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Depositional Environments and Reservoir Quality Potentials of Campanian Sediments at Macgregor, Afikpo Basin, Nigeria

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ABSTRACT

A road-cut section and a quarry face of outcropped Campanian sediments of Afikpo basin were studied to determine the environments of deposition and the reservoir quality potentials of facies. Lithofacies identified include Shale, interlaminated silt and clay, wavy-laminated sandstone, burrowed cross laminated sandstone, cross bedded sandstone and thick/very thick bedded sandstone. To determine intra-facies grain size trend, samples were collected at the base and at the top of facies. Nine samples were analysed for grain size/granulometric properties distribution. Granulometric parameters/ properties were determined using Gradistat software. Grain size distribution curves of all sandstone facies showed that particle grain sizes ranged from fine to pebbles and bimodal which implied the combination of fluvial and marine sourced sediment typical of an estuary. The bivariate plots of intra-facies granulometric parameters however showed the domination of fluvial supply/processes. Facies characteristics and associations indicate that the Campanian sediments were deposited in estuary sub-environments which include Bayhead delta, Tidal inlet fill and Offshore/offshore transition zone. Bayhead delta sandstone is lower coarse- to very coarse- grained, poorly sorted, near symmetrical to positive skewed, varied kurtosis and has an internal depositional surface lined with impermeable mud. Therefore, it has potential for low quality reservoir. But the shoreface sandstone is generally moderately sorted, very fine- to coarse-grained positive skewed, platykurtic to mesokurtic and therefore has potential for good quality reservoir. While tidal inlet fill sandstone is homogenous, mean upper medium grained, moderately sorted, positive to strongly positive skewed and mesokurtic; and therefore, has potential for the highest quality reservoir.

1. Introduction

The Campanian sediments called Nkporo Group, consisting Afikpo sandstone and Nkporo shale in the Afikpo Basin were deposited during the marine transgression phase in one of the cycles of marine transgression and regression that controlled paleo-deposition of sediments in the Southern Benue Trough of Nigeria (Rayment, 1965; Marat, I972).

The regional marine transgression of terrestrial environment characterized by drainage pathways for sediment supply and variable autogenic factors as well as folded and highly indurated bed rocks as a result of the Santonian thermo-tectonic events of folding and magmatic intrusions would have resulted in the deposition and preservation of sediments in sub-paleoenvironments. Such paleo-environments would require adequate outcrop exposure of facies distribution for their interpretations. A sedimentary outcrop is an analogue of subsurface sedimentary architecture that can be studied to understand ancient sedimentary processes and environments. A road-cut through an outcrop and sand quarry face of an outcrop are beautiful cross sections that reveal distribution of lithologies, sedimentary structures, grain sizes and bounding surfaces.

The grain-size trend/distribution and lithofacies types/ characteristics as revealed in an outcrop section help to understand ancient depositional processes and give definite interpretations of depositional environments. Therefore, the study of road-cut sections and quarry faces of a sedimentary outcrop can help to develop sedimentary models that can be used to predict the distribution of sedimentary natural resources in the subsurface and used as a guide in the exploitation of the resources. It can be used as an analogue data to predict the reservoir quality of sands units deposited in a similar tectonic/stratigraphic setting. The road-cut sedimentary ridge and sand quarry site at Macgregor- Afikpo, Afikpo Basin, provided this opportunity. The sedimentary rocks at Macgregor and environs belong to the Nkporo Formation or Group that consist of sandstone and dark to black shales, minor limestone and oolitic ironstone beds (Okoro et al., 2012).

The sandstone member which underlies the hilly terrain of Afikpo main town and that of Macgregor is commonly called the Afikpo sandstone. Stratigraphically, the Nkporo Group and its sandstone Members represent Campanian successions in the Afikpo basin that uncomfortably overlies the Turonian Amasiri Sandstone of the Eze-Aku Group (Simpson, 1954; Reyment, 1965; Ukaegbu and Akpabio, 2009) (Fig. 1).

The paleoenvironment of deposition of Nkporo Formation has been interpreted by some authors. Simpson (1954) and Reyment (1965) have interpreted it as shallow marine and brackish water sediment. Okoro et al. (2012; 2020) interpreted the sandstone members of Nkporo Formation including that of Macgregor and environs as estuarine deposits and the shale member as open marine deposit in a transgressive setting based on lithofacies characteristics. They determined reservoir potential of sandstone facies using thin section characteristics.

Though the sedimentary exposures at Macgregor and environs have been studied by the aforementioned-authors and some others, a recent visitation however showed that erosion and quarry activities have revealed some structures and features probably hitherto not yet documented. Also, none to the best of our knowledge used the combination of lithofacies characteristics with intra-facies grain size gradient, granulometric grain size distribution and bounding surfaces characteristics to determine the environments of deposition and reservoir quality potentials.

The determination of reservoir quality potentials is very important because sandstone deposited in a transgressive setting like that of Afikpo Basin formed petroleum reservoirs in some major petroleum provinces in the world. Therefore, the aim of this paper include: 1) to document the recent revealed structures/features, 2) the advancement on the interpretations of the environments and processes of deposition using the combinations of lithofacies and bounding surfaces characteristics, and intra-facies granulometric properties distributions, and 3) determination of reservoir quality potentials of identified sandstone facies.

1.1. *Geological Setting and Study Area Location*

The Afikpo Basin, where the study area is located, is one of the sub-basins in the Southern Benue Trough of Nigeria (Fig. 1a). The Benue Trough runs diagonally from Northeast to Southwest of Nigeria. It is part of the Cretaceous to early Tertiary Western and Central African Rift System. It is about 800 km long from Gulf of Guinea to Chad basin (Ofoegbu, 1990). It represents the third (R3) and failed arm of R1-R3-R3 (rift-rift-rift) triple junction during the late Jurassic – Early Cretaceous breakup of the western Gondwanaland now located at the Gulf of Guinea of Africa (Burke et al., 1972; Whiteman, 1982). The R1 and R2 successfully opened to form the Atlantic Ocean that today separates the African and south American continental plates, whereas the R3 failed, as an aulacogen and formed the Abakaliki-Benue Trough, now commonly refer to as the Benue Trough of Nigeria.

The Benue Trough is divided into three structural and sedimentation domains: Southern, Central and Northern Benue Troughs. The Southern Benue Trough had a stable platform or craton on the west and east called Anambra and Ikpe platform respectively.

Benue Trough had cycles of sediment deposition between Aptian and Turonian. The first two cycles of depositional processes which include fluvial, marine and fluvio-marine resulted in the deposition and preservation of The Asu River group (Aptian-Albian) and Eze-Aku/Agwu/Keana Formations (Late Cenomanian-Turonian/Coniacian) (Akande et al., 2011). During the Santonian, there was collisional tectonism associated with regional folding and traces of magmatic intrusions along the Benue Trough which resulted in the uplift of sediment fill in the southern Benue Trough to form the Abakaliki anticline. Consequently, the then western Anambra and Eastern Ikpe platforms to the then southern Benue Trough now down warped to form the Anambra and Afikpo Basins respectively (Fig.1a).

After the Santonian compression, the focus of sediment deposition was now in the two basins but with more on the sister Anambra Basin. Conversely, erosion was more on the Afikpo Basin which resulted in the complete removal of the Coniacian Agwu shale and the Campanian sediment now directly overlying the Turonian sediment (Umeji, 2013). The last cycle of sediment depositional processes in the southern Benue Trough resulted in the deposition and preservation of Campano-Maastrichtian sediments called proto-Niger deltaic sequences comprising the marine Enugu/Nkporo Formation, deltaic Mamu Formation, Fluvial or fluviomarine Ajali and Nsukka Formations (Reyment, 1965; Amajor, 1987).

2. Data Set and Method of Study

2.1. *Data Set and Equipment*

Outcrops were used for this study and they are a road-cut sedimentary ridge (L1) and a civil construction sands quarry site (L2) located at Macgregor, along Amasiri – Afikpo Road, Afikpo North Local Government Area of Ebonyi state, Nigeria (Fig. 1b). The global positional system (GPS) coordinates of L1 and L2 are N05°53.63^{I}, E007°55.154^{I} and N05°53.759^{I}, E007°54.897^{I} respectively. The road-cut ridge has a length of about 215 m (Figs. 2a-b), while the quarry site consists of remnant of a sedimentary ridge that has been mined for civil construction sands over the years (Fig. 3).

The sedimentary sections at both locations (L1 and L2) revealed interesting sedimentary architecture and rock properties which include lithologies, physical and biogenic sedimentary structures, bed thicknesses and paleo-depositional surfaces. The equipment used for the outcrops' study are hammer, hand lens, measuring tape, sample bags, pen, handheld global positioning system, camera and compass clinometer.

2.2. Method of Study

To achieve the aim of this research, the method of study was divided into the following sections:

2.2.1. Sedimentary Facies Determination

Field mapping exercise was undertaken to study these physical parameters exposed in the road-cut and quarry sections of the outcrops in order to identify facies and bounding surfaces. The facies were named based on the dominant lithology, sedimentary structures and thickness. The lithofacies identified were labelled accordingly.

