

Impact of Structural Dynamics on Hydrocarbon Retention of The Deposits in The Enugu Axis of The Cretaceous Anambra Basin

By

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Abstract

The relationship among the southern Nigeria's inland basins is a direct result of formative tectono-sedimentary interaction within and adjacent to the basins. A full understanding of the nature of these interactions, especially how they were controlled by the structural dynamics of the basins, remains a challenge. This work investigates the mechanisms that directly defined the structural events and sedimentary processes, and the hydrocarbon generation and trapping processes in the Anambra Basin. Insight from regional cross-sections was used to highlight a genetic link among the tier-basins from the distal offshore to the onshore, across the Cretaceous – Paleogene (K-Pg) that outcrops in the Enugu Axis. This Axis was defined and illustrated as the geographical region where the axial plane of the Enugu crestal high projects to the surface.

A regional seismic line was interpreted, and the results corroborated with those from well data and field studies to show a relatively continuous structural trend, from the oceanic to the continental crust and their overlying formations. This showed that the Enugu Axis of the Anambra Basin is an anchor point, a projection of the paleo-margin serving as a transition from laterally depth-equivalent but diachronous deposits, to highs in the Benue Trough. The Cenozoic major synthetic faults, and the initiation of displaced blocks in the Niger Delta, are deeply rooted and controlled by the Cretaceous events, including the rifting and magnetic intrusions. These highs and lows affecting the top of the Cretaceous deposits are the drivers that locate and lead to the activation of blocks that slide above the base of the Akata Formation, or equivalent base, of the Cenozoic Niger Delta formations. These magmatic events are relatively near surface and exposed beyond the Anambra Basin, in the Benue Trough. This understanding provides a premise for study of the Cretaceous basins using information from the well-known geology of the associated Niger Delta, whose seismic, well and other subsurface data abound.

This work used such data and methods to analyze the roles of the basins' structural activities in defining the proven petroleum systems and prospects in the area. A similar pattern of deposition in the present-day continental shelf margin explains the clinoform morphology at the subsiding slopes of the late Cretaceous Anambra Basin delta and the pressure transmission that leads to hydrocarbon leaks, gas flares and retained petroleum prospects in the Enugu Axis. A new "plane-wing" concept further explains the anomalies, fold structures and very high dips or upturned units observed in the Benue Trough.

Keyword: Paleo-margin, K-Pg boundary, Plane-wing, Clinoform, Thalweg, Overpressure

Introduction

The Anambra Basin and the Southern Benue Trough were formed by the rifting following the separation of the South American and African Plates in the middle Mesozoic^{1, 2, 3}. The resulting triple junction formed the Atlantic Ocean while the failed arm formed the structural axis for

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¹ King, L., (1950). Speculations upon the outline and mode of distribution of the Gondwanaland. Geol. Mag., 87, 352-359

² Burke, K.C., Dessauvagie, T.F. And Whiteman, A.J., (1972). Geologic history of the Benue valley and adjacent areas. In: Dessauvagie, T.F. and Whiteman, A.J. (eds.), African Geology, Ibadan University Press, 187 - 205

³ Nwachukwu, S.O., (1972). The tectonic evolution of the Southern portion of the Benue Trough, Nigeria. Geol. Mag., 109, 411-419.

rifting and troughing within the African continent. The first phase of the rifting was a divergent pre-rift of lower Cretaceous and the second phase was the syn-rift of Aptian, both of which are well documented alongside other rifting processes^{4,5,6,7}. In the lower Albian, crustal stretching reached the Gulf of Guinea to form the Abakaliki depression and the Anambra platform south of the Benue Trough. The Santonian shortening phase resulted from the collision between the African and the European plates and led to the folding of the structures. The depression was inverted to give rise to the Abakaliki Anticline in the SE, while the Anambra platform subsided to form the Anambra Syncline in the NW^{8,9,10}.

The aulacogen, or the failed arm of the triple junction, extended across the northern Niger Delta, through the Anambra Basin and to the Benue Trough. The evolution affected the substrata and continues to play an important role in the slopes, subsidence and uplift within the NE-SW structural trend, affecting their dynamics. Sedimentary deposits glide down this structural trend, at intermittent break or margins, leading to profiles that are deposited perpendicularly into depocenters or depositional belts.

Aims and Objectives of the Study

The aim of this study is to understand the structure and dynamics of the Cretaceous Anambra Basin and the Southern Benue Trough. This includes the understanding of the structural activities and the sedimentary profiles as they relate the formative processes of the rift basins and the present-day pressure and fluid flow patterns leading to hydrocarbons trapping, retention and leakages. The objective is to throw more light on the relationships among the tear-basins and show how the overlays and juxtaposition among their subunits control the mechanisms that emplaced the proven petroleum prospects in their area.

There was need to further explain the anomalies, fold structures and very high dips or upturned units observed in the Benue Trough. These objectives necessitated a regional understanding that required the use of available subsurface data and models for the study. The comprehensive structural and sedimentary study is intended to demonstrate if there is a continuity in the depositional belts from the proximal southern Benue Trough, through the Anambra Basin, to the distal Niger Delta. A better understanding will enhance resources development and guide on how to optimize the shallower gas and oil deposits, and unconventional resources, previously assumed as risky in the basins. It was also important to review the abundant findings from outcrop studies carried out in the area and tie them to a regional seismic cross-section and well data across the oil and gas fields in the basins.

⁴ Offodile, M.A., (1976). A review of the Geology of the Cretaceous of the Benue valley. In: KOGBE, C.A., (ed), Geology of Nigeria. Elizabethan Publishing Co., Lagos, 319-330.

⁵ Wright, A.E., (1976). Review of the Origin and Evolution of the Benue Trough in Nigeria. Department of Earth Sciences, Open University, Milton Keynes.

⁶ Petters, S.W., (1978). Stratigraphic evolution of the Benue Trough and its implication for the upper Cretaceous paleogeography for West Africa. *Journal of Geology*, 86, 311- 322.

⁷ Benkhelil, J. 1989. The origin and evolution of the Cretaceous Benue Trough, Nigeria. *Journal of Africa Earth Sciences*, 8, 251-282.

⁸ Murat, R. C., (1972). Stratigraphy and Paleogeography of the Cretaceous and Lower Tertiary of Southern Nigeria. In T. F. J. Dessauvage and Whiteman (eds), *African Geology*, Ibadan University Press, Nigeria. 251-266.

⁹ Oboh-Ikuenobe, E. F., G. C. Obi and C. Jaramillo, (2005). Lithofacies, palynofacies, and sequence stratigraphy of Palaeogene strata in Southeastern Nigeria, *Journal of African Earth Sciences* 41(1-2), 79-101

¹⁰ Nwajide, C.S., 2013. *Geology of Nigeria's Sedimentary Basins*. CSS Bookshop Ltd., Lagos, 565p.

Data and Methodology

Much 2D and 3D seismic data sets covering the onshore and offshore across the Nigerian oil fields are stored in the repositories of the regulatory authorities and oil and gas operators, some of which were made available for studies. This work has benefited from such data as well as from published well data, specifically well logs, such as gamma ray, used for correlation of bedding units.

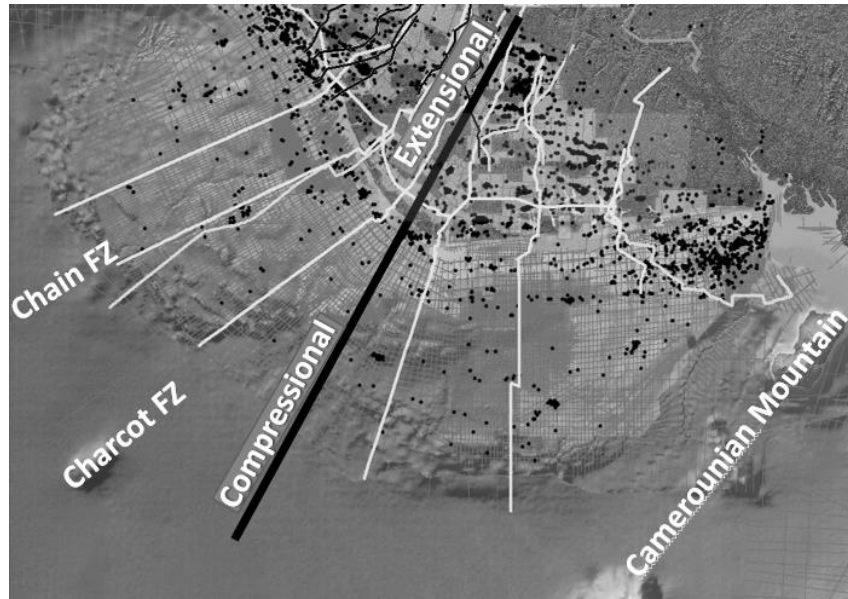
The method used was to assemble different seismic sections to form composite lines from offshore to onshore, relying on existing sub-sections and similar correlations. Well markers, with prior integrated biostratigraphic information, were used for the calibration of horizons to their relative ages and for tying them to stratigraphic charts. This helped in the interpretation of depositional environments and upscaling them to regional trends across the shelf margin, paleo-deltas and inland Cretaceous Anambra Basin.

Relevant information from offset well positions was projected to the line of section, in the absence of available well or seismic data intercepting the line of section. Insights from gravimetric maps and subsurface structural constructs were integrated to the abundant field work data in the Enugu Area of the Anambra Basin. Outcrop studies in the Anambra Basin and the southern Benue Trough, and studies carried out in partnership with universities, were pioneered by the author to this effect. Information therefrom was complemented with measurements of pore pressures and tests carried out in the Elvee laboratory following hydrocarbon fluid sampling in the area. Previous models were also integrated to cover the regional scope and meet the objectives of the paper.

