface under fair weather.	This facies association is characteristically consistent with the Lower Shoreface and Upper Shoreface facies successions of Amir Hassan et al. (2013) , although our interpretation of storm's influence is at variance with these authors. Differences in interpretation might have been influenced by sampling bias due to the concentration of the current study on sandstones	$\Phi = 19.96\%$ (n = 6) mD (n = 6)
Sand flat to mixed flat complexes (FA 2)	Massive/structureless sandstone (RF 3) Wavy- to flaser-bedded sandstone (RF 4) Silty- to clayey-sandstone (RF 5) horizontal laminated sandstone (RF 6) Flaser bedded sandstone (RF- 8)	Typically Fining upward succession of dominantly fine-grained sandstone beds (0.2–15 cm) often separated by very thin mud laminae from the hummocky cross-stratified sandstone (RF 1) or disconnected by thin sand laminae from the lenticularly bedded sandstone facies of RF 7. RF 6 sharply or gradationally passes upward to RF 3, which is structureless and often moderately bioturbated, and sometimes upward to flaser bedded sandstone (RF 8), which is in turn overlain by wavy -flaser -bedded sandstone (RF 4) or rarely the RF 7. The RF5 is sharply and basally disconnected from the RF8. Overall, bioturbation intensity varies and typically range from 5 to 75%.	Tide and wave dominated processes conjointly affecting sediment deposition in the sand-flat and mixed flat region under fair weather.	Correlated with the tidal bar facies association of Amir Hassan et al. (2013) and somewhat with the heterolithic facies successions (FS 3 and FS 4) of the analogue Belait Formations (Collins et al., 2018).	$\Phi = 12.77\%$ (n = 15) K = 1.900 mD (n = 15)
Mud-flat deposits (FA 3)	Lenticularly bedded sandstone facies (RF 7)	Occurs as 0.1–1.2 m sand ripples, lenses and beds that are typically disconnected and isolated from one another by cm-scale argillaceous materials (shale, silt, and clay beds). The FA 3 typically passes upward sharply into the RF 5 of the FA 2, and it sharply overlies flaser bedded sandstones and sometimes (RF 8) the Wavy- to flaser- bedded sandstone (RF 4) of the FA 2	Deposited in slack water influenced by mixed tide and fluvial processes in the mud flats or subtidal environments.	Amir Hassan et al. (2013) suggested this deposit was formed in a restricted, low energy, tide-dominated environment, inshore embayment or subtidal flat environment, which is in consonance with our interpretation. Facies with similar characteristics (tide and river influenced bar/channel/delta with low energy) have also been recognised in the Belait Formations in the Baram Delta area (Collins et al., 2018).	$\Phi = 13.44\%$ (n = 3) K = 2.013 mD (n = 3)

Table 3

Variation in poro-perm values with mineralogy and burrow intensity in the reservoir facies of the Nyalau Formation.

Facies code	Nyalau Reservoir Facies	Helium Porosity (%)	Klinkenberg Permeability (mD)	% QFC	Bioturbation Intensity (%)
RF 1	Hummocky cross-stratified sandstones	12.40–15.38 (13.60)	4.690–8.285 (5.891)	Q = 75.04, F = 13.77, C = 11.19.	Minor (5–15)
RF 2	Trough cross-stratified sandstones	8.85–14.37 (12.32)	1.458–1.823 (1.657)	Q = 86.08, F = 6.60, C = 7.32.	Minor (5–10)
RF3	Massive/structureless sandstones	3.26–22.14 (11.46)	0.005–3.828 (1.721)	Q = 87.94, F = 5.60, C = 6.46	Moderate to intense (40–75)
RF 4	Wavy- to flaser bedded sandstones	3.07–4.17 (3.72)	0.003–0.104 (0.037)	Q = 91.30, F = 2.60, C = 6.09.	Minor to moderate (10–55)
RF 5	Silty - to clayey sandstones	11.40–13.40 (12.27)	1.298–1.425 (1.363)	Q = 78.88, F = 5.38, C = 15.75.	Rare to minor (5–20)
RF 6	Horizontally laminated sandstones	16.69–21.53 (19.55)	3.743–4.577 (4.366)	Q = 88.32, F = 4.58, C = 7.11.	Minor to moderate (15–35)
RF 7	Lenticular bedded sandstones	11.52–16.21 (13.44)	0.583–1.983 (1.148)	Q = 91.75, F = 0.00, C = 8.25.	Moderate 35–65
RF 8	Flaser bedded sandstones	13.13–21.87 (16.85)	1.849–2.309 (2.013)	Q = 85.56, F = 9.06, C = 5.37.	Minor (0–25)

N/B values in parentheses are average porosity and permeability. %QFC was obtained from quantitative XRD data ([Fig. 6](#)). It shows the proportional percentage of Quartz-feldspar and clay minerals in each reservoir Facies. The percentage feldspar in Quartz (Q)–feldspar (F)–clay (C) is equal to total feldspar (Albite + K–feldspar) divided by summation of Q–F–C and expressed in percentage, while percentage clay minerals in Q–F–C is the total composition of identified clay minerals (kaolinite + chlorite + illite) divided by summation of Q–F–C and expressed in percentage. Percentage quartz, percentage quartz is the quartz composition divided by the summation of Q–F–C.

slow ([Middleton, 1966](#); [Middleton and Hampton, 1976](#)). Therefore, the lithological features and bioturbations in the FA 2 suggest deposition in subtidal to intertidal environments ([Fig. 4](#)).

The FA 3 is the rarest of the identified FAs, and it comprises only lenticularly bedded sandstone facies (RF 7). The FA 3 typically overlies the heterolithic facies (RF 4 or RF 8), and its occurrence in the Nyalau

Formation is dominantly characterised by fining upward sequence (Table 2, Fig. 2). Lenses of sandstones trapped within relatively thicker claystone and mudstone units are somewhat consistent with sediment deposited in upper intertidal reaches of tidal mudflat (Reineck and Wunderlich, 1968; Dalrymple et al., 1992). Although not exclusive, conditions that favoured deposition of laminated muds with relatively

little sandstone units are known to occur within the upper intertidal zone.

An annotated depositional model (Fig. 12) of the three facies association construed from the studied sandstones suggest sediment deposition in a series of sub-environments (lower-to-upper shoreface and subtidal-to-intertidal) within a coast-to-coastal barrier island system.

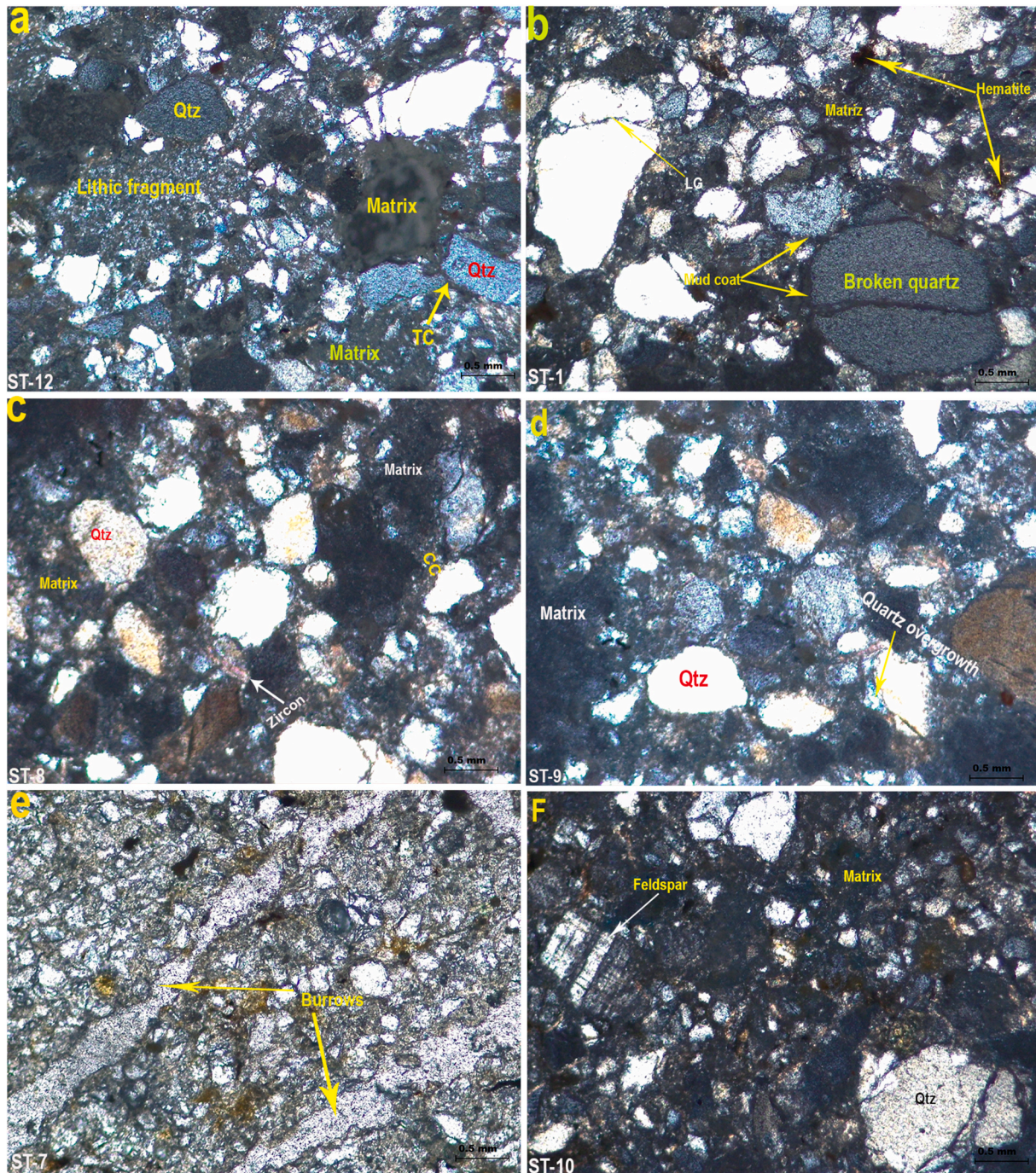


Fig. 5. Thin section photomicrographs of representative sandstone samples of some identified reservoir facies (RF) in the Nyalau Formation. (a) moderately well sorted and matrix-supported framework (xpl) in a sample representing the lenticular bedded sandstone reservoir facies (RF 7), (b) long-grain contact, broken quartz, and mud-coated grains (xpl) in a representative sample of the Horizontally laminated sandstone reservoir facies (RF 6), (c) zircon grain within grain supported sandstone with clay cement bounding grains together (xpl) in Hummocky cross-stratified sandstones reservoir facies (RF 1), (d) poorly sorted grains with pore-filling mud in the matrix-supported framework of fine to coarse-grained (ppl) in the wavy-to flaser bedded sandstones reservoir facies (RF 6), (e) elongated burrows with brownish hematite precipitate in fine-grained well-sorted sandstone (ppl) of the massive/structureless sandstone reservoir facies (RF 3), (f) plagioclase feldspar and quartz in fine to medium-grained sandstone (xpl) of the trough cross-stratified sandstone reservoir facies (RFII). Note that Qtz = quartz, CC = clay cement, Hem = hematite cement, TC = tangential contact, LC = long contact. Scale = 0.50 mm, Magnification 10x, xpl = cross polarised, ppl = plane polarised light, ST-refers to sample locations as indicated in Fig. 1C. Reservoir facies codes correspond to those in Tables 1 and 2

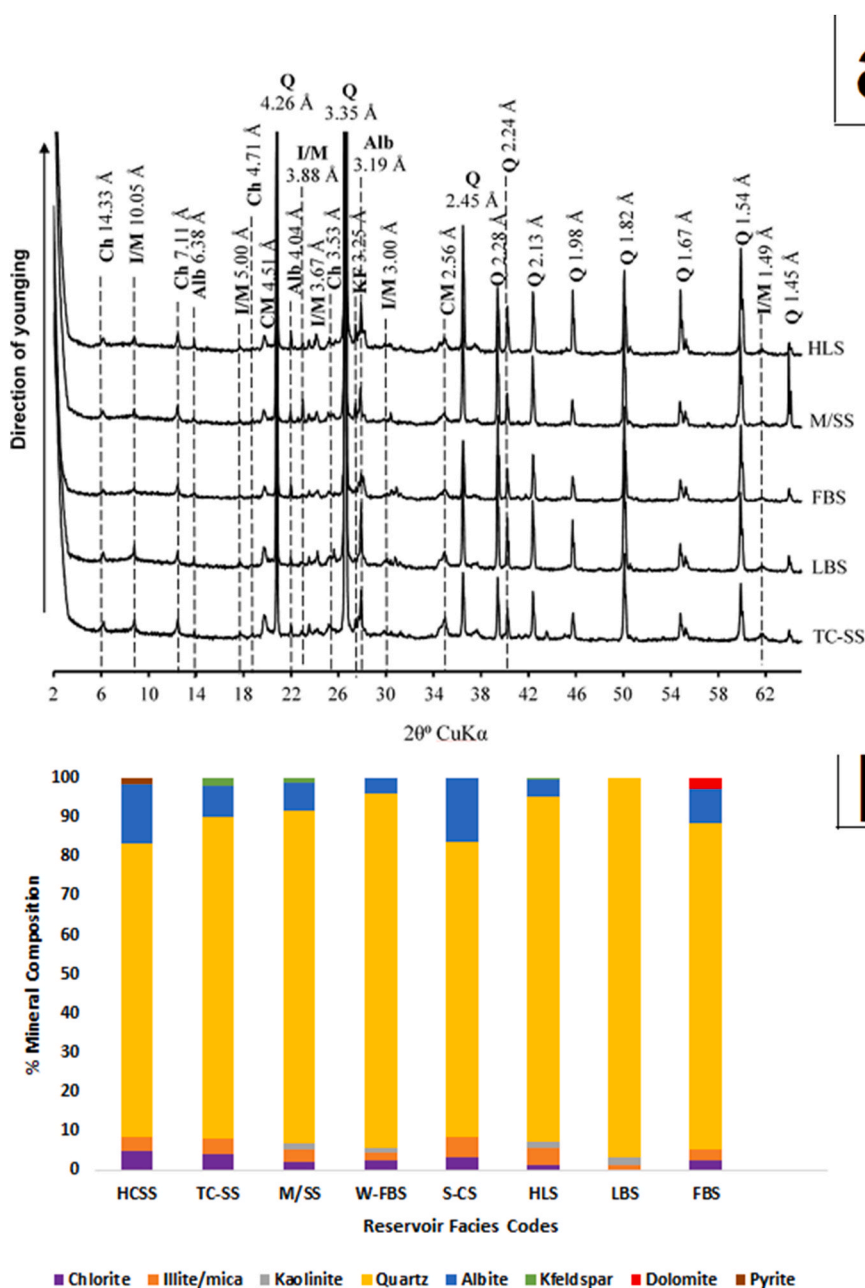
Amir Hassan et al. (2013) suggested that the entire FAs of the Nyalau Formation were deposited in nearshore and coastal to coastal plain depositional settings, and the vertically stacking patterns of the successions are indicative of repeated cycles of prograding wave-dominated shoreface sequences, which are overlain through an erosional surface by more tidally influenced successions.

