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SEDIMENTOLOGY AND PETROLEUM POTENTIALS OF POST-SANTONIAN ROCKS IN THE NORTHEASTERN ONSHORE DAHOMEY BASIN, SOUTHWESTERN NIGERIA

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ABSTRACT

Core samples of Post-Santonian shales, sandstones and limestone from Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu boreholes were investigated through foraminiferal paleoecology, petrography, grain size distribution and geochemical analyses to characterized their sedimentology and hydrocarbon potential. Planktic and benthic foraminfera species recovered from the shales include Heterohelix sp, Hedbergella sp., Globigerinoides sp. and Lenticulina, Bolivina, Orthokastina, Ammobaculites, Dentalina sp, etc. The limestones are mainly bioclastic packstone with few micrites, grainstone, and wackestone. Sandstones across the study areas are fine to medium grained and poor to moderately sorted except for the Igbotu that are medium-coarse grained, and moderately well sorted. The average value of TOC (wt%), HI (mgHC/gTOC), TMax (oC) and VRo (%) of the source rocks range from 1.3 - 2.3, 18.5 – 86, 287 - 419 and 0.47 - 0.52 respectively.
Sandstones are predominantly medium grained, moderately sorted, very positively skewed and mesokurtic to platykurtic suggesting a product of medium energy of transportation similar to both beach and river settings, thus indicating a fluvio-deltaic paleoenvironment. Foraminifera paleoecology of the shales suggested they are product of shallow marine probably within 50 m water depth and also the bioclastic limestone microfacies are mainly shallow marine within moderate to low energy setting such as shoreward and sub tidal environment. The Post-Santonian shales and limestones have lean and immature organic matter that cannot contribute to the discovered offshore oil and gas accumulation nor the bitumen deposit in Dahomey Basin. Though the thick and widely spread Post-Santonian shales could be further explored for unconventional hydrocarbon.

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1 INTRODUCTION

Dahomey Basin is one of the inland sedimentary basins in Nigeria with interesting paleogeography history and potentials for mineral resources. Its evolution began with the parting of Africa and South America continental plates in the late

Jurassic due to series of tectonic events (De Matos, 2000). The tectonic events involve trans-extensional movement of the Romanche, Chain and Charcot fracture zones within the continental crust of the Gulf of Guinea area (Brownfield and Charpentier, 2006). Gulf of Guinea province comprises of other basins such as Ivory Coast, Tano, Saltpond, Central, and the Keta in the West Africa (De Matos, 2000, and Brownfield and Charpentier, 2006) (Fig. 1).

Majority of these basins extend from the offshore to the onshore areas. Recently, many of these contiguous basins have become areas of abundance petroleum resources in Africa and most especially the Dahomey, Seme, Ivory Coast and Tano basins where commercial discoveries of petroleum have been reported. Dahomey Basin in the last one decade began to receive more research attention because of better technology leading to oil discovery in the offshore and the government renewed interest towards developing the abundant bitumen deposit in the onshore part. The onshore part host huge limestone deposit, a major raw material for the production of cement for Nigeria and neighbouring African countries. The limestone deposit is concentrated at the northwestern part of the basin while the bitumen deposit within the Afowo sandstone is in the northeastern side. This bitumen or tar sand still

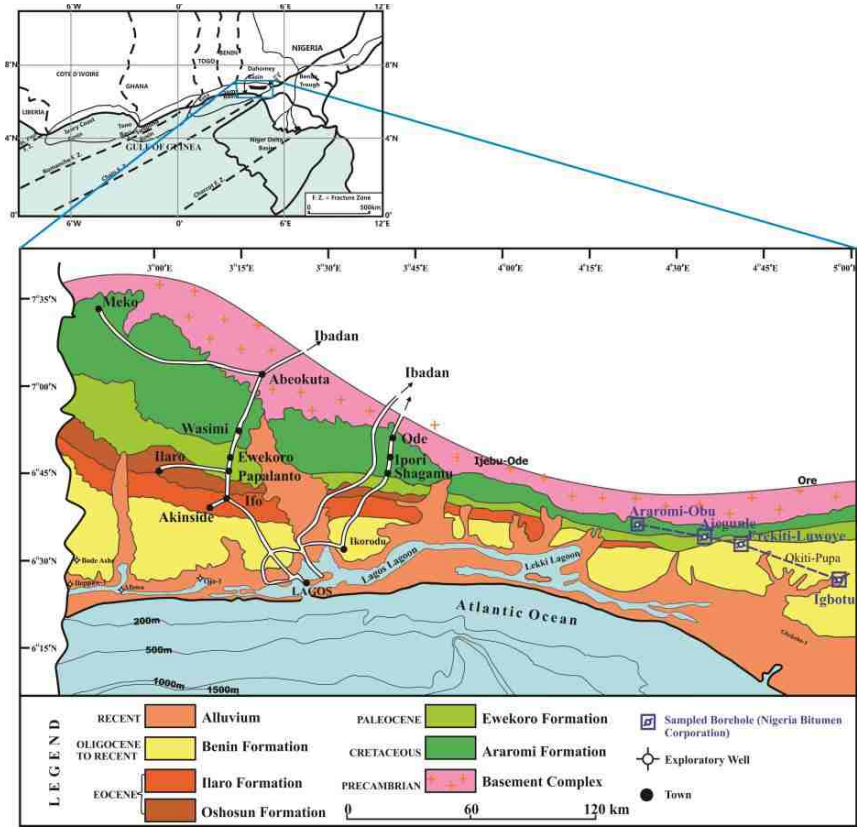


Figure 1. Geological map of the Dahomey Basin showing the locations of the sampled boreholes in the northeastern part of the basin (Modified after Gebhardt et al. 2010) Inset: Map showing the transform fault during the parting of Africa and South America plate). (After Brownfield and Charpentier, 2006 and Akande et al. 2012)

remain a major research subject in terms of unraveling the genesis and quality of the heavy oil. Despite the numerous previous works on the basin's evolution, stratigraphy, sedimentology, geophysics and many other aspects of geoscience's studies in Dahomey Basin (Adegoke et al., 1972, Odigi and Brown-Awala, 1992, Okosun 2000, Adekeye et al., 2004 and Oladele and Ayolabi, 2014), sedimentary petrography, geochemistry and paleoecology information on the rock successions in the northeastern onshore part of the basin still remain scanty. Therefore, this study intends to contribute more geological data on the sedimentology, paleoecology and petroleum potentials of sedimentary rock units encountered in four shallow core holes namely Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu within the northeastern part of the basin (Fig. 1). These boreholes penetrated some rock units impregnated by the bitumen and the basement.

2.0 Geology and Stratigraphy of Dahomey Basin

The oldest rock of Ise Formation in the Dahomey Basin lies directly on the fractured continental crystalline basement. This fractured basement has been subjected to transcurrent

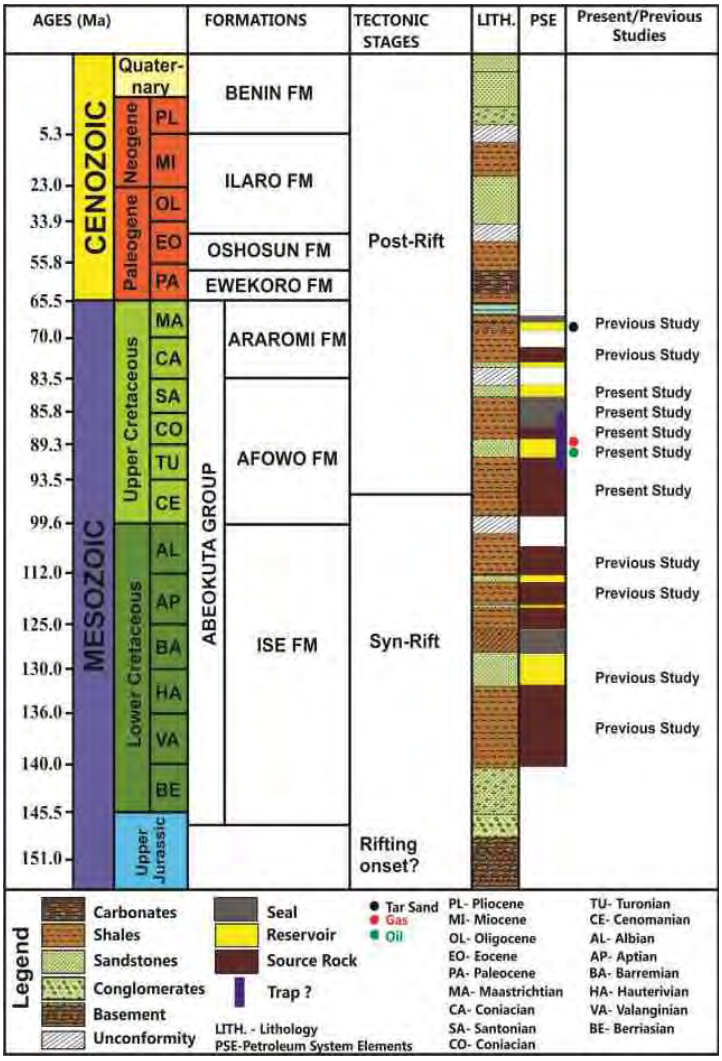
faults movement which developed into series of horsts and grabens features that controlled sedimentation in the basin (Brownfield and Charpentier, 2006). The separation stages of South America and Africa plates imprint the rift structures that were conspicuous in integrated seismic, aeromagnetic and well data analysis (Babalola, 1990). The continental crust was subjected to stretching and this led to the upsurge of mantle material and formation of rift valleys as the subsidence from isostatic adjustments of mantle material continues. Continental sedimentation set in through the available depositional space followed by marine deposition as the margins of South American and African continents drifted wide apart (Adegoke, 1969, Ako et al., 1980, Omatsola and Adegoke, 1981, Adediran and Adegoke, 1987 and Brownfield and Charpentier, 2006).