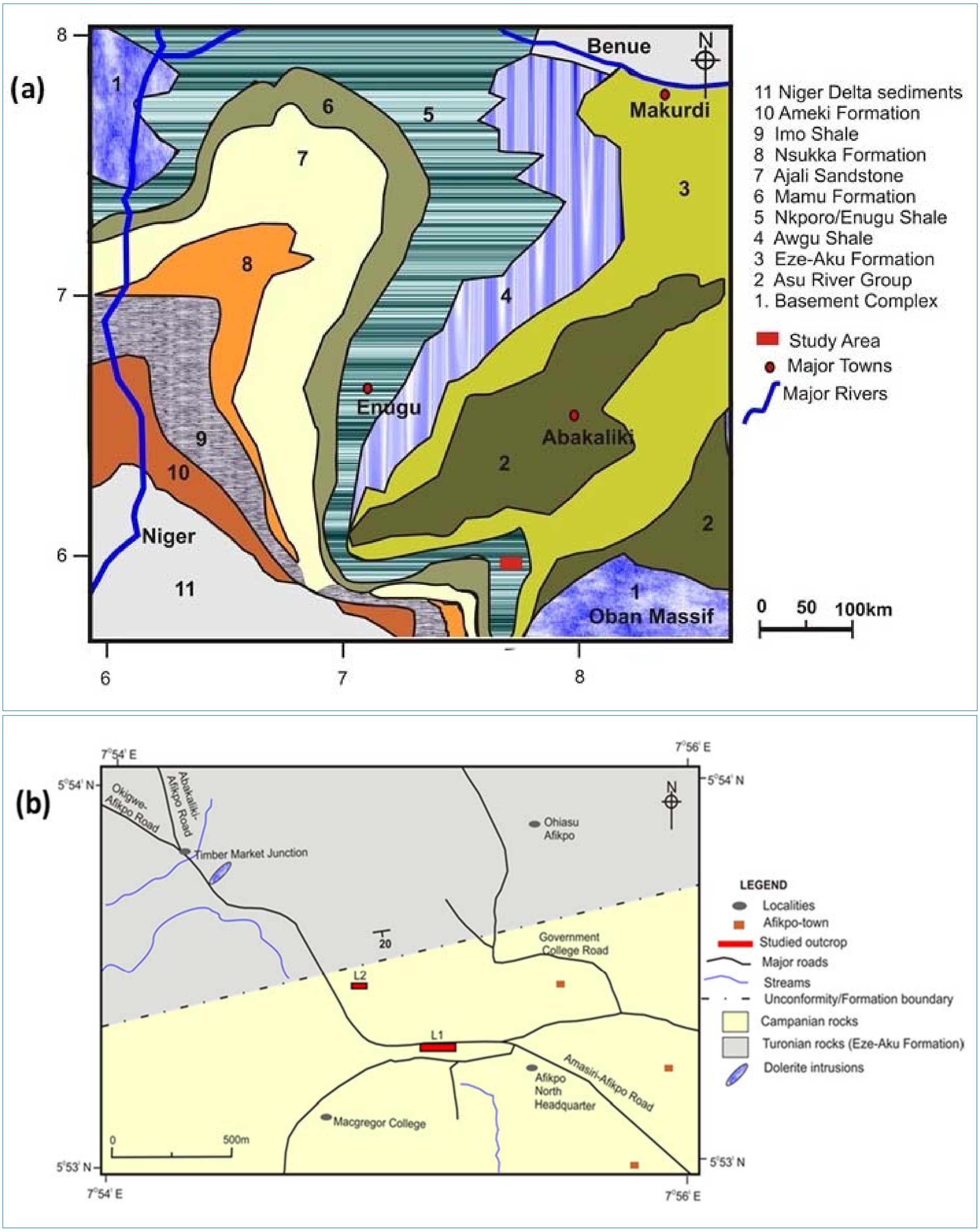

Fig. 1. Fig. 1. (a) Geology map of Southern Benue Trough, consisting Anambra and Afikpo basins, with the study area indicated (after the Nigerian Geological Survey Agency, 2023; Okogbue and Aghamelu, 2010). (b) Geological map showing location of studied outcrop, formation types/boundary, streams, network of roads for accessibility from major cities/towns and localities. L1= Location 1 (road cut ridge). L2 = Location 2 (Sands quarry site)

Fig. 2: (a) Right and (b) left wing of the road-cut sandstone ridge at location 1 showing different facies/sampling spots. Height of the man used for scale is 1.8 m

A photomosaic of outcrops showing bounding surfaces and lithofacies types were taken. A close-up photograph of the diagnostic features of facies were taken with a well-known scaled object in placed. Compass clinometer was used to determine the angles of dips or paleocurrent directions where cross stratifications identified. Beds' thicknesses were measured with a measuring tape and recorded on the field note. Freshly exposed rock samples of facies were taken for laboratory analysis.

Fig. 3. Facies distribution in sand quarry site at location 2. The compass clinometer used for scale is 10 cm long

2.2.2. Grain Size Distribution and Granulometric Properties Determinations

Samples were collected from each facies for grain sizes analysis. Where facies have well defined boundaries, sample was collected at the top and at the bottom and labelled accordingly. Grain size analysis was done using sieving method. Nine samples were altogether collected for analysis.

2.2.2.1. Sieving method and granulometric properties determinations

Samples were pulverized, and ovum dried separately. Between 100 to 150 g was measured out of sample with an electronic weighing balance. The sample was then screened through sets of millimetre sized sieves strapped tight on an electronic shaker and shaken for 10 minutes based on the methods of Folk (1980). The weight of sample retained in each sieve was weighed and its percentage of the initial measured sample weight calculated as percentage weight retained. The cumulative weight of sample retained in each sieve was calculated. The millimetre sieve sizes were converted to phi (ϕ) scale using Krumbein (1934) method with Microsoft excel software. The cumulative percentage weights of samples retained were both plotted against grain sizes using the phi scale with the same excel software. The values of weight retained and the corresponding sieve sizes in phi values were inputted into Gradistat version 9.1 software for the plotting of histogram distribution and the calculations of mean, mode, inclusive graphic standard deviation (sorting), inclusive graphic skewness and kurtosis of grain sizes using Folk and Warden (1957)'s formulas.

2.2.3. Depositional Processes and Environment Determinations

Ichnofossils types/content (diversity and abundance), sedimentary structures, grain size trend and bounding surfaces identified in each facies were first used to infer their environment of deposition. Thereafter, bivariate plot of mean grain sizes and inclusive graphic skewness against inclusive graphic standard deviation (sorting) were used to determine the environmental fields the facies were deposited based on the methods of Friedman (1967) and Folks (1980), respectively. The bivariate plot of inclusive graphic skewness and inclusive graphic standard deviation (sorting) against the median grain sizes were used to established the physical process of sediment deposition based on the method of Stewart (1958), but modified by defining field boundaries using trend direction as the source of sediment, tectonic setting and pleo-climatic condition were taken to be different. The information obtained from the bivariate plots, the granulometric parameters and the associations of facies were combined to establish the definite sub-environments of deposits. Finally, granulometric properties which include mean grain size and inclusive graphic standard deviation (sorting) were used to predict the reservoir quality potentials of the sandstone facies.

3. Results and Interpretations

3.1. Facies Types/Characteristics and Interpretations

This section presents the description and interpretations of facies identified in the outcrops and the interpretations of the intra-facies grainsize sieve analysis results. The derived sieve analysis data and granulometric properties are presented in Tables 1 and 2.

3.1.1. Facies A (FA): Wavy-Laminated Sandstone

This facies is light grey in colour and slightly consolidated. It has no visible burrows. Wavy current laminations are the dominant sedimentary structure (Figs. 2a, 3 and 4). It occurs as the basal unit of the road-cut face of the study outcrop L1. Grain size analysis shows that grain size particles ranged from very fine to very fine gravel but with middle medium as mean or average grain size (Fig. 5a; Table 1). Therefore, it is classified as lightly very fine gravelly coarse sand. The grain size distribution is bimodal (0.73 and 2.24Φ), moderately sorted, fine or positive skewed platykurtic (Fig. 5b; Table 2).

Interpretations: Light grey colour suggests less oxygenated water depth environment. Lack of burrows indicate environment not favourable for the proliferation of macro-organism (MacEachern et al., 2005). The moderate sorting of the grains indicates moderate influence of winnowing wave processes and minimal fluvial influence (Oyanyan and Oti, 2015a). Bimodal distribution of grain sizes suggests two sources of sediment supply (marine and fluvial) but with one dominant. Wavy current laminations indicate wave current deposition above fair-weather wave base in marine environment (Boggs, 2006; Nichols, 2009). The general characteristics suggests lower shoreface or distal delta front deposition as a location where oscillatory and shoaling wave processes operate (Catuneanu, 2006).

Fig. 4. Wavy-laminated sandstone. Length of pen used as scale = 14.3 cm

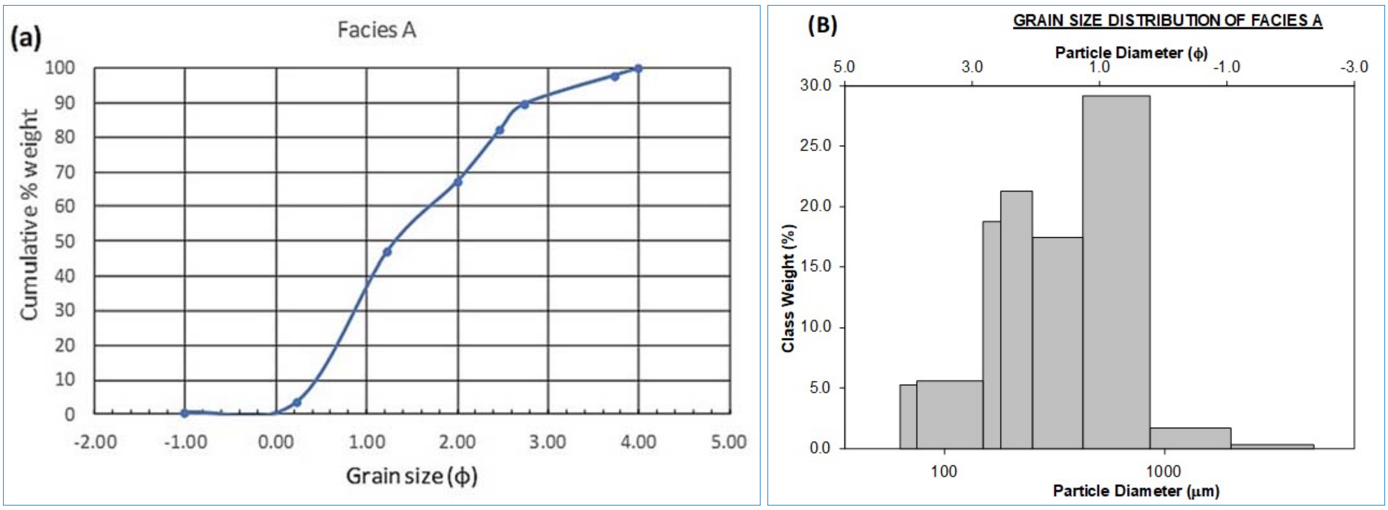

Fig. 5. Grain size distribution in Wavy-Laminated Sandstone (facies A). (a) Cumulative frequency distribution, (b) Histogram showing bimodal grain size distribution

Table 1. Measures from grain size distributions curves for statistical calculations

%	A ϕ sizes	B1 ϕ sizes	B2 ϕ sizes	C1 ϕ sizes	C2 ϕ sizes	D1 ϕ sizes	D2 ϕ sizes	E1 ϕ sizes	E2 ϕ sizes
95	3.32	2.9	2.68	2.63	3.15	2.64	2.52	2.91	2.9
84	2.51	2.5	2.19	1.92	2.04	1.79	1.4	2.05	1.92
75	2.25	2.1	1.72	1.45	1.52	1.22	1.02	1.25	1.39
50	1.32	1.08	0.98	0.92	0.98	0.62	0.3	0.65	0.59
25	0.78	0.61	0.58	0.55	0.62	-0.08	-0.58	-0.09	-2.2
16	0.6	0.41	0.40	0.37	0.48	-0.42	-0.95	-0.42	-2.92
5	0.3	-0.15	0.0	-0.04	0.18	-0.9	-1.6	-1.08	-3.62

