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Palynofacies Depositional Environment, Source Rock Potential and Structural Traps on Outcropping Lithostratigraphic Units of the Nsukka Formation in Ikpankwu Area

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Abstract

Detailed high-resolution palynofacies depositional environment, source rock potential and structural hydrocarbon entrapment mechanisms of the outcrop lithostratigraphic sections of the Nsukka Formation revealed the structural trap style, hydrocarbon production potential framework and migration pathway for reserves of the formation for hydrocarbon generation for the first time. Structured and unstructured phytoclasts, amorphous organic matter, opaque particles, marine and terrestrial microflora designate the visual organic matter components of the formation. The cardinal palynofacies constituents shows thermally mature Type II/III kerogen with thermal alteration index (TAI) 2+ to 3+ and vitrinite reflectance index (%Ro) 0.5% to 1.3%; generated in sediments highly rated as a potential source for liquid and gas hydrocarbons. Terrestrial phytoclasts are products of Kerogen Type III (gas prone) while the pronounced oil surface seep prone shales of the Nsukka Formation are the essential resultant products of Kerogen Type II (oil prone) palynofacies elements. Palynofacies palaeoenvironment of deposition array indicate shallow marine settings with deep marine influenced macro environments, embedded as products of lower and upper deltaic plains. Petroleum systems key structural trap element consists hanging wall closures, footwall closures along with in filled and open joints structures within faulted and unfaulted sandstone units. Primary and secondary migration petroleum pathway is sandstones pores and fractures which are the key principal mechanism in the formation of petroleum accumulations in reservoir beds. The key structural trap complexity, source rock potential and paleoenvironment investigation projects oil drilling pathway and exploration campaign in the Formation.

Keywords: *Source rock; Structural trap; Palynofaices; Depositional environment; Nsukka Formation.*

1. Introduction

The sedimentary cycles of the Anambra Basin depict a systematic attribute of an inland sedimentary basin based on the depositional environment, lithofacies and palaeontology principles of the Late Maastrichtian to Danian aged sediments. The proven hydrocarbon reserves of the basin ranked in hydrocarbon richness next to Niger Delta Basin in terms of optimized quality and quantity of oil and gas exploration and exploitation in the basins. Anambra Basin typified an inland intracratonic basin architecture sited adjacent to Niger Delta terrane of Nigeria. The studied sections were located at the Ikpankwu and Okigwe vicinity within Nsukka Formation of the Anambra Basin, bounded by latitudes 5°00’ N and 6°00’ N and longitudes 7°15’ E and 7°30’ E (Fig. 1).

Numerous palynofacies classification schemes of palynomaceral, palynofacies, palynodebris and kerogen [1-5] were proposed for a definite palynofacies identification and interpretation in identifying potential source rocks in petroleum exploration. However, the palynofacies scheme model of Tyson [4-5] was utilized to delineate the hydrocarbon prospectivity of the formation.

The occurrence of numerous Palmae flora of Longapertites group, *Proxapertites operculatus*, Spinizonocolpites group, *Constructipollenites ineffectus* and triporates (*Echitriporites trianguliformis*-Proteacean) angiosperms along with regular to common occurrence of Early to Late Maastrichtian *Proteacidites dehaani*, *Buttinia andreevi* and *Foveotriletes margaritae* was recorded as age diagnostic floras of Late Maastrichtian age for the formation [6-11] while [7-8,11] denoted the Danian stratigraphic age of the formation. *Echitriporites trianguliformis*, *Monocolpites marginatus*, *Syncolporites subtilis*, *Constructipollenites ineffectus* and *Periretisyncolpites giganteus* were regarded as stratigraphic index taxa for the middle to Late Maastrichtian Patti Formation [12

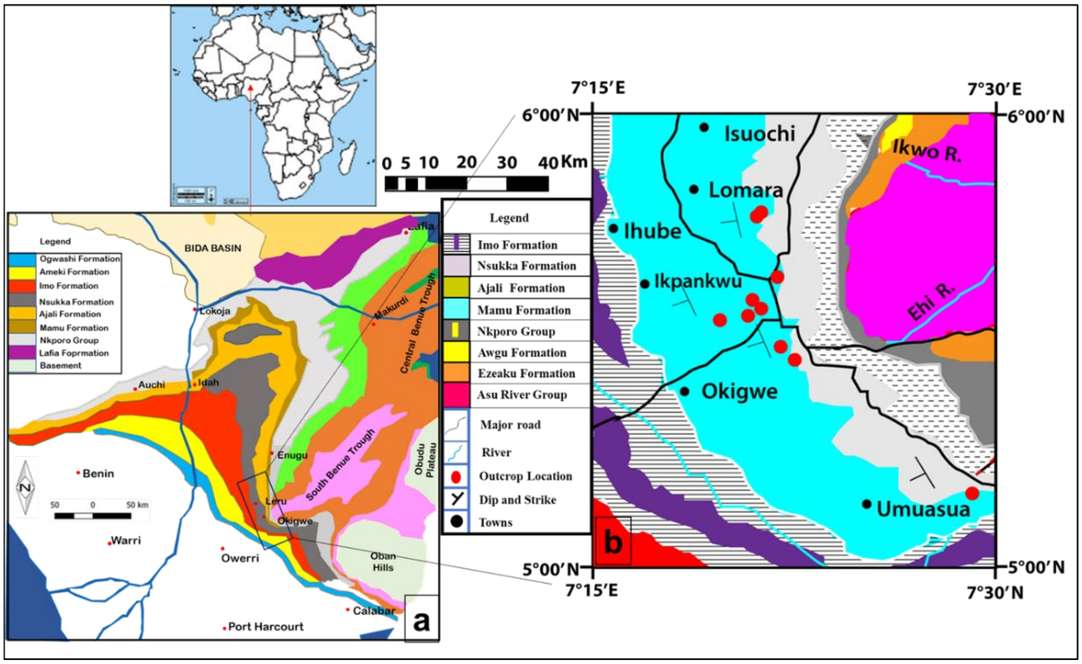


Fig. 1. (a) The regional geology of southern Nigeria showing the Anambra Basin (modified after Nigerian Geological Survey Agency, 2009). (b) The geological map of the study area showing outcrop locations, dip and strike of the studied sections of the Nsukka Formation

