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Research Article

Sedimentology, Depositional Architecture and Paleogeography of Turonian to Early Maastrichtian Successions, Western Flank of Abakaliki Anticlinorium

William John*, Ezike OR, Onuigbo EN

Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria

ABSTRACT

This work was carried out to delineate surface geologic boundary between the southern Benue Trough and the Anambra Basin, determine the depositional environments and paleogeography of the encountered formations across the basins. Three formations were mapped with their boundaries delineated and they include: the Eze-Aku Sandstone Facies and the Awgu Shale (including the Agbani Sandstone Member) of the southern Benue Trough and the Nkporo Formation (including the Owelli Sandstone Member) of the Anambra Basin. The environments of depositions were interpreted through integration of lithology, textures, sedimentary structures and boundary contacts between one bed and another. Three lithofacies units were interpreted within the Eze-Aku Sandstone Facies. They are: the basal unit consists of dark grey fissile shale which grades upsection into siltstone and capped by trough cross-bedded and bioturbated pebbly sandstone. The Eze-Aku Formation is interpreted to be deposited in a lower delta plain (bay fill) facies associations which includes the interdistributary bay and the crevasse splay–natural levee environments. The Awgu Formation is interpreted to be deposited in a subaqueous delta plain facies association with the lower Awgu Shale being deposited in prodelta environment while the overlying Agbani Sandstone was deposited in delta mouth bar environment. The uppermost part of the Agbani Sandstone is interpreted to be deposited in a fluvial point bar facies association exhibiting lower channel floor, mid bar and upper bar environments.The Nkporo Formation is characterized by a tidally influenced estuarine deposits facies association with the lower Owelli Sandstone being deposited in environments ranging from tidal channels to intertidal flat. Overlying this unit is the Nkporo Shale which is interpreted to be deposited in environments ranging from offshore through lower–middle shoreface to intertidal flats. Paleocurrent analysis of the three formations indicates that the sediments of the Eze-Aku Formation were sourced possibly from the Oban Massif in the ESE direction of the current, the Awgu and Nkporo Formations paleocurrents plots showed a NNE direction showing that its provenance could possibly be from the older sediments of the Abakaliki Anticlinorium.

Keywords: Depositional Architecture; Paleogeography; Benue Trough; Anambra Basin

INTRODUCTION

LThe study area is bounded by Latitudes 6°0' 0" N and 60 8' 0" N and Longitudes 7°26' 0" E and 7°30' 0" E (Figure 1). The area is very much undulating with the ridges that are flanked at the sides by swales. The ridges are mainly underlain by sandstones while the shales underlain the swales. Access to outcrop locations was possible through major roads and minor roads leading to various towns and some foot paths and river channels. The Abakaliki Anticlinorium in the southern Benue Trough forms a divide with the younger sediments being deposited at the eastern and western flank of it. Our study centers on the sediments deposited within the western flank of the Anticlinorium with the aim of establishing the boundary between the Benue Trough and the Anambra Basin and determining paleogeography and paleoenvironments of the

Correspondence to: William John, Department of Geological Sciences, Nnamdi Azikiwe University, Awka, Nigeria, E-mail: ne.ajaegwu@unizik.edu.ng

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deposits using evidences from field geological mapping and detailed outcrop descriptions across the basins.

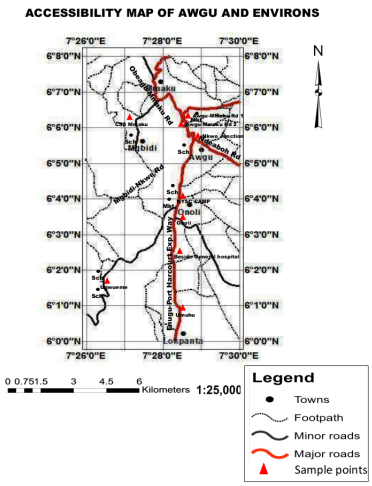

Figure 1: Low power shows a cystic lining epithelium and tumour islands in the stroma. Hyperchromatic basal cell layer and loosely arranged suprabasal layers are also appreciated.

Geological studies in south eastern Nigeria dates to the early 1960's, but most of the published information from these studies relate to general geologic observation and description from fossil assemblages. The first stratigraphic study of the south eastern Nigeria basins [1-5]. The basins' stratigraphy and paleogeography have been studied and described by various workers, such as believed that Eze-Aku Formation was deposited in a tectonically controlled basin with shales emplaced under marine conditions and the sandstones coinciding with the regressive phases of the epeiric sea movements [6-10]. The three major controls in sequence stratigraphic interpretation are tectonic, sea-level changes and sedimentation. The role of synsedimentary deformation structures in the generation of sequences in the area [11]. Their study noted four evidences of episodic subsidence during the Campanian-Maastrichtian period. A review of the petroleum potentials of the Benue Trough and the Anambra Basin and opined that they exist in some similarity in terms of stratigraphy, tectonics and organic geochemical evaluations of the basins with the contiguous basins of Chad and Niger Republics and Sudan [12]. Working on the eastern flank of the Abakaliki Anticlinorium gave a detailed classification of the Eze-Aku Sandstones facies and their stratigraphic successions [13]. The lithofaies of the Nkporo and Manu Formations in the Afikpo area using Markov Chain statistical analysis and dated the sediments using foraminiferal and palynological analyses [14]. In all the study so far, no one has attempted to integrate the stratigraphy of the southern Benue Trough to the adjoining Anambra Basin. We wish to achieve this purpose by erecting a sequence stratigraphic succession across the basins. This work will lead to further understanding of the petroleum systems of the area as search for discovery of more hydrocarbons in the frontier basins in Nigeria is in a top gear.

Geologic setting of the southern benue trough and anambra basin

The tectonic history of Southern Benue Trough, Southeastern Nigeria dates back to the pre-Albian times. [15, 16] The Abakaliki-Benue Trough originated as a failed arm of triple junction rift-ridge system, which led to the separation of Africa from South America during the Aptian/Albian (Figure 2). During the Early Cretaceous rifting processes were the dominant factor controlling the development of Nigeria's sedimentary basins. Important sinistral strike-slip movement occurred along the Benue Trough which was translated into extension in the east Niger rifts [17].

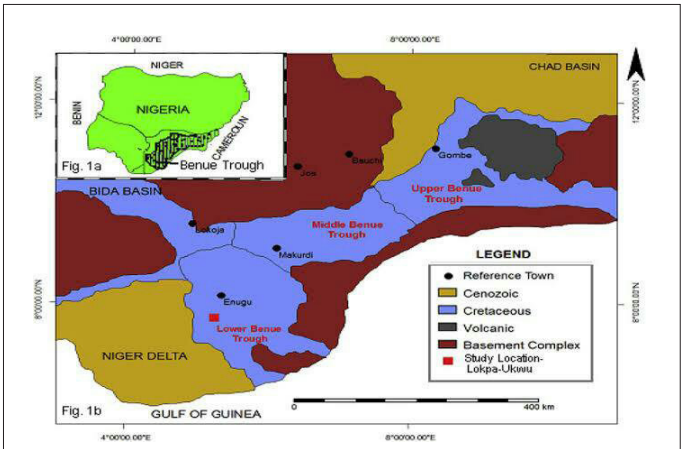

Figure 2: Map showing Geological Units of Benue Trough.

