



Lapai Journal of Science and Technology, Vol. 10, No. 1 (2024)

PROVENANCE AND PALEOENVIRONMENTS OF THE SHALES OF PATTI AND ENAGI FORMATIONS IN BIDA BASIN, NORTH CENTRAL NIGERIA: EVIDENCE OF MARINE COVERAGE IN THE CAMPANIAN – MAASTRICHTIAN

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ABSTRACT

The lateral equivalent Campanian- Maastrichtian shales of Patti and Enagi formations in the Bida Basin were investigated for provenance and paleoenvironments through inorganic geochemistry and foraminiferal paleoecological studies. The shales exposed at Ahoko, Patti Formation and at subsurface in a borehole at Gulu, Enagi Formation are grey to black and massive with about 10m and 28m thicknesses, respectively. Gulu shales consist mainly of benthonic foraminifera assemblages with representative species of *Ammotium sp.*, *Ammobaculites sp.*, *Haplophragmoides sp.*, *Trochammina sp.*, *Miliammina sp.*, *Pseudobilivina sp.*, *Spiroplectammina sp.*, and *Textularia sp.* while the shale from Ahoko included similar benthic foraminifera and macro fossils like molluscs. Their paleoecology suggests a slightly reduced saline marine environment ranging from brackish to the continental shelf. Vanadium to nickel ratio ranging from 0.6 to 3.3 in Ahoko and 0.2 to 52.6 in Gulu suggests mixed marine and terrigenous (fluvial) sources under dysoxic to oxic conditions with more marine influence in the shales of Gulu. Paleo-oxygenation indicated by V/Cr ratio of 0.1 to 4.3 in Ahoko and 0.6 to 6.3 in Gulu which are below 4.5 shows that paleo-conditions were more oxic with very sparse period of anoxic conditions for those above 4.5. SiO₂ and Al₂O₃ are the most abundant oxides of the shales with average values of 57.6% and 26.9% in shales from Ahoko, and 51.3% and 27.5% in Gulu shale respectively suggesting more influx of terrigenous and argillaceous sediments of the fluvial settings in the south. Average Al₂O₃/TiO₂ of 14.3 in Ahoko, and 23.4 in Gulu indicates that their sediments were sourced from intermediate igneous and felsic rocks respectively. Their degree of weathering estimated from the chemical index of alteration (CIA) ranges from 94 - 107, thus indicating a high degree of chemical weathering in hot and humid tropical climates. K₂O/Na₂O against SiO₂ and other indices suggest an active continental margin with a mixture of intermediate, mafic, and felsic igneous rock for the source of the sediments for the shales of Patti and Enagi formations. The paleo-conditions of the studied shales are similar across the basin and this suggests a wide coverage of sedimentation of marine shale across the basin during the



Campanian to Maastrichtian which could be a potential petroleum source or sealing rocks in the Bida Basin.

Keywords: Bida Basin, Geochemistry, Paleoecology, Paleoenvironment, Provenance

INTRODUCTION

The study area covers the Enagi and Patti formations in the Northern and Southern Bida Basin, North Central Nigeria. Bida Basin is an intra-cratonic basin with structural outlook trending NW-SE from Kontagora in the north to an area slightly beyond Lokoja/Dekina axis in the south (Adeleye, 1972, Braide, 1992, Obaje, 2009, Ojo, 2011) (Fig.1 and Fig. 2). The subsurface Enagi Formation was accessible through a research borehole at Gulu village, Lapai L.G.A of Niger State, and the exposed shales of Patti Formation at Ahoko in Kogi State.

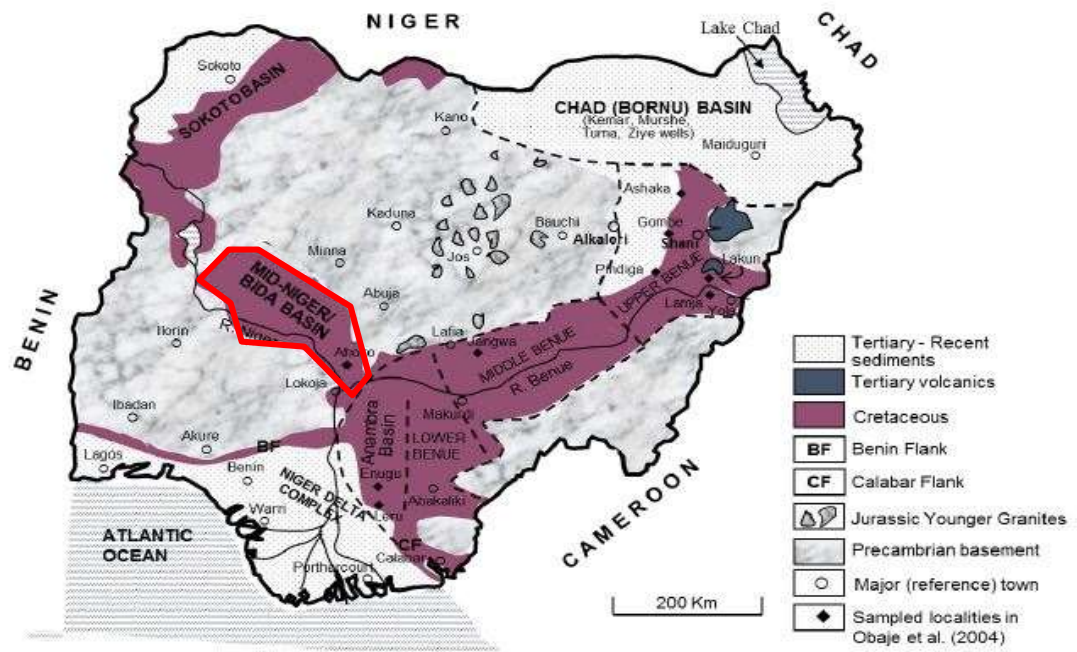


Figure 1: Map of Nigeria showing the position of the Bida Basin (Obaje, 2013).