4.3. Petrography and mineralogical composition

Optical petrographic data revealed that the sandstones are fine-to medium-grained, consisting of 77% quartz, 9% feldspars, and 14% rock fragments mean detrital components, and they essentially fall within the sublitharenite and lithic subarkose fields in the plotted QFL diagram (Fig. 4; Appendix 1). The quartz grains are dominantly monocrystalline, while the feldspars are mostly plagioclase (Fig. 5; Appendix 1). The detrital grains are moderate-to well-sorted, sub-rounded to sub-angular, and are generally supported in clay-dominated matrix with

minimal grain-to-grain contacts (Fig. 5a, b, d-f). Observed grain contacts were mainly tangential (Fig. 5a, c) and long (Fig. 5b, f) types. Rare occurrences of fragmented quartz grains and zircon were observed (e.g., Fig. 5b, c, f). The matrix is dominated by muddy materials and clay minerals (Fig. 5a-d), whereas quartz cement/overgrowths, and sometimes dolomite and pyrite, are only identified in a few samples (Fig. 5). Mud-filled burrows are observable in some thin sections (Fig. 5e). Although the mineral composition in all facies appears similar, except for the absence of pyrite and dolomite in all representative samples of the flaser bedded sandstones facies, there are variations in their relative abundances (Fig. 6a; Appendix 1).

XRD and SEM data show that the sandstones are essentially composed of illite, kaolinite, and chlorite clay minerals, while smectite is present in trace amounts (Figs. 6 and 7). Smectite is present as fine perpendicular honeycomb fabrics/webs lining and bridging the pores (Figs. 7a and 8a), whereas kaolinite occurs as face-to-face vertically stacked vermiform of pseudo-hexagonal booklets filling intergranular



a

Fig. 6. (a) X-ray diffractograms of selected samples showing whole-rock mineral variations with reservoir facies of the Nyalau Formation. Note that plotted facies are from the same outcrop section and in true stratigraphic order but not necessarily resting on one another. Ch = chlorite, I/M = illite/mica, Alb = Albite, CM = clay minerals, KF = K-feldspar, K = kaolinite. Facies codes used are as earlier defined in Fig. 3 and Table 1. (b) Bar chart showing mean mineral distribution across the delineated reservoir facies of the Nyalau Formation. Mineral compositions are percentage averages of representative samples of each facies as obtained from XRD analysis. Note that HCSS is hummocky cross stratified sandstones facies, TC-SS is trough cross-bedded sandstone facies, M/SS is Massive to structureless sandstones facies, W-FBS is wavy to flaser bedded sandstones, S-CS is silty-to clayey sandstones, HLS is horizontally laminated sandstone facies, LBS is lenticular bedded sandstone facies, and FBS is flaser bedded sandstone facies.

b

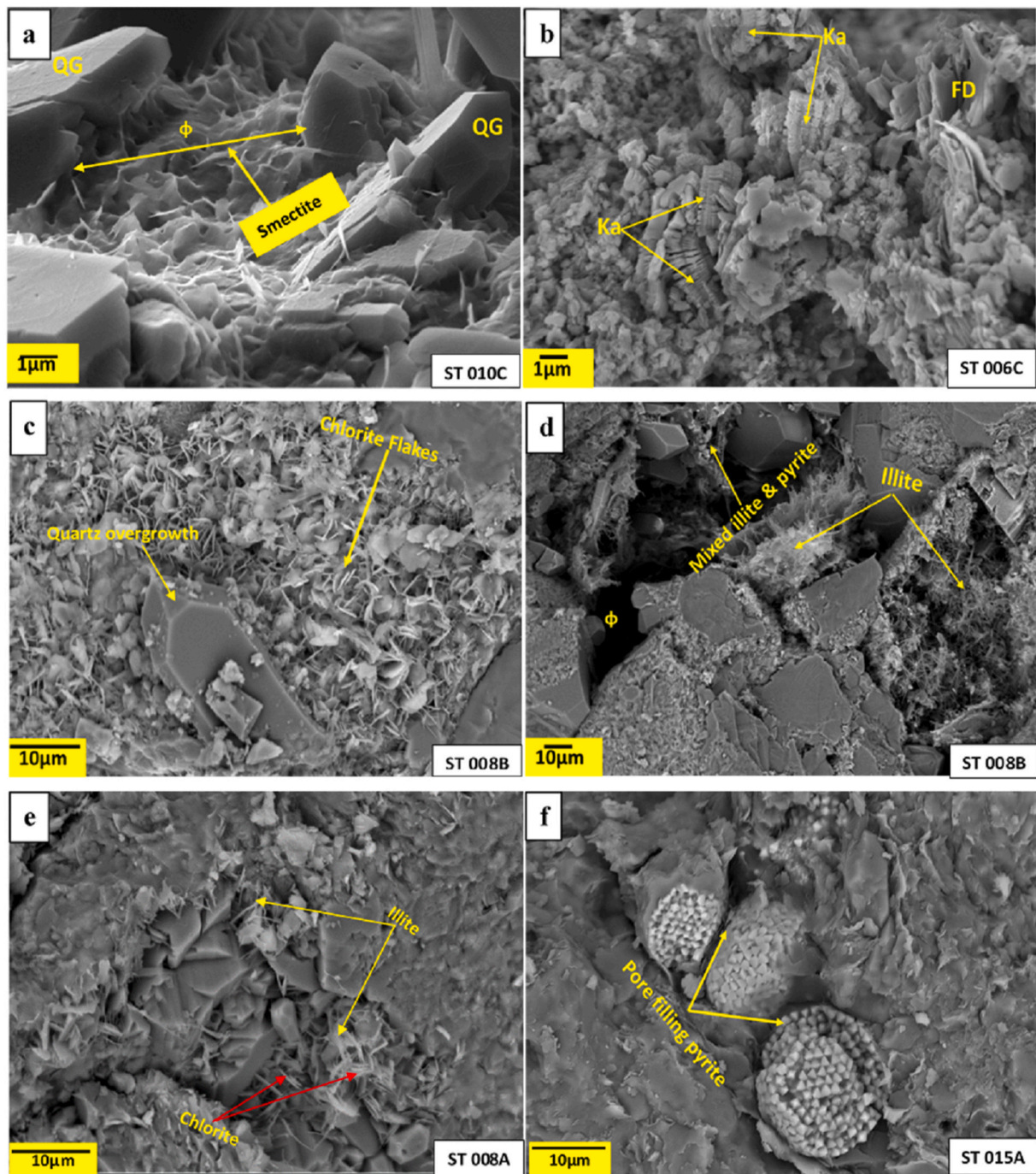


Fig. 7. Scanning electron photomicrographs of the Nyalau Formation reservoir sandstones: (a) network of smectite filling pores in a representative sample of the flaser bedded sandstone reservoir facies; (b) kaolinite sheets and dissolved feldspar within pore spaces of the horizontally laminated sandstone reservoir facies; (c) euhedral authigenic quartz overgrowths associated with chlorite flakes in the massive to structureless sandstones reservoir facies; (d) disaggregated pyrite filling pores and pore-bridging illite in a sample of the massive to structureless sandstones reservoir facies; (e) assorted clay minerals replacing/filling secondary porosity of altered detrital grains in the wavy to flaser bedded sandstone reservoir facies; (f) euhedral authigenic pyrite clusters filling secondary pores and quartz cement in a representative sample of the lenticular bedded sandstone reservoir facies. Note that QG = quartz grain, Ka = kaolinite, FD = dissolved feldspar, and ϕ = porosity.

pore spaces (Figs. 7b and 8b). Chlorite occurs as small euhedral to pseudo-hexagonal perpendicular crystals rimming grain surfaces, filling, and lining pore walls (Figs. 7c and 8c). Illite is distinguished by its filamentous, platy, and thin flakes ribbon crystals coating grain surfaces, filling, and bridging pore spaces (Figs. 7d and 8d). The clay minerals were also observed replacing and filling secondary (intragranular) pores of altered detrital grains (Fig. 8d and e). Well-crystallised authigenic rhombic quartz crystals were observed within pore spaces (Fig. 7c, e; 8e) and syntaxial quartz overgrowth around detrital monocrystalline quartz

grain, which growth was likely inhibited by pore-lining clays (Fig. 5d). Pyrite, when present, occurs as closely packed euhedral framboidal crystals staining clays and filling pore spaces (Fig. 8f). Intergranular (primary) and intragranular (secondary – mostly associated with feldspar dissolution) microporosities are preserved in several instances in the sandstones (Fig. 7a, d; 8f). The relative contents of the clay mineral are small compared to the detrital minerals, with chlorite being the most abundant clay mineral in all facies types, though completely lacking in the lenticular bedded sandstones reservoir facies (Figs. 6–8).

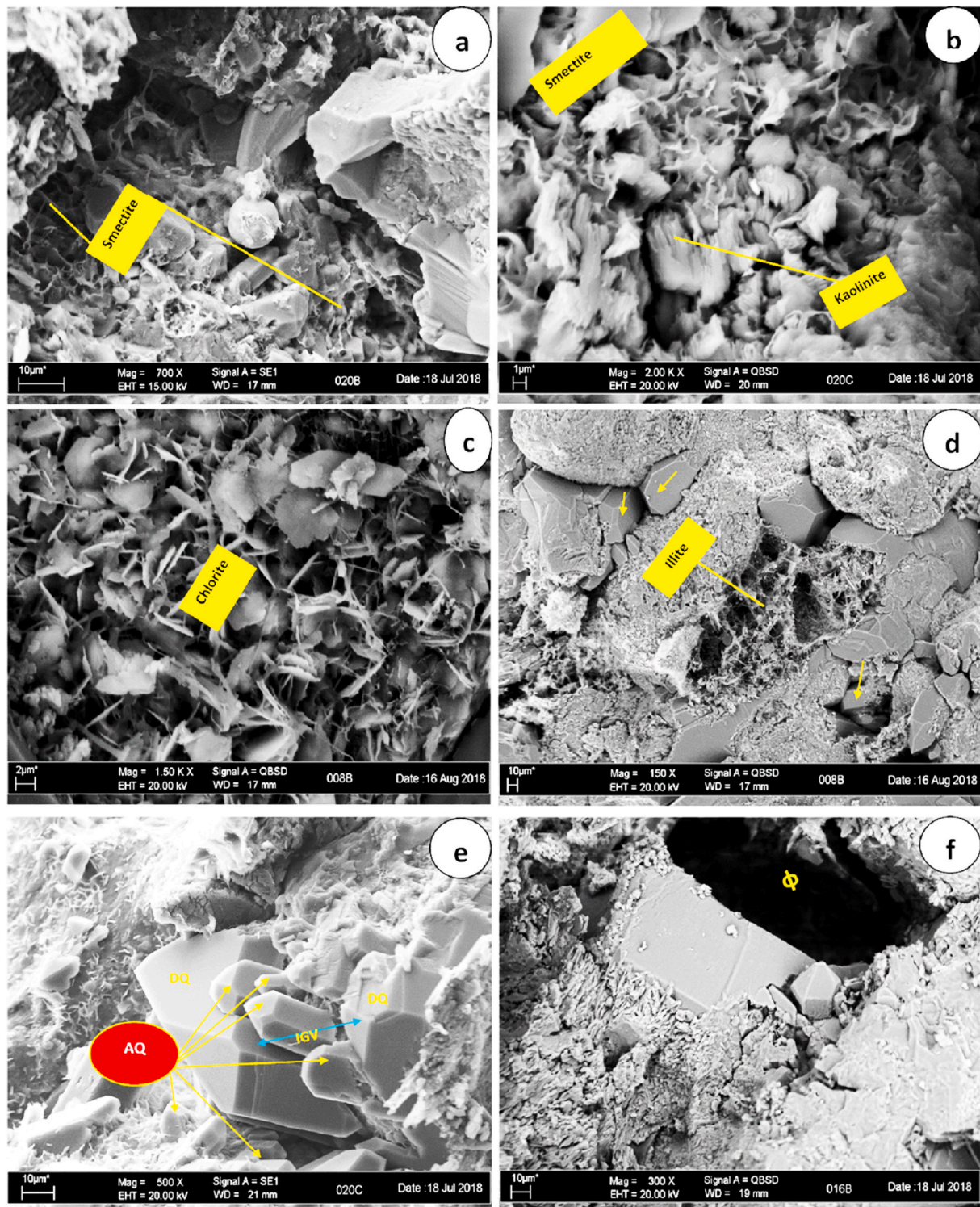


Fig. 8. SEM images showing authigenic signatures in the Nyalau Sandstone: (a) evolving smectite network within pore system (b) mixed kaolinite-smectite, (c) pore-filling chlorite flakes, (d) convoluted illite strands and pore-filling authigenic quartz crystals (yellow arrows), (e) authigenic quartz crystals (yellow arrow) filling intergranular pores, and evolving chlorite flakes within pore spaces, and (f) secondary porosity due to the dissolution of unstable feldspar grains quartz dissolution. AQ, IG, and DQ represent authigenic quartz, intergranular volume, and detrital quartz, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.4. Porosity and permeability