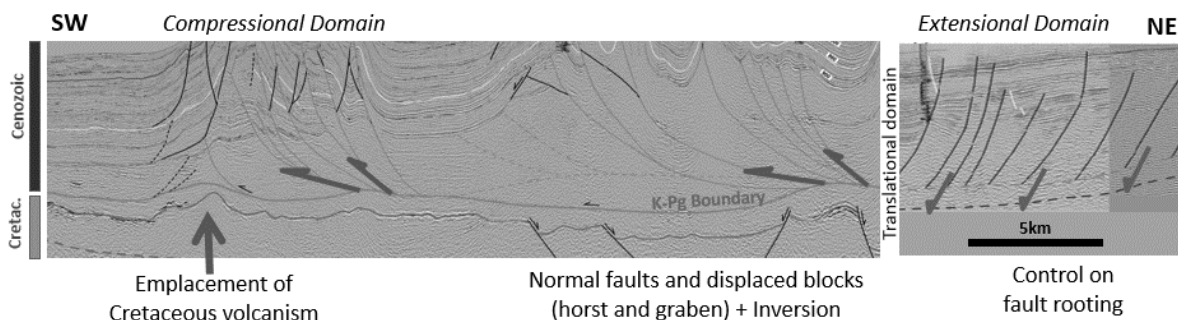
INSIGHT FROM A REGIONAL CROSS SECTIONS

Offshore Niger Delta: K-Pg Boundary and the Decollement Layer

Both 2D and 3D data sets show the extensional and compressional domains of the gravity-driven tectonics in the Niger Delta. Figure 1a shows a few lines on which the regional interpretation is based. Figure 1b shows that farther in the deep offshore, two kinds of fault architecture may be identified: reverse faults due to thrusting of the upper units, and the normal faults below the hot shales at the base of the Akata Formation (on which the upper thrust sheet glides to form imbricate thrusts structures). Below the basal decollement unit of the Akata Formation are the Cretaceous sediments at depth, associated with hardening (often due to magmatism) and the normal faulting before the emplacement of the overlying distal toe thrusts riding on the decollement layer of the upper unit.



- a. Lines used for regional cross-section, showing relationships to the Chain and Charcot lineaments, adjacent structures and different seismic vintages acquired in the area



- a. Tectonic inversion interpreted in particular sections may not be visible on regional lines^{11,12}

Figure 1: Map view with lines of section and seismic cross section showing the Cenozoic extensional and compressive zones (with reverse or thrust faults) overlying the Cretaceous sediment (with normal faults) at depth

There is a tectonic inversion: the deposit below the Akata Formation has normal faults while the upper unit gliding above it has reverse faults. The normal faults are of the Cretaceous, interpreted on this deep units exceptionally imaged by seismic data in the deep offshore Nigeria. This shows that farther in the deep offshore, the Cenozoic delta overlies the Cretaceous at depths of seismic blurry imagery, whose Cretaceous-Paleogene (K-Pg) boundary may be identified even at the distal zones. The boundary was formerly known as, and still sometimes

¹¹ Nosike, L., (2009). Relationship between Tectonics and Vertical Hydrocarbon Leakage: A Case Study of the Deep Offshore Niger Delta. PhD Thesis, University of Nice-Sophia Antipolis, France, 281 p.

¹² Barbier, V., (2010). Tectono-sedimentary study of the delta of Niger using the Sobrarbe Delta, Ainsa, Spain, as field analogue, Master's Thesis Report.

referred to, as the Cretaceous-Tertiary (K-T) boundary. “K-Pg” or “K-T” may be used interchangeably while labelling the figures in the subsequent sections.

Implication of the K-Pg Boundary

The transition zone between the Cenozoic Niger Delta and the Cretaceous Anambra Basin, the K-Pg boundary is deeply buried in the deep offshore, beyond the depth of prolific oil trapping. These features are poorly imaged at such depth but detectable indirectly by their orogenic and arching signatures on regional seismic data. The arrow in Figure 1b shows the emplacement of Cretaceous volcanism, as is evident also in the Anambra Basin and the southern Benue Trough. This event helped in correlating the decollement top, all the way from offshore to the onshore, to where this unit separating the lower Cretaceous and the upper Cenozoic sediments outcrop in the Enugu area of the Anambra Basin. In the subsequent sections, the K-Pg boundary is traced from deep in the subsurface offshore to where it outcrops.

It is shown in later sections that the regional magnetic anomalies and the flexures / fracture zones (mainly the Chain and Charcot Fracture Zones), align with these composite fault roots, directly relating to weak zones and structures emplaced during the rifting phase affecting the Cretaceous deposits. The resulting structural lows lead to sediment fills with alternating marine and continental deposits, listric faulting and hydrocarbon trapping. Structural rebounds, accommodated by translational movement above the Cretaceous / base of Cenozoic hot shales, limit impact of shallower Cenozoic deformation on the Cretaceous blocks or substratum. That is why faulting is less frequent below the transition from Cenozoic to Cretaceous as shown in Figure 1b.

This link between the Niger Delta and the southern Benue Trough is the transition outcropping in the Anambra Basin, where the Cretaceous thermotectonics led to hardening and controlled gravity deposits on subsiding slopes today seen as outcropping tectono-sedimentary features (the syn- and post-deformational deposits).

Anambra Syncline: “Plane Wing” Concept

The Benue Trough was affected by the lateral ramping due to relative movement of the European plate against the African plate. At the eastern flanks, the results of the strike-slip movement along the axis of the regional transform fault (fracture zones) created a “plane-wing” displacement mechanism. The deposits that thin out at the basin flanks were moved in the lateral direction as shown in Figure 2 (inset schematic). This created subsiding lows on which sediments were deposited after the Santonian deformation, in the transition from the Benue Trough to the Anambra Basin.

Sediments were then transported down the slope into the Anambra Basin during the late Cretaceous. In the early Cenozoic, some of them were eroded and alongside with new sediment, were transported to begin to fill the Niger Delta in the south. This means that sedimentary piles are displaced to the west and eventually to the south, leading to peculiar profiles in the uppermost part of the Cretaceous Anambra Basin. This creates a depositional trend that changes direction laterally over time, as shown by the angle θ_1 . This angular evolution of trend would appear as cut-offs in the continuity of sediments, depending on how a cross-section is taken across the area the Anambra Basin transition to the Benue Trough. This is most obvious in the various attempts to create continuous stratigraphic sequences based on field work. A proper line of section would be a random line that runs as X-Y-Z₂ instead of X-Y-Z₁ in Figure

2. Line Y-Z₂ is perpendicular to the initial fill into the Anambra syncline. Multiple lines of sections are therefore used to compare features in the X-Y-Z₂ trend before projecting them to the interpreted regional NE-SW cross section. This helped in throwing more light to the morphology of deposits in the K-Pg boundary.

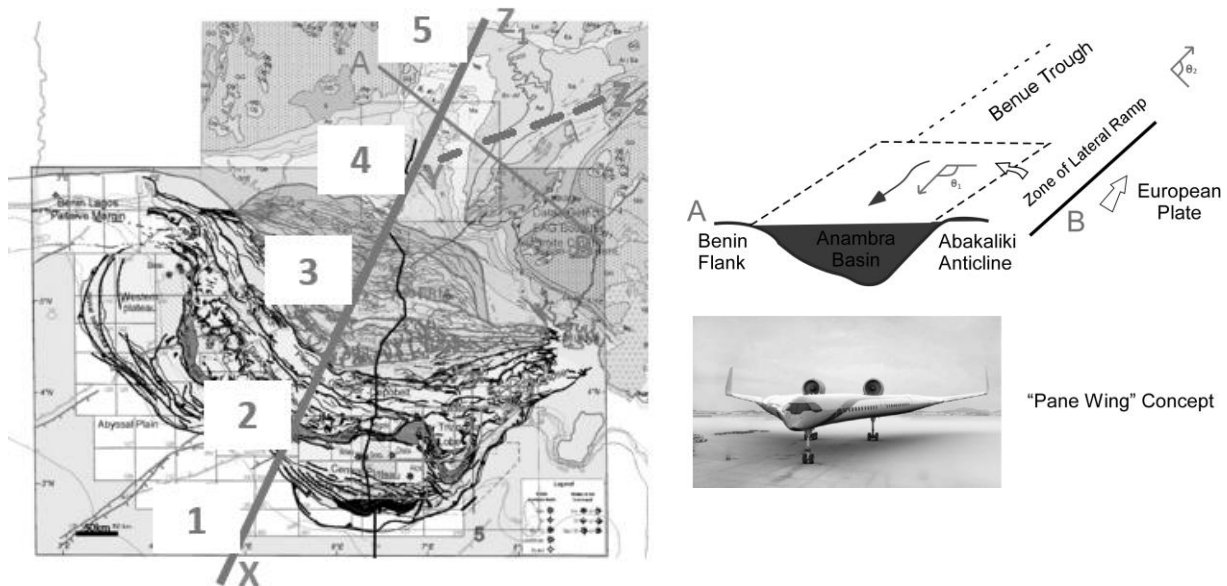


Figure 2: Map of the interpreted regions (Zones 1 to 5) and the NW-SE cross section showing the Anambra Basin in context of the Benue Trough (with the inset image to the right showing the plane-wing concept)

The angle θ_2 implies stress rotation of not just the sedimentary pile, but large-scale tectonic plate movement that drive major folds where they hinge northwards to form a wedge. The features of stress rotation are evident where the displaced European plate wedges partially to the north, further affecting structures in the Benue Trough and beyond. Whereas the impact of depositional trench changes on slope sediments would lead to reworking and such lateral fairway closures that would occur along multidirectional, fluvial channel complexes and their levees, the impact of stress impact on large scale related folding will be major biaxial ramping.

The plane wing concept explains the relative movement of the basin flanks with respect to the European plate. This kinematics explains the features observed in the field, including evidences of stress-rotation as well as likely upturned units in the Benue Trough, and suggests the presence of 3-way and possibly 4-way closures at location of lateral fault ramps. These structures, when de-derisked with seismic campaigns, may highlight major petroleum traps, as is common in the compressive fold belts of the Niger Delta where lateral ramps have been shown by sigmoidal faults and high-quality depth imaging using 3D seismic data (Nosike, 2009). Zones 1 to 5 numbered in Figure 2 are interpreted in the later sections.

Regional Stratigraphy and Depositional Sequences

The line of section across the Anambra Basin is often taken almost interchangeably from the NE-SW to the NW-SE. It has been shown that there is a difference in the sedimentary profile when viewed from an angular trend in one line of section from the north to the south, compared to when viewed at a right angle, from NW to the SE trend across the slope from the Benue Trough high to the Anambra Basin. The projection of information from the various studies and sectional view-points limits the accuracy of interpretation. The line of section for the regional

interpretation in the current work is a representative view, where other lines of information are projected to the regional cross-section.

In this representative view, the Cretaceous sediments run from offshore, below the Cenozoic Niger Delta, and become exposed as the Anambra lithofacies. While the Cenozoic Niger Delta sediments thickened southwards to the offshore, the Cretaceous sediments thickened but was uplifted northwards. Dominant prograding sequences and transition to early Cenozoic were preceded by retrograding sequences in the late Cretaceous. This was also the time of the transition from the Anambra Basin Delta, with signatures today recorded in the Cretaceous - Cenozoic boundary. This includes the pseudo-deltaic clinoforms described in this work.

