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Exhumed hydrocarbon traps in Afikpo Basin, Southeastern Benue Trough, Nigeria: Analog for the Upper Cretaceous-Cenozoic Play of the Gulf of Guinea

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ABSTRACT

Two exhumed hydrocarbon traps crop out in the Afikpo Basin of the Southeastern Nigeria, each at the unconformity formed during the Santonian tectonic event. Oil accumulations are indicated by a pore-fill or pore lining of solid bitumen within the Campanian - Maastrichtian sandstone-dominated Ameta-Ozziza and Ebori Usumtong formations. Three types of trap geometries can be identified in the field: the wedge-out, channel and strike valley fills are found in the Amete-Ozziza and Ebori Usumtong areas of central Afikpo region. The Nkporo Formation (0 - 44m) consists of Alluvial fans, distributary and tidal channels; marine and fluviodeltaic deposits. The sandstones are dominantly quartzarenites and minor amount of subarkoses and arkoses, petrographic fabric, such as dissolved feldspar, clay and late quartz cements, are consistent with burial depths in excess of 3km. The sandstones generally have relatively good to moderate porosities, about one-half of which was primary. The distribution of each trap can be mapped out, allowing sealing elements to be defined. The two exhumed traps Ameta-Ozziza and Ebori Usumtong were stratigraphic and structural traps, with Campanian - Maastrichtian unconformable mudstone, and normal faults are the two top sealing elements. This article gives a preliminary description of two exhumed hydrocarbon traps in the Afikpo Basin; these traps became thermally degraded and exhumed during terminal Cretaceous tectonics involving magmatism and regional uplift. The stratigraphic relationship in the Afikpo basin is significant to hydrocarbon entrapment. The exhumed traps may indicate future plays on the largely unexplored lower Benue Trough of Nigeria where at a reasonable depth sandstone is overlain uncomfortably by the source rock of Nkporo shale which may be a favourable area of petroleum prospecting. The former ridges created during the Maastrichtian tectonics with unconformity surface may form collecting reservoirs for oil. These traps described are similar to that of oil fields in the North Sea. The author believes that Afikpo structures will provide useful analogs in detailed study of the subsurface reservoirs of the Niger Delta and Gulf of Guinea oil provinces in West Africa.

Key words: Exhumed, Hydrocarbon traps, Afikpo Basin, Upper Cretaceous-Cenozoic Play, and Gulf Guinea.

INTRODUCTION

The geology of the Cretaceous Benue Trough and the Cenozoic Niger Delta is known through some basic published works [8], [10], [17]; [34]; [35], [4], [3] and [7]. Three major structural units exist in the Lower Benue Trough: the Anambra sub basin, Abakaliki Anticlinorium and Afikpo sub basin. The main lithostratigraphic characteristics and the relationship between the Afikpo Basin and Niger Delta are presented in Fig.1. The Cretaceous section has not been penetrated beneath the Niger Delta Basin, the youngest and southern most sub-basins in the Benue-Abakakliki trough [32]. Lithologies of Cretaceous rocks deposited in what is now the Niger Delta basin can only be extrapolated from the exposure section in the next basin, the Afikpo basin (Fig.1). From the Campanian through the Paleocene, the shoreline was concave into the Anambra and Afikpo basins respectively, resulting to river-dominated sedimentation during regression. The Campanian/Maastrichtian Nkopro shale was deposited during a major transgression in the Afikpo basin. The distribution of the Nkporo shale beneath the Niger Delta is unknown. In the Paleocene, another major transgression occurred in both the Anambra and Afikpo basins that led to the deposition of the Imo shale and the Akata shale in the Niger Delta basin area. In the Eocene, sedimentation changed to being wave-dominated [32]. At this time, deposition of paralic sediments began in the Niger Delta Basin as the sediments prograded southward towards the sea.

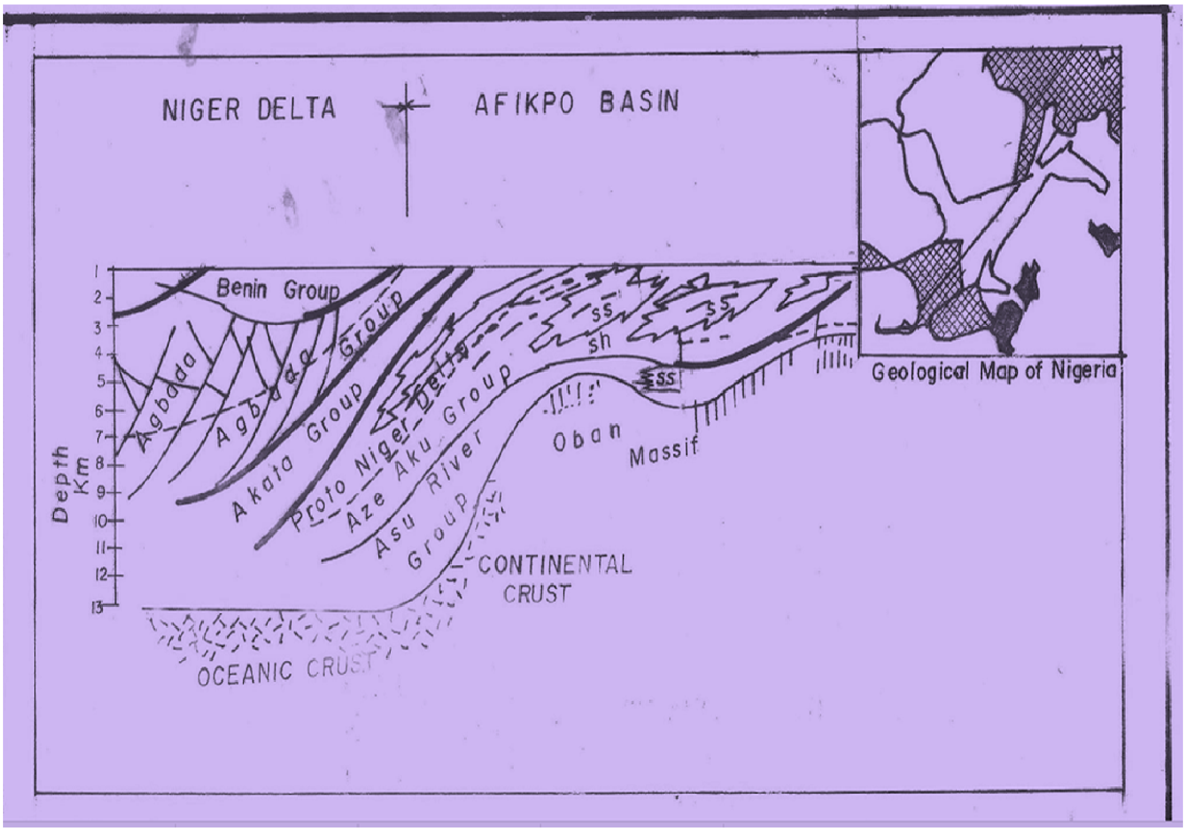

Figure 1: Synthetic Cross Section from the Niger Delta to Afikpo Basin Showing the Relationships between the various Lithostratigraphic units. The basement depth is obtained from the geophysical data

The Cenozoic Niger Delta is a thick accumulation of Tertiary sediments at the southern extremity of the Benue Trough. The history of the Niger Delta started after the terminal tectonic Maastrichtian event [23]. The Niger Delta marks completely the connections between the continental structures which originated the Benue Trough and oceanic fracture zones of the same age [6]. The Niger Delta is divided into five major concentric geomorphological depositional settings (depobelts) with three distinct lithostratigraphic units Fig. 1 (Akata Group, Agbada Group and Benin Group [33]; [11]; representing prograding depositional facies. The Akata facies at the base of the delta is of marine origin and is composed of thick shale sequences (potential source rock), turbidite sand (potential reservoirs in the deep water, and minor amounts of silt and clay. Geochemical evidence indicates that the Akata shale is of both marine and terrestrial in origin [21], transported to deep water areas characterized by low energy conditions and oxygen deficiency [22]. The formation underlies the entire Tertiary delta just as the Campanian Nkporo shale underlies the proto-Niger Delta Afikpo basin.

