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Reservoir Assessment Through Facies Analysis, Petrography and “Kotlyakhov” Approach: A Case Study of the Sandy Members of Pindiga Formation, Northern Benue Trough (Gongola Sub-Basin), NE Nigeria

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ABSTRACT

The Gongola sub-basin of the Northern Benue Trough (NE Nigeria) is a frontier hydrocarbon exploration basin that is presently under investigation. It is part of the West and Central African Rift System (WCARS), a rift system from which several petroleum exploration successes have been recorded. The Nigerian economy relies heavily on oil and gas that are currently being exploited in the Niger Delta petroleum province, it accounts for about 10% of domestic products and its revenue represents around 86% of total export revenue. Consequently, in order to expand the country's resource base and to search for replenishments to the existing reserves, it is imperative to explore for hydrocarbons in the inland frontier basins, especially the Gongola Sub-basin of the Upper Benue Trough, where exploration activities have recently kick-started. This research has confirmed key controls on morphology of the depositional environments of Sandy Members of Pindiga Formation using influence of wave, tide and river processes which are controlled by shoreline movements with sediment supply and accommodation. The sandy members show good porosity values ranging from 7.0 to 34.0% (average $\phi = 15.7\%$) with many beds having very good to excellent and Permeability values ranges from 41.9 to 217.6 mD with average of 89.3 mD which is classified as fair to high reservoir. The quality of these reservoir sands is strongly linked to their depositional systems and this research can serve as a guide for future seismic exploration especially within in Gongola sub-Basin.

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1.0 Introduction

The sandy members of Pindiga Formation (Dumbulwa, Gulani, and Deba Fulani Sandstones) are sandwiched between Kanawa and Fika Shales Members which are located within the Gongola Basin of the Northern Benue Trough. The name "Pindiga Formation" was first proposed by Carter et al. (1963) referring to the "Calcareous Beds" and "Clay-Shale" described earlier by Barber et al. (1954). These sandy members are deposited as a result of complex interactions of offshore (waves, tides and storms); and onshore (fluvial) processes, which leads to development of several coastal environments along the pre-existing shorelines due to regressive episode pre-dating the mid-Cretaceous global transgressive event (Shettima et al., 2018). Generally, coastal deposits are potential reservoirs to hydrocarbon, good aquifers to groundwater and also host coal and solid mineral resources (Goro et al., 2021).

Recently, the Nigerian National Petroleum Corporation (NNPC) located hydrocarbons reservoir within the Bima and Yolde Formations in Kolmani River II well, which was spudded in the Gongola Sub-basin of the Northern Benue Trough, NE Nigeria (Petroleum Africa, 2019). Thus, the Bima and Yolde Formations are now established hydrocarbon reservoirs. Additionally, the younger sandy members of the Pindiga Formation, consisting of Dumbulwa, Gulani, and Deba Fulani sandstones (Figure 2), could potentially form hydrocarbon reservoirs in the basin. In addition, a study on the depositional process and other factors that influence the reservoir quality (RQ) of the Pindiga Formations is timely, as it would guide the present exploration activities and improve the sandstones' RQ predictions in the basin.

Nonetheless, there are excellent exposures of Gulani Member to the west of Malya village (N10° 44' 0.3", E11° 41' 37.6"), Deba Fulani Formation at Damfami Stream (N10° 06' 46", E11° 17' 28"), and Dumbulwa Formation at Badabdi Hill (N10° 56' 59", E11° 25' 14") (Fig. 1). These exposures provide an ideal opportunity to study lithofacies, petrography and petrophysics of these sandy members of the Pindiga Formation. The main aim of this

research is to determine the RQ of the sandy members.

2.0 Geological background

The Pindiga Formation is composed of three (3) lithogenetic units of five (5) members. The sandy members of interest (Dumbulwa, Gulani, and Deba Fulani Sandstones) are sandwiched between Kanawa and Fika Shales Members which are located within the Gongola Sub basin of the Northern Benue Trough (Figure 2). To date, the processes that lead to the creation and evolution of Benue Trough remain controversial even though basically there are two (2) major schools of thoughts; the rift and the pull-apart models. The sedimentary history of the Gongola Sub basin ranges from Aptian to Palaeocene though pre-Aptian sediments were reported by some authors (e.g., Zaborski, 1998) as oldest deposits.

The Benue Trough is subdivided into three main structural and sedimentary domains (the Lower, Middle and Upper Benue); each domain has recorded a distinct structural and sedimentary record (Benkhelil, 1988). Benue Trough stretches for over a thousand kilo meter in length with width varies between fifty and hundred and fifty kilo meters, hosting more than 6000 m of Cretaceous - Tertiary sediments associated with volcanic plugs (Shettima et al., 2017). The stratigraphic sequence in the Benue Trough comprises essentially of a thick continental and paralic sandstones, shales, and coal measures, with shallow shelf shales and limestones (Murat, 1972; Petters, 1978). Chronologically, the Precambrian Basement is unconformably overlain by the Aptian-Albian Bima Sandstone, which is the oldest, thickest, and most extensively outcropping formation in the trough (Carter et al., 1963; Guiraud, 1990; Abubakar, 2006; Mamman et al., 2010).

The Yolde Formation which is a transitional interbeds of shale, siltstone and calcareous mudstone overlain Bima Sandstone (Maigari, 2011). It was described earlier by Falconer (1911) and Barber et al. (1954) as 'transition beds' between the Bima Group and the Pindiga Formation and the name was first used by Carter et al. (1963) locating the type section in Yolde stream western part of Yola Sub basin. Conformably overlying the Yolde Formation are

the colossal beds of limestones and thick shales of Pindiga Formation (Kanawa, Dumbulwa/Gulani/Deba Fulani; Fika Members) of Zarboski (1998) in the Gongola Sub basin and their lateral equivalents are the Dukul, Jessu, Sekule, Numanha and Lamja Formations in the Yola Sub basin. Overlying these formations are the poorly to moderately sorted sediments of

Gombe Sandstone (Campanian – Maastrichtian) of Zarboski *et al.* (1998) in the Gongola Sub basin. The succession is capped by sandstones of the Kerri-Kerri Formation (at least to the West of Gombe town) in the Gongola Sub basin.