Figure 3 shows an extract of the stratigraphic chart highlighting formations of the Anambra Basin and the different orders of sea level changes. The varying dips measured locally in the upper Anambra Basin may be due to the sagging at the transition from Cenozoic to the Cretaceous, in the upper units not affected by the Santonian deformation. Restoration and depth models have shown that the impact of post-formational sagging alone is enough to explain such low dips ($<7^\circ$)¹³. In these areas, alternating deposition of high energy continental lowstand systems tracts and low energy highstand marine shales create alternating sequences of reservoir-seal pairs. The arrow in Figure 3 shows the shallowing of the Cretaceous, from offshore to the onshore, towards the Anambra Basin in the north. The colour code of the stratigraphic units is intended to fairly match that of the interpreted representative units in the regional cross-section of Figures 7 to 11 (Zone 1 to 5 of the regional cross section) below.

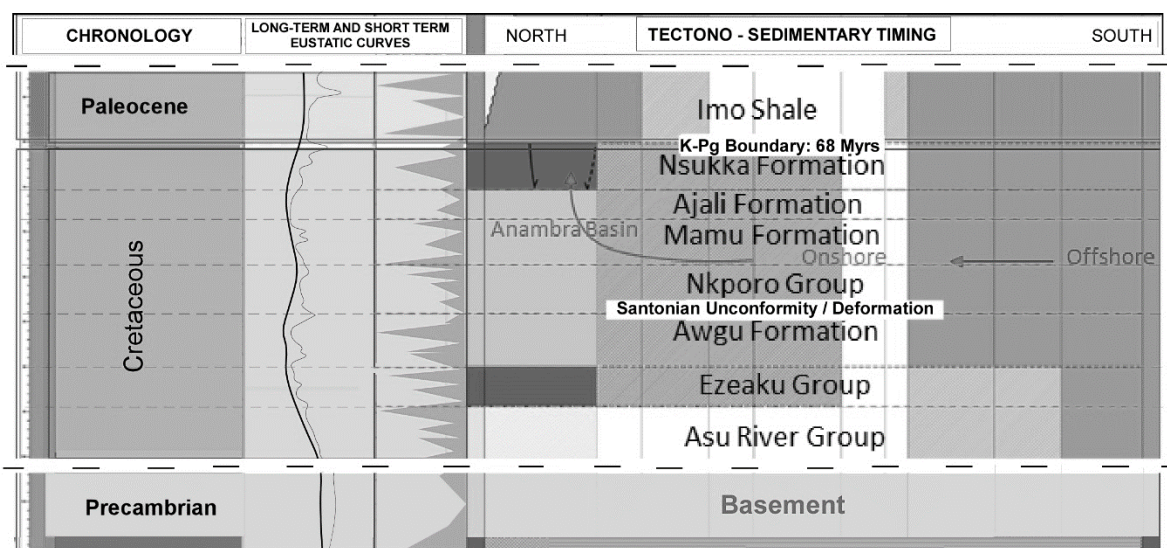


Figure 3: Extract from regional stratigraphic chart highlighting the Anambra Basin section and the main formations (stratigraphic units, thickness not to scale, delineated in the regional cross-section)

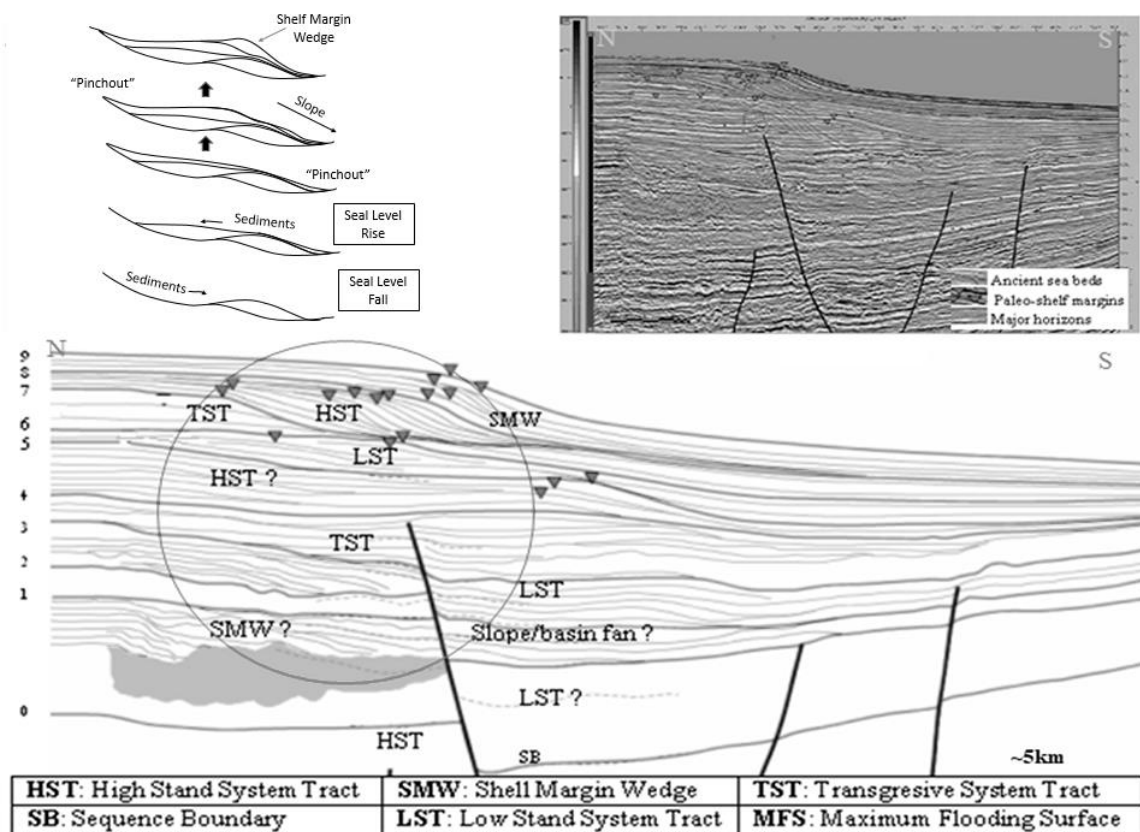
Major tectono-sedimentary events from late Cretaceous to the Cenozoic have been identified, especially the impact of the Santonian deformation and the subsiding basin at the K-Pg boundary as shown in subsequent sections. Highs in the Cretaceous create anchors, leading to the deposition of clinoforms at slopes due to eustasy, and the emplacement or activation of

¹³ Nosike, L., (2009). Relationship between Tectonics and Vertical Hydrocarbon Leakage: A Case Study of the Deep Offshore Niger Delta. PhD Thesis, University of Nice-Sophia Antipolis, France, 281 p.

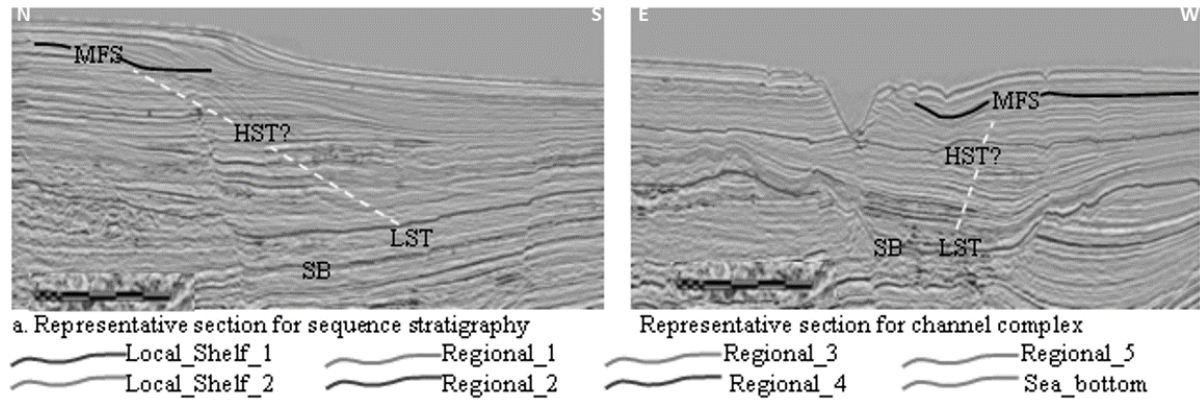
normal faults due to displacement downslope. Similar structures were constructed in the Enugu area of the Anambra Basin, where varying but low dipping beds show structures that cannot be attributed to either structural or sedimentary process alone. They suggest a tectono-sedimentary process, where the sediments are deposited along wide subsiding slopes.

An evolving continental margin provides larger scale deposits that show slope features. Clinoform structures formed in this situation would extend much longer and have more planar morphology than those in the active shelf break; their lengths are expected to be in the order of several kilometres and may have lower dips. Their related large-scale shaly drapes and closures at the top- and down-laps, which may present as pinchouts when seen in local exposures at the field, explain effective shallower oil and gas traps in the Enugu area of the Anambra Basin.

In a two-dimensional view, a clinoform is seen as a sigmoidal depositional surface due to the slopy basin margin geometry in which they were mainly deposited. However, similar sloping accommodation space in ancient margin or subsiding lows away from present day or recent deltaic margin formed similar deposits, with dominant shale or mud covers during high sea level, then incision and high energy sedimentary fills during low sea level. The principles of clinoform deposits at shelf margin and how they are used for sequence stratigraphy are embodied in Figure 4a, in Nigerian shelf margin region, where the morphology is clearly visible.



a. Clinoform morphology created due to depositional sequences on subsiding slope highlighting present-day- and paleo-clinoforms (*top-left: evolution of a shelf margin clinoform*)



b. Correlation of shelf margin depositional sequences to equivalent episodes of deposition and channel fills further offshore

Figure 4: Interpretation of clinoforms at the shelf margin and tying them to proximal and distal depositional sequences during sea level rise and fall¹⁴

These intervals were correlated from near shelf to the deep offshore levels, which was possible in the shallow interval (Figure 4b). Similar correlation is made on a larger scale to the onshore Niger Delta and the inland basins. These correlations show that although continuity may be difficult to establish at depths, there was a continuous deposition along a structural axis from the inland basins to offshore, and migrating shelf margins at different times. Despite local structural limits and depositional gaps, the process created continuous sequences of deposition and stratification seawards and shoreward over the entire rift zone that extended from the then nascent Atlantic Ocean to the Benue Trough.

