Petrographic and stratigraphic analyses of Palaeogene Ogwashi-Asaba formation, Anambra Basin, Nigeria

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An integrated analytical approach comprising petrographic, geochemical, and sedimentological studies was carried out in thirteen outcrop and four subsurface samples of the Pakaeogene Ogwashi-Asaba Formation in the Anambra Basin. The goal was inferring about source rock, transport history, tectonic setting, depositional environment and hydrocarbon potentials. Sandstones are coarse to medium grained, moderately to poorly sorted, fine to nearly symmetrically skewed. Bivariate plots of skewness against sorting and sorting against mean size indicate a fluvial depositional environment. Most of the sandstone exhibit bimodality, which indicated more than one source. Those are lithic arenites comprising 64% rock fragment, 31% quartz, 5% feldspar which suggest that they are mineralogically immature sands. The ternary plot of the framework elements revealed that they are derived from an orogen which is taken to be a molasse trough formed between basin and craton. Geochemical analysis showed the prevalence of SiO_2 (5.84-84.57%) and total Fe (12.69-92.07%) over all other oxides. This points to an oxidizing, sub aerial environment, which favours the formation of hematite. SiO_2/A_2O_3 ratio indicates chemical immatureness. Organic analysis in lignite gave TOC 1.60-3.13%. Vitrinite dominated maceral suggested has the source potential for gas. Scatter plots (tissue preservation vs. gelification index) indicated on swamps as depositional environment of lignite.

Key words: Ogwashi-Asaba Formation, Anambra Basin, Palaeogene, sandstone lithofacies, Nigeria

1. INTRODUCTION

The Anambra Basin (SE Nigeria) consists of rhythmic clastic sequence of sandstones, shales, siltstones, mudstones and sandy shales interbedded with coal seams.[32] It covers about 40 000 km^2 and a thickness of 6 km. The Anambra Basin was exploring from 19th century and has been a major geological centre for coal exploration since 1909. Assessment of petroleum potential has been done, especially the geochemical evaluation of the shales. The Ogwashi–Asaba Formation is identified within the Palaeogene Anambra Basin, i.e. Afikpo Geosyncline.[31] This formation is also referred to as the Lignite “series”.[33] The Formation is characterized by widely differing lithologies comprising alternation of clays, sands, grits and lignites.

Numerous reports exist that described the occurrence, areal extent and economic importance of the lignite seams.[1, 3, 4, 5, 13, 17, 33, 37, 47] Those results asked for defining transport history and depositional environment of the sediments using their lithological/petrographic character-

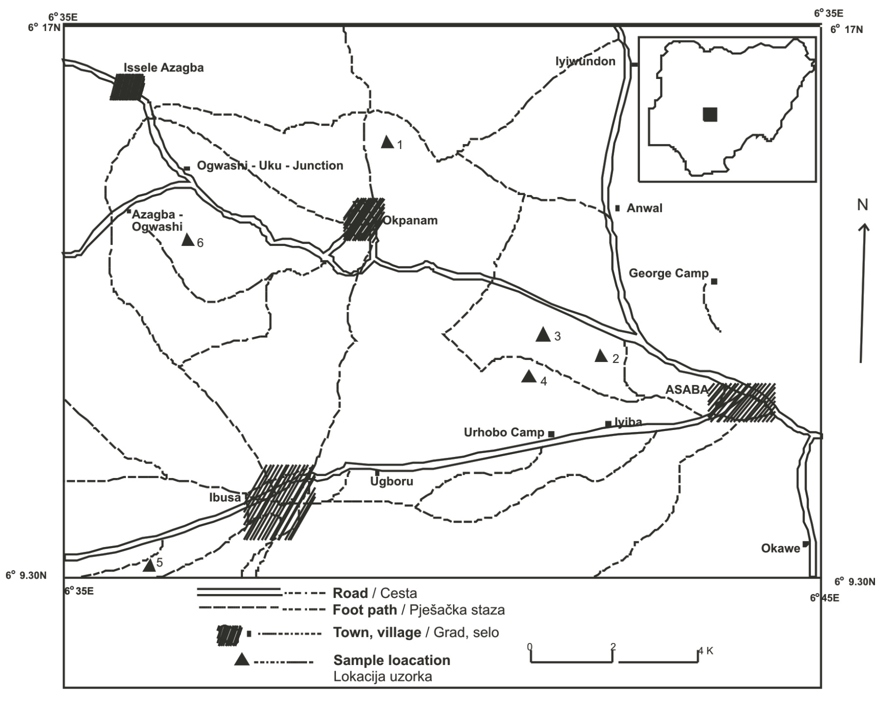

Fig. 1. Sample Location Map (inserted map of Nigeria showing study area)
Sl. 1. Karta lokacija na kojima su uzeti uzorci (karta Nigerije s prikazanim područjem proučavanja)