Table 2. Statistically derived parameters of grain sizes of samples

Parameters	Facies samples				
	A	B	B2	C1	C2
Median grain size (ϕ)	1.32 Medium sand	1.08 Medium sand	0.98 Coarse sand	0.92 Coarse sand	0.98 Coarse sand
Graphic mean grain size (ϕ)	1.47 Middle medium sand	1.31 Middle medium sand	1.18 Upper medium sand	1.1 Upper medium sand	1.14 Upper medium sand
Inclusive GSD (sorting) (ϕ)	0.94 Mod. sorted	1.07 Poorly sorted	0.94 Mod. sorted	0.88 Mod. sorted	0.92 Mod. sorted
Inclusive graphic Skewness	0.25 PS	0.18 PS	0.20 PS	0.19 PS	0.34 SPS
Kurtosis	0.84 PTK	0.94 MSK	1.04 MSK	1.22 LPK	1.25 LPK

Acronyms: PTK= Platykurtic, MSK= Mesokurtic, LPK = Leptokurtic, VPTK = Very platykurtic, PS = positive skewed, SPS = Strongly positive skewed, Symm. =Symmetrical

3.1.2. Facies B (FB): Burrowed cross Laminated Sandstone

This facies is reddish brown coloured coarse-grained sandstone. It is characterised by vertical and Conjugate *Skolithus* burrows (Figs. 2a, 3 and 6). It is cross laminated with layers' thickness less than 1cm. Fresh surface revealed rare mud drapes on lamination surfaces. The thickness of the lithofacies is approximately 1m. It is underlain by wavy-laminated sandstone (FA) with a gradational boundary and overlain by cross bedded sandstone (described below) with a sharp boundary. It is slightly consolidated. The grain size distribution curves of samples collected from the bottom (B1) and the top (B2) indicate grain size coarsening upward trend with sediment changing from very fine gravelly coarse sand at the bottom to fine gravelly coarse sand at the top (Fig. 7a). Poorly sorted, mean middle medium sands at the bottom grades to moderately sorted, mean upper middle medium sands at the top (Fig 7b; Table 2). Sediment grain size distribution at both bottom and top are however both positive skewed mesokurtic and bimodal (Table 2; Fig. 7b).

Interpretations: Reddish brown colour indicates subaqueous deposition in oxygenated shallow water depth environment and lack of organic matter (Boggs, 2006). The rare mud drapes suggest minor influence of tide fluctuations on sediment deposition in shoreface depositional environment (Dashtgard et al., 2021). Minor tidal influence can be attributed to the reduced rate of accommodation creation via tectonic subsidence as a result of the reduced tectonic activity of the basin after the Santonian thermo-tectonic event. The vertical burrows indicate suspension feeders in an environment of high energy, high rate of sedimentation and shallow water depth, hence represents *skolithus* ichnofacies in transitional marine environment such as middle/upper shoreface or proximal delta front (Pemberton et al, 2009; Oyanyan and Oti, 2015b).

Fig. 6. Conjugate vertical (Skolithus) burrows in burrowed laminated sandstone. At the lower part of the picture are sub-rounded to rounded pebbles eroded down from coarser facies at the upper part of the successions. Length of pen used as scale = 14.3 cm

The low diversity of burrows could be attributed to salinity stress and high sediment supply in brackish water environment. The low ichno-abundance could be attributed to high hydraulic forces associated with wave energy that keep sediment in suspension, thereby increasing the water turbidity that gradually decrease suspension feeding behaviour (Oyanyan and Oti, 2015b). The upward coarsening of grain sizes suggests progradation as result of rate of supply of sediment greater than the rate of sea level rise (Catuneanu, 2006). The same skewness and kurtosis values but increased in sorting from bottom to top indicate constant depositional process but with increasing wave energy in a typical progradation setting.

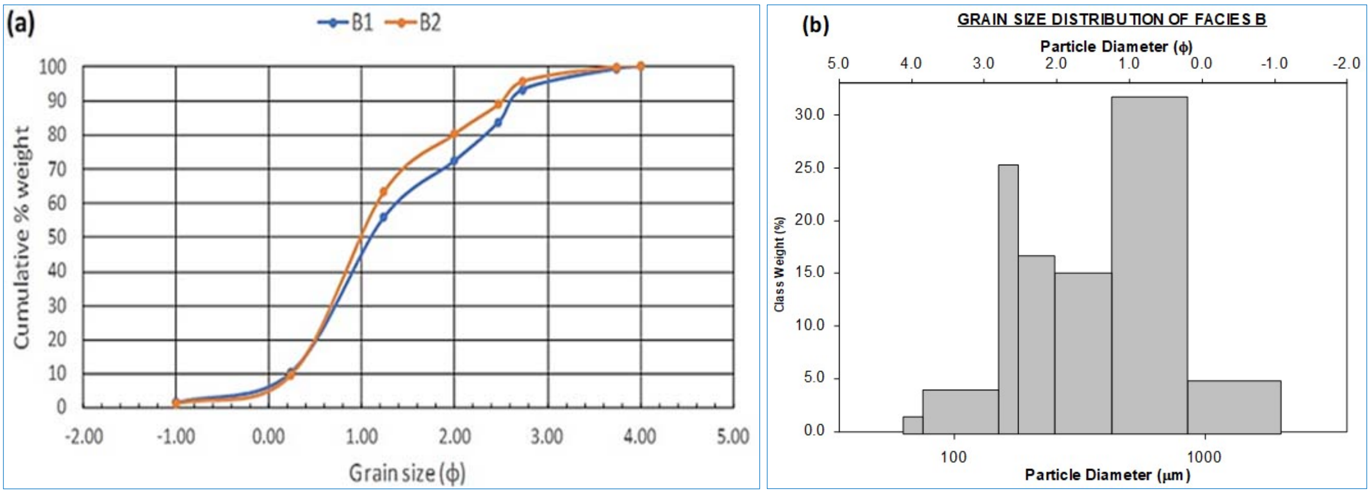

Fig. 7. Grain size distribution in burrowed cross laminated sandstone (facies B). (a) Cumulative frequency distribution curves showing upward coarsening of grains and (b) Histogram showing bimodal grain size distribution

3.1.3. Facies C (FC): Cross Bedded Sandstone

Light brown coloured coarse-grained sandstone. It is characterised by planar cross stratification with layer thickness more than 1cm (Figs. 2a and 8). It is not indurated. At L1, the cross stratifications dips with an average angle of 21° to South West, which is toward the location of the adjacent bed rock (Eze-Aku Formation). No visible mud drapes on freshly exposed bed surfaces, unlike the underlying FB. At L1, the facies thickness ranged from 0.3 to 0.5m as it thins towards the east and thickens towards the west.

The basal contact with underlying facies is sharp (Fig. 3). It is truncated vertically by a flat sharp surface (Fig. 8b). It has rare *palaeophycus* and *skolithus* burrows. The grain size distribution curves of samples collected from the bottom (C1) and the top (C2) showed slight fining upward trend though the mean grain size remained upper medium from bottom to top (Fig. 9; Table 2). The grains are also moderately sorted and leptokurtic at both bottom and top. The grain size skewness however changes from fine or positive skewness at the bottom to very fine or strongly positive skewness at the top. Like the above described facies, grain size distribution is also bimodal.

Interpretations: Light brown colour indicates deposition in an oxygenated environment and lack of organic matter content. The rare burrows indicate high rate of sediment that did not give room for more burrowing by indwelling organisms (Gingras et al, 2007). The lack of mud drapes on bedding surfaces, unlike the underlying lithofacies, indicates the prevalence of strong current that keeps clay and silt particles in suspension during sediment deposition. The cross-beddings truncated by a surface overlain by horizontal beddings indicate migration of straight crested dune in lower flow regime followed by high flow regime plane bed deposition after a period of erosion or sediment non deposition. The dipping of beds towards to location of adjacent bed rock is landward dipping of beds that indicate deposition by flood current during marine transgression. The sharp basal contact, slight fining upward of grains and change from positive skewness at the bottom to strongly positive skewness at the top imply deposition in a channelized unidirectional flow with decreasing current. Same mean grain size, kurtosis and sorting at both top and bottom indicate very little or slight internal variability typical of a tidal inlet fill or deposit (Galloway and Cheng 1985; Hubbard, et al., 2002). The sharp basal contact is therefore interpreted as a tidal ravinement surface (TRS) which results from the landward migration of the zone of maximum tidal energy (Cattaneo and Steel, 2003). The flat sharp top surface boundary indicates the erosion of the older deposits by wave erosion and therefore interpreted as wave ravinement surface (WRS) in a transgressive deposit.

3.1.4. Facies D/E (FD/E): Thick/Very Thick Bedded Sandstone

Succession of thick/very thickly bedded, light brown and slightly very fine gravelly coarse- to fine gravelly coarse-grained sandstones units, "D" and "E" separated by an inclined depositional surface. The depositional surface is lined with gravel around the crest and with thin iron crust down the slope (Figs. 2, 3 and 10). The lower unit "D" has maximum thickness of 1.10 m while the upper unit D has maximum thickness of 1.3 m. The thickness of the facies decreased down-slope. Close-up photo of the gravel veneered surface shows round to well-rounded pebbles (Fig. 10b).

Close-up view of the units shows parallel or horizontal beddings (Fig.10d). The base of the lower unit "D" is a long, sharp and erosive boundary that truncates a planar cross bedded unit below. No trace of bioturbation. Though inclined, no slope controlled soft sediment deformation structures. Grain size distribution curves show coarsening upward trend with mean grain size in facies units D and E grading from lower coarse to upper coarse and very coarse respectively (Figs. 11a and b; Table 2). The grains in the two facies units are generally poorly sorted and slightly bimodal (Figs. 11d and e). Skewness ranged from near symmetrical to positive. The kurtosis changes from mesokurtic in unit "D" to leptokurtic and very platykurtic in unit "E".

Interpretations: The parallel or horizontal beddings surfaces indicate upper flow regime and plane bed deposition typical of high energy depositional environment (Nichol, 2009). An inclined depositional surface lined with impermeable mud indicate clinoform (Patruno and Helland-Hansen, 2018). The thin iron crust is a chemical sediment precipitated from flood water rich in iron oxide (Boggs, 2006). Therefore, the thin iron crust represents the flooding or inundation of depositional surface and water level stabilization when the rate of sediment supply dropped below the rate of continuous relative sea level rise in a transgressive setting. The iron crust was however eroded from dune crest by a high energy current or storm wave. The Gravel veneered part of the inclined surface indicates the effect of stormy wave or high energy erosion on the clinoform. The upward increase in bed thickness indicates continuous increase in rate of sediment supply resulting in a progradational trend. The grain size distribution curves and kurtosis showed coarsening upward successions deposited and preserved under similar environmental conditions of high and increasing energy.