The oil and gas prospectivity studies of the Niger Delta Basin revealed the structural trap style anticlinal dip closures, footwall and hanging wall closures, faulted rollover anticlines, collapsed-crest structures, horst block and sub-detachment structure elements of the downdip formations of the basin [13-17]. However, the key structural traps of the hanging wall closure, footwall closures, horst and collapsed-crest structure from the seismic and outcropping units of the Anambra Basin were reported by [18-19].

The geology analysis of the evolution of the Anambra Basin sectionalized the sediments of the basin into the northern and western parts heralded by post Santonian sediments. This was initiated by the separation of the African and South American Plates during the Middle Mesozoic [20-21]. The structural, stratigraphic and combination traps architecture of the Anambra Basin [18] denoted similar Santonian tectonic events of [22] that epitomized the deformation, folding, faulting and uplifting of the pre-Santonian sediments in the Onitsha area due to the depression caused by the tectonic uplift of the Benue Trough terrane. The Nkporo Formation of Campanian-Early Maastrichtian is the oldest stratigraphic sequence of the Anambra Basin which is successively overlain by the Middle Maastrichtian aged Mamu Formation composed of paralic sequences of mudstone and coal facies. The Ajali Formation of Middle to Late Maastrichtian [23] was overlain by the paralic coal sequences of the Nsukka Formation stratigraphic unit with variable ages of Maastrichtian to Danian [8-9,23] and Late to Latest Maastrichtian [24]. The Nsukka Formation facies is relatively younger in the western trends while the lower coaly shale facies harbours the type locality of [7-8] but the top sandy facies is situated in the south.

The Nsukka Formation lithofacies are deposited in the southwestern domain of the Anambra Basin visible on outcrops at Ubahu-Olamaboro (middle section of the coal bearing part) Udi, Oji and Awgu area as well as in the northern fringes of Okigwe and Umulolo area [8].

The first-hand detailed analysis of the palynofacies depositional environment and hydrocarbon potential portrays the explicit hydrodynamic signatures of the palynofacies groups to analyse the stratigraphic sequences and lateral facies change events of the shallow marine realm and petroleum migration pathway mechanics. Source rock potential elements of the study highlighted the palynofacies characterization, organic thermal maturation and source rock appraisal for conventional hydrocarbon prospectivity arrays. The significant structural entrapment mechanisms of the formation portray the link between the source rock and structural trap elements of the petroleum system as well as the migrating pathway for hydrocarbon prospectivity initiative along with oil and gas drilling campaigns within the Anambra Basin.

2. Description of the stratigraphic sections

The exposed quarry section in Ikpankwu area of Okigwe, off Enugu-Port Harcourt road, 27 m thick consist of grey siltstone, mud rocks, shale and sandstone lithologic facies. The basal unit consists of dark grey carbonaceous shale with siltstone lamination that gradually thickens to 5 to 10 cm thick bands. This shale unit is intermittently overlain by plane planar laminated sandstone and relatively medium to fine grained consolidated sandstone along with consolidated bioturbated sandstone some in places. The lateral facies change dynamics of the formations is prevalent in the heterolithic, parallel laminated silt and shale with erosional base which contains rip up clasts. The siltstone beds of the study is dark grey colored in some places with well-preserved biogenic structures in the consolidated white-slightly pink siltstone bed at the Ikpankwu section. Fine-grained sandstone and shale facies are intermittently weathered in some places.

3. Materials and methods

Shale, dark mudstone and siltstone were selected for kerogen analysis. This entailed palynofacies slide preparation and microscopic identification of the various particulate organic matter were executed at the palynology laboratory at the department of Geology, University of Nigerian Nsukka. The samples were analysed in the laboratory with hydrofluoric (HF) acid for removal of silicates and HCl for removal of carbonates. HCl treatment was not utilized since the sediments were not calcareous. The samples were cleaned for removal of contaminants before 10 g were measured and crushed and immersed to digest in hydrofluoric acid for forty-eight hours. The digested samples were sieve-washed, dispersed in polyvinyl alcohol before the prepared slides were logged with biological microscope. The Stratabugs software of StrataData Ltd. was used for statistical data analysis. Archetypal outcrops with good structural configuration in the studies sections were studied. Detailed structural features interpretation was achieved by proper measurements of the trends of fault system with brunton compass and a Global Positioning System (GPS). The structural elements were utilized for trap classifications while its effect in hydrocarbon exploration were discussed.

4. Results

4.1. Palynofacies event

Palynofacies investigation presents a direct channel for obtaining visual properties and relative abundance frequency of the particulate organic matter types [5]. The land derived structured and unstructured plant debris phytoclast group is the most dominant particulate organic matter type with relative abundances of 90% while the mean amorphous organic matter and other marine biota are 10%. Figure 2 presents the palynofacies percentage abundance of the Nsukka Formations but variability abundance of palynofacies assemblages is reported as a product of environment and climate fluctuations during sediment deposition [25]. The particulate organic matter groups are dominated by structured land derived organic matter of partly dark brown to brown structured phytoclasts (20%), pollen and spores (7.5%), and opaque particles (21%). The occurrence of amorphous organic matter (8%) and marine species (2%) were also visualized (Figs. 3-4).