istics and textural parameters in order to evaluate the source and maturity of the various facies and assessment of hydrocarbon potential.

2. GEOLOGIC SETTINGS

The geology of the Anambra Basin has been documented by various workers.[3,16,27] The basin is a synclinal megastructure located at the southwestern edge of the Benue Trough in Nigeria (Figure 1). The proto Anambra Basin was a platform during Albian–Santonian period with reduced sedimentation. Major folding episode occurred in the Benue Trough during Late Cretaceous, i.e. Santonian.[10] The Santonian event uplifted Abakaliki–Benue Trough into Abakiliki Anticlinorium, and created the Anambra Basin.[3, 25, 37, 41] Today basin included 6 km thick sediments of Campanian to Miocene ages. Structurally, it is located between Cretaceous Benue Trough and Delta.[24, 32] Sedimentation in the Anambra Basin continued with Campanian-Maastrichtian marine and paralic sediments of the Nkporo/Enugu Shales and the Owelli Sandstones. These formations are overlain by Mamu Formation (lower coals measure), Ajali Sandstone, Nsukka Formation (upper coal measure), Imo Formation, Ameki Formation and Ogwashi–Asaba Formation (Figure 2). Sediments in the Anambra Basin are of continental, fluvial and shallow marine type.[3, 29, 31, 32]

The Ogwashi–Asaba Formation is identified within the Palaeocene Anambra Basin (Afikpo geosynyncline).[31] The formation is characterized by alternation of clays, sands, grits and lignites.[12, 47] The formation occurs mainly in Benin, Asaba, Onitsha and Owerri areas (Figure 1).

Reyment[37] suggested Oligocene–Miocene age for this formation, but palynological results by the work of Cherie et al.[21] assigned a Middle Eocene age to the basal part. The Ogwashi–Asaba Formation is a surface lateral equivalent of the Agbada Formation which occurs in the subsurface of the Niger Delta.[6, 7, 41]

AGE (m. y)		ABAKALIKI - ANAMBRA BASIN	AFIKPO BASIN
30	Oligocene	Ogwashi-Asaba Formation	Ogwashi-Asaba Formation
54.9	Eocene	Ameki/Nanka Formation/ Nsugbe Sandstone (Ameki Group)	Ameki Formation
65	Palaeocene	Imoi Formation Nsukka Formation	Imoi Formation Nsukka Formation
73	Maastrichtian	Ajali Formation Mamu Formation	Ajali Formation Mamu Formation
83	Campanian	Npkoro Oweli Formation/Enugu Shale	Npkoro Shale/ Afikpo Sandstone
87.5	Santonian	Agbani Sandstone/Awgu Shale	Non-deposition/erosion
88.5	Coniacian	Agbani Sandstone/Awgu Shale	Eze Aku Group (incl. Amasiri Sandstone)
	Turonian	Eze Aku Group	Eze Aku Group (incl. Amasiri Sandstone)
93 100	Cenomanian-Albian	Eze River Group	Eze River Group
119	Aptian Barremian Hauterivian	Unnamed Units	
Precambrian		Basement Complex	

Fig. 2. Stratigraphic subdivision of Abakaliki-Anambra-Afikpo Basin for Early Cretaceous-Tertiary strata in the south-eastern Nigeria (modified from ref.[27])

Sl. 2. Stratigrafska raščlamba bazena Abakaliki-Anambra-Afikpo za razdoblje od donje krede do tercijara u jugozapadnoj Nigeriji (modificirano prema ref.[27])

3. METHODOLOGY

Field data were taken from successive outcrops at quarries, valleys and river/stream channels, and measured to gather information on the rock types and their stratigraphy. Samples are taken from Asaba, Azagba-Ogwashi, Okpana and Ibusa areas (Figure 1). Data about texture, colour, grain size, thickness, sedimentary structures, rock types and logs are collected.