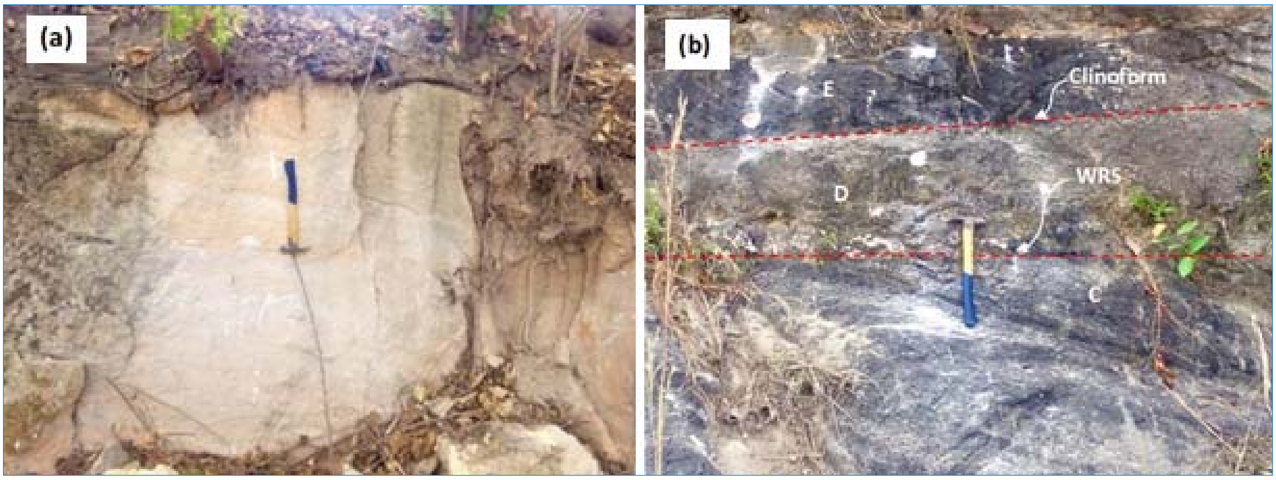

Fig. 8. (a) A fresh surface of Cross bedded sandstone facies (FC) with rare burrows in L1. (b) Shows flat wave ravinement surface (WRC) truncating the inclined or cross bedded sandstone facies (FC) overlain by downdip thinning very thick/thick beds separated by inclined surface (clinoform) in L1. Length of hammer used for scale = 0.47 m

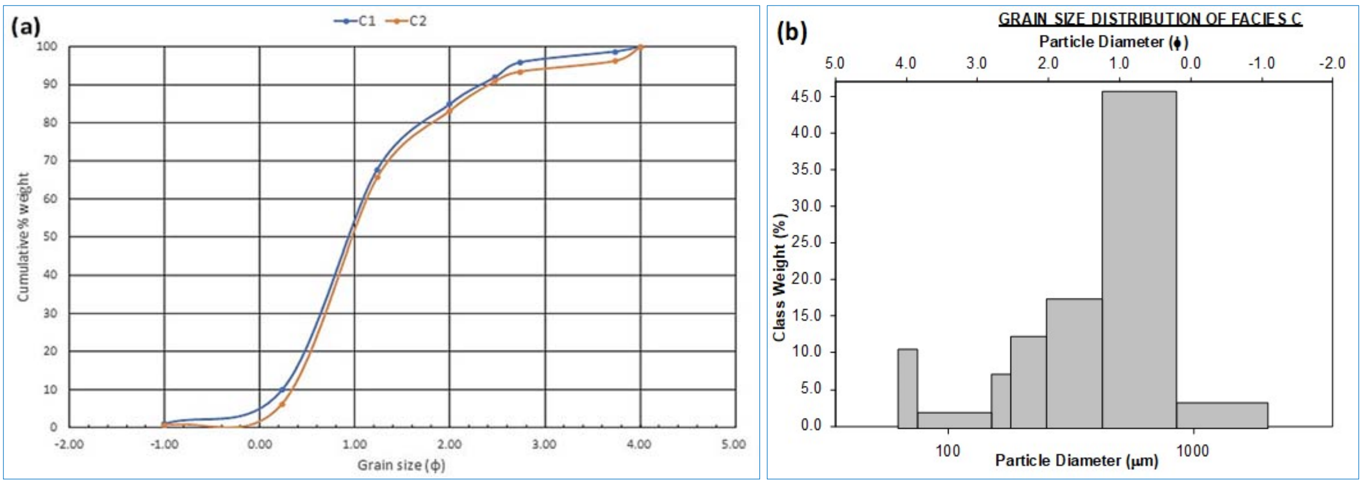

Fig. 9. Grain size distribution curves of cross bedded sandstone (facies C). (a) Cumulative frequency curves showing slight fining upward trend. (b) Histogram distribution of grain sizes showing bimodal distribution

Very coarse grains and poor sorting indicate a direct link to a distributary channel (Olariu and Bhattacharya, 2006). The inclination of strata and the coarsening units implies delta slope progradation (Olariu and Bhattacharya, 2006). The absence of slope-controlled deformation structures implies subaerial delta and not that of open marine (Patruno and Helland-Hansen, 2018). The lack of trace of bioturbation can be attributed to the high rate of sediment supply and rapidly fluctuating brackish- to fresh- water conditions in a typical bayhead deltas (Simms et al., 2018). The combination of poor grains sorting, upward coarsening trend, clinoformed bedsets (clinothems) with downdip decrease in bed thickness and absence of ichnofossils indicate bayhead delta deposit in fluvial or upper estuary (Aschoff, et al., 2018).

3.1.5. Facies SC (FSC): Interlaminated Silt and Clay

Interlaminated silt and clay with alternation of light grey and brown colour. No visible evidence of bioturbation (Fig. 12). It grades downward and upward to shale and wavy laminated sandstone respectively. It outcropped in L2.

Interpretation: Light grey and brown colours indicate lack of organic matter and deposition in less oxygen rich environment. Though slightly rich in oxygen, the lack of bioturbation indicates high clay sediment deposition that did not give room for bioturbation by benthonic organisms. The alternation of light grey and light brown colour indicates variations in water depth induced by tide (Angus et al., 2020). The absence of sand indicates place of deposition quite distant from point of fluvial input. To be underlain by shale and overlain by wave laminated sandstone suggest tidally modulated barred shoreface (Angus et al., 2020). Therefore, it is a product of fluctuating slack-water suspension deposition in tide affected shallow marine environment. It suggests offshore- shoreface transition zone or prodelta depositional environment.

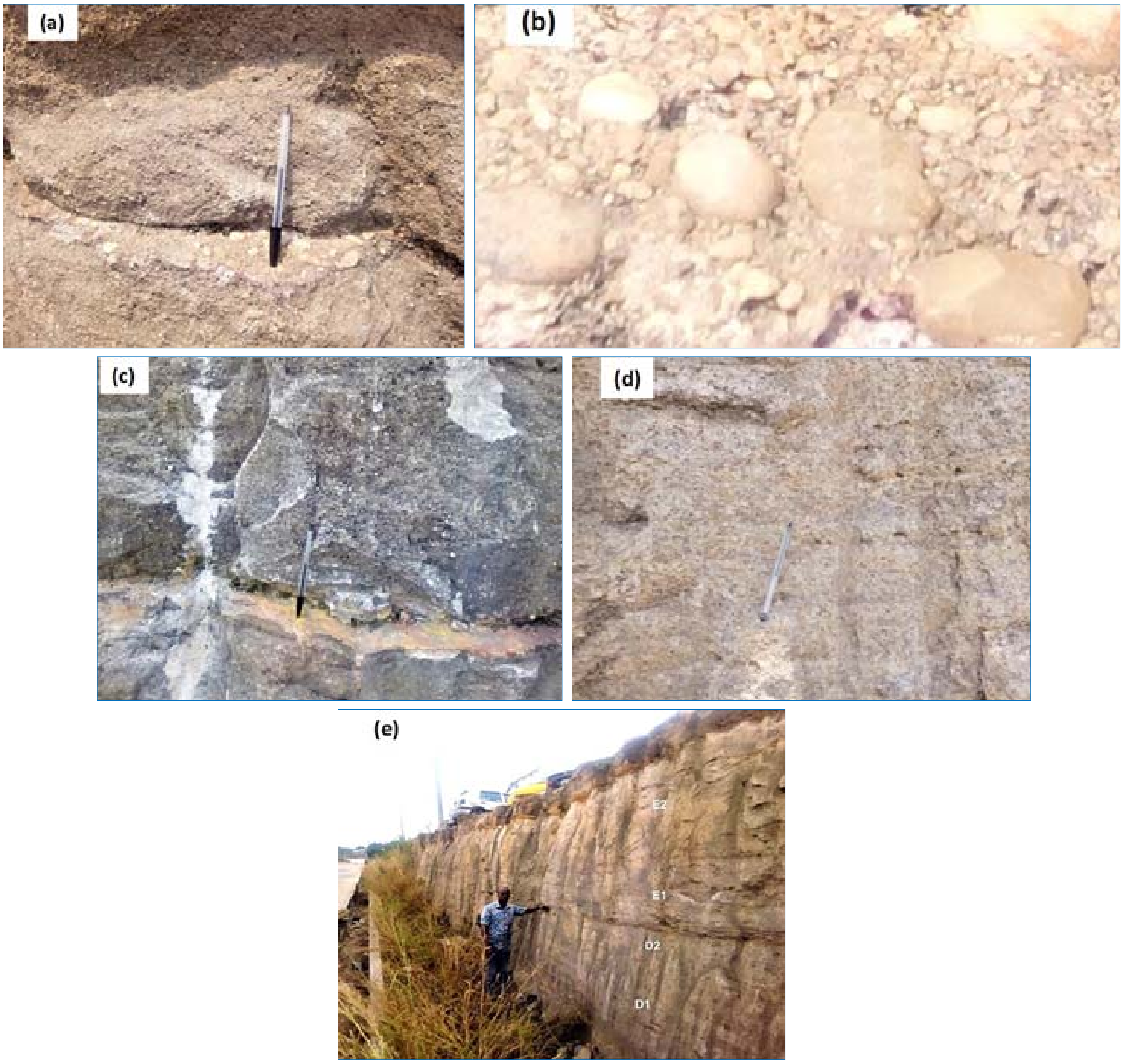

Fig. 10. (a) Close-up picture of the gravel veneered erosive surface separating thick and very thick bedded sandstone units D and E. Pen used for scale is 14.3 cm (b) Close-up picture of the veneer of granules and pebbles on a depositional surface. The pebbles are rounded to well-round. (c) Shows thin iron crust on the erosive surface. (d) Close-up picture of thickly bedded sandstone showing horizontal bedding. Pen used for scale is 14.1 cm. (e) Successions of clinoformed bedset (clinothem), characterised by coarsening upward grain size trend and downdip decrease in thickness. It shows sampling points of facies. Height of the man used for scale = 1.65 m