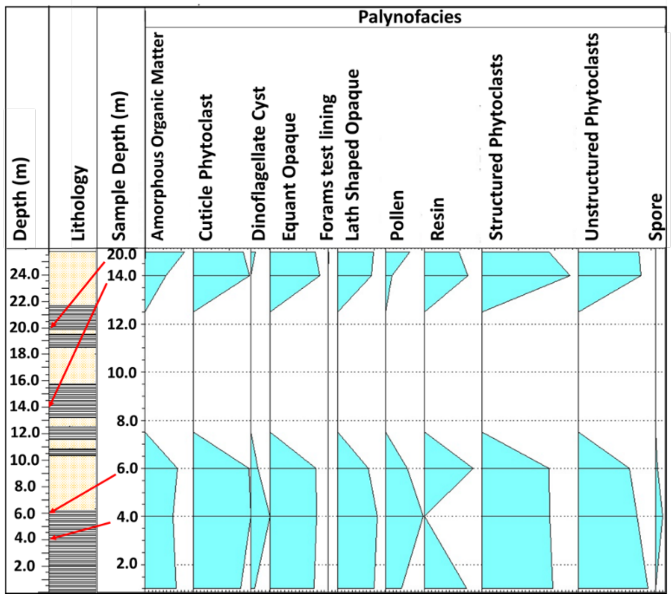


Fig. 2. Abundance frequency distribution of palynofacies elements from the representative section of the Nsukka Formation at Ikpankwu Quarry

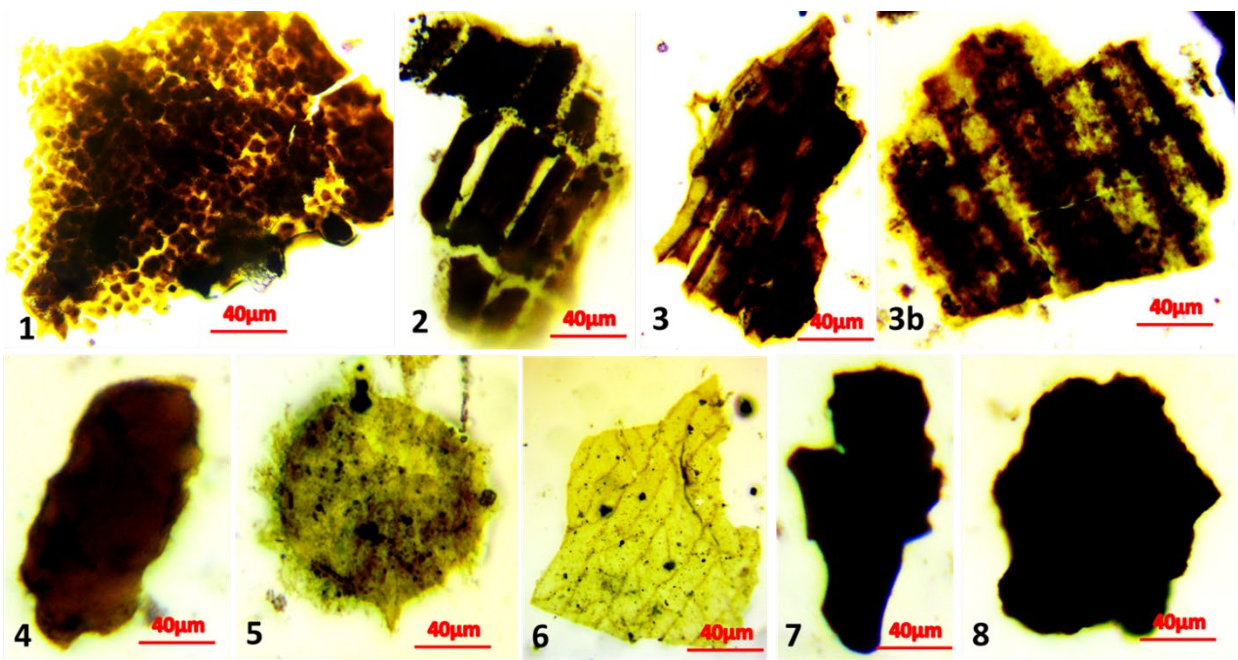
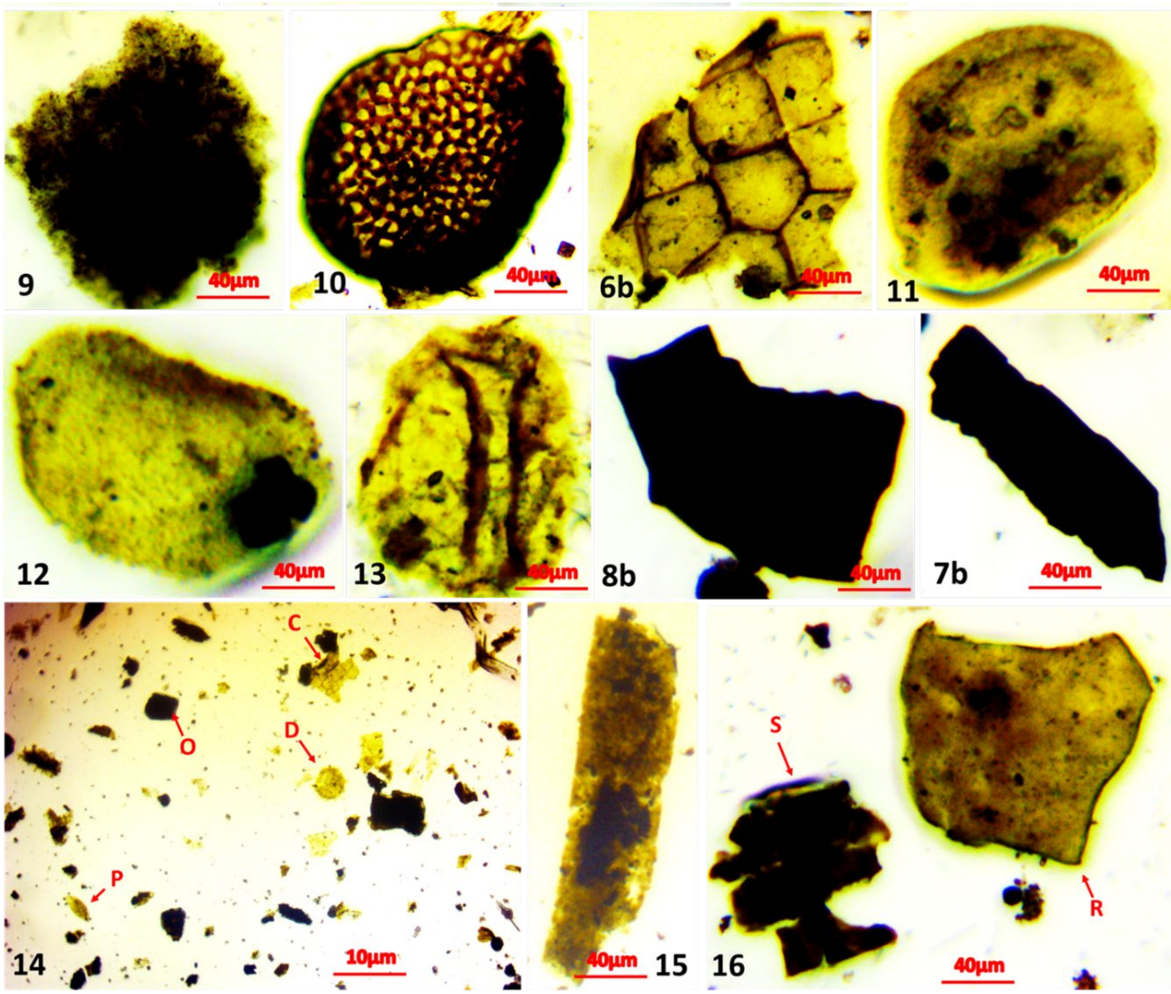


