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Tectono-Stratigraphy of Benin Basin, West Africa

Minapuye I. Odigi[a*], Soronnadi-Ononiwu[b], G. C. Prince S. Momta[c], Oduah A. Anthony[d]

[a]*Centre for Petroleum Geosciences, Institute of Petroleum Studies, University of Port Harcourt, Port Harcourt, Nigeria*

[b]*Niger Delta University, Wilberforce Island, Yenagoa, Nigeria*

[c,d]*Department of Geology, University of Port Harcourt, Port Harcourt, Nigeria*

[a]*Email: minapuyeodigi@gmail.com,* [b]*Email: chijokesoronnadi@gmail.com*

Abstract

This study presents the tectono-stratigraphic analysis of part of the rift-Benin basin. Datasets from both seismic and biostratigraphy were integrated to identify sequences and structural elements present in the field. Key objectives of the study include: reconstruction of the depositional history of the area using seismic-stratigraphic principles, to identify sequences and structural elements that possess potentials for hydrocarbon entrapment. The seismic-stratigraphic method was adopted to delineate key chronostratigraphic surfaces in the study area which are relevant to hydrocarbon accumulation. Four mega-sequences identified in the study area include: Albian sequence, the Cenomanian-Coniancian, the Campanian – Maastrichtian and Paleocene-Neogene sequences. The Cretaceous sequences are grouped into two depositional sequences designated as 1 and 2. The study has shown that the basin is aligned generally East-West with boundaries delimited by an East-West transform fault system and North-South structural arches. The interplay of these stratigraphic features has revealed three unconformity- bound surfaces. Two sequences of Cretaceous age have been delineated, which include sediments deposited between Albian and Maastrichtian (Abeokuta Formation).

Keywords: Rift Basin; Chronostratigraphy; Benin Basin; Sequences; Unconformities; Hydrocarbon entrapment.

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* Corresponding author.

1. Introduction

Recent exploration trends have focus on the exploration of Deepwater Tertiary Passive margins, however interest is shifting to the precursor rift basin architecture and petroleum systems associated with continental break-up. Frontier exploration opportunities exist in both under explored play and new plays in mature precursor rift basins of North and South Atlantic margins including Gulf of Guinea, the former Soviet Union, Middle East and Far East.

The Benin basin is a frontier basin which extends from the Volta- Delta through Togo and Benin Republic to the Benin Hinge line in the Nigerian arm (Figure 1). The basin forms part of the Gulf of Guinea province, which comprises of basins that developed along the continental margin following the separation of the African and South American continents.