The Turonian marine transgression witnessed the termination of the generally regressive conditions that existed during the Cenomanian. In the Southern Benue Trough, the Turonian is represented by the Eze-Aku Group. This Group consists of hard grey and black calcareous shale, limestone and siltstone of the Eze-Aku Formation, and the inter-fingering regressive sandstones of Agala and Amasiri Formations which outcrop within the Afikpo synclinorium on the South East margin of the Abakaliki Anticlinorium. The Southern Benue Trough witnessed the end of regression in the Santonian with the full emergence in the Abakaliki area. The Coniacian-Santonian regression gave rise to the deposition of the Agbani Sandstone/Agwu Shale in the southern Benue Trough. There is a marked non-deposition of the Coniacian-Santonian Sediments in the Afikpo syncline (eastern flank of the anticlinorium); hence the Awgu Shale is missing in the Afikpo syncline stratigraphy. However, Awgu Shale and its sandstone member the Agbani Sandstone are very dominant in the western flank of the Abakaliki Anticlinorium.Reported that the Agbani Sandstone (Awgu Sandstone) outcropping at Ugwueme in awgu area is impregnated with heavy tarry oil and rest unconformably on the folded Awgu Shales.The post Santonian is marked by an extensive subaerial unconformity in the Anambra Basin as well as the Abakaliki and Afikpo Synclines. Earlier workers took the Nkporo Group as the first oldest sedimentary deposit in the Anambra Basin (Figure 3). But recent works by [18] opened

up the possibility of having pre-Santonian sediments, at least at the northwestern part of the Basin, hence assisting in clearing the controversies associated with it. The Nkporo Group forms the basal facies of the late Cretaceous sedimentary cycle in the Anambra Basin, deposited during late Campanian. The Nkporo Group is generally exposed at Leru, about 74kilometer along Enugu-Port Harcourt Expressway, and is described as a coarsening upward deltaic sequence of shales and inter-bedded sands and shales with occasional thin beds of limestone deposited during a short interval of marine transgression [19]. The Nkporo Group is made up of three formations: the Afikpo/Owelli Sandstone, the Nkporo and the Enugu Shales. The Afikpo Sandstone is exposed at the eastern flank while the Owelli Sandstone is exposed at the western flank of the Abakaliki Anticlinorium.

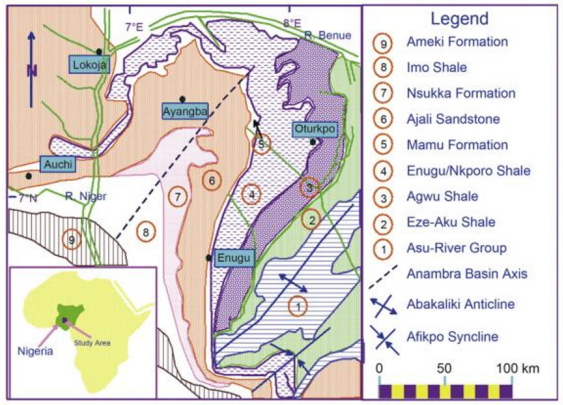

Figure 3: Geologic map of southeastern Nigeria showing the Abakaliki Anticlinorium and the formations at its eastern and western flanks.

MATERIALS AND METHODS

The materials used for the study include some field mapping tools such as base map, compass clinometer, measuring tapes, hand lenses, grain size comparator, field notebook, rock sample bags, digital camera and global positioning system (GPS). The laboratory materials used include: transmitted light binocular microscope, SedLog version 3.0, excel spread sheet and other relevant journals for studying of the previous works in the study area.

The methods employed are field and laboratory studies. The field mapping involves delineation of geologic boundaries, detailed outcrop logging, and measurement of attitudes of beds and cross beds azimuth (especially the trough cross beds).

Field mapping

Detailed field mapping was carried out with the aid of the base (topographic) map, GPS for locating the study sections in the map and compass clinometer for determining the trend of the geologic boundaries. The boundaries were inferred from the gradual changes in lithology, vegetation and topography. However, the boundaries between one formation and other were inferred based on the gradational changes in lithofacies.

Outcrop study

Outcrop logging was carried out at different locations where they are exposed as a result of road cut, erosion and stream channels. The observation and recording of the features started from the base of the exposures. The geological features recorded are: the lithotypes, bed thickness, grain size, colour, mineral composition, nature of contact between one bed and the other, the sedimentary structures which include physical, biogenic and chemical, attitude of the bed and cross bed azimuth. The intensity of bioturbations at different beds was noted while illustrations of their structures were made on the field notebook. Dilute HCl were applied to beds suspected to contain carbonates for possible confirmation.

Depositional sequence

Facies association and their component depositional environments were interpreted using classical text book models [20].

Paleocurrent analysis

The paleocurrent indicators are oriented sedimentary structures interpreted to have been deposited by ancient flows. The varieties of possible paleocurrent indicators include cross beds, pebble imbrications, ripple crest orientation, sole marks etc. The shapes of the paleocurrent indicators provide unique information about the flow directions. However, trough cross beds were properly exposed in the encountered formations; hence, their azimuths were measured in the field and plotted using rose diagrams [21]. The rose diagrams were used for provenance studies.

RESULTS AND DISCUSSION

Results

Lithostratigraphic units: Three lithostratigraphic units delineated in the study area are the Eze-Aku Sandstone facies, the Awgu Formation and the Nkporo Formation (Figure 4).

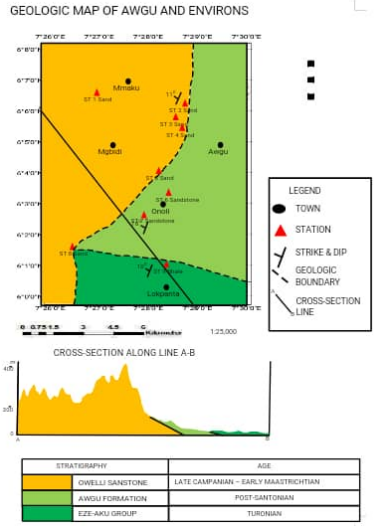

Figure 4: Geologic map of the study area showing the encountered formations, their boundaries and the bed attitudes.