Rock successions ranging from the Cretaceous to Neogene age have been reported to have formed by various depositional environments and paleoconditions ranging from fluvial, deltaic to marine and oxic to anoxic respectively. The oldest Cretaceous sediments of Abeokuta Group comprise of the Ise Formation (Fm), Afowo Fm and Araromi Fm. Abeokuta group was succeeded by the Paleogene-Neogene Ewekoro Formation (Paleocene), Akinbo Formation (Late Paleocene to early Eocene) Eocene Oshosun, Ilaro Fm, and the youngest Pleistocene to Recent Benin Fm (Table 1). (Ako et al., 1980, Omatsola and Adegoke, 1981, and Okosun, 1996)

Ise Formation

This formation consists of a basal conglomerate overlain by coarse to medium grained sandstones with interbedded kaolinite (Omatsola and Adegoke, 1981 and Adediran and Adegoke, 1987). It is exposed at Onikintibi and J4 areas of Ogun State unconformably overlying the weathered basement. The fauna assemblage recorded suggests a Neocomian to Aptian age for the Ise Fm (Adegoke, 1969). Shell-BP geologists recovered some sporomorphs such as *Cicatricosisporites sp., pilosisporites, trichopapillosus*, etc from the Ise-2 well. These

Table 1 Chronostratigraphic chart of the Dahomey Basin showing key tectonic stages in relation to the geologic Formations and lithologies (Adeoye et al., 2020)



assemblages also suggest a Neocomian or possibly Valanginian – Barremian age (Omatsola and Adegoke, 1981) (Table 1).

Afowo Formation

This entails coarse to medium grained sandstones with thick interbedded shales, siltstones and pyritized clay. The lower part of the Afowo Fm consists of well sorted subrounded fluviatile sandstones with brackish to marine shales (Omatsola and Adegoke, 1981; Adediran and Adegoke, 198). The outcropping basal sequences of the formation is present along J4 – Iwopin road where the sandstones are impregnated with migrated and biodegraded hydrocarbons. This formation was assigned a Turonian age (Billman, 1976) on the basis of palynomorph assemblages which include *Elytranths* sub zone and *Multiporopollenites aff. M. maculosus* zone. The Turonian age was further confirmed by the presence of planktic foraminifera biozonation in offshore X-well and coastline Ise-2 exploratory well (Adekeye et al., 2019) with the presence of *Whiteinella archaeocretacea* which marks the

boundary of late Cenomanian and early Turonian.**Araromi Formation**

Araromi Formation contains fine-medium grained sandstone at the lower part and is overlain by shales and siltstones with interbedded carbonates (Omatsola and Adegoke, 1981 and Okosun, 1990). The shales colour are light grey to black consisting of abundant Planktic and benthic foraminifera, o*stracods*, pollens and spores. The Araromi Fm is Maastrichtian in age (Omatsola and Adegoke, 1981).

Ewekoro Formation

The Paleocene Ewekoro Fm overlies the Afow Fm (Table 1). Four limestone microfacies described in the formation consist of sandy bromicrosparite, shelly biomicrite, red phosphatic biomicrite and algal biosparite. The structure, texture and fossil content of the limestones indicate a shallow marine environment of deposition (Adegoke et al. 1971b). There is predominance of macrofaunas like *nautiloids, pelecypods, gastropods* and *scaphopods* and sizable coral fauna in the limestone (Adekeye and Akande, 2004). The existence of *Globorotalia pseudobulloides, Globorotalia velascoensis, Globorotalia acuta,* and *Globigerina* and *trigoculinoids* in the formation suggest a Palaeocene age (Reyment, 1966 and Adegoke et al., 1971b). The glauconite above the limestone and within the shale has average of 54+2.7 Ma radioactive age within the Palaeocene (Adegoke et al., 1971b).

Akinbo Formation

Akinbo Fm unconformably lies above the Ewekoro Formation and has been assigned Upper Paleocene to Lower Eocene age. The base consists of glauconitic unit above the Ewekoro Formation and the top of the formation is a greyish sand with little clay. The greenish grey glauconites consist of bands and lenses of limestones near the base. The Akinbo Formation is divided into the upper and lower units. The upper unit is sparsely fossiliferous, with shale overlain by massive mud and sands. This unit lacks bands and lenses of limestone and glauconites but consists of pyrite crystals and small spherulitic ironstone. The lower shale is associated with bands and lenses of limestone and glauconites of an approximate thickness of 0.6 m. The lower unit is highly fossiliferous containing molluscs and poorly preserved foraminifera (Adekeye, 2005).

Oshosun Formation

Oshosun Fm succeeded the Akinbo Formation and has been assigned a Lower Eocene- Middle Eocene (Table 1). It consists of unconsolidated sandstones, clayey shale, greenish to grey laminated shales and clays. They are phosphatised with textures varying from disseminated, vesicular and nodular bodies to oolitic and concretionary types (Adegoke, 1969, Okosun, 1990, Odigi and Brown-Awala, 1992). Adegoke (1969) reported the fossil assemblage in the Oshosun Fm to comprises of molluscs, corals, fishes and sea snakes as well as pelagic and planktic foraminifera which suggested that the marine environment is more dominant in their deposition contrary to the lagoon and swampy environments suggested by Russ (1924).

Ilaro Formation

Jones and Hockey (1961) reported Ilaro Fm assigned an Eocene age to have attained a thickness of about 37-60 m. Borehole studies in the Dahomey Basin across Nigeria, Benin and

Togo revealed the occurrence of a marine well-developed sequence of nearshore and continental, sandy beds above the Oshosun bed which is now referred to as the Ilaro Fm. The sandstones consist of predominant quartz grains, which are subrounded to rounded at the base of the formation indicating a texture characterizing beach or shoreline and nearshore deposit (Jones, 1964). Fossil are very sparsely scattered within the sandstones and more also the occurrences of some benthic foraminifera have been described.

3.0 Methodology

Four limestone and seven sandstones samples were cut into slabs of about 1cm thick and prepared for petrographic study. The surface of each sample was then smoothened with 100grits carborundum in slurry until no more trace of pits and impression were noticeable. The samples were then placed on a hot plate at about 95 ^{o}C to dry up. Equal proportion of araldite and hardener 93 ^{o}F were mixed in a small dish that was placed on the hot plate. They were then mounted on the glass slide and left for another thirty (30) minutes on the hot plate. They were then removed, cooled, and grounded to about 0.3 mm thin layer on the glass slide with occasional observations under the petrological microscope. They were further covered with glass slides using Canada balsam as adhesive for study with petrological microscope. Twenty-one selected samples of unconsolidated sandstones and siltstones were subjected to mechanical dry sieving with sieve sizes 2.36, 1.6, 1.18, 0.5, 0.30, 0.25, 0.112, 0.063 and <0.063 mm. 100 g each was weighed and carefully put into the topmost sieve arranged in descending order of sieve sizes on a mechanical sieving machine. Sieving was carried out for at least five minutes and the grains retained in each sieve were weighed, recorded and subjected further to statistical analysis.

Forty-three shale samples from Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu wells were subjected to the preliminary procedures of digestion, washing and picking of the forams. Each of the chipped samples were put into different plastic container and 10 % hydrogen peroxide solution added for digestion. The digested sample were placed under consistent water flow, washed and sieved with 0.063 μm mesh. The retained particle after careful washing were air dried and carefully stored in sealed plastic bottles and properly labelled. Small quantity of the washed and air-dried residues was placed under binocular microscope for identification, picking and description of the foraminifera species and any other associated microfossils. The different species identified and were further subjected to Scanning Electron Microscope at Johann Wolfgang Goethe, University, Frankfurt am Main, Germany for photographs. Sixteen shale and limestone samples were crushed into powder form and 100g weighed into oven sterilized crucibles. In order to remove carbonates, Hydrochloric acid was added and later drained off from the sample for about 6 hours before it was transferred to an oven set at 60 ^{o}C overnight. The carbonate free sample were loaded in the Leco-analyser for combustion and TOC measurements. The Rock-Eval II pyro-analyser of Espitalie et al., 1984 was adopted to determine the hydrocarbon generative potential variables (S_1, S_2), and thermal maximum (Tmax).

4.0 Results

4.1 Lithologic Description of the Sampled Boreholes

Rocks such as sandstones, shales, claystones and carbonates constitute the lithologies of Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu boreholes (Fig. 2).

4.1.1 Lithologic Descriptions of Araromi-Obu Borehole

This shallow borehole located on the feather-edge of Dahomey basin on the co-ordinates N 06^0 38.020', E 004^0 27.594'and elevation of 90 m above mean sea level (Fig. 2) and penetrated a total depth of 142 m. The upper segment of the borehole consists of sandstones, the middle part consists of shales and carbonates while the basal part is a mixture of shale and sandstones. The 31 m thick basal sandstone is brownish to mottled colour, fine to medium grained and poorly sorted while the topmost sandstones are moderately sorted. A bitumen unit of about 12 m thick occur at

