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Analysis of Petroleum System for Exploration and Risk Reduction in the South-eastern Inland Basins of Nigeria

Chidozie I. Princeton Dim[1] K. Mosto Onuoha[1], Okwudiri A. Anyiam[1], Ikenna C. Okwara[1], Ifeanyi A. Oha[1], Ikenna A. Okonkwo[1], Chukwudike G. Okeugo[1], Elijah E. Nkitnam[2], Bertram M. Ozumba[3]*

[1] Department of Geology, Faculty of Physical Sciences, University of Nigeria, Nsukka, Enugu State, Nigeria
[2] Department of Geology and Geophysics, Federal University of Ndufu-Alike Ikwo, Ebonyi State, Nigeria
[3] Department of Geology, Federal University of Technology, Owerri, Imo State, Nigeria

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Abstract

Although several acreages exist within the inland basins of southeastern Nigeria, the distribution of key petroleum system elements and associated generation, migration and accumulation processes have not been fully understood. This has hindered extensive exploration and subsequent development plans within these important hydrocarbon provinces. In this paper, outcrop, well logs and seismic data have been integrated with sequence stratigraphic and geochemical modelling techniques to allow for better understanding of the petroleum system elements and processes within the inland basins. Results from petroleum system analysis reveal the existence of two key petroleum systems namely, the Albian-Santonian system of the Abakaliki Basin and the Campano-Maastrichtian system of the Anambra Basin. Integrated analytical studies using sequence stratigraphic and geochemical modelling techniques unravelled the presence and distribution of source, reservoir, seal packages and associated generation, migration and accumulation processes. Structurally, the presence of hanging walls, footwalls, horst blocks and collapsed crest trapping systems provided both possible hydrocarbon migration pathways for generated hydrocarbons and good entrapment for hydrocarbon accumulation. Common Risk Segment (CRS) maps indicate zones of low, moderate and high risks intervals, which are prospective and favourable for hydrocarbon exploration. This study thus, provides a guide to oil and gas exploration and potential in the inland basins of Nigeria.

Keywords: *Albian-Santonian system; Campano-Maastrichtian system; Abakaliki Basin; Anambra Basin; Common Risk Segment Maps.*

1. Introduction

Studies have shown that a petroleum system exists wherever all the essential elements and processes are known to occur or are thought to have a reasonable chance of occurring [1-2]. Exploration for petroleum in Nigeria's inland basins dates back to the colonial era, when reports of hydrocarbon shows (seeps and smell) by geologists of Shell-BP and preindependence Geological Survey of Nigeria, spurred initial oil prospecting efforts in the Aba-kaliki Basin of the southern Benue Trough, Anambra Basins and Niger Delta Basin [3]. These exploration studies were limited due to little or no subsurface data. However, with an array of recently acquired data from various sources, there is now a better understanding of the petroleum system elements and processes of Nigeria's inland basins. This paper aims at integrating data from outcrop, well and seismic with sequence stratigraphic and burial history analysis, to better understand the petroleum system and establish prospective and favourable zones that will provide suitable guide for hydrocarbon exploration and production in Anambra and Abakaliki basins of southeastern Nigeria. The key objectives are to identify the key petroleum system elements that will aid in generating an Event Chart and further insight on the existing petroleum systems and reconstruct a common risk segment map using information from map extent of key petroleum system elements to unravel prospective and favourable zone.

2. Geologic framework

The initiation and evolution of the sedimentary basins of southeastern Nigeria is well documented in several studies [4-7]. From the Albian to Santonian, the depositional centre was the NE-SW trending Abakaliki-Benue Trough, which was terminated during the Santonian inversion event. With the folding of the Benue Trough into the Abakaliki Anticlinorium and the Afikpo and Anambra Synclines, deposition shifted to the south-eastern, southern and western flanks of the structure, forming the Anambra Basin [8-9]. The study area lies within Abakaliki Basin (Southern Benue Trough) and Anambra Basin, which consists predominantly of Early to Mid-Cretaceous (Albian to Santonian) and Upper Cretaceous (Campanian-Maastrichtian) clastic sediments [10-11] (Figs. 1; 2; 3a and 3b). The Abakaliki Basin consists of three groups, namely: i) Asu-River Group (Middle Albian to Lower Cenomanian age), related to the earliest stages of the basin's formation [12-13]; ii) Eze-Aku Group (Cenomanian to Late Turonian age) consisting of shallow marine sandstones, shales and limestones [14-15]; and iii) Awgu Group (Coniacian to Santonian age), which records the beginning of the regression that culminated in the uplift that ended the first tectonic phase [12]. Sedimentation in the Anambra Basin began with the deposition of the Campanian Nkporo Group (Owelli, Nkporo, and Enugu formations), succeeded by the Late Campanian to Maastrichtian Mamu Formation, Ajali Formation, and ended with the late Maastrichtian age Nsukka Formation [16]. The sediment packages were deposited during an overall regressive cycle within fluvio-tidal, deltaic, shelfal and marine settings [17-18].

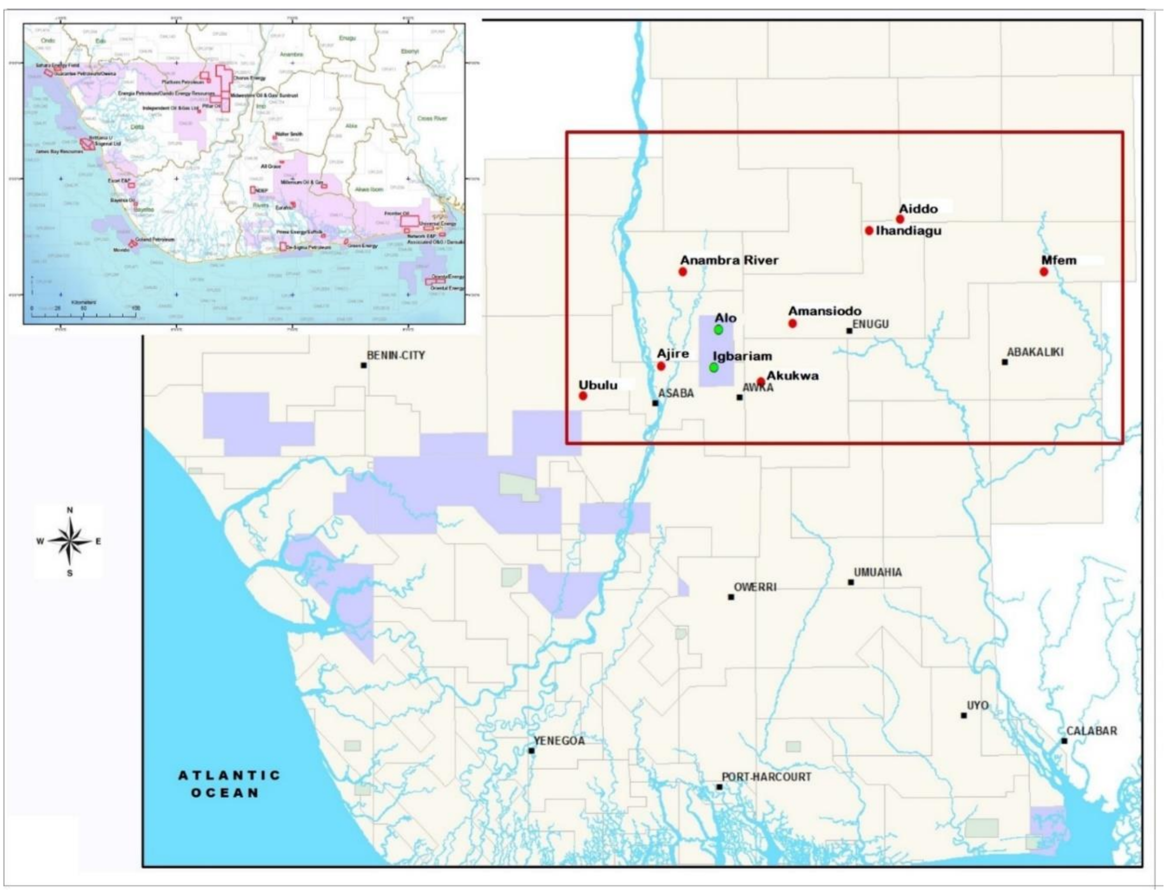

Fig. 1. Concession map of the southern Nigeria showing the well bore distribution in the study area (within the red box)