¹⁴ Nosike, L., (2006). Seismic mapping and tectono-sedimentary analysis of the post-Pliocene interval offshore Eastern Niger Delta, Master's Thesis, University of Pau and Pays de l'Adour (UPPA), 42pp.

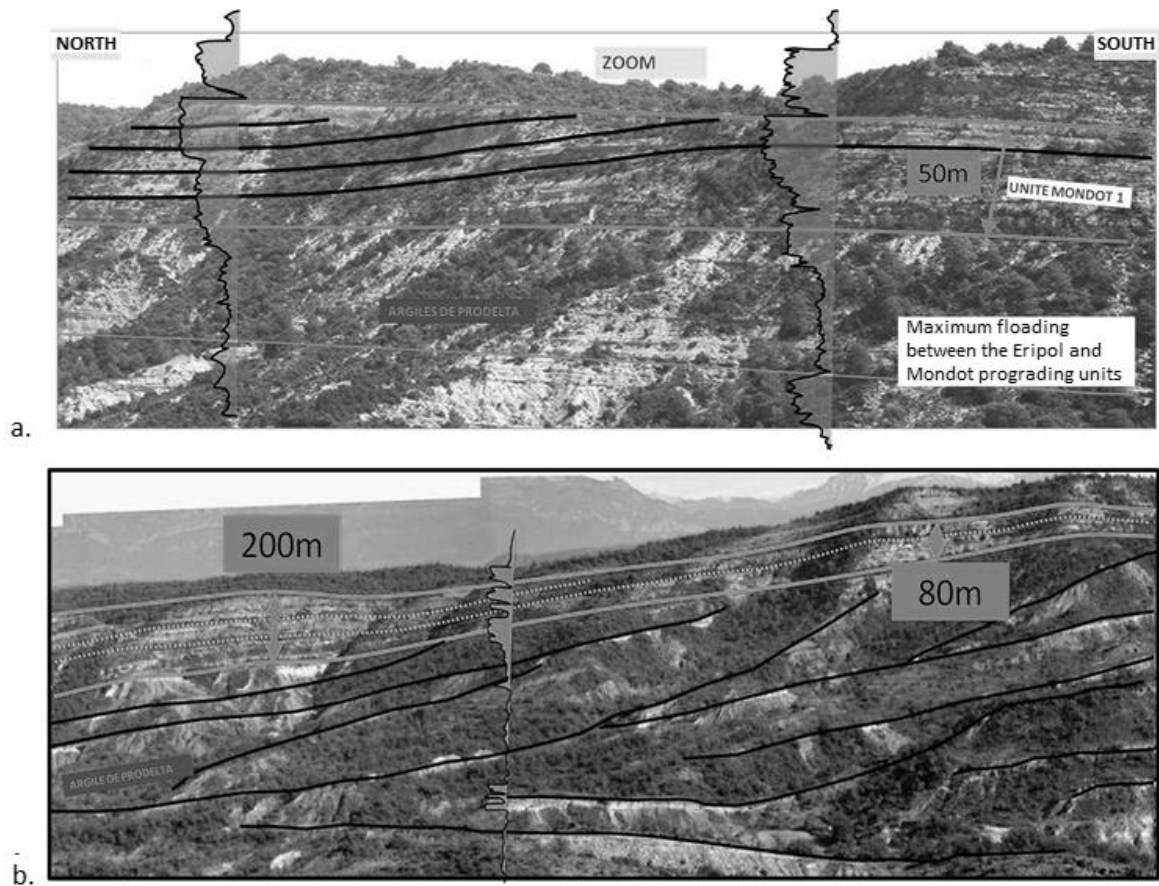


Figure 5: Clinoforms from field observation at the western flank of the Ainsa syncline in Sobrarbe. *a.* is a more planar morphology than *b.*¹⁵

Figure 5 is an analogy of field exposure of clinoforms, showing a relatively planar and a more angular morphology, in the Sobrarbe Delta in Spain.

Zonation from Offshore to Onshore - Inland Basins

During the opening of the Atlantic Ocean in the middle Mesozoic, the transform faults and weak zones formed the trend of the graben that developed within the African craton and the Benue Trough. The normal faults at its boundary controlled the subsidence, the flexural plate movements and the Santonian deformation of the Benue Trough. This is within the same genetic trend with the Niger Delta, although different tectonic episodes have led to tiering of the basins or sub basins, where sedimentary fillings and basin forms occurred at different times. A continuous structural axis may be established with sufficient seismic data and well correlations, as shown in the sections below. This helped to explain the stratigraphic activity and sedimentary profiles, as well as hydrodynamics or flow patterns due to pressure differential / differential burial.

¹⁵ Barbier, V., (2010). Tectono-sedimentary study of the delta of Niger using the Sobrarbe Delta, Ainsa, Spain, as field analogue, Master's Thesis Report.

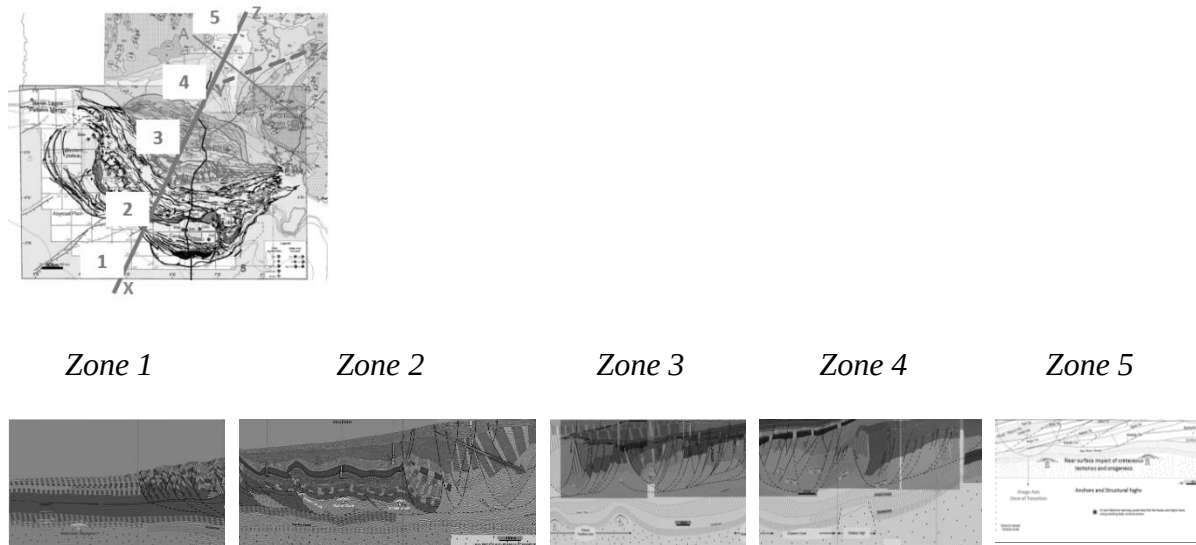


Figure 6: Zonation to show a genetic relationship from offshore to onshore within the aulacogen that formed the Niger Delta, the Anambra Basin and the Benue Trough^{16,17,18,19}

Zone 1 – 5 (Figure 6) is a regional cross section along line X-Y-Z to give insight on tentative understanding on the Anambra Basin and the Southern Benue Trough. The zones, from distal, through the conventional offshore, to the onshore Niger Delta and the Cretaceous Anambra Basin and the southern Benue Trough, have been labelled 1 to 5 accordingly. With reference to the numbered zones, the depths of interest may be followed across seismic lines to gain insight on the Cretaceous – Paleogene boundary. The Cretaceous deposits at this depth were traced to the near-shore and eventually at the area of interest inland, highlighting the basin structure and dynamics with respect to structural activities and trap formation. In the figures below, the seismic cross-sections are topped with other related work, as inset maps or sections, field observations or depositional belts that have been established in literature or previous works.

Zone 1: Distal Ultra-Deep Offshore

Zone 1 runs from the abyssal region in the distal offshore to the beginning of the imbricate thrust structures (Figure 7). The abyssal zone is mainly filled with fine grained or biogenic material and thin organic rich shales. Cretaceous activities had remained relatively low at depth due to less deposition, subsidence or crustal destruction away from the regional transform zones.

The less burial as well as less impact of the wedging systems that occurs at the end of the toe-thrust are due to translational movement of Cenozoic deltaic sediments. The main activities

¹⁶ Nosike, L., (2006). Seismic mapping and tectono-sedimentary analysis of the post-Pliocene interval offshore Eastern Niger Delta, Master's Thesis, University of Pau and Pays de l'Adour (UPPA), 42pp.

¹⁷ Nosike, L., (2009). Relationship between Tectonics and Vertical Hydrocarbon Leakage: A Case Study of the Deep Offshore Niger Delta. PhD Thesis, University of Nice-Sophia Antipolis, France, 281 p.

¹⁸ Nkwocha, E., Laurent Guy, Francois Raissou, Livinus Nosike and Vincent Clergy, 2011. Regional Seismic Interpretation of Eastern Niger Delta Petroleum Province for Structural, Stratigraphic and Depositional Framework, Collaborative Work and Poster Presentation.

¹⁹ Nosike, L., 2022a. Pore Pressure Evolution in the Anambra Basin and Implication for Hydrocarbon Leakages. Prepress review.

driving displacement of the units are in the near shore deltaic area, propagating from the extensional to the compressive domain that ends before the abyssal depths. The impact of these activities is seen in the distal imbricate fold belt. Among the features in the north of this Zone are frontal and lateral ramps, pockmarks and cusped lobate structures of sedimentary piles at surface²⁰ (Nosike, 2008).