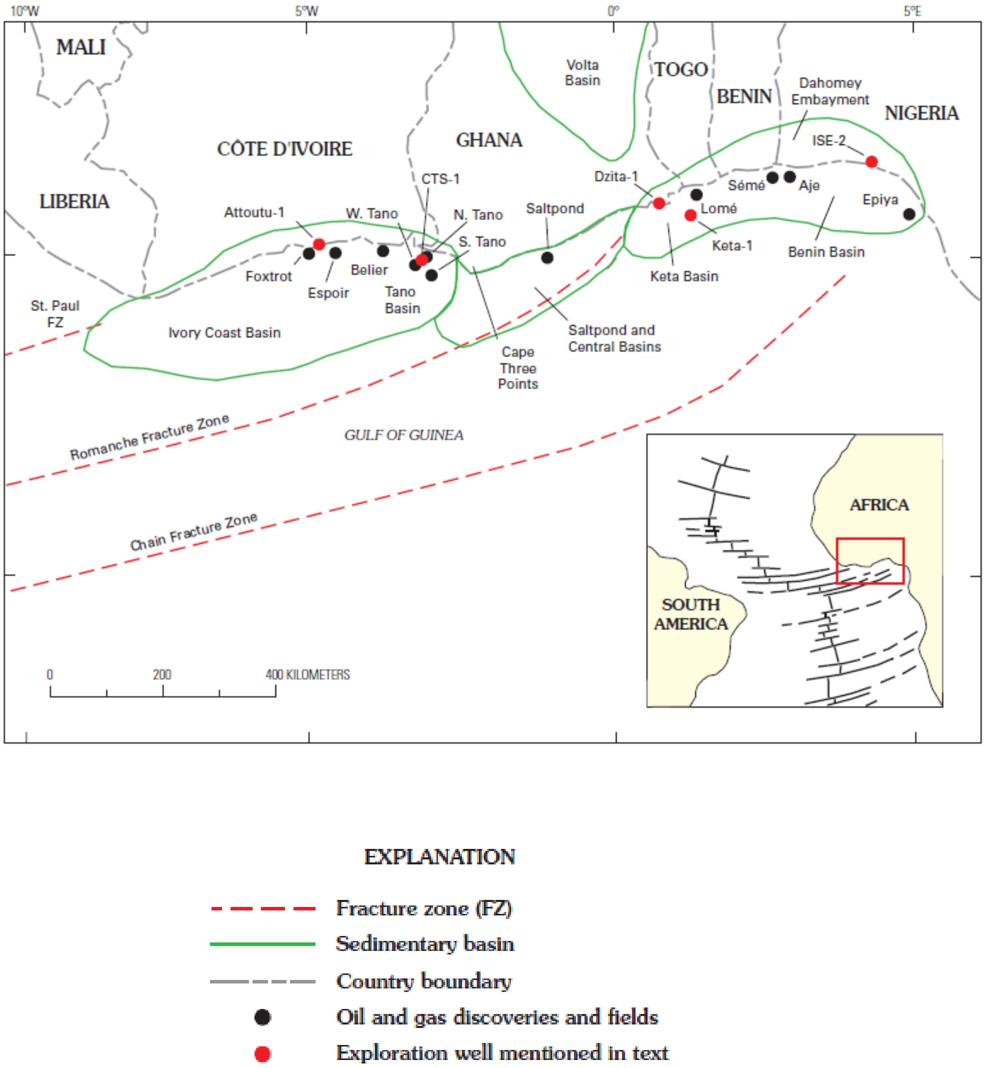

Figure 1: Major features of the Gulf of Guinea Province, West Africa. Modified [21].

The sector of the Benin basin under investigation is a physiographically defined region of deformed continental shelf sediments. The Benin basin is bounded by series of ridges which dissect the basin into sub-basins. Two offshore petroleum systems, namely, the Cretaceous and Tertiary rocks have been identified in the basin [8]. The eastern portion of the basin in the Nigerian sector, is described to contain extensive wedge of Cretaceous to Recent sediments, up to 3000m, which thickens towards the offshore [25], where commercial hydrocarbon quantity have been discovered in the Republic of Benin [5].

In terms of evolutionary position, the Benin basin is a marginal basin or a marginal sag basin [20], which developed following the Mesozoic continent-continent break-up between African and South American plates, which also affected the Cretaceous sediments of the entire Benue Trough. In both cases, the folding, cleavage, and fracturing occurred with shearing attributed to transpression along major transcurrent fault zones. The thermal regimes including hydrothermal activity and low-grade metamorphic recrystallization were quite similar both occurring before or during the tectonic phase of compression. The similarities between these domains may be explained by the geological conditions that prevailed during the early stages of formation of these intracontinental wrench-controlled basins. Important differences started to appear during the Late Cretaceous when the newly created Côte d'Ivoire-Ghana Margin, which is prominent in the Côte d'Ivoire-Ghana Marginal Ridge adjacent to the oceanic lithosphere, began to subside as a consequence of progressive cooling, whereas the Benue domain was submitted to restricted marine and continental sedimentary conditions, ending in the Maastrichtian by a general emergence of the domain [10] deposits, which is overlain by the Benin deposits.

1.1 Gulf of Guinea Province

The Gulf of Guinea Province is made up of the following basins: Ivory Coast, Tano, Satpond, Central, Keta, Benin basin and the Dahomey embayment in the northwestern part of the Gulf of Guinea (Figure 2). These basins share common structural and stratigraphic characteristics, in that they are wrench-modified basin [13] and contain rocks ranging in age from Ordovician to Holocene [21]. The eastern boundary of the Benin Basin comprises of the Niger Delta Province [22], whereas the West African Central Province forms the western boundary. The Gulf of Guinea formed at the culmination of late Jurassic to early Cretaceous tectonism that was characterized by both block and transform faulting superimposed across an extensive Paleozoic basin during breakup of the African, North American and South American paleocontinents. The Gulf of Guinea has undergone a complex history, which is sub-divided into pre-transform (Late Proterozoic to Late Jurassic), syn-transform (Late Jurassic of Early Cretaceous) and post-transform (Late Cretaceous to Holocene) stages of basin development. These three stages are referred to as the pre-rift or intracratonic, syn-rift or rift and post-rift or drift stages [15,21,33,12]. These structural basins are aligned generally east-west with boundaries delimited by an east-west transform fault system (Figure 3).