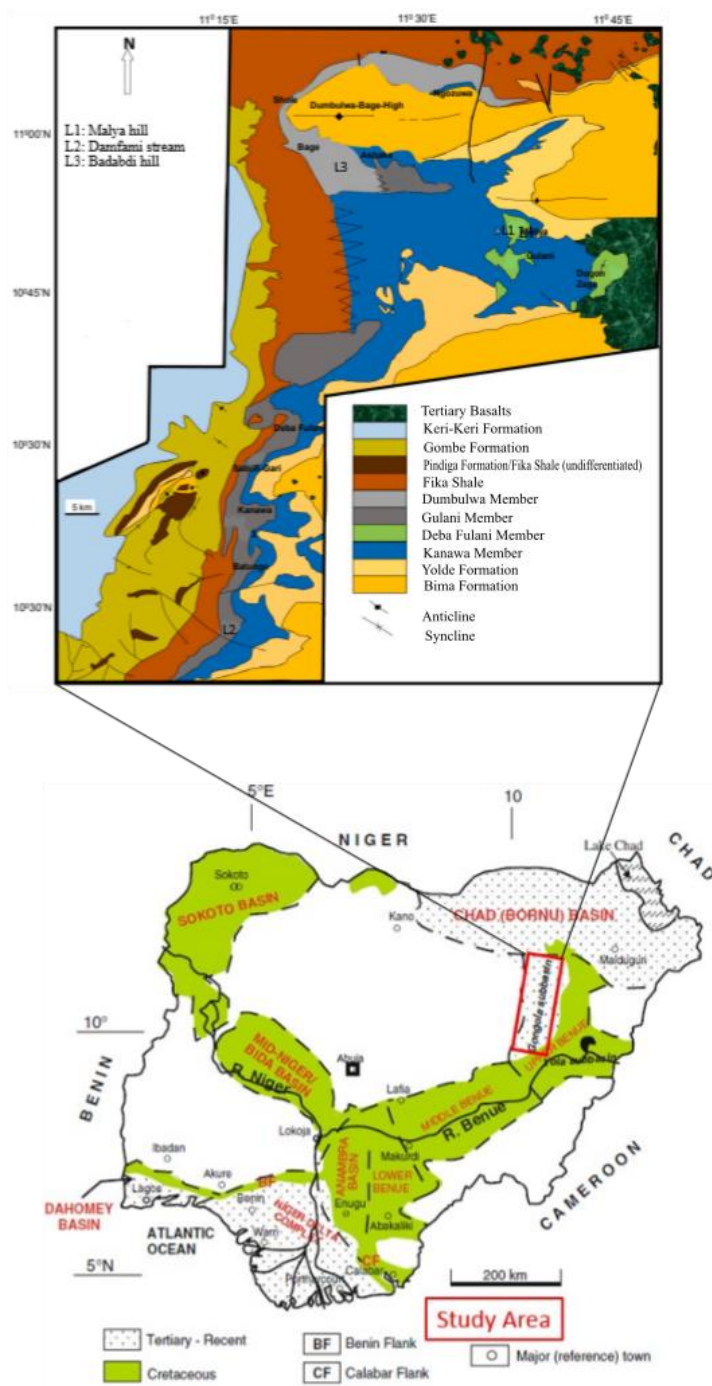


Figure 1. Map of Nigerian sedimentary basins showing the Gongola sub basin of the Northern Benue Trough (Modified after Obaje, 2009 and I. A. Goro et al., 2021).

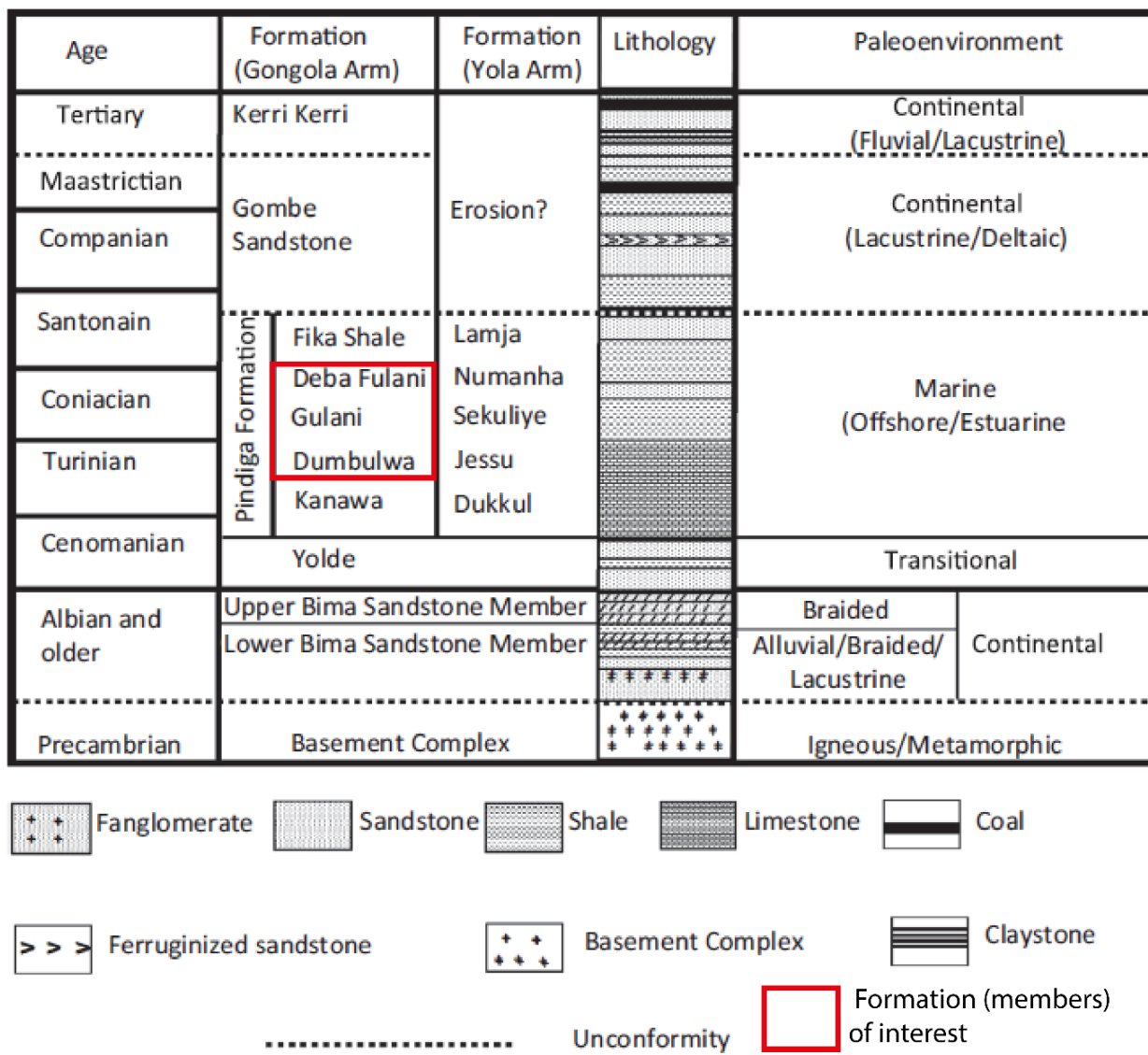


Figure 2. Stratigraphic succession of the Upper Benue Trough (adapted from Tukur *et al.*, 2015). The red square indicates the geologic formations of interest in the study area.

3.0 Materials and method

28 samples were collected from discrete portions of the exposures at least one each from different lithofacies. Depositional environments were interpreted based on textural characteristics, and sedimentary structures while description of reservoir lithofacies were based on outcrop sedimentological studies. Petrography was done using Leica DM750P microscope in order to determine the reservoirs textural features and compositions such as grain type, grain size, sorting, and pore volume by point counting using JMicroVision and ImageJ software packages. Some of the thin sections were

impregnated with blue resin to highlight primary and secondary optical porosities. Porosity was determined via image analysis (visual porosity) and water absorption technique. Visual porosity was obtained by quantifying morphological aspect of pores and calculating the porosity percentage based on $[\%P = \text{Pores Area} / \text{Total Area} \times 100]$, while the porosity obtained by water absorption technique (WAT) and was determined by the water mass that fills the pores after immersion of oven dried samples for at least 72hrs. It was expressed as percentage of water mass absorbed with respect to the total mass of dried samples $[\%W.A. = (W_w - W_d) / W_d \times 100]$ (Andreola et al., 2000), where W_w wetted

sample, Wd oven dried sample. Permeability was calculated using 'Kotryakhov' formular [$k = \frac{d \cdot \phi^3}{72 \cdot (1 - \phi)^2}$], (Kotryakhov 1949) where, k = permeability, ϕ = porosity.

4.0 Results

4.1 Sedimentary lithofacies and facies association

Three (3) outcrop sections from Badabdi, Damfami and Malya villages were logged and their lithostratigraphic logs are shown in Figure 1. Seven (7) lithofacies and five (5) facies associations were established.

4.1.1 Dampami Stream Section

This out crop section is located at Dampami stream and characterized by heterolithic bedding at the base which marks the boundary between Kanawa (shales) and Deba Fulani (sandstone) Members (Figure 3). It has a general coarsening upward sequence with presence of phosphatic conglomerates and blackish stains in places indicating possible organic matter (Figure 3A). The sandstone beds are coarse grained to granules and pebbly in places dominated by trough cross-bedding with few plana and herringbone cross-stratifications (Figure 3 & 4).



Figure 3: Pictorial view of Dampami Stream Section showing various lithologies and sedimentary structures (A; Dark stains of possible organic matter, B; Trough cross-bedded sandstone, C; Parallel laminated sandstone, D; Some layers containing Phosphatic conglomerates, fish bones and vertebrate spines fragments, E; Heterolithic beds depicting signatures of various coastal sub-environmental processes.