The paralic Agbada Group is the target for hydrocarbon exploration and development in the Cenozoic sequence of the Niger Delta. The formation consists of paralic siliciclastics representing the actual deltaic portion of the sequence. The clastics accumulated in delta-front, delta-topset, and fluvio-deltaic environments. The Nkporo shale is overlain by delta-front, delta-topset, and fluvio-deltaic facies [23].

The Afikpo Basin had witnessed three tectonic episodes namely; the Cenomanian, Santonian and the terminal tectonic Maastrichtian event [23]. The three Cretaceous tectonic episodes produced three megasequences that are characterized by sandstone reservoirs and shales as source rocks. Both Santonian and Maastrichtian tectonism resulted to deformation, uplift, magmatism and erosion of uplifted pre-and post-Santonian sediments. The post-Santonian sediments were deposited unconformably on the older sediments. The post-Santonian sediments were further deformed by the terminal Cretaceous tectonism that manifested in the form of faults, joints, fractures and magmatic activity.

Geochemical studies of these shales from the pre-Santonian Cretaceous stratigraphic units suggest the presence of gas than oil. The post-Santonian strata have the potential to generate oil and gas [23], [26], [18]. The Nkporo Formation of the Anambra and Afikpo basins is considered to be relatively a good source rock [20]; [23], and has been rated an oil and gas prone basin that is worthy of attention. Oil seeps have been reported in the post-

Santonian sediments northwest of Usumtong and Ozziza-Amate. The seeps occur in the basal unit of the post-Santonian sandstones which rest on the unconformity plane of the folded Eze-Aku Group. This stratigraphic relationship is significant to hydrocarbon entrapment. Oil accumulation in the Afikpo Basin is indicated by the presence of solid bitumen filling the pores in the Campanian-Maastrichtain sandstone. The spur for oil exploration in the Anambra Basin by Shell D'Arcy, began in the 1930s, and was pronged into (a) the recording of oil smells, stains and seepages, and (b) the stratigraphic setting of interbedded shales and sandstones with some limestones, as seen on outcrops. Oil seep had been reported at the foot of the scarp slope of the Enugu north of Lokpanta.

Solid bitumen within the Upper Cretaceous sandstone in the Anambra Basin of the Lower Benue region was encountered by [12], [13], [14], [15] and [16]. It has been known that hydrocarbons are often trapped adjacent to unconformities, in both structural and stratigraphic settings. Regional stratigraphic and sedimentological studies play an important role in defining the location of favourable unconformity zones in time and space. Liquid petroleum exudes in the form of springs and seepages that reached the surface along fractures, joints, fault planes and unconformities. Oil floats to the surface of water, and gas bubbles out and escapes into the atmosphere. As the Upper Cretaceous-Cenozoic play has reached maturity, exploration has become important, and to better understand reservoir geometry and the importance of unconformity and sealing properties, suitable outcrop-scale analogs have been sought. Although, some analogs have been used to understand fully the sedimentology and structure of Cenozoic play in the Niger Delta, none, to the author's knowledge, presents time-equivalent units from the Afikpo basin. The use of Afikpo basin in the southeastern region of the Lower Benue Trough is crucial and important since the Upper Cretaceous basin is a proto-type of the Cenozoic Niger Delta.

REGIONAL GEOLOGY OF SOUTH EASTERN NIGERIA

The evolution of sedimentary basins in South-Eastern Nigeria (Fig.2) followed the opening of the South Atlantic and the break-up of the South American and West African plates in late Jurassic times. The proto-basin of the Benue Trough was the failed arm of an RRR triple junction which extended from the Northern limits of the Niger Delta Basin to the Chad area in the northeastern Nigeria.

A review of the tectonic framework of the country has demonstrated that the Benue Trough system was indeed a rejuvenation of existing basement fractures. Wrench movements along these faults resulted in blocks faulting and formation of several sedimentary basins (Fig. 3).

The Benue Trough system had in the past been conveniently subdivided into the lower, middle and upper Benue Trough. However recent aeromagnetic and gravity data across the entire system has demonstrated the distinct nature of these basins each with its well defined sedimentary succession and separated by positive anomaly areas. Sediment thicknesses of up to 8km have been recorded in some of these basins within the Trough [27], [28].

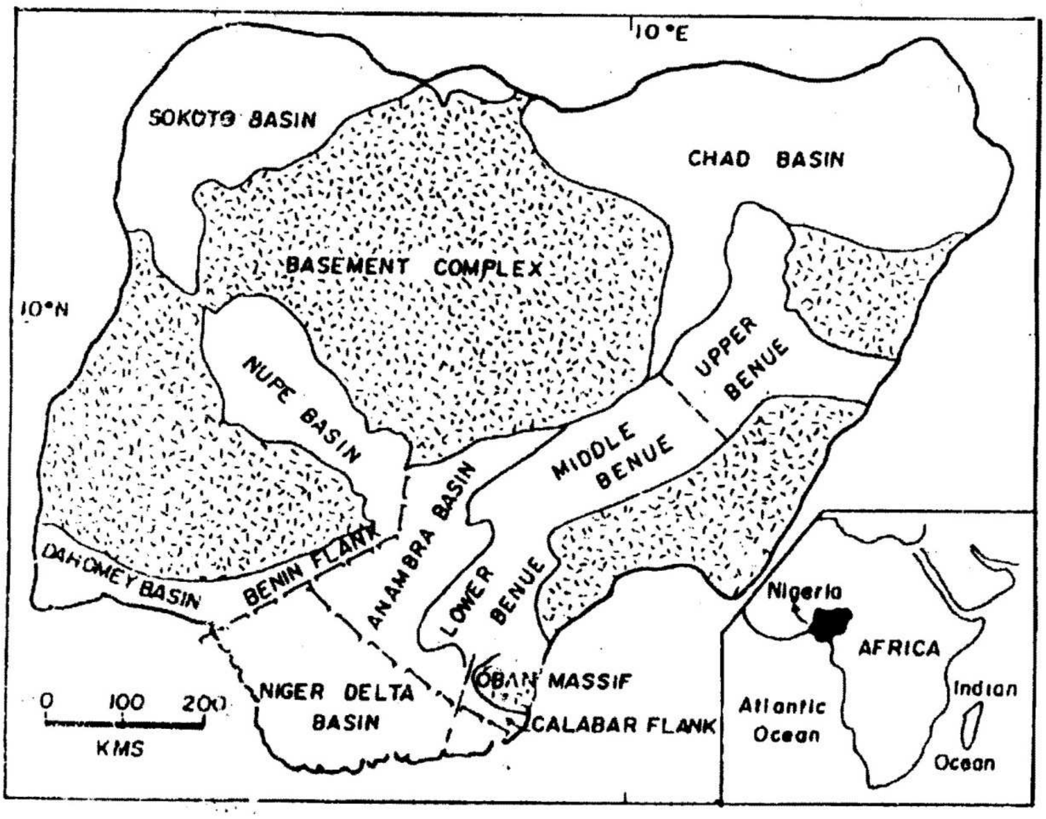

Fig. 2: map of Nigeria showing the location of the Benue Trough (Basin) and South-Eastern sedimentary basins