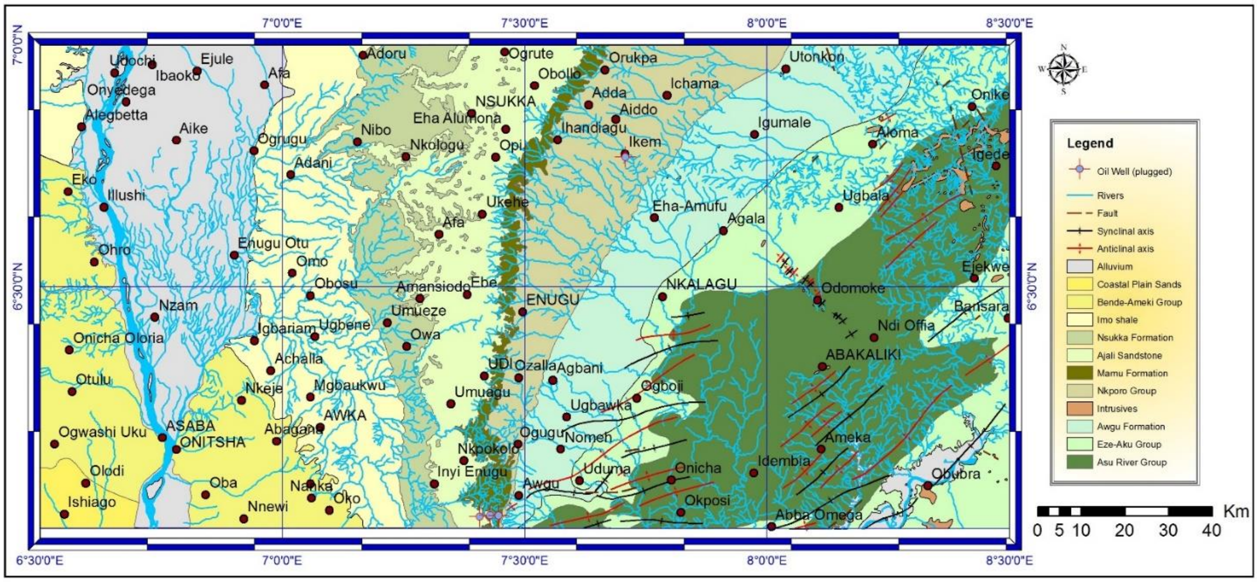

Fig. 2. Geologic map of the southeastern Nigeria, showing the Benue Trough and the Anambra Basin the spatial distribution of wellbores across the study area

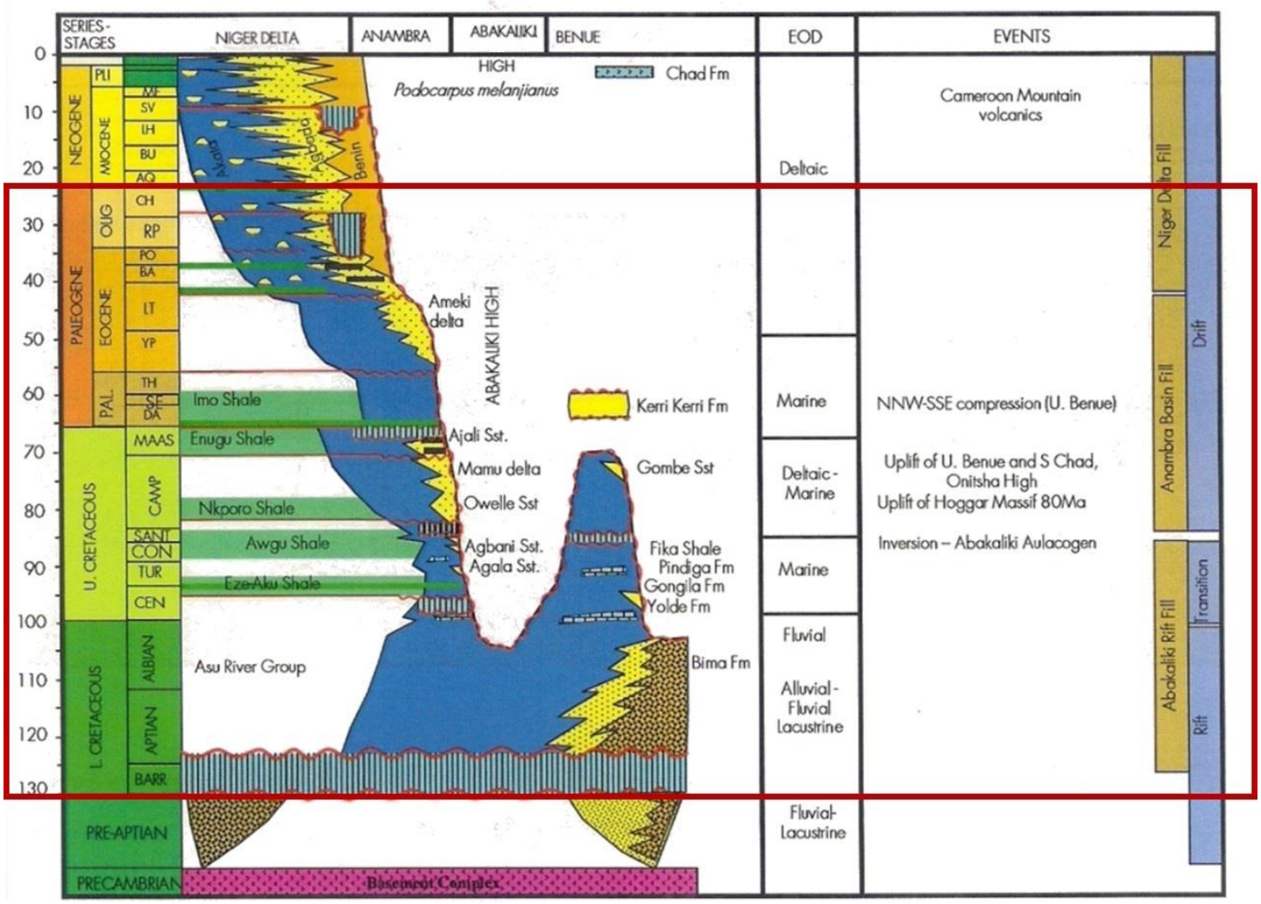

Fig. 3a. The Stratigraphy of some of the Nigerian Inland Basins (*after Ozumba* [10])