Sedimentology: The lithologic descriptions in the study area were based on the systematic observations of the outcrop sections and measurements of bed attitudes, cross bed azimuths and thickness of individual beds. The exposed sections of Eze-Aku were found along Umuhu-Lokpanta Road (Figures 5 and 6) while that of Agbani Sandstones and Nkporo Group are partially exposed in Awgu town and Awgu-Mmaku road respectively [22-24]. The Nkporo Group identified in the study area include Owelli Sandstone and Nkporo Shale which extended to Mmaku town. However, the ancient sea movement in the western flank of Abakaliki Anticlinorium exposed at Awgu and its environs is regressively stretching from Late Santonian with deposition of Agbani Sandstone to Early Maastritchian with the deposition of Owelli Sandstone.

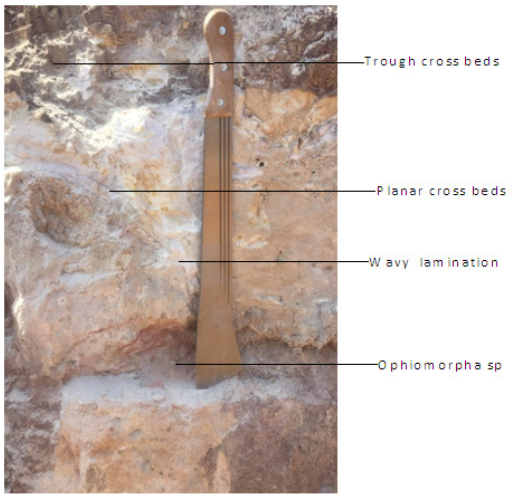

Figure 5: Outcrop Section of Eze-Aku Formation at Umuhu.

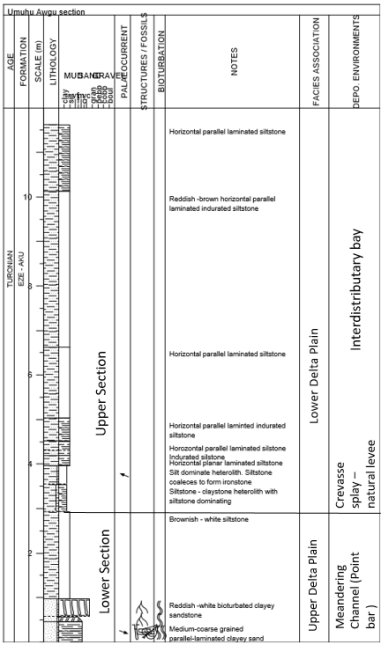

Figure 6: Interpreted Lithologic Section of Eze-Aku Formation at Umuh.

Lithology and facies analysis: The description of outcrop and the interpretation of the environments of depositions are discussed section by section below.

Umuhu locality: The Eze-Aku Sandstone facies exposed in this locality is situated within Umuhu and accessible through track road running off Lokpanta-Umuhu road. The outcrop section is situated within latitude N06°01/ 2// and longitude E007°28/ 30// with ground elevation of 109 m. The section is about 11.6 m thick. It consists of 2.8 m basal section and 8.8 m upper section. The lower unit of the basal section consists of medium to coarse grained, parallel laminated and bioturbated clayey sand with a leaf imprint. This unit is overlain by a 0.5 m very fine to silty sand unit with rootlet. Overlying this unit is a coarse to pebbly, reddish-white bioturbated clayey sandstone with scour base. This third unit equally contained rootlet. The fourth and last unit in this section is a thick brown-white siltstone. This basal section is interpreted to be deposited in an upper delta plain facies association with depositional environment interpreted as meandering channel (point bar). The upper section starts with alternating siltstone-claystone heteroliths which is overlain by indurated horizontal laminated siltstone. Above these units is a sequence of horizontal parallel laminated siltstones. This deposits are interpreted to be deposited a lower delta plain (bay fills deposits) facies associations existing within the realm of river-marine interaction.The environments of deposition consists of crevasse splay – natural levee and interdistributary bay. The outcrop and the interpreted lithologic sections. The above outcrop section shows structues like planar cross beds, trough cross beds, wavy lamination and trace fossils such as Ophiomorpha sp. as indicated by the lines on the outcrop.

Ugwueme waterfall section: The Agbani Sandstone outcropping at the Ugwueme is impregnated with Tar-sand with spring water rushing down the cliff in form of water fall. The section shows the contact between the Awgu Shale and the Agbani Sandstone which overlies it. The outcrop section is situated within latitude N06°01/ 40.15// and longitude E007°26/ 35.3// with ground elevation of 153 m. The section is about 11 m thick and consists of a 3.5 m thick basal dark grey shale unit. The top of the basal unit consists of oil impregnated coarse to very coarse-grained sandstone (Tar Sand) of about 2 m thick. The upper boundary bedding plane is aligned with the oil showing that the bed is unconformable with the bed above it. The unconformity is evidence of the boundary between the Benue Trough and the Anambra Basin. The upper part of the section consists of 5 m thick coarse to very coarse-grained massive sandstone which is interpreted as the Owelli Sandstone. The section ended with brownish siltstone of about 0.5 m thick. Observed in the outcrop was the rarity of trace fossils which may be due to fluctuating salinities, intolerable conditions and rapid accumulations of sediments over the burrowing organisms as evidenced by the total disappearance of sedimentary structures at the massive sandstone. This section shows subaqueous delta plain facies association which was interpreted as prodelta to delta mouth bar and natural levee environments. The outcrop and lithologic sections are shown in Figures 7 and 8.

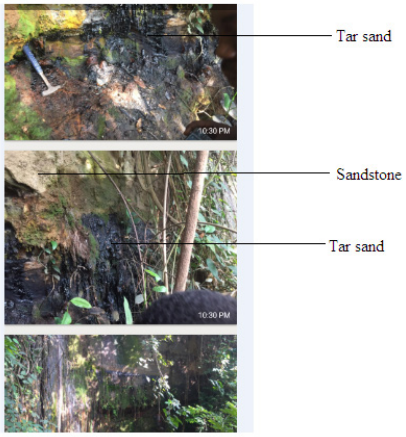

Figure 7: Minimum Amplitude extraction on reservoir zone on Sw impedance volume showing the distribution of the gas saturation.

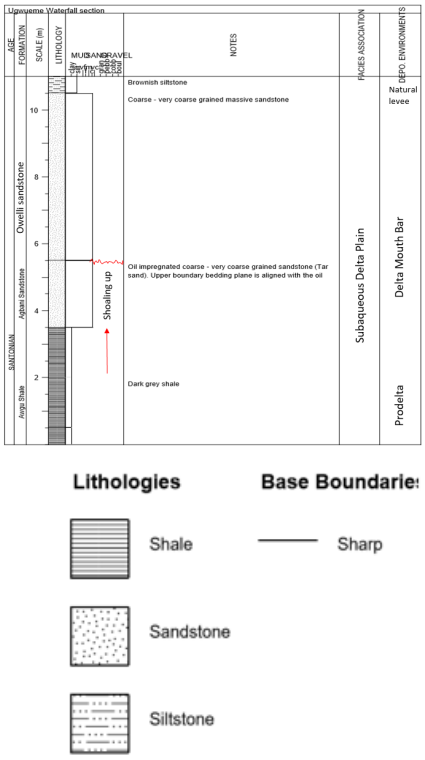

Figure 8: Minimum Amplitude extraction on reservoir zone on Sw impedance volume showing the distribution of the gas saturation.