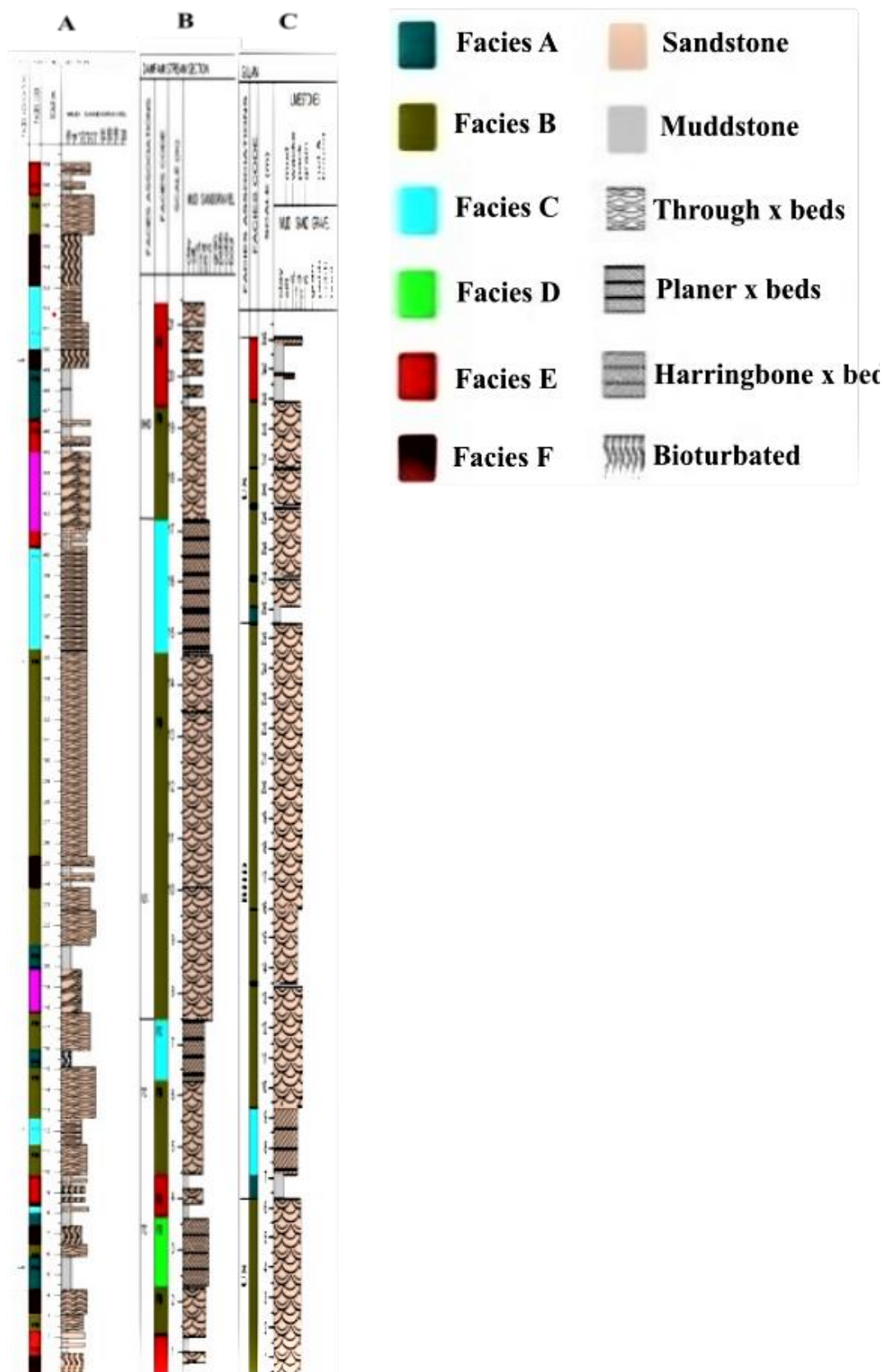


Fig.4: Lithostratigraphic sections depicting facies and facies associations of the study area. [A] Badabdi Hill (N10° 56' 59", E11° 25' 14"), [B] Damfami Stream (N10° 06' 46", E11° 17' 28"), [C] Malya (N10° 47' 20.8", E11° 41' 31.9").

4.1.2 Malya Section

This section has a general coarsening upward sequence (Figure 5) also, the cycles range between 1.2 – 14.0m with muddy parts highly bioturbated (Figure 5), the bioturbations decrease towards the sandy part of the beds. The top of the section is characterized by

selective weathering pattern, the mudstones are grey - pinkish mostly and silty in places while the sandstones are pinkish grey – light brown, plana and trough cross-bedded at the top of the section with very coarse-grained sandstone and granulestones at the base of cross-sets in places (Figure 4 & 5).



Figure 5: Pictorial view of some lithologies from Malya section showing coarsening upward sequence.

4.1.3 Badabdi hill Section

The outcrop is located to the west of Malya village, much of the layering is showing regular pattern. The base of the section is made up of coarsening upward sequence which changed to fining upward towards the top. The sandstone beds are very fine grained to granulestones,

with trough cross-beddings, parallel laminations, and some soft sediment deformational structures in places while the mudstone shows some nodules in places. It is believed to be part of the Dumbulwa sandstone (Figure 4 & 6).



Figure 6: Pictorial view of Badabdi hill Section showing various lithologies and sedimentary structures.

Table2: Sedimentary lithofacies description and their interpretations.

Facies code	Lithofacies description	Texture	Sedimentary structure and geometry	Interpretation
F – A	Mudstone (Figure 4A)	- Clay and Shale	- Laminated, fissile or massive - Erosional or sharp bases - Depositional units: 5 cm to 9m	Deposition in slope and basinal settings during low energy and by suspension settling
F – B	Trough cross bedded sandstone (Figure 4B)	- Fine- to Very coarse-grained sandstone - Moderately to moderately well sorted	- Trough cross - bedding - Erosional to gradational bed contacts	Deposition by migration of ripples with irregular crests which form as a result of high flow velocity or low water depth in a nearshore environment.
F – C	Parallel laminated sandstone (Figure 4C)	- Fine to very coarse-grained sandstone - Moderately to moderately well sorted	- Parallel lamination - Erosional to sharp bed contacts - Individual beds thickness:10 cm- 5.5 m	Deposition at higher flow velocity or even lower depth
F - D	Herringbone cross bedded sandstone (Figure 4D)	- Very fine to Very coarse-grained sandstone - Poorly to moderately sorted	- Herringbone cross bedding - Bed thickness: 60 cm - 1.4 m - Erosional to gradational bed contacts	Herringbone cross beds like bipolar cross beds are indication of reversal tidal current environment

F – E	Heterolithic Sandstone (Figure 4E)	<ul style="list-style-type: none"> - Very fine-grained sandstone to siltstone and clay - Moderately to well sorted 	<ul style="list-style-type: none"> - Lenticular sandstone - Interlayered sandstone and clay - Sandstones are laminated 	Distinct bedding planes separating individual sandy and muddy layers of heterolithic deposits indicates tidal environment
F – F	Bioturbated Sandstone (Figure 4H)	<ul style="list-style-type: none"> - Very fine to Very coarse-grained sandstone - Poorly to moderately sorted 	<ul style="list-style-type: none"> - Bioturbated - Individual bed thickness: 25 cm - 8 m - Sharp to gradational bed contacts - Thallasinoides and opiomorpher trace fossils 	Deposition in lower energy conditions and marine environment, with low sedimentation rate
F – G	Conglomerate facies (Figure 4I)	<ul style="list-style-type: none"> - Very fine to gravelly sandstone - Poorly sorted 	<ul style="list-style-type: none"> - Phosphatic nodules, fish and vertebrate spines and bones - Beds thickness: 5cm - 62cm - Sharp to gradational bed contacts 	Phosphates are known to be deposited in wide range of environment from shallow, near-shore, or low energy environment