Fig. 3. Photomicrographs of palynofacies elements in the Nsukka Formation; D = Dinoflagellate cyst; O = opaque debris; S = structured phytoclast, C = cuticle; P = pollen, R = Resin

1. Degraded black brown phytoclast; 2. Partly degraded black brown phytoclast; 3. Well-structured phytoclasts; 4. Resin particles; 5. Dinoflagellate cyst; 6. Cuticle; 7. Lath shaped opaque particle; 8. Equant opaque debris; 9. Amorphous organic matter; 10. Matanomadhiasulcites (Liliacidites) maximus (Sexana) Kar, 1985; 11. Longapertites marginatus Van Hoeken-Klinkenberg, 1964; 12. Palynomorph; 13. Pollen; 14. Particulate organic matter components of the Nsukka Formation; 15. Resin; 16. Palynofacies elements of the Nsukka Formation.



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5. Discussion

5.1. Palynofacies depositional environment

The paleoenvironment reconstruction of the study posits abundance of well-preserved land derived palynofacies microflora (90%) over marine events (10%), indicative of shallow marine depositional environment with outer neritic influences. The depositional cycle of the Nsukka Formation consists of a predominant terrestrial phytoclasts and palynomorphs of coal and mudrock facies forming environment due to the previously reported northerly coaly and southerly shale paleoenvironment attributes of the formation. Oscillating depositional environment events was reported between the lower and upper deltaic plains fluctuating from tidal flat, lagoon, tidal bar, raised bog and reed swamp in the north to nearshore open marine settings southerly [6-8,23]. The integrated palynofacies and lithofacies characters in paleoenvironment analysis of Zubair Formation Iraq denoted similar palynofacies hydrodynamics distributions on swamp and marsh depositional settings oscillating from delta top, delta front, prodelta and open marine conditions [26-27].