The Campanian-Maastrichtian sedimentary fill in the Bida Basin indicates that full-marine conditions were not established as documented in the age equivalent of the shallow marine



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Nkporo and the deltaic Mamu formations during the Upper Campanian and Maastrichtian transgressive in the adjacent Anambra Basin (Murat, (1972, Benkhelil, 1989, Akande and Erdtmann, 1998). A comparison of sedimentary thicknesses in the two basins indicates that the Anambra Basin filled up to 8km compared with an average of 4 km of Campanian-Maastrichtian sediment in the Bida Basin (Akande and Erdtmann, 1998). Previous studies on the petroleum potentials of Bida Basin were concentrated on the known exposed shale at Ahoko, subsurface shale at Kudu, basinal sediment thickness, and structural settings (Ojo, 1984, Ojo and Ajakaiye, 1989, Akande et al 2005, Nton, and Okunade, 2013. Obaje et al., 2020,). Exploration activities by Nigerian National Petroleum Company Limited (NNPCL) have been recently resumed with advanced techniques in geophysics through FTG and 2D seismic images that reveal older sediment up to about 3km below the Campanian – Maastrichtian sequences in some parts of the basin. Despite that the previous and recent studies have led to searching for deeper subsurface source rock for possible hydrocarbon discovery, the seemly well-known Enagi and Patti formation hosting dark to grey shales still need further assessment of their provenance and depositional environments. The provenance and depositional environment of the Enagi and Patti shales will give more details about their capability as a source or potential sealing rocks for any older hydrocarbon prospect or groundwater. This study is motivated to access fresh samples for geological, geochemistry, and paleoecology studies of the shale obtained from a new subsurface location at Gulu (Fig. 2) (Enagi Formation) and Ahoko outcrop (Patti Formation) to reconstruct their provenance and paleoenvironments.

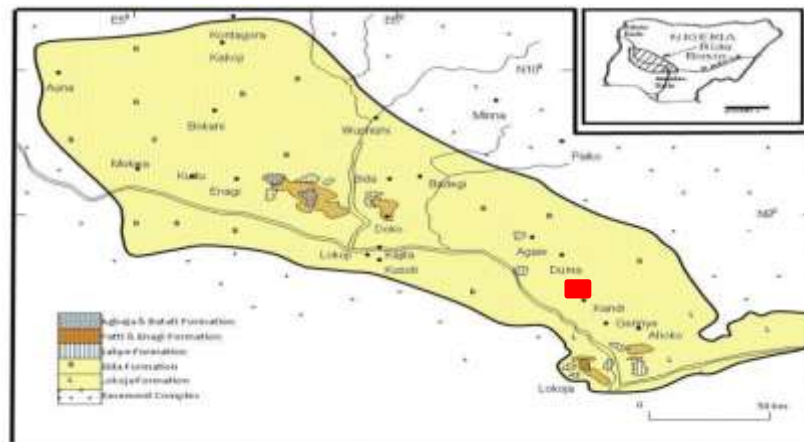


Figure 2: A simplified geological map of the Bida Basin showing the study location at Gulu in the red box (Modified after Adeyele, 1976).



GEOLOGY OF THE BIDA BASIN

Bida Basin has a gently down warped trough whose origin is closely connected with Santonian orogenic movements in southeastern Nigeria and the Benue Trough. Its sedimentary fill comprises post-orogenic molasse and thin unfolded marine sediments (Adeleye, 1974) trending NW-SE from Kontagora in Niger State to an area slightly beyond Lokoja in the south. It is delimited in the northeast by the basement complex and Sokoto Basin and merges with the Anambra in the southeast (Braide, 1992; Obaje, 2009). At the southern end, Bida Basin trends perpendicular to the main axis of the Benue Trough and the Niger Delta Basin and is regarded as the extension of the Anambra Basin, both of which were major depo-centers during the third major transgressive cycle in the Late Cretaceous. Landsat imagery, borehole logs, and gravity-negative anomalies similar to the adjacent Benue Trough and typical of rift structures suggest that the Bida basin is bounded by a system of linear faults trending NW-SE (Ojo, 1984; Ojo and Ajakaiye, 1989; Udensi and Osazuwa, 2004). Spectral analysis of the residual total magnetic field in different sections of the basin showed that the average depth to basement is about 3.4 km, with sedimentary thicknesses of up to 4.7 km in the central and southern parts of the basin (Udensi and Osazuwa, 2004). The rece

nt 2D seismic and FTG imagery from (NNPCL) (unpublished) discovered about 7 km of sediment thickness in the basement. This is new information on the stratigraphic successions in the Bida Basin suggesting the presence of pre-Santonian sedimentary succession deposited during the opening of the South Atlantic Ocean in the Early Cretaceous period.

Stratigraphy of the Bida Basin

Bida Basin is divided into Northern and Southern (or Lokoja) Sub-Basins with different stratigraphy but similar sedimentation packages and history (Fig. 3).