A total of 17 samples were selected for laboratory analyses of granulometry, petrography and organic compounds (TOC and maceral). The granulometric studies were carried out with nine samples of unconsolidated sandstone in a set of stacked British standard mesh sieves comprising 1180, 1000, 850, 600, 212 and 75 microns, shaken by a Ro–Tap Shaker. Techniques adopted for graphic construction of frequency curves are as given by Agagu.[2] Mathematical solutions are as proposed by Friedman[19] and Lindholm.[23] Mean diameter, standard deviation, skewness and kurtosis values were calculated using linear interpolation of the cumulative weight percentiles of ϕ_5, ϕ_{16}, ϕ_{25}, ϕ_{50}, ϕ_{75}, ϕ_{84} and ϕ_{95}. Maceral analysis was conducted on three lignite samples. The samples were crushed and pulverized into a mesh of 1.18 – 1.16 mm. Hardener and epoxy at a ratio of 1:3 was prepared. Standard laboratory techniques of digesting sediments with potassium dichromate and sulphuric acid were used to process samples for the TOC analysis according to Wackley-Black[46] Wet Oxidation method. The oxides of Al, Fe, Mg, Na, K, Si, Ca and Mn were determined using the Atomic Absorption Spectrometry (AAS) method of the Swiss buck 2000 model.

4. RESULTS AND INTERPRETATION

Results of all analytical techniques in the study are presented below. A critical assessment of each set of the results has aided its proper interpretation and discussion.

4.1. Results

The summary of calculated results from grain size analysis is presented in Table 1. The graphic mean size (M) for the sandstone varies from 0.10 to 2.20 with an average mean size of 0.98, which is coarse. Inclusive graphic standard deviation (Si) ranges from 0.82 to 1.91 suggesting moderately to poorly sorted sandstones. Inclusive graphic skewness values (SK1) of –0.07 to 0.84 indicate near symmetrical to very fine skewed. The grain size distribution values plotted on histograms show predominantly bimodal pattern. The non-normal kurtosis values recorded here are characteristics of bimodal sediments

Table 1. Summary of Calculated Results of Grain Size Analysis

S/N	Sample No	ϕ_{50} median	M Mean	(δ_1) Standard deviation (sorting)	(SK_1) Inclusive graphic skewness	(K_G) Graphic kurtosis	Interpretation
1	OGS/1/003	1.60	1.60	1.12	-0.07	0.93	Medium grained, poorly sorted, near symmetrical, mesokurtic
2	OGS/2/003	0.65	0.81	0.86	0.37	1.28	Coarse grained, moderately sorted, very fine skewed, leptokurtic
3	OGS/3/003	0.57	0.66	0.82	0.17	1.05	Coarse grained, moderately sorted, very fine skewed, mesokurtic
4	OGS/1/004	1.77	1.78	0.87	-0.01	1.20	Medium grained, moderately sorted, near symmetrical, leptokurtic
5	OGS/2/004	1.75	2.20	1.91	0.39	1.31	Fine grained, poorly sorted, very fine skewed, leptokurtic
6	OGS 221 – 250	1.10	1.03	0.83	-0.16	1.08	Medium grained, moderately sorted, coarse skewed, mesokurtic
7	OGS 93 – 122	0.22	0.23	0.89	0.01	0.83	Coarse grained, moderately sorted, near symmetrical, platokurtic
8	OGS 138 – 174	0.38	0.38	1.01	0.40	1.03	Coarse grained, poorly sorted, very fine skewed, mesokurtic
9	OGS 205 - 221	0.12	0.10	1.01	0.48	1.02	Coarse grained, poorly sorted, very fine skewed, mesokurtic