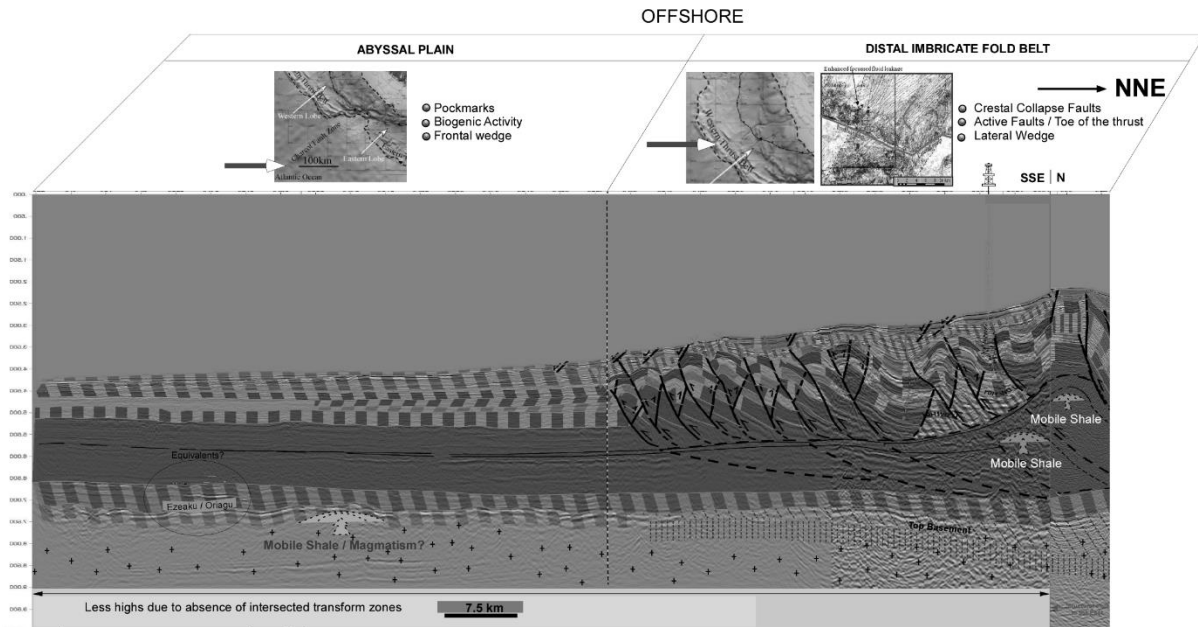


Figure 7: Ultra deep offshore and the abyssal region showing less activity in the Cretaceous units at depth

Zone 2: Offshore Niger Delta

Zone 2 is the region where the displacement of blocks from the extensional domain reaches the deep offshore where they hinge to form a wedge, often multiply faulted (Figure 8). From the shelf margin, the last array of normal faults drives the block displacement through the translational domain to the beginning of the compressive domain in the south. Mobile shales driven under pressure to the fault-propagation and fault-bend folds, are also shown in the figure. The arrow shows how ancient shelf margin and faults create subsiding slopes in regions where both structure and sediment load affect accommodation space.

In the inset figures and map above Figure 8, from the left, zones of pockmarks (indicating shallow fluid activities, vents, overpressure and mud volcanoes from deeper units are shown). Frontal and lateral ramping created intersection points that served as weak zone for such fluid expulsion²¹. The biaxial ramping created 3-and 4-way anticlinal closures that have trapped substantial hydrocarbon in the major oil fields in the Nigerian deep offshore. To the right of the inset images atop Figure 8 is the correlation of nearshore markers from the shelf to recent channels offshore (cf: Figure 4). As explained in the previous section, although these may be

²⁰ Nosike, L., C. Wibberly, C. Jardiné, and Pacalin, Y., (2008). The Role of Tectonics in Geopressure Compartmentalisation and Hydrocarbon Leakage in the Deep Offshore Niger Delta: YORSGET Extended Abstracts, Trabajos de Geologia, 6p.

²¹ Nosike, L., (2009). Relationship between Tectonics and Vertical Hydrocarbon Leakage: A Case Study of the Deep Offshore Niger Delta. PhD Thesis, University of Nice-Sophia Antipolis, France, 281 p.

obscured at depth, such correlations show that there is a genetic relationship between the onshore and the offshore depositional sequences, due to the same underlying structural trend that created weak zones and accommodation space for the deposition.

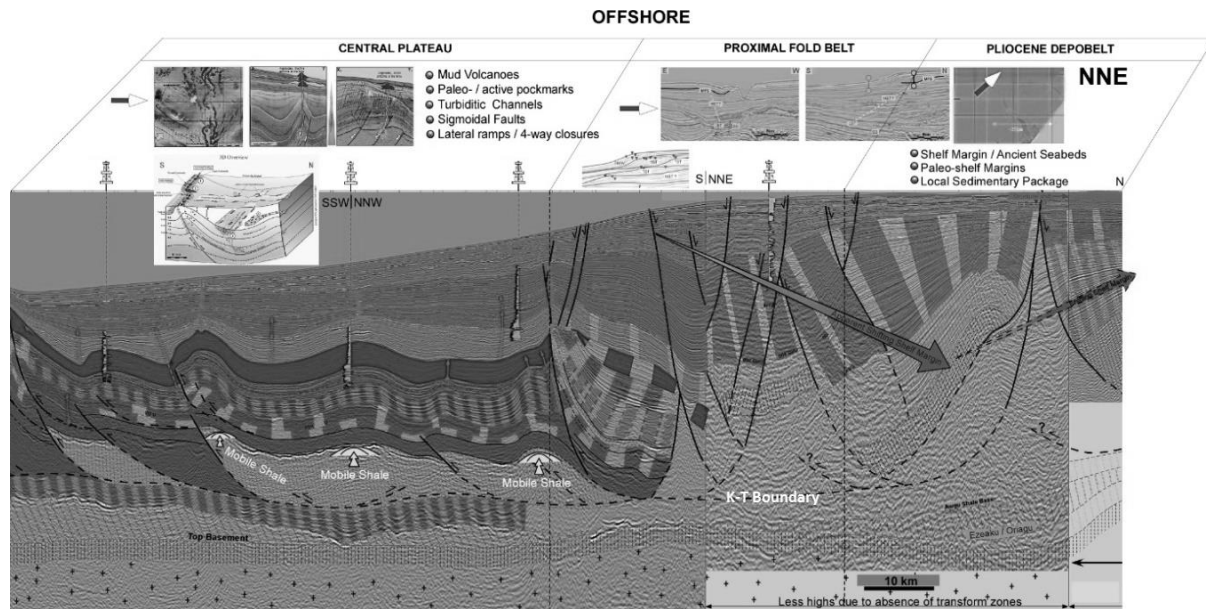


Figure 8: Shelf margin, extensional, translational and the beginning of the compressive domain offshore Niger Delta

The fluvial depositional flow from the onshore reaches the delta margins and eventually drives turbiditic currents across the slope to deposit pseudo-equivalent turbiditic channel complexes and lobes offshore. In the inland Cretaceous Anambra Basin and the associated ancient delta, there were alternating sea level changes depositing sandstone or sandy reservoirs covered by fine grained sediments and hemipelagic shales. The shaly drapes above create relatively shallow local traps at the subsiding areas in the Anambra Basin, especially in the Enugu Axis transition between the Cenozoic and the lower Cretaceous sediments. The underlying fold had created a margin that presents as subsiding slopes and clinoforms at the area where the K-Pg or K-T boundary outcrops.

Zone 3: Onshore Niger Delta

In Zone 3, the pronounced impact of the Cretaceous orogeny due to magmatic activities is evident. Their intersection on the seismic line highlights that the magmatic highs align with the regional transform zones (the fracture or transform zones shown in Figure 1). Figure 9 shows the Charcot transform zone and the projection of the Abakaliki high, intersected at an angular trend with the cross-section (shown in Figure 1), such that they confirm the impact of the transform zones on the magmatism as well as leeway for flexural glide of the European plate relative to the African plate (which created the Abakaliki Anticline as presented in Figure 2). This further clarifies the understanding of the “plane-wing concept” (earlier on discussed) and possible ramping and anticlinal closures in the area.

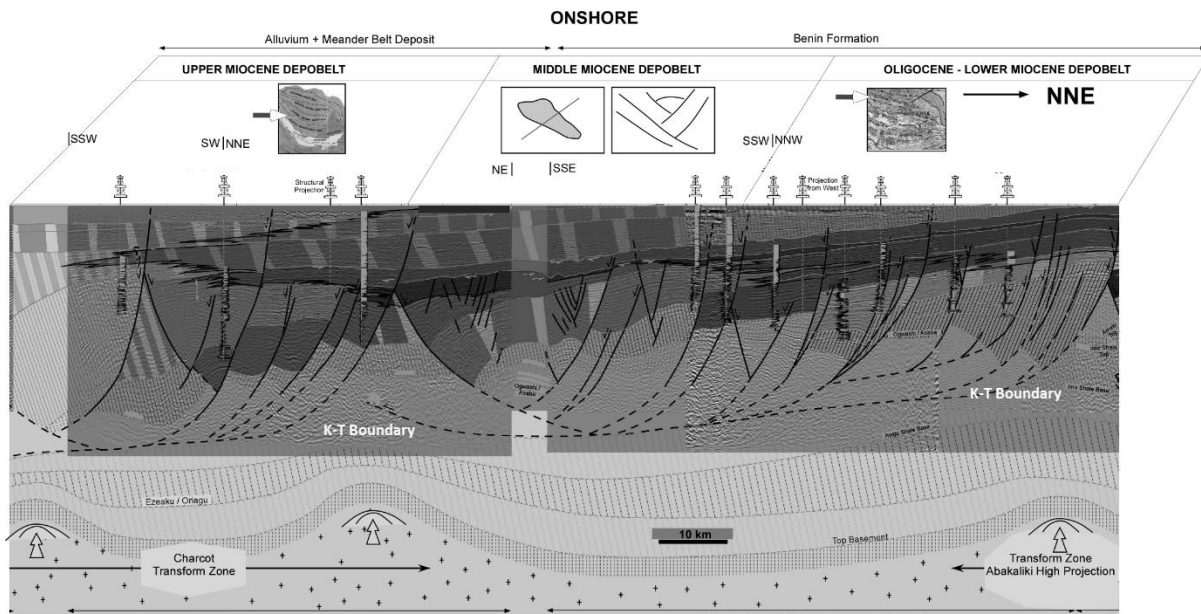


Figure 9: Onshore Niger Delta showing the different depobelts and the alignment of the Cretaceous magmatic events to the regional transform zones and the arching leading to highs / paleo-orogeny

Above the Cretaceous arching signatures at this zone are the growth faults, with synthetic and antithetic segments, amply described in literature for the onshore Niger Delta. The upward-pointing arrows below a concave cover (Figure 9) indicate magmatism, which created the up-thrust or hardening, leading to differential burial and faulting. The deep faults are rooted at the initiation of slope laterally between these magmatic highs above the basement, where the upwelling of magma created igneous orogeny into the Cretaceous. The illustrations atop the seismic section, inset in Figure 9, show the Upper Miocene through the Middle Miocene to the Oligocene-Lower Miocene Depobelts. Figure 9 also shows the K-Pg or K-T boundary, which is later traced to its surface expression, where the onshore-Cenozoic deposits laterally transition to the Cretaceous outcrops.