In South-eastern Nigeria they include the Abakaliki, Anambra and Afikpo Basins, as well as other minor basins such as the Calabar Flank and Mamfe Embayment which together form the lower Benue Trough. The Paleogene basin has been influenced mainly by the later generation transform faults (Charcot, Chain, Ascension & St. Pauls) which emanate from the mid-Atlantic ridge system and now extend only into the Tertiary basin. Up to 12km sediments have been deposited within the central part of the Niger Delta basin, much of which is above oceanic basement.

CONTROLS ON SEDIMENTATION

The sedimentary succession in South-eastern Nigeria can be sub-divided into three mega-tectonic phases. Each phase was confined to the defined sedimentary basins and controlled principally by subsidence rates. These are the Albian to Coniacian (Abakaliki Basin), Upper Campanian to Paleocene but minor control which affected the spatial variation in the depositional patterns was the eustatic sea level changes. At least five major transgressions of southeastern Nigeria sedimentary basins from the late Cretaceous to Eocene times, three of which are correlatable to the global eustatic sea level chart with possible links to the Tethys sea across the Sahara Desert being established. Later transgressive events also occur within the Tertiary Niger Delta on which the present subdivision of the stratigraphy into cycles has been based.

The sedimentary infill of the trough include deep to shallow marine clastics and carbonates, as well as continental deposits. These deposits include turbidites, (transitional) shelf facies, carbonate platforms, deltas as well as alluvial fans and fluvial deposits. Volcanic intrusive and pyroclastics are present in several parts of the basin, interbedded with sedimentary facies of different stratigraphic ages.

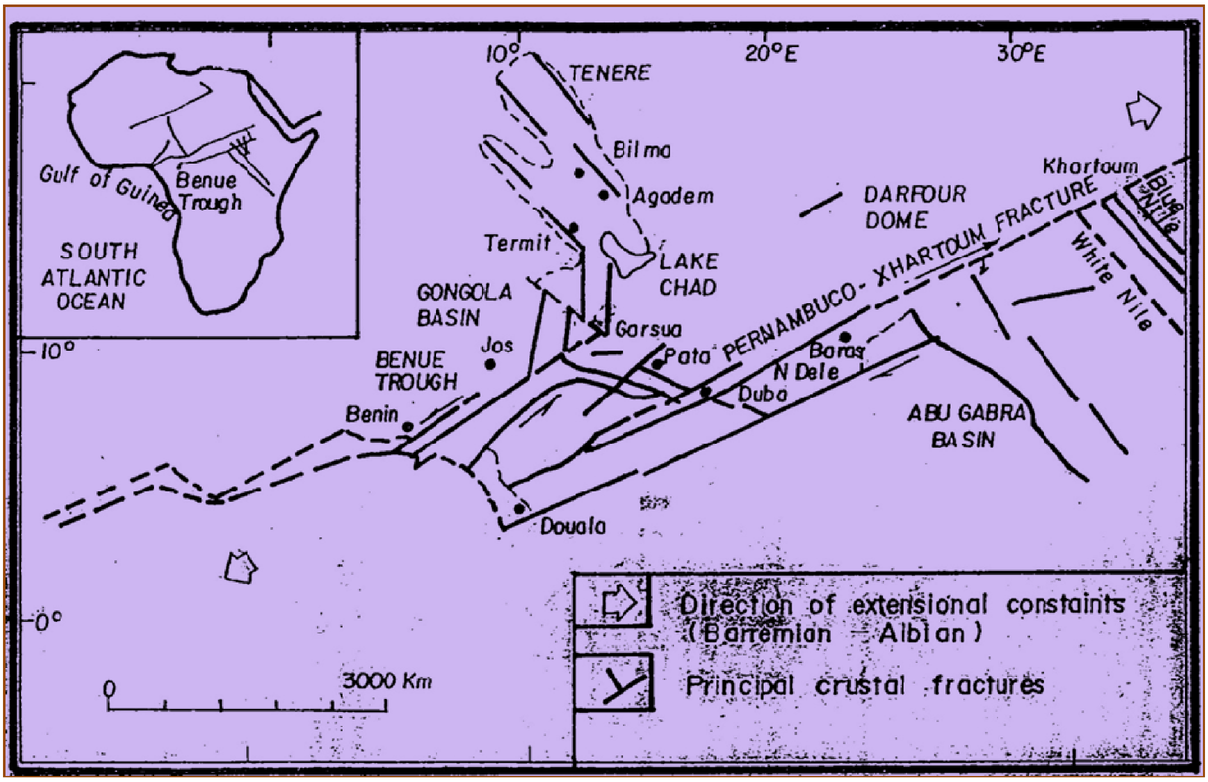

Fig. 3 Regional Structural map showing the major fracture subsystems in the West and Central African region, after [29]

GEOLOGICAL SETTING AND STRATIGRAPHY

The Benue Trough is a linear NE-SW trending intra- continental basin. Structurally it consists of series of N-E trending transform fault system, anticlines and synclines. In the Afikpo basin, transform faulting was reactivated during late Maastrichtian terminal tectonic event [25]. The basin was modified by sinistral strike-slip activity. The sedimentary fill in the Afikpo basin is divided into three tectonic -stratigraphic mega sequences; the Asu River Group, Eze-Aku Group and proto-Niger Delta succession (Fig. 4). The proto-Niger Delta basin comprise of Campanian-Maastrichtian and Paleocene sediments which are post-unconformity formations. The Nkporo Formation in the Afikpo syncline area thins towards the NW and SE at the trough margins of the basin. The Mamu Formation lies conformably upon the Nkporo Formation. The Nkporo Formation is the basal formation of the Campanian-Maastrichtian sediments, and is relatively undisturbed but intruded by igneous rocks. High geothermal gradients prevail in this area close to the intrusives. Simple synsedimentary growth faults and tectonic structures such as folds and slike-slip faults are present in the Afikpo subbasin [19], [23]; [24].