The pre-transform section consists of Precambrian to Triassic rocks occurring in the Volta and Tano basins of Ghana. This section has been penetrated by drilling in the Saltpond, Tano and Keta basins. The pre-rift stage is interpreted to be largely a period of erosion and non-deposition in the Keta basin. The pre-transform rocks in the Benin basin are represented by the lower part of the Ise Formation [15,16].The continental syn-transform sedimentary rocks show evidence that volcanic and fault activity may have started in the Early Jurassic in Ivory Coast basin. Block faulting and graben filling characterized the initial stage of tectonism followed by transform or extensional faulting in the Gulf of Guinea province. The keta basin contains cretaceous sediments. The end of the syn-tranform stage is delineated by a major unconformity which separated it from the post-transform rocks of marine origins [15]. The post-transform rocks consist of predominantly marine Cenomanian to Holocene sandstones, shales and minor carbonate rocks deposited in alternating regressions and transgressions [15] [12].The province is defined by the U.S Geological survey (USGS) to consist of the coastal and offshore areas of Cote d' Ivoire, Ghana, Togo, Benin, and the western part of the coast of Nigeria, from the Liberian border east to the west edge of the Niger Delta. The various basins that formed within this province include the Ivory Coast, Tano, Central, Saltpond, Keta, Benin and the Dahomey embayment. These basins share common structural and stratigraphic characteristics, and are wrench-modified basins [13]. The Benin basin (Dahomey), which is the focus of this paper, is described as an extensive miogeoclinal wedge [25,35,31]. It extends from the Volta- delta area in Ghana to the Okitipupa Ridge, east of Lagos. The miogeoclinal wedge of sediment developed through Early to Late Cretaceous and Cenozoic times as the African and South American lithospheric plates separated [35].

1.2 Location, Geology and Stratigraphy of Benin Basin

The Benin basin is an extensive sedimentary basin. It extends from South Eastern Ghana in the west to the western Flank of the Niger Delta (Figure 2). The study area is situated in OML 113 in the Benin basin between latitude $04^{0}0722$N and longitude $01^{0}45$'E offshore South-Western Nigeria (Figure 3).The axis of the Benin and the thickest sediments occur slightly west of the border between Nigeria and the Republic of Benin [32,32,5]. The Benin basin is a rift basin and is bounded on the West by faults and other tectonic structures associated with the landward extension of the Romanche fracture zone. Its eastern limit is marked by the Benin Hinge line, a major fault structure marking the western limit of the Niger Delta basin. The Tertiary sediments of the Benin basin thin out and are partially cut off from the sediments of the Niger Delta against this ridge of basement rocks.

The Dahomey basin is the on-shore part and eastern extension of the Benin basin (Figure2).The sedimentary formations of the Dahomey basin outcrop in an arcuate belt roughly parallel to the ancient coastline. The oldest dated sediments onshore consist of lower Cretaceous grits and sandstones with thin interbedded mudstone [1].