Zone 4: Outcropping Cenozoic Deposits Onshore and the Inland Basin

Zone 4 has been extensively studied in outcrops, during field trips where the emphases is laid on the Cenozoic Niger Delta deposits such as Benin, Ogwashi, Asaba and the Ameki Formations. Whereas this zone has outcropping Cenozoic sediments such as the Imo Shale, the wells to the NNE targeted the Cretaceous (Anambra Basin) sediments below. As such the inland oil fields in Anambra and Enugu States are referred to as that those of the Anambra Basin. The underlying Cretaceous deposits continued NNE-wards to the surface and are exposed as the Anambra Basin. In Figure 10, the lateral boundary between the oceanic crust and the continental crust occurs at depth of the basement and is shown with some degree of uncertainty.

The Onitsha high provided an anchor-point, beyond which are subsiding flanks. with normal faults. The faults were formed due to instability of the tilting Cretaceous units. The thickening of sediments SSW-wards is indication of the thalweg, or eventual depocenter that received the sedimentary transport, as the hydrographic network sloped down from the Cretaceous high NNE-wards. This zone of transition created features suitable for hydrocarbon trapping, like that of the present-day shelf margin, when fluctuating sea level deposits alternating seal and reservoir rocks. The reservoir-seal pairs formed not only vertical low-permeability lithological

covers, but also lateral closures further north at the extremities of depositional clinoforms at the margins. These dynamics or mechanisms controlled the tectono-sedimentary activities in the Anambra Basin and southern Benue Trough.

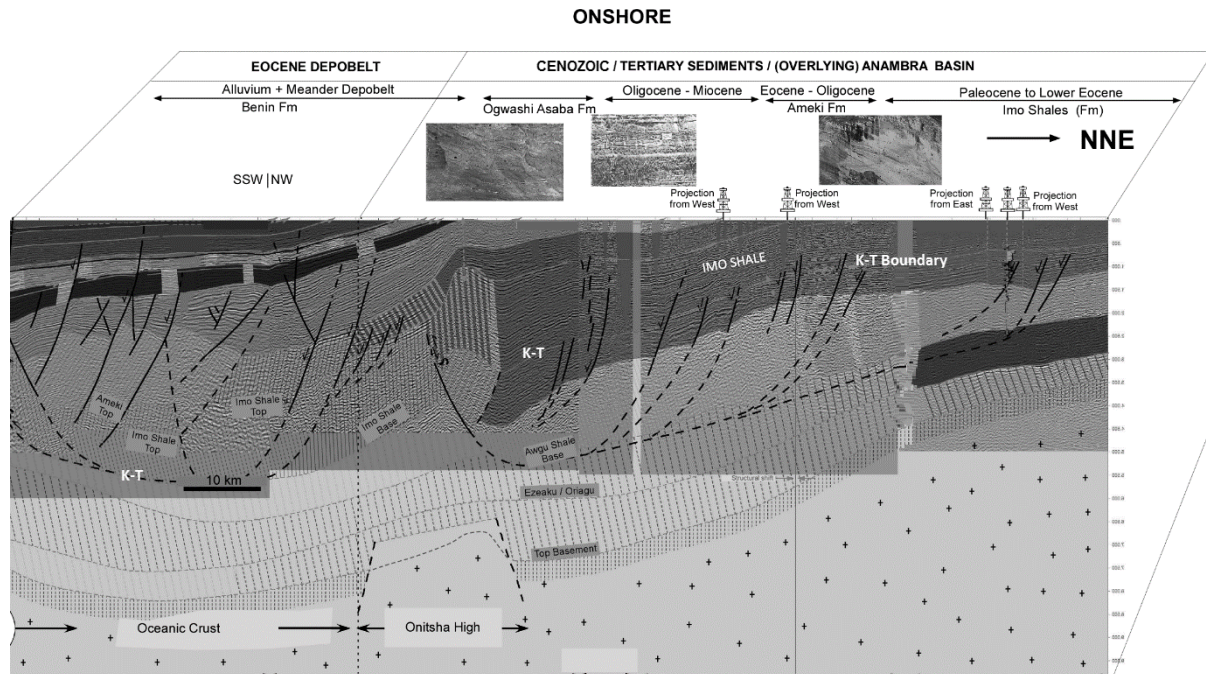


Figure 10: Onshore / Inland basin highlighting the outcropping Tertiary/Cenozoic deposits and the underlying Cretaceous deposits up-dipping or shallowing (to later outcrop as the Anambra Basin).

Closer to where the Anambra Basin outcrops northwards, there is a change in fault timing: normal faults, which were formally rooting in the Cenozoic deposits southward, now roots in the Cretaceous. Also, the faults are blind (buried) in the NNE section of Figure 10, while remaining active (outcropping) in the south. This implies structural activity at a margin, with the delta migrating southwards due to gravity tectonics as well as sediment supply and thickening of the sedimentary pile southwards. The buried fault tops, whose tips align and are tilted in the same southward direction, attest to ancient margin of the Anambra Basin delta, which had formed the subsiding slope with extensional faults, and clinoform deposits, as in recent time shelf margin.

The thicker basement rock to the north shows the configuration of a deltaic low or a thalweg, which has served as accommodation space for sediment transport and deposit westward into the Anambra Basin and down-shore into the ocean. The ancient geography suggests that this area had been subsiding at the time of deposition, leading to the trapping structures in the area. The effective seal of the shaly drapes across such structure explains why high-pressure gas, for example, would be efficiently trapped at shallow depths of less than 300 m in the present day. The drapes and shales deposited during the highstand or high sea level rise are exposed at road construction / road cuts, shallow water wells, with swelling clay rheology²².

²² Nosike, L., (2022b). A Study of the Gas Fire at a Water Well in the Caritas University Premises, Amorji Nike, Enugu. NAPE Annual International Conference and Exhibition, 20pp.

Zone 5: Cretaceous Anambra Basin and the Benue Trough

Zone 5 is the main outcropping area of the Cretaceous Anambra Basin and the southern Benue Trough. In the absence of a seismic line in this region, tentative geologic layering (Figure 11) has been proposed to explain the observations in field, well data and seismic correlation from the south in Zone 4. In Figure 11, part of the northern section of Zone 4 is added to form continuity in Zone 5. Atop the image in Figure 11 are the outcrop exposures of the Ajali, Enugu, Nsukka Formations and indicators of hydrocarbon trapping and leakages, exemplified by the Ugwueme oil seeps^{23, 24, 25, 26, 27, 28, 29}. The zone has been amply studied in the field; however, the absence of seismic line makes it difficult to properly represent field observation and correlation of adjacent strata. The attempt to place the units in the current study is tentative (Figure 11) and it is hoped that seismic campaign foreseen in the area will help to properly tie the units.

The observation of laterally equivalent by diachronous units, without major regional faults or structural displacement to offset the units suggests similar signatures of clinoforms, deposited in subsiding slopes at the ancient shelf margins or deltaic slope of the Anambra Basin. For example, in the Enugu axis, the region encircled in in Figure 11b, the Owelli Sandstone and adjoining units are shown to probably close laterally down-dip and up-dip, as is the case in clinoforms and associated depositional structures. Compare with the diagram showing the shelf margin deposits, where the units pinch out down-dip and up-dip (illustrated in Figure 4). Similar episodes formed the top and downlaps, and the pinchouts on the ancient deltaic units, made up of alternating marine and continental deposits in the Anambra Basin.

In Figure 11, Cenozoic sediments outcrop southwards (SSW) while Cretaceous Anambra Basin sediments outcrop northwards (NNE). The upward-pointing arrows below a concave cover indicate magmatism, which created the upwelling and igneous hardening, leading to differential burial and faulting. Normal faults may be rooted laterally inbetween these magmatic highs above the basement, as was observed in the Niger Delta at depths below the decollement layer. These impacts of Cretaceous orogeny have been consistent and more evident when observed across the affected units overlying the basement from offshore to onshore.

The paleo-margin in the Cretaceous Anambra Basin indicate the transition to the highs in the Benue Trough, the accommodation space on which the units exposed at the Enugu axis were deposited. The Enugu axis corresponds to a paleo-margin, a local rise to the north and depressed slope to the south, over which transgressive and regressive sequences deposited an inter-bedding of marine shales amid continental coal beds and siltstones / sandstones. The area with the correlation of multiple layers (encircled area of Figure 11) has delineated the Nsukka, Ajali, Mamu, Enugu Formations of the Anambra Basin that were tied to fewer units down-dip

²³ Reyment, R. A., (1965). Aspects of the Geology of Nigeria. University of Ibadan Press, p.48-60.

²⁴ Ekweozor, C.M., (1990). Geochemistry of Oil Sands of SW Nigeria. In: Ako, B.D. and Eni, E.I., Eds., Occurrence, Utilization and Economics of Nigeria tar Sands, Proceedings of NMGS Tar Sand Workshop, Ago-Iwoye, p. 50-62.

²⁵ Ekweozor C. M. and G. I. Unomah, (1990). First Discovery of Oil Shale in the Benue Trough, Nigeria. Fuel, Vol. 69, pp 502 – 508.

²⁶ Sonibare, O. O, O. A. Ehinola and R. Egashira, (2005). Thermal and geochemical characterization of Lokpanta oil shales, Nigeria, Energy Conversion and Management, Vol. 46, Issue 15-18, p. 2335-2344.