The He-porosity (ϕ_H) and Klinkenberg permeability (K_k) values in the sandstones widely vary, ranging from 3.07% to 22.14% (average = 12.90%) and 0.003 to 8.285 mD (average = 2.28 mD), respectively

(Table 2). The horizontally laminated sandstones facies have the highest ϕ_H value (19.55%), while the lowest ϕ_H value is recorded in the wavy-to flaser-bedded sandstones facies (3.72%). In contrast, the latter has the highest average K_k value (5.891 mD), while the hummocky cross-stratified sandstones facies have the lowest average value (0.037 mD)

(Table 2). The K_k displays a weak relationship with ϕ_H (Fig. 9; $R^2 = 0.35$). The wavy-to flaser-bedded sandstones facies plot in the tight reservoir quality field, while the trough cross-stratified sandstones, silty - to clayey sandstones, and lenticular bedded sandstones are all in the fair reservoir quality field. The flaser bedded sandstones, horizontally laminated sandstones, and hummocky cross-stratified sandstones are located in the fairly good reservoir quality field. The massive/structureless sandstone is dispersed across all the fields on the reservoir quality classification plot (Fig. 9). Generally, the amounts of quartz, feldspar and lithic fragments in the samples do not significantly relate with the ϕ_H and K_k in the Nyalau Formation reservoir sandstone (Fig. 10). However, the ϕ_H values exhibit a positive trend with increasing quartz contents in the horizontally laminated sandstones, flaser bedded sandstones, and lenticular bedded sandstone reservoir facies (Fig. 10a) and with increasing lithic fragments contents in the hummocky cross-stratified sandstones (Fig. 10e). The ϕ_H values increase with increasing chlorite content only in the trough cross-stratified sandstone facies (Fig. 11a) but decrease with increasing kaolinite and illite in the horizontally laminated sandstones, silty - to clayey sandstones, and lenticular bedded sandstone facies (Fig. 11c, e). Conversely, increase in percentage chlorite, illite and clay gave rise to consistent decline in permeability trend in the hummocky cross-stratified sandstone facies (Fig. 11b, d, e). Although less conspicuous, this inverse permeability trend is also construable with increasing illite and chlorite in the trough cross-stratified sandstone facies (Fig. 11b, d).

5. Discussion

5.1. Facies control on reservoir quality

Overall, the measured poro-perm values in this study are lower than the mercury porosity reported by Siddiqui et al. (2016) for the Nyalau Formation sandstones but are significantly higher than those reported by Adepehin et al. (2020) for the subsurface successions of this formation (Fig. 9). The presented data show that five (RF 1, RF 2, RF 5, RF 6, and RF 7) of the eight characterised reservoir facies have near homogenous poro-perm values that grouped them into statistically distinct fields (Fig. 9). The clustering of samples representing the same facies suggests the influence of depositional control (facies) on porosity and permeability and perhaps relative uniform responses of the facies to pore-reducing diagenetic processes. Conversely, the significantly noticeable distance between a sample each of the RF 4 and RF 8 from their respective facies fields, is interpreted to be indicative of non-uniform post-depositional fluid-flow controls on the samples, and by implications, the lesser influence of facies. The dispersal of the massive/structureless sandstone (RF 3) samples across the classification fields correspond to limited facies control (Fig. 9), and perhaps disproportionate alteration of the syn-depositional fluid-flow parameters, which resulted in their high heterogeneous reservoir quality (Pryor, 1973; Houseknecht, 1987; Lai et al., 2016).

The wavy-to flaser-bedded sandstones facies have the lowest ability to store and transmit fluids (Table 2). They are classified as tight reservoir quality sandstones (Table 2), consistent with previous documentation in the subsurface reservoir of the Nyalau Formation (Adepehin et al., 2020). The contrasting difference in the qualities of the

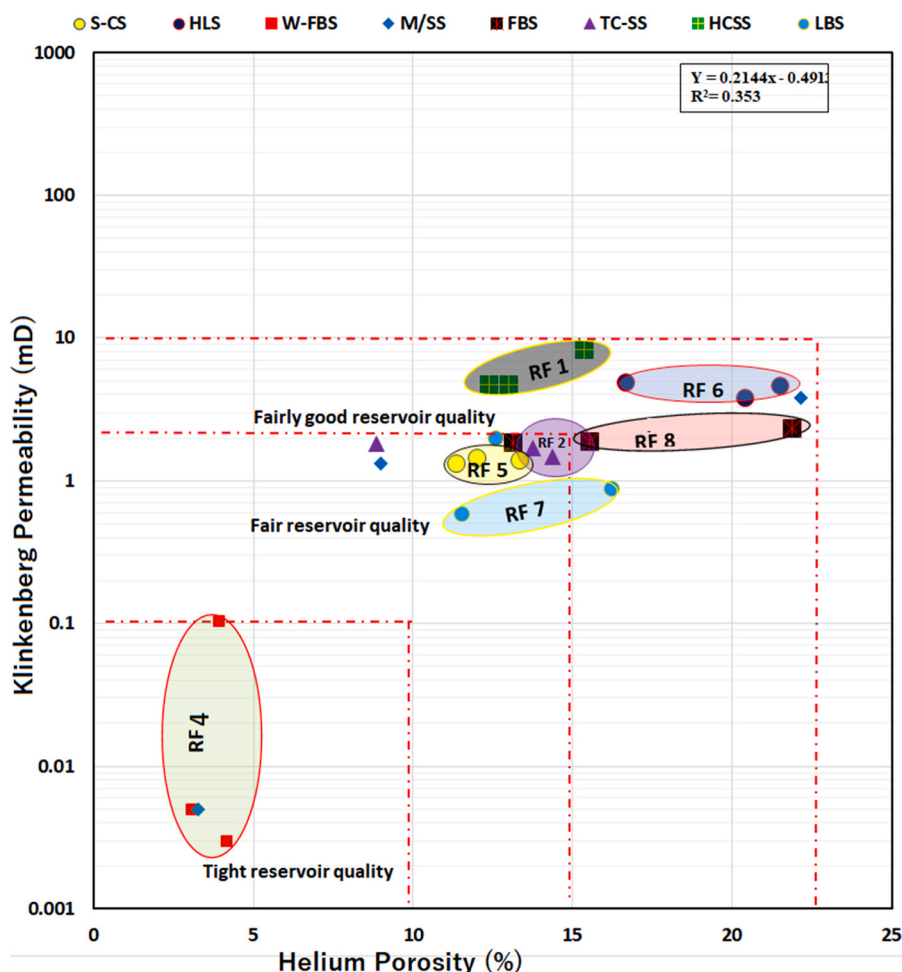


Fig. 9. Petrophysically-ranked poro-perm values of the Nyalau Formation reservoir facies based on the bivariate relationship of Klinkenberg permeability and ambient helium porosity. Note the relative proximity of points representing the RF 1, RF 2, RF 4, RF 5, RF 6, and RF 7, which is interpreted to be indicative of the influence of facies and near-uniform response to diagenetic modification. The scattering of points representing the RF 3 reflects differential samples responses to diagenesis (including bioturbation) and indicate that depositional facies have no significant control on fluid-flow parameters. The reservoir quality classification shown is based on subjective cut-offs and adapted from Zou et al. (2012) and Adepehin et al. (2020) schemes.

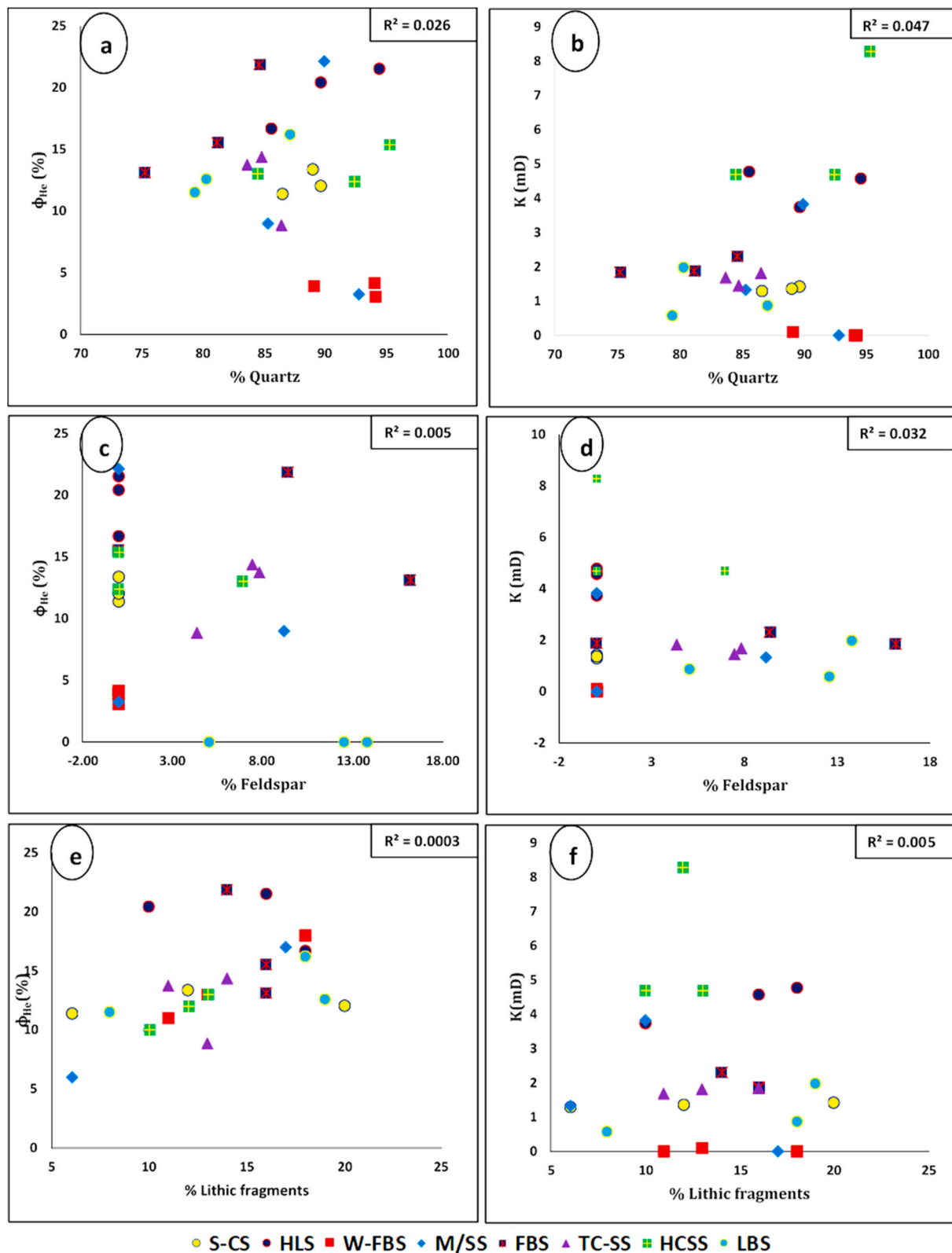


Fig. 10. Bivariate plots showing relationships of quartz (a&b), feldspar (c&d), and lithic fragments (e&f) on porosity and permeability of representative samples of the Nyalau Formation reservoir facies. Note that HCSS is hummocky cross stratified sandstones facies, TC-SS is trough cross-bedded sandstone facies, M/SS is Massive to structureless sandstones facies, W-FBS is wavy to flaser bedded sandstones, S-CS is silty-to clayey sandstones, HLS is horizontally laminated sandstone facies, LBS is lenticular bedded sandstone facies, and FBS is flaser bedded sandstone facies.