4.1.4 Granulometric

Table 1: Summary of the granulometric analysis

	L8B1	L8B3	L8B5	L8B7	L8B8	L8B11	L8B12	L5B1	L5B5	L5B21	L5B14	L5B20	L5B15
SAMPLE TYPE:	UMWS	UMWS	UMWS	UWS	UMWS	UMS	BPS	UPS	TPS	UMS	BPS	UMS	BPS
TEXTURAL GROUP:	Sand	Sand	Sand	Sand	Sand	S. G Sand	S.G Sand	SG Sand	Sand	Sand	SG Sand	Sand	Sand
SEDIMENT NAME:	MWSMS	WSMS	MWSFS	WSMS	MWSMS	SVFGMS	SVFGMS	SVFGMS	PSFS	WSCS	SVFGMS	MSFS	PSFS
MEAN (f)	M.S 1.484	M.S 1.512	F.S 2.415	M.S 1.590	M.S 1.182	M.S 1.215	M.S 1.427	MS1.821	FS 2.169	MS 1.320	MS 1.426	FS 2.285	FS 2.628
SORTING (f)	MWS 0.523	WS 0.361	MWS 0.614	WS 0.425	MWS 0.668	MS 0.880	PS1.008	PS 1.048	PS 1.133	MS 0.969	PS 1.079	MS 0.877	PS 1.003
SKEWNESS (f)	SYM	VFSk 0.340	SYM 0.031	VFSk 0.473	CS -0.166	SYM - 0.015	CS- 0.143	SYM 0.065	SYM 0.009	Fsk 0.280	SYM 0.006	SYM 0.083	VFSk 0.322
KURTOSIS (f)	VLp 2.543	VLp 2.312	PI 0.882	VLp 2.300	Lp 1.377	Lp 1.168	Lp 1.258	Ms 1.008	Lp 1.172	Ms 0.918	Ms 0.918	Ms 0.987	Lp 1.142
MODE 1 (f):	1.486	1.486	1.987	1.486	1.486	1.486	1.987	1.987	1.987	0.734	1.486	1.987	1.987
MODE 2 (f):			3.863				3.487		3.863		3.863		3.863
MODE 3 (f):									0.734				
D ₁₀ (f):	0.665	1.269	1.635	1.278	0.363	0.301	0.195	0.498	0.685	0.274	0.024	1.246	1.595
D ₅₀ (f):	1.488	1.512	2.401	1.536	1.340	1.375	1.615	1.800	2.172	1.141	1.423	2.184	2.429
D ₉₀ (f):	2.101	2.212	3.161	2.334	1.721	2.349	3.313	3.158	3.755	2.805	2.875	3.432	3.872

	L5B32	L5B4	L5B13	L5B27	L5B17	L5B11	L5B2	L1B8	L1B4	L1B12	L1B10	L1B1	L1B15	L1B7	L1B9
SAMPLE TYPE:	UMWS	UMS	UMS	UMWS	UMS	UMWS	BMS	UMS	TPS	BMS	UMS	BPS	UMWS	UMS	UMS
TEXTURAL GROUP:	Sand	SGS	SGS	Sand	Sand	Sand	SGS	G Sand	SGS	GS	SGS	SGS	SGS	SGS	Sand
SEDIMENT NAME:	MWSFS	SVFGMS	SVFGMS	MWSFS	MSFS	MWSFS	SVFGMS	VFGCS	SVFGMS	VFGCS	SVFGCS	SVFGCS	SVFGCS	SVFGCS	MSCS
MEAN (f)	FS 2.358	MS 1.672	MS 1.292	FS 2.284	FS 2.337	VFS 3.566	FS 2.237	CS 0.534	MS 1.261	MS 1.024	CS 0.441	CS 0.946	CS 0.773	CS 0.951	MS 1.320
SORTING (f)	MWS 0.653	MS 0.768	MS 0.862	MWS 0.645	MS 0.706	MWS 0.594	MS 0.837	MS 0.903	PS 1.033	PS 1.797	MS 0.762	PS 1.228	MWS 0.665	MS 0.747	MS 0.969
SKEWNESS (f)	SYM - 0.045	SYM 0.089	FSk 0.135	FSk 0.277	FSk 0.111	SYM 0.076	VFSk	SYM - 0.006	SYM - 0.054	VFSk 0.433	FSk 0.181	SYM 0.090	FSk 0.127	FSk 0.185	FSk 0.280
KURTOSIS (f)	Ms 1.015	Lp 1.328	Ms 1.079	Ms 1.055	Ms 1.075	VLp 2.863	Lp 1.340	VLp 1.516	VLp 1.613	VLp 1.601	L 1.221	PI 0.866	Lp 1.173	L 1,318	M 0.918
MODE 1 (f):	1.987	1.486	1.486	1.987	1.987	3.487	1.987	0.734	1.486	-0.002	-0.002	-0.002	0.734	0.734	0.734
MODE 2 (f):							3.863		-0.002	3.863		1.486			
MODE 3 (f):								3.487							
D ₁₀ (f):	1.444	0.680	0.323	1.486	1.416	2.954	1.353	-0.621	0.003	-0.766	-0.359	-0.629	-0.030	0.236	0.274
D ₅₀ (f):	2.313	1.638	1.257	2.144	2.243	3.550	2.061	0.571	1.414	0.596	0.365	0.878	0.749	0.884	1.141
D ₉₀ (f):	3.121	2.800	2.582	3.134	3.175	3.951	3.556	1.607	3.174	3.705	1.361	2.680	1.668	1.974	2.805

UMWS ;Unimodal Moderately well sorted, BMWS ; Bimodal Moderately well sorted, UMS ; Unimodal Moderately sorted, BPS ; Bimodal poorly sorted, BMS ; Bimodal Moderately sorted, UWS ; Unimodal well sorted, UPS ; Unimodal poorly sorted, UPS ; Unimodal poorly sorted, TPS ; Timodal poorly sorted, MWSMS ; Moderately Well Sorted Medium Sand, MWSVFS ; Moderately Well Sorted Very Fine Sand, MSFS ; Moderately Sorted Fine Sand, VFGCS ; Very Fine Gravelly Coarse Sand, SVFGCS ; Slightly Very Fine Gravelly Coarse Sand, SVFG ; Slightly Very Fine Gravel, WSCS ; Well Sorted Coarse Sand, MWS Moderately Well Sorted, WS ; Well Sorted, MSFS ; Moderately Sorted Fine Sand, MWSFS ; Moderately Well Sorted Fine Sand, PSFS ; Poorly Sorted Fine Sand, MS ; Moderately Sorted, PS ; Poorly Sorted, MdS ; Medium Sand, FS ; fine Sand, FSk ; Fine Skewed, VFSk ; Very Fine Skewed, CSk ; Coarse Skewed, SYM ; Symmetrical, Lp ; Leptokurtic, VLp ; Very Leptokurtic, PI ; Platykurtic, Ms ; Mesokurtic.