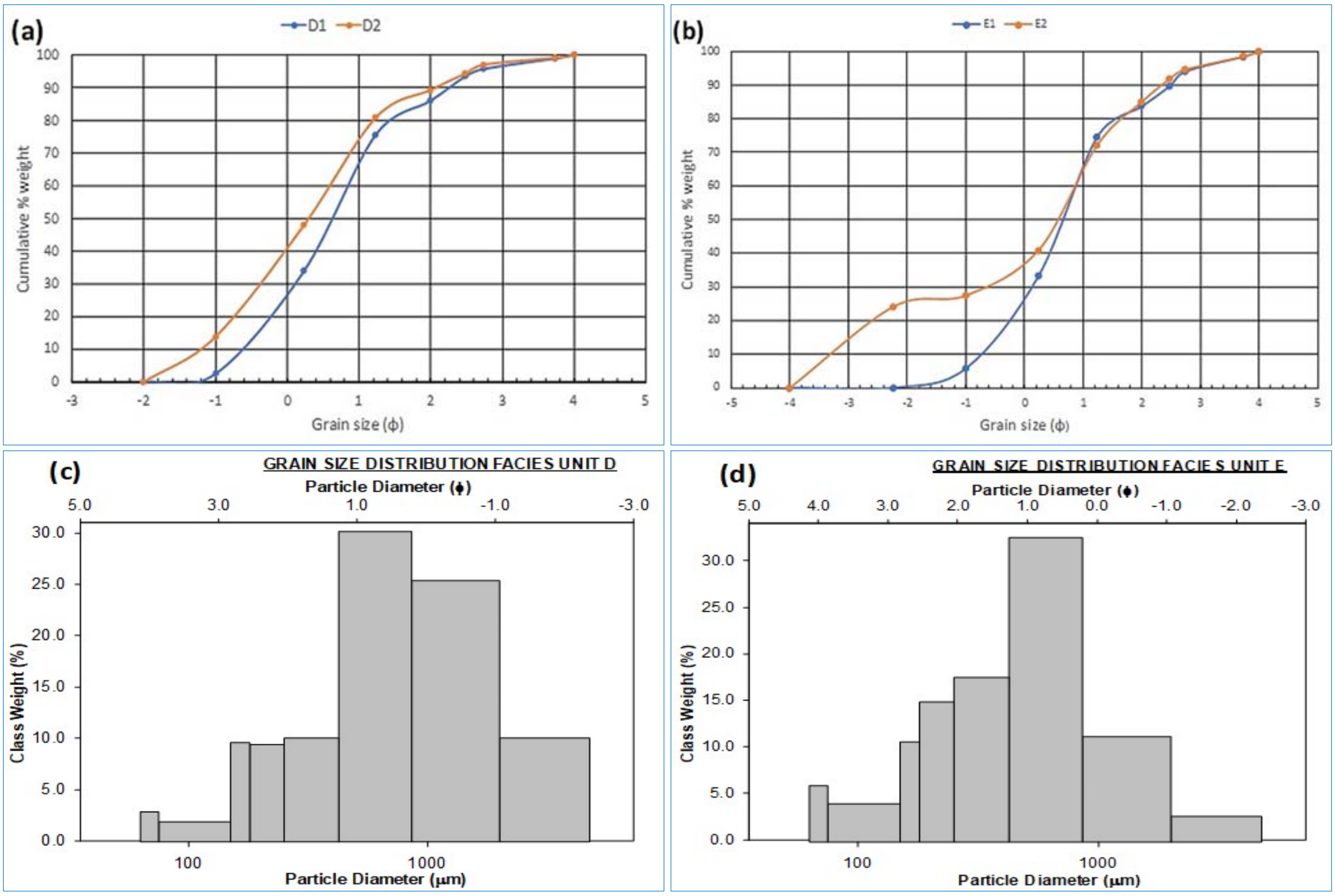

Fig. 11. Grain size distribution curves in thick/very thick bedded sandstone (facies D/E). (a) Cumulative frequency distribution of unit "D" indicating upward coarsening trend and mainly traction deposition. (b) Cumulative frequency curves of unit "E" indicating poor sorting, upward coarsening of grains and mainly traction and minor bedload deposition. (d) and (e) Histogram showing slight bimodal or near symmetrical distribution of grains

Fig. 12. Interlaminated clay and silt grading up to wavy current laminated sandstone at L2. The length of pen used as scale is 14.4 cm

3.1.6. Facies (FS): Shale

This facies is a fissile and dark to brownish grey coloured sedimentary fines (Fig. 13a). Weathered surface is brownish in colour. It is not indurated and lack any traces of bioturbation. It directly overlain the highly indurated Eze-Aku sandstone with a sharp boundary (Fig. 13b). It outcropped only in L2 (Fig. 3).

Interpretations: The boundary between the non-indurated and the highly indurated rock is an unconformity- a disconformity surface (Nichols, 2009). Abrupt change from indurated sandstone to shale indicate marine flooding/ abrupt deepening and the boundary, a flooding surface (Catuneanu, 2006). The flooding surface that merged with the disconformity surface or sequence boundary in the landward side of the basin is a transgressive surface underlying transgressive systems tract (Emery and Meyers, 1998). The dark grey colour suggests organic matter composition. Shale represents suspension settling during slack water in low energy depositional environment. The brownish colouration of weathered surface can be attributed the oxidation of iron sulphide (pyrite) deposited along mud in reducing or anoxic and low energy condition (Nichols, 2009). The lack of bioturbation could be attributed to oxygen stress in an environment of the deposition. Therefore, the shale indicates open marine or offshore depositional environment.

3.2. Bivariate Plots and Interpretations

The cross plots of inclusive graphic skewness versus inclusive graphic standard deviation (sorting) shows that the sandstone facies were all mainly fluvial sourced (Fig. 14a). The dominance of fluvial signatures increased over time from the basal FA to FD/E. This is in line with histogram grain size distribution that shows decreased bimodality of grain size distribution over time such that the percentage weight of secondary modal grains (representing non-fluvial sourced) decreased from 22% in FA to 2.5% in FD (Figs. 5 and 11). Similarly, the cross plot of inclusive standard deviation (sorting) versus the mean grain size showed that all sandstone facies are fluvial sands, and none is beach sands (Fig.14b). The cross plot of median grain size versus standard deviation (sorting) and skewness showed that facies were deposited by fluvial processes except FA and the top of FC (Fig. 15a). The dominance of fluvial process also increased over time from the deposition of FA to that of FD/E. The two cross plots showed that FD/E was deposited in the zone of fluvial processes and distant from the zone of wave process, while the other facies are close to the zone of wave processes. This finding unequivocally implies that the successions of facies unit "D" and "E", though coarse upward and deposited in upper flow regimes, are not beach deposits.

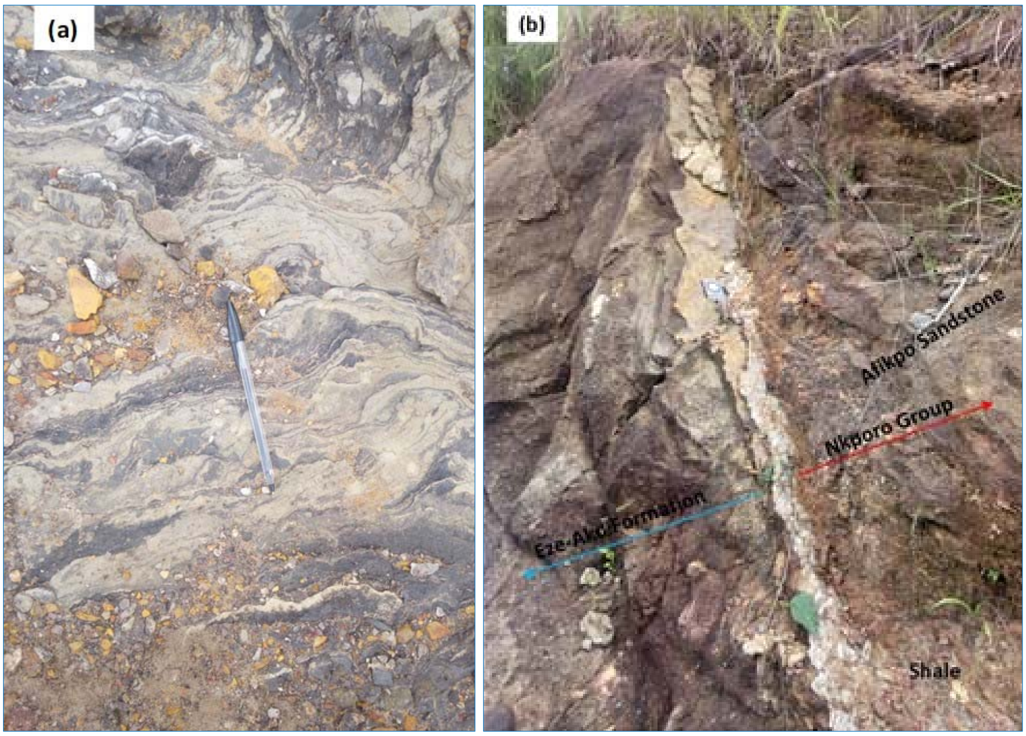

Fig. 13. (a) Dark grey coloured shale. Pen used for scale is 14.3 cm (b) Disconformity/transgressive surface separating the highly indurated Turonian Eze-Aku sandstone and the Campanian sediments at location 2. Compass clinometer used for scale is 10 cm

3.3. Facies Associations and Depositional Environments Interpretations

The characteristics of the described facies and their associations resulted in the identification of the following sub-environments of deposition (Fig 16):

3.3.1. Bayhead Delta

The association of poorly sorted coarsening upward facies units "D" and "E" bounded at the base by relatively flat wave ravinement surface but internally separated by inclined gravel- to mud-lined surface is interpreted as Bayhead delta developed in fluvial or upper estuary (Aschoff et al., 2018; Hubbard et al., 2002). It consists of succession of clinothems that gradually thins down-depositional dip (Figs. 10 and 16). It is mainly fluvial sediment deposited by high energy fluvial process in a transgressive setting as indicated by the poorly sorted coarse grains, lack of trace fossils and the presence of structures of upper flow regime deposition as well as the bivariate plot results. It is therefore interpreted as a regressive bayhead delta that resulted from sediment input overwhelming the rate of relative sea level rise at river mouth to sea boundary (Simms et al., 2018).