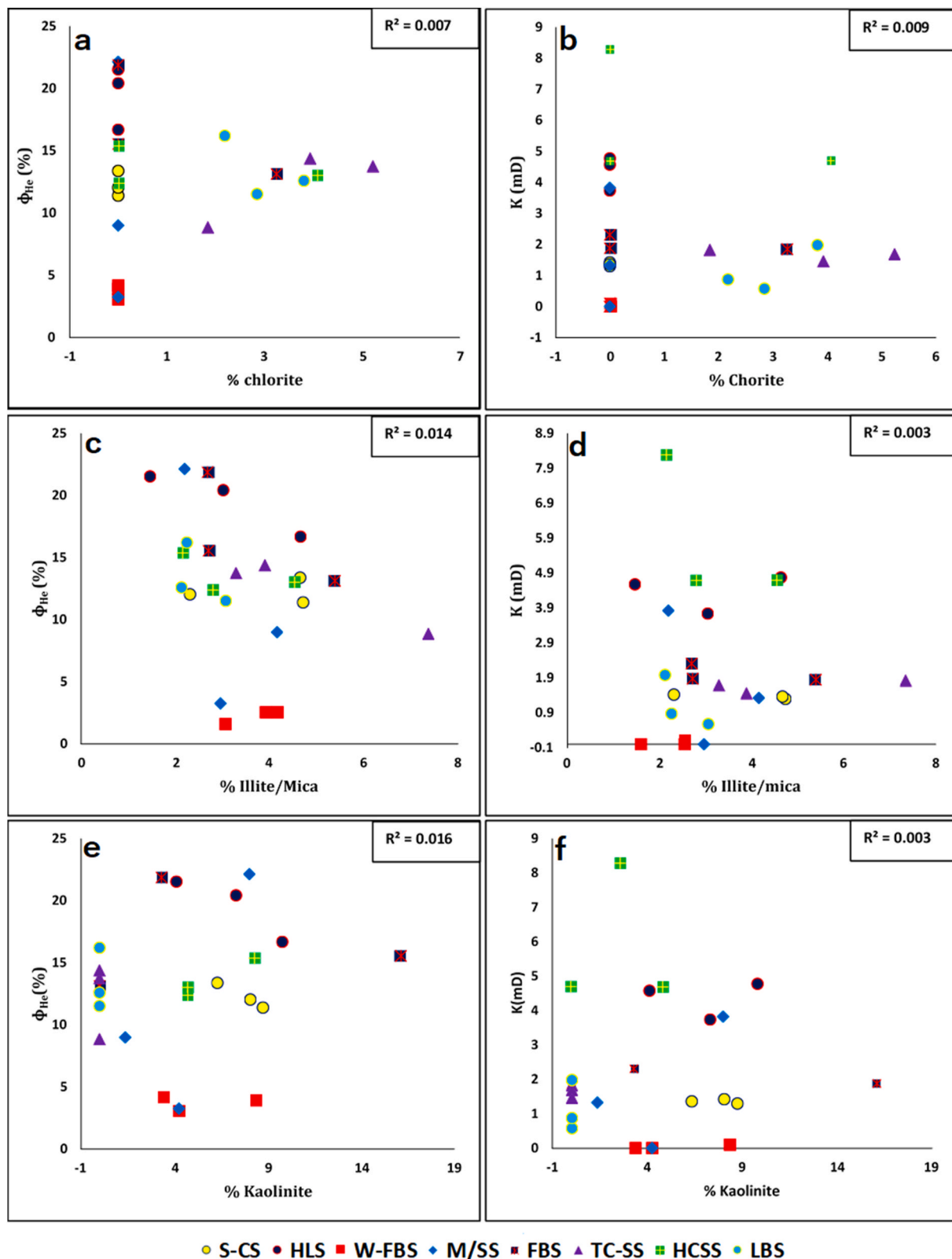


Fig. 11. Relationship of main clay minerals and poro-perm datasets in the siliciclastic reservoir facies of the Nyalau Formation, Borneo. a, c, and e show bivariate plots of helium porosity and percentage chlorite, illite/mica, and kaolinite, respectively, while b, d, and f show trend of permeability with percentage chlorite, illite/mica, and kaolinite, respectively. Note that HCSS is hummocky cross stratified sandstones facies, TC-SS is trough cross-bedded sandstone facies, M/SS is Massive to structureless sandstones facies, W-FBS is wavy to flaser bedded sandstones, S-CS is silty-to clayey sandstones, HLS is horizontally laminated sandstone facies, LBS is lenticular bedded sandstone facies, and FBS is flaser bedded sandstone facies.

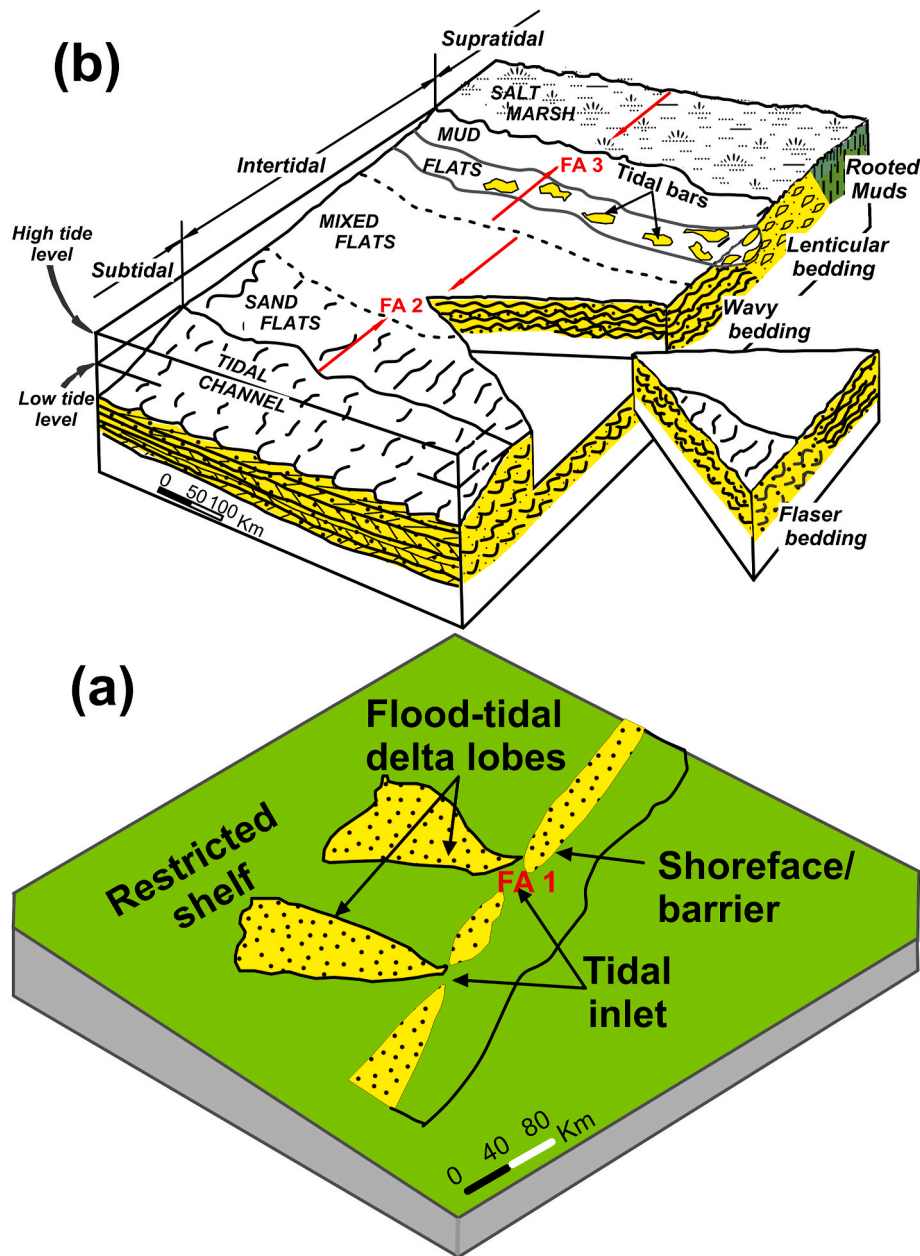


Fig. 12. Block diagram representing the depositional model of the shoreface deposits (FA 1), sand flat-to-mixed flat complex (FA 2) and mudflat deposited (FA 3) facies association of the studied Nyalau reservoir sandstone facies (after Reinson, 1992; Lucas et al., 1998).

trough cross-stratified sandstone (RF 2), silty - to clayey sandstones (RF 5), and lenticular bedded sandstone (RF 7) with relatively high mean poro-perm values and the flaser bedded sandstones (RF 8), horizontally laminated sandstones (RF 6), and hummocky cross-stratified sandstones (RF 1) with much higher values further suggests indicates the influence of depositional control on the reservoir qualities of the sandstones (Fig. 12). The reasonably good reservoir qualities of the flaser bedded sandstones, horizontally laminated sandstones, and hummocky cross-stratified sandstones can be attributed to their relatively uniform grain sizes (Table 1), well-sorted nature, and low clay contents that collectively suggest sedimentation of mature sediments in high energy depositional environment (Meckel, 1967; Middleton and Hampton, 1976; Dott and Bourgeois, 1982; Dumas and Arnott, 2006; Dim et al., 2019). On the other hand, the heterolithic wavy-to flaser-bedded sandstones, lenticular bedded sandstones, and flaser bedded sandstones facies contain considerable amounts of muds within the sandstones, significantly reducing pore connectivity and pore sizes (Ramón and

Cross, 1997). Converse to the wavy-to flaser-bedded sandstones, the higher poro-perm values in lenticular bedded sandstone and flaser bedded sandstones are interpreted to be due to their relatively lower mud contents than the former. Unlike other facies with distinct and near-homogeneous reservoir qualities, the heterogeneous reservoir attributes of the massive/structureless sandstone are likely due to the widely varying B.I (Table 2). (Buatois et al., 1999; Jackson et al., 2005; Tonkin et al., 2010; Baniak et al., 2015; Gingras et al., 2016; La Croix et al., 2017). It is however difficult to ascertain whether the structureless characteristics of this reservoir facies resulted as a syn-depositional feature, a product of severe post-depositional obliteration or an interplay of both processes.

Overall, the occurrence of the mean highest porosity (19.96%) and permeability (3.774 mD) values in the shoreface deposits (FA 1) indicate that sandstones deposited in the shoreface sub-environment would yield better reservoir quality than those in the intertidal sub-environments (Table 2). Although sands in the lower shoreface are often siltier than

the characteristically well-winnowed upper shoreface deposits, the domination of wave action and alongside known storm influence jointly act to produce laterally extensive and very good quality reservoirs and aquifers (Table 2). Shoreface facies with excellent reservoir quality have been reported in Sandakan Formation, Borneo (Siddiqui et al., 2020), Agbada Formation, Niger Delta (Mode et al., 2017), Bahariya Formation, northern Western Desert, Egypt (Selim et al., 2021). This notwithstanding, the excellent reservoir quality of shoreface systems may be drastically lost due to increasing diagenetic alterations (Lawan et al., 2021).

Given the contrasting relationship between the documented average porosity (12.77%) and permeability (1.900 mD) in the defined sand flat to mixed flat complexes (FA 2), it can be construed that several unconnected pore spaces accounted for the recorded porosity values (Table 2). This anomaly probably resulted from the high silty and muddy textures within RF 3 and RF 5. This is perhaps exacerbated by the high argillaceous interbeds in the heterolithic facies (RF 4, RF 6, and RF 8), which traditionally disconnect vertical permeability. However, published data on tidal bar facies from the Permian Upper Cape Hay Formation, Bonaparte Basin, Australia, indicated that siliciclastic tidal systems reservoir may still preserve producible fluid-flow quality, even under post-depositional subsurface conditions (Saiag et al., 2016). This is however thought to be subjective to prevailing basinal geotectonic, porewater chemistry, burial depth, and bioturbation (e.g., Ahfaf et al., 2021a, b).

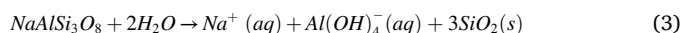
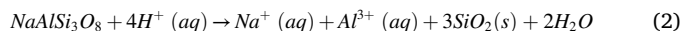
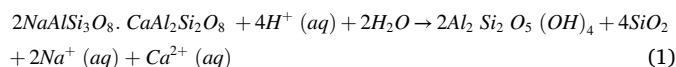
Though with porosity (13.44%) and permeability (2.013 mD) that exceed the tight reservoirs threshold ($\phi = 10.00\%$, $K = 1\text{mD}$), the reservoir quality of the mudflat deposits is based on limited data (Table 2), and rigorous discussion on its producibility cannot be robustly discussed. This notwithstanding lenticular bedded sandstone facies are well documented to have good reservoir quality (e.g., Saiag et al., 2016; Adepehin et al., 2019c; Barshap and Worden, 2022). Although the formation of this facies is not exclusive to coastal systems, the inherent depositional signature in the facies suggest similar producibility parameters as in other depositional sub-environments.