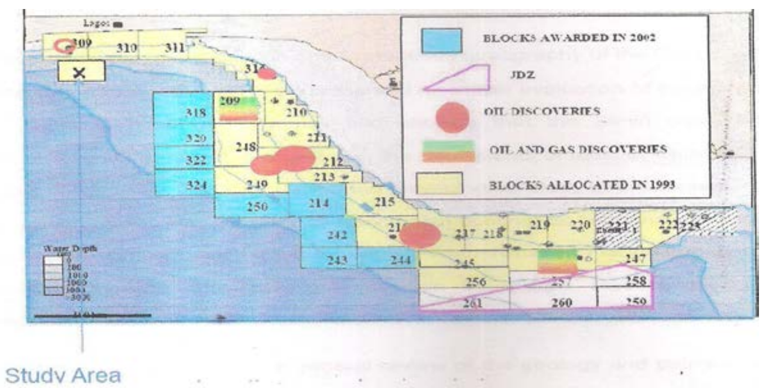

Figure 2: Location Map of the Study Area

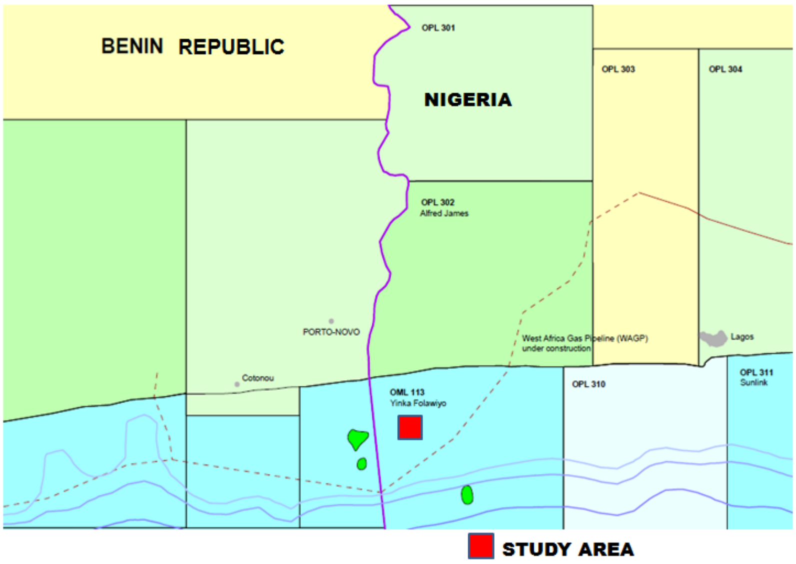

Figure 3: Concession map showing OML 113

The continental sediments were deposited in a series of rapidly subsiding fault controlled depressions on the basement complex. They are progressively overlain by finer, detrital sandstones, siltstones and shales of a transitional nature. The youngest Cretaceous strata are marginal to fully marine sands and shales of Maastrichtianage. The onshore Cretaceous strata are conformably overlain by Paleocene limestones referred to as Ewekoro Formation in the west, grading laterally to the east is the Araromi Formation comprises of shale with interbedded limestone and marl stringer and the marine shales of Imo Formation. The Paleocene shales and limestones are overlain by marine Eocene phosphate bearing mudstones and shales with sandy interbeds in the West (Oshoshun Formation and grey mudstones Ameki Formation) overlain by the transitional to continental dominantly sandy llaro Formation.The Cretaceous sequence of rocks in the offshore Benin basin has been subdivided into three recognizable lithostratigraphic units of formational rank. They are referred to as the Abeokuta Group [1]. These three lithostratigraphic units are the Ise Formation, Araromi Formation and the Afowo Formation (Figure 4). The tectono-evolution of the Benin basin is presented in Figure 5 which is similar to the Later Cretaceous Afikpo basin of the lower Benue trough of Nigeria.

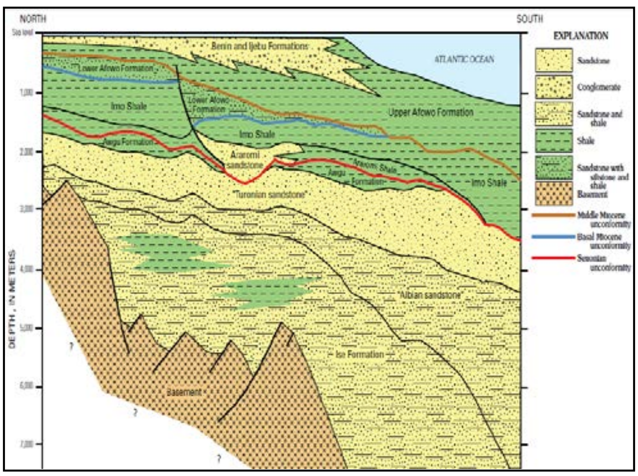

Figure 4: Generalized geoseismic cross section of offshore part of Benin Basin, Gulf of Guinea Province [16].

The work carried out by [30] showed that the Benin basin is composed of series of horst and grabens. Biostratigraphic and palynological study of the sequences in the Isegraben shows a succession of Neocomian continental sequence resting unconformable on the basement complex, succeeded by upper Albian-Turonian marginal marine and lacustrine deposits, which is overlain by marine Maastrichtian-Paleocene strata. The succession begins with the Abeokuta Group, comprising of the Ise Formation overlying the basement complex, followed by the Araromi Formation and terminating the Cretaceous with the Afowo Formation a coarsed to medium grained sandstone, as the youngest sediment. Despite several classification schemes on the stratigraphy of the Benin basin, there are still controversies on age assignments and nomenclature of the different lithological units [26].