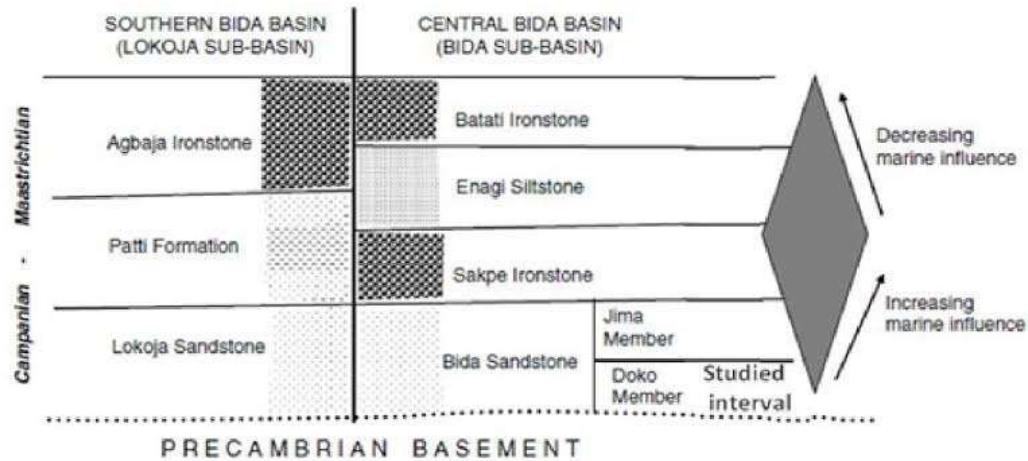


Figure 3: Stratigraphic successions in the Bida Basin (After Akande et al., 2005).

The northern part of Bida Basin comprises the oldest Bida Formation followed successively upward by Sakpe, Enagi, and Batati formations in their order of successions which are equivalent to the three successions of Lokoja, Patti, and Agbaja formations in the southern part. Bida and Lokoja formations are equivalent with similar lithological constituents of conglomerates, cross-bedded and poorly sorted sandstones, and claystone. Bida formation is divisible into two members, namely the Doko Member and the Jima Member (Fig. 3). The Doko Member is the basal unit and consists of mainly poorly sorted pebbly arkoses, sub-arkoses, and quart arenite sandstone. These are thought to have been deposited in a braided alluvial fan setting (Braide, 1992a). Wave ripples (ripple marks) and large-scale cross beddings are very prominent in the Doko village. Bioturbation structures consisting mainly of *Thalassinoides* and *Ophiomorpha* burrows exist within the two formations (Adeleye, 1972; Ladipo et al., 1994; Akande, 2005; Obaje, 2009, 2020). The Jima sandstone Member is considered as the more distal equivalent of the upper part of the Lokoja Sandstone, where similar features also occur. Planar and tabular crossbedding occur in many horizons of the Jima Member (Allen, 1970; Obaje, 2013).

Patti Formation overlain the Lokoja Formation in the south correlating with the Enagi Formation in the northern part because they consist of siltstones as the dominant lithology with fewer shales and sandstones. Sakpe Formation succeeded the Bida Formation comprising of oolitic and pisolitic ironstones with sandy claystone followed by oolitic



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ironstones (Adeleye, 1972; Ladipo et al., 1994; Akande, 2005). Its exposures are rarely encountered in the basin however, prominent outcrops and exposures of the Sakpe Formation occur in the village of Sakpe. (Adeleye and Dessauvagie, 1972). The siltstone of the Enagi Formation deposited above Sakpe is generally whitish to grey-white in color and well sorted. Shales of the Enagi Formation are exposed only at Pattishabakolo village but also penetrated by research boreholes at Kudu (Obaje et al., 2020) and at Gulu (this study) all in Niger State. Patti shales, the equivalent of the Enagi shale are well exposed at Ahoko and Gegu Beki villages in Lokoja State, southern Bida basin. The Patti Formation appears to have been deposited in marginal shallow marine to brackish water conditions identical to the depositional environment's similar lithologic units of the Manu and Ajali Formations in the Anambra Basin (Ladipo, 1988; Adeniran, 1991; Nwajide and Rwijers, 1996).

The Patti and Enagi formations are overlain by the Upper Maastrichtian Agbaja and Batati formations (lateral equivalents) respectively (Fig. 3). These consist of oolitic, pisolitic, and concretionary ironstones deposited within a continental to shallow marine setting ((Adeleye, 1972; Ladipo et al., 1994; Akande, 2005; Obaje, 2009). Batati Formation consists of argillaceous, oolitic, and goethitic ironstones with ferruginous claystone and siltstone and minor shaley beds some of which yielded nearshore shallow marine to freshwater fauna (Adeleye, 1974).

MATERIALS AND METHOD

The field mapping exercise took place in June 2023 when traverses were taken through the exposed outcrops. This activity includes a bed-by-bed description of outcrops exposure of the Enagi Formation in Gulu. These observations were not presented in this work because the emphasis is on the subsurface shale below the outcropping siltstones in the study area. The rocks from the research borehole at Gulu were sampled and logged. A total of 12 shale samples from the Gulu borehole and Ahoko outcrop were disaggregated and digested with 10% hydrogen peroxide to recover foraminifera. The samples were soaked in diluted hydrogen peroxide to disaggregate the fine sediments and thereafter washed through a sieve with mesh openings of 63 micrometers under running. The mud passed through the sieve leaving behind a concentration of sand-size material which may include foraminifera. The material is then rinsed onto a filter paper placed within a funnel, drained, and air-dried in a contamination-free environment. The grains observed were not stacked together because it is mud free. The samples were satisfactorily cleaned, air-dried, and stored properly in a labeled vial for microscopic examination at the Department of Geology and Mineral



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Science's laboratory. Major oxides (wt%) and trace elements concentrations/compositions (ppm) were determined using the XRF method. A total number of eleven (11) major oxides and forty-seven trace elements were obtained through the XRF procedure at the Nigeria Geological Survey Agency, Kaduna.