5.2. Diagenetic control and evolution mechanisms

In addition to the interpreted influence of depositional facies on reservoir quality, diagenetic controls on the fluid-flow parameters are discernible. The dominance of matrix-supported framework with minimal grain-to-grain contacts over the grain-supported framework with closer grain-to-grain packing and contacts somewhat suggests mild diagenetic compaction (Figs. 5, 7 and 8) (e.g., Worden and Burley, 2003; Adepehin et al., 2019a). Enhanced by compactional load from overlying strata, the essentially muddy/clay matrix of the Nyalau Formation reservoir sandstones has been dispersed within the pore-systems (Fig. 5), thus contributing to poro-perm occlusion. This compaction-induced redistribution of clay-sized matrices within the sandstone framework is perhaps the principal cause of depositional porosity loss in the sandstones, although authigenic clay and quartz cement are also present (Figs. 7 and 8). In addition, the presence of fractured quartz grains (Fig. 5b, f) shows mechanical compaction somewhat contributed to diagenetic alterations in the reservoir sandstones notwithstanding its matrix-dominated framework (Appendix 1) (e.g., Mansurbeg, et al., 2008; Lai et al., 2018).

Chemical compaction in the reservoir sandstones of the Nyalau Formation is less common but indicated by the observed breakdown of non-micaceous detrital components and framework grain dissolution (FGD) (Figs. 7d and 8d, f). Grain dissolution may result in the enhancement or destruction of reservoir fluid-flow parameters, depending on the complex interplay between dissolution and precipitation reaction (Zhu and Lu, 2009). FGD usually involves the reaction of organic acids, produced from CO_2 generated from the early maturation of organic matter (shale) to dissolve aluminosilicate, organic complex agents (ligands) and methane gas (Siebert et al., 1984). The resultant

aqueous solution permeates contiguous sandstone bodies and dissolves aluminosilicate grains as illustrated in the following equations.



FGD in an open diagenetic system allows for the leaching of the by-products from leached grains, thus enhancing poro-perm (Wilkinson et al., 1997; Zhu et al., 2004, 2008; Zhang et al., 2014; Yuan et al., 2015a, b, c). Conversely, in a comparatively closed diagenetic system, the by-products of FGD are generally retained and reformed as diagenetic clay and/or quartz cement (Giles and De Boer, 1990; Chuhan et al., 2001; Higgs et al., 2007).

The rare occurrence of K-feldspar (KAlSi_3O_8), the dominance of albite ($\text{NaAlSi}_3\text{O}_8$), and quartz cement, as well as the presence of authigenic clay minerals and low poro-perm values in the reservoir, are suggestive of moderate FGD (Table 2; Figs. 6 and 8). This is perhaps best typified by the inverse correlation of % kaolinite (flaser bedded sandstones) and % illite (trough cross-stratified sandstone and lenticular bedded sandstone) with %feldspar displayed by some reservoir facies (Fig. 13a–c). The consistent decrease in feldspar content with increasing %kaolinite in the flaser bedded sandstone and massive/structureless sandstone facies (Fig. 13a) likely suggest Kaolinitisation of feldspar – precipitation of kaolinite from dissolving K-feldspar (Seki and Kennedy, 1964; Worden and Burley, 2003; Adepehin et al., 2020). Similarly, the converse trend between percentage feldspar and illite in the trough cross-stratified sandstone and lenticular bedded sandstone facies (Fig. 13c) also suggest illitisation of feldspar in these facies. Chuhan et al. (2000) indicated that the preponderance of kaolinite over K-feldspar, such that K-feldspar: kaolinite <1 and the general co-existent of kaolinite with illitic clay at the detriment of K-feldspar are perhaps the two indicators of kaolinitic illitisation in diagenetic sandstone. Hence, the fact that the K-feldspar-kaolinite ratio in all studied samples is generally below one, except in the massive/structureless sandstone facies further shows that feldspar is probably the precursor for both kaolinite and illite clays within the pore system of the reservoir Nyalau Formation.

The dissolution of framework grains and the subsequent precipitation of authigenic minerals (dominantly kaolinite and illite) in the Nyalau reservoir facies is a probable indicator of a closed diagenetic system (e.g., Schmidt and McDonald, 1979a, 1979b; Bjørlykke, 1984; Siebert et al., 1984; Surdam et al., 1984; Meshri, 1986; Giles and De Boer, 1989; Smith and Ehrenberg, 1989; Zhu and Lu, 2009). Geochemically, a closed diagenetic environment is characterised by low migration efficiency, weak material exchange (Wu et al., 2021). This accounts for why secondary pores created by grain dissolution are often refilled by authigenic minerals (Figs. 8 and 9). Hence, the rarity of significant effective porosity and/or permeability enhancement in the samples (Figs. 5, 8 and 9). To better understand the influence of diagenetic signatures on the porosity and permeability, point counted intergranular volume (IGV), undifferentiated matrix and amalgamated percentage cement and replacements were plotted alongside the Klinkenberg poro-perm values (Fig. 14). The observed depression in the porosity/IGV and permeability track and the corresponding peakedness in the matrix/cement track indicate that matrix, and most importantly cement has an inverse relationship with porosity in the wavy-to flaser-bedded sandstones. Similarly, the same trend is construable from the peakedness in porosity/IGV and permeability vis-à-vis the relatively low values of the matrix and cement. Thus, confirming the differential response of sandstone facies to diagenesis, and alluding to cementation as a major porosity reducer in the subsurface successions of the Nyalau Formation.

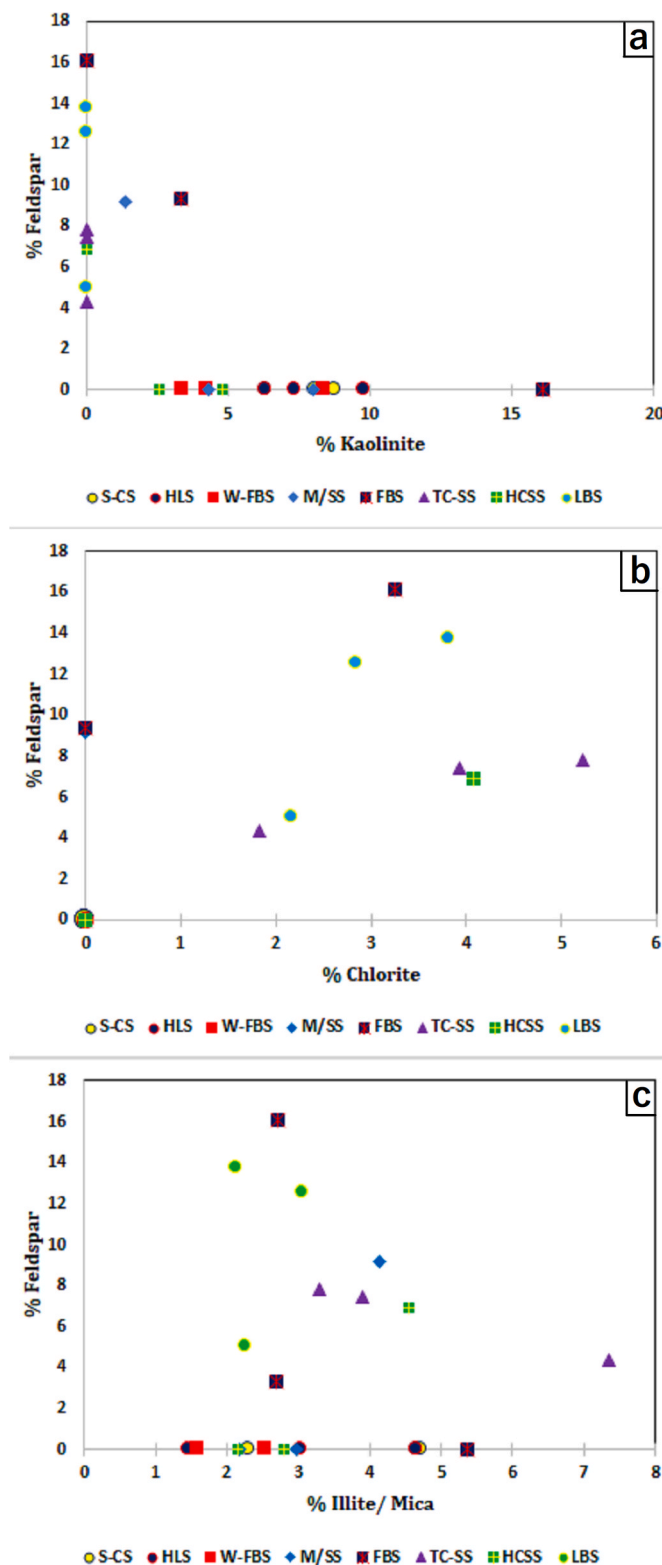


Fig. 13. Relationship of percentage feldspar composition with (a) kaolinite, (b) chlorite, and (c) illite/mica in the reservoir facies of the Nyalau Formation. Note that HCSS is hummocky cross stratified sandstones facies, TC-SS is trough cross-bedded sandstone facies, M/SS is Massive to structureless sandstones facies, W-FBS is wavy to flaser bedded sandstones, S-CS is silty-to clayey sandstones, HLS is horizontally laminated sandstone facies, LBS is lenticular bedded sandstone facies, and FBS is flaser bedded sandstone facies.

5.3. Impacts of the clay minerals on fluid flow

Clay mineral heterogeneity can significantly impact the quality of sandstone reservoirs (Mode et al., 2013; Wilson et al., 2014, 2016; Adepehin et al., 2019a, b, c). The relative abundance, textural occurrence, and morphology of the different clay minerals have different effects on reservoir qualities (e.g., see reviews in Worden and Burley, 2003; Xi et al., 2015). Generally, clay minerals occurring as pore-lining, pore-filling, and pore-bridging clays (e.g., smectite, illite, chlorite, and kaolinite) reduce permeability and porosity, whereas grain-coating chlorite can preserve porosity at a deeper burial depth. For instance, honeycomb illite/smectite mixed-layer mainly occlude primary pores and thus destroy reservoir quality (especially porosity), whereas fibrous and flaky illite crystals tend to plug pore spaces and pore-throats, which can significantly reduce pore connectivity (permeability) and lower reservoir quality by dividing macro-pores into micropores. Pore filling chlorites are commonly small crystals and tend to reduce pore-throat diameters but do not have strong effects in occluding pore spaces; however, grain coating chlorite is capable of inhibiting quartz cementation/overgrowths and thus can preserve reservoir qualities, especially porosity (e.g., Morad et al., 2010; Mode et al., 2013).

The petrographic observations (thin section and SEM) of the studied samples showed that the clay minerals mainly occur filling and lining the pore spaces with different morphologies (Figs. 5, 7 and 8), suggesting their potential detrimental impacts on reservoir qualities of the sandstones by decreasing intergranular effective porosity and permeability for fluid flow. These deductions are evidenced by the decreasing porosity and permeability with increasing amounts of the clay minerals - illite, kaolinite, and chlorite in most of the reservoir facies (Fig. 11). The lack of significant correlation between the amount of the clay minerals and poro-perm properties (Fig. 11) and the weak relationships between porosity and permeability (Fig. 9) probably reflect the effect of micropores in present in reservoir fines, with very negligible permeability. This is supported by the weak positive relationship between chlorite and porosity in the trough cross-stratified sandstone (RFII) facies, while kaolinite shows a decreasing trend in the hummocky cross-stratified sandstones, and none of these shows any relationship with permeability.

5.4. Wider implications for onshore subsurface reservoir quality

Since porosity generally reduces with depth, owing to the influence of increasing compactional load, the poor-to-fairly good reservoir quality of the studied analogue sandstones indicates that subsurface reservoir units within the Cycles I-III successions in the Sarawak Basin may have significantly deteriorated. In the offshore Balingian Province of the Sarawak Basin, significant porosity loss in the Nyalau Formation to an average of 7.5–15% at subsurface depth ≥ 2.5 km has been reported (Maden and Abolins, 1999). This likely indicates that the reservoir quality in the subsurface onshore would drastically diminish at depth > 2.5 km since the offshore porosity values double the quoted porosity range at a shallower depth. Consequently, this is consistent with the documented porosity and permeability reduction for subsurface onshore successions of the Nyalau Formation at shallow depth (< 1.5 km) in the Bintulu area (Adepehin et al., 2020).