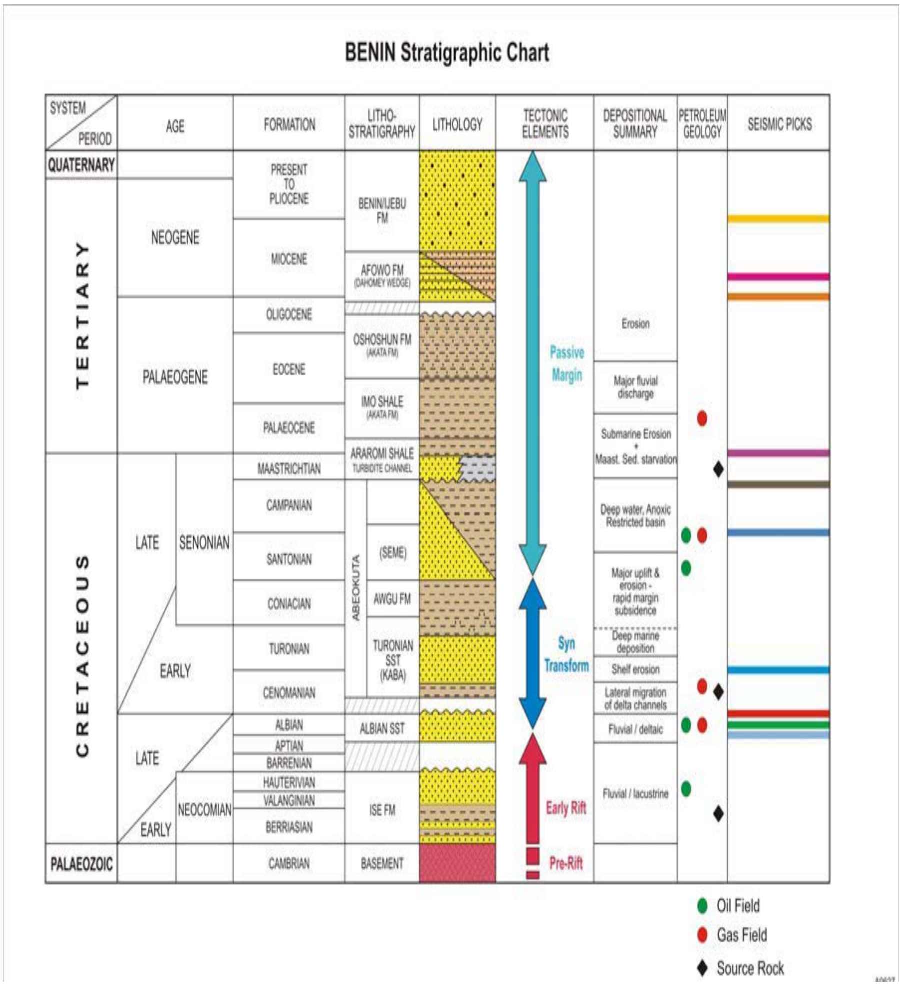

Figure 5: Generalized Stratigraphy of the Benin (Dahomey) Basin and the Lower Benue Trough (Afikpo basin) (modified [3].

2. Method of study

Limitations of the study is the lack of core and high resolution biostratigraphic data. The materials used for this study include well, seismic and chronostratigraphic data. The sequence stratigraphy method adopted in this work is based on the work of [34] which sub-divided sedimentary packages into unconformity-bound units that are traceable on seismic sections. The unconformity surfaces are referred to as sequence boundaries. Three seismic lines A-B, B-C and C-D were used to map the sequences in the field. The sedimentary successions in the basin were divided into stratigraphic sequences using the principle of seismic stratigraphy [34]. Generally, sequence stratigraphic interpretation is based on the use of high resolution biostratigraphy, well logs, cores and seismic data. Seismic stratigraphic approach adopted in this study was used to identify three mega sequences. Key chronostratigraphic surfaces identified on the seismic section (unconformities) were correlable with the stratigraphic data from the generalized stratigraphic column (Figure 6) of the offshore part of Benin basin, and time-depth chart used as control. The ages of the sequence boundaries were delineated using the chronostratigraphic data. This was done by using the chronostratigraphic data that shows geologic ages of various formation tops and their corresponding depth. The stratigraphic column [16,24], were adopted as a template for the identification of different formation and stratigraphic sequences as annotated on the seismic sections.

3. Results & discussion

The results of the seismic analysis revealed three megasequences that form the stratigraphic units in the basin. These are: the Albian sequence, the Cenomanian-Coniancian sequence and the Campanian–Maastrichtian. These were all identified on seismic sections (Figures 7, 8 & 9) and in the Late Cretaceous Afikpo basin [29].

3.1 Seismic Stratigraphic and Depositional Sequences

Two major depositional sequences bounded by three sequence boundaries (SB_1, SB_2 and SB_3) interpreted from the seismic sections include: the Albian sequence, the Cenomanian-Coniancian, and the sequence boundary of the Campanian-Maastrichtian sequence represented as SB_3. The terminal Cretaceous sequence seems to be absent in this basin towards the offshore location but present onshore in land sedimentary basin particularly the Afikpo basin. Each of these boundaries are separated by a major unconformity identified based on seismic facies termination pattern. These sequences have also been reported to exist in this basin by previous workers [29,30,29]. The Albian sequence is also reported in the Afikpo basin, Lower Benue Trough, identified as the Asu River Group.

Sequence Boundary 1: Albian

The first sequence is bounded below by a disconformity, where there exist a contact between the Aptain-Albian sedimentary rocks and the top of the basement. This boundary occurs at a depth of 3700m (Figure7) on the seismic section. This is the deepest sequence in the area. The age of this sequence is between Neocomian-Albian [30,28]. Two Formations of Early Cretaceous age within this sequence are, the Ise, lying unconformably on the basement complex and overlain by the Afowo Formation [2]. The Early Cretaceous Asu River Group of the Afikpo Basin, Lower Benue Trough also consists of a basal unit the Awi Formation lying unconformably on the basement complex of the Oban Massif, and overlain by the Abakaliki Formation [29]. The Cretaceous succession comprises of three megasequences delineated by four unconformities [29].

The Ise Formation

This occurs in sequence one. It overlies unconformably the basement complex of south western Nigeria and consists of conglomerate, grits, coarse-medium grained sands, interbedded with kaolinite [28]. The age is Albian and is overlain by the Afowo Formation [30].