GEOLOGICAL FRAMEWORK OF THE AFIKPO BASIN

The Afikpo basin became the centre of major deposition following the Santonian folding in South-Eastern Nigeria. Compressional uplift of the lower Benue Trough succession (Albian to Coniacian) along NE-SW axis was accompanied by tectonic inversion and downwarping of the Afikpo platform. Estimates of total sediment thicknesses in the Afikpo Basin from gravity measurements range from 4-6km; out of which 3 km were deposited during the late Cretaceous sedimentation phase (Campanian to Maastrichtian). Three regional structures were formed during the Cenomanian, Santonian and terminal Maastrichtian Cretaceous tectonics [23]. The terminal Maastrichtian Cretaceous tectonics resulted to the evolution of the Cenozoic Niger Delta

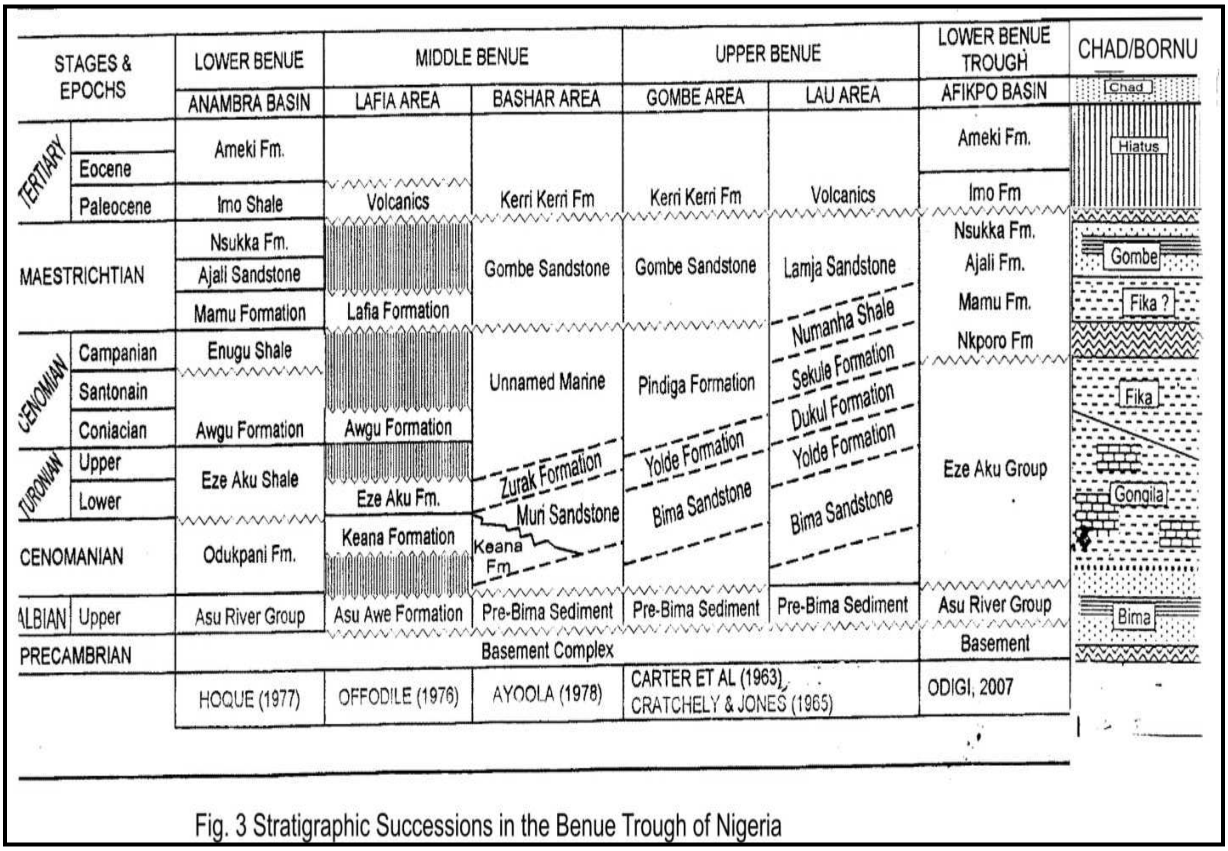

Fig. 4 Stratigraphic Successions in the Benue Trough

six tectonic elements characterize the region during this sedimentation phase. These include the Anambra and Abakaliki Anticlinorium to the west, the Afikpo basin, Mamfe Embayment to the east, and the Niger Delta and Oban Massif to the south (Fig.2). The two subbasins, Anambra and Afikpo experienced different subsidence rates resulting in greater sediments accumulation in the Southern area. This differential sedimentation pattern also reflects differences in the extents of the eustatic sea level rise which began in early Maastrichtian times and culminated in the Paleocene. Thus, eustacy and subsidence controlled the basin volume infill, the distribution of the sedimentary facies and the depositional characteristics of each formational unit within the succession. The Afikpo basin fill consists of three megasequences; the Albian-Cenomanian, Turonian-Conician and Campanian-Maastrichtian.

These basin fill have been used to reconstruct a sequence stratigraphic framework for the Afikpo Basin.

The Campanian- Maastrichtian successions include the Nkporo Formation, Mamu Formation, Ajali Formation and the Nsukka Formation restricting to the southeast and southwest of the basin. The Mamu Formation clearly demonstrates this in its depositional pattern with changes in relative sea level. In the Afikpo basin, the Nkporo Formation comprises of twelve (12) members including the basal Afikpo Sandstone and Nkporo shale. Exhumation of deeply buried Cretaceous strata occurred during widespread uplift of the Campanian-Maastrichtian rock masses during the late Maastrichtian.

DEPOSITIONAL FRAMEWORK

The post-Santonian Nkporo formation Campano-Maastrichtian sequence is subdivided into four lithofacies associations: alluvial fan complex, estuarine, tidal channel and fan delta front. These have been used to infer the depositional setting of the Nkporo Formation. In plan view the fan delta front, estuarine and tidal channel facies occur in the eastern while the alluvial fan complex deposits predominate in the eastern and western sectors (Fig. 5). The Nkporo Formation forms a belt that roughly parallels the trend of the Benue Trough. The Campano-

Maastrichtian facies are flanked in the north and south by older strata belonging to the pre-Santonian Abakaliki Trough. Stratigraphically, the alluvial fan represents coastal progradation over a shallow shelf.

The Nkporo shale was laid down in a marine environment during the Late Campanian transgression in the Afikpo Basin and It passes laterally into the Afikpo Sandstone [31]; [23]. The Nkporo shales become increasingly arenaceous west of Uwutu and eventually pass into sandstones such as the Afikpo Sandstone. The Nkporo shales were deposited mainly in the Afikpo Basin while the Enugu shales are predominant in the Anambra Basin [31], [35], [23].

MATERIALS AND METHODS

Fresh outcrop samples were collected for detailed petrographic analysis. Modal analysis of thin section was carried out using the point counting method. Petrographic analysis is used to identify the mineralogy, textural and porosity characteristics of the sandstones studied. Shale samples of interest were subjected to TOC and Rock-eval pyrolysis. Detail laboratory description of samples collected is contained in [24] and [26] respectively. Biostratigraphic analysis is used for the determination of the foraminiferal content and depositional environment interpretation.

RESULTS AND DISCUSSION

Paleoreservoir

The sedimentary evolution of the Afikpo domain can be outlined using outcrop data and correlations could be made along a section connecting several outcrops. The analysis of the sedimentological and stratigraphical characteristics of the deposits indicates three main periods in the evolution of the basin. A Pre-Senonian history characterised by a strong subsidence in the Abakaliki domain while the Afikpo domain remained a platform where mud was deposited in a shallow restricted marine environment.