Table 2a. Result of Thin Section Analysis Showing Mineralogical Composition

S/N	Sample No	Monocrystalline Quartz %	Feldspar %	Rock Fragment %	Cement %	Matrix %
1	OGS/1/002	30.0	2.9	9.0	55.6	2.5
2	OGS/2/002	10.0	8.5	42.5	38.5	0.5
3	OGS/3/002	8.0	9.5	47.0	27.5	8.0
4	OGS/1/003	23.0	4.5	42.2	9.8	20.5
5	OGS/2/003	50.0	2.9	34.3	9.3	3.5
6	OGS/3/003	60.0	3.1	27.4	7.5	2.0
7	OGS/1/004	35.0	4.2	41.8	4.5	14.5
8	OGS/2/004	48.0	3.8	23.0	8.5	16.7
9	OGS/3/004	18.5	5.6	8.5	5.7	61.7

Table 2b. Recalculated Percentage of Quartz, Feldspar, Rock Fragment and MMI

S/N	Sample No	Quartz %	Feldspar %	Rock Fragment %	MMI %
1	OGS/1/002	30.0	2.9	67.1	0.43
2	OGS/2/002	10.0	8.5	81.5	0.11
3	OGS/3/002	8.0	9.5	82.5	0.09
4	OGS/1/003	23.0	4.5	72.5	0.30
5	OGS/2/003	50.0	2.9	47.1	1.00
6	OGS/3/003	60.0	3.1	36.9	1.50
7	OGS/1/004	35.0	4.2	60.8	0.54
8	OGS/2/004	48.0	3.8	48.2	0.92
9	OGS/3/004	18.5	5.6	75.9	0.23

even where such modes are not evident in the frequency curves.[42]

The mineralogical composition of framework components of the sandstones and other minerals are presented in Tables 2a and 2b. Quartz is 31%, rock fragment is 64% and feldspar is 5%. Ternary plot of the framework elements adopted from Pettijohn[35], allowed sandstones to be classified as lithic arenite (Figure 3). The feldspars found in the sand are detrital and are made up of potassic and sodic feldspars. Silica cement is present in the form of microcrystalline and crystalline aggregates in pores and as overgrowth on silica grains. The quartz

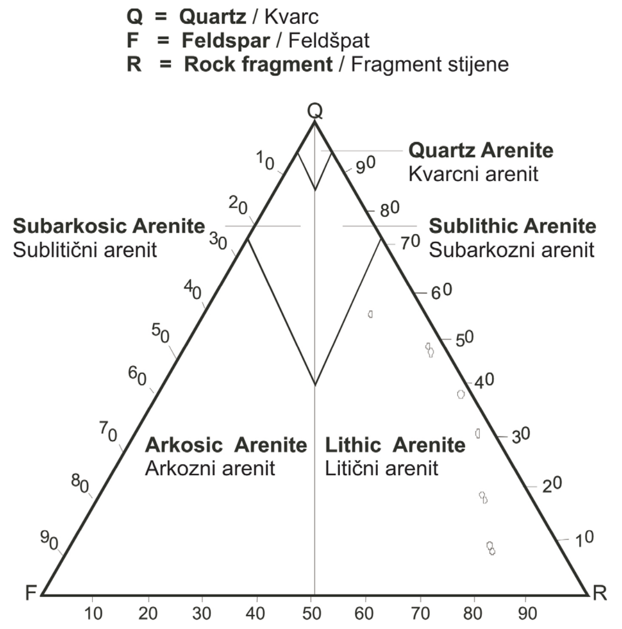

Fig. 3. Ternary plot of framework composition of sandstones in the study area (after ref.[35])

Sl. 3. Trojni (ternarni) prikaz sastava pješčenjaka proučavanog područja (prema ref.[35])

grains are rounded to subrounded while some exhibit embayed shapes which points to compaction of the sediments.

The relative abundance of major elements revealed dominance of SiO_2, Al_2O_3 and total Fe for the sandstones (Table 3). On contrary, low values of MnO_2, Na_2O, K_2O, CaO and MgO were recorded. Those data suggest that the sediments are aluminous and alkali, metally poor. Such attribute is typical for lithic arenites.[34] SiO_2 values, ranging between 84.01 and 40.35wt.%, have been reported for lithic arenites associated with coal formation.[36]

Results of lignites TOC analysis are shown on Table 4. Average TOC value is 2.21%. Maceral compositions of the lignites are shown on Table 5. Humanite (vitrinte) content ranges from 83.7 to 94.4 (mean=87.8%). Liptinite contents are from 1.5 to 2.3% (mean=5.13%). Inertinites contents are from 4.1 to 12.4% (mean = 7.1%). The result shows that the lignites are vitrinite dominated coal lithofacies. The Tissue Preservation Index (TPI) and Gelification Index (GI) were also determined from maceral composition according to Diesel[15]:

GI=(Vitrinite + Macrinite)/(Semifusinite + Fusinite + Intertodetrinite) (1)

TPI=(Vitrinite A + Semifusinite + Fusinite)/(Vitrinite B + Macrinite + Intertodetrinite) (2)

The calculated GI values range between 9.3 and 34.4 while TPI values ranges from 0.1 to 0.2, where vitrinite A and B are considered as humotellinite and humocollinite respectively.

4.2. Interpretation

An integration of the results from all the different analytical techniques employed led to a more reliable interpretation and discussion of the transport history and depositional environment of the Ogwashi-Asaba Formation. This has greatly enhanced the evaluation of the source and maturity of its various facies, and thus assessed their hydrocarbon potentials.

4.2.1. Transport history

The size of clastic sediments generally tends to decrease down current, although strong river current may carry large pebbles or coarse-grained detritus a long distance away from their source, while the finest clay and silt are (found in playa lakes) deposited closer to source area. Therefore, grain size depends largely on current velocity and paleorelief topography.

Fifty six percent of the sandstones are fine skewed which shows that the velocity of depositing current was lower than the average velocity responsible for the deposition of medium to coarse-grained fraction.[38] It also suggests a unidirectional currents and selective deposition for those sandstones. The moderate to poor sorting is indicative of short episodes of transportation and water level fluctuation of the depositing current. The high percentage of sedimentary rock fragments in the form of cherts clearly shows that the sediments have experienced a short transportation history and intense chemical weathering because chert-rich sands, in most cases signify a very local (deposition almost "in situ") origin.[18] A

Table 3. Major Elemental Concentration of Ogwashi - Asaba Formation

S/N	Sample No.	MnO_2, wt%	Na_2O, wt%	K_2O, wt%	CaO, wt%	MgO, wt%	Total Fe, wt%	SiO_2, wt%	Al_2O_3, wt%	Rock Type
1	OGS/2/001	0.03	0.26	0.16	TRACE	0.03	67.45	3.71	28.18	Claystone
2	OGS/4/003	0.02	0.81	1.09	TRACE	0.25	27.29	34.44	36.38	Claystone
3	OGS/1/002	0.01	0.37	0.54	TRACE	0.12	60.12	37.90	1.16	Sandstone
4	OGS/2/002	TRACE	0.27	0.21	0.01	0.05	81.65	17.50	1.73	Sandstone
5	OGS/3/002	0.01	0. 20	0.21	0.02	0.08	92.07	5.84	1.55	Sandstone
6	OGS/1/003	0.02	0.82	1.20	TRACE	0.23	59.72	29.95	8.27	Sandstone
7	OGS/2/003	0.02	5.55	1.95	TRACE	0.26	23.96	64.49	3.74	Sandstone
8	OGS/3/003	0.01	0.54	0.40	TRACE	0.18	12.69	84.57	1.36	Sandstone
9	OGS/1/004	0.02	0.95	1.09	TRACE	0.30	35.84	56.05	5.46	Sandstone
10	OGS/2/004	0.02	0.90	0.91	TRACE	0.18	23.33	67.60	7.06	Sandstone

Table 4. Result of Total Organic Carbon (TOC) Analysis

S/N	Sample No	TOC %	Average TOC %
1	OGS/1/001	1.60	2.21
2	OGS/005	1.90	
3	OGS/006	3.13	

more intense weathering in the source area could have led to decomposition of feldspar, hence their low content downstream. The rounded to sub-rounded quartz grains are probably resulting of erosion before deposition. This is confirmed with the observation of rounded quartz overgrowth and micro quartz bubbles filled with liquid.[18]