Sequence Boundary 2: Cenomanian

The second sequence boundary lies between the Albian and Cenomanian sediments, and bounded below by an unconformity at depth of 1957 m and above by another sequence boundary at a depth of about 1295m. These surfaces are recognized on the seismic section using the seismic facies pattern (lapouts). It is correlated to be the Abeokuta Formation overlain by Araromi and Imo Shale, interpreted to have been deposited in marginal marine and inner shelf environments. The second sequence in the Afikpo basin Lower Benue Trough, South Eastern Nigeria, is bounded below by Cenomanian unconformity. The Abeokuta Group of the Benin basin is correlable to the Eze-Aku Group of the Lower Benue Trough. The Eze-Aku Group sediments were deposited in a marginal marine and inner shelf environment. The rock facies in this sequence are interpreted to be and correlable to the shales of Araromi and Imo in the upper section deposited in a marine environment. Between the second and the third Campanian-Maastrichtain sequences is the third sequence boundary referred to as Santonian unconformity.

Sequence Boundary 4: Maastrichtian

This sequence is underlain by the Late Cretaceous sediments, and above, is the Early Tertiary sedimentary units. The sequence marks the end of Cretaceous sedimentation, terminated by Terminal Cretaceous tectonism [29]. It occurs at the depth of 1000m on the geoseismic section.

3.2 The Benin Basin and the Lower Benue Trough

The Benin basin and the Benue Trough display several similar sedimentary and tectonic features [25]. The two basins have records of Early Cretaceous rifting, with grabens filled by continental deposits and formed under extension followed by transtensional movements due to intracontinental wrenching [25]. Other researchers have also stated that both basins have a record of compressional tectonics at different times, the Late Albian – Cenomanian in the the Benin axis, and the Santonian in the Lower Benue Trough. Stratigraphically, the work carried out in the Lower Benue Trough [29], revealed the three megasequences, which include, the Albian sequence, comprising of the Asu River Group; the Cenomanian-Coniancian unconformity (Eze-Aku Group), and the Campanian-Maastrichtian sequence. These sequences have also been identified in the offshore portion of the Benin basin. In the Benue Trough, the Awi Formation of Albian age lies unconformably on the basement complex, which coincides with the Ise Formation of Albian age in the offshore Benin basin, lying unconformably on the basement complex. The both sediments are described as very coarse grained continental sandstones. In the both domains, the Aptian–Albian sedimentary successions show clear evidence of sedimentary instability, including water escape structures, sand pipes, convolute laminations, slumps, and listric normal faults [11,18].

3.3 The Significance of Sequence Boundaries

The Benin – Dahomey basin and the Benue Trough were formed during the Early Cretaceous under similar tectonic conditions and continental sedimentary environments. Early stages of sedimentary infilling were characterized by the deposition of subaerial, lacustrine, deltaic, and transitional marine sediments, successively, from the Late Jurassic to the Early Cretaceous.

Intracontinental transcurrent faulting that occurred in the Aptian–Albian, was superimposed on earlier rifting structures, resulting in pull-apart sub-basins. The extensional-transtensional tectonics caused unstable conditions during the sedimentation, resulting in syn-sedimentary deformations such as water-escape structures, listric normal faults, slumps, and intraformational conglomerates. From the Albian to the end of the Cretaceous, the two domains were under marine conditions, and there was deposition of shallow-water carbonates of fine terrigenous sediments. Compressional movements occurred in the late Albian–Cenomanian along the marginal basins, and during the Santonian in the Lower Benue Trough resulting in intense deformations in both domains, with folding, cleavage, and shearing. Thermal events, partly related to the compressional phase, were recorded in the sediments of the two basins, including hydrothermal activity and low-grade metamorphic crystallizations.

After the compressional event, the two basins have different evolutions; the Benin axis became a passive margin, with open marine sedimentation, while the Lower Benue Trough was almost completely uplifted when a second compressional phase occurred.

The megasequences are recognized in the Lower Benue Trough [29], and those of the Benin basin traced on the geoseismic section using the Vail model, has helped in the reconstruction of the deposition history and tectonic evolution of these basins. These data are of significance in terms of hydrocarbon prospecting and mineral exploration in these basins. It has been documented that these Cretaceous sequences contains reasonable quantity of hydrocarbon especially towards the offshore location in the Benin axis of the basin. This is more obvious on the continental slope where there is an evidence for the expansion of the Later Cretaceous sequences with significant thickness of deep water clastics [14].

3.4 Structural Styles and Development

Four (4) unconformities were identified in the frontier inland Late Cretaceous Lower Benue basin while in this study three (3) unconformities have been identified on the seismic sections (Figures 8, and 9). This was done by correlating the stratigraphic column (Figure 6) for well 3 and the seismic section from where these features have been picked. A disconformity exists at the top of basement at a depth of about (3,700 msec or 3,700 msec).This is the sediment-basement contact in the study area. The second unconformity occurred at 1957m as indicated in Figure8. This disconformity may be due to tectonism in the Benue trough that affected many parts of the Gulf of Guinea province [16]. A third unconformity occurred at 1295 m, and may have resulted from depositional hiatus which occurred in Oligocene in the Benin basin. Using discontinuity of reflections on the seismic sections, normal faults have been picked out and labeled as F_1 , F_2, F_3, F_4, F_5, F_6, and F_7 (Figure 8). Two normal faults labeled F_1 and F_2 have been identified in the section BC while five (5) normal faults labeled F_3, F_4, F_5, F_6 and F_7 are identified in section CD (Figure 8) and labeled F_3, F_4, F_5, F_6 and F_7. Fault F_3 is listric judging from the spoon shape.