During the Post-Santonian period which follows the major tectonic phase the Afikpo platform started to subside and an East to West prograding deltaic system developed while the Nkporo Formation was deposited in the major and minor synclinal axes of the basin. The Santonian to Campanian was characterized by sedimentation in the Afikpo Basin, suggesting that the Santonian was not just a folding phase in the Lower Benue Trough, but also of structural inversion. In the Afikpo basin, deltaic sedimentation was preponderant [1], [2] at this time with transition to marginal marine environment.

The deltaic system was stopped during the Upper Maastrichtian by the occurrence of a major marine transgression. During this period, the deltaic deposits were partly reworked in the Ajali Sandstones which do not show any important thickness variations across the Afikpo domain.

During the Lower Tertiary, a new deltaic system, the Niger Paleodelta, started to prograde along the basin axis. A last marine transgression event occurred with the deposition of the Eocene Imo Formation.

The Nkporo Formation is Campanian-Maastrichtian in age [23] formed the reservoir unit in all two exhumed traps. The Amate-Ozziza and Ebori Usumtong traps are located east and southeast of Afikpo, sandstone beds within the overlying Nkopro Formation have pores filled with bitumen (Fig.6). The detail sedimentology of the Nkporo Formation is discussed below. The Amate-Ozziza and Ebori Usumtong Sandstones are above the unconformity surface. The sandstones tend to be overlain by transgressive marine shales of the Nkporo Formation which act as both hydrocarbon source rock and seal.

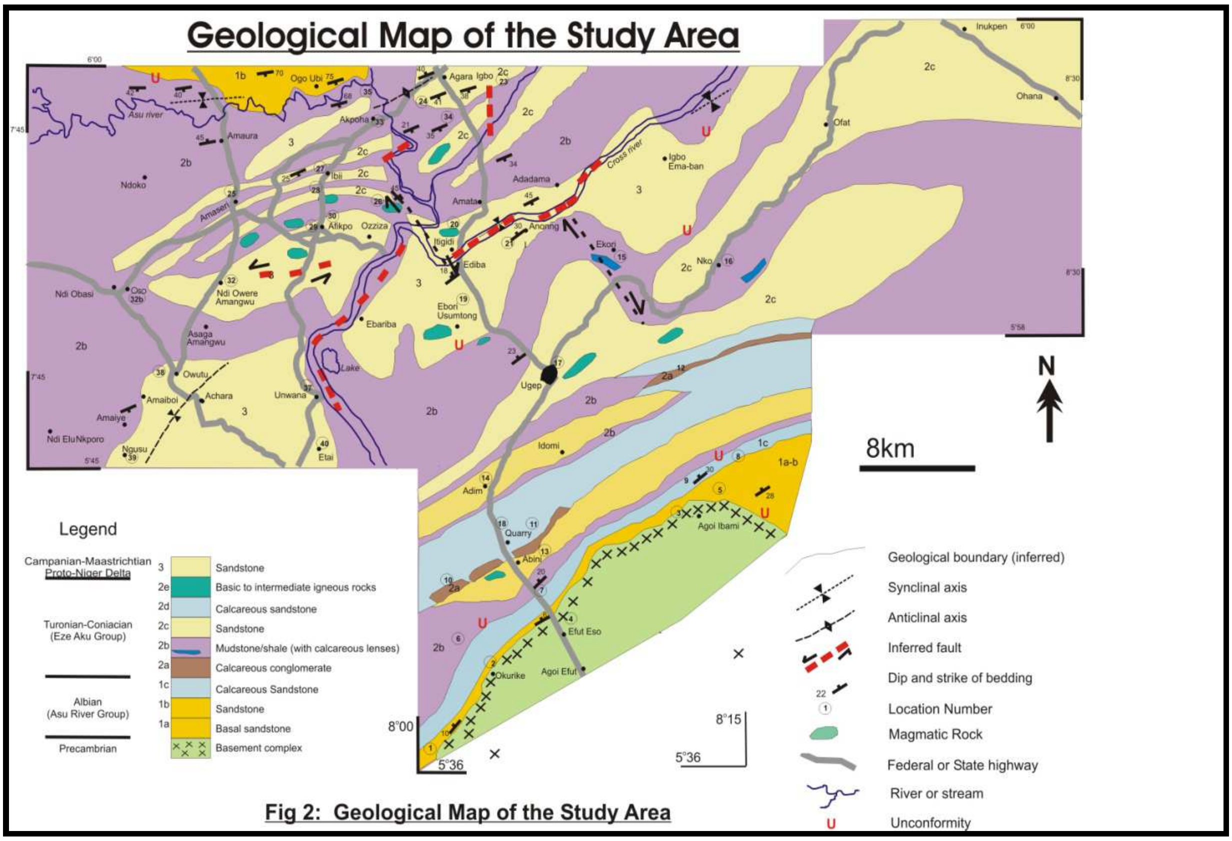

Fig. 5 Geological Map of the study area

Fig. 6 Field photograph of sandstone beds within the overlying Nkopro Formation have a pore fill of bitumen

Nkporo Formation

The Nkporo Formation rests on the post Santonian unconformity plane and consists basically of sandstones, shales and coal which accumulated during the Early Campanian. The sediments of the Nkporo Formation are composing of widespread sandstones, mudstones and shales exposed along the major synclinal structures [23]. The Nkporo Formation have been subdivided into two distinct lithological units, a lower unit (PM1) dominated by fluvial and fluviodeltaic strata and an upper unit (MP2) dominated by tidally influenced and estuarine sandstones.

The basal sandstone unit of the Nkporo Formation is the Afikpo and Ozziza Sandstones deposited in a non-marine depositional environment and it is an important regional sequence boundary in the Afikpo Basin. In the Afikpo and Ozziza areas, it rests on the deformed pre-Santonian rocks. MP1 is developed in Ndi Owerre Amangwu, Afikpo,

Ameta-Ozziza, Edibi, and Akpoha constitutes the continental deposits while the Itigidi-Adadama, is marine in origin [23]. These deposits are overlain by the transgressive shale during the late Campanian. It consists principally of medium to very coarse grained sandstones and pebbly sandstones with subordinate conglomerates, mudstones and impure coals. Wood and other plant fragments are locally abundant. Cross-bedding within this unit indicates southwest transport direction. The presence of marine macrofossils in the fluviodeltaic strata suggests that this unit was largely deposited in shallow shoreline environment. A thick mudstone-dominated unit in the Akpoha area is bioturbated and it is the base of the fluviodeltaic sequence which may indicate a deltaic influence in the region. The fluviodeltaic formation consists of stacked sequences of sandstone and mudstone arranged as three overall coarsening-upward cycles. Sandstone unit is at the tops of the cycles contain plant detritus, rootlets, and small-scale fining upward sequences, indicating fluvial deposition in a deltaic setting.

PM2 is composed of well sorted medium to coarse-grained sandstones with bimodal cross-bedding and bioturbated structures. The trace fossil *Diplocraterion babicahii* is locally abundant. The dominant sediment transport direction during the deposition of this unit continued to be toward the south. Individual cross-beds within foreset commonly have regularly thicknesses, suggesting the influence of tidal currents during deposition.

The large-scale coarsening-upward cycles represent the gradual transition from offshore/outer shelf to shallow-marine and fluvial environments and progradation of basin-margin facies. Marine sedimentary indicators are predominant within sandstone units at the top of the cycles. These represent marine shelf and shoreface environments.