3.3.2. Shoreface

This is the region of the shelf between the low-tide mark and the depth to which waves normally affect the sea bottom (Nichols, 2009). The facies association consists of lower shoreface defined by wavy-laminated sandstone (FA) and upper shoreface defined by burrowed crossed laminated sandstone (FB). Generally, it is a moderately sorted, very fine- to coarse-grained sandstone. It has a gradational contact with the underlying interlaminated silt and clay facies (FSC) and truncated on top by erosional surface. The wavy-laminated sandstone implies deposition in a wave dominated shoreface. The combination of shoreface and bayhead or river delta facies in a vertical sequence indicate deposition in wave dominated estuary with the shoreface in lower estuary dominated by wave (Figs. 16 and 17). Shoreface is a basal component of barrier island, whether in transgressive, regressive or aggradational shoreline setting (Galloway and

Cheng 1985). The erosional surface implies that the core barrier or beach facies of the barrier sequence was eroded.

3.3.3. Tidal Inlet Fill

Tidal inlet is a tidal current maintained channel that provides a connection between the ocean and the estuary (FitzGerald et al., 2014). Tidal inlet fill facies was defined by moderate grain size sorting, subdued vertical rain size grain size gradient, scoured basal contact and landward dipping of beds. It pinched out towards the shoreface sediment and thickened toward the location of the adjacent bed rock (the indurated Eze-Aku sandstone), It has sharp basal contact with the underlying shoreface sands and sharp contact with the overlying bayhead delta sands (Fig. 16). Just like the shoreface, tidal inlet fill is also a component of coastal barrier in lower estuary (Fig. 17; Galloway and Cheng, 1985; Catuneanu, 2006).

3.3.4. Offshore/Offshore Transition Zone (Marine)

Marine-offshore/offshore transition zone is defined by the association of shale (FS), and interlaminated silt and clay (FSC) facies (Figs. 16 and 17). They are interpreted to be deposited in anoxic to slightly anoxic environment from above to below storm base as indicated by laminations, colour characteristics and lack of bioturbation. The facies FS grade to facies FSC and then to FB with gradational contacts indicating coarsening upward trend. It has a sharp basal contact with the adjacent indurated Eze-Aku sandstone. The basal contact was interpreted as unconformity/marine transgression surface. Therefore, the facies association represents deposition in marine environment-offshore/ offshore transition zone.

4. Discussion

4.1. Depositional Environments and Transgressive Settings

The facies described above clearly showed successions of coarsening upward units suggesting shoreline progradation. But the stratigraphic setting of Afikpo basin showed that the studied Campanian sediments were deposited in a transgressive setting (Akande et al., 2011). The criteria for recognising deposits of transgressive setting include gradual or irregular landward shift of facies, landward dipping of beds and upward deepening of facies culminating in a zone or surface of maximum flooding (Cattaneo and Steel, 2003).

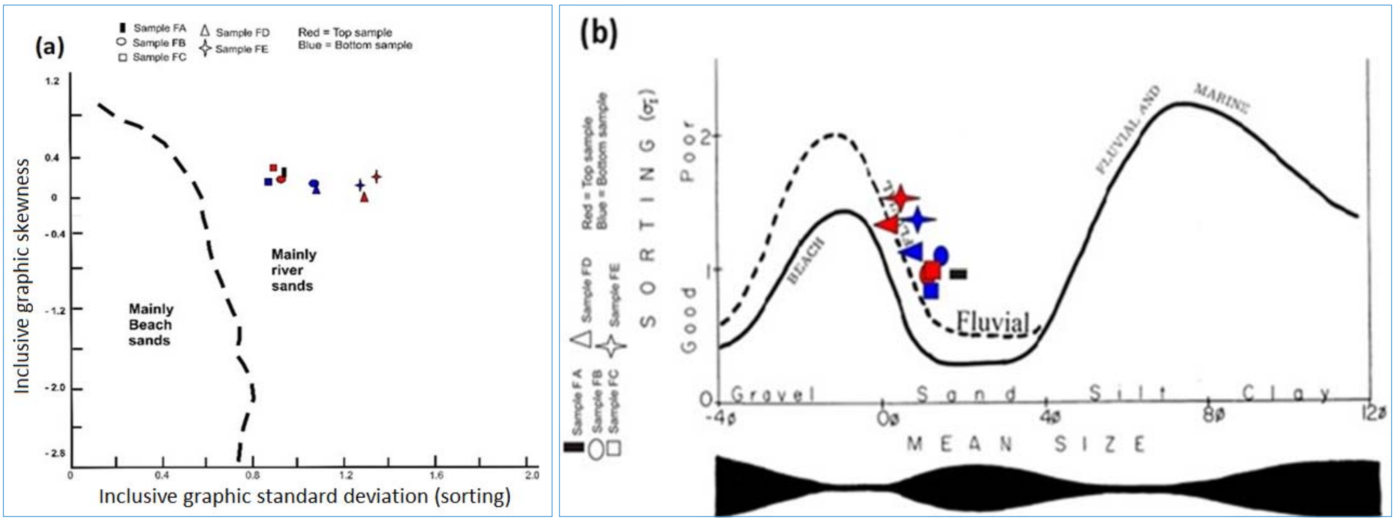

Fig. 14. (a)Bivariate plot of inclusive graphic skewness versus inclusive graphic standard deviation (sorting) (after Friedman, 1967). It shows all the sandstone facies are mainly fluvial sourced. (b) Bivariate plot of inclusive standard deviation (sorting) versus the mean grain sizes (after Fox, 1980). It shows the complete absence of beach sands among the sandstone facies

The Landward dipping of beds of tidal inlet facies and the landward shifting of barrier or deltaic facies successions (lower and upper shoreface) close to the adjacent bedrock, an indurated Eze-Aku Formation indicate marine transgression in response to sea level rise (Aschoff et al., 2018). The transgressive setting is further buttressed by the presence of the underlying transgressive surface and associated flooding shale as well as the cannibalization of the deposits by bounding surfaces interpreted as tidal and wave ravinement surfaces. In a transgressive setting, estuaries are formed, which can either be tide or wave dominated (Boggs, 2006; Nichol, 2009). Coarsening upward successions are mainly deposited in sub-environments in wave dominated estuary.

The low abundance/diversity of ichnofossils and the bimodal histogram distributions of grains sizes in all the facies indicate estuary where there is salinity stress as a result of mixing of fresh and sea water; and sediment supplied from both river and marine sources. The processes that transport and deposit sediment were a combination of river and wave and/or tidal processes. The typical sub-environments in wave dominated estuary are bayhead delta in the upper estuary, lagoon in the middle or central estuary; and beach-barrier, flood-tidal delta and tidal inlets in the lower estuary or estuary mouth (Hubbard et al., 2002; FitzGerald et al., 2014) (Fig. 17).

Bayhead delta is formed under transgressive setting when the transgression of the open shoreline dominated by waves is faster than the transgression of the river that supplies sand to the basin (Catuneanu, 2006; Oyanyan and Oshinowo, 2020). Also, as noted by Nichols et al. (1994), bayhead delta will be underdeveloped in where estuaries are filled with marine source-sediments during continued relative sea level rise.The bayhead delta deposits lack much structures associated with wave and tidal current as its location is far from the effects of strong waves and tidal currents. Rather, it is poorly sorted and characterised by fluvial formed structures and is overlain by fluvial deposits that fines upward. The bivariate plots of granulometric properties clearly showed the dominant of fluvial processes in the deposition of the stratigraphic units.

The bayhead delta facies was also identified by Okoro et al. (2020). The characteristics of the bayhead delta facies described here is like most of the bayhead deltas described by Aschoff et al. (2018). This is in line with their findings that the bayhead deltas are largely built by river-generated currents followed by systematic reworking. The successions of offshore, lower shoreface, upper shoreface and tidal inlet fill indicate barrier system in lower estuary of wave dominated transgressive shoreline (Fig. 16). Unlike the bayhead delta deposits, the barrier-beach environment deposits are characterised with structures formed mainly by wave current and by minimal tidal current, and moderately to well sorted grains. Barrier retreat is typical of transgressive settings. In accretionary transgression, accelerated relative sea level rise leads to barrier overstep or stillstand, when barrier progradation and accumulation of locally thicker transgressive deposits occur (Cattaneo and Steel, 2003).

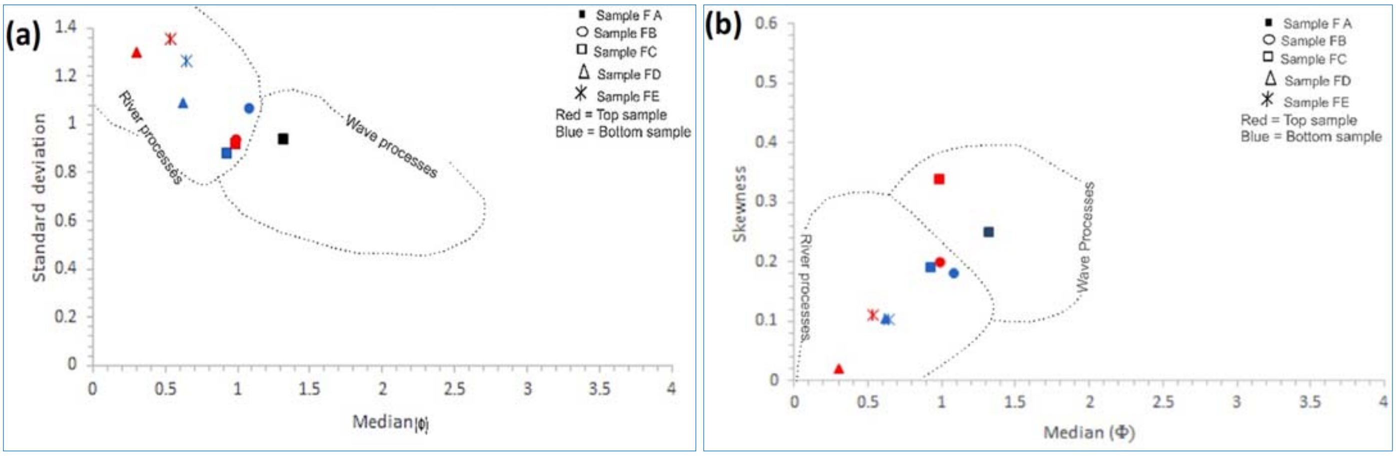

Fig. 15. Bivariate plot median grain size versus inclusive standard deviation (sorting) and skewness (after Stewart, 1958). It shows the increase of fluvial process from bottom to top of the vertical successions of facies

Therefore, coarsening upward trend is not only found in a regressive setting. Punctuation of long-term transgression by repeated short-term regressions is due to the common tendency for sediment-supply rates to outmatch, for short periods, the rate of increase in accommodation (Cattaneo and Steel, 2003). Therefore, the formation of the components of barrier systems and the succession of clinothems of bayhead delta can be attributed to the high rate of sediment supply over the rate of marine transgressing especially at the river channel mouth. The small-scale barrier gave the sediment entry point some levels of protection from the influence of wave and tidal reworking resulting in the poor sorting of grains.