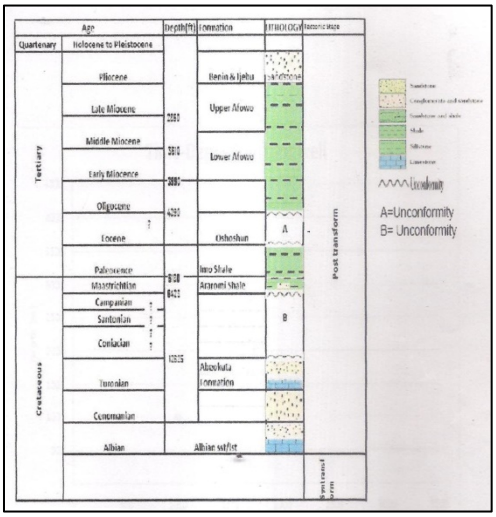

Figure 6: Stratigraphic Column for Well 3

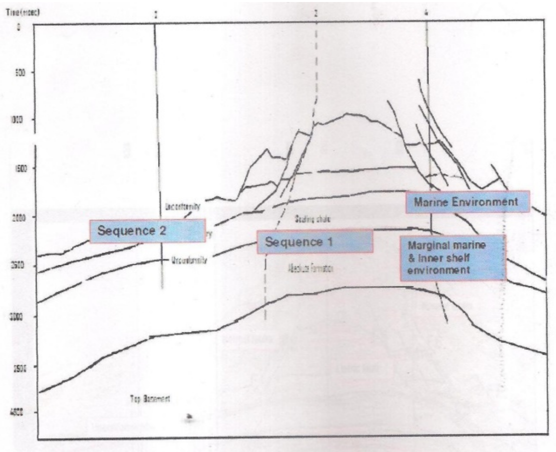

Figure 7: Interpreted position of two sequences identified and their depositional environments.

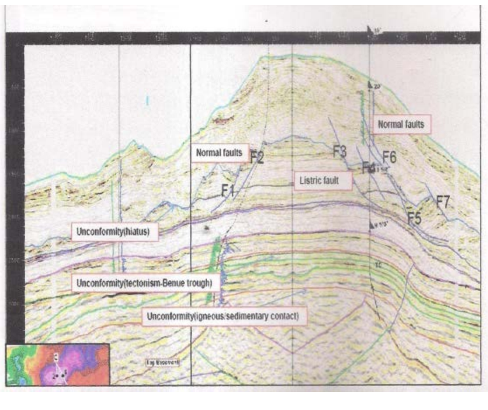

Figure 8: Interpreted position of faults and unconformities

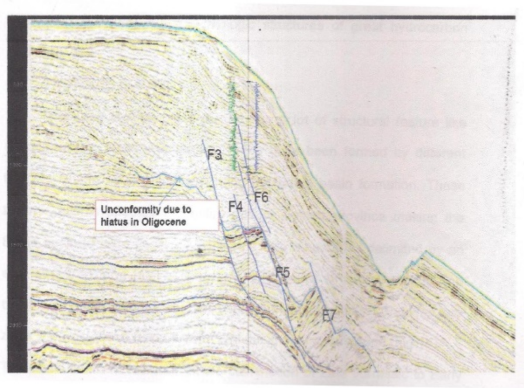

Figure 9: NW-SE seismic section showing position of topmost unconformity and faults through well 4

4. Discussion

The Benin basin is found to be bounded on the east by the Niger Delta and west by the Keta basin and north by the Dalomey embayment. The basin is characterized by transform faulting, rifting forming graben and horst and several unconformities interplaying with stratigraphic features to form geologic structures of great hydrocarbon implications.

4.1 Tectonic Elements

It is observed that the study area possess structural features like unconformities, faults, diapric structures that appear as ridges. These have been formed by different tectonic events which occurred during the Benin basin formation. These tectonic events affected the entire Gulf of Guinea province making the Benin basin to align generally east-west with boundaries delimited by an east-west transform fault system and north-south structural arches. The three main fracture zones which affected the basin are the St. Paul fracture zone, the Romanche fracture zone and the chain fracture zone. The Benin basin was formed at the culmination of Late Jurassic to Early Cretaceous tectonism that was characterized by both block and transform faulting superimposed across an extensive Paleozoic basin during the breakup of the African, North American and South American paleocontinents. The thick continental crust of the African and South American platform started to breakup, forming divergent basins or pull apart graben separated by transform faults [6].