General hospital, awgu: The Agbani Sandstone is exposed at this section. The sandstone is a member of the Awgu Formation. The section is located at Awgu town which was accessed using major road beside General Hospital, Awgu. The area situates within latitude N06°02/ 29.7// and longitude E007°28/ 29.4// with ground elevation of 176 m. The section is a relatively small outcrop of about 5.2 m thick. The basal part is a 0.56 m thick well sorted, brownish very fine-grained sandstone unit. This unit is overlain by 1.04 m thick poorly sorted, clast - supported conglomeratic sandstone. The sandstone is characterized by planar cross beds. The upper unit of the section consists of a 3.5 m thick heterolithic made of sandstone interbedded with silty-clay. There are elements of convolution in some of the beds. It noted that among the vertical sequence of a meander point bar sand body is a section which overlies a large scale cross bedded unit consisting of repeated cyclic sedimentation units of climbing ripple, convolute laminations and parallel well sorted sand lamination. This is typical of what this section represent. The facies association is therefore interpreted as fluvial point bar with the basal unit interpreted as interdistributary bay environment. The upper unit ranges from lower bar, exhibiting channel floor to middle bar and upper bar environments. The outcrop and lithologic sections are shown in Figures 9 and 10 below. The sandstone on the above outcrop section forms a wedge as indicated by the hammer and line. The erosional surface and sedimentary structure such as planer cross beds are equally indicated by the lines on the outcrop section.

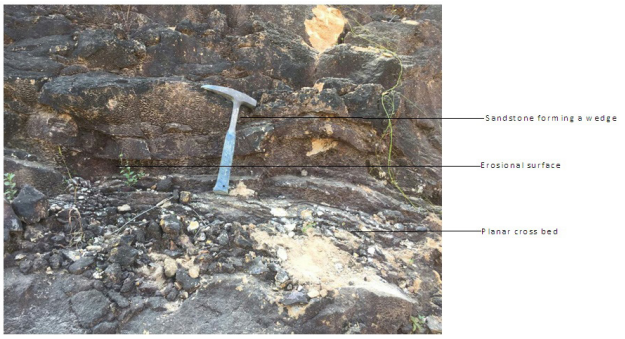

Figure 9: Outcrop Section of Awgu Formation beside General Hospital, Awgu.

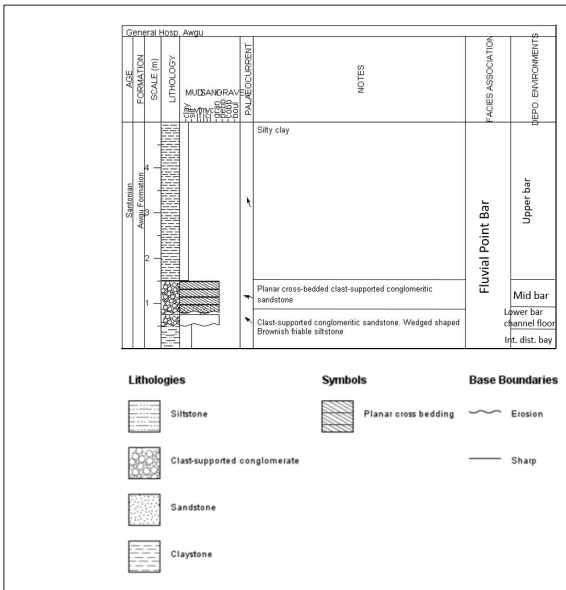

Figure 10: Lithologic Section of Awgu Formation beside General Hospital, Awgu.

Nkwombanano junction, along awgu-mmaku road: The Nkporo Formation is exposed at edge of Awgu-Mmaku road at a junction called Nkwombanano within Awgu town (Figure 11). The ridge runs parallel to Awgu-Mmaku road. The outcrop section is situated within latitude N06°05/ 47.6// and longitude E007°28/ 52.5// with ground elevation of 195 m. It is about 12.3 m thick. The basal part is the Owelli Sandstone. The exposed basal bed is of about 0.8 m thick and consists of bioturbated brownish medium to coarse grained sandstone. Above the basal bed is a unit of 0.1 m thick consisting of silt-clay heteroliths with silt dominating. This unit is overlain by fine to medium grained bioturbated reddish brown sandstone of about 0.2 m thick. The middle part of the section consists of successions of reddish-brown silt-clay heteroliths (silt dominant), shale-silt heteroliths (shale dominant), conglomeratic sandy silt, brownish fissile shale and poorly sorted (fine to very coarse grained) planar cross bedded sandstones. Above this alternating heterolithic unit is the Nkporo Shale. It consists of dark grey fissile shales of about 7.4 m thick. The general variability in the intensity of bioturbation, generally fining-upward sequence and channeling characters, delineation of stillstand units within the complex and reversal of paleoflow which characterizes the section were used in interpreting the section as estuarine deposits (upper reaches of an estuary) facies association. The interpreted depositional environments range from tidal channels to intertidal flat. The outcrop and lithologic sections are shown in Figure 12.

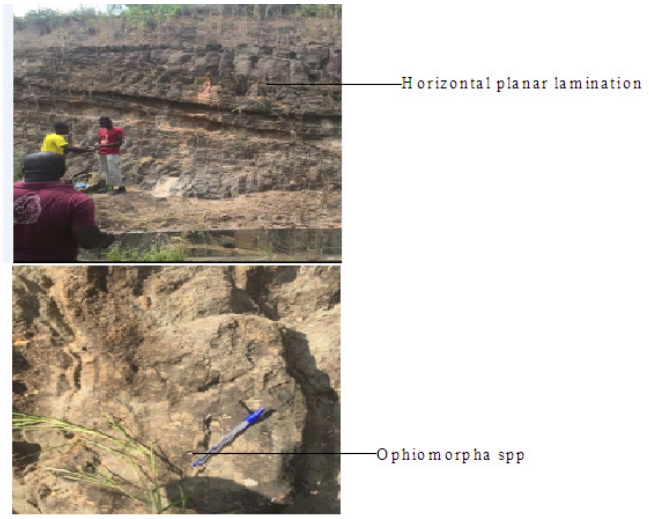

Figure 11: Outcrop Section of Nkporo Formation at Nkwomban.