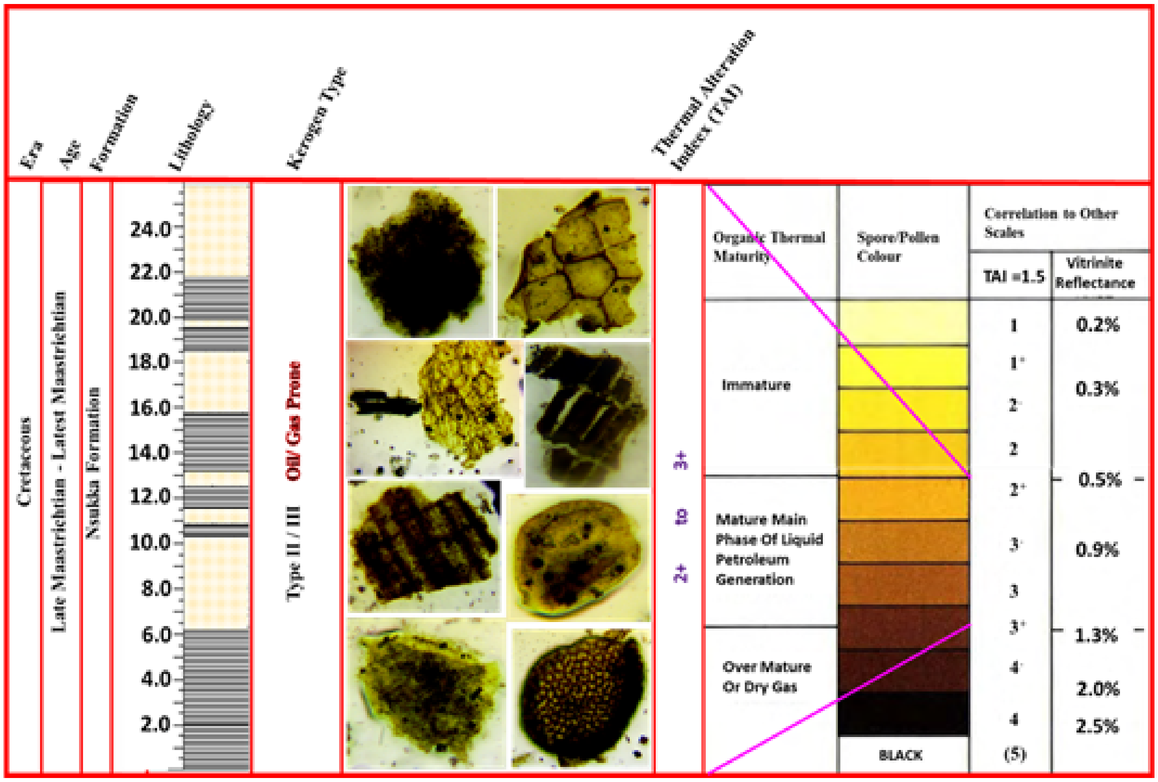

Fig. 4. Palynofacies, kerogen types and organic thermal maturation of the Nsukka Formation section, Ikpankwu

The lithofacies units of the Nsukka Formation exhibits wide dissimilarity and rapid lithological change characteristic (Fig. 5) of sediments deposited in fluvial, estuarine and deltaic environments due to the tides, current and wave effect of the marine realm. The lithofacies prototypes are shale, mudstone, siltstone, heteroliths, parallel laminated siltstone and shale with cross bedded sandstone at Okigwe and Ikpankwu vicinity. The palynofacies quantitative attributes of mudrock lithologies illustrated that the structured terrestrial particles, degraded plant remains are relatively of high frequency in claystone (shale) beds [25]. This correspond to the quality and quantity of the palynofacies constituent of the shale prone lithologies of the Ikpankwu section epitomized (Fig. 3) in the high abundance of medium to large sized structured phytoclasts and pollen and spores of land origin over (Fig. 2) marine palynomorph and AOM of the study.

The plane parallel lamination, heteroliths of silt and shale and erosional base with rip up clasts indicated deposition under high energy conditions as well as episodic events of flooding within the upper deltaic plain. Flaser and lenticular bedding structures in the Nsukka Formation are products of paucity of sand and clay respectively in the flood plain or fluctuations in the energy of the transportation medium [23]. The mudrock dominated heterolith units indicates fluctuating current depositional systems [28] but the non-occurrence of dinocyst marine microflora in some of the mudrock facies negates tidal influences. The occurrence of dinocyst in consensus with lithofacies units show that the palynofacies group of the study was formed in the relatively distal anoxic to suboxic environment in open marine lagoon or brackish settings. The presence of dinoflagellates substantiates the high frequency of medium to small equidimensional opaque phytoclasts in the study (Fig. 3), which shows that few intervals in the formation were deposited in distal setting under suboxic to oxic condition unsuitable for the preservation of AOM (8%). The frequency of AOM could have been outshined by the high occurrence of terrestrial phytoclasts (90%).