Petroleum Implications

Oil and gas occurrences in the Gulf of Guinea province are concentrated in Cretaceous reservoirs on the continental shelf and adjacent onshore extensions in two basin area:

1. Ivory Coast to Tano basins (Espoir field of Cote d' Ivoire and Ghana
2. The Keta basin (Lome discovery) to the Benin basin (Aje field) of westernmost Nigeria.

4.2 Hydrocarbon Source Rocks

Upper Albian reservoirs in the Benin basin may have been sourced from Devonian shales [24] as the alternative of an upper Cretaceous source.

Oil seeps in outcrops of Later Cretaceous tar sands in the Benin basin are interpreted to be sourced from Neocomian lacustrine strata such as were drilled into in the Ise-2 well [19]. These source rocks contain type 1 kerogene with total organic (TOC) contents as much as 4 percent and the richest source intervals having hydrocarbon indices (HI, mg hydrocarbon/g organic carbon) greater than 500HI,mg. The Coniacian Awgu Formation, the Maastrichtian Araromi shale and Paleocene to Eocene Imo shale contain marine source rocks in the offshore part of the Benin basin. These source rocks contain type 2 and 3 kerogene with TOC contents ranging from 2 to more than 5 weight percent which were deposited from the north western part of the Niger Delta westward to Keta basin [19]. The richest source rocks have hydrogen indices greater than 500HI, mg.

4.3 Generation and migration

The most important hydrocarbon generation within the Gulf of Guinea province is from upper Albian and Cenomanian source rocks which are distributed throughout the offshore part of the province; these strata are expected to increase in thickness and source rock quality into deepwater. The main area of hydrocarbon generation as interpreted by [24] is the offshore parts of the Benin basin eastwards to the Niger Delta. These probable oil kitchens are present in the deepwater parts of the Basin where source rocks have reached a temperature of at least 100^0C and vitrinite reflectance of 0.6 percent [24]. Hydrocarbon generation started in late Miocene in the Benin basin and continues to present. The unconformities and faults could be zones of migration for hydrocarbon.

4.4 Reservoirs

Seismic data indicate that a thick lower Cretaceous syn-transform section in the offshore part of the Benin basin contains probable sandstone reservoir units [16] deposited in fluvial to deltaic environments. Some slope fans have been identified in the Araromi shale [16] above the regional Maastrichtian unconformity [24]. The Araromi sandstone unit has been interpreted as a slope fan in the Benin basin. Proven fault-block traps are in the upper part of the syn-transform section in the Benin basin [23].

4.5 Traps and seals

Syn-transform anticlinal traps detected by seismic data are associated with the terminations of regional fracture zones in the offshore part of Benin basin.

Known hydrocarbon accumulations are associated with erosional fill traps in the post-transform section in both shallow and deepwater areas. This type of trap is characterized by the Aje field of Benin basin where the west end of the reservoir is sealed by a shale filled channel.

Seals associated with syn-transform reservoirs are formed by both shales and faults, whereas seals associated with post-transform rocks are generally shales.

5. Summary & conclusions

The Benin basin is found to be bounded on the east by the Niger Delta basin and west by the Keta basin, and north by the Dahomey embayment. It is a rift basin characterized by transform faulting and rifting forming grabens and horsts, and several unconformities interplaying with stratigraphic features to form geologic structures of great hydrocarbon implications. The tectonic history of the basin is traced to the events that affected the entire Gulf of Guinea. The three main fracture zones which affected the basin are; St. Paul Fracture Zone, the Romanche Fracture Zone, and the Chain Fracture Zone.

Three unconformities are identified based on geoseismic mapping. These are the Aptian-Albian, Cenomanian-Coniancian, and Campanian-Maastrichtian sequences, which thicken towards the offshore location. Sequences 1 and 2 identified have been correlated to be the Ise and Abeokuta Group respectively deposited in a continental and marine environments respectively. Results of field outcrop mapping of the Lower Benue Trough tallies with the geoseismic analysis of the offshore Benin basin in [29].

In conclusion, the Benin basin has stratigraphic features (sequence boundaries) of great significance to hydrocarbon accumulation. Delineation of sequence boundaries will enhance the understanding of depositional mechanisms and steer explorationists towards prospects which may have been bypassed. The three unconformities identified are chronostratigraphic surfaces generated by tectonic activities. They form an important hydrocarbon migration pathway, and are characterized by coarse grained clastic sedimentary rocks.

6. Recommendations

Based on the results of the study, the following recommendations are presented.

1) Future wells should targeted at structural features like unconformities as this could be zones of hydrocarbon accumulation.
2) Detailed biostratigraphic analysis be carried out in the field.
3) A detailed sequence stratigraphic studies is required to delineate sequence and sequence boundaries as to enhance the understanding of depositional processes, and to steer exploration towards prospects which may have been missed.

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