Although depositional facies and cement were identified as the dominant control on porosity and permeability in the studied sandstone reservoir facies, we theorised that the onshore subsurface equivalents of the Cycles I-III would be significantly affected by the sediment compaction, owing to the overburden loads on the reservoir units. Notwithstanding the promising organic geochemical datasets of the Nyalau Formation, the poor reservoir quality establishes that non-connected pore spaces within the carrier beds would constitute significant petroleum exploration risk in the study area. This is particularly true for facies associations 2 and 3 that are interpreted to have been deposited alongside mud-rich lithological components within the intertidal zone (Fig. 12). Although published data on the Upper Cape

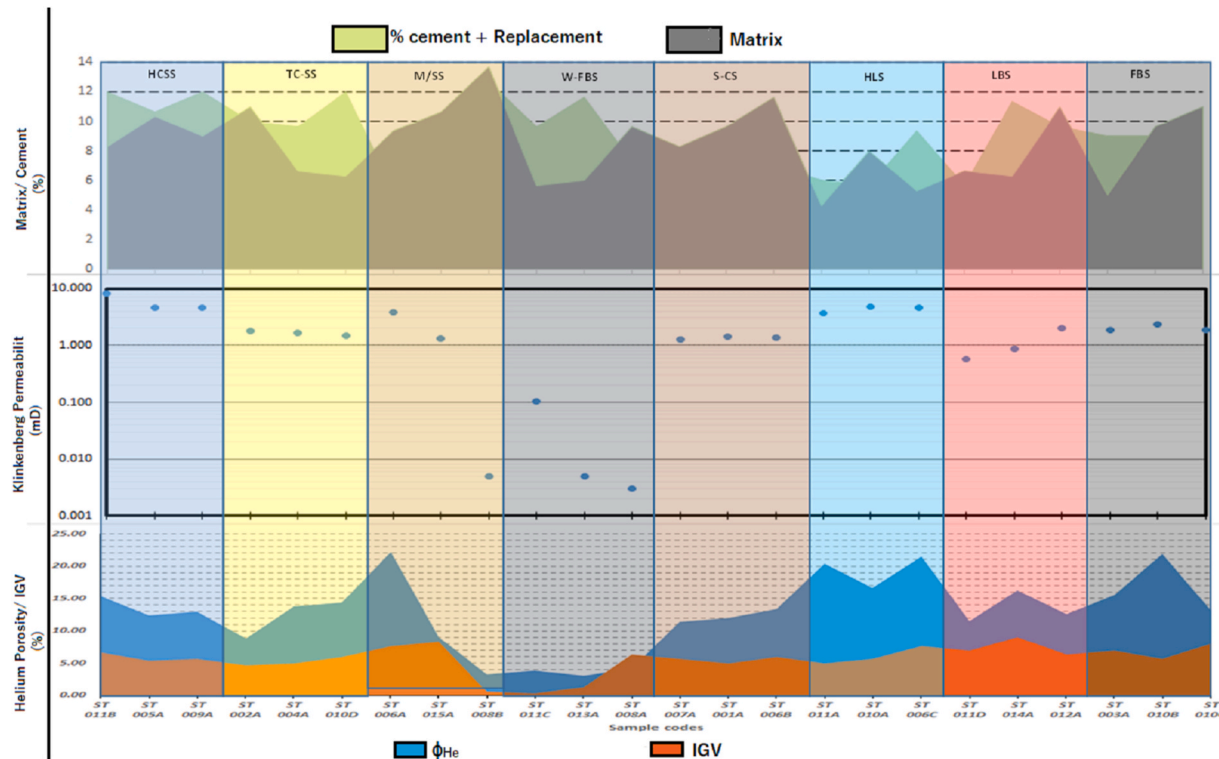


Fig. 14. Correlation panel showing the variation of petrophysical parameters with point counted cement and matrix. Cement here represents the total sum of quartz overgrowth, quartz cement, feldspar cement, pore filling illite, replaced feldspar, carbonate cement, clay coating, chlorite, mica, pyrite, and hematite.

Hay Formation tidal sandstones, Bonaparte Basin, Australia indicates inconsistent preservation of porosity (20%) and permeability (100 mD) in intertidal sandstones at depth below 3575 feet (Saïag et al., 2016), the conspicuous reduction in these petrophysical parameters that is consistent with increasing clay components gives credence to this interpretation.

Although the dissolution of mineral grains yielded some secondary porosity (e.g., Figs. 7d and 8d, f), the partial to complete filling of the secondary pores by authigenic minerals (Figs. 7 and 8) in most samples indicate that the subsurface sequence would perhaps experience consistent porosity loss with depth. Facies representing the subtidal to intertidal wavy-flaser bedded sandstone would have experienced greater porosity loss due to its high mud proportion. In contrast, high energy depositional facies, such as hummocky cross-stratified sandstones and trough cross-bedded sandstone would perhaps yield greater resistance to diagenetic modifications in the subsurface. Overall, production from the Nyalau Formation in the onshore Central Sarawak Basin would warrant a significantly enhanced recovery procedure to mitigate the effects of the arrays of facies and diagenetic heterogeneities in the studied reservoirs to ensure optimum recovery. This contribution shows that depositional signatures of coastal reservoirs could have a lasting impact on reservoir quality, notwithstanding the overprint of diagenetic alterations. Thus, it provides useful insights into assessing coastal sandstones' reservoir quality in other petroleum provinces of the world.

6. Conclusions

The reservoir sandstones of the coastal Nyalau Formation in Onshore Sarawak comprises of eight reservoir facies: (1) the hummocky cross-stratified sandstone, (2) trough cross-stratified sandstone, (3) massive/structureless sandstone, (4) wavy-to flaser bedded sandstones, (5) silty-to clayey sandstones, (6) horizontally laminated sandstones, (7) lenticular bedded sandstones, (8) flaser bedded sandstones, which are

amalgamated into three reservoir facies associations and interpreted to be deposited as shoreface, subtidal-to-intertidal, and tidal mudflat deposits. The reservoirs sandstones are tight to open, with porosity as low as 3.07% and permeability range between 0.003 and 8.285 mD. Shoreface deposits would yield better reservoir quality than siliciclastic reservoirs deposited in the intertidal zone. Illite, mica, and undistinguished clay minerals are vertically enriched with depth in the outcrops, while feldspar and quartz composition generally dwindle with increasing depth. Although mineral grain dissolution created significant secondary porosity, the development of authigenic quartz crystals, clays, and other precipitated materials significantly reduced pore spaces. Increased quartz composition yielded an insignificant increase in the poro-perm trend while increasing feldspar and lithic fragments compositions resulted in a steady decline in porosity and permeability values. Similarly, chlorite and illite contents of the sandstone have an inverse relationship with porosity and permeability, while kaolinite appears to give rise to microporosity significantly. Modifications of the initial depositional conditions yielded complex interaction dynamics between the dissolution of primary grains and precipitated clay by-products in a closed sandstone system. The study shows that authigenic imprints can produce heterogeneous reservoir quality in sandstones notwithstanding the uniformity of depositional conditions or facies.

Declarations

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Availability of data and material

Additional data used are uploaded as appendix 1.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

- Abdullah, W.H., 1997a. Evidence of early generation of liquid hydrocarbon from suberinite as visible under the microscope. *Org. Geochem.* 27 (7), 591–596.
- Abdullah, W.H., 1997b. Common lipinitic constituents of Tertiary coals from the Bintulu and Merit-Pila coalfield, Sarawak, and their relation to oil generation from coal. *Geol. Soc. Malays. Bull.* 41, 85–94.
- Adepehin, E.J., 2019. Reservoir Quality Study of Oligo-Miocene Siliciclastic Sandstones in Onshore Central Sarawak, NW Borneo: Implications from Outcrops and Subsurface Datasets. PhD thesis. submitted to the National University of Malaysia, p. 299pp.
- Adepehin, E.J., 2014. Petrophysical Effect of Clay Heterogeneity on Reservoirs Properties. Lambert Academic Publishing, Saarbrücken, Germany, ISBN 3659523631, p. 168pp.
- Adepehin, E.J., Ali, C.A., Zakaria, A.A., Konjing, Z., 2020. Post-depositional controls on siliciclastic tight reservoirs: implications from the oligocene Nyalau Formation (cycle 1), onshore central Sarawak, Borneo. *Mar. Petrol. Geol.* 111, 786–806 [org/10.1016/j.marpetgeo.2019.09.004](https://doi.org/10.1016/j.marpetgeo.2019.09.004).
- Adepehin, E.J., Ali, C.A., Zakaria, A.A., Bankole, O.M., 2019c. Occurrences and characterisation of textural and mineralogical heterogeneities in analogue reservoir sandstones: case study of the onshore Central Sarawak, NW Borneo. *Arabian J. Geosci.* 12 (16), 1–22.
- Adepehin, E.J., Ali, C.A., Zakaria, A.A., Sali, S., 2019b. Predicting fluid-flow controls in recycled orogenic sandstones: the Nyalau Formation, onshore Sarawak Basin, NW Borneo, 1. In: EAGE/AAPG Workshop on Reducing Exploration Risk in Rift Basins, vol. 2019. European Association of Geoscientists & Engineers, pp. 1–5. [org/10.3997/2214-4609.202076011](https://doi.org/10.3997/2214-4609.202076011).
- Adepehin, E.J., Ali, C.A., Zakaria, A.A., 2019a. Textural and petrological characteristics of possible reservoir sandstones in the onshore Balingian Province, NW Borneo. In: AIP Conference Proceedings, vol. 2111. AIP Publishing, 060002. <https://doi.org/10.1063/1.5111264>, 1.
- Adepehin, E.J., Ali, C.A., Zakaria, A.A., Sali, M.S., 2018. An overview of 20 years' hydrocarbon exploration studies and findings in the Late Cretaceous-to-Tertiary Onshore Central Sarawak, NW Borneo: 1997–2017 in retrospect. *J. Petrol. Explor. Prod. Technol.* 9 (3), 1593–1614 [org/10.1007/s13202-018-0591-8](https://doi.org/10.1007/s13202-018-0591-8).
- Ahfaf, M.M.A., Adepehin, E.J., Ali, C.A., Jamil, H., Lubi, S.P., 2021a. Controls on the compositional framework and petrogenesis of Early Cretaceous first cycle quartzose sandstone, North Gondwana. *Sediment. Geol.* 424, 105982 [org/10.1016/j.sedgeo.2021.105982](https://doi.org/10.1016/j.sedgeo.2021.105982).
- Ahfaf, M.M.A., Ali, C.A., Jamil, H., Adepehin, E.J., 2021b. Pore modification mechanisms in a deeply buried non-marine sandstone: the early cretaceous upper sarir sandstone formation, sirte basin, Libya. *J. Petrol. Sci. Eng.* 205, 108813 [org/10.1016/j.petrol.2021.108813](https://doi.org/10.1016/j.petrol.2021.108813).
- Ajdukiewicz, J.M., Lander, R.H., 2010. Sandstone reservoir quality prediction: the state of the art. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 94 (8), 1083–1091.
- Amir Hassan, M.H., Johnson, H.D., Allison, P.A., Abdullah, W.H., 2016. Sedimentology and stratigraphic architecture of a Miocene retrogradational, tide-dominated delta system: Balingian Province, offshore Sarawak, Malaysia. In: Hampson, G.J., Reynolds, A.D., Kostic, B., Wells, M.R. (Eds.), *Sedimentology of Paralic Reservoirs: Recent Advances*, vol. 444. Geological Society, London, Special Publications, pp. 215–250. <https://doi.org/10.1144/SP444.12>.
- Amir Hassan, M.H., Johnson, H.D., Allison, P.A., Abdullah, W.H., 2013. Sedimentology and stratigraphic development of the upper Nyalau Formation (Early Miocene), Sarawak, Malaysia: a mixed wave-and tide-influenced coastal system. *J. Asian Earth Sci.* 76, 301–311.
- Amir Hassan, M.H., Johnson, H.D., 2012. Fieldtrip to NW Sarawak: sedimentological aspects of river-, wave- and tide-influenced coastal depositional systems: the Early Miocene Nyalau Formation. Bintulu, Sarawak 1, 61 (Petrofac Malaysia Ltd).
- Baniak, G.M., Gingras, M.K., Burns, B.A., Pemberton, S.G., 2015. Petrophysical characterization of bioturbated sandstone reservoir facies in the upper Jurassic Ula formation, Norwegian North Sea, Europe. *J. Sediment. Res.* 85 (1), 62–81.
- Barshap, D.V., Worden, R.H., 2022. Reservoir quality and sedimentology in shallow marine sandstones: interplay between sand accumulation and carbonate and clay minerals. *Mar. Petrol. Geol.* 135, 105398 [org/10.1016/j.marpetgeo.2021.105398](https://doi.org/10.1016/j.marpetgeo.2021.105398).
- Beard, D.C., Weyl, P.K., 1973. Influence of texture on porosity and permeability of unconsolidated sand. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 57 (2), 349–369.
- Ben-Awuah, J., Eswaran, P., 2015. Effect of bioturbation on reservoir rock quality of sandstones: a case from the Baram Delta, offshore Sarawak, Malaysia. *Petrol. Explor. Dev.* 42 (2), 223–231.
- Bjørlykke, K., 2014. Relationships between depositional environments, burial history, and rock properties. Some principal aspects of diagenetic process in sedimentary basins. *Sediment. Geol.* 301, 1–14.
- Bjørlykke, K., 1984. Formation of secondary porosity: how important is it? In: McDonald, D.A., Surdam, R.C. (Eds.), *Clastic Diagenesis (Part 2 Aspects of Porosity Modification)*, vol. 37. AAPG Memoir, pp. 277–286.
- Bjørlykke, K., Jahren, J., 2012. Open or closed geochemical systems during diagenesis in sedimentary basins: constraints on mass transfer during diagenesis and the prediction of porosity in sandstone and carbonate reservoirs. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 96 (12), 2193–2214.
- BouDagher-Fadel, M.K., 2015. Biostratigraphic and Geological Significance of Planktonic Foraminifera, Updated second ed. UCL Press, London, p. 298.
- BouDagher-Fadel, M.K., 2018. Evolution and Geological Significance of Larger Benthic Foraminifera. UCL Press, London, p. 693.
- Breitfeld, H.T., Hennig-Breitfeld, J., BouDagher-Fadel, M.K., Hall, R., Galin, T., 2020. Oligocene-Miocene drainage evolution of NW Borneo: stratigraphy, sedimentology, and provenance of Tatau-Nyalau province sediments. *J. Asian Earth Sci.* 195, 104331 [org/10.1016/j.jseas.2020.104331](https://doi.org/10.1016/j.jseas.2020.104331).
- Brindley, G.W., Brown, G., 1980. Crystal Structure of Clay Minerals and Their X-Ray Identification. Mineralogical Society, London, p. 495p.
- Chuhan, F.A., Bjørlykke, K., Lowrey, C.J., 2001. Closed system burial diagenesis in reservoir sandstones: examples from the Garm Formation at Haltenbanken area, offshore mid-Norway. *J. Sediment. Res.* 71 (1), 15–26. <https://doi.org/10.1306/041100710015>.
- Buatois, L., Mangano, G., Carr, T., 1999. Sedimentology and ichnology of Paleozoic estuarine and shoreface reservoirs, Morrow Sandstone, Lower Pennsylvanian of southwest Kansas, USA. *Curr. Res. Earth Sci.* 1–35. <https://doi.org/10.17161/cres.v0i243.11783>.
- Chuhan, F.A., Bjørlykke, K., Lowrey, C., 2000. The role of provenance in illitization of deeply buried reservoir sandstones from Haltenbanken and North Viking Graben, offshore Norway. *Mar. Petrol. Geol.* 17 (6), 673–689.
- Collins, D.S., Johnson, H.D., Baldwin, C.T., 2020. Architecture and preservation in the fluvial to marine transition zone of a mixed-process humid-tropical delta: middle Miocene Lambir Formation, Baram Delta Province, north-west Borneo. *Sedimentology* 67 (1), 1–46.
- Collins, D.S., Johnson, H.D., Allison, P.A., Damit, A.R., 2018. Mixed process, humid-tropical, shoreline-shelf deposition and preservation: middle Miocene-Modern Baram Delta Province, northwest Borneo. *J. Sediment. Res.* 88 (4), 399–430.
- Cullen, A., 2014. Nature and significance of the West Baram and tinjar lines, NW Borneo. *Mar. Petrol. Geol.* 51, 197–209.
- Dalrymple, R.W., 1992. Tidal depositional systems. In: Walker, R.G., James, N.P. (Eds.), *Facies Models: Response to Sea-Level Changes*, pp. 195–218.
- Dalrymple, R.W., Knight, R.J., Zaitlin, B.A., Middleton, G.V., 1990. Dynamics and facies model of a macrotidal sand-bar complex, coquebay bay—salmon river estuary (bay of fundy). *Sedimentology* 37 (4), 577–612.
- Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *J. Sediment. Res.* 62 (6), 1130–1146.
- de Oliveira, G.L.P., Ceia, M.A., Missagia, R.M., Archilha, N.L., Figueiredo, L., Santos, V. H., Neto, L.L., 2016. Pore volume compressibilities of sandstones and carbonates from Helium porosimetry measurements. *J. Petrol. Sci. Eng.* 137, 185–201.
- Dim, C.I.P., Onuoha, K.M., Okwara, I.C., Okonkwo, I.A., Ibemesi, P.O., 2019. Facies analysis and depositional environment of the campano-maastrichtian coal-bearing mamu Formation in the anambra basin, Nigeria. *J. Afr. Earth Sci.* 152, 69–83.
- Dott, R.H., Bourgeois, J., 1982. Hummocky stratification: significance of its variable bedding sequences. *Geol. Soc. Am. Bull.* 93, 663–680.
- Dumas, S., Arnott, R.W.C., 2006. Origin of hummocky and swaley cross-stratification—the controlling influence of unidirectional current strength and aggradation rate. *Geology* 34 (12), 1073–1076.
- Ehrenberg, S.N., 1993. Preservation of anomalously high porosity in deeply buried sandstones by grain-coating chlorite: examples from the Norwegian continental shelf. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 77 (7), 1260–1286.
- Folk, R.L., 1968. Petrology of Sedimentary Rocks. Hemphill's, Austin, Texas, p. 170.
- Fui, H.K., 1978. Stratigraphic framework for oil exploration in Sarawak. *Geol. Soc. Malays. Bull.* 10, 1–14.
- Giles, M.R., De Boer, R.B., 1989. Secondary porosity: creation of enhanced porosities in the subsurface from the dissolution of carbonate cements as a result of cooling formation waters. *Mar. Petrol. Geol.* 6 (3), 261–269. [https://doi.org/10.1016/0264-8172\(89\)90005-6](https://doi.org/10.1016/0264-8172(89)90005-6).