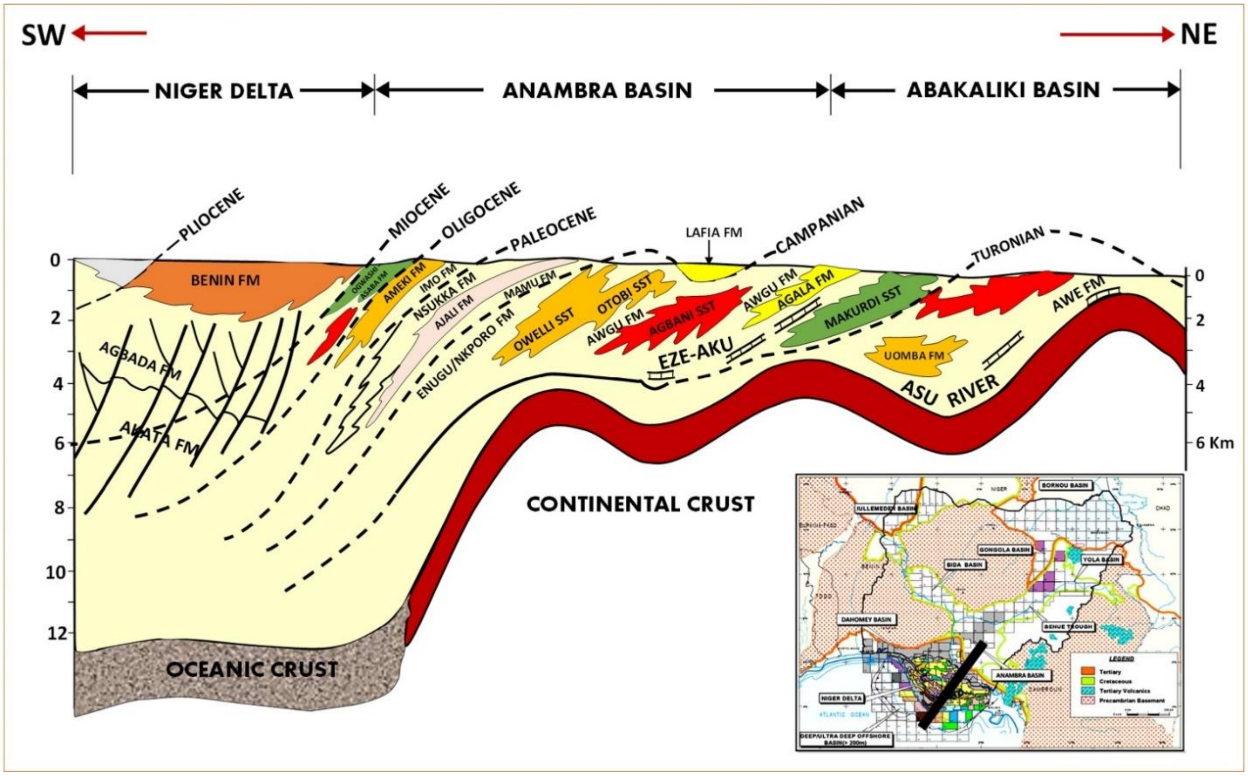

Fig. 3b. Cross section of the showing lithostratigraphic units of Abakaliliki, Anambra and Niger Delta Basins *(after Benkhelil [11])*

3. Methodology

This study integrates data from outcrops, well, and seismic to generate a sequence stratigraphic framework and geochemical model of the basin. Representative outcrops within the Anambra and Abakaliki basins were mapped, to document rock units and structural features that constitute potential elements of petroleum system. Well log sequence stratigraphic correlation was also carried out, constrained by biostratigraphic data [19-20]. Region-wide correlation was also carried out across the study area to understand the behaviour of sediment packages within lithostratigraphic unit. Lithological thicknesses were estimated for each formation at various intervals of occurrence in all the wells to enable better understanding of subsurface sand-shale thickness distributions across various geologic ages. Information obtained from published geochemical data was used to reconstruct burial history and model hydrocarbon generation. 2D seismic sections were interpreted to highlight key stratigraphic packages and structural configuration. A common risk segment map was also generated to better define hydrocarbon prospective areas.

4. Results and discussion

4.1. Outcrop and Lithostratigraphic Studies

Outcrop studies indicate the lithostraitigraphic units of the Abakaliki Basin are seen in quarry, road-cut and river-cut sections (Fig. 4a-4m). Asu-River Group consists mainly of arkosic, non-fossiliferous fanglomerates, shales, limestones and sandstones [12-14]. The Eze-Aku Group consists of sandstones, shales and limestones. The Amaseri Sandstone and Eze-Aku Shale, which belong to the Eze-Aku Group are well exposed in the Amaseri area of Afikpo, southeastern Nigeria (Fig. 4a and 4b). The Awgu Group (Agbani Sandstone and Awgu Shale) are well exposed in the southeastern part of Nigeria. Generally, the lithostratigraphic units of the Abakaliki Basin were affected by the Santonian tectonic event that led to sediment deformation. Hence, exposed stratigraphic packages in the basin are tilted fold limbs with high dips (Fig. 4a). On the other hand, the lithostratigraphic units of the Anambra Basin that were deposited after the Santonian event, show little or no tectonic dip. The Nkporo Group, which is the oldest lithostratigraphic unit in this basin, consists of carbonaceous shales and sandstone members of deltaic origin [17] (Fig. 4d and 4e). This unit is overlain by the coal-bearing Mamu Formation that consists of alternating sandstones, sandy shales, mudstones, and sub-bituminous coal seams [16]. The outcrop of the Mamu Formation is well exposed on the Udi Bypass and Miliken/Onyeama Hills in Enugu, southeastern Nigeria. Overlying the Mamu Formation is the Ajali Formation, which comprises predominantly of sandstones with interbeds of clay laminae (Fig. 4h). The Nsukka Formation, which is the youngest lithostratigraphic unit in the basin consists of dark shales and sandstones, with thin coal seams (Fig. 4k; 4l and 4m).

Basin wide correlation carried out using well log data reveals that the oldest formation (the Nkporo Formation) consists of a 300 – 600 m thick sediment package while the overlying Mamu Formation consists of 600 – 1200 m thick sediments that are in turn overlain by 400 – 600 m thick unit of the Ajali Formation (Fig. 5). Sediments of the overlying Nsukka Formation are 20 – 50 m thick. The distribution of shale units across the area shows that the Campano-Maastrichtian shale package of the Lower Mamu Formation and the Enugu Shale constitute the thickest shale play of 200 – 860 m (Fig. 6a-6j and 7). Relatively high are the thicknesses of shales of Turonian - Cenomanian and Paleocene ages. Well correlation further reveals that sediment thicknesses are thin at the flanks and thicker towards the central part of the study area. The basin-wards thickening of sediment package observed in well correlation are probably evidence of structural influence (faulting) on stratigraphy (Fig. 5 and 8). These near vertical fault structures offer possible hydrocarbon migration pathways for generated hydrocarbons within the basin and could provide good entrapment mechanism for hydrocarbon accumulation, as proven in the prolific neighbouring Niger Delta Basin [21].

4.2. Sequence stratigraphic correlation and framework

Interpretation of well logs have shown that the study area consists of over 4 km (12000 ft) thick sediment package (Fig 5; 8a-8 and 9a). Thirteen chrono-stratigraphic surfaces (six maximum flooding surfaces - MFSs and seven sequence boundaries - SBs). The MFSs mark regional seals that cap reservoir units across the entire area. Well log sequence stratigraphic correlation using theses stratigraphic surfaces along NE-SW dip section shows that the shallow and deepest depositional sequences (SEQ 1 and SEQ 6) are discontinuous, whereas the intermediate sequences (SEQ 3 - SEQ 4) are continuous. Depositional sequences which are defined by SBs [19-20] are associated with reservoir, source and seal packages (key petroleum system elements) belonging to various systems tracts that include the lowstand system tracts (LST), transgressive system tracts (TST) and highstand system tracts (HST) that are laterally continuous and quite correlatable even at deeper stratigraphic intervals, which have not yet been penetrated (Fig. 5b). Depositional sequence thickness decreases at younger intervals, from about 3500 ft (1200 m) to about 1000 ft (350 m). This probably indicates sediment packages deposited rapidly during high-frequency, fluvio-deltaic-eustatic sea level oscillations. Genetic units or systems tracts show variable thicknesses across wells from the northeast to southwest. In addition, stratigraphic sequences generally dip southerly and sediment packages thicken down-dip (in basinward direction). This basinward thickening of sediment, observed in well correlation and seismic mapping, could be attributed to high rate of subsidence and deposition associated with syndepositional structural influence on stratigraphy [18, 21] (Fig. 9a and 10). Sequence stratigraphic analysis based on transgressive-regressive cycle, reflects a second-order cycle (ca. 44 My) composed of two transgressive-regressive parasequence pairs, reflecting relative sea level fluctuations [17]. However, a more in-depth interpretation reveals a subdivision into third-order packages (0.3-5 My), whose constituent sequence form the systems tracts, reflecting six repetitive patterns of transgressive-regressive packages with thirteen (13) delineated chrono-stratigraphic surfaces (seven SBs and six MFSs).