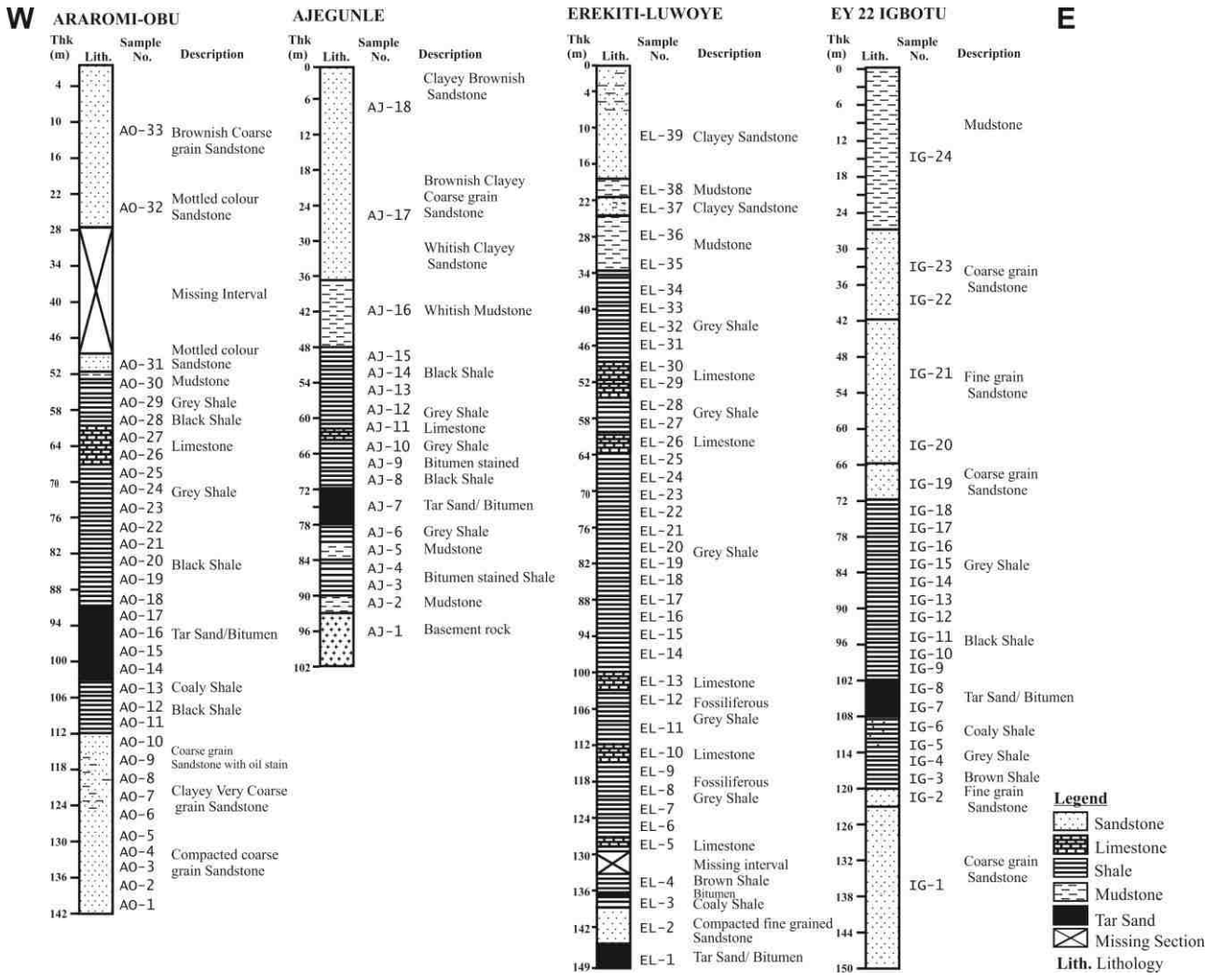


Fig. 2 Lithostratigraphic sections of Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu boreholes located at the northeastern part of Dahomey Basin, Nigeria.

about 96 m. The shales are laminated, fossiliferous, partly coaly, greyish and up to 59 m thick in the middle part of the section. This litholog generally reveals an alternating cycle of high energy and quite water conditions interchanging successive coarse materials (sand deposit) and finer ones (shale deposit) suggesting influence of transgression (fluvial system) and transgression events (marine or deep water). This pattern is observable in all the boreholes suggesting the regression and transgression events is widely spread and registered across the study areas.

4.1.2 Lithologic Descriptions of Ajegunle Borehole

Ajegunle borehole is located on the coordinate of N 06 37.646', E 04 34.0851 with an elevation of 86 m penetrated a total depth of 101 m reaching the crystalline basement (Fig. 2). Lithologies penetrated consist of sandstones, shales, mudstone, claystones and limestone. Sandstone is about 43 m thick and are fine to medium grained with some clayey part and moderately to poorly sorted. Part of the sandstones host the 4 m thick bitumen unit. The shale is very fissile, fossiliferous, grey to black colour and up to 24 m. Massive mudstone unit of about 1 m thick overlies the lower shale unit while the whitish and compacted claystone is about 3 m thick. A fine grained and compacted limestone unit of about 9 m thick also occurs in the middle part of the section. The lithology assemblages in Ajegunle borehole revealed both fining and coarsening upward sequence suggesting varied depositional environments ranging from fluvial to deltaic and marine settings (Ojo, 2004 and Ojo, et al 2012).

4.1.3 Lithologic Descriptions of Erekiti-Luwoye Borehole

This borehole is located on the coordinates of N 06 35.304' and E 004 36.987', elevation of 90 m with total depth to basement of 149 m penetrating sandstone, shales, claystones, and tar sand units (Fig. 2). A compacted and 6m thick fine-grained sandstone occur at the base of the section above the bitumen impregnated basement and 19 m thick unconsolidated clayey and poorly sorted sandstone similar to a proximal alluvial occurs at the top of the section. In between the sandstones are about 105 m thick, fossiliferous, grey, black and massive shale unit interbedded with light grey, massive, highly fossiliferous and compacted 1 m to 6 m thick limestone beds. Erekiti-Luwoye section like others reveals an alternating sandstones, shales and carbonate beds. The interchanging fining and coarsening upward rock sequence of sandstones suggest imprint of fluvial settings and assemblage of bivalves such as brachiopods, pelecypods and algae filaments, deltaic in the limestone and shales are indicative of shallow marine environments (Ojo et al., 2021).

4.1.4 Lithologic Descriptions of Igbotu Borehole

Igbotu borehole is also located on the onshore Dahomey Basin on the coordinates of N 06 24.663', E 004 53.464', elevation of 3m with total depth of 150 m (Fig. 2). It consists of three lithological units of sandstones, shales and mudstones. The sandstones occur at the upper and lower part of the cored section. Lower sandstone is moderately sorted, medium grained and about 27m thick while the upper sandstone is about 45 m thick, moderately sorted with medium to coarse

grain textures. Grey to black shales of about 42m thick occurs in the middle part of the section interbedded with tar sand. No macrofossil was identified in this shale. The topmost 27 m thick mudstone bed is clayey and massive with no visible fissile structure similar to a flood plain deposit. The section reveals an alternating sandstones, shales and mudstone beds with dominant fining upward pattern suggesting a fluvial dominated setting.

4.2 Limestone Petrography

Limestone commonly forms in clear, warm, shallow marine waters as organic and biogenic remains of organism settles down. It can also be form in a non-marine environment such as fresh water lakes where algal mounds and marlstone (mixture of carbonates and argillaceous sediments) are common (Wilson, 1975, Sengupta, 2007). Other examples of non-marine carbonates were travertine in hot springs, spongy, porous carbonates deposits associated with natural springs and stalactites and stalagmites formed within caves. Biochemically formed carbonate

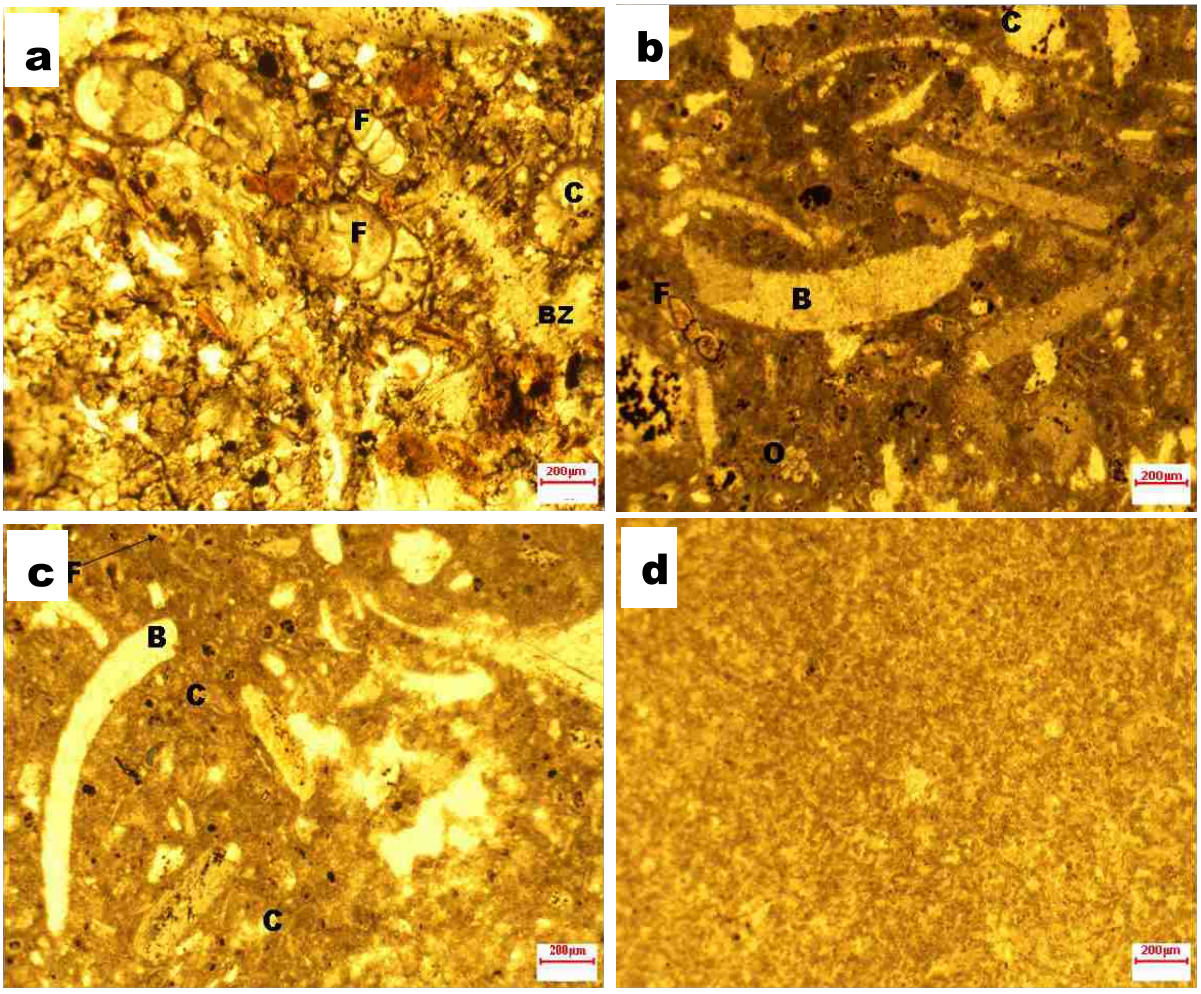


Fig. 3. Representative photomicrograph of sample from (a) Erekiti-Luwoye (EL-10), (b) Erekiti-Luwoye (EL-25, EL-26, EL-28) and Araromi Obu (AO-25) and (c) Araromi Obu (AO-24) and Erekiti-Luwoye (EL-12, EL-18 and EL-22) and (d) Araromi Obu (AO-26, AO-28), Erekiti-Luwoye (EL-5, EL-16), and Ajegunle (AJ-13) (F= Forams, BZ= Bryozoan, C= Corals, O= Oolites, B= Brachiopod)