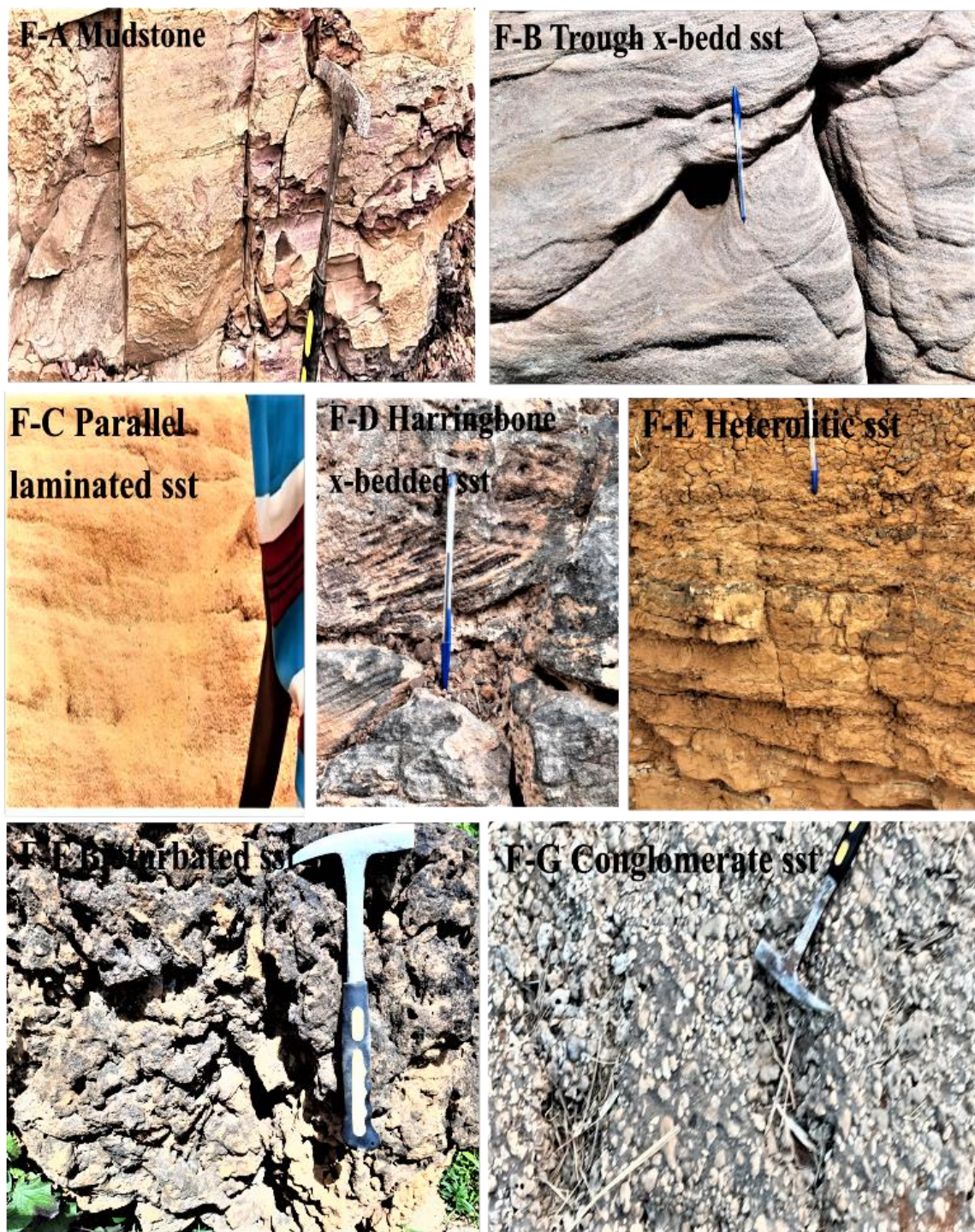


Figure 7: Photographs of the established lithofacies. (A – G)

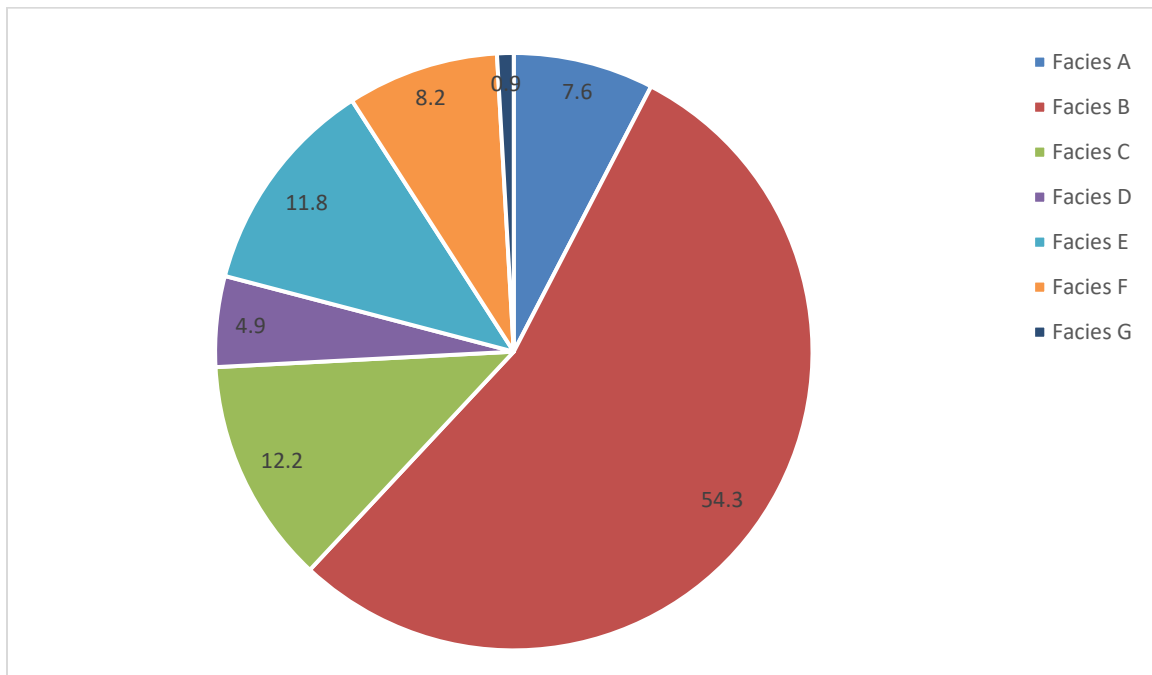


Figure 8: Pie chart of the different facies' types in the studied samples

4.2 Facies Associations

4.2.1 Upper Shoreface facies association (US)

This facies association consists mostly of fine to medium grained sandstone to granulestone ranging in thicknesses from few cm to 7.1 m, mostly low or no trace fossils. common sedimentary structure is trough cross-stratification, mostly unidirectional with few bipolar.

Hinged on sedimentary structures and lack of much fossil assemblage, this environment is interpreted as an upper shoreface. The coarse-grained size of the sandstones and the lack of mudstones indicate a very high energy environment seaward and closer to the beach (Harms et al., 1975). Weak/low bioturbation also suggested environment with high energy such as an upper shoreface (Gani et al., 2008).

4.2.2 Tidal Chanel facies association (TC)

This facies association is made up of heterolithic facies of mudstones to very fine-grained sandstones, trough cross-bedded, herringbone cross bedded sandstones underlain by conglomerate

facies especially at the Dampami stream section (Figure 3 & 4). This succession displays mixed tide with fluvial influence.

The heterolithic facies indicate a migrating tidal channel, where mudstones were deposited during period of no tidal change (i.e. slackwater periods) and the sandstones were deposited when the tides were going in and out (Thomas et al., 1987). Though fundamentally abundant in tide-dominated environments, but can also be found in lacustrine and fluvial environments (Reineck and Singh 1980; Flemming and Bartholomä 1995; Davis and Dalrymple 2012). Herringbone cross-beds like bipolar cross-beds are indication of reversal tidal current (Tucker, 2004) while the small-scale coarsening-upward cycles of the heterolithic facies point to seaward progradation of tidal flat in a tide dominated shoreline (Mangano and Buatois, 2004).

Bioclastic fragments of sand-sized, unclassifiable pieces up to sizeable pieces of shelly material and bone are generally from break up of biogenic debris due to current activities in higher energy portion of the sea (Nichols, 2009).

4.2.3 Bay Head Delta facies association (BHD)

This facies association consists of coarsening upward cycles of 1-15m thick that comprises grey mostly laminated mudstone at the base dominated by planar bedded sandstone towards its top. It is found at Dampami stream in the northern part of the study area which is dominated by Deba Fulani Sandstone, Malya section and also at the base of Badabdi hill section to the south (Figure 4).

According to Aschoff et al., (2018), overall coarsening-upward pattern; appearance of small-scale clinofolds, increasing abundance of mud interbeds towards the clinofold toe are the among major signatures of bay head delta. Boyd, (2010) suggested progradation of the bay head delta into central estuary into bay mudstone for the coarsening-upward while mudstone as bay head prodelta sediments and the sand prone as bayhead delta front and distributary mouth bar.

4.2.4 Mid Estuary facies association (ME)

This facies association consists of grey and laminated mudstone, mottled and bioturbated with *Ophiomorpha* trace fossils in places (Figure 5). This is more pronounced at the northern part of the study area which is dominated by Deba Fulani sandstone.