Fig. 4. Representative outcrop of various geologic formations in the inland basin. a) Fold limb with thick sediment package of well-stratified fine to coarse-grained sandstone unit in northwest of Afikpo town, off Amoso-Amaseri Road (outcrop exposure on the Amaseri Sandstone (Abakaliki Basin) ridge at Crush Stone Industry quarry site). b) Interstratification of sandstone and shale unit showing a thinning-upward sand and thickening-upward shale package exposed on Ibii Sandstone ridge (Marlum Civil Engineering quarry site) of Akpoha-Afikpo road, Afikpo, c) Oil seep in Owelli Sandstone at the foot of Enugu Cuesta, near Ugwueme village – thought to have been sourced from shales of Awgu Formation of Abakaliki Basin *(after Nwajide [13])*. d) A road-cut exposure of the thick shale characterized by siltstone/sandstone interstratification in the Enugu Formation, near Onitsha road flyover in Enugu. Note the heterolithic (interstratification of sandstone, siltstone and shale) package at the middle section with evidence of a listric fault, typical of growth fault system. e) Road cut exposure of the Enugu Formation showing normal fault on thick shale with siltstone interbeds, geologists positioned on the handing wall and footwall (outcrop at Amagu along Enugu – Port Harcourt expressway). f) Normal faulting of thin siltstone/ironstone and shale package in Enugu Formation exposed at a road cut exposure at Four Corner, Ozalla Junction, along Enugu-Port Harcourt expressway. g) The middle section of Fig. 3d showing a heterolithic interval with well-developed growth fault in the Enugu Formation exposed near Onitsha road flyover in Enugu, southeastern Nigeria (Note rollover structures on both hanging wall and the footwall). h) Very thick sandstone characterized by interstratified thin clay bands exposed at a quarry section in Alabama Hills, behind ABSU, off Okigwe - Afikpo road. i) Normal fault structure in Nsukka Formation showing the down-thrown (hanging wall) and up-thrown (footwall) block exposed at Ikpankwo quarry, off Enugu – Port Harcourt express expressway. j) Anastomosing joint structures that could serve as pathway for fluid migration, occurring within the basal shale unit of the Enugu Formation. k) Coal seam (indicated by yellow line) occurring with carbonaceous laminated sandstone units in the Mamu Formation exposed at Onyeama Mine section, along Enugu – Onitsha Express Road. l) Normal fault at Ikpankwo quarry, off Enugu – Port Harcourt express expressway. Arrow indicates displaced/juxtaposed fault blocks. m) Coal bed of Mamu Formation exposed at the base of thick carbonaceous sandstone at Udi By-pass, SE Nigeria. Note persons (approximately 1.8 m) and geologic hammer (30 cm) for scale

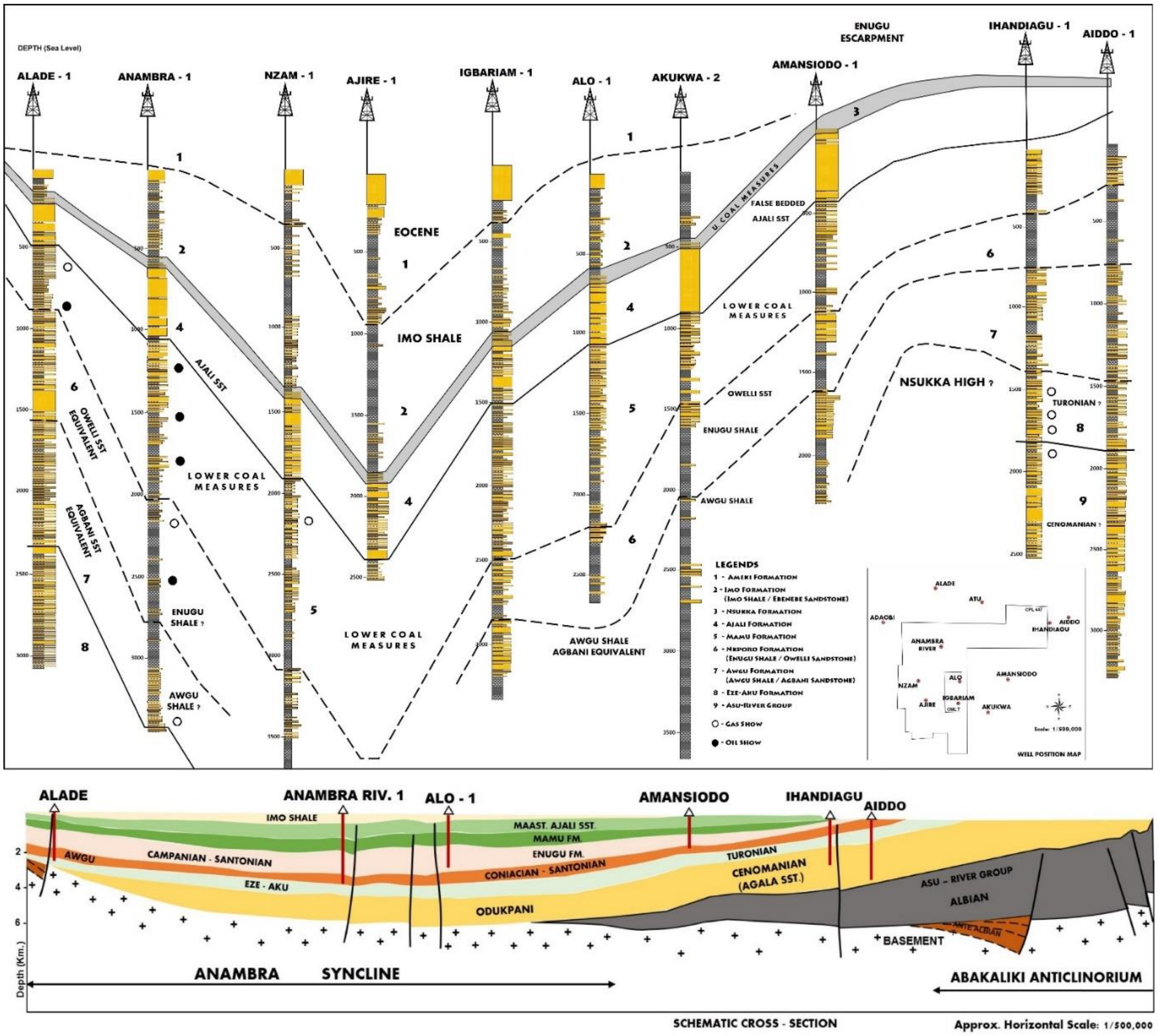

Fig. 5. Multiple dip line correlation section showing lithostratigraphic units and hydrocarbon shows in the Southern Benue Trough (Turonian-Santonian), Anambra Basin (Campanian-Lower Paleocene?) and Niger Delta (Paleocene); Aiddo-1, Ihandiagu-1, Amansiodo-1, Akukwa-2, Alo-1, Igbariam-1, Ajire-1, Nzam-1, Anambra River-1 and Alade-1 with a schematic cross section showing wellbore and sediment package with possible associated near vertical faults. Inset map is the study area showing the spatial distribution of wellbores *(after Onuoha and Dim [21])*

4.3. Petroleum system elements and processes

Studies have shown the existence of two petroleum systems namely; a) the Albian-Santonian (early to mid-Cretaceous) system of the Abakaliki Basin (Southern Benue Trough). The potential hydrocarbon source or charge in the Abakaliki Basin are the mature Turonian Eze-Aku and Coniacian Awgu shales [22-23]. The reservoir type in the basin is essentially of clastic sandstones, which comprise mainly of interbedded sandstone bodies of Eze-Aku Formatiom (Amaseri Sanstone) and Agbani Sandstone (Awgu Formation) that have poor to moderately hydro-carbon reservoir quality [15]. Entrapment mechanisms were formed during the Aptian-Albian rifting, which may have created basement normal faults whose throw continues to increase as subsidence increases. These faults formed structural traps which were reactivated and enhanced in the Tutonian renewed rifting. In addition, the early Cenomanian post rift and later Santonian deformation led to the formation of folds and fault that serves as structural styles within the basin.