- Giles, M.R., De Boer, R.B., 1990. Origin and significance of redistributional secondary porosity. *Mar. Petrol. Geol.* 7 (4), 378–397. [https://doi.org/10.1016/0264-8172\(90\)90016](https://doi.org/10.1016/0264-8172(90)90016).
- Gingras, M.K., MacEachern, J.A., Dashtgard, S.E., Ranger, M.J., Pemberton, S.G., Hein, F., 2016. The significance of trace fossils in the McMurray Formation, Alberta, Canada. *Bull. Can. Petrol. Geol.* 64 (2), 233–250.
- Gugliotta, M., Kurcinka, C.E., Dalrymple, R.W., Flint, S.S., Hodgson, D.M., 2016. Decoupling seasonal fluctuations in fluvial discharge from the tidal signature in ancient deltaic deposits: an example from the Neuquén Basin, Argentina. *J. Geol. Soc.* 173 (1), 94–107.
- Guillen, A., Calcagno, P., Courrioux, G., Joly, A., Ledru, P., 2008. Geological modelling from field data and geological knowledge: Part II. Modelling validation using gravity and magnetic data inversion. *Phys. Earth Planet. In.* 171 (1–4), 158–169.
- Hall, R., 1998. The plate tectonics of Cenozoic SE Asia and the distribution of land and sea. In: Hall, R., Halloway, J.D. (Eds.), *Biogeography and Geological Evolution of SE Asia*. Backhuys Publishers, Leiden, The Netherlands.
- Higgs, K.E., Zwingmann, H., Reyes, A.G., Funnell, R.H., 2007. Diagenesis, porosity evolution, and petroleum emplacement in tight gas reservoirs, Taranaki Basin, New Zealand. *J. Sediment. Res.* 77 (12), 1003–1025. <https://doi.org/10.2110/jsr.2007.095>.
- Houseknecht, D.W., 1987. Assessing the relative importance of compaction processes and cementation to reduction of porosity in sandstones. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 71 (6), 633–642.
- Howell, J.A., Skorstad, A., MacDonald, A., Fordham, A., Flint, S., Fjellvoll, B., Manzocchi, T., 2008. Sedimentological parameterization of shallow-marine reservoirs. *Petrol. Geosci.* 14 (1), 17–34.
- Hubbard, D.K., Oertel, G., Nummedal, D., 1979. The role of waves and tidal currents in the development of tidal-inlet sedimentary structures and sand body geometry; examples from North Carolina, South Carolina, and Georgia. *J. Sediment. Res.* 49 (4), 1073–1091.
- Hutchison, C.S., 2005. *Geology of North-West Borneo*. Sarawak, Brunei and Sabah. Elsevier, Amsterdam, Netherlands, p. 421.
- Jackson, M.D., Yoshida, S., Muggeridge, A.H., Johnson, H.D., 2005. Three-dimensional reservoir characterization and flow simulation of heterolithic tidal sandstones. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 89 (4), 507–528.
- Jiang, L., Liu, Y., Teng, Y., Zhao, J., Zhang, Y., Yang, M., Song, Y., 2017. Permeability estimation of porous media by using an improved capillary bundle model based on micro-CT derived pore geometries. *Heat Mass Tran.* 53 (1), 49–58.
- Jong, J., Idris, H.A.B.M., Barber, P., Kessler, F.L., Tan, T.Q., Uchimura, R., 2017. Exploration history and petroleum systems of the onshore Baram Delta, northern Sarawak, Malaysia. *Bull. Geol. Soc. Malays.* 63, 1–24.
- Kazimierz, T., Jacek, T., Stanislaw, R., 2004. Evaluation of rock porosity measurement accuracy with a helium porosimeter. *Acta Montanistica Slovaca Rocnik* 9, 316–318.
- Kumar, N., Sanders, J., 1976. Characteristics of shoreface storm deposits; modern and ancient examples. *J. Sediment. Res.* 46 (1), 145–162. <https://doi.org/10.1306/212F6EDD-2B24-11D7-8648000102C1865D>.
- La Croix, A.D., MacEachern, J.A., Ayranci, K., Hsieh, A., Dashtgard, S.E., 2017. An ichnological-assemblage approach to reservoir heterogeneity assessment in bioturbated strata: Insights from the Lower Cretaceous Viking Formation, Alberta, Canada. *Mar. Petrol. Geol.* 86, 636–654. <https://doi.org/10.1016/j.marpetgeo.2017.06.024>.
- Lai, J., Wang, G., Ran, Y., Zhou, Z., Cui, Y., 2016. Impact of diagenesis on the reservoir quality of tight oil sandstones: the case of Upper Triassic Yanchang Formation Chang 7 oil layers in Ordos Basin, China. *J. Petrol. Sci. Eng.* 145, 54–65.
- Lai, J., Wang, G., Wang, S., Cao, J., Li, M., Pang, X., He, Z., 2018. Review of diagenetic facies in tight sandstones: diagenesis, diagenetic minerals, and prediction via well logs. *Earth Sci. Rev.* <https://doi.org/10.1016/j.earscirev.2018.06.009>.
- Legler, B., Hampson, G.J., Jackson, C.A., Johnson, H.D., Massart, B.Y., Sarginson, M., Ravnås, R., 2014. Facies relationships and stratigraphic architecture of distal, mixed tide- and wave-influenced deltaic deposits: lower Sego sandstone, western Colorado, USA. *J. Sediment. Res.* 84 (8), 605–625.
- Liechti, P., Roe, F.W., Haile, N.S., 1960. The geology of Sarawak, Brunei, and the western part of North Borneo. *Borneo Bulletin* vol. 3. Kuching: Geological Survey Department of British Territory in Borneofirst ed.
- Lucas, S.G., Heckert, A.B., Estep, J.W., Hunt, A.P., Anderson, O.J., 1998. Stratigraphy, paleontology and depositional environments of the lower permian robledo mountains formation of the hueco group, robledo mountains, New Mexico. In: Lucas, S.G., Estep, J.W., Hoffer, J.M. (Eds.), *Permian Stratigraphy and Paleontology of the Robledo Mountains, New Mexico*, Bulletin-New Mexico Museum of Natural History and Science, vol. 12, pp. 29–42.
- Lunt, P., Madon, M., 2017. A review of the Sarawak Cycles: history and modern application. *Bull. Geol. Soc. Malays.* 63, 77–101.
- Madon, M., Kim, C.L., Wong, R., 2013. The structure and stratigraphy of deep-water Sarawak, Malaysia: implications for tectonic evolution. *J. Asian Earth Sci.* 76, 312–333.
- Madon, M., 1999. Basin types, tectono-stratigraphic provinces, structural styles. In: *The Petroleum Geology and Resources of Malaysia*. Kuala Lumpur: PETRONAS, Malaysia, pp. 77–112.
- Madon, M., Abolins, P., 1999. Balingian province. In: *The Petroleum Geology and Resources of Malaysia*, vol. 1. PETRONAS, Kuala Lumpur, pp. 345–367.
- Mansurbeg, H., Morad, S., Salem, A., Marfil, R., El-Ghali, M.A.K., Nystuen, J.P., Caja, M. A., Amorosi, A., Garcia, G., Iglesia, A.L., 2008. Diagenesis and reservoir quality evolution of palaeocene deep-water, marine sandstones, the Shetland-Faroes Basin, British continental shelf. *Mar. Petrol. Geol.* 25, 514–543.
- Manzocchi, T., Carter, J.N., Skorstad, A., Fjellvoll, B., Stephen, K.D., Howell, J., Matthews, J.D., Walsh, J.J., Nepveu, M., Bos, C., 2008. Sensitivity of the impact of geological uncertainty on production from faulted and unfaulted shallow-marine oil reservoirs: objectives and methods. *Petrol. Geosci.* 14 (1), 3–15.
- Mason, T.R., Christie, A.D.M., 1986. Palaeoenvironmental significance of ichnogenus *Diplocraterion* torell from the Permian vryheid formation of the Karoo Supergroup, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 52 (3–4), 249–265.
- Mat-Zin, I.C., Tucker, M.E., 1999. An alternative stratigraphic scheme for the Sarawak Basin. *J. Asian Earth Sci.* 17 (1–2), 215–232.
- Meckel, L.D., 1967. Origin of pottsville conglomerates (pennsylvanian) in the central appalachians. *Geol. Soc. Am. Bull.* 78 (2), 223–258.
- Meshri, I.D., 1986. On the reactivity of carbonic and organic acids and generation of secondary porosity. In: Gautier, D.L. (Ed.), *Roles of Organic Matter in Sediment Diagenesis*, vol. 38. SEPM Special Publication, pp. 123–128.
- Miall, A.D., 1978. Tectonic setting and syndepositional deformation of molasse and other nonmarine-paralic sedimentary basins. *Can. J. Earth Sci.* 15 (10), 1613–1632.
- Middleton, G.V., 1966. Experiments on density and turbidity currents: I. Motion of the head. *Can. J. Earth Sci.* 3 (4), 523–546.
- Middleton, G.V., Hampton, M.A., 1976. Subaqueous sediment transport and deposition by sediment gravity flows. In: Stanley, D.J., Swift, D.J.P. (Eds.), *Marine Sediment Transport and Environmental Management*. John Wiley, New York, NY, pp. 197–218, 1976.
- Mode, A.W., Anyiam, O.A., Solomon, I.J., 2017. Depositional environment and reservoir quality assessment of the Bruks Filed, Niger Delta. *J. Petrol. Explor. Prod. Technol.* 7, 991–1002.
- Mode, A.W., Adepehin, E.J., Anyiam, O.A., 2013. Petrophysical effects of clay heterogeneity on reservoirs' properties: case study of "Brown Field" Niger Delta, Nigeria. *Nigerian Assoc. Petrol. Explor. Bull.* 25 (1), 61–69.
- Moore, D.M., Reynolds Jr., R.C., 1997. *X-ray Diffraction and the Identification and Analysis of Clay Minerals*, second ed. Oxford University Press, Oxford, p. 378p.
- Morad, S., Al-Ramadan, K., Ketzer, J.M., De Ros, L.F., 2010. The impact of diagenesis on the heterogeneity of sandstone reservoirs: a review of the role of depositional facies and sequence stratigraphy. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 94 (8), 1267–1309.
- Nichols, G., 2009. *Sedimentology and Stratigraphy*. John Wiley & Sons, p. 411pp.
- Ola, P.S., Adepehin, E.J., 2017. Sedimentological interpretation of coastal ditch cuttings: implications for subsurface geology and provenance in Dahomey Basin, Nigeria. *Arabian J. Geosci.* 10 (3), 65. <https://doi.org/10.1007/s12517-016-2821-z>.
- Ostermeier, R.M., 1995. Deepwater Gulf of Mexico turbidites-compaction effects on porosity and permeability. *SPE Form. Eval.* 10 (2), 79–85.
- Peng, L., Leman, M., Nasib, B., Karim, R., 2004. Stratigraphic lexicon of Malaysia. In: Kuala Lumpur: Geological Society of Malaysia, p. 162.
- Pittman, E.D., 1992. Relationship of porosity and permeability to various parameters derived from mercury injection-capillary pressure curves for sandstone. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 76 (2), 191–198.
- Plink-Björklund, P., Hampson, G.J., Steel, R.J., Burgess, P.M., Dalrymple, R.W., 2008. Wave-to-tide facies change in a campanian shoreline complex, chimney rock tongue, Wyoming-Utah, USA. *Recent Adv. Model. Shallow Marine Stratigraphy: SEPM (Soc. Sediment. Geol.) Spec. Publ.* 90, 265–291.
- Pryor, W.A., 1973. Permeability-porosity patterns and variations in some Holocene sand bodies. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 57 (1), 162–189.
- Ramón, J., Cross, T., 1997. Characterization and prediction of reservoir architecture and petrophysical properties in fluvial channel sandstones, middle Magdalena Basin, Colombia. *CT&F-Ciencia, Tecnología y Futuro* 1 (13), 19–46.
- Reineck, H.E., Wunderlich, F., 1968. Classification and origin of flaser and lenticular bedding. *Sedimentology* 11 (1–2), 99–104.
- Reinhard, M., Wenk, E., 1951. Geology of the colony of north Borneo. *Geol. Survey Department British Territories Borneo Bull.* 1.
- Reinson, G.E., 1992. Transgressive barrier island and estuarine systems. In: *Facies Models Response to Sea Level*. Geological Association of Canada hlm, Alberta, pp. 179–194.
- Saïag, J., Brigaud, B., Portier, É., Desaubliaux, G., Bucherie, A., Miska, S., Pagel, M., 2016. Sedimentological control on the diagenesis and reservoir quality of tidal sandstones of the upper Cape Hay Formation (permian, Bonaparte Basin, Australia). *Mar. Petrol. Geol.* 77, 597–624.
- Schmidt, V., McDonald, D.A., 1979a. The role of secondary porosity in the course of sandstone diagenesis. In: Scholle, P.A., Schluger, P.R. (Eds.), *Aspects of Diagenesis: SEPM Special Publication*, vol. 26, pp. 175–207.
- Schmidt, V., McDonald, D.A., 1979b. Texture and recognition of secondary porosity in sandstones. In: Scholle, P.A., Schluger, P.R. (Eds.), *Aspects of Diagenesis: SEPM Special Publication*, vol. 26, pp. 209–225.
- Seki, Y., Kennedy, G.C., 1964. The breakdown of potassium feldspar, $KAlSi_3O_8$ at high temperatures and high pressures. *Am. Mineral.* 49 (11–12), 1688–1706.
- Selim, S.S., Wafdy, R., Khadrah, A.A., 2021. Sedimentological analysis and reservoir quality of the early Cenomanian transgressive sandstones, northern Western Desert, Egypt. *J. Petrol. Sci. Eng.* 197, 107948 <https://doi.org/10.1016/j.petrol.2020.107948>.
- Siddiqui, N.A., Mathew, M.J., Ramkumar, M., Sautter, B., Usman, M., Rahman, A.H.A., El-Ghali, M.A., Menier, D., Shiqi, Z., Sum, C.W., 2020. Sedimentological characterization, petrophysical properties and reservoir quality assessment of the onshore Sandakan Formation, Borneo. *J. Petrol. Sci. Eng.* 186, 106771 <https://doi.org/10.1016/j.petrol.2019.106771>.
- Siddiqui, N.A., Rahman, A.H.A., Sum, C.W., Mathew, M.J., Menier, D., 2016. Onshore sandstone facies characteristics and reservoir quality of Nyalau Formation, Sarawak, East Malaysia: an analogue to subsurface reservoir quality evaluation. *Arabian J. Sci. Eng.* 41 (1), 267–280.
- Siebert, R.M., Moncure, G.K., Lahann, R.W., 1984. A theory of framework grain dissolution in sandstones. In: McDonald, D.A., Surdam, R.C. (Eds.), *Clastic Diagenesis (Part 2 Aspects of Porosity Modification)*, vol. 37. AAPG Memoir, pp. 163–175.