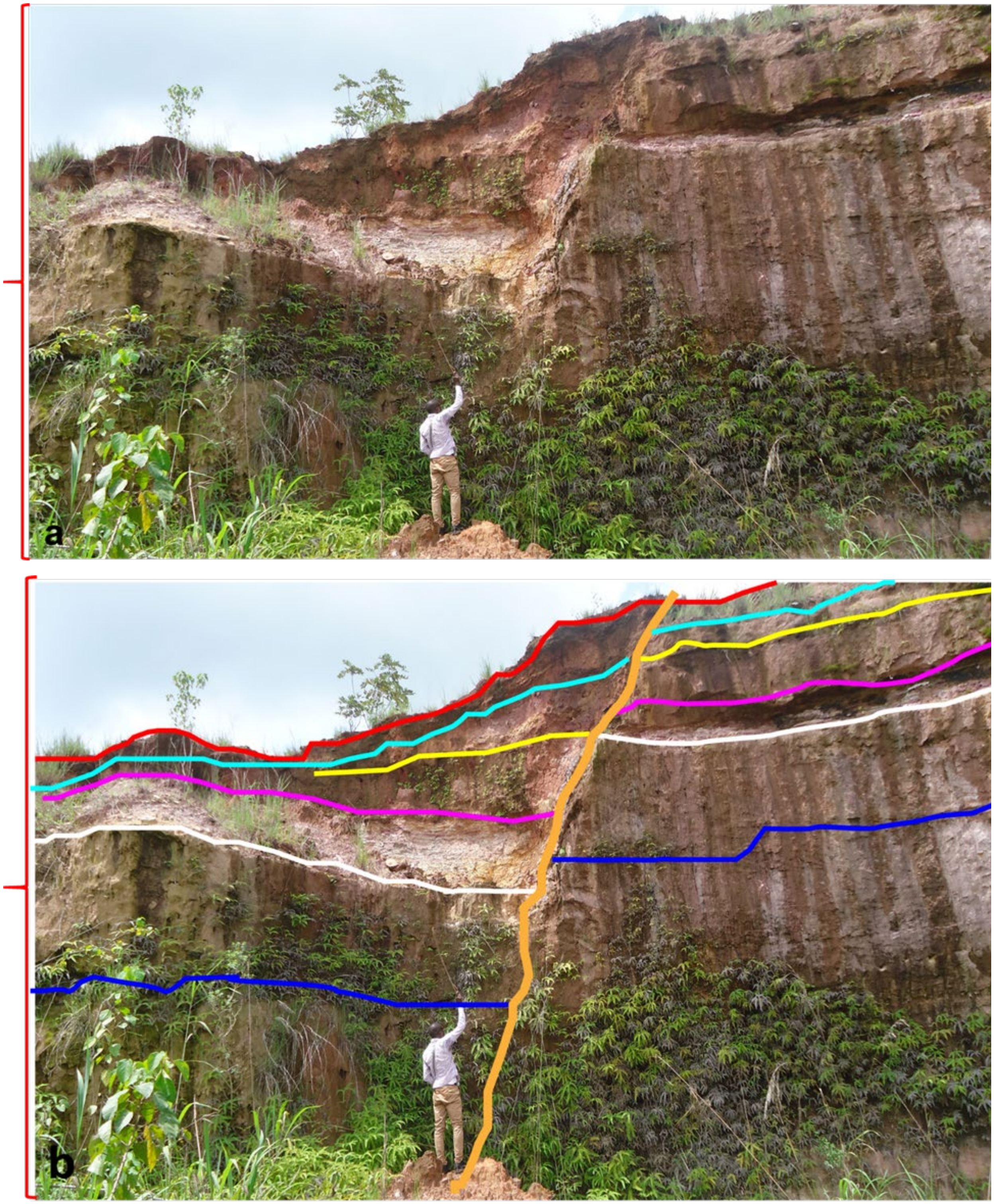

Fig. 5.a Normal Fault on Outcrop section of the Nsukka Formation of Anambra Basin exposed at Ikpankwo quarry. 5.b Normal fault system of the Nsukka Formation of Anambra Basin showing the hanging and footwall components at Ikpankwo quarry. (Scale: Geologist = 1.8 m) illustrates sediment package on the hanging wall (dislocated) and foot wall of the fault block.

High occurrence of opaque phytoclast illustrates proximal shelf settings which is a product of intense oxidation, recycling, and forest fires of land derived plants [29-30]. Pteridophyte fern spores (0.5%) which are mainly produced by hygrophilous plants of the freshwater algae signify local or seasonal humid state during deposition [31]. The combined lithofacies and palynofacies appraisal of the Nsukka Formation strata provides a better understanding of how integrated lithofacies and particulate organic matter data provide even clues about paleoenvironments and changes in sea level as the delta evolved and became a major hydrocarbon province. The coal lithologic unit of the formation was noted as a deposit of TST in lower deltaic plain [6,8] along with other LST, TST and HST events of the formation [6,16].

5.2. Source rock potential

The hydrocarbon exploration and exploitation significance of the Nsukka Formation induced the high resolution palynofacies analysis model of Anambra Basin for a prospective quality liquid and gas hydrocarbons which can be connected to the development of oil and gas probe campaigns in the region. The palynofacies types and thermal alteration of particulate organic matter prospects of the Nsukka Formation is shown in Figure 4.

The organic matter components of the study are made up of quality and quantity of dark brown AOM (8%) and other marine biotas, large well-preserved brown to dark brown structured phytoclasts (20%), cuticle (14%), lath-shaped and equant opaque debris (21%), and degraded wood remains (Fig. 2). A spike of pollen and spores with well-preserved large palynofacies elements and opaque debris imply deposition close to parent vegetation due to the quality and size ranges of the debris. However, the palynofacies assemblages of the Nsukka Formation has an uneven equilibrium of marine biota with AOM and terrestrial phytoclasts, pollen and spores (Fig. 2). This was pictured in the high abundance of structured phytoclasts and pollen and spores of land origin over (Fig. 2) marine palynomorph and AOM (10%) which suggests close proximity to organic vegetation source of terrestrial origin than marine origin.

The palynofacies elements of Nsukka Formation indicates the organic matter constituents of Kerogen Type II / III which is Gas / Oil Prone (Fig. 4). Palynofacies of the study has Kerogen Type III (gas prone) linked with overwhelming abundant terrestrial phytoclasts, palynomorphs and little amorphous organic matter of terrestrial and marine origin. The marine biota of the AOM and dinoflagellate species are the determining factor for the Kerogen Type II which is Oil Prone palynofacies group.

The spore/pollen colouration index illustrates the diagenesis and thermal alteration of sediments which posit the blue print of chemical change and lithifications of sedimentary rocks. Palynofacies biodegradation and thermal alteration of particulate organic matter led in particular to abundant brown to dark brown terrestrial phytoclasts in the study (Fig. 3). The spore/pollen colouration index ranges from light brown to dark brown which signify mature and oil generation to production of wet gas and transition to dry gas stage. This thermal maturation colour index parallels thermal alteration index (TAI) 2+ to 3+ and vitrinite reflectance index (%Ro) 0.5% to 1.3% of [32]. The vitrinite reflectance index (%Ro) range scheme of [34] falls within 50 – 150 catagenic (Ro: 0.5 – 2.0) which is comparable to the proposal of [32] and the study. Similar palynofacies elements was reported in the subcroping Niger Delta Basin where the highest TOC and HI standard was depicted in non-marine swamp, marsh and floodplain reflecting proximity to organic source [32]. Physical and chemical alteration of sedimentary rock prior and after deposition is relatively obvious on palynomorphs, structured and unstructured phytoclasts and resin in the study (Fig. 3). The Niger Delta Basin palynofacies and kerogen report of [25,32,36] and the Nsukka Formation palynofacies results of the study illustrate a visible incontrovertible similarity between the Cenozoic outcropping Nanka, Ogwashi formations and the subcroping Agbada formation as well as the Upper Cretaceous to Early Paleogene Nsukka Formation. These similarity reports were hinged on the palynofacies types, quality and quantity of the particulate organic matter inherent in the Niger Delta and Anambra basins’ formations with even paleoenvironment style.