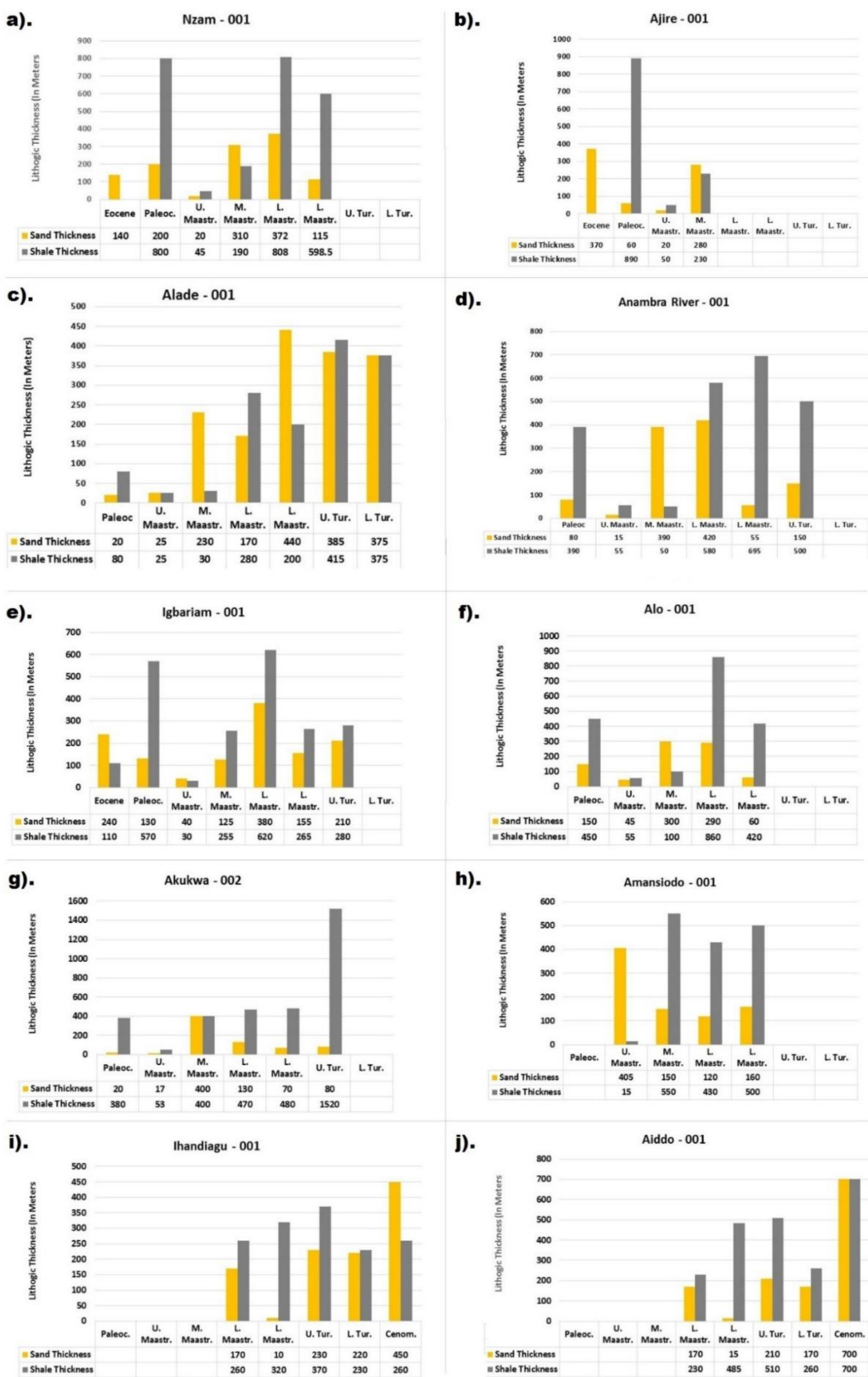

Fig. 6. Distribution of sand-to-shale percent across ages, across several wells *(after Onuoha and Dim [21])*

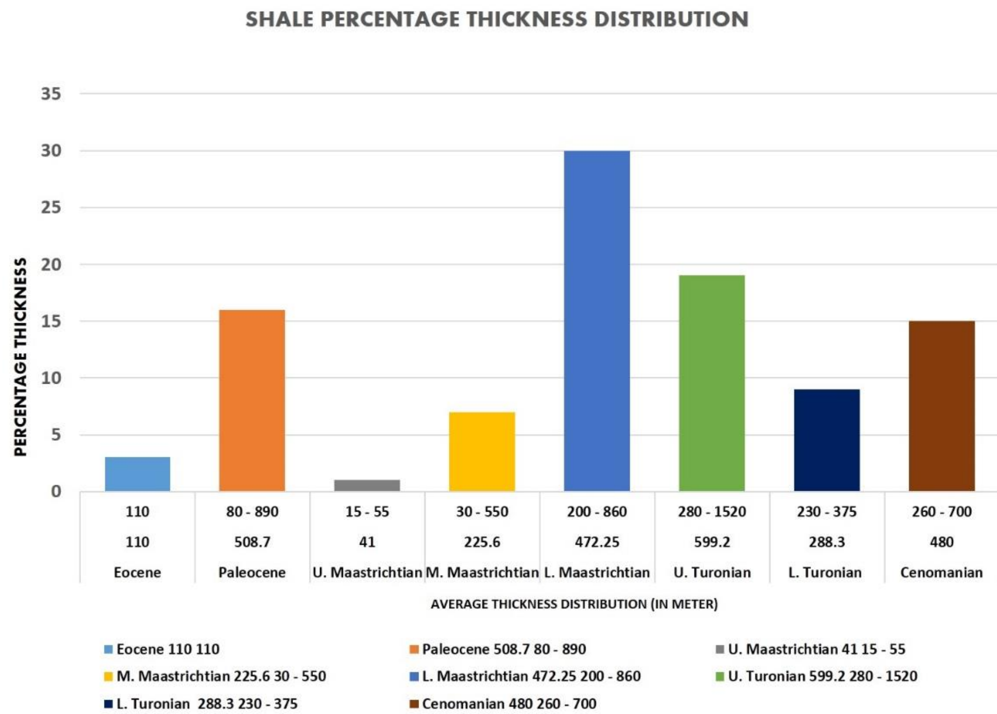

Fig. 7. Gross shale thickness distribution chart by age across the Anambra Basin estimated from subsurface well data *(after Onuoha and Dim [21])*

The major seals in the basin are mainly the interbeded shales and mudstones of Awgu and overlying Nkporo formations. b) the Campano-Maastrichtian (Late Cretaceous) system of the Anambra Basin that has its major charge from the marginally mature shales of Nkporo with terrigenous inputs from Mamu Shales and Coals, which have been proven to be viable source rocks with fair to good geochemical parameters - kerogen type, total organic carbon (TOC), and Hydrogen Index [22, 24]. The reservoirs in the Anambra Basin are clastic sandstones, which comprise mainly of interbedded sandstone bodies of Nkporo, Mamu and Ajali formations that have adequate hydrocarbon reservoir quality [17, 23]. Traps within the basin were formed possibly due to south-westward stacking of sediment which created differential subsidence basinward [5]. This could have caused the development of syndepositional growth faults during the Campanian renewed thermal subsidence in the Anambra Basin. The presence of the growth faults and associated rollover anticlinal structures offer possible traps for hydrocarbon accumulation. The seal packages are mainly the shales of Nkporo, Mamu and Nsukka the overlying Imo Formation (Paleogene) of the Niger Delta Basin, which have not undergone any regional deformation.

Reconstruction of the burial and thermal histories of sediments in the basin (Fig. 11a-11c), reveals the occurrence of three major episodes in the basins. a) The subsidence in the Turonian time that corresponds to the second phase of renewed rifting in the basin, which is of less magnitude relative to initial rifting and basin opening of the Aptian-Albian times. This subsidence gave rise to the deposition of marine shales of Eze-Aku in the Turonian and Awgu Shales in the Coniancian. b) The compressional uplift (inversion) in the Santonian, that gave rise to the Abakaliki Anticlinorium, the thermal subsidence of the western platform (Anambra Basin) and eastern (Afikpo Syncline). c) Thermal subsidence in the Campanian-Maastrichtian time, which brought about the erosion of the Abakaliki fold belts and deposition of the erosion materials on the rapidly subsiding western and eastern basins. From the burial history charts and plots, the onset of hydrocarbon generation from all the source rocks buried in the deepest parts of the basin as well as those buried to intermediate depths extended over a narrow range of 53 my – starting at 83 my for the Eze-Aku Shale to 30 my for the Nkporo Shale [25].