rocks were derived from the buildup of shells, corals, algal and faecal debris. Clean, shallow, calm, and warm marine waters environment favour calcium carbonate concentration in the shells and skeletons because they derived the needed ingredients from sea water. These shell and skeletal debris accumulate as sediment that were lithified into carbonate after the animals die (Dunham, 1962, Sengupta, 2007). Sample EL-10 from Erekiti-Luwoye has skeletal grains of coated forams, corals and bryozoans (Fig. 3a) with little or no mud (micrite). The samples from EL-25, EL-26, EL-28, and AO-25 contains fossils of foraminiferal, Brachiopod, Corals, Oolites etc and are mud supported (Fig. 3b). AO-24, El-12, EL-18 and EL-22 also contain foraminiferal, brachiopods, corals, pelecypod, and non-skeletal material which forms minor amounts of intraclasts (Fig. 3c). AO-26, AO-28, EL-5, EL-16, and AJ-13 comprises of mud or micrites greater than 75 %, quartz grain of about 3 % and slightly bare of sparry calcite cements with no evidence of any bioclastic grains (Fig. 3d).

4.3 Sandstones Grain Size Distribution

The provenance, transport history and paleoenvironment of rocks such as sandstones can be deduced from their grain size (Folk and Ward, 1957, Friedman, 1979, and Bui et al. 1990). The grain size properties of sandstones from Araromi Obu, Ajegunle, Erekiti-Luwoye and Igbotu boreholes were deduced from statistical variables (mean, standard deviation (sorting), skewness and kurtosis) and presented in Table 2. The data will further aid in the reconstruction of the past history of sandstones from source to the basin.

4.4 Foraminifera Assemblages

The planktic and benthic foraminifera assemblages recovered from the studied shale samples helps in the reconstruction paleoenvironments. The planktic species are

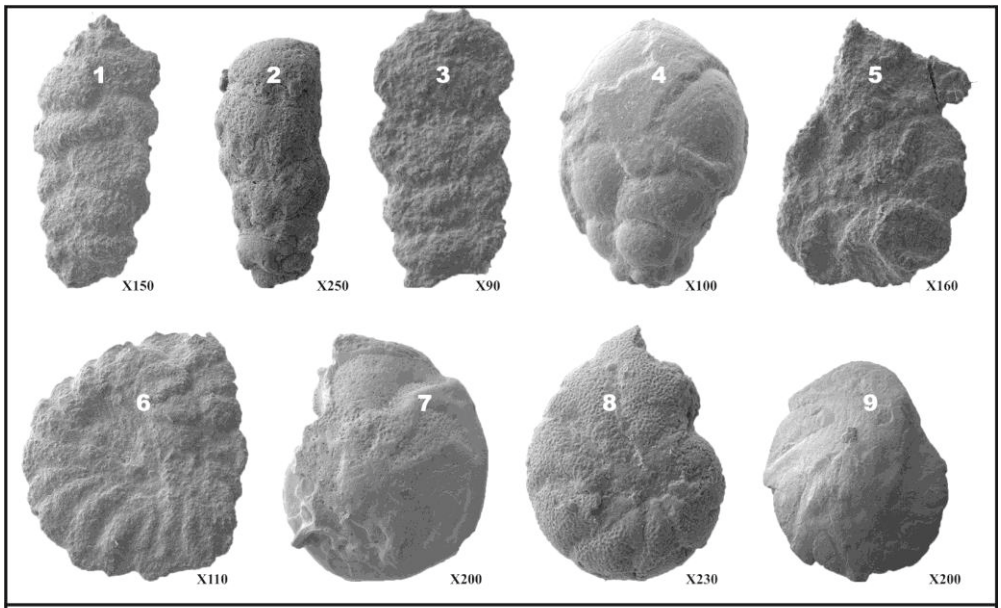


Figure 4. SEM photographs of some selected diagonistic benthic foraminifera recovered from the studied shale

Table 2. Results of the textural parameters and interpretations of sandstone in the northeastern Dahomey Basin.

Sample No	Well Name	Values (Phi)				Interpretation			
		Mean	Sorting	Skewness	Kurtosis	Mean	Sorting	Skewness	Kurtosis
AO3	Araromi Obu	1.75	0.94	-0.03	0.92	Medium Sand	Moderately Sorted	Near Symmetrical	Mesokurtic
AO4	Araromi Obu	1.85	1.19	0.13	0.89	Medium Sand	Poorly Sorted	Negatively Skewed	Platykurtic
AO5	Araromi Obu	1.53	1.27	-0.14	0.76	Medium Sand	Poorly Sorted	Negatively Skewed	Platykurtic
AO6	Araromi Obu	2.15	0.93	0.19	0.91	Fine Sand	Moderately Sorted	Negatively Skewed	Mesokurtic
AO31	Araromi Obu	2.65	0.74	0.11	1.02	Fine Sand	Moderately Sorted	Positively Skewed	Mesokurtic
AO32	Araromi Obu	2.35	0.96	0.06	1.01	Fine Sand	Moderately Sorted	Near Symmetrical	Mesokurtic
AO33	Araromi Obu	1.64	1.31	0.06	1.21	Medium Sand	Poorly Sorted	Near Symmetrical	Leptokurtic
AJ17A1	Ajegunle	1.95	1.10	0.11	1.11	Medium Sand	Poorly Sorted	Positively Skewed	Leptokurtic
AJ17A2	Ajegunle	2.07	1.14	0.02	1.03	Fine Sand	Poorly Sorted	Near Symmetrical	Mesokurtic
AJ17B1	Ajegunle	2.52	0.93	-0.03	1.07	Fine Sand	Moderately Sorted	Near Symmetrical	Mesokurtic
AJ17B2	Ajegunle	2.56	0.98	-0.06	1.05	Fine Sand	Moderately Sorted	Near Symmetrical	Mesokurtic
AJ18	Ajegunle	1.10	1.41	0.19	1.04	Medium Sand	Poorly Sorted	Positively Skewed	Mesokurtic
EL39A	Erekiti-Luwoye	2.53	1.21	-0.16	0.94	Fine Sand	Poorly Sorted	Negative Skewed	Mesokurtic
IG1A	Igbotu	1.27	0.62	-0.05	1.16	Medium Sand	Moderately Well Sorted	Near Symmetrical	Leptokurtic
IG1B	Igbotu	1.23	0.63	-0.09	1.12	Medium Sand	Moderately Well Sorted	Near Symmetrical	Leptokurtic
IG19	Igbotu	1.19	0.62	-0.17	1.05	Medium Sand	Moderately Well Sorted	Negatively Skewed	Mesokurtic
IG20	Igbotu	1.87	0.75	-0.11	1.21	Medium Sand	Moderately Sorted	Negatively Skewed	Leptokurtic
IG21A	Igbotu	1.23	0.65	0.03	1.29	Medium Sand	Moderately Well Sorted	Near Symmetrical	Leptokurtic
IG21B	Igbotu	1.22	0.60	0.00	1.29	Medium Sand	Moderately Well Sorted	Near Symmetrical	Leptokurtic
IG22	Igbotu	0.29	0.94	-0.10	0.73	Coarse Sand	Moderately Sorted	Negatively Skewed	Platykurtic
IG23	Igbotu	0.79	0.79	-0.75	0.90	Coarse Sand	Moderately Sorted	Strongly Negatively Skewed	Platykurtic

Globigerina bulloides, Globigerina pseudotriloba, Globigerina subcretacea, Globigerinoides sp, Heterohelix reussi, Heterohelix sp, Rugoglobigerina cretacea, Rugoglobigerina esnehensis. The benthics are *Afrobolivina, Anomalina sp, Bolivina sp, Bulimina sp, Cibicides sp, Cyroidinoides frizzelli, Dentalinella sp, Fursenkoina sp, Gavelinella sp, Globorotalites conicus, Lenticulina sp, Legena sp, Nodosaria limbata, Nonionella sp, Orthokarstina sp, Praebulimina sp, Pyramidine minima,* and *Textularia hockleyhensis.* (Fig. 4). Foraminifera occurrences in the shale of Araromi-Obu, Ajegunle, and Igbotu (Fig. 5) are generally