RESULTS

Sedimentology

Enagi Formation at Gulu village penetrated by a borehole to a total depth of about 80 m encountered claystone at the upper part, shale in the middle and sandstones at the base of the well (Fig. 4). The surface area of the borehole location consists of about 60 m thick siltstone, the most dominant exposed rock of Enagi Formation in the northern Bida Basin area overlying the subsurface 18m thick brownish claystone. This siltstone is typically greyish, brownish, and highly ferruginized in some places. It is characterized by its fine-grained texture and the presence of nodules and concretionary ironstone.

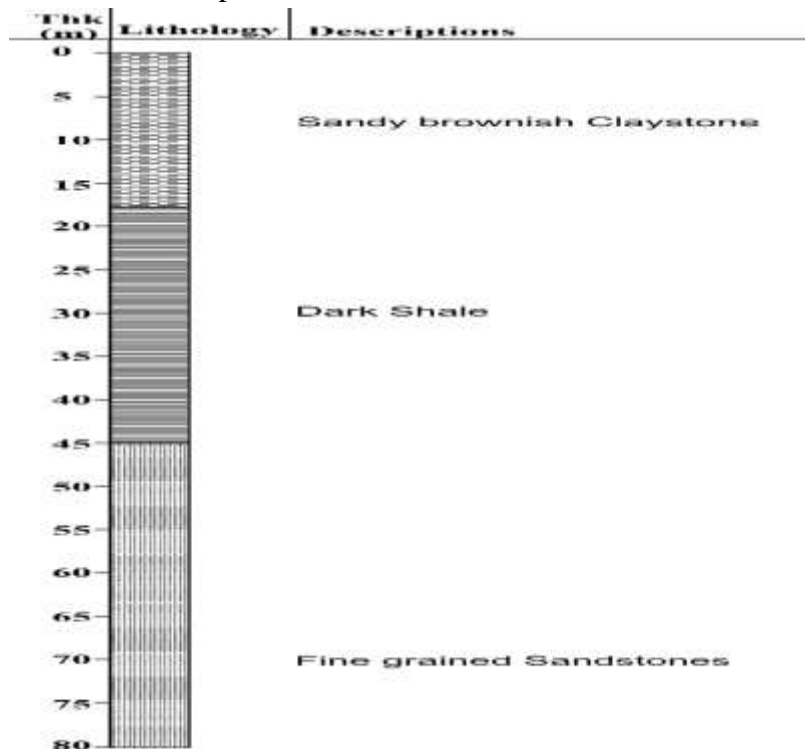


Figure 4: Lithologic section of a borehole that penetrated the Enagi Formation at Gulu, Northern Bida Basin.



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The 30m thick shale within the middle part of the borehole ranges from grey to black in color with the presence of coaly particles and sandy at some intervals (Fig. 4). The paleoecology and paleoenvironment of this subsurface shale of Enagi Formation and outcrop shale of Patti Formation in the southern part are the main subjects of this study. Shales of the Patti Formation at the Ahoko section are generally grey to dark in color, partly coaly, nodular, and massive (Fig. 5). They are interbedded with the concretionary ironstone. Some of the shales reveal imprints of molluscs trace fossils of corals and plenty of yellowish minerals suspected to be pyrite.

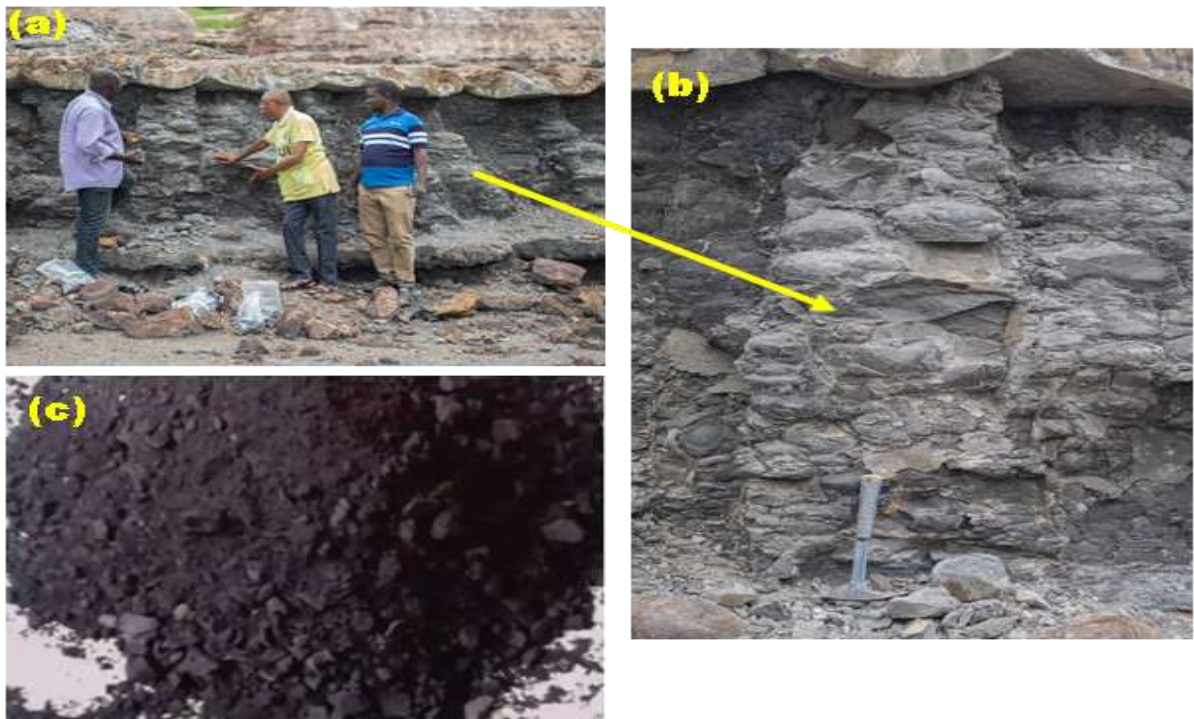


Figure 5: Field Representative photograph of (a) and (b) Dark Shale of Patti Formation exposed at Ahoko southern Bida Basin (c) Dark shale encountered on Gulu borehole within Enagi Formation, Northern Bida Basin.