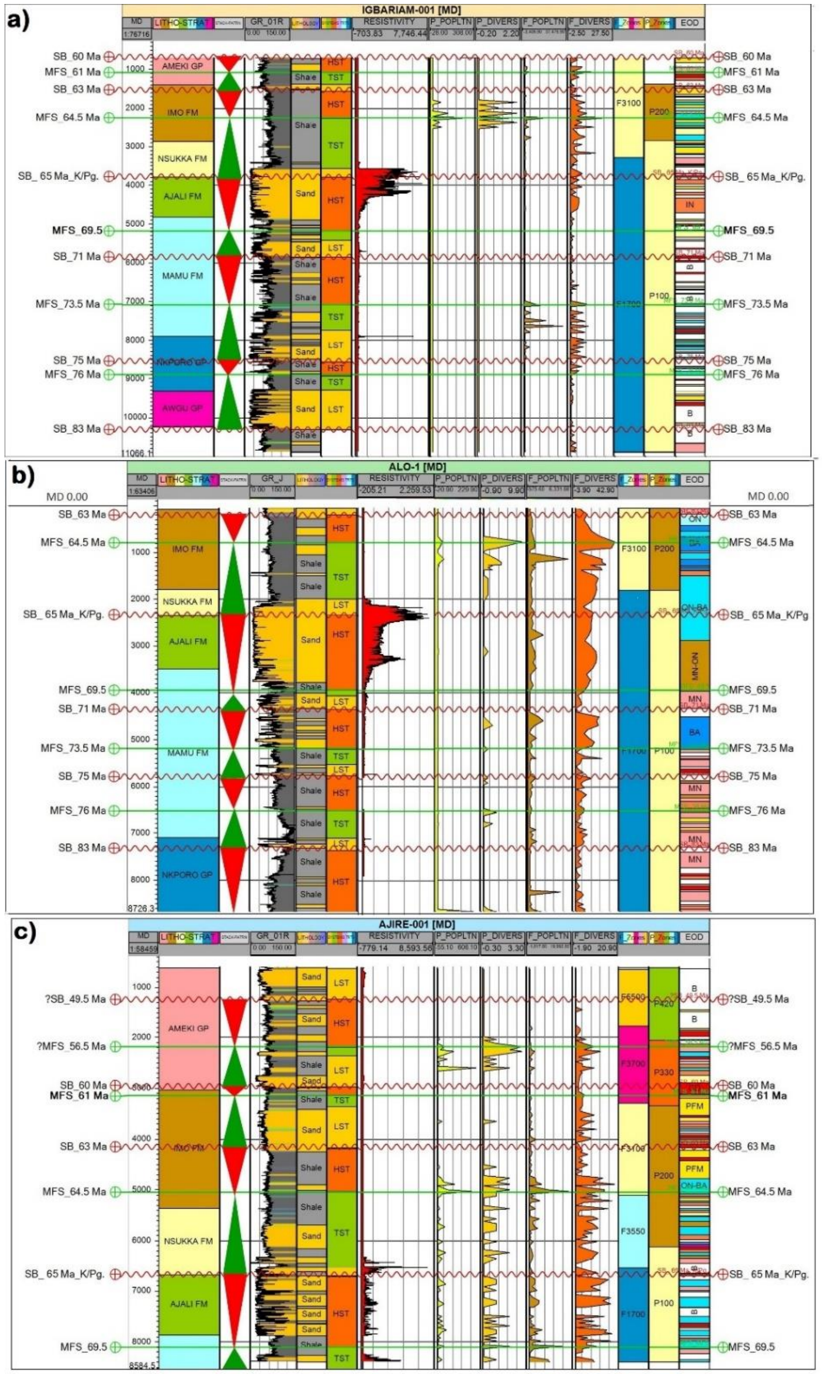

Fig. 8. a) Well log sequence stratigraphic correlation and interpretation of Ajire-001 well study (NB: the occurrence of eight stratigraphic bounding surfaces (four sequence boundaries and four maximum flooding surfaces). b) Well log sequence stratigraphic correlation and interpretation of Alo - 001 well study (NB: the occurrence of nine stratigraphic bounding surfaces, five sequence boundaries and four maximum flooding surfaces). c) Well log sequence stratigraphic correlation and interpretation of Igbariam-001 well study (NB: the occurrence of eleven stratigraphic bounding surfaces e six sequence boundaries and five maximum flooding surfaces). d) Well log sequence stratigraphic correlation (on dip section) and interpretation showing thirteen (13) stratigraphic bounding surfaces (6 MFSs and SBs) and six (6) depositional sequences. NB: Sediment packages thickens down-dip due to structural (Fault e F) influence on stratigraphy *(after Dim, et al. [18])*

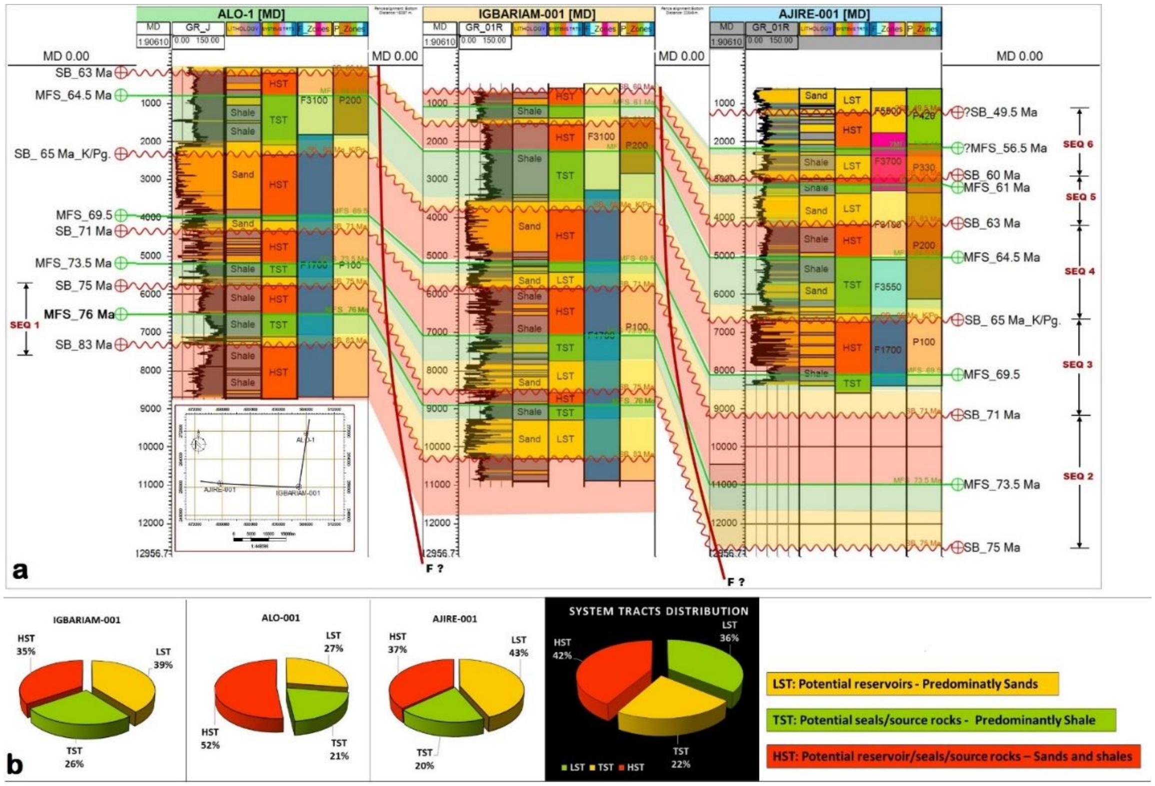

Fig. 9. a) Well log sequence stratigraphic correlation (on dip section) and interpretation showing thirteen (13) stratigraphic bounding surfaces (6 MFSs and 7 SBs) and six (6) depositional sequences (SEQ 1 - SEQ 6). Note that sediment packages thicken down-dip due to structural (Fault – F) influence on stratigraphy. b) Pie chart showing the distribution of potential reservoir, seal and source rocks within the systems tracts across wells *(after Dim et al. [18])*