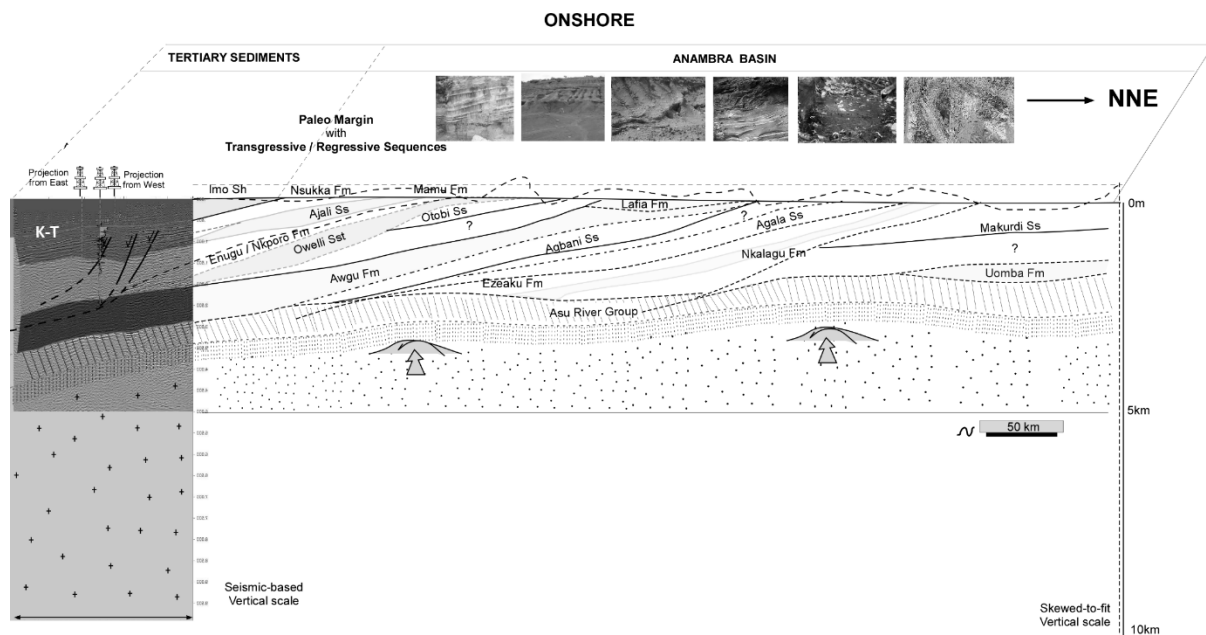
²⁷ Nosike, L., (2020). Exploration and Production Geoscience – Comprehensive Skills Acquisition for an Evolving Industry, Delizon Publishers, p. 227-264.

²⁸ Nwajide, C.S., (2013). Geology of Nigeria's Sedimentary Basins. CSS Bookshop Ltd., Lagos, 565p.

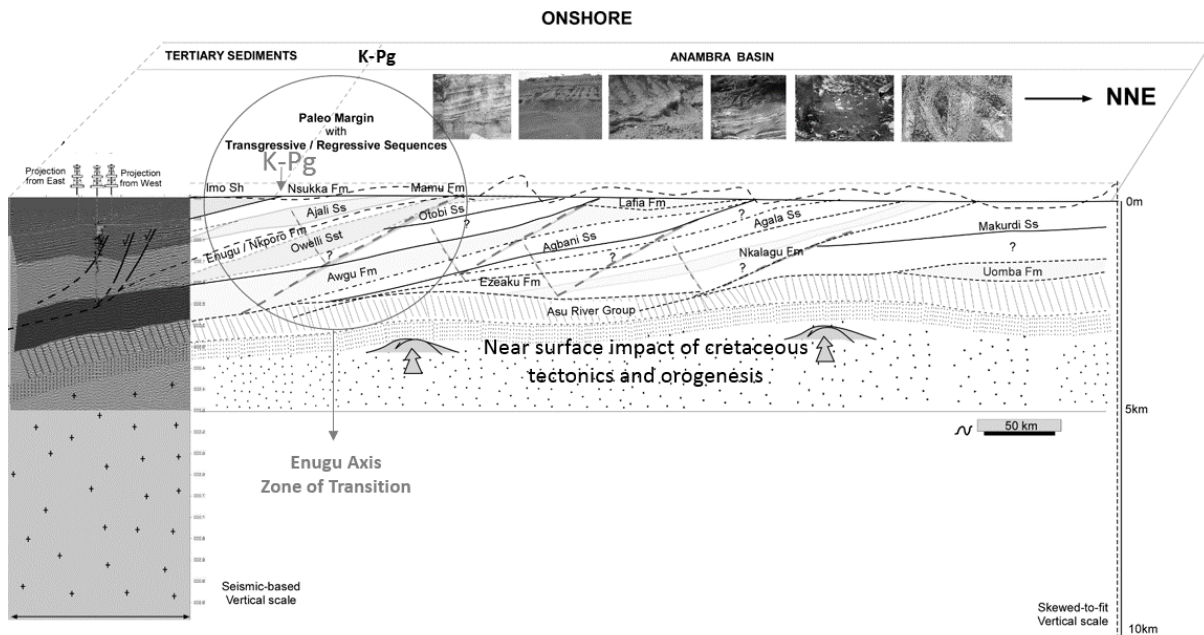
²⁹ Nwajide, C.S., (2022). Geology of Nigeria's Sedimentary Basins 2nd Edition. Albishara Educational Publishers., Enugu, 693p.

Impact of Structural Dynamics on Hydrocarbon Retention of The Deposits in The Enugu Axis of The Cretaceous Anambra Basin

in the seismic interpretation. The oil bearing and producing intervals targeted in the Anambra River and other neighboring oil fields in the subsurface are actually the lateral equivalents of these formations, the Awgu and the Nkporo Groups. Based on well data and outcrop information, this model suggests that most of the interpreted units in the encircled area top-lapped and down-lapped to close at the top and base. As such, they pinched-out and are hardly separable in wells drilled downdip (cf: Figure 4a). Such closures produce multiple traps laterally within the same reservoir sets. Up-dip, they close and are adjoined to the immediate adjacent strata and lateral equivalents in the southern Benue Trough.



a. Depositional profile showing lateral equivalents of diachronous sediments and impact of orogenesis as arrows and arcs



b. Delineated units of the Anambra Basin at the K-Pg boundary and possible fault trends shown as red broken lines

Figure 11: Tentative depositional profile and delineation of units in the Enugu axis of the Anambra Basin and southern Benue Trough suggesting large scale clinoform morphology at the outcropping K-Pg boundary

Among the other units of the southern Benue Trough to the north are the Awgu, Ezeaku, and Asu River Groups, which lie unconformably below the upper Anambra Basin units. These formations also have their equivalents in the central and northern Benue Trough. The profiling of the units will require a proper depth imaging by seismic campaigns for in-depth interpretation. The underlying Basement Complex is represented below the interpreted regional cross-section presented in this work. Its impact on the tectonics and orogeny affecting the inland Cretaceous deposits is relatively nearer to the surface compared to that on the Niger Delta southwards. The limitation of this tentative depositional profile is that, despite efforts to corroborate several works in the region, the interpreted 2D line of section is only representative of wide expanse of basins and geomorphologies, in which several attitudes of the bedding units overlie an undulating basement. Lateral variation in the depositional signatures means that some interpretations are only a projection of conceptual models onto the line of section.

Enugu Axis of The Anambra Basin

Outcropping K-Pg Boundary

The Enugu Axis is the upper flank of the syncline that forms the Anambra Basin. The word Enugu means “Hill Top” or “Mountain Top” in Igbo language, signifying the high topography due to coaly ridges and mountainous highs that occur locally in the area. Regionally, these highs are underlain by Cretaceous formations that, as seen from the interpreted seismic cross-section, tapers down, below the Niger Delta in a dipping structure, to the depocenter seaward. This positions the Enugu area as a crestal high, a structural axis, at the limit of the Anambra Basin (Figure 12). Erosion washed sediments down, from the high elevation at the margin between the Cretaceous ridge or escarpment northward, to the gentle slope southwards. Subsequently, the ancient coastal lowland southward was filled with Cenozoic sediments.

The lithostratigraphic units exposed in the Enugu area of the Anambra Basin are post-Santonian deposits, which are not directly affected by the deformation, except for its later impact on their sagging. Santonian deformation had created a high and eventual slope to the SW and seawards. The stacking of late Cretaceous sediments in this southerly direction promoted the formation of growth faults. Rejuvenation of movements on the faults displaced and juxtaposed alternating marine and continental deposits across the strata. This is highly conducive for the formation of both stratigraphic and structural traps, with suitable shale or mudrock seals and pinchouts where subsiding lows formed clinoforms. Above this is the Imo Shale Formation shown in Figure 10, which is the base of the Cenozoic deposits, described as part of the Niger Delta Basin.

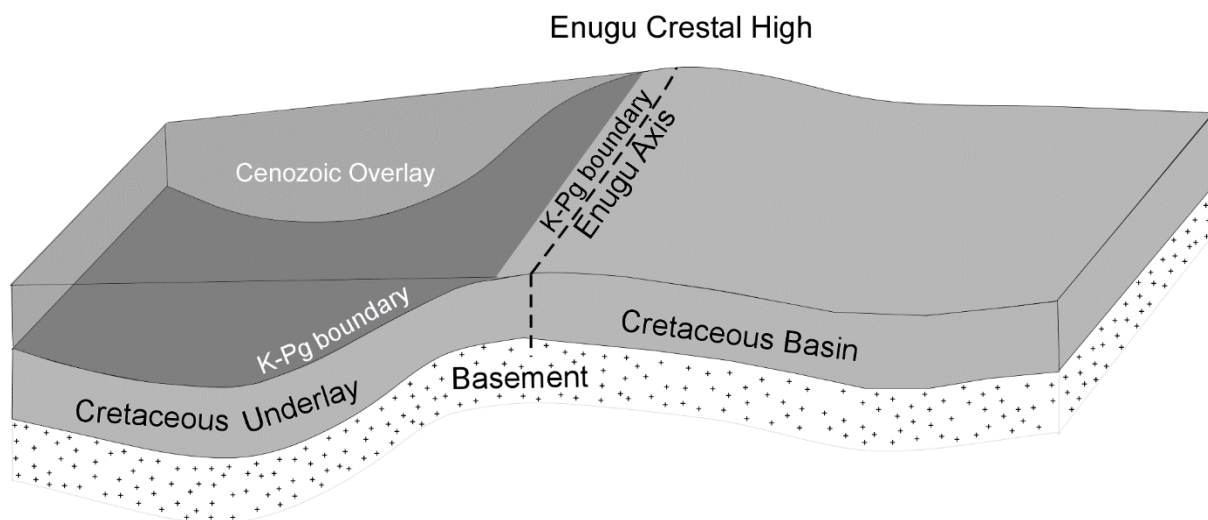


Figure 12: Enugu Axis illustrated as the geographical region where the axial plane of the Enugu crestal high projects to the surface

The K-Pg boundary is identified along the Enugu-Onitsha expressway, where the uppermost parts of the Nsukka Formation are seen as inselbergs. The K-Pg boundary lies in that upper part, which are isolated resistant Nsukka formation deposits, beginning from Ezeagu Local Government Area along the Enugu Onitsha expressway. After that, the base of the Cenozoic Imo Formation, traced along the expressway, lies at the Oji River area. Farther down-dip, the shaly aspect of the formation occurs as swelling clay unit leading to potholes and damaged roads. The transition from the Cretaceous Nsukka Formation to the Paleocene Imo Formation is shown in Figure 11.