Major Oxides and Trace Elements

The major oxides from Gulu shales show enrichment in SiO_2 , Al_2O_3 , Fe_2O_3 , and TiO_2 above CaO , MgO , SO_3 , P_2O_5 , Na_2O , MnO which are significantly little in percentage or not even detected in some of the samples. The values of SiO_2 , Al_2O_3 , Fe_2O_3 , TiO_2 , CaO , MgO , Na_2O



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and MnO in Gulu and Ahoko shales range from 44.4-59.1 %, 25.4-31.3 %, 7.6 -12.3%, 1.1 -1.3 %, 0.2-0.3%, 0.01-0.10%, 0.2-0.6%, and 0.02-0.06 % and 53.8-62.9 %, 23.3-28.7%, 2.8 -4.4%, 1.6 -2.4 %, 0.01-0.37%, 0.01-0.06%, 0.87-1.20%, and 0.01-0.03% respectively (Table 1). SiO₂, Al₂O₃, Fe₂O₃, and TiO₂ are the most dominant oxides in the shales across the two formations. Trace elements of these samples include elements such as vanadium, zircon, manganese, barium, chromium-molybdenum, cobalt, cadmium, and others (Table 2). The concentrations of these elements range from below the detection limit (bdl) to several parts per million (ppm) or parts per billion (ppb). The behavior of trace elements during sedimentation processes is complex due to factors like weathering, diagenesis, province, physical sorting, adsorption, and metamorphism (Taylor and McLennan, 1985).

Table 1: Major oxides (%) in the shale samples from Ahoko and Gulu, southern and Northern Bida Basin respectively

Sample No.	SiO ₂	CaO	MgO	K ₂ O	Na ₂ O	TiO ₂	MnO	P ₂ O ₅	Fe ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃ /TiO ₂
Ahoko Shale											
AH1-GC1	53.82	0.36	0.04	1.69	0.87	2.38	0.03	1.24	4.06	28.73	12.1
AH1-GC2	55.22	0.37	0.06	1.70	0.64	2.22	0.03	0.89	4.07	29.08	13.1
AH2-GC1	57.70	0.23	0.03	2.12	0.99	1.91	0.01	0.84	4.42	27.02	14.1
AH3-GC1	56.10	0.01	0.01	2.12	0.78	1.81	0.02	0.66	3.84	27.88	15.4
AH3-GC2	57.59	0.01	0.01	1.96	0.87	1.57	0.02	0.59	3.00	28.61	18.2
AH4-GC1	60.22	0.01	0.01	2.23	1.00	1.73	0.02	0.54	3.42	23.30	13.5
AH5-GC1	62.86	0.01	0.01	2.22	1.20	1.68	0.01	0.56	2.79	23.45	14.0
Gulu Shales											
GU-20-GC1	44.44	0.30	0.01	0.40	0.11	1.28	0.053	0.57	11.14	30.84	24.0
GU-22-GC1	42.99	0.20	0.09	0.46	0.09	1.20	0.046	0.56	9.76	31.27	26.1
GU-28-GC1	53.55	0.21	0.08	0.43	0.12	1.23	0.03	0.70	9.90	27.31	22.2
GU-28-GC2	59.06	0.22	0.05	0.35	0.06	1.14	0.024	0.65	7.58	25.17	22.1
GU-37-GC1	57.75	0.28	0.07	0.42	0.07	1.10	0.032	0.72	9.80	24.45	22.2
GU-37-GC2	50.76	0.28	0.05	0.40	0.05	1.22	0.028	0.28	12.32	26.30	21.6
GU-38-GC1	44.48	0.23	0.10	0.42	0.09	1.18	0.058	0.53	11.25	29.58	25.0
GU-38-GC2	57.65	0.23	0.03	0.37	0.08	1.06	0.022	0.60	9.31	25.16	23.8



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Table 2: Trace elements in (ppm) of shale samples from Ahoko and Gulu southern and Northern Bida Basin respectively

Samples	V	Cr	Cu	Sr	Zr	Ba	Zn	V/N	V/Cr
Ahoko Shale									
AH1-GC1	12.2	76.9	17.4	382.9	125.9	197.5	50.2	0.6	0.16
AH1-GC2	50.5	390.2	17.6	210.0	220.2	837.2	70.0	1.06	0.13
AH2-GC1	91.6	84.0	21.2	1,000.0	177.8	20.0	54.9		1.09
AH3-GC1	77.9	535.6	19.0	1,040.0	171.8	68.0	16.7	1.59	0.15
AH3-GC2	21.0	13.6	10.5	103.2	404.0	70.0	93.1	1.08	1.54
AH4-GC1	46.5	10.7	37.5	975.2	124.3	1350.0	102.3	3.32	4.35
AH5-GC1	50.0	54.6	36.6	385.8	233.3	90.0	82.7	1.04	0.92
Gulu shale									
GU-20-GC1	415.3	65.9	217.5	130.6	219.0	1550.0	164.6	52.6	6.3
GU-22-GC1	174.8	129.0	33.7	305.0	288.8	118.8	19.2		1.4
GU-28-GC1	13.0	22.8	8.9	353.4	38.0	910.0	33.3		0.6
GU-28-GC2	16.0	10.9	12.2	360.6	68.0	13.0	34.2	4.9	1.5
GU-37-GC1	8.3	9.5	5.2	11.6	1.7	545.0	169.0	0.2	0.9
GU-37-GC2	43.2	26.9	24.5	561.4	198.6	21.0	15.2	5.1	1.6
GU-38-GC1	127.6	1,040.0	5.5	294.1	102.8	12.0	46.2	7.2	0.1
GU-38-GC2	352.2	68.1	165.4	180.9	271.0	125.9	81.6	13.2	5.2