The age of the Nkporo Formation in the Afikpo area is early to late Campanian, 76 Ma [23]. Ammonites have been collected from the base and middle of the formation. This constrains the age of the base of the formation as early Campanian.

SANDSTONE PETROLOGY

Petrological study of fifteen (15) sandstones from Campanian-Maastrichtian sequence that contain hydrocarbon show differences in mineralogy and texture. Petrographic study shows that the sandstones of the Campanian-Maastrichtian sequence are mainly quartz arenites with subordinate amount of arkoses and subarkoses (Fig.7).

Detail account of the petrology of the Campanian-Maastrichtian sandstones is presented in [24].

These sandstones were deposited in a fluvial-dominated deltaic environment. (Fig.8) is a thin-section photomicrograph of porous and permeable sandstone associated with hydrocarbon stains. Sandstones from this sequence contain about 1.0-6.0% K-feldspar, carbonate grains, quartz overgrowth and subordinate amount of calcite cement. Most of the sandstones contain K-feldspar. The primary pore system is relatively rich in kaolinite clay in these sandstones.

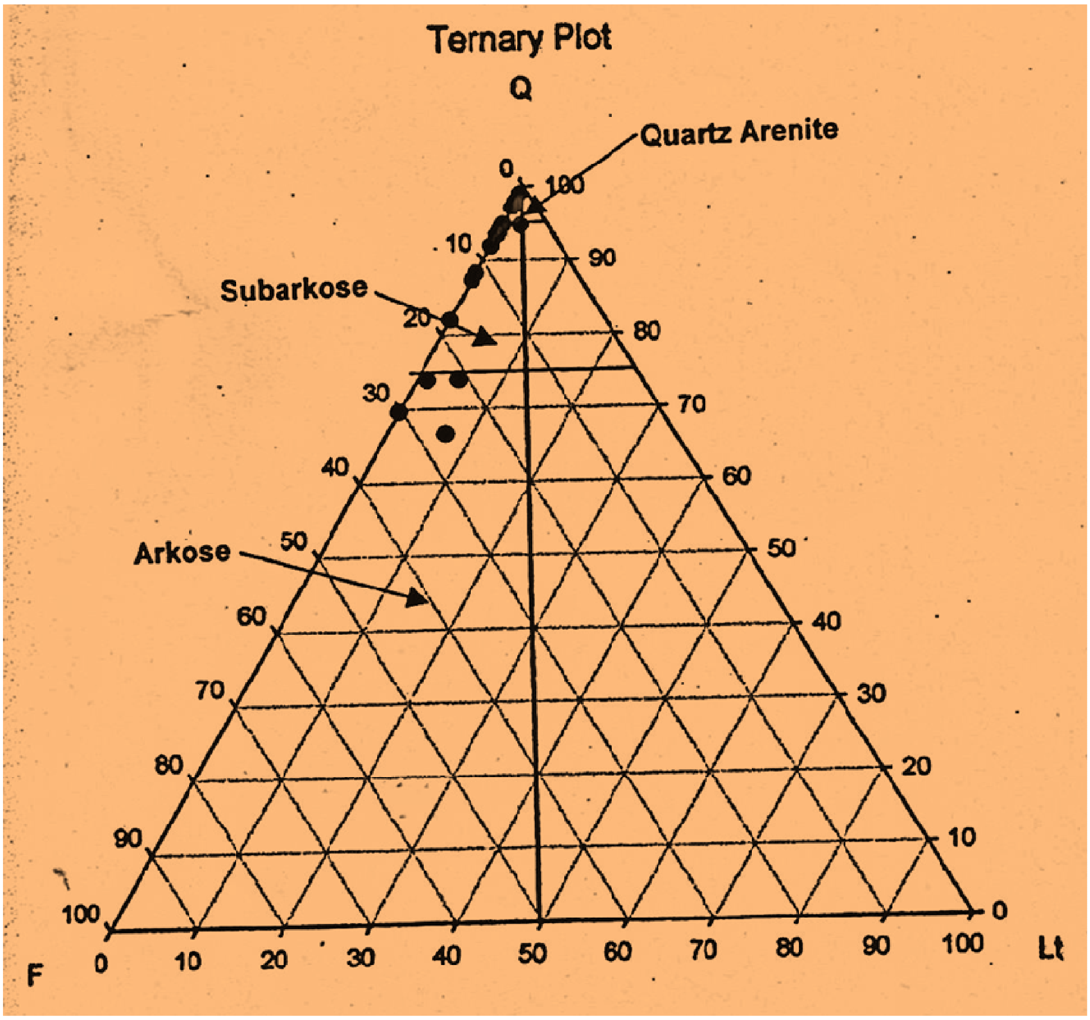

Fig. 7 Q-F-Lt Ternary diagram for sandstone from Campanian-Maastrichtian [24]

The sandstone-rich Nkopro Formation has variable compositions. The sandstones vary from arkose to quartzarenite. The sandstones are dominated by monocrystalline quartz showing strained extinction. K-feldspar forms up to 5 % percent of the rock. Plagioclase feldspar is absent in most of the sandstones (Fig. 8) and has undergone total alteration. Sandstones contain both biotite and muscovite in small quantities in carbonate-cemented samples. Lithic fragments of metamorphic and sedimentary origin form a minor component.

AUTHIGENIC MINERALOGY

K-feldspar cement occurs as overgrowths on K-feldspar grains in optical continuity with the detrital grains. Fractures in some K-feldspar grains are in filled by K-feldspar cement, indicating that this phase of cementation occurred after some burial and compaction. The overgrowths are clear and less susceptible to diagenetic alteration, remaining after dissolution of the host grain.

Carbonate cements occur in some of the samples. Ferroan calcite is present as poikilotopic cements. Calcite and dolomite cements also occur in some of the thin sections. Carbonate cements infill primary pore space and replace detrital grains.

Clay cements, occur as microcrystalline pore-filling aggregates, representing an important diagenetic phase. Although the precipitation of clays is recorded both early and late in the diagenetic history, the main phase of clay cementation postdates quartz cementation.

Solid bitumen is found occluding pore space in some of the samples from Ozziza and Ebori-Usumtong areas. In some samples the pore space between detrital quartz grains is filled by solid bitumen, and in other some samples, however, solid bitumen fills some of the quartz and clay cements.