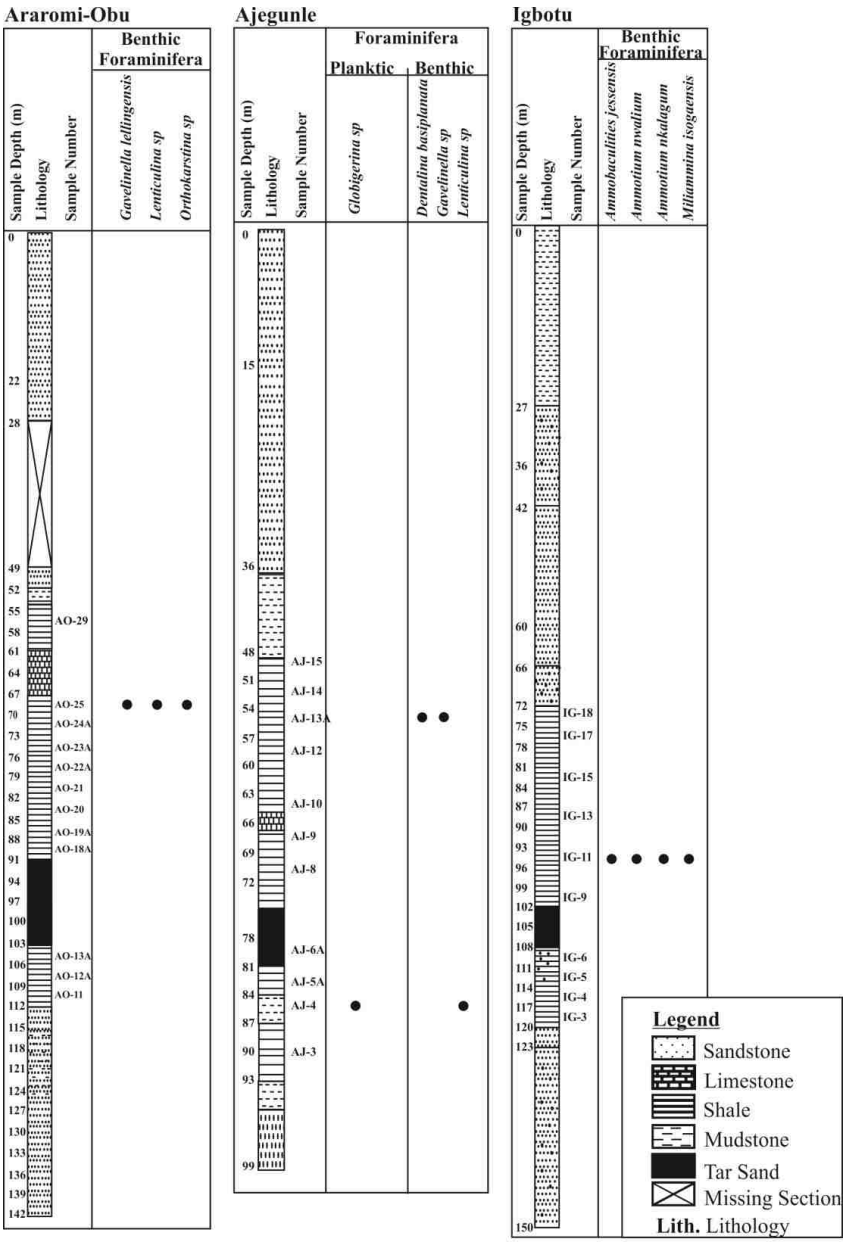


Fig. 5. Chart of planktic and benthic foraminifera and the interval where they occur in Araromi-Obu, Ajegiunle and Igbotu boreholes

poor but fairly significant in Erekiti-Luwoye shales (Fig. 6).

4.5 Organic Geochemistry

The technique of Rock-eval pyrolysis developed by Espitalie *et al.* (1984) was used on pulverised shales and limestone samples to an elevated temperature of about 600°C to determine the free or volatile hydrocarbon (S_1), cracked or pyrolysed hydrocarbon (S_2), volatile carbon dioxide (S_3) and the thermal maximum (T-max). Hydrogen, oxygen and production indices were derived from S_1, S_2, and TOC as presented in Table 3.

Leco TOC

The Araromi-Obu, Ajegunle, Erekiti-Luwoye and

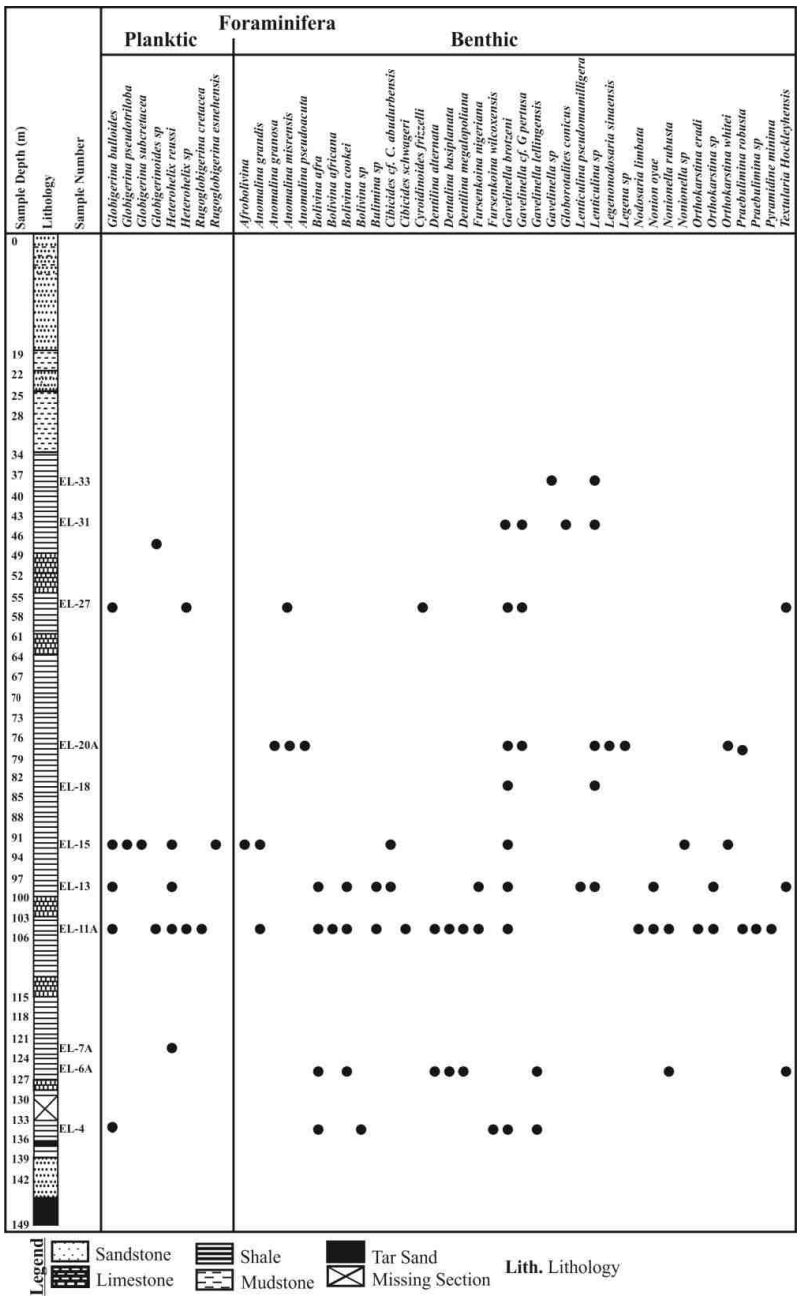


Fig. 6. Chart of planktic and benthic foraminifera representative species and the interval where they occur in Erekiti-Luwoye borehole

Igbotu shales have TOC value ranging from 0.3 – 8.0 wt% (mean 2.3 wt%), 0.1 – 2.2 wt% (mean 1.3 wt%), 0.3 – 2.4 wt% (mean 1.3 wt%) and 0.3 – 7.2 wt% (mean 2.0 wt%) respectively. The limestones have TOC value ranging from 0.2 – 0.7 wt% averaging 0.3 wt% (Table 3).

Hydrogen Index (mgHC/gTOC)

Shale samples of Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu shales have hydrogen index (HI) value ranging from 2 - 144 mgHC/gTOC (mean 39.2 mgHC/gTOC), 7 - 84 mgHC/gTOC (mean 30 mgHC/gTOC), 8 - 148 mgHC/gTOC (mean 50 mgHC/gTOC) and 4 - 66 mgHC/gTOC (mean 39 mgHC/gTOC) respectively (Table 4.13). The limestones have HI value ranging from 10 – 86 mgHC/gTOC averaging 35.7 mgHC/gTOC (Table 3).

Genetic Potential ($S_1 + S_2$)

Genetic potential of shales in Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu values range between 0.05 – 1.97 KgHC/t of rock (mean 0.8 kgHC/t rock), 0.01 – 0.9 kgHC/t rock (mean 0.5 kgHC/t rock), 0.11 – 2.44 kgHC/t rock (mean 1.1 kgHC/t rock), and 0.04 – 4.55 kgHc/t of rock (mean 2.2 kgHC/t rock) respectively. Limestone samples range from 0.05 – 0.21 kgHC/t rock with average of 0.2 kgHC/t rock (Table 3).

4.5.4 Thermal Maximum (T-Max °C)

Shales thermal maturity (Tmax) values in the Araromi-Obu, Ajegunle, Erekiti-Luwoye and Igbotu range between 304 – 422 °C (mean 380 °C), -1 – 424 °C (mean 297 °C), 305 – 423 °C (mean 399 °C), and -1 – 408 °C (mean 287 °C) respectively (Table) while that of limestone ranges from 411 – 422 °C with average of 419 °C. Vitrinite reflectance measurements on the shales from the boreholes as above range between 0.49 – 0.52 % VRo (mean 0.47 %), 0 – 0.51 % VRo (mean 0.51 %), 0.43 – 0.55 % VRo (mean 0.5 %), and 0.51 – 0.55 %VRo (mean 0.52 %) respectively (Table 3).

5.0 Discussion

5.1 Limestone Microfacies

Limestone petrography was carried out for the purpose of classifying them into microfacies and reconstruct their depositional environments. The limestone grains and fabric textural properties are related to depositional environment in Folks (1959) and Dunham (1962) where four limestone microfacies are recognized as the bioclastic grainstone, bioclastic packstone, bioclastic wackestone and micrites (Fig. 3 a-d).