The mudstone represents suspension settling in low energy environment (Bhattacharya and MacEachern, 2009) while the lamination records fine grained sand deposition as a result of tidal currents (Buatois et al., 1998). Due to its nature and association, it is presumed to be deposited in the central bayhead portion (e.g Dalrymple et al., 1992; Buatois et al., 1999; Boyd, 2010).

4.2.5 Mud-dominated shelves facies association (MDS)

This facies associations consist of interbedded grey mudstone sometimes laminated and planar bedded sandstone with wavy surface in places with sporadic bioturbations towards the top of the section. The mudstone ranges in thickness from 2 – 7 m while the sandstone ranges from 0.3 – 1.2 m with a general coarsening upward sequence. This facies association was discovered at the northeastern parts of the study area.

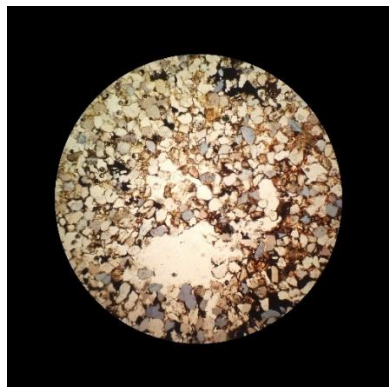
Some shelf areas are wave- and storm-dominated, but receive excess of mud and relatively little sand (Nichols, 2009). So, the high thickness of the mudstone represents reworked suspended load by wind - driven geostrophic current across shelf (McCave 1984). The wavy surface in some sandstone also suggested wave reworking. The coarsening up character that commence with shelf mud, passing upward gradationally into muddy sand, interbedded sand and mudstone point to stormwave-dominated shelf (Nnaji, 2015).

4.3 Petrography

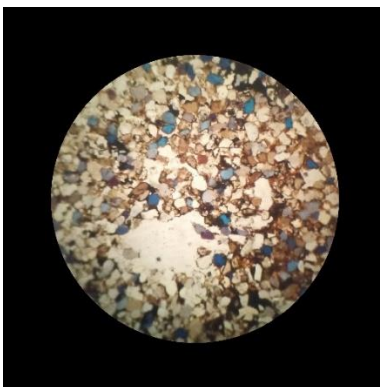
The studied samples show: Arkoses (50%) and Quartzarenites (27.8%) which are the most abundant sandstone types followed by Subarkoses (22%) (Figure 9). The major component of the samples is detrital quartz, and monocrystalline with few polycrystalline, as well

as undulose quartz and metaquartzite varieties (45.3–98.1%) (Figure 9) (Table3). Feldspars (1.6–

53%) (Table3) and rock fragments (0.2–3.5%) are common (Table3)



Photomicrographs of L1B10 under PPL, 40XL



Photomicrographs of L1B10 under XPL, 40XL

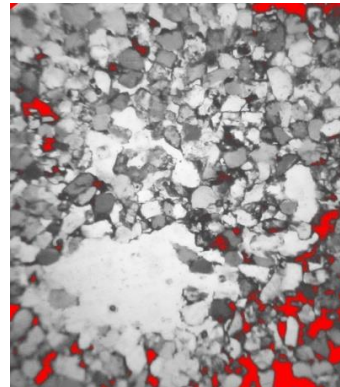


Image J. Photomicrographs of L1B10, 40XL



Photomicrographs of L5B5 under PPL, 40XL



Photomicrographs of L5B5 under XPL, 40XL

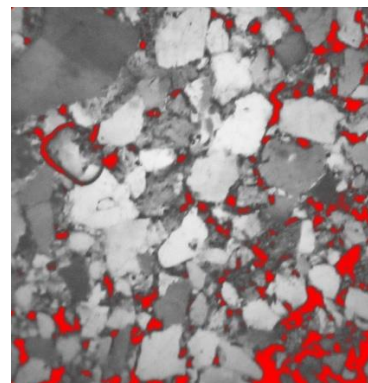
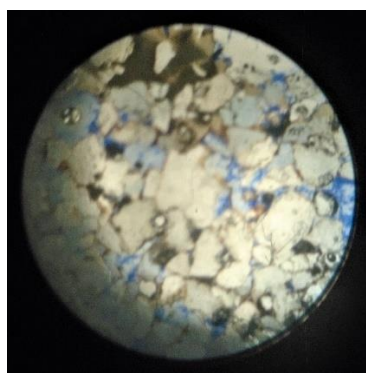
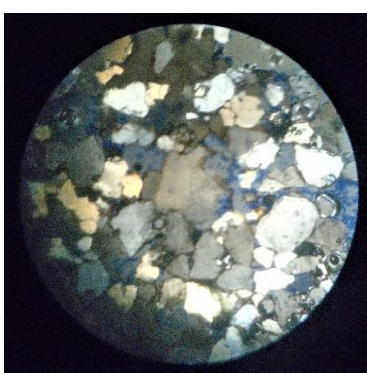


Image J. Photomicrographs of L5B4, 40XL



Photomicrographs of L8B1 under PPL, 40XL



Photomicrographs of L8B1 under XPL, 40XL



Image J. Photomicrographs of L8B1, 40XL

Table 3: Petrographic point count and petrophysical data

S/N	SAMPLE	SORTING	ROUNDNESS	SPHERICITY	GRAIN CONTACT	FRAMEWORK COMPONENTS			Visual Porosity (%)	Measured Porosity (%)	Calculated Permeability (mD)
						Quartz (%)	Feldspar (%)	Rock Fragment (%)			
1	L1B1	Moderately sorted	Rounded	High	Long pointed	86	13.5	0.5	9.8	14.0	122.7
2	L1B4	Moderately sorted	Subangular	Low	Long	97	2.6	0.4	12.7	13.0	79.6
3	L1B7	Well sorted	Subrounded	Low	Long	74	25	1	6.3	12.0	46.0
4	L1B8	Moderately well sorted	Rounded	High	Point	94.6	4.0	1.4	16.6	7.0	89.1
5	L1B9	Moderately sorted	Subrounded	Low	Long pointed	96.5	2.4	1.1	9.6	16.0	97.7
6	L1B10	Well sorted	Subangular	Low	Long	95.2	3.6	1.2	8.9	18.0	217.6
7	L1B12	Moderately sorted	Subrounded	High	Long	95	3.2	1.3	8.8	7.0	87.5
8	L1B15	Moderately sorted	subangular	Low	Long pointed	95	3.5	1.5	10.6	8.0	86.4
9	L5B1	Moderately sorted	Subangular	Low	Long	75	20	5	5.9	10.0	49.3
10	L5B2	Moderately sorted	Subangular	Low	Long pointed	73	25	2	4.6	24.0	106.4
11	L5B4	Moderately sorted	Subrounded	Low	Long pointed	70	28.5	1.5	7.5	20.0	98.9
12	L5B5	Moderately sorted	subangular	low	Long pointed	63.2	35	1.8	6.9	18.1	62.2
13	L5B11	Moderately sorted	subangular	Low	Long pointed	75	23	2	5.3	20.6	91.5
14	L5B13	Moderately well sorted	Subangular	Low	Long pointed	75	19	6	6.9	22.3	142.0
15	L5B14	Moderately sorted	Subrounded	Low	Long pointed	60	38	2	7.4	7.0	49.4
16	L5B15	Moderately sorted	Subrounded	Low	Long pointed	55	44	1	3.7	14.1	51.6
17	L5B17	Moderately sorted	Subrounded	Low	Long pointed	65	33	2	3.1	13.0	50.1
18	L5B20	Moderately sorted	Subrounded	High	Long pointed	75	23.8	1.2	5.7	11.4	41.9
19	L5B21	Moderately sorted	Subangular	Low	Long	60	38	2	7.0	12.8	94.9
20	L5B27	Moderately sorted	Subangular	Low	Long pointed	45.3	53	1.7	8.4	13.7	50.1
21	L5B32	Poorly sorted	Subangular	Low	Long pointed	47.5	49	3.5	9.6	19.0	59.2
22	L8B1	Moderately well sorted	Subrounded		Long	98.0	1.6	0.4	12.3	13.0	75.6
23	L8B3	Well sorted	Subrounded		Long pointed	97.8	1.7	0.5	16.8	24.0	127.3