Between the lower estuary consisting the barrier bar and the upper estuary consisting the bayhead delta is the middle estuary or central basin which is a zone of low energy typical of a lagoon (Catuneanu 2006) (Fig. 17). Lagoon succession is typically mudstone, often organic-rich, with thin, wave-rippled sand beds (Boggs, 2006). Organic rich facies are dark grey to black. It is however noted that the facies profile in the two locations clearly showed the omission of the central basin or middle estuary deposition. It is either it was eroded just like the core barrier or beach component of the barrier island was eroded or it was not preserved due to low accommodation creation by subsidence and high sediment supply triggered by high paleo-depositional slope following the Santonian thermo-tectonic folding and induration of the adjacent bedding rocks (Fig. 17). From the foregoing, the sandstone facies were deposited in environments with large ratio of river-load input to relative sea level rise. Perillo (1995), gave evolutionary sequence of an estuary characterized by large ratio of river-load input to relative sea level rise to include:

1. Flooding of fluvial valley by sea,
2. Coastal plain progradation,
3. Barriers development and
4. River delta development.

The succession of facies clearly conformed with this evolutionary sequence with offshore/offshore transition facies representing sea flooding, shoreface and tidal inlet facies representing coastal plain progradation and barrier development, while bayhead delta facies represents the river delta development.

4.2. Reservoir Quality Potentials of Facies

Estuarine sands form petroleum reservoirs while clays, muds or shales form seals or fluid flow barriers (Hubbard et al., 2002). The quality of the reservoirs is indicated by porosity (the ability to store fluid) and permeability (the ability to release fluid when penetrated by well). These parameters vary with grain size, sorting and types/abundance of burrows in facies as well as along depositional dip (Tonkin et al., 2010; Jackson et al., 2013; Oyanyan and Oti., 2015a). The textural and or granulometric properties and the types/abundance of burrows of the described facies gave insight to their reservoir quality potential. The following examined the reservoir quality potential of the different described sedimentary facies.

4.2.1. Bayhead Delta Reservoir

Bayhead delta have the thickest sandstone with mean grain size that ranged from lower coarse to very coarse and generally poorly sorted. The coarse grain size implies sandstone with large pore that will result in high porosity, but the poor sorting implies low permeability potential as the fine matrix will block the pore-throats connecting the large pores. Therefore, this bayhead delta sandstone facies will form reservoir of low quality as far as releasing the stored fluid is concerned. Also, the impermeable mud-lined surfaces identified within the bayhead delta facies will act as baffles to vertical flow of fluid or where laterally extensive can vertically compartmentalized the reservoir.

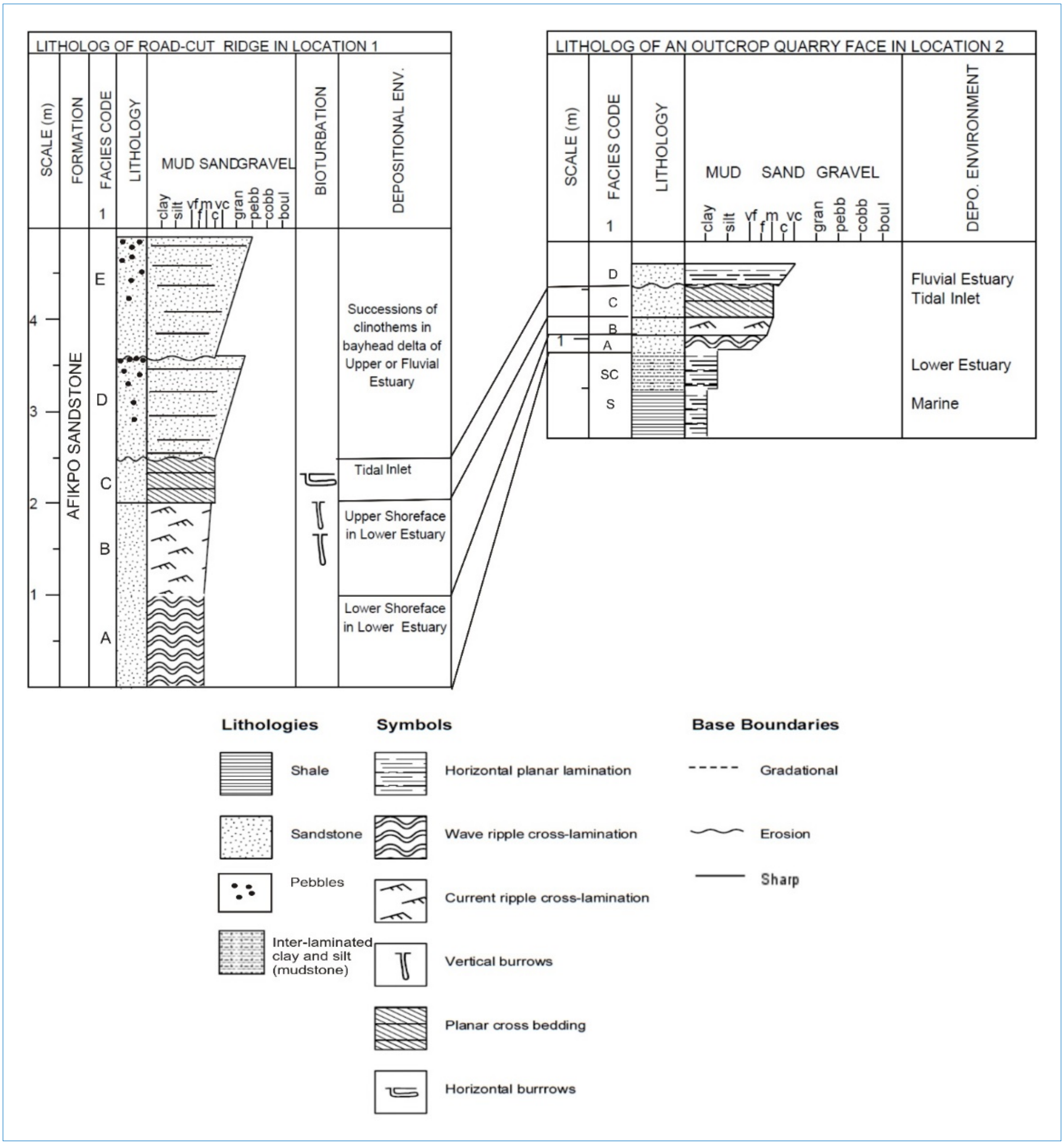

Fig. 16. Facies log of the two outcrop sections

4.2.2. Shoreface Reservoir

The shoreface sands have mean grain size that ranged from middle medium at the base to upper medium at the top. It is generally moderately sorted, except the base of the upper shoreface facies that is poorly sorted as a result of decrease in the influence of fair-weather wave and increase in the influence of tide (Table 2). The upper part of the deposit is characterised by sand-filled clean-walled burrows (Fig. 6). These characteristics imply potential for high porosity and permeability. The clean-walled burrows at the top implies potential for enhanced vertical permeability. Therefore, the shoreface sands will make good quality reservoir for petroleum.

4.2.3. Tidal Inlet Fill Reservoir

Tidal inlet fill sands are moderately sorted and has subdued grain size gradient with mean grain size of upper medium from bottom to top (Table 2). It is homogenous and characterised by rare sand-filled clean-walled burrows and lack of mud drapes on the cross-stratification boundaries. These characteristics imply potentials for high porosity and permeability and should form reservoir with the highest quality. This finding is in line with that of Hubbard et al. (2002) who also found out that among the wave dominated estuary deposits of the lower Cretaceous Bluesky Formation of the Peace river area in Alberta, Canada, tidal inlet fill sands that is also homogenous made the highest reservoir quality.

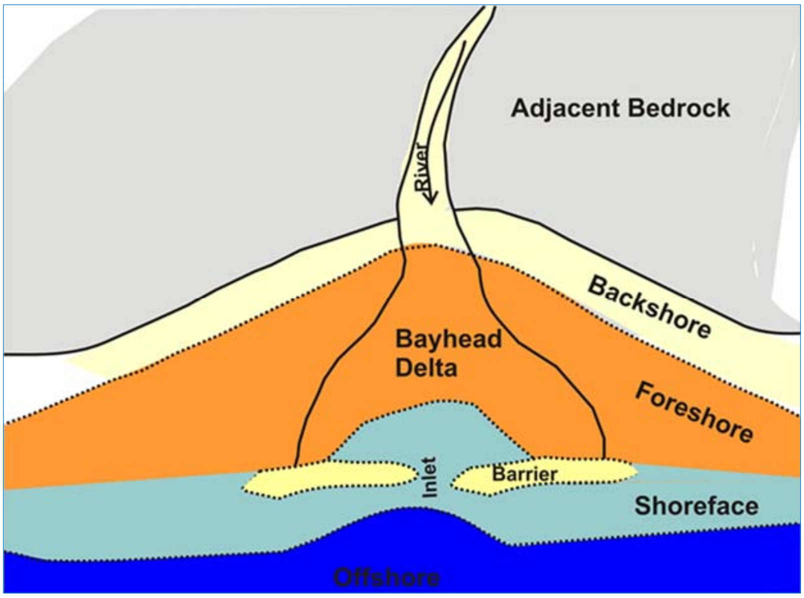

Fig. 17. Typical depositional environment model showing sub-environments from fluvial dominated upper estuary to wave dominated lower estuary

5. Conclusions

Six facies characterised the Campanian sediment outcropped at Macgregor, Afikpo Basin. They are: 1. Shale, 2. Interlaminated silt and clay, 3. Wavy-laminated sandstone, 4. Burrowed cross laminated sandstone, 5. Cross bedded sandstone and 6. Thick/very thick bedded sandstone. Almost all histogram distribution of grain sizes in all the sandstone facies are bimodal which implied the combination of fluvial and marine sourced sediment typical of an estuary. But based on bivariate plots of intra-facies granulometric parameters, fluvial supply and processes dominated the environments of deposition resulting in the rate of sediment supply greater than rate of relative sea level rise. The physical characteristics and associations of facies indicate that the Campanian sediments were deposited in estuary sub-environments which include: 1. Bayhead delta in upper or fluvial estuary, 2 Tidal inlets and shoreface in lower estuary and 3. Offshore/offshore transition zone in open marine. The central basin or middle estuary facies were eroded. The granulometric parameters of the sandstone facies can serve as analogue data for the understanding of subsurface petroleum reservoir deposited in a similar stratigraphic setting. Bayhead delta sandstone is lower coarse- to very coarse- grained, poorly sorted, near symmetrical to positive skewed, varied kurtosis and has internal bedding surfaces lined with impermeable mud. Therefore, it has potential for low quality reservoir. But the shoreface sandstone is generally moderately sorted, very fine- to coarse-grained, positive skewed, platykurtic to mesokurtic and therefore, has potential for good quality reservoir. While tidal inlet fill sandstone is homogenous and moderately sorted, positive to strongly positive skewed and mesokurtic; and has subdued grain size gradient with mean grain size of upper medium from bottom to top. Therefore, it has potential for the highest quality reservoir.