Awgu-mmaku road 1 (4 km from nkwombanano junction): The Owelli Sandstone exposed at this section is located at about 4 km away from Nkwombanano Junction and is accessible through Awgu-Mmaku road. The outcrop section is situated within latitude N06°05/ 14.1// and longitude E007°28/ 57.5// with ground elevation of 278 m. The section is about 12 m thick. It consists of a basal 0.9 m thick of dark grey fissile shale which is overlain by a 0.3 m thick silt dominated heterolith with clay. This is overlain by about nine successions of sandstone facies with grain sizes that range from fine – medium – coarse – conglomerate. The section is characterized by the presence of planar cross beds and trace fossils such as Ophiomorpha sp. The topmost unit of the section consists of parallel laminated sand dominant heterolith with siltstone of about 2.4 m thick. The facies association is interpreted as lower reaches of an estuary with the basal unit of the section interpreted as intertidal flat environment. The middle part of the section is interpreted as tidal channel environments while the topmost unit is interpreted as intertidal flat environment. The outcrop and lithologic sections are shown in Figures 13 and 14. The outcrop section is bioturbated. The section comprises of shale at the base and siltstone that overlies the shale. However, the sandstone overlies the siltstone with presence of planar cross beds and all are indicated by the lines drawn on the outcrop section above.

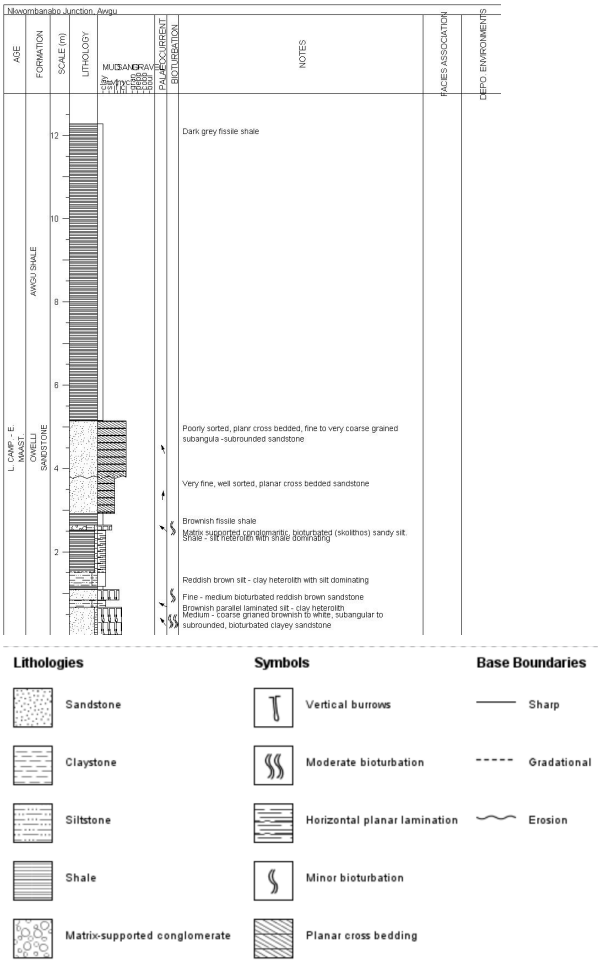

Figure 12: Lithologic Section of Nkporo Formation at Nkwombanano Junction showing both the Owelli Sandstone and the overlying Nkporo Shale.

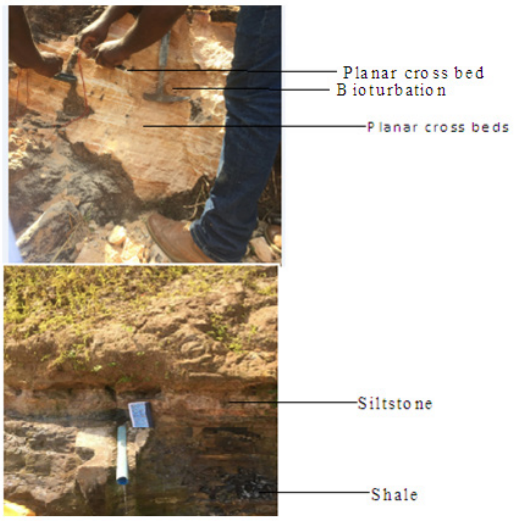

Figure 13: Outcrop Section of Nkporo Formation along Awgu-Mmaku Road 1.

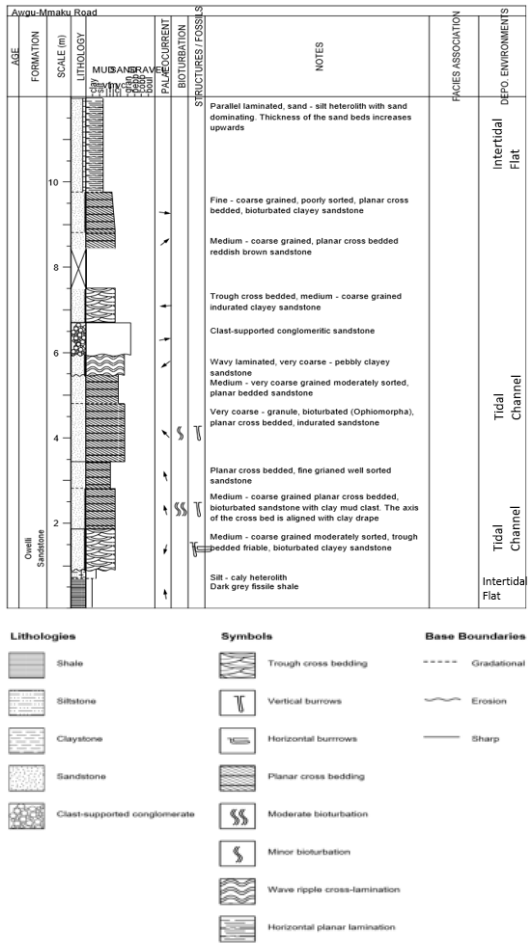

Figure 14: Lithologic Section of Nkporo Formation along Awgu-Mmaku Road 1

Awgu-mmaku road 2: The Owelli Sandstone exposedat this section is located at 6 km from Awgu-Mmaku Road 1 and was equally accessible using major road along Awgu-Mmaku road. The outcrop section is situated within latitude N06°06/ 8.1// and longitude E007°28/ 40// with ground elevation of 283 m. The section is about 15.42 m thick and consists of 0.78 m basal clay – siltstone heteroliths with clay dominating. It is characterized by the presence of flaser beddings. This lower unit is overlain by intercalations of siltstone and sandstone facies. Overlying this unit is a series of bioturbated, planar cross bedded conglomeritic sandstone facies while the topmost part consists of clay – siltstone heterolithic facies with siltstone dominating. The facies association is interpreted as lower reaches of an estuary with the basal part interpreted as intertidal flat environment. The middle part is interpreted as tidal channels, while the topmost unit indicated an intertidal flat environment. The outcrop and lithologic sections are shown in Figure 15.