Bioclastic Grainstone Microfacies

These are grain-supported framework Dunham (1962) with intergranular space filled with clear calcite cement. They have bioclast of foraminiferal, Bryozoan, and corals and lithoclasts that are closely packed. Skeletal grains recognized in these microfacies include coated forams, corals and bryozoans only in sample EL-10 of Erekiti-Luwoye borehole (Fig. 3a). The sample consists of well sorted bioclast grains with no mud (micrite) and classified as bioclastic grainstone. The little to no mud is probably as a result of the influence of moderate to high-energy wave effect in a shallow marine environment. Such microfacies have been suggested (Dunham, 1962) as product of high-energy where mud cannot accumulate or winnowing of previously deposited muddy sediments. The carbonates of EL-10 unit is considered as the shoreward facies on shoals and tidal flat environments (Akande and

Table 3. Rock-Eval data of shales from the Araromi Obu, Ajegunle, Erekiti-Luwoye and Igbotu boreholes.

S/n	Boreholes	Depth (m)	Fm	Lithology	TOC	S_1	S_2	S_3	TMax	HI	OI	PI	VRo
ARAROMI OBU													
1	Araromi-Obu	52	Araromi	Grey Shale	0.49	0.04	0.01	0.30	304	2	61	0.80	n.d.
2	Araromi-Obu	58	Araromi	Limestone	0.30	0.02	0.03	1.30	422	10	439	0.40	n.d.
3	Araromi-Obu	61	Araromi	Limestone	0.30	0.01	0.08	0.45	417	27	151	0.11	n.d.
4	Araromi-Obu	67	Araromi	Grey Shale	0.30	0.01	0.07	0.55	404	23	182	0.12	0.49
6	Araromi-Obu	82	Araromi	Grey Shale	1.16	0.04	0.17	1.39	386	15	120	0.19	0.52
7	Araromi-Obu	103	Araromi	Coaly Shale	8.04	0.46	0.99	5.64	382	12	70	0.32	0.41
8	Araromi-Obu	109	Araromi	Grey Shale	1.26	0.15	1.82	1.02	422	144	81	0.08	0.44
AJEGUNLE													
9	Ajegunle	51	Araromi	Grey Shale	2.07	0.09	0.14	1.28	376	7	62	0.4	0.51
10	Ajegunle	54	Araromi	Limestone	0.71	0.19	0.61	0.46	429	86	65	0.24	n.d.
11	Ajegunle	60	Araromi	Grey Shale	0.85	0.20	0.71	0.68	424	84	80	0.22	n.d.
12	Ajegunle	66	Araromi	Black Shale	2.18	0.25	0.45	1.63	388	21	75	0.36	n.d.
13	Ajegunle	81	Araromi	Mudstone	0.11	0.00	0.01	0.68	-1	9	613	0.00	n.d.
EREKITI-LUWOYE													
14	Erekiti-Luwoye	37	Araromi	Grey Shale	1.26	0.37	0.41	2.34	410	33	186	0.47	0.49
15	Erekiti-Luwoye	43	Araromi	Grey Shale	1.19	0.19	0.19	0.82	411	16	69	0.50	n.d.
16	Erekiti-Luwoye	49	Araromi	Grey Shale	1.05	0.16	0.22	0.85	412	21	81	0.42	n.d.
17	Erekiti-Luwoye	55	Araromi	Grey Shale	0.30	0.04	0.02	0.43	305	7	145	0.67	0.49
18	Erekiti-Luwoye	58	Araromi	Limestone	0.24	0.03	0.05	0.37	411	21	155	0.38	n.d.
19	Erekiti-Luwoye	64	Araromi	Grey Shale	0.41	0.06	0.05	0.27	344	12	66	0.55	n.d.
20	Erekiti-Luwoye	67	Araromi	Limestone	0.23	0.02	0.04	0.21	419	18	93	0.34	n.d.
21	Erekiti-Luwoye	76	Araromi	Grey Shale	0.63	0.06	0.05	0.80	406	8	128	0.55	0.43
22	Erekiti-Luwoye	85	Araromi	Grey Shale	0.43	0.05	0.21	0.30	422	48	69	0.19	n.d.
23	Erekiti-Luwoye	88	Araromi	Limestone	0.31	0.05	0.16	0.30	413	52	97	0.24	n.d.
24	Erekiti-Luwoye	97	Araromi	Grey Shale	1.66	0.11	2.33	1.00	422	140	60	0.05	0.52
25	Erekiti-Luwoye	106	Araromi	Grey Shale	2.41	0.23	3.57	1.73	423	148	72	0.06	0.52
26	Erekiti-Luwoye	118	Araromi	Grey Shale	2.39	0.15	2.08	1.72	398	87	72	0.07	0.55
27	Erekiti-Luwoye	124	Araromi	Grey Shale	1.69	0.85	0.97	1.04	422	57	61	0.47	n.d.
28	Erekiti-Luwoye	136	Araromi	Grey Shale	1.98	0.20	0.5	1.18	411	25	60	0.29	n.d.
IGBOTU													
29	Igbotu	57	Araromi	Grey Shale	3.87	1.21	2.56	5.21	368	66	135	0.32	0.51
30	Igbotu	87	Araromi	Grey Shale	7.20	1.10	3.45	9.45	375	48	131	0.24	0.5
31	Igbotu	111	Araromi	Grey Shale	0.25	0.03	0.01	0.53	-1	4	213	0.75	0.55
32	Igbotu	117	Araromi	Grey Shale	0.86	0.13	0.33	1.43	408	39	167	0.29	0.51

(n.d = not determined, Fm = Formation. Units: TOC =wt %, S_1 = kg/t, S_2 = Kg/t, T-max = °C, HI/OI = mg/g TOC, VRo =%)

Mucke, 1993, Elueze and Nton, 2004, Adekeye et al., 2005).

Bioclastic Packstone Microfacies

The microfacies found in EL-25, EL-26, EL-28, and AO-25 samples (Fig. 3b) is classified as bioclastic packstone because they are grain-supported consisting of bioclasts of foraminiferal, brachiopod, corals, and oolites and mud matrix less than 10 %. Packstones indicate some sets of depositional features such as mud content suggesting lower-energy process and the abundant grains suggest higher-energy process. Packstone can originate from compacted wackestones, and early or late infiltration of mud in previously deposited mud-free sediments. This

may suggest a high-volume production of grains in calm water, or record of mixing by burrowers within different layers of sediment. They are deposited in a shallow marine water where the dominant bioclast particles move from environment with high energy to a low energy setting.

Bioclastic Wackestone Microfacies

The microfacies of AO-24, El-12, EL-18 and EL-22 (Fig. 3c) consists of micrites with more than 10% coarse grains composed of remains of organisms such as foraminifera, brachiopod, corals or other lithoclasts. They are essentially mud supported microfacies (Ojo, 2004) and classified as bioclastic wackestone. Bioclasts constituents include remains of forams, brachiopods, corals, pelecypod, and non-skeletal material forms minor amounts of intraclasts. The microfacies are generally poorly sorted, deficient of deep basinal, biological and sedimentological features such as lamination. This microfacies shows high diversity and abundance of micro and macrofauna probably formed in shallow open marine environments likened to a subtidal, low energy water below normal wave base shelf lagoon.

Micritic Carbonate Microfacies

Sample AO-26, AO-28, EL-5, EL-16, and AJ-13 from Araromi Obu and Erekiti-Luwoye boreholes consists of extremely fine-grained carbonate probably produced chemically or biochemically (Fig. 3d). It has very few bioclasts and the carbonate grains are generally less than 5 % (Dunham, 1962). The micrites is greater than 75 %, quartz grain of about 3 % and is slightly bare of sparry calcite cements with no evidence of systematic shape sorting due to the nature and size of matrix. They are commonly formed in an environment favourable for slow sedimentation such as lagoon where depth of water is <10m (Akande et al., 1988), open shelf near the lower slope and deeper shelf margin. They are classified as micritic microfacies.

5.2 Depositional Environments

5.2.1 Shale

Paleoecology of foraminifera reveals their habitation in a very wide oceanic environment ranging from the shore to the deep-water in the continental slope environments. Benthic foraminifera are adapted to relatively shallow water where required temperatures, oxygen, and nutrient for their metabolism are available (Bernhard, 1986, Bruchert et al., 2000). They dwell within the upper ~10 cm of the sediment-water interface (Murray, 1991, 2006). Planktic foraminifera are known to change with latitude, depth and saltiness of water from one environment to another. They are found richly in many open ocean areas of the world where the surface salinity values range between 34 and 37 parts per thousand (0/00) (Sverdrup, et al., 1942). The shales from Erekiti-Luwoye borehole yield most abundant planktic and benthic foraminifera from the study area. Samples from Araromi – Obu, Ajegunle and Igbotu revealed very few foraminifera with low number of individual and species. The benthics are generally abundant than the planktics across the study area. Planktic species include *Heterohelix sp, Hedbergella sp.* and *Globigerinoides sp.* while the benthics are *Lenticulina, Bolivina, Orthokastina, Ammobaculites, Dentalina sp, Eponides sp, Nodosaria, robulus sp., Bulimina, and Anomalina*

sp (Fig. 4). They are generally marine species that dwells in shallow water environments. The benthic occurrence in the shales suggests they were essentially deposited in an inner neritc shallow marine environments of water depths < 50 m. Planktic species are not, in themselves, characteristic of any depth zone, as their habitat in life is principally the upper layers of the off-shore water masses (Smith, 1955). But it's noteworthy the shell of planktic foraminiferal assemblage that are not dissolved increases towards the open water and very scarce in the nearshore environments of continental shelves (Phleger and Parker, 1951, Bandy, 1956 and Rottman, 1978).