Foraminiferal Assemblages

Previous studies reported some scanty arenaceous benthic species of foraminifera (Petters, 1986) in Ahoko shales and also imprints of molluscs cup coral, and colonial corals on the shales. Gulu shales are generally sandy and yield a low foraminiferal population and diversity. Some of the representative benthic foraminifera species from Gulu shales are the few monotonous species (Fig. 6). Sample G22F- has very few foram species which include *Ammotium nwalium*, *A. nkalagum*, *A. bornum*, *Ammobaculites coprolithiformis*, *Haplophragmoides bauchensis*, *Haplophragmoides sp.* Sample G24F - *Ammotium nwalium*, *A. nkalagum*, *A. bornum*, *Ammobaculites coprolithiformis*, *Haplophragmoides bauchensis*, *Haplophragmoides sp.*, *Haplophragmoides sabecebensis*, *Trochammina tallorana*, *A. amabensis*, *Miliaminapetila*, *Miliamina sp.*, *Pseudobilivina variana*, *Spiroplectammina bausorum*. G28F - *Ammotium nwalium*, *A. nkalagum*, *A. bornum*,



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Ammobaculites coprolithiformis, *Haplophragmoides bauchensis*, *Haplophragmoides sp.*, *Haplophragmoides sabecebensis*, *Trochammina tallorana*, *A. amabensis*, *Miliamina petila*, *Miliamina sp.*, *Pseudobolivina variana*, *Spiroplectammina bausorum*. G36F - *Ammotium nwalium*, *A. nkalagum*, *A. bornum*, *Ammobaculites coprolithiformis*, *Haplophragmoides bauchensis*, *Haplophragmoides sp.*, *Haplophragmoides sabecebensis*, *Trochammina tallorana*, *A. amabensis*, *Miliamina petila*, *Miliamina sp.*, *Pseudobolivina variana*, *Spiroplectammina bausorum*, *Texturaria hockleyensis*, *Textularia sp.* G38F - *Ammotium nwalium*, *Ammotium sp.*, *Ammobaculites coprolithiformis*, *Haplophragmoides bauchensis*, *Haplophragmoides sp.*, *Haplophragmoides sabecebensis*, *Trochammina tallorana*, *Miliamina petila*, *Miliamina sp.* The forams here are robust but few monotonous (Fig. 6).

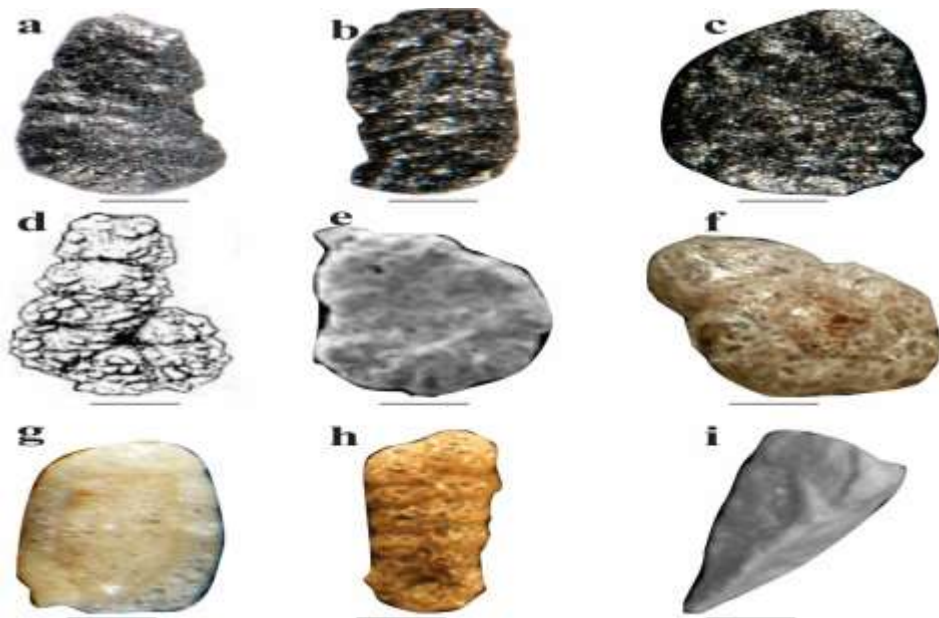


Figure 6: Representative benthic foraminifera (100 μm) recovered from Gulu shale, Enagi Formation in northern Bida Basin ((a) *Ammotium nwalium*, (b) *Ammotium bornum*, (c) *Ammotium nkalagum*, (d) *Ammobaculites coprolithiformis*, (e) *Haplophragmoide sbauchensis*, (f) *Trochammina tallorana*, (g) *Miliamminapetila*, (h) *Spiroplectammina bausorum*, (i) *Textularia hockleyensis*).



DISCUSSION

Provenance of Gulu and Ahoko Shales

The application of major oxide enrichment or depletion in provenance, clay mineral assessment, and terrigenous influx of sedimentary rock is significant because major oxides are essential products of the weathering of pre-existing rocks. Silicas are mostly derived from terrigenous detrital quartz with rare biogenic sources. Silica is often associated with argillaceous sediments such as clay minerals (Pettijohn, 1975) (Fig. 7). The bivariate plot of K_2O against Na_2O reveals that the shales of Ahoko, Patti Formation, and Gulu, Enagi Formation are not enriched in quartz minerals (Fig. 7).