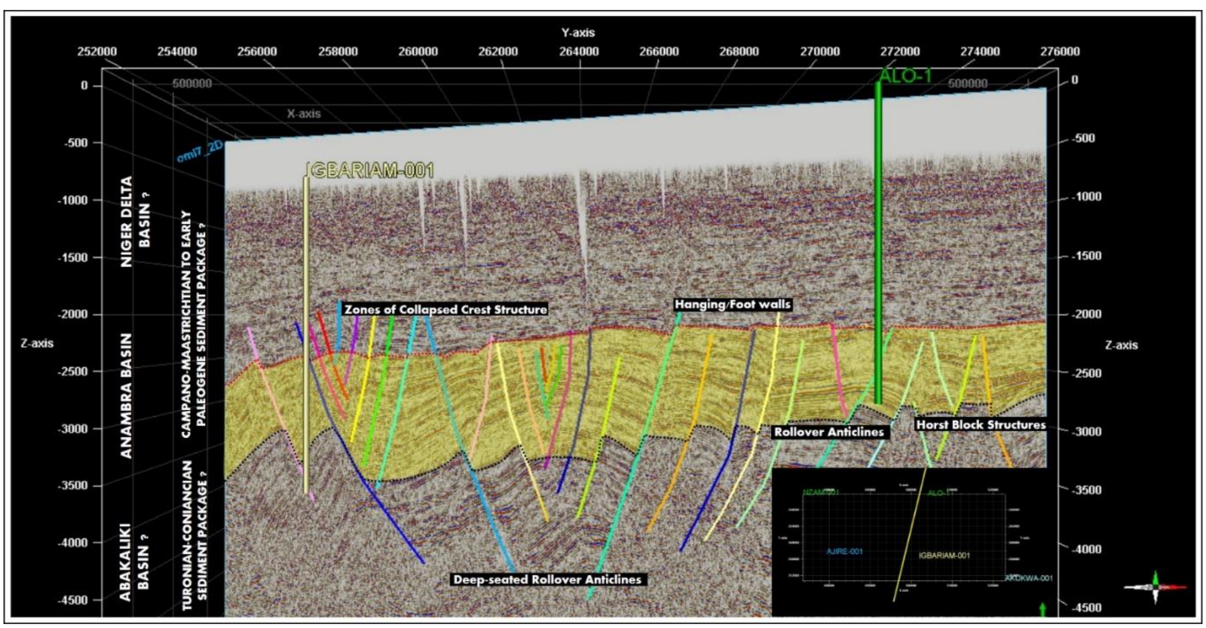

Fig. 10. 2D Seismic section with wellbores in the Anambra basin showing sediment packages and interpreted fault structures which could act as possible migratory pathways and entrapment mechanism. Inset is map view of 2D seismic line *(after Dim et al. [18])*

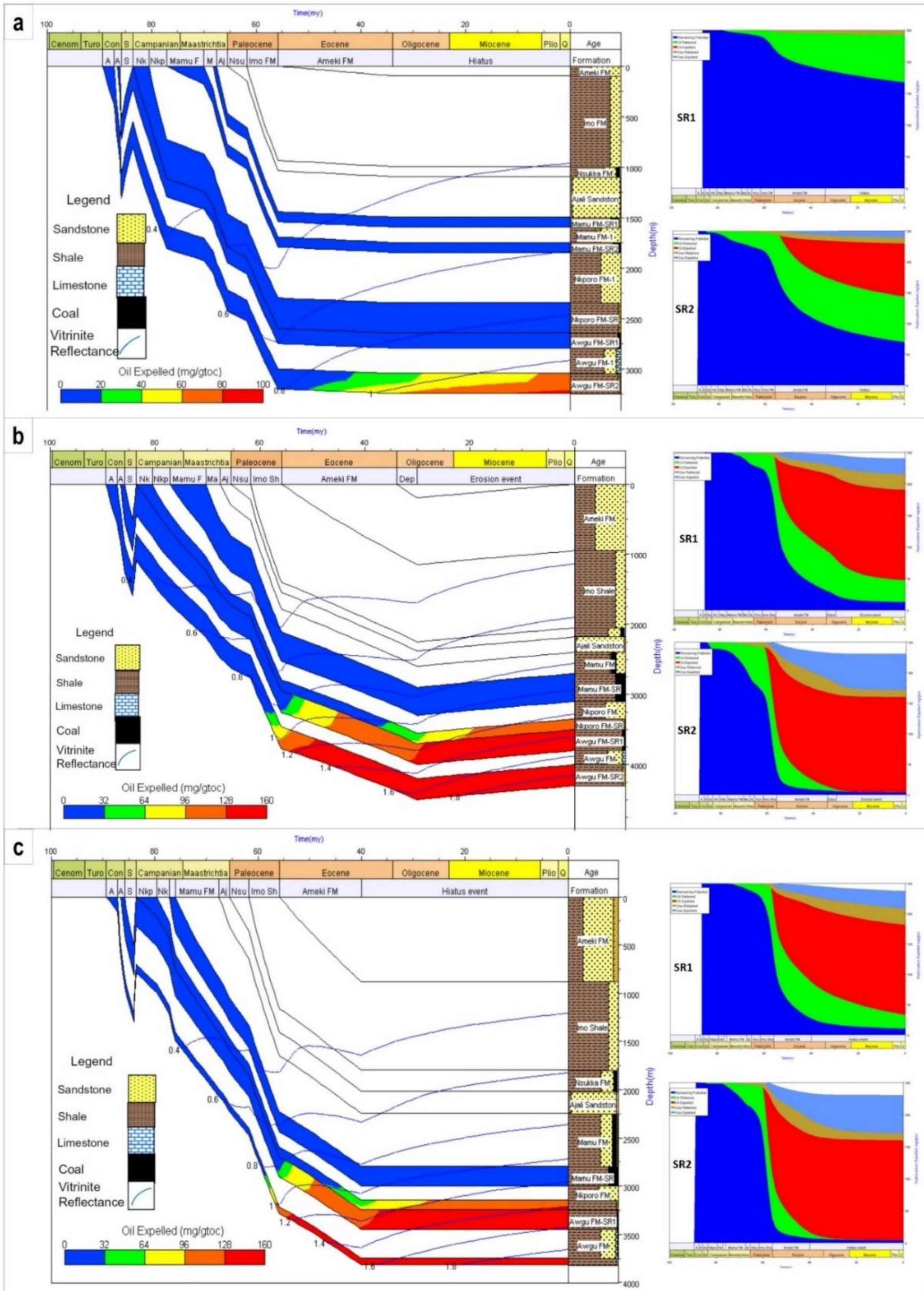

Fig. 11. a) Burial history of the Igbariam-1 well (key well) – with applied variable heat-flow. Expelled, retained and residual hydrocarbons chart for upper source unit SR1 and lower source unit SR2 source unit in Igbariam-1 well (Key Well). b) Burial history chart for Iji-1 well (Pseudo 1), with the buried source units in heavy colours. Expelled, retained and residual hydrocarbons chart for upper source unit (SR1) and lower source unit (SR2) in Iji-1 well (Pseudo 1). c) Burial history chart for Ajire-1 well (Pseudo 2), with the buried source units in heavy colours. Expelled, retained and residual hydrocarbons chart for upper source unit (SR1) and (b) lower source unit (SR2) in Ajire-1 well (Pseudo 2) *(after Anyiam, et al.,* [25]*)*.

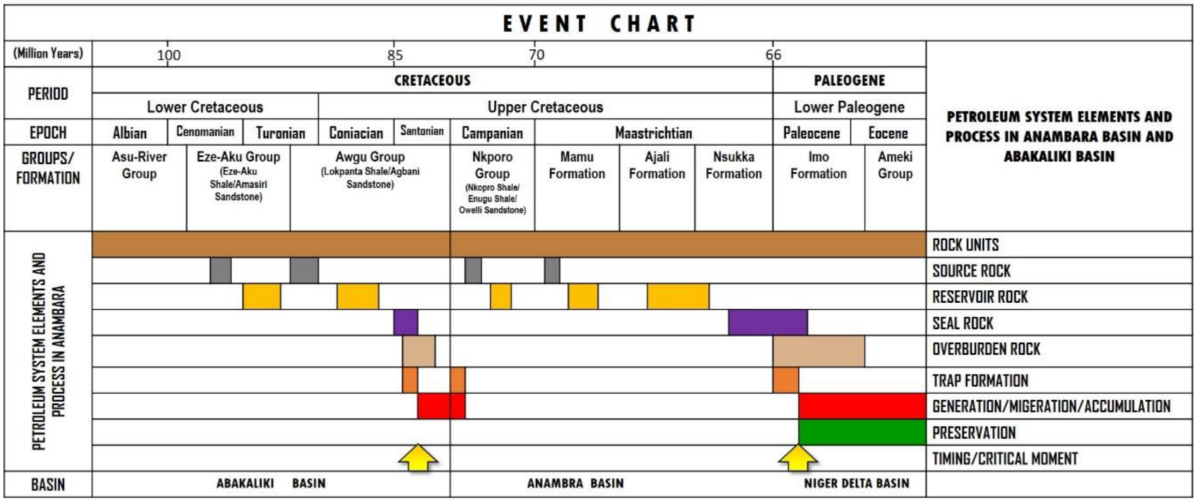

Fig. 12. Petroleum System Chart of Albian-Santonian and Campano-Maastrichtian (Cretaceous) Hydrocarbon Systems in the Anambra Basin and Abakaliki Basin respectively.