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References

Akande, S.O., Egenhoff, S.O., Obaje, N.J., Erdtmann, B.D., 2011. Stratigraphic Evolution and Petroleum Potential of Middle Cretaceous Sediments in the Lower and Middle Benue Trough, Nigeria: Insights from New Source Rock Facies Evaluation. Petroleum Technology Development Journal: An International Journal 1, 1-34.

Amajor, L.C., 1987. Paleocurrent, petrography and provenance analyses of the Ajali Sandstone (Upper Cretaceous), south eastern Benue Trough, Nigeria. Sedimentary Geology 54, 47-60.

Angus, L., Hampson, G.J., Palci, F., Fraser, A.J., 2020. Characteristics and context of high-energy, tidally modulated, barred shoreface deposits: Kimmeridgian-Tithonian sandstones, Weald Basin, Southern U.K. and Northern France: Journal of Sedimentary Research 90, 313-335. https://doi.org/10.2110/jsr.2020.19.

Aschoff, J.L, Olariu, C., Steel, R.J., 2018. Recognition and significance of bayhead delta deposits in the rock record: A comparison of modern and ancient systems. Sedimentology 65, 62-95. https://doi.org/10.1111/sed.12351.

Boggs Jr., S., 2006. Principles of Sedimentology and Stratigraphy. Fourth Edition. Pearson Prentice Hall, USA, 676 pp.

Burke, K.C., Decasualise, Y.F.J., Whiteman, A.J., 1972. Geological history of the Benue valley and adjacent areas. In. T.F.J. Dessauvagie and A. J. Whiteman (Ed), African Geology University of Ibadan press, Ibadan, pp 187-205.

Cattaneo, A., Steel, R.J., 2003. Transgressive deposits: a review of their variability. Earth-Science Reviews 62 (3-4), 187-228. https://doi.org/10.1016/S0012-8252(02)00134-4.

Catuneanu, O., 2006. Principles of Sequence Stratigraphy. Elsevier B. V. publ, 387 pp.

Dashtgard, S.E., Vaucher, R., Yang, B., Dalrymple, R.W., 2021. Hutchison Medallist 1. Wave-Dominated to Tide-Dominated Coastal Systems: A Unifying Model for Tidal Shorefaces and Refinement of the Coastal-Environments Classification Scheme. Geoscience Canada, Geoscience Canada, Journal of the Geological Association of Canada 48 (1), 5-22. https://doi.org/10.12789/geocanj.2021.48.171.

Emery, D., Meyers, K., 1998. Sequence stratigraphy. Blackwell science publication, 297 pp.

Fetter, C.W., 1990. Applied Hydrogeology. CBS Publishers and distributors, India, 592 pp

FitzGerald, D., Georgiou, I., Miner, M., 2014. Estuaries and Tidal Inlets. In: Masselink, G. and Gehrels, R. (Eds), Coastal Environments and Global Change, First Edition. John Wiley & Sons, Ltd. Publ. pp. 268 -298.

Folk, R. L., 1980. Petrology of Sedimentary rocks. Hemphill Publishing Company, Austin, Texas 78703, USA, 190 pp.

Folk, R.L, Ward, W.C., 1957. Brazos river bar: A study in the significance of grain-size parameters. Journal of Sedimentary Petrology 27, 3-26.

Friedman, G.M., 1967. Dynamic processes and statistical parameters compared for size frequency distribution of beach and river sands: Journal of Sedimentary Petrology, 37, 327-354.

Galloway, W. E., Cheng, E.S., 1985. Reservoir Facies Architecture in a Microtidal Barrier System, Frio Formation, Texas Gulf Coast. Bureau of Economic Geology, W. L. Fisher, Director, The University of Texas at Austin, Austin, Texas, 78713. Report Investigation No. 144, 43 pp.

Gingras, M.K., Bann, L., MacEachern, J. A., Pemberton, G., 2007. A Conceptual Framework for the Application of Trace Fossils. In: MacEachern, J.A., Bann, K.L., Gingras, M.K., Pemberton, S.G. (Eds.), Applied Ichnology, SEPM, Tulsa, ISBN-10: 1565761332, pp.1-26.

Hubbard, S. M., Gringras, M., Pemberton, S. G., Thomas, M.B., 2002. Variability in wave dominated estuary sandstones: Implications on subsurface reservoir development. Bulletin of Canadian Petroleum geology 50 (1), 118-137.

Jackson, C.A., Mode, A.W., Oti, M.N., Adejinmi, K., Ozumba, B., Osterloff, P., 2013. Effects of Bioturbation on Reservoir Quality: An Integration in Reservoir Modeling of Selected Fields in the Niger Delta Petroleum Province. NAPE Bulletin 25 (1), 29-42.

Krumbein, W.C., 1934. Size frequency distribution of sediments: Journal of Sedimentary Petrology 4, 65-77.

MacEachern, J.A., Bann, K.L., Bhattacharya, J.P., Howell, C.D. Jr, 2005. Ichnology of Deltas: Organism Responses to the Dynamic Interplay of Rivers, Waves, Storms and Tides. SEPM, 37 pp.

Nichols G., Boyd, R. and Penland, S., 1984. Stratigraphic response of wave-dominated estuaries to different relative sea-level and sediment supply histories: Quaternary case studies from Nova Scotia, Louisiana and eastern Australia. In: Dalrymple, R.W., Boyd, R., Zaitlin, B.A. (eds.). Incised-valley Systems: Origin and Sedimentary Sequences. SEPM (Society for Sedimentary Geology), Special Publication 51, 265-283.

Nichols, G., 2009. Sedimentology and Stratigraphy. Wiley and Blackwell Publ. (second edition), 432 pp.

Nigerian Geological Survey Agency, 2023. Geological Maps. 31 Shettima A. Munguno Crescent, Behind Julius Berger HQs., Utako District, PMB 616 Garki, Abuja. Nigeria.

Okogbue, C.O., Aghamelu, O.P., 2010. Comparison of the geotechnical properties of crushed shales from south-eastern Nigeria. Springer-Verlag publication. Bulletin Engineering Geology and Environment 69, 587-597.

Okoro, A.U, Igwe, E.O., Umo, IA., 2020. Sedimentary facies, paleoenvironments and reservoir potential of the Afikpo Sandstone on Macgregor Hill area in the Afikpo Sub-basin, south eastern Nigeria. SN Applied Sciences 2, 1862. https://doi.org/10.1007/s42452-020-03601-5.

Okoro, A.U, Onuigbo, E.N., Akpunonu E.O., Obiadi I.I., 2012. Lithofacies and Pebble Morphogenesis: Keys to Paleoenvironmental Interpretation of the Nkporo Formation, Afikpo Sub-Basin, Nigeria. Journal of Environment and Earth Science 2 (6), 26-38.

Olariu, C., Bhattacharya, J.P., 2006. Terminal Distributary channels and delta front architecture of river-dominated delta systems. Journal of Sedimentary Research 76, 212-233. https://doi.org/10.2110/jsr.2006.026.

Oyanyan, R.O., Oshinowo, O.O., 2020. Structural and Stratigraphic Styles of Growth Faulted Shallow Marine Deposits in an Eastern Offshore Depobelt Oil Field, Niger Delta, Nigeria. American Journal of Earth Sciences 7 (2), 13-24.

Oyanyan, R.O., Oti, M.N., 2015a. Down-Dip Cross Sectional Variability in Sedimentological and Petrophysical Properties of Late Oligocene Shoreface Parasequence Reservoir, Greater Ughelli Depobelt, Niger Delta. Petroleum Technology Development Journal: An International Journal 5 (2), 92-117.

Oyanyan, R.O., Oti, M.N., 2015b. Sedimentology and Ichnology of Late Oligocene Delta Front Reservoir Sandstone Deposit, Greater Ughelli Depobelt, Niger Delta. American Journal of Geosciences 5 (1), 12-25. https://doi.org/10.3844/ajgsp.2015.12.25.

Patruno, S., Helland-Hansen, W., 2018. Clinoforms and clinoform systems_ Review and dynamic classification scheme for shorelines, subaqueous deltas, shelf edges and continental margins. Earth-Science Reviews 185, 202-233. https://doi.org/10.1016/j.earscirev.2018.05.016.

Pemberton, G., MacEachern, J., Gingras, M., Bann, K., 2009. Atlas of Trace Fossils. 1st Edn., Elsevier Science, Amsterdam, ISBN-10: 0444532323, 300 pp.

Perillo, M.E., 1995. Geomorphology and Sedimentology of estuaries. Elsevier publ. 470 pp.

Reijers, T.J.A., Petters, S.W., Nwajide, C.S., 1997. The Niger Delta Basin. In: Selley, R. C. (Eds), The African Basin. Elsevier Publication, New York, pp 150-172.

Reyment, R. A., 1965. Aspects of the Geology of Nigeria. Ibadan University Press. 145 pp.

Selly, R.C., 2000. Applied Sedimentology (second edition). Academic press publication, pp 543.

Simms, A.R., Rodriguez, A.B., Anderson, J.B., 2018. Bayhead deltas and shorelines: Insights from modern and ancient examples. Sedimentary Geology 374, 17-35. https://doi.org/10.1016/j.sedgeo.2018.07.004.

Simpson, A., 1954. The Nigerian Coal Field: The geology of parts of Onitsha, Owerri and Benue Provinces. Geological Survey Nigeria Bulletin 24, 1- 67.

Stewart Jr, H.B., 1958. Sedimentary reflections of depositional environment in San Miguel lagoon, Baja California, Mexico. AAPG Bulletin 42 (11), 2567-2618. https://doi.org/10.1306/0bda5bfa-16bd-11d7. 8645000102c1865d.

Tonkin, N.S., McIlroy, 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 Bulletin 94 (7), 1059-1078.

Ukaegbu, V.U., Akpabio, I.O., 2009. Geology and Stratigraphy of Middle Cretaceous Sequences Northeast of Afikpo Basin, Lower Benue Trough, Nigeria. Pacific Journal of Science and Technology 10 (1), 518-527.

Umeji, O.P., 2013. The South and Central Benue Trough: Stratigraphic Revisions.

Whiteman, A., 1982. Nigeria: Its Petroleum Geology, Resources and Potentials. Vol. 1 and 2. Graham and Trotman Ltd.: London. UK.