- Smith, J.T., Ehrenberg, S.N., 1989. Correlation of carbon dioxide abundance with temperature in clastic hydrocarbon reservoirs: relationship to inorganic chemical equilibrium. *Mar. Petrol. Geol.* 6 (2), 129–135. [https://doi.org/10.1016/0264-8172\(89\)90016-0](https://doi.org/10.1016/0264-8172(89)90016-0).
- Sondergeld, C.H., Ambrose, R.J., Rai, C.S., Moncrieff, J., 2010. Micro-structural studies of gas shales. In: SPE Unconventional Gas Conference. Society of Petroleum Engineers.
- Surdam, R.C., Boese, S.W., Crossey, L.J., 1984. The chemistry of secondary porosity. In: McDonald, D.A., Surdam, R.C. (Eds.), AAPG Memoir vol. 37, 127–150. *Clastic Diagenesis (Part 2 Aspects of Porosity Modification)*.
- Ta, T.K.O., Nguyen, V.L., Tateishi, M., Kobayashi, I., Saito, Y., Nakamura, T., 2002. Sediment facies and Late Holocene progradation of the Mekong River Delta in Bentre Province, southern Vietnam: an example of evolution from a tide-dominated to a tide-and wave-dominated delta. *Sediment. Geol.* 152 (3–4), 313–325.
- Tiab, D., Donaldson, E.C., 2015. *Petrophysics: Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties*, third ed. Gulf professional publishing, Waltham, USA, p. 913.
- Tjia, H.D., 2000. Tectonic and structural development of Cenozoic Basins of Malaysia. In: Geological Society of Malaysia Annual Geological Conference. Geological Society of Malaysia, Pulau Pinang, pp. 3–15.
- Togunwa, O.S., Abdullah, W.H., Hail, M., Jose, P., 2015. Organic geochemical and petrographic characteristics of Neogene organic-rich sediments from the onshore West Baram Delta Province, Sarawak Basin: implications for source rocks and hydrocarbon generation potential. *Mar. Petrol. Geol.* 63, 115–126 [org/10.1016/j.marpetgeo.2015.02.032](https://doi.org/10.1016/j.marpetgeo.2015.02.032).
- Tonkin, N.S., McLroy, D., Meyer, R., Moore-Turpin, A., 2010. Bioturbation influence on reservoir quality: a case study from the Cretaceous Ben Nevis Formation, Jeanne d'Arc Basin, offshore Newfoundland, Canada. *AAPG Bull.* 94 (7), 1059–1078. <https://doi.org/10.1306/12090909064>.
- Wilkinson, M.D., Darby, R.S., Haszeldine, G.D., 1997. Secondary porosity generation during deep burial associated with overpressure leak-off: fulmar Formation, United Kingdom Central Graben. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 81, 803–813.
- Wilson, M.J., Wilson, L., Patey, I., 2014. The influence of individual clay minerals on formation damage of reservoir sandstones: a critical review with some new insights. *Clay Miner.* 49 (2), 147–164. <https://doi.org/10.1180/claymin.2014.049.2.02>.
- Wilson, M.J., Shalaby, M.V., Wilson, L., 2016. Clay mineralogy and unconventional hydrocarbon shale reservoirs in the USA. I. Occurrence and interpretation of mixed-layer R3 ordered illite/smectite. *Earth Sci. Rev.* 158, 31–50.
- Worden, R.H., Burley, S.D., 2003. Sandstone diagenesis: the evolution of sand to stone. *Sandstone diagenesis: Recent and ancient* 4, 3–44.
- Worden, R.H., Morad, S., 2000. Quartz cementation in oil field sandstones: a review of the key controversies. In: Worden, R.H., Morad, S. (Eds.), *Quartz cementation in sandstones* 29, 1–20.
- Wu, H., Zhao, J., Wu, W., Li, J., Huang, Y., Chen, M., 2021. Formation and diagenetic characteristics of tight sandstones in closed to semi-closed systems: typical example from the Permian Sulige gas field. *J. Petrol. Sci. Eng.* 199, 108248 <https://doi.org/10.1016/j.petrol.2020.108248>.
- Wulf, G.R., 1962. Eroded oscillation ripple marks in cretaceous newcastle sandstone, Wyoming, and South Dakota. *J. Sediment. Res.* 32 (2), 327–329.
- Xi, K., Cao, Y., Jähren, J., Zhu, R., Bjørlykke, K., Haile, B.G., Zheng, L., Hellevang, H., 2015. Diagenesis and reservoir quality of the lower cretaceous quantou formation tight sandstones in the southern songliao basin, China. *Sediment. Geol.* 330, 90–107.
- Yuan, G.H., Cao, Y.C., Jia, Z.Z., Gluyas, J., Yang, T., Wang, Y., Xi, K., 2015a. Selective dissolution of feldspars in the presence of carbonates: the way to generate secondary pores in buried sandstones by organic CO₂. *Mar. Petrol. Geol.* 60, 105–119. <https://doi.org/10.1016/j.marpetgeo.2014.11.001>.
- Yuan, G., Gluyas, J., Cao, Y., Oxtoby, N.H., Jia, Z., Wang, Y., Xi, K., Li, X., 2015b. Diagenesis and reservoir quality evolution of the Eocene sandstones in the northern dongying sag, bohai bay basin, east China. *Mar. Petrol. Geol.* 62, 77–89.
- Xu, X., Liu, L., Li, X., Yang, W., Cao, Y., Ma, H., He, A., Wang, R., Leng, H., Zhu, Y., Chen, Z., 2021. Sequence stratigraphy, sedimentary characteristics of barrier coastal sedimentary system of the Benxi Formation (Gaoqiao area, Ordos basin) and favorable reservoir distribution. *Energy Rep* 7, 5316–5329. <https://doi.org/10.1016/j.egy.2021.08.173>.
- Yuan, G., Cao, Y., Gluyas, J., Li, X., Xi, K., Wang, Y., Jia, Z., Sun, P., Oxtoby, N.H., 2015c. Feldspar dissolution, authigenic clays, and quartz cements in open and closed sandstone geochemical systems during diagenesis: typical examples from two sags in Bohai Bay Basin, East China. *AAPG (Am. Assoc. Pet. Geol.) Bull.* 99 (11), 2121–2154.
- Zhang, Y., Kaiser, K., Li, L., Zhang, D., Ran, Y., Benner, R., 2014. Sources, distributions, and early diagenesis of sedimentary organic matter in the Pearl River region of the South China Sea. *Mar. Chem.* 158, 39–48.
- Zheng, Q.L., Li, S.Z., Suo, Y.H., Li, X.Y., Guo, L.L., Wang, P.C., Zhang, Y., Zang, Y.B., Jiang, S.H., Somerville, I.D., 2016. Structures around the tinjar-west Baram line in northern Kalimantan and seafloor spreading in the proto-south China Sea. *Geol. J.* 51, 513–523.
- Zhu, C., Lu, P., 2009. Alkali feldspar dissolution and secondary mineral precipitation in batch systems: 3. Saturation states of product minerals and reaction paths. *Geochem. Cosmochim. Acta* 73 (11), 3171–3200.
- Zhu, X.M., Chen, H.Q., Zhong, D.K., Zhang, Q., Zhang, S.W., Lu, X.X., 2008. Mechanism of secondary pore formation and prediction of favorable reservoir of Paleogene in Jiyang sag, eastern China. *J. China Univ. Geosci.* 19, 675–684.
- Zhu, X.M., Zhong, D.K., Zhang, Q., Zhang, L., 2004. Sandstone diagenesis and porosity evolution of Paleogene in Huimin depression. *Petrol. Sci.* 3, 23–29.
- Zou, C., Zhu, R., Liu, K., Su, L., Bai, B., Zhang, X., Yuan, X., Wang, J., 2012. Tight gas sandstone reservoirs in China: characteristics and recognition criteria. *J. Petrol. Sci. Eng.* 88, 82–91.