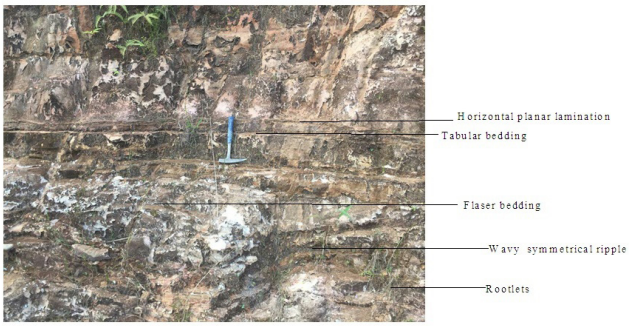

Figure 15: Outcrop Section of Nkporo Formation along Awgu-Mmaku Road 2 showing the lower and the middle units.

Community secondary school, mmaku: An outcrop exposure in the upper part of Nkporo Formation is seen at Community secondary school, mmaku (Figure 16), where it situates within latitude N06°06/ 15.2// and longitude E007° 27/ 10// with ground elevation of 318 m. The entire exposed unit is about 7.3 m in thickness and comprises of shale, ironstone and sandstone facies. The basal unit is of about 2 m and comprises highly fissile dark grey shale which is overlained by oolitic ironstone of about 1m in thickness. The middle part of the section consists of clay-silt heterolithic facies showing horizontal parallel lamination structure with thickness of about 0.7 m. This is overlain by intercalations of sandstone and shale facies of about 1.9 m thick. The sequence is capped by about 1.7 m thick sand-silt heteroliths with sandstone dominating. The facies association is interpreted as Shoreface. The environment of deposition shows a shallowing in environment. The basal section is interpreted as offshore – lower shoreface which is succeeded upsection with environment interpreted as lower – middle shoreface. The outcrop and lithologic sections are shown in Figures17 and 18.

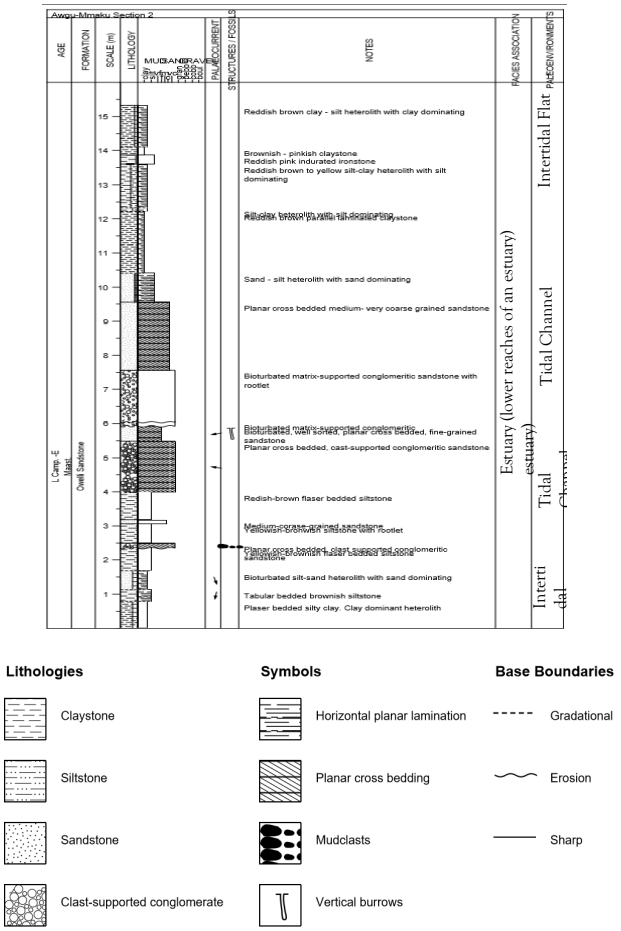

Figure 16: Lithologic Section of Nkporo Formation along Awgu-Mmaku Road 2.

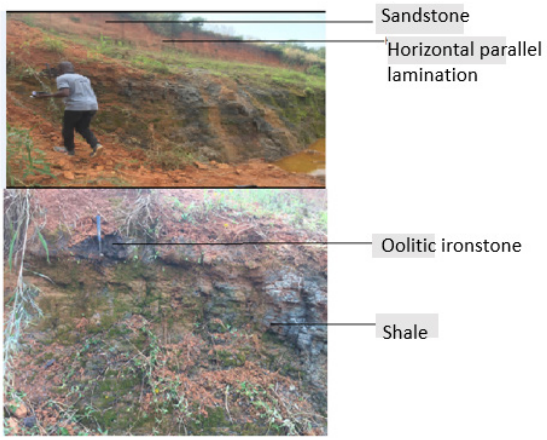

Figure 17: Outcrop Section of Nkporo Formation at Community Secondary School, Mmaku. The biro at the lower section is showing the oolitic ironstone.

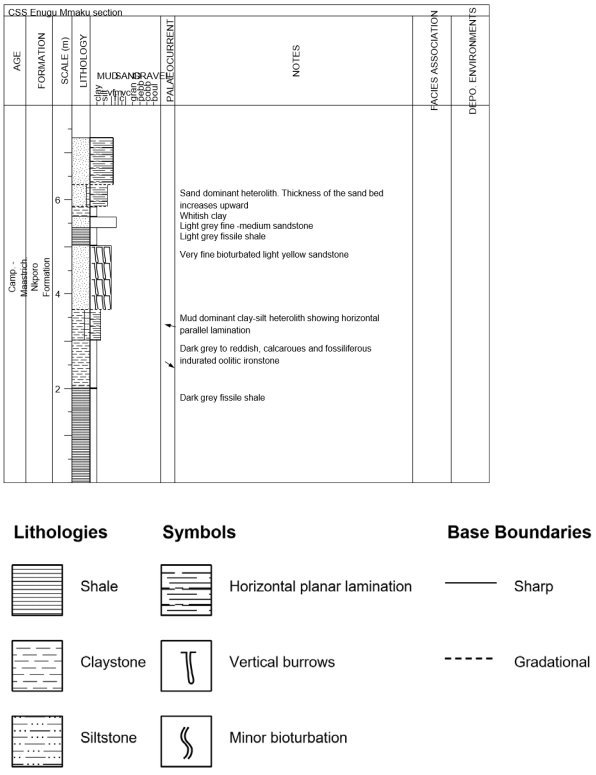

Figure 18: Lithologic Section of Nkporo Formation at Community Secondary School, Mmaku.