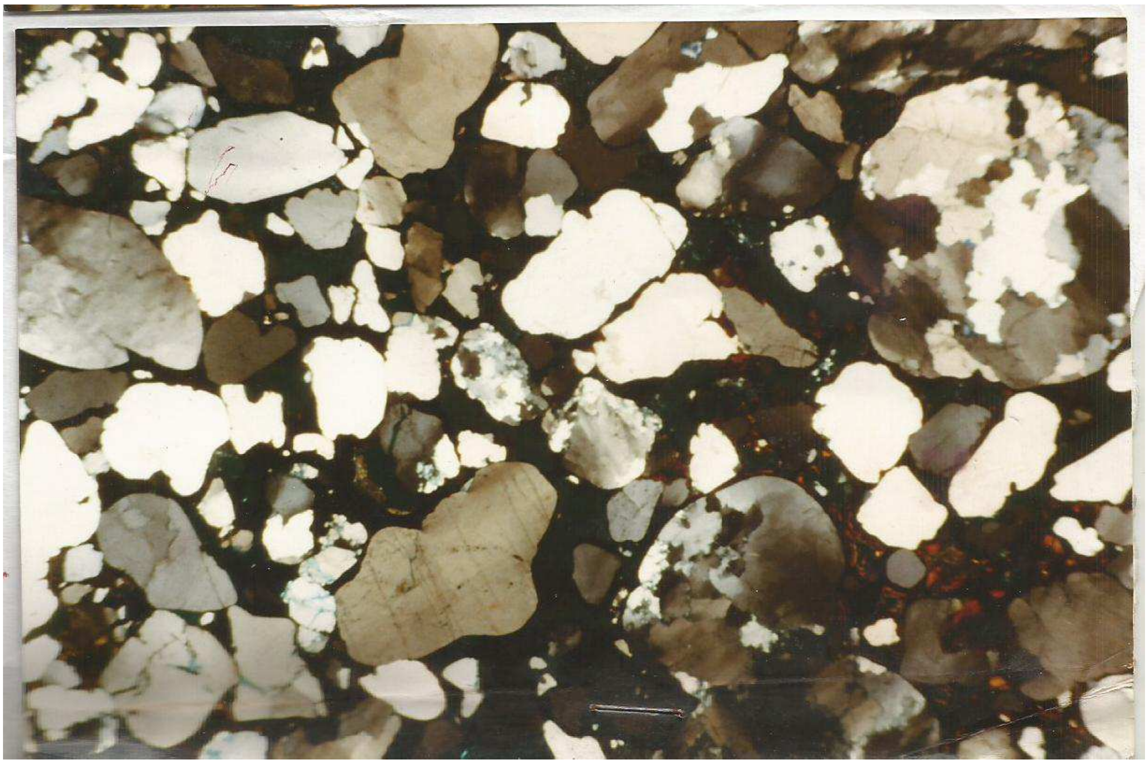

Fig.8. Thin-section photomicrograph of porous and permeable sandstone associated with hydrocarbon stains Detrital Mineralogy

Compaction
Evidence of compaction is provided by grain breakage, concave-convex contacts between quartz grains, bending of micas around grains, and grain fracturing.

Paragenesis
The sequence of events, based on thin-section study, is shown in Fig. 9.

Calcite: Although quite common, authigenic calcite is not pervasive cement in the sandstone. It typically occurs as a pore-fill and grain replacement in well-defined, sporadically developed zones with vertical dimensions of up to several meters. Calcite cement occurs in 2 % percent of the pore space. Stained thin sections revealed the presence of both non-ferroan and ferroan varieties.

Ankerite: Very minor amounts < 1 percent of the samples are present in sandstones throughout the interval studied. Abundances rarely exceed 4 percent and range up to a recorded maximum of 10 % percent.

Siderite: Siderite in trace proportions is also very common in the outcrop samples. Abundances greater than 2 % percent of the samples and ranging up to a recorded maximum of 23 % percent are rare and spatially limited. Siderite occurs as a partial replacement of feldspars, rock fragments and micas.

Feldspar*:* Feldspar cements are present in the arkoses and subarkosic sandstones of the sandstones. Like quartz, feldspar cement occurs as syntaxial overgrowths on detrital grains. Altered plagioclase grains leave ragged, etched grain as oversized secondary pores.

Kaolinite: Authigenic kaolinite is very common in the sandstones analyzed. Absolute abundances commonly exceed 8% of the samples and it has a range of about 15 % percent throughout the interval over the outcrop area. In the east of the outcrop area, kaolinite abundance decreases with values less than 2 % percent of the samples. It typically forms randomly orientated, delicate booklet and accordion-like, loosely to densely packed aggregates of euhedral pseudo-hexagonal plates, which line and infill scattered pores and replace labile feldspar grains.

Illite: The sandstones from *the* upper and lower part of the lithostratigraphic units show much higher percentages of illite. Illite cements form-interstratified species which reflect the composition of the porewaters of the sandstones. Illitization of early diagenetic kaolinite requires K, which is derived mainly from dissolution of K-feldspar. Other diagenetic clays locally present in trace amounts are chlorites.

Smectite/illite: Mixed-layer illite-smectite and discrete illite occur in the sandstone west of the study area. Illite-smectite forms meshworks of irregular crinkled flakes orientated perpendicular to grain surfaces. Authigenic illite-smectite and illite occurs as a product of labile grain alteration, typically forming in this situation a pore-filling cellular or honeycomb structure in which crystals are either sheet-like or more commonly exhibit no well-developed morphology. The identification and interpretation of the mixed-layer clays is important as it forms the only expanding component in the reservoir.