5.3. Structural Trap

The lithostratigraphic section of the Nsukka Formation at a quarry section in Ikpankwu vicinity of Okigwe, few kilometres off Enugu-Port Harcourt road portrays some key structural styles (Figs. 5-7) with attribute of a good hydrocarbon trap system. The structural styles are Footwall and Hanging wall.

Footwall: The footwall of a normal fault is an upthrown or un-displaced fault block in a structurally disfigured setting consistent with listric fault structural system. The upthrown fault block aspect of the normal fault (Fig. 6) and listric fault dimensions of the growth fault punctuates rock thickening on the downthrown fault block as predominant structural style in Nigerian sedimentary basins. These fault block systems were envisaged in the seismic and outcrop delineated structural traps of the Niger Delta Basin and Anambra Basin [13,18,36-38]. According to these works the fault blocks are juxtaposed against the downthrown walls unit which exhibits a sealing fault block characteristic, so providing an entrapment for fluid and liquid hydrocarbon accumulation which geologically is fruitful in the presence of reservoir rocks flanked by a non-reservoir rock package.

Hanging wall: The hanging wall of the faulted block at Ikpankwu area illustrates normal fault system where the downthrown fault block of structurally distorted setting relates to normal fault (Fig. 5) and listric fault (growth fault). These fault blocks are related to rollover anticlines or tilting of overlying fault block and are put next to the footwalls. Rollover structure, geometry and liquid hydrocarbon bearing attributes of the structures were reported in the subsurface Niger Delta [39]. However, Juxtaposed strata within the normal fault and listric fault hanging wall block are good entrapment for hydrocarbon and other fluids. This is confirmable when potential sandstone reservoir units are between non-reservoir shale rock sequences (Fig. 6).

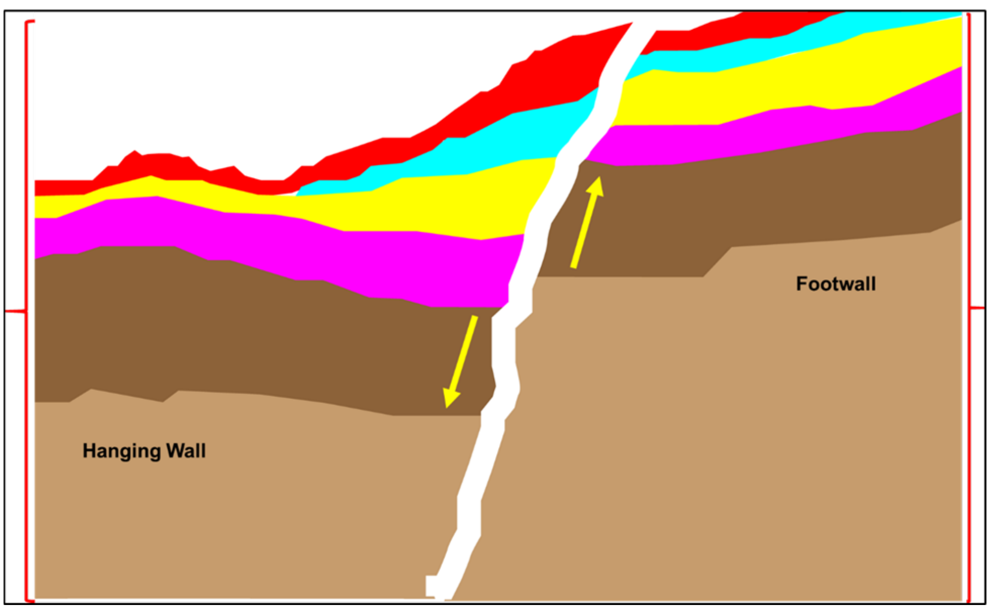

Fig. 6. Normal Fault pictograph demonstrating the trapping elements at Ikpankwu outcrop section of the Nsukka Formation, off Enugu–Port Harcourt road, SE Nigeria. Indicates sediment package on the hanging wall (dislocated) and foot wall of the fault block

5.4. Fault Systems of Nsukka Formation and petroleum migration pathway

The concept of basin modelling and petroleum exploration instigated the petroleum geology analysis to understand the petroleum migration physical mechanics between a source rock and first entrapment (secondary migration) of sedimentary rocks [18,40-44]. Absence of migration in micropores, mesopores and the efficacy of diffusion in hydrocarbon flow to macropores and fractures were illustrated by [45] as the major primary migration pathway indices during diffusion of liquid and gas hydrocarbon in source rocks. Primary petroleum migration is the principal processes to consider in effective unconventional oil and gas generation because when and the quantity of hydrocarbons did or did not migrate form source rock (primary migration) is vital in unconventional shale petroleum exploration (Fig. 7).