Paleocurrent analysis of the study area

This analysis was achieved with the help of sedimentary structures such as cross beds. They are called paleocurrent indicators. There are different types of cross beds such as trough, planar, hummocky and herring bones cross beds but the most common cross bed encountered during the field work was the trough and planar cross beds. The bearing of the bisetrics of the trough cross beds were used to interpret the ancient flow movement in the western flank of Abakaliki Anticlinorium exposed at Awgu areas.

Paleo-flow data of eze-aku formation

The dip directions of the bisetric of the trough cross beds measured in the exposure of the Eze-Aku Sandstone facies are shown in Table 1. These dip directions were plotted to determine the dominant flow direction (Figure 19). The Paleocurrent plot above is for Eze-Aku Formation, indicating that sediments were transported from the East South East (ESE) portion into the basin. From the geological map of Nigeria, the sediments may be coming from the Oban Massif. The paleocurrent rose plot from Table 2 is shown as Figure 20. The paleocurrent distribution is south westerly with dominant node in south-south west direction. This suggests that the sediments were derived primarily from the North-North Eastern (NNE) direction. The sediments however, could be sourced from the older rock of the Abakaliki Anticlinorium

Table 1: Trough cross bed azimuths measured at Eze-Aku Formation.

S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH
1	2920	11	2950	21	2820	31	2960
2	2860	12	2910	22	2820	32	2960
3	2980	12	3000	23	2830	33	2990
4	2840	14	3050	24	2870	34	2980
5	3020	15	2970	25	2860	35	2860
6	2800	16	2980	26	2860	36	2920
7	2820	17	2920	27	2790	37	2920
8	2840	18	2920	28	2780	38	285
9	2810	19	2930	29	2790	39	2560
10	2930	20	2940	30	2860	40	255

Table 2: Azimuths of the trough cross beds obtained from Awgu Formation.

S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH
1	750	11	1160	21	3100	31	3020
2	1000	12	1150	22	3200	32	3260
3	1150	13	1120	23	3240	33	3200
4	1060	14	1100	24	3000	34	3150
5	1220	15	1000	25	3020	35	3120
6	1150	16	1020	26	3200	36	3220
7	1750	17	1040	27	3280	37	760
8	780	18	1060	28	3150	38	780
9	750	19	1020	29	3100	39	1000
10	760	20	1000	30	3000	40	1150

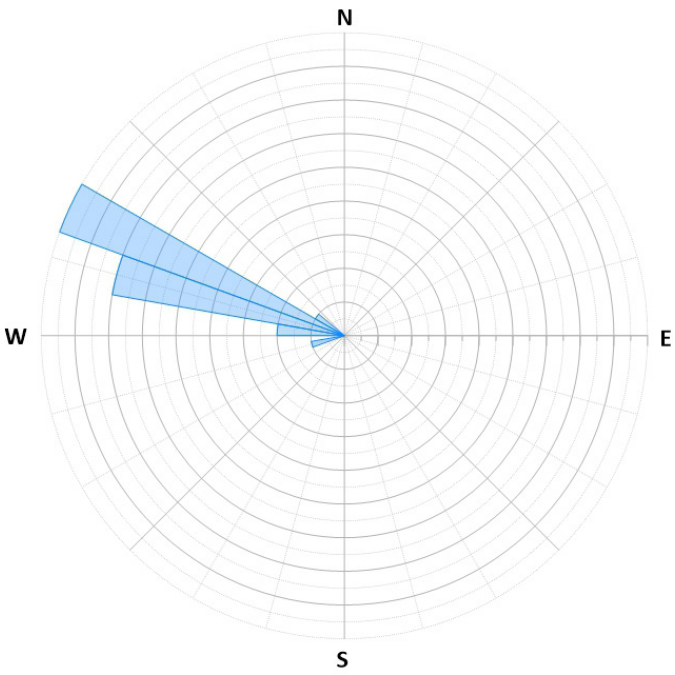

Figure 19: Rose diagram of trough cross beds showing the direction of flow of current that deposited the Eze-Aku Formation.

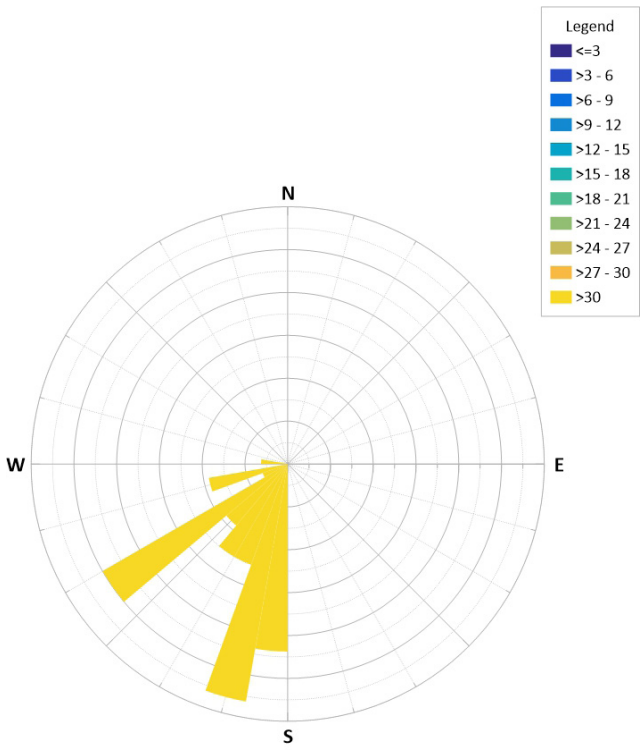

Figure 20: Rose plot of the trough cross beds showing directional flow of current in Awgu Formation.

Paleo-flow data of nkporo formation

The paleocurrent rose plot from Table 3 is shown as Figure 21. The Paleocurrent plot above is for Nkporo Formation, indicating that sediments were transported from the East-North Eastern (ENE) provenance area into the basin.

Paleocurrent rose plots

The paleocurrent analysis of the three formations indicates that the sediments of the Eze-Aku Formation were sourced possibly from the Oban Massif with the ESE direction of the current. The Awgu Formation paleocurrent indicates an NNE direction,

Table 3: Azimuth of the Trough cross beds in Nkporo Formation.