24	L8B5	Moderately well sorted	Subrounded		Long pointed	98.1	1.6	0.3	21.5	33.0	92.3
25	L8B7	Well sorted	Subrounded		Long pointed	97.5	2.3	0.2	24.6	34.0	172.8
26	L8B8	Moderately well sorted	Subrounded		Long pointed	97.3	1.9	0.8	8.7	12.0	78.5
27	L8B10	Moderately sorted	Subrounded		Long pointed	97.1	2.5	0.4	10.5	16.0	97.5
28	L8B11	Poorly sorted	Subangular		Long	85.1	12.6	2.3	22.4	7.2	52.0

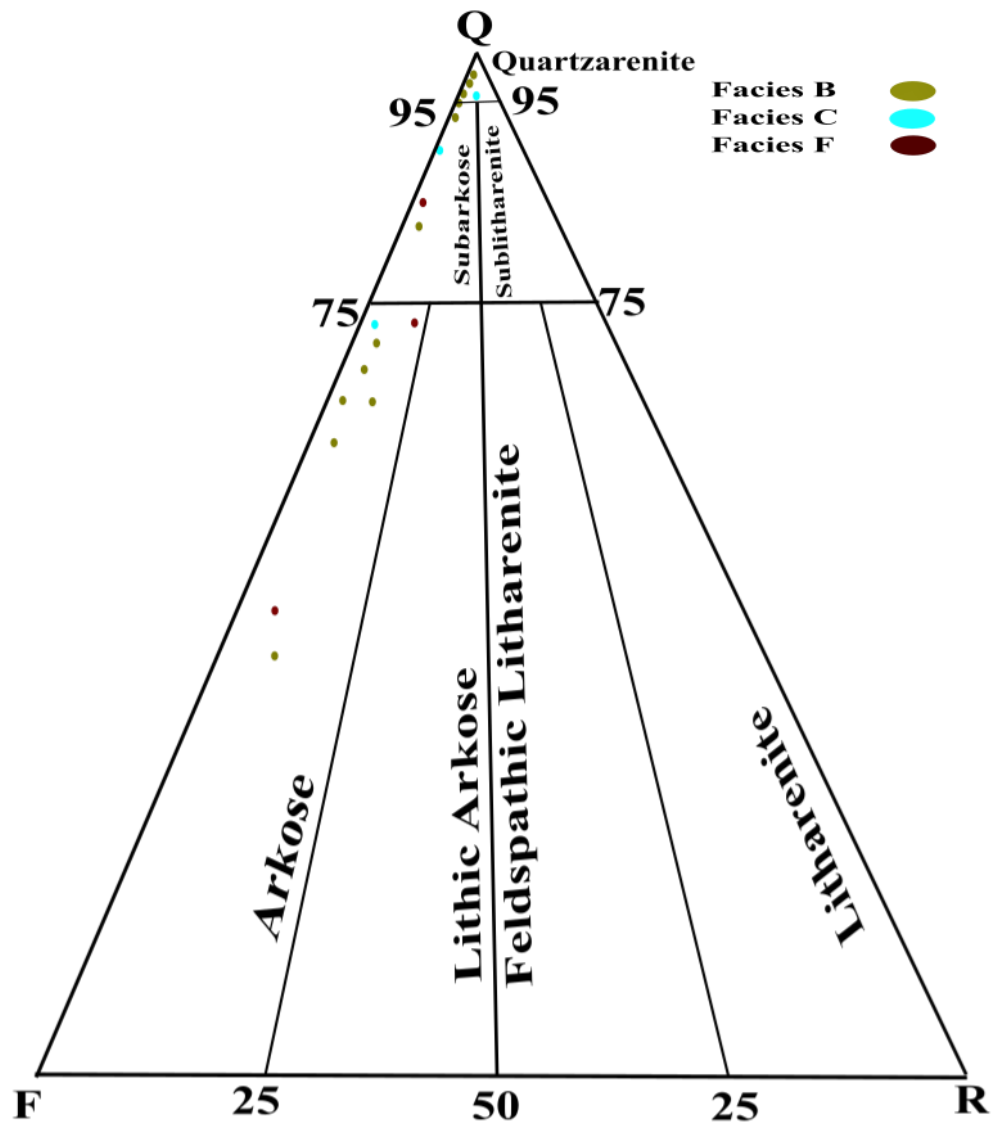


Figure 10: Ternary diagram showing the main compositions of the major facies studied, based upon Folk (1980) scheme.

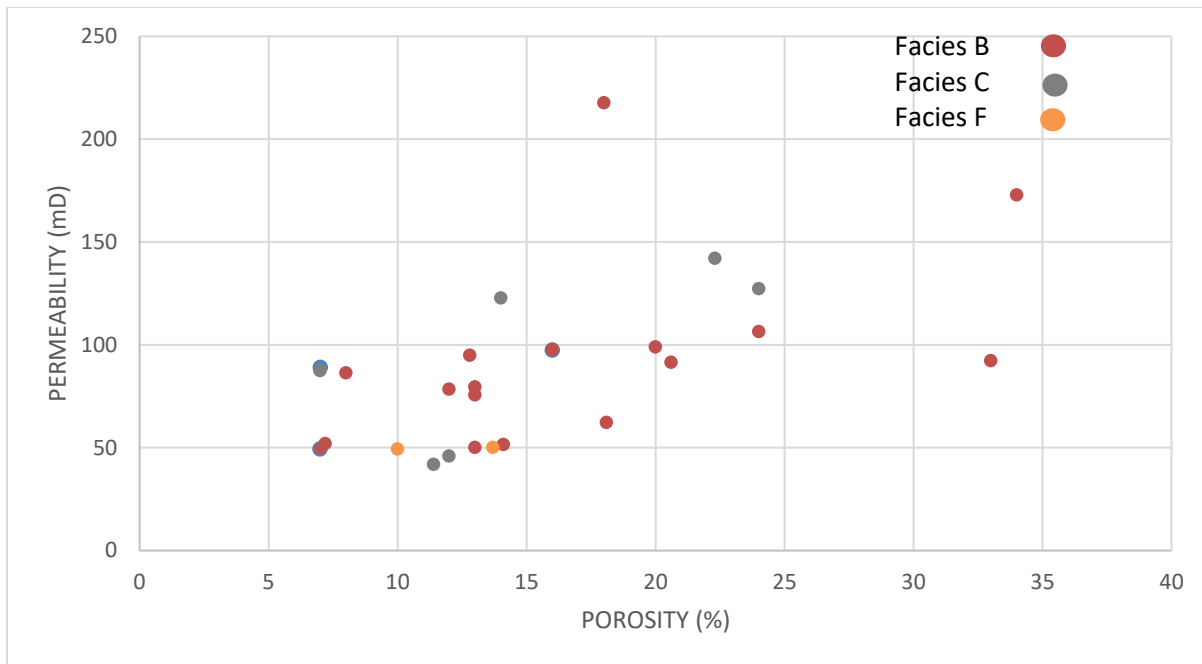


Figure 11: Permeability/porosity relationship of major facies

Table 4: Permeability Grading Standard Table (SY/T6285-1997)

Permeability (mD)	Penetration rating	Pore Structure Type
$k \geq 2000$	Hypertonic	Class I
$500 \leq k < 2000$	Hypertonic	Class II
$50 \leq k < 500$	Medium Penetration	Class III
$10 \leq k < 50$	Hypotonic	Class IV
$1 \leq k < 10$	Ultra-low osmotic	Class V
$0.1k < 1$	Ultra-hypotonic	
$k < 0.1$	Non-permeable	

5.0 Discussion

Lithofacies and Lithofacies associations studies on the sandy members depicts sub environments within coastal region (e.g Davis 2021). The basal succession of the units displays regressive deposits due to coarsening upward sequence (especially, at Dampami stream section) while some of the successions (e.g upper parts of Badabdi hill section) are characterized by transgressive successions representing sub environment dominated by wave and tide that

covers the progradational sequence, pointing to a varying coastal morphology with a net landward trajectory regime (e.g Plint 2010).