The impact of the older folded southern Benue Trough sediments on the younger late Cretaceous Anambra Basin sediments, created the feature of interest, including the clinoform trap structures, which transition to and is capped by the Paleocene Imo Formation southwards. This and the other overlying Cenozoic strata provided the cover and enough sediments to generate overpressure in the rapidly subsiding basin southwards. This condition led to the transmission up-dip, northwards in the Enugu Axis, charging the overpressure wells and prospects in the area.

Pore Pressure Evolution

It is seen from Figure 10 that the shales of the Imo formation constitute a regional seal in Zone 4, whereas the underlying units of the Cretaceous Anambra Basin extend across fault tips,

partially compartmentalized, but providing enough continuity at the extreme NNE for possible pressure transmission from the depocenter (southwards) to the up-dipping overpressure units (northwards). Meteoric charging has been suggested by workers to partly account for the observed overpressure in the Anambra Basin wells. However, such charging is insufficient to explain the higher overpressure at depth³⁰. Current study and recent pore pressure analysis suggest that overburden alone in the southern depocenter is enough to generate such overpressure, which is then transmitted up-dip alongside hydrocarbon fluids charging the Anambra Basin wells³¹. Blind faults may also be sourcing pressured fluids from deeper units into the carrier strata.

Differential burial (thickening down-dip and thinning up-dip) leads to overpressure, transmitted from downdip to the Enugu axis. Established pore-pressure envelopes based on field and laboratory measurements, and pore pressure prediction results, show dynamic transfer to explain hydrocarbon trapping at relatively shallower intervals. Centroid effect made the shallower porous units to exhibit pressures relatively higher than the average pressure for that depth. The overpressure encountered at intervals in some of the wells drilled in the Anambra River field may be used as offset well information to guide the assessment of the closely associated encircled case studies in the Enugu axis. When the depth of overpressure at the units interpreted on the seismic section downdip at the depocenter is compared and extrapolated up-dip to the Enugu axis, it shows that it is the equivalent strata that transmit the overpressure from the south to breach the seals in certain places and leak in the Enugu axis northwards.

Hydrocarbon Retention and Leaks / Recent Gas Flare

The efficient shallower hydrocarbon trapping in the Enugu axis, explained by the shaly covers or drapes and clinoform signatures, is evidenced by several observations. In the recent gas flare in the Amorji Nike community of Enugu State, the gas probably emanated from a shallow accumulation, coal seam methane in fractured units, or from formation gas in a reservoir³². However, since the known coal beds are in the Mamu Formation far above the depth of the event, coal gas as a source was considered unlikely. This leaves the concept of actual traps in shallow clinoforms as most likely.

There was a sudden emergence of crude oil in normal water well at an agricultural centre at the Akpuoga Nike area in the Enugu State, about ten kilometres away from the zone of the Amorji Nike gas flare incident³³. Slicks have been observed as traces in shallow soakaways in this location, but not sufficient to confirm tertiary oil migration prior to this time. The water well had been existing for over six years and served as normal unpolluted water for fishery in the agricultural centre. Few weeks after the gas flare incident, it was observed that large amount of crude oil had accumulated in the well. It is not certain if these incidents are related, owing to the distance separating the wells and the different fluid types, but it indicates the presence of liquid hydrocarbon occurring alongside gas in the same region. It requires further investigations as the relevant agencies were notified.

³⁰ Onuoha, K. M., (2005). A Closer Look at the Petroleum Potential of the Anambra Basin: - Inputs from Geophysics and Geohistory. In: Hydrocarbon Potentials of the Anambra Basin: Geology, Geochemistry and Geohistory Perspectives, Okogbue, C. O., (ed), Proceedings of the First Seminar Organized by the Petroleum Technology Development Fund (PTDF) Chair in Geology, University of Nigeria Nsukka, p.47-81.

³¹ Nosike, L., (2022b). A Study of the Gas Fire at a Water Well in the Caritas University Premises, Amorji Nike, Enugu. NAPE Annual International Conference and Exhibition, 20pp.

³² Nosike, L., (2022b). A Study of the Gas Fire at a Water Well in the Caritas University Premises, Amorji Nike, Enugu. NAPE Annual International Conference and Exhibition, 20pp.

³³ Nosike, L., (2022b). A Study of the Gas Fire at a Water Well in the Caritas University Premises, Amorji Nike, Enugu. NAPE Annual International Conference and Exhibition, 20pp.

Results and Discussion

It has been amply indicated in literature that the promising reservoir units in the Anambra Basin are gas prone, based on the petroleum results of the reservoirs that encountered gas in previous wells. However, recent studies show that there might be more oil than earlier on expected, evidenced by the reported oil slicks and suitable architecture for efficiently trapping oil in relatively shallower intervals. The previous wells that targeted the lower coal measures indicated results for liquid hydrocarbons, and the present correlations have shown that they are the major units that form suitable traps in the Enugu axis.

The Anambra Basin was a subsiding platform at the time of deposition. The succession of deposits on the sagging slope of the basin provided suitable stratigraphic and structural traps in the Enugu axis. The changing down-lapping convex and top-lapping concave shape of strata provided the architecture for local closures consistent with clinoform morphologies in deltaic margins. The focus on suitable trapping structure in this region had been the vertical impermeable lithological seals. The present study emphasizes the role of clinoform closures with porosity diminution up-dip, especially in the presence of lateral fault boundaries.

Prospects for Development

The units in the Enugu axis of the Anambra Basin have trapped hydrocarbons at shallower intervals, leading to uncertainty on the seal cover and quantity. The present work has shown that such shallower traps are possible due to the clinoform structures formed at a subsiding paleo-margin. It has provided a better understanding of the hemipelagic shaly drapes, which can be efficient seal even at shallower depth. The traps may be target developments for local utility and where they have extensive lateral scale, it can be substantially economical. While large volumes of gas had been considered a developmental risk in the past, it is now considered positive due to plan for extensive gas utilisation. Developmental risk is further reduced where gas occurs with liquid hydrocarbons as has been observed in the vicinity of reported recent gas flare at Amorji Nike in the Enugu axis.

Shelfal landforms provide sequences of marine and continental deposits, relating to short cycle changing sea levels, which emplaced the reservoir and seal intervals encountered in the interpreted cross-sections. That the formation targeted by the Anambra River wells and the adjoining Oil Prospecting Licenses (OPLs) trapped hydrocarbons indicate that the equivalent units exposed further up-dip in the Enugu axis would trap hydrocarbons as well. This is because despite being uplifted and exposed in places, lateral seals and hemipelagic draping, in the ancient deltaic margin depositional architecture, provided enough efficient intermittent seals and tectono-stratigraphic traps.

Target areas for prospects and development are:

1. Equivalent units correlated to hydrocarbon producing formations south of the basin, overlain by Cenozoic sediment cover downdip.
2. Post-Santonian deformation units compartmentalized to form trap systems (even if outcropping in present day).
3. Sandstones that have enough subsurface tilting due to clinoform morphology and stratigraphic / hemipelagic draping across their lateral extent
4. Regions with possible fractured coal bed methane, or other producible coal seam, silts and unconventional hydrocarbons.

Coal seam may be produced by drilling in-situ, using new unconventional technologies. Smaller accumulation may exist in stratigraphic traps and local gas pockets which occur in silty units intercalated within shaly formation. This would need to be quantified using seismic data, highlighting the need for more seismic acquisitions in the area. High resolution seismic data will be most useful for the shallower deposits with clinoforms morphology. Hopefully, attention would be given to this resource in view of the inland Cretaceous basins' development in Nigeria.

Summary and Conclusion

At the initiation of the triple junction, the heating of the lithosphere, differential stretching, and thinning created regional transform or fracture zones. The tear zones that continued into the inland region up-dip at intermittent wedges and highs as magmatism resulted in eventual hardening of igneous orogeny. Those highs continued to serve as the crestal uplift driving sediment deposition and gliding of sedimentary pile downslope, across marginal lows to the deltaic depocenters. This created a structural link during the Cretaceous - Cenozoic time, with similar play dynamics, from the Niger Delta deep oil generating units to the Enugu Axis as limit of the Anambra Basin, from the south to the north.

Genetic Relationship of the Tier Basins

The tier basins: Niger Delta, Anambra Basin and Benue Trough, share the same structural axis, genetically related to the failed arm of the triple junction during the opening of the Atlantic Ocean. However, different episodes of deposition following tectonic movements led to deformation and formation of sub-basins. The different aging and changing, paleo-physiography presented different hydrocarbon results, and therefore different exploitation mechanisms and petroleum economics for the Cretaceous Anambra Basin and Southern Benue Trough today.

In the deep offshore, magmatic signals correlated across depths to the inland, show arching of the Cretaceous units (post-upwelling hardening) at the K-Pg boundary, leading to differential burial and served as initiator for major faulting in the overlying Niger Delta. Similar impact of magmatism is seen in the Cretaceous Benue Trough. The Anambra Basin is the transition between the southern Benue Trough and the Niger Delta, presenting a deltaic margin, a subsiding slope on which special clinoform structures form drapes and efficient seal covers for relatively shallower and yet substantial hydrocarbon traps. This might prove more cost effective for exploitation in clusters in the Enugu axis.

Implication for Hydrocarbons Prospectivity

The late Cretaceous sediments of the Anambra Basin were deposited in similar deltaic conditions as present day Niger Delta, especially in the transitional zones from shore to then marine lows, with ancient deltas, sand channels and complex reservoir fairways stacking complex architectures in hemipelagic shales or other fine sediments, as well as an initial lacustrine deposits following the rifting / crustal opening stage. The implication is that most of the methods used for hydrocarbon prospectivity in the Niger Delta will be useful in the Anambra Basin. The paleo-Anambra platform and its opening to the ocean was also a delta with evolving shoreface. The Cretaceous may then be studied in association with the well-known and developed overlying Cenozoic Niger Delta.

Conclusion

The basin structure and dynamics of the inland Cretaceous Basins have shown similar dynamics with that of the Niger Delta, including the tectono-sedimentary processes such as detachment, tectonic inversion, clinoforms and trap formation. The prior missing link emphasized in this work is the Cretaceous tectonics and volcanic orogenesis. These events led to uplifts that controls gravity deposits on subsiding slopes, with tectono-sedimentary features identified at depths in the Niger Delta and seen where they outcrop in the Anambra Basin and the southern Benue Trough. The syn- and post-deformational deposits are particularly seen in the Enugu Axis, being the transition zone or the K-Pg boundary. These features are poorly imaged but detectable on the interpreted regional seismic data, with hopes that further targeted seismic campaigns will lead to a better understanding of the proposed tentative depositional models and their associated hydrocarbon traps.