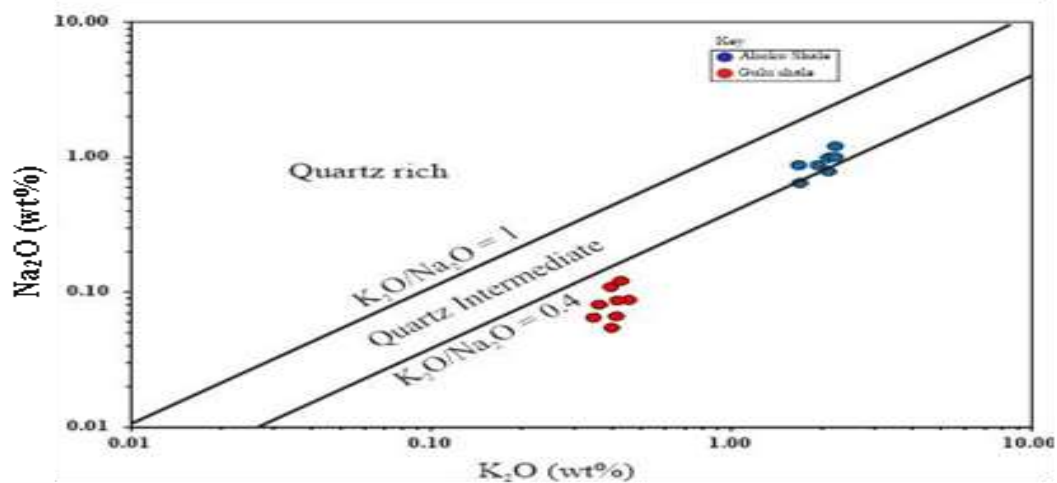


Figure 7: A bivariate plot of Na_2O/K_2O showing the quartz content of samples from Gulu which has poor quartz and Ahoko sample with intermediate to poor quartz. (After Crook, 1974).

Ahoko's shale in the southern Bida Basin has intermediate to poor quartz minerals while that of Gulu shale in the northern part of the basin is poor in quartz. This result is congruence with the mineralogical composition expected for shales which are mainly from clay minerals that essentially form from precipitation of dissolved solute or very fine-grained suspended materials. However, it appears there are more quartz minerals in Ahoko shale than in Gulu probably from the influx of coarse terrigenous sediments. The concentration of Al_2O_3/TiO_2 ratio in a siliciclastic sedimentary rock sourced from granitic to mixed granitic and basaltic rocks are classified based on their mafic, intermediate, and felsic chemical composition of values ranging from 3 – 8, 8–21 and 21 – 70 respectively ((Amajor, 1987, Hayashi et al., 1997 and Adeoye et al., 2020). Ahoko's shale has an Al_2O_3/TiO_2 ratio ranging from 21.6 –



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26.1% while Gulu's shales range from 12.1 – 18.1 (Table 1) suggesting that Ahoko's shales are sourced from felsic igneous origin while Gulu shales are from intermediate igneous rock. The discriminant factor 1 against discriminant factor 2 of Roser and Korsch (1988) (Fig. 9) further suggests that Ahoko's shales received input as well from an intermediate igneous source and Gulu's shale from mafic igneous rock. The plot of SiO_2 against $\text{K}_2\text{O}/\text{Na}_2\text{O}$ for Ahoko and Gulu shales indicates that their tectonic settings are from an active continental margin (Roser and Korsch, 1986). (Fig 8).

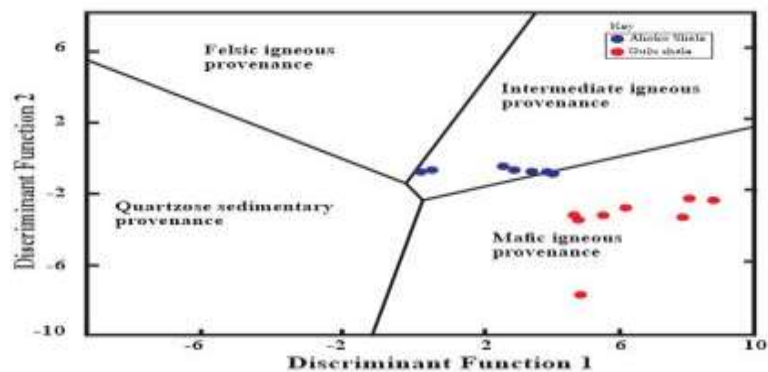


Figure 8: Plot of discriminant functions F1 and F2 for the Ahoko and Gulu shale after Roser and Korsch (1988).

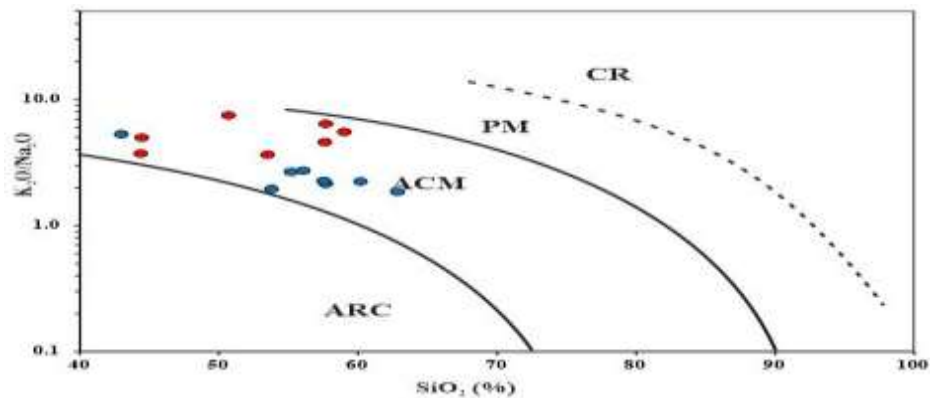


Figure 9: Tectonic setting discrimination of shales from the Ahoko and Gulu shales (Modified after Roser and Korsch, 1986)