With domination of wave action, mixed energies on transgressive coastline that results in proper winnowing of the bay head delta, their reservoir quality is expected to be good to excellent and laterally continuous. Sands of the tidally influenced channel sands are not laterally continuous, but are restricted within the channels in a vertical stack system. Also, the

Upper Shoreface are usually laterally continuous with appreciable thickness and good porosity and permeability values of up to 34% / 217 mD respectively.

Within the geological framework, heterogeneity has multiple scales i.e. from core scale-well scale

to reservoir scale (Tang and Liu 2008). Based on pore structure, grain size and composition (Table 3&5), grain packing, lamination and bedding styles, sedimentary structures (Figure 7).

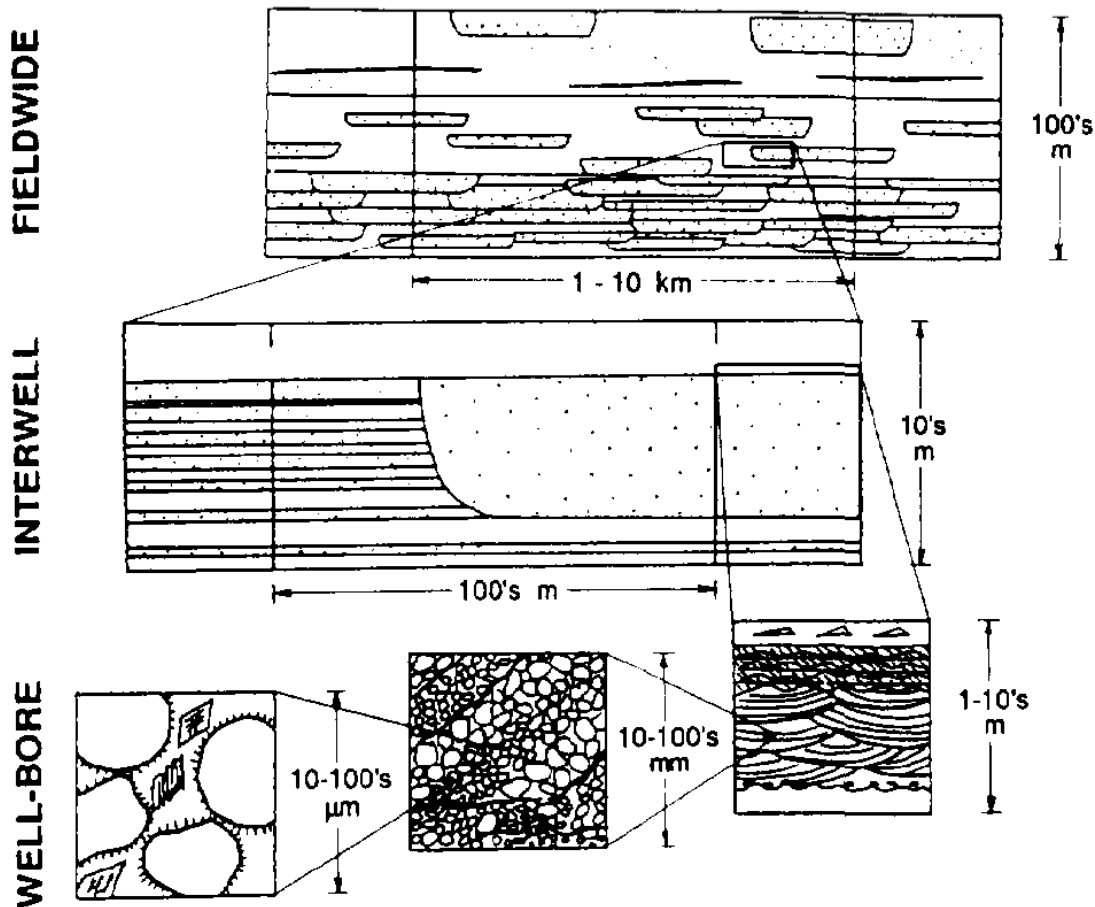


Figure 11: Levels of reservoir heterogeneity (Modified from Weber, 1986.)

Folk (1957) classification, the point-count data (Table 3) indicate the sandstones range from arkose to quartz arenite with moderate to high textural/compositional maturity and are generally fine to slightly gravelly sand grain size, sub-angular to rounded with poor to well sorting most of them having moderately well sorting (Table 1). Coarser grains sandstones with lower pore fillings clays and higher amount of ductile grains have best reservoir quality while sandstone with pore fillings clays (e.g kaoline)

between 10 – 30 % have deleterious effects on reservoir quality, reducing porosities and permeabilities to generally < 10 % and < 1 Md, respectively (Bello et.al,2021).

Majority of the samples are moderately well sorted to moderately sorted except samples; L8B12, L5B1, L1B4, L1B12, and L1B1 that are poorly sorted which all have relatively low - medium permeability values. By implication poorly sorted samples from the study area have

low permeability values compared to the moderately and moderately well sorted samples. 46% of the studied samples are having symmetrical skewness, 29% fine skewed followed by 18% very fine skewed and lastly 7% coarse skewed. Sample having symmetrical skewness have permeability values ranging from 49.3 - 98 mD which is relatively low to moderate permeability values. Samples having very fine skewness mostly have high permeability values while Samples having fine skewness have permeability values ranging between 46-217 mD and lastly though only one sample has coarse skewness with 78.5 mD.

The kurtosis results of the studied samples show 36% leptokurtic, 32% mesokurtic, 25% very leptokurtic and 7% platykurtic with permeability values ranging between 46-217 mD, 47-142 mD, 75.5-172 mD, and 92-122 mD respectively. By implications, samples with very leptokurtic have moderate to high values of permeability, those with leptokurtic and platykurtic mostly have relatively higher values while mesokurtic generally have low values with few exceptional. The sandy members show good porosity values ranging from 7.0 to 34.0% (average $\phi = 15.7\%$) with many beds having very good to excellent (e.g Siyar et al., 2018). like U. Mio. Sandstone reservoir of Gulf of Mexico having 4 - 36% porosity, C tidal and shallow clastic reservoir of Tarim basin with porosity range of 3.4 - 22.6%, Pli sandstones and siltstones of South Caspian basin with porosity range from 5 - 19 % e.t.c. These shows a bimodal distribution for some of the samples reflecting variations in lithology and facies, as indicated by divergent average and median values. In this study, a relatively more reliable porosity from water absorption technique (WAT) was chosen to compute the permeability values avoiding overestimation. A detailed comparison between Visual and WAT values of porosity (Table 2) shows little discrepancies.

Permeability values in sandy members ranges from 41.9 to 217.6 mD with average of 89.3 mD (Table 2) (e.g Bakken Formation of United State with 100 mD, Siberian Basin of Russia with 160 mD, Rio Del Rey basin of Cameroon with values

varying between 52.75 - 278.5 mD e.t.c.) which is classified as fair to high reservoir (Glover 2000) having medium penetration and class III pore structure type (SY/T6285-1997). Permeability/porosity data exhibit a linear relationship (Figure 6) with few samples deviating, depicting most of the pores are generally connected (Zhao 2022).

6.0 Conclusion

- This research has established that major controls on depositional environments morphology can easily be prevised from the influence of wave, tide and river processes which are influenced by shoreline fluctuations with sediment supply and accommodation created.
- The porosity, permeability and pore structure of the sandy members if couple with adequate accumulation of hydrocarbon and a good caping material will form a reservoir (e.g U. Mio. Sandstone reservoir of Gulf of Mexico) that hydrocarbons can be produced commercially.
- With nature of the heterogeneity of the sandy members there will be less challenges of residual oil distribution, fluids flow direction, matrix permeability, and drainage efficiency of the reservoir, as well as lateral sweep ability of subsequent recovery projects.
- The RQ is strongly linked to their depositional processes like that of Bruks Field whose quality is influenced by the energy of the tidal current and input of shallow marine wave that cleaner sands were deposited.
- This research should be a guide for future seismic exploration especially within these sandy sandstones.

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