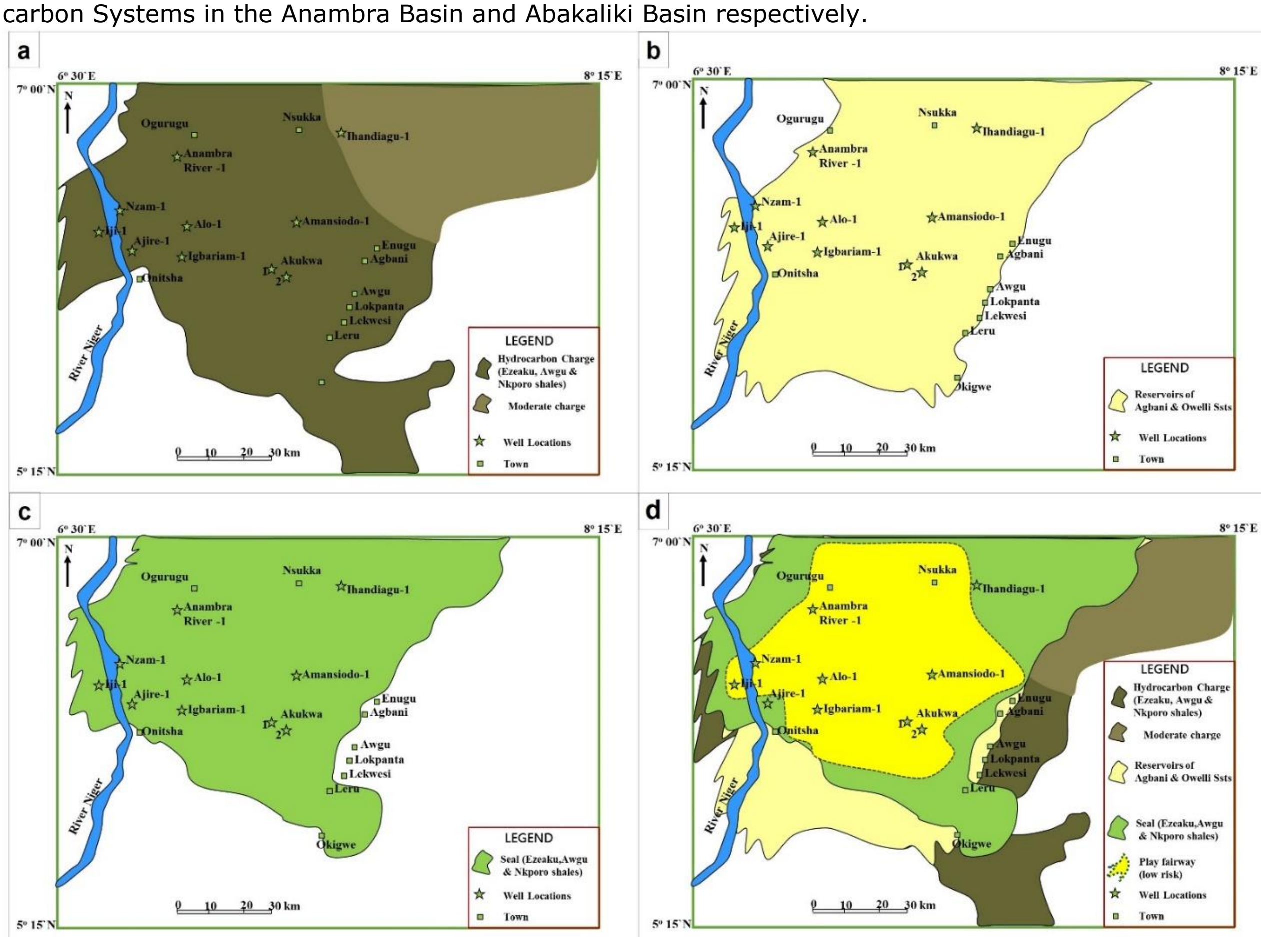

Fig. 13. a) Subsurface hydrocarbon charge for Eze-Aku, Awgu, and Nkporo source rocks in the play. b) Subsurface reservoir distribution for Owelli and Agbani Sandstones in the play. c) Subsurface top and lateral seal for Awgu and Nkporo interbedded shales in the play. d) Composite common risk segment map showing the southern Benue Trough (Abakaliki Basin) and Anambra Basin play fairway. Note the low-risk zone to the west of the area *(after Anyiam et al. [28])*

Studies have shown that during the pre-Campanian period, enormous volumes of hydrocarbons generated by the Cenomanian-Turonian source rocks (underlying Awgu Group and Lokpanta Shales of the Abakaliki Basin) before the Santonian uplift, might have migrated through these structures probably to shallower horizons, part of which may be contributing to the Niger Delta reserves [3, 26]. There is also evidence of oil shows associated with the Lokpanta Shale exposure in the basin, one of which has been correlated with the oil seepage from the Owelli Formation (reservoir package) of the Nkporo Group [24-25, 27]. The presence of key petroleum system elements and processes in both Abakaliki and Anambra basins is a good indication of the existence of two petroleum systems that span from lower Cretaceous to upper Cretaceous (Fig. 12).

Determination of the most prospective sections of the basin favourable for hydrocarbon exploration and exploitation was deciphered from generated common risk segment maps (Fig. 13a-13c). Evaluation of play fairway and risk analysis through overlying the various play elements maps such as source (charge), reservoir, and seal rocks integrated with other petroleum system processes (timing, trap formation, hydrocarbon generation and migration) reveal that there exists a zone of low risk that should be viable, not only for conventional, but also for unconventional petroleum resources [28] (Fig. 13d). Thus, applying risk analysis to the play fairway level in frontier basins permits channelling of exploration effort into the most prospective parts of the Basins.

5. Conclusion

Integrating outcrop, well logs and seismic data has allowed for better understanding of the petroleum system elements and processes within the inlands basins of southeastern Nigeria. Outcrop data indicates the presence of reservoir (sandstone packages), source/seal (shale packages), and associated structural styles for hydrocarbon accumulation. Sequence stratigraphic analysis suggests the existence of depositional sequences that comprise genetic units (LST, TST and LST). The LST and HST sandstones of the Mamu and Ajali formations constitute the reservoir package, whereas TST shales of the Imo Formation offers good seal rock package for the region. These genetic units make up the poor to good reservoirs with favourable thickness, mature to marginally source and laterally extensive seal packages. Studies revealed that presence of seeps possibly due to the updip migration of hydrocarbon from Eze-Aku and Awgu source rocks into the Owelli Sandstone (Nkporo Formation) in the Ugwueme area of southeastern Nigeria, which have been attributed to Santonian unconformity that lies between the pre-Santonian deposits and the Campano-Maastrichtian deposits in the Abakaliki Basin. This constitute a major risk which affected the sealing capacity

Structural styles such as hanging walls, footwalls, horst blocks, and collapsed crest structures (are also evident in seismic section) provide possible hydrocarbon migration pathways for generated hydrocarbons and good entrapment mechanism for hydrocarbon accumulation, as proven in the prolific neighbouring Niger Delta Basin. Hence, a valid petroleum system exists within the Anambra and Abakaliki basins, with the highly bituminous Lokpanta Member of the Eze-Aku Shale Group and the Nkporo Shales identified as targets for commercially viable hydrocarbon resources. Generated common risk segment maps indicate a low risk zone for the southwestern part of the study area. These results confirm that the southwestern part of the study area is the most prospective section, i.e. the section most favourable for hydrocarbon exploration and exploitation.

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To whom correspondence should be addressed: Chidozie I. Princeton Dim, Department of Geology, Faculty of Physical Sciences, University of Nigeria, Nsukka, Enugu State, Nigeria, princeton.dim@gmail.com; princeton.dim@unn.edu.ng