S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH	S/N	AZIMUTH
1	354°	11	3100	21	2970	31	720
2	3480	12	680	22	2980	32	3440
3	660	13	2750	23	3020	33	700
4	3400	14	2900	24	3000	34	520
5	3200	15	700	25	1250	35	3020
6	3200	16	100	26	3220	36	2750
7	3150	17	150	27	520	37	150
8	350	18	2900	28	180	38	350
9	500	19	300	29	100	39	2900
10	3000	20	300	30	2780	40	350

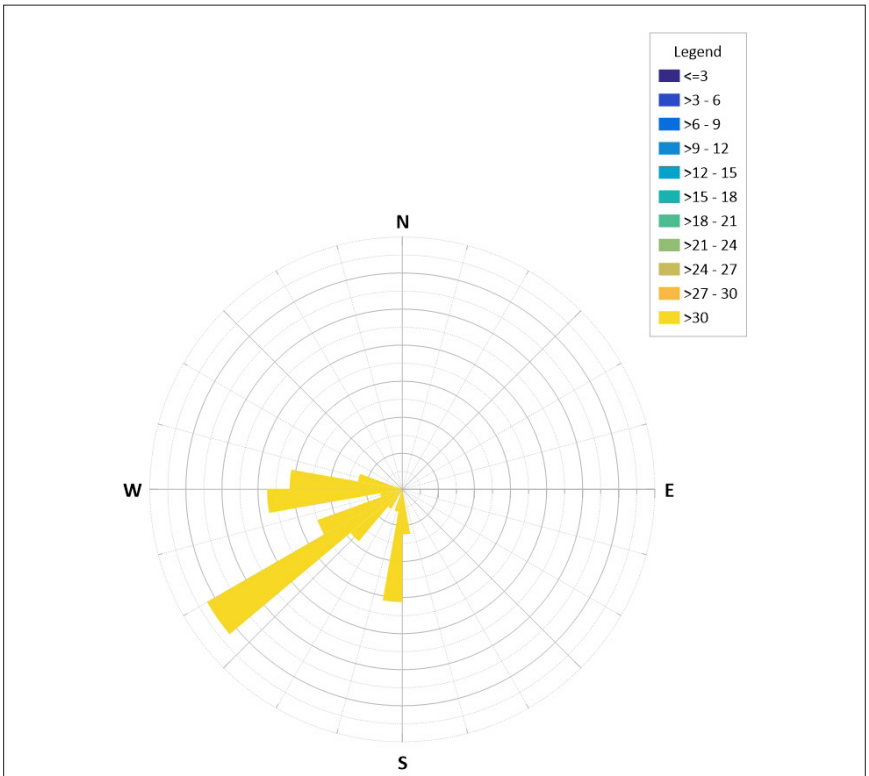

Figure 21: Rose diagram of trough cross beds showing the directional flow of current in Nkporo Formation.

showing that its provenance could be possibly from the older sediments of the Benue Trough. However, the current that deposited the Nkporo Formation came from the ENE direction which indicates that the sediments were sourced possibly from the Abakaliki Anticlinorium.

Stratigraphic succession

The basin fill that started with the Eze-Aku sandstone facies appears to be more regressive and the ancient sea reverses its movement to become transgressive with deposition of Awgu Shale. The sea reverses again to regression when the Agbani Sandstone was deposited. The Agbani Sandstone was seriously disturbed with tectonics showing evidence of folding and faulting during the Santonian time. This event could be accompanied by erosion that incised into the Awgu Formation creating a valley. The valley got filled during the stillstand with the deposition Owelli Sandstone. Once the valley was completely filled, the sea began to rise rapidly with the deposition of the Nkporo Shale.

Facies association

The Eze-Aku Sandstone facies is interpreted to be deposited in a lower delta plain characterized by interdistributary bay and crevasse splay – natural levee environments. The delta condition prevails over the Awgu Formation but extended from the lower delta plain to subaqueous delta plain. It begins with prodelta shales and extended to delta mouth bar with the deposition of the Agbani Sandstone. Towards the end of the Agbani Sandstone, the sea continues to recede and approached into a fluvial point bar environment. The sequence from the Eze-Aku Sandstone facies up to some parts of the Awgu Shale infilled during a regressive phase.

The next sea level movement episode started with a stillstand where the basal Agbani Sandstone was deposited within the delta mouth bar environment. The subsequent tectonic episode that involved faulting, folding and erosion of parts of the Agbani Sandstone however, destroyed other evidence of the sea level movement.

The next transgressive movement started at the base of the Nkporo Group with the deposition of the Owelli Sandstone in a stillstand stacking pattern. The infilled sediment of the Owelli Sandtsone is interpreted to be deposited in a tidally influenced estuary as an incised valley fill (IVF). The Eze-Aku Formation was deposited in lower delta plain (bay fill) facies association which includes the interdistributary bay and crevasse–splay natural levee environments. The Awgu Formation was deposited in a subaqueous delta plain facies association; the lower Awgu Shale was in prodelta environment and the overlying Agbani Sandstone was deposited in a delta mouth bar environment. The uppermost part of Agbani Sandstone was deposited in a fluvial point bar facies association. The Nkporo Formation is characterized by a tidally influenced estuarine deposits facies association with the lower Owelli Sandstone being deposited in environments ranging from tidal channels to intertidal flat.

Environments of deposition

The Eze-Aku Formation and the lower part of the Awgu Shale were interpreted to be deposited within deltaic environment. The Agbani Sandstone which overlies the Awgu Shale was deposited in a fluvial point bar environment while the overlying Owelli Sandstone was deposited in an estuarine environment. The Nkporo Formation was deposited in a more marine environment ranging from offshore to middle shoreface.

CONCLUSION

The paleogeographic reconstruction was possible by integrating the results obtained from stratigraphic successions, facies analysis, biogenic structures and paleocurrent analysis. The key lithofacies encountered in the study area include shale, clay, siltstone and sandstone lithofacies. The facies association analyzed during the study started with lower delta plain (bay fill) facies association with the Eze-Aku Sandstone being deposited in environments which include interdistributary bay fill and crevasse-splay natural levee. The delta facies association prevails over Awgu Formation and extended to subaqueous delta plain facies association. The subaqueous delta plain which started with lower Awgu Shale was in a prodelta environment, while the overlying Agbani Sandstone was deposited in a delta mouth bar environment. The uppermost part of Agbani Sandstone was deposited in a fluvial point bar facies association. The Nkporo Formation is characterized with tidally influenced estuarine and shoreface zone facies association with Owelli Sandstone being deposited in environment ranging from tidal channels to intertidal flat and the uppermost part of the Nkporo Shale being deposited in an environment ranging from offshore to middle shoreface. The presence of biogenic structures such as Ophiomorpha and rootlets could be an evidence of tidally dominated environment and this could be the case of Owelli Sandstone in Nkporo Group while the rarity of bioturbation in the sandy portions depicts an environment hostile to organisms because of high sedimentation rates and unstable salinity which could be possibly the case of Agbani Sandstone located at Ugwueme water fall. The paleocurrent analysis as interpreted with the help of rose plots unveiled three possible provenance areas for the sediments of Eze-Aku, Awgu and Nkporo Formations as Oban Masif with the EES direction of the current, older sediments of Benue Trough with NNE direction of the current and the Abakaliki Anticlinorium with EEN direction of the current respectively.

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