5.2.2 Limestone

The limestone microfacies including bioclastic grainstones, bioclastic packstones, bioclastic wackestone and micrite are dominantly marine organisms such as foraminifera, brachiopods, bryozoans, pelecypods and corals. Some of these organisms e. g. brachiopods exhibit variable salinity range from brackish (hyposaline) to slightly hypersaline environments (Fig. 3 a - d). Nearly all brachiopods are sessile organism that live in shelf waters ranging from high to low latitude settings. The grainstone reflect well sorted bioclast grains with no mud as a result of the influence of high-energy wave in the shallow marine environments characteristics of shoreward and tidal flat environment similar to the type reported in Akande and Mucke (1993), Elueze and Nton (2004), Adekeye et al. (2005). Wackestone microfacies shows poor sorted and deficient of deep basinal features such as lamination. This microfacies shows high diversity and abundance of micro and macrofauna probably formed in shallow open marine environments. Fine mud matrix in the micrites is greater than 75 %, peculiar to an environment favourable for slow sedimentation such as open shelf near the lower slope and deeper shelf margin. This is characteristics of subtidal, low energy water below normal wave base shelf and lagoon.

5.2.3 Sandstones

The sandstones from Araromi Obu, Ajegunle, and Erekiti-Luwoye are fine to medium grained and poor to moderately sorted while the samples from Igbotu boreholes are medium to coarse grained, and moderately to moderately well sorted. Summarily, average mean and sorting indicates that sandstones in onshore study area of the Dahomey Basin are predominantly medium grained and moderately sorted. Skewness and kurtosis value range from -0.17 – 0.19 (Phi) averaging 0.23, and 0.62 – 0.92 (Phi) averaging 0.82 (Phi) respectively suggesting that the sandstones are very positively skewed and mesokurtic to platykurtic. These two parameters indicate a medium energy of transportation likened to reworked sediments of middle to lower river regime or beach settings (Friedman, 1979 and Ojo, 2012). Moderate sorting and positive skewness have been used as an indicators of low energy environment characterized by differential deposition with fairly consistent water current typical of fluvial and beach environments (Tucker, 1988). More also multivariate parameters from grain size (Table 3) reveals that the sandstones have input from both shallow marine and fluvial settings suggesting a fluvio-deltaic depositional environment for the sandstones. While other statistical variables such as Kurtosis versus skewness and standard deviation against mean and skewness ((Fig. 7 and

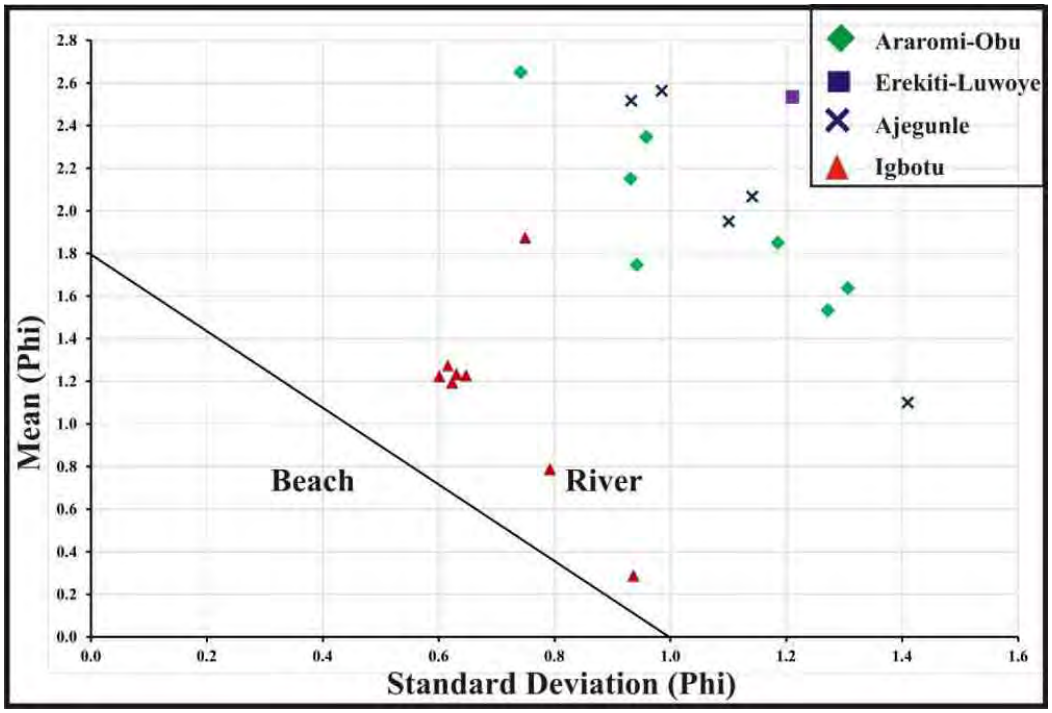


Figure 7. Plot of Standard deviation vs Mean of the Post Santonian sandstones from the Araromi Obu, Ajegunle, Erekiti Luwoye and Igbotu coreholes.

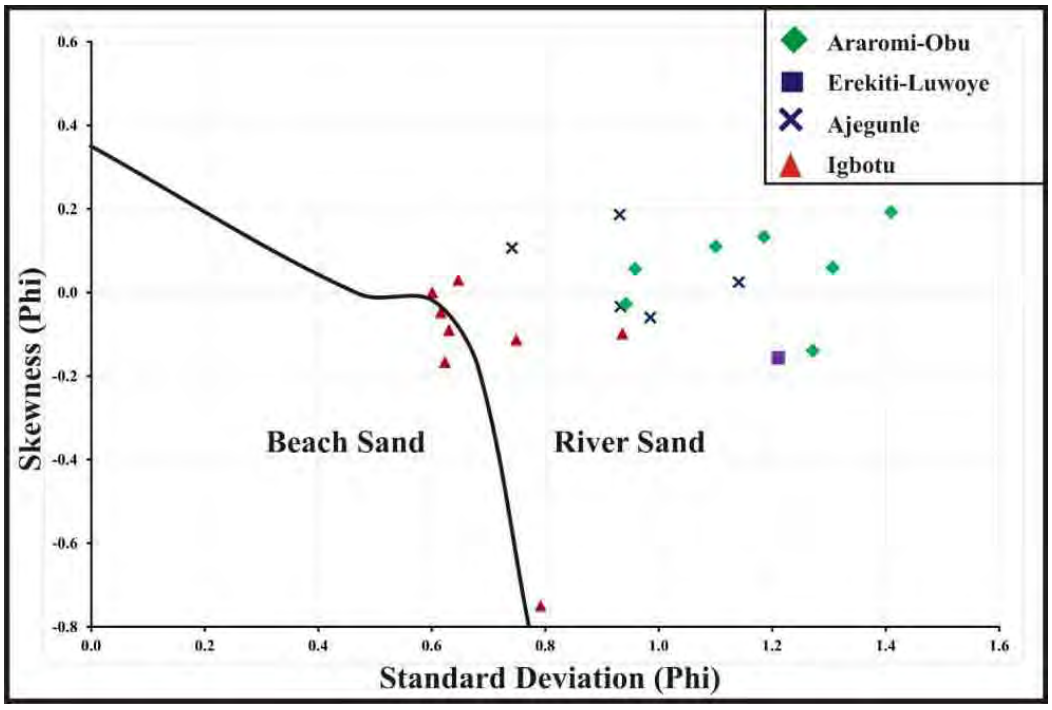


Figure 8. Plot of Standard deviation vs Mean of the sandstones from the Araromi Obu, Ajegunle, Erekiti Luwoye and Igbotu coreholes.

Fig. 8) Friedman, 1967, 1979, and Ojo, 2012) suggests a predominance of fluvial origin for all the sandstones.

5.3 Petroleum Potentials

The presence of good and mature source rocks is the first necessary condition towards existence of hydrocarbon in a basin (Peter and Cassa, 1994). The exploration efforts then move on to the assessments of other important petroleum elements such as the reservoir, seal, trap, and processes including generation, migration, timing and accumulations (Katz et al. 2000). An effective elements and processes of a petroleum system proven by the current commercial production of oil and gas in the offshore area and large bitumen deposit in the onshore part has been established. The source rocks being the Cenomanian-Turonian shale with good and mature organic matter contributing oil and gas to the petroleum system within the basin since the Paleocene (Adeoye et al 2020). These source rocks with well preserved organic matter deeply buried around the coastal area and offshore part of the basin is not traceable at the study area. They are probably not deposited or eroded away in the onshore area of the basin which is an uplifted environment constituting "feather edge" and where the crystalline basement rocks delineate the Dahomey Basin. This explains why the deepest borehole, Erekiti-Luwoye has the total depth to basement of 150 m (Fig. 2) revealing a burial depth that is insignificant to petroleum generation. The shales and limestones on this onshore northeastern part are classified as fair to good source rocks with potential for only gas (Figs. 9 - 11). Moreover, foraminiferal paleoecology suggests shallow marine depositional environments characterized by oxic water conditions where assemblage of Type III gas-prone kerogen and reworked Type IV inert