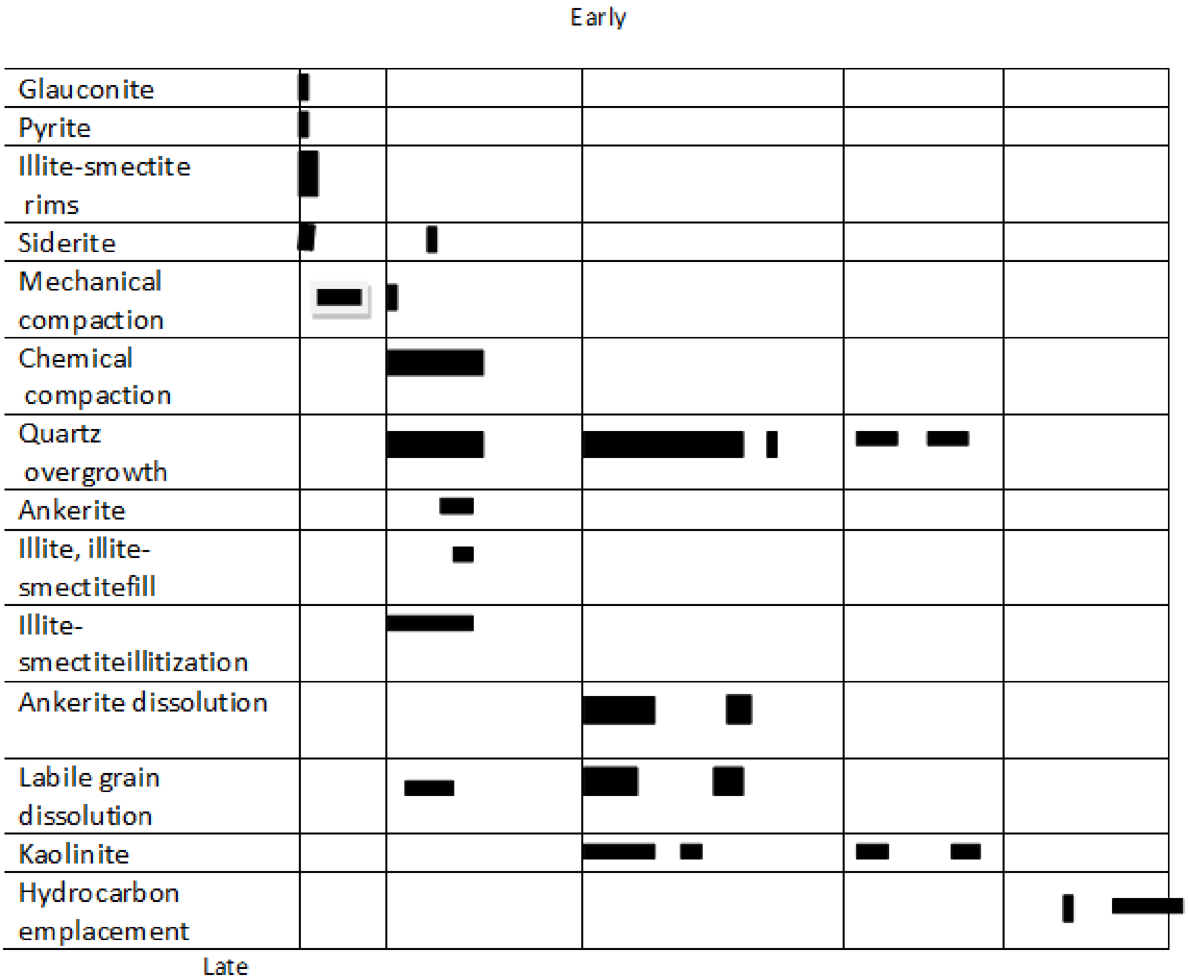

Fig. 9 Summary of diagenetic events in the Nkporo Sandstone

Smectite: Minor amounts of smectite are present in a few samples obtained from outcrops close to the Abakaliki anticlinorium where igneous rocks of basic to ultra-basic character occur. Bentonitic clays have also been recognized along the Abakaliki anticlinorium. Except for these occurrences, all smectites detected in sandstones are related to near-surface weathering processes.

Trap Geometries

Three types of trap geometries can be identified in the field: the wedge-out, channel and strike valley fills are found in the Amete-Ozziza and Ebori Usumtong areas of central Afikpo region. The structures both appear to be very similar. The Ozziza and Ebori- Usumtong Sandstones are 16 km long and 8 km wide rest on the Santonian regional unconformity. The unconformity traps relies on a combination of trapping mechanisms, which rely largely in part on a planar or gently folded unconformity. The unconformity traps observed in the study area are the 'buried hills'. It is the unconformity surface that has the trapping geometry. Beneath the unconformity surface, two zones can be distinguished. The lower zone is one of decrease porosity. The upper zone is one of increase porosity. In the upper zone iron and carbonate are removed in solution; micas, feldspars, and illitic clays are altered to kaolin and the total clay content is reduced by leaching. Detrital silica grains can be corroded in the more porous sand, though silica cementation may occur in the less permeable sand. The upper zone of leaching, and hence increased secondary porosity, varies from decimeters to hundreds of meters in thickness. The second lower zone is one where porosity is decreased by precipitation of the minerals percolating down from the zone above. Silica and iron oxide are the dominant cements. The overall effect of these substances is to decrease the porosity and permeability of this zone.
The terminal Cretaceous tectonics created overlaps, folding and faulting conditions that may have formed the traps capable of holding oil and gas pools. The sandstone reservoir rests on the shale and the unconformable Campanian mudstones and forms the only proven top sealing element. The lower truncation edge of the reservoir sandstones occurs to the east of the major regional fault, which does not form a top-sealing element. The Nkporo shale forms the bottom seal.

The oil and gas pools are associated with the buried pre-Santonian folded eroded sediments. The reservoir sandstones are interconnected zones of porosity extending over 10kms that formed traps. The reservoir is resting on the unconformity, while the sediments overlying the reservoir provide the top seal. Thin section point count and direct measurement indicate that the porosity of Campanian-Maastrichtian sandstone in the study area is around 20 percent, which the value used here. There are lower values which may be due to late quartz and clay cementation. A value of porosity, prior to the formation of solid bitumen in samples using point counting, exhibits a wide variation of porosity of up to 27 percent.

A Likely Source Rocks?

The organic geochemistry of the Nkporo shale potential source rocks cropping out in the Afikpo Basin including the Campanian-Maastrichtian strata is presented [26]. The following is a brief summary of potential source rocks of the Campanian-Maastrichtian strata. The post- Santonian Campanian-Maastrichtian strata are organic-rich (TOC <1). The minimum amount of organic carbon needed to generate a commercial amount of oil is set as 0.5%. The organic geochemistry of the shales and mudstones of the Late Campanian-Maastrichtian when compared with the underlying Eze-Aku Group strata suggest that the younger strata has a better potential hydrocarbon source rocks [26]. The TOC, HI. OI, S_2 and T_{max} values further suggest the oil and gas that was accumulated along the unconformity is from the younger Cretaceous strata particularly in the Nkporo Formation. Maturity parameters generally indicate immature to early-mature mudstones outcropping at the surface in the Afikpo area, although locally they are post mature owing to their proximity to dolerite sills and gabbroic rocks. The organic geochemistry TOC, HI. OI, S_2 and T_{max} values of the Akata shale is similar to the Nkporo shale [23]. The post Santonian sediments have a maturation level that falls within the oil window and have moderate to high content of organic richness.

Timing of Events

The timing of trap formation, secondary hydrocarbon migration, and trap destruction are constrained by field relations. The Amete-Ozziza and Ebori Usumtong traps were completed in the Late Campanian- Maastrchitian with the deposition of mudstone and shale above the Early Campanian reservoirs. The timing of hydrocarbon generation and migration is poorly constrained. The removal of post Santonian strata in the Afikpo area as a consequence of Santonian uplift precludes the construction of a detrital burial history. Primary, secondary and Tertiary migration seepages are the three processes that occurred in the Afikpo basin.

Two period of oil movement may occur during the Campanian-Maastrichtian; the primary and secondary migration. The first movement came after the fold had been formed and that faulting occurred later, dropping the free-gas cap down to a lower position than the oil in the fault block. There was a free intercommunication across the faults which permit much of the oil to occur as seepages.

The proximity of the traps to magmatic rocks suggests that secondary migration pre-dates the Maastrichtian magmatism. At the southern part of Afikpo, faults are crosscut by intrusions; suggest that secondary migration into the traps occurred prior to intrusion of a dolerite sill at the end of Maastrichtian. These sills preferentially intrude the mudstone and therefore tend to concentrate just above the base of Maastrichtian unconformity, which forms an important regional top sealing element. Heat flow from the dolerite sill intruded into mudstone would have elevated the country rock temperature; cracking of oil would proceed rapidly. Thermal alteration probably played a major role in the formation of the solid bitumen.

CONCLUSION

In this article, the authors present preliminary descriptions of a number of hydrocarbon traps in the Afikpo area of southeastern Nigeria; these traps became thermally degraded and exhumed during late Maastrichtian magmatic and regional uplift. These traps are similar to that of oil fields in the North Sea [30]. The author believes that Afikpo structures will provide useful analogs in detail studies of Niger Delta and Gulf of Guinea oil provinces-type reservoirs in West Africa. Detail outcrop studies will give information on sandstone architecture, spatial variation in diagenesis, fault sealing and sealing properties, and migration pathways. In addition, these exhumed traps may indicate a future play on the largely unexplored inland basin of Nigeria. Exhumation of deeply buried Cretaceous strata occurred during widespread uplift of the Campanian-Maastrichtian rock masses during the late Maastrichtian.

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