Depositional Environment of the Shales of Ahoko and Gulu

The depositional environments of foraminifera species present in the Gulu shales point to shallow marine intertidal regions. Foraminifera habitats are good indicators for paleo water depth, paleoclimate, and other paleoenvironmental conditions of host rocks. The low number and few species indicate that the environments were not particularly favorable for foraminifera growth or survival at the time these shales were deposited. The relatively low occurrence of foraminifera may be attributed to the high percentage of sand and organic matter in the shales (Adeoye et al., 2020). The scarcity of foraminifera species in G22F samples suggests that the depositional environment can either be oligotrophic (low nutrient) or anoxic (lack of oxygen) as this condition can limit the growth and survival of many foraminifera. However, the sand content in the Ahoko's shales is significant for causing low nutrient levels peculiar to shallow water environments. The monotonous benthic foraminifera species indicate a shallow, stable, and uniform marine depositional environment. The presence of *Trochammina tallorana* and *Textularia hockleyensis* suggests that they were deposited in a coastal plain setting with some influence from terrestrial (oxic) sources. The presence of molluscs and corals suggests shallow water, a marginal marine to the lagoonal environment for Ahoko shales. Petters (1986) reported the occurrence of some diversity of arenaceous foraminifera common in the Patti Formation where shallow marine depositional conditions are known to have prevailed.

Vanadium to nickel ratio ranging from 0.6 to 3.3 in Ahoko and 0.2 to 52.6 in Gulu suggests mixed marine and terrigenous (fluvial) sources under dysoxic to oxic conditions with more marine influence in the Enagi shale (Table 2) (Galarraga, et al., 2008, and Adeoye et al., 2020). Paleo-oxygenation indicated by a V/Cr ratio of 0.1 to 4.3 in Ahoko and 0.6 to 6.3 in Gulu which are below 4.5 shows that paleo-conditions were more oxic with very short periods of anoxic conditions for those above 4.5 (Table 2) (Adegoke et al., 2014). The nickel and vanadium plots of Galarraga et al., (2008) suggest that the shales have marine input with shallow, oxic to dysoxic water conditions for Ahoko shales, Patti Formation in the south but a little deeper oxic to anoxic water condition for Gulu Shales, Enagi Formation in the northern Bida Basin (Fig. 10).

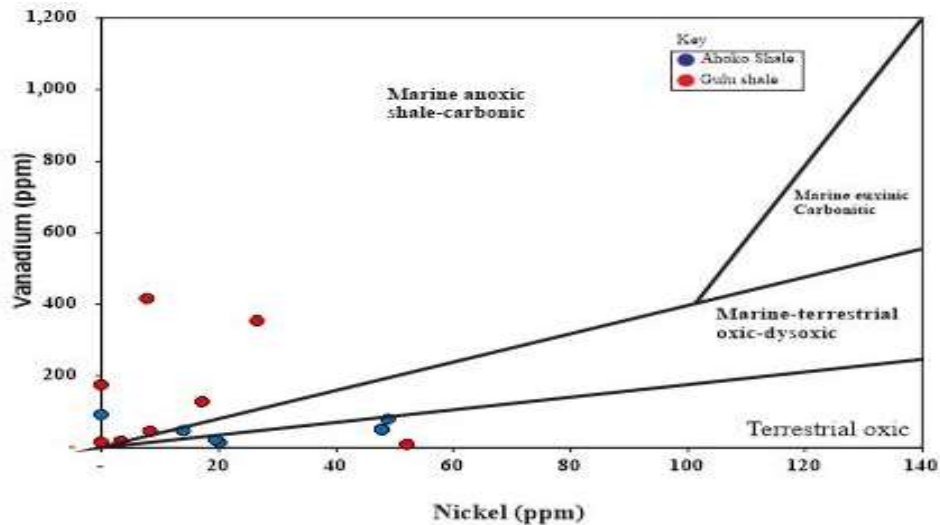


Figure 10: Cross plot of vanadium versus nickel of Ahoko and Gulu shale showing that the sediments had marine and terrestrial sources and were deposited under anoxic to oxic conditions. (Adapted after Galarraga et al., 2008).

CONCLUSIONS

This work investigated the shales of Patti and Enagi Formation, Bida Basin exposed at Ahoko in the south and in Gulu borehole in the northern area of the basin for provenance and depositional environments reconstruction. The sedimentology, foraminiferal assemblages, and inorganic geochemical composition of the shales suggest that:

- i. the Ahoko and Gulu shales are grey to black, coaly and massive;
- ii. the quartz content of the Ahoko shale has more quartz constituents ranging from intermediate to poor than the Gulu shale which is poor in quartz base on the ratio of their K_2O against Na_2O ;
- iii. the foram recovered from Gulu are mainly benthic species including *Ammotium nwalium*, *A. bornum*, *Ammobaculites coprolithiformis*, *Haplophragmoides bauchennsis*, etc. and the presence of molluscs and corals suggest shallow water, marginal marine to the lagoonal environment for the Ahoko shale
- iv. Ahoko's shales are sourced from felsic to intermediate igneous rocks while those of Gulu are sourced from intermediate to mafic igneous sources in an active continental margin
- v. Ahoko and Gulu shales are deposited in a marine environment varied within oxic, dysoxic to anoxic paleo-conditions. The marine water is hereby confirmed to have



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covered Bida Basin where shales of Patti and Enagi formations were deposited with deeper conditions within the northern part of the basin.

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