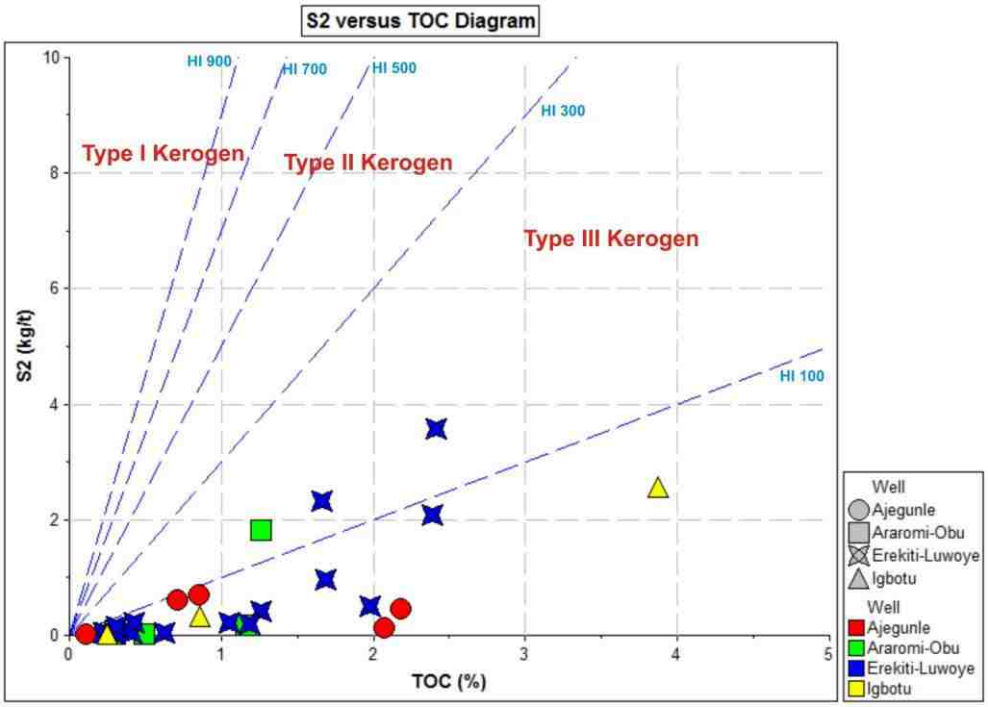


Figure 9. Plot of S_2 against TOC wt% showing the distribution of organic matter types of the source rocks of northeastern shallow boreholes.

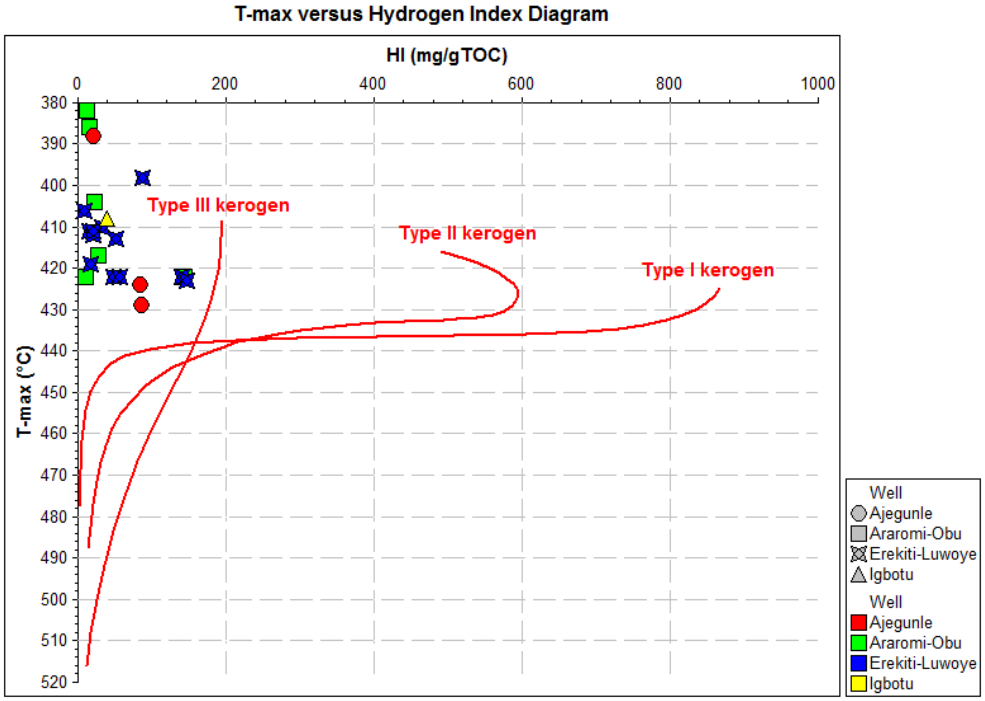


Figure 10. Plot of HI against Tmax showing the organic matter types of the source rocks from the four shallow boreholes in the northeastern part of the basin.

Table 4. Genetic potential of shales (After Peter and Cassa, 1994 and Dembicki, 2009)

Petroleum Potential	**S_1 (kgHC/t rock)**	**S_2 (kgHC/t rock)**
Poor	0 - 0.5	0 - 2.5
Fair	0.5 – 1	2.5 – 5
Good	1 – 2	5 – 10
Very Good	2 - 4	10 – 20
Excellent	> 4	> 20

kerogen are common (Fig. 10). The genetic potential of the source rocks (S_1 + S_2) which represents the amount of hydrocarbon that the kerogen is able to produce under adequate temperature for a period of time, (Tissot and Welte, 1984, Peter and Cassa, 1994 and Dembicki, 2009) shows that few shales have good genetic potentials while the majority are poor.

The rock genetic potential depends on the quality and quantity of kerogen, which in turn are functions of the original organic matter source during deposition, and microbial degradation and rearrangement of the organic matter in the sediments during burial (Table 4) (Peter and Cassa, 1994, and Dembicki, 2009). The thermal maximum of the Rock-Eval pyrolysis (Tmax) is generally below 430 °C and the vitrinite reflectance measurement (VRo) ranging between 0.47 – 0.52 % (Fig. 11) suggests that all the source rocks are immature. This investigated post Santonian source rocks with lean and immature

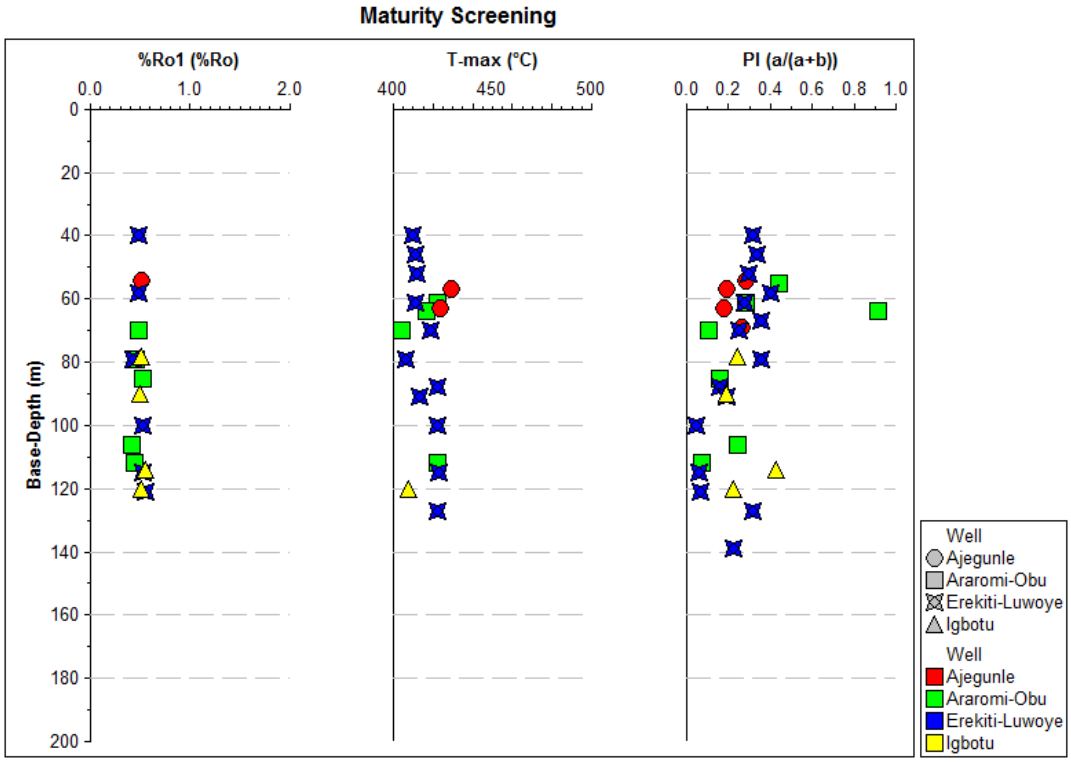


Fig. 11. Plots of vitrinite reflectance, Tmax and Production index against depth showing that the source rocks are immature in all the boreholes.

organic matter located around the onshore area could not have contributed to the commercial discovery of the offshore nor the abundant bitumen deposit in the onshore part of the basin. Though some segment of the Post-Santonian successions in the coastline to the offshore are well buried within the graben structure and become significant intervals for hydrocarbon generation (Adekeye et al 2019).

6.0 Conclusions

Dahomey Basin in south western Nigeria extends from onshore area through the coastal area into the deep offshore of Atlantic Ocean. It hosts large deposit of limestone for cement production and bitumen in the onshore part and commercial oil and gas field in the offshore segment. Shales, limestone and sandstones are the main lithologies in the northeastern part of the basin subjected to sedimentological and petroleum potential assessment in this study. The shales are grey to black, laminated, fossiliferous, stained by bitumen at some intervals and averagely up to about 36 m thick while some of the limestone units are up to 6 m thick comprising bioclastic wackestone, packestone, grainstone, and micrite. Rock successions in the boreholes are essentially post Santonian succession as suggested by the presence of Campanian to Maastrichtian *Globigerina bulloides* planktic foraminifera biozones. Both the shales and limestones are fair to good immature source rocks with potential for only gas and could not have contributed to the bitumen/tar sand deposit within the study area nor the offshore petroleum system. Though some successions of this post Santonian successions

within the present coastline to the offshore are well buried within the graben structure and have been reported as a significant interval for hydrocarbon generation. The sandstones are up to 46 m thick at some interval and grain sizes varied from fine, medium to coarse and generally poor to moderately well sorted. It is better as reservoir or an aquifer within the Igbotu area because of its being coarse and moderately well sorted. They are essentially classified as fluvio-deltaic facies.

Declaration of competing interest

The authors have no known conflicting financial interests that could have appeared to influence the work reported in this paper.

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