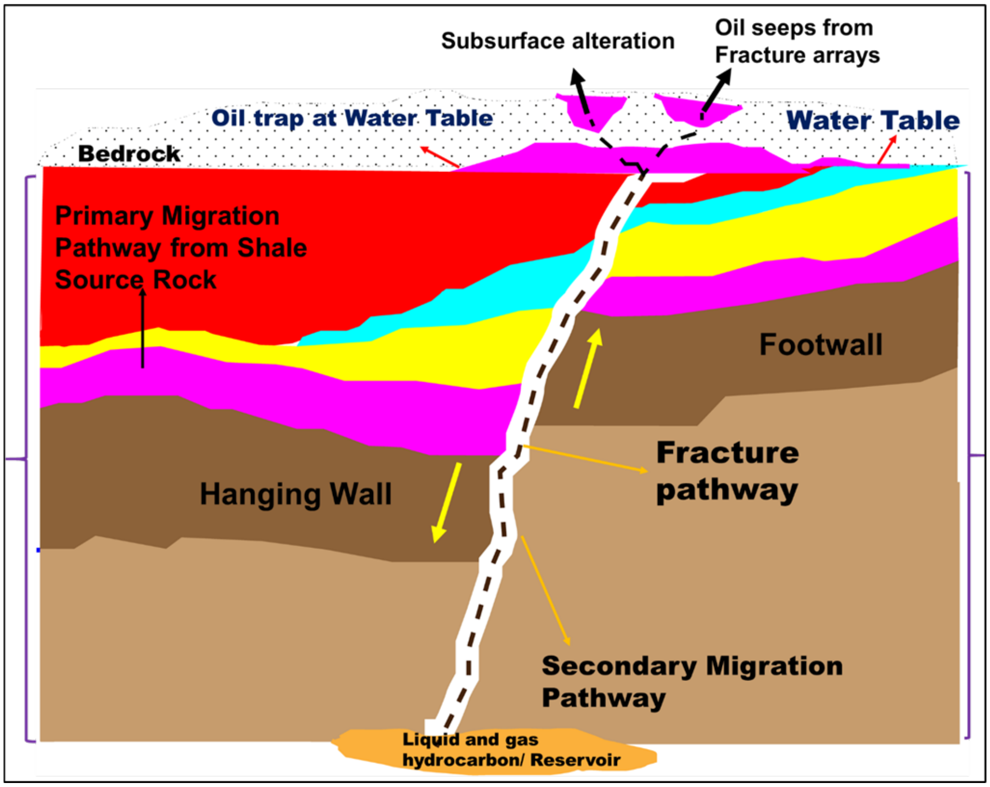

Fig. 7. Normal fault system of the Nsukka Formation of Anambra Basin showing schematic design of fracture pathway, seepage processes and dispersal mechanisms at Ikpankwo quarry. {} Indicates sediment package on the hanging wall (dislocated) and foot wall of the fault block

Depositional environment synthesis are products of lithofacies, rock texture and bedding plane of the sedimentary sequences which denote the basic parameters vital in potential fluid migration pathways across the primary interparticle pore space of the rock [45]. Coal seams and the black carbonaceous shale facies can serve as the source or seal rocks whereas the consolidated cross bedded sandstone, siltstone, and heteroliths are possible reservoir rocks of the petroleum system in the study area (Fig. 5). Generally, mudrock source rocks are possible pathways for the migration of liquid and gas hydrocarbon generated from the kerogen of the Nsukka Formation designated as Kerogen Type II and III (Fig. 4) with oil and gas petroleum synthesis.

Primary and secondary oil route and migration pathways of the source rock of Nsukka Formation were observed (Fig.5-7) as residual and generating oil seeps of common oil-staining on rock sequences and water flow of [45]. The primary migration oil stain nomenclature was regarded as normal oil-staining [45], highly viscous [45] and partly or completely solidified [48].

Microfractures are traditionally stimulated during oil generation in source rocks which depicts the sedimentary structure as a migratory pathway [49-51]. Microfractures and macro fractures were recorded as significant migration conduit for petroleum expulsion from source rocks of the Bakken Shale, Lower Toarcian and La Luna formation [45-47,52]. Statistical quantity of fractures, fracture width, distribution and orientation in the Nsukka Formation (Fig. 5-7) were significant during sediment-petrographical analysis to determine the origin of fractures to find out the link to the time of petroleum expulsion from source rock. The main macro fracture prototype of the Nsukka Formation in Ikpankwu area is the normal fault (Fig. 5-7) with key structural traps of hanging walls and footwalls previously simplified.

The natural gas flare at Caritas university at 6° 30' 27" N and 7° 34' 35" E, coordinate depicts production gas flare as confirmed evidence of leakage (Fig. 7) from petroleum accumulation trap in Anambra Basin which depicts altered by surface dispersal petroleum efflux/seeps category of [42]. In accordance to the lithostratigraphic age of the Enugu Formation type area (Late Campanian-Early Maastrichtian) and lack of stratigraphic age determination of any generated hydrocarbon, the source rock and primary migration pathway of the flared gas is an irresolute scientific act/debate. The Late Maastrichtian to Danian Nsukka Formation or any other older or younger formation could strengthen the source rock and primary migration pathway of the accumulated petroleum.

However, expulsion fractures formed during petroleum generation and tectonic fractures were the two genetic types of fractures active during the Anambra Basin development and subsidence of the Niger Delta Basin tectonic events (Figs. 5-7). The open stage of the Nsukka Formation fracture creation in tectonic evolution of the Anambra and Niger Delta basins were also reported in basin modelling and petroleum exploration in the region [6,16,22,53-57].

6. Conclusion

The composition, colour, quantity and quality of organic matter of the Nsukka Formation revealed the petroleum source potential consistent with kerogen Type II/III which are Gas / Oil prone, with thermal alteration index (TAI) 2+ to 3 and vitrinite reflectance index (%Ro) values of 0.5% to 1.0%. Terrestrial phytoclasts are products of Kerogen Type III (gas prone) while the pronounced oil seep prone shales of the Nsukka Formation are the essential resultant products of Kerogen Type II (oil prone) palynofacies elements. The combined quality and quantity of the palynofacies elements in paleoenvironment reconstruction of the Nsukka Formation indicate shallow marine settings with deep marine influenced macro environments embedded as products of lower and upper deltaic plains; oscillating from tidal flat, lagoon, tidal bar to nearshore settings with deep marine influences. Key structural traps consist of hanging wall closures, footwall closures along with in filled and open joints structures within faulted and unfaulted sandstone units. Primary and secondary migration pathway is sandstones pores and fractures which are the key mechanism in the formation of petroleum accumulations in reservoir beds.

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