4.2.2. Maturity of sandstones as measure of stable rock end-state

Maturity, which measures the approach of clastic sediment towards the stable end-state, is expressed texturally, mineralogically and chemically. It is one of the most important keys to understanding the nature of depositional environment, providing descriptive terminologies that indicate the effectiveness of sedimentary process, such as winnowing, sorting and abrasion of detritus. The sandstones of analysed formation are texturally immature and have relatively high percentage of clay (>5%) and high sorting values (>1.0ϕ) as defined in Folk.[18] The mineralogical maturity index (MMI) ranges from 0.09 to 1.50 (Table 2b) showing that the sediments are mineralogically immature based on the numerical scale of mineralogical maturity proposed by Nwajide and Hoque.[28]

According to Hayes[20], sublithic and subarkosic arenites are both mechanically and chemically unstable. Based on the fact that alumina, being the least mobile oxide, persists in sediments even beyond a single cycle of sedimentation. The silica-alumina ratio of argillaceous sediments (e.g. sandstones) therefore may be used as a chemical index of maturity.[22,34] The SiO_2/Al_2O_3 ratio averages 3.80, hence the sandstones are chemically immature.

4.2.3 Source rock tectonic setting

The erosion of areas with high relief usually yields immature and poorly sorted sediments due to turbulence and rapid deposition. However, in areas of high altitudes (relief) but with relatively flat zones, some inter-stream areas may remain. Erosion of these areas yield maturely weathered detritus. This is usually the case with river system that opens into a platform or shallow basin above sea level. The coexistence of rounded quartz grains and clays in the sediments readily supports this point. The ternary plot of framework modes (QFR) for sandstones of this formation[14] reveals their tectonic setting to be that of a recycle orogen provenance (Figure 4). This provenance is thought to be a reworked materials from a molasse trough formed between the basin and the craton. Lithic sandstones have been reported from interior tectonic lands (in contrast to craton) associated with molasses facies resulting from orogenic uplift of a geosyncline or subduction margins. This explanation can be linked to the uplift of the Ikang Trough in the Calabar Flank[47] and the subsequent deposition of sediments in upper delta front of the Niger Delta Basin.

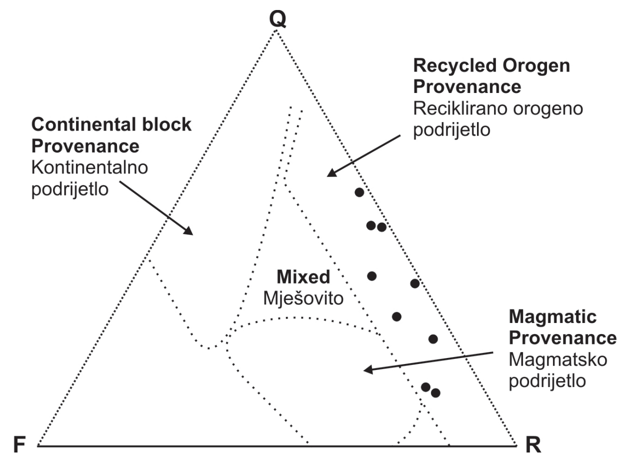

Fig. 4. Ternary plot of framework models for sandstones of Ogwashi-Asaba formation (modified after ref.[14])
Sl. 4. Trojni (ternarni) prikaz modela pješčenjaka Ogwashi-Asaba formacije (modificirano prema ref.[14])

4.2.4 Depositional environment

In this study, the depositional environment is interpreted in terms of the maceral composition, TOC content, textual parameters and lithofacies.[8,26,30] The probable inference from the statistical grain size distribution parameters, couple with bivariate plots of skewness against sorting[19] and plots of sorting versus mean size

Table 5. Result of Maceral Analysis Showing Maceral Composition of Lignites From Study Area

S/N	Sample No	Vitrinite	Humotellinite	Humocollinite	Humodetrinite	Liptinite	Sporinite	Cutinite
1	OGS/1/001	85.3	3.2	20.6	61.5	2.3	0.4	0.3
2	OGS/005	83.7	1.5	10.1	72.1	11.6	1.6	7.9
3	OGS/006	94.4	2.1	10.0	82.3	1.5	0.5	0.2

Resinite	Liptodetrinite	Alginite	Inertinite	Fusinite	Semifusinite	Inertodetrinite	Macrinite	Total
1.6	-	-	12.4	3.7	-	5.8	2.9	100.0
2.1	0.2	-	4.7	-	-	2.5	2.2	100.0
0.3	0.5	-	4.1	-	0.7	2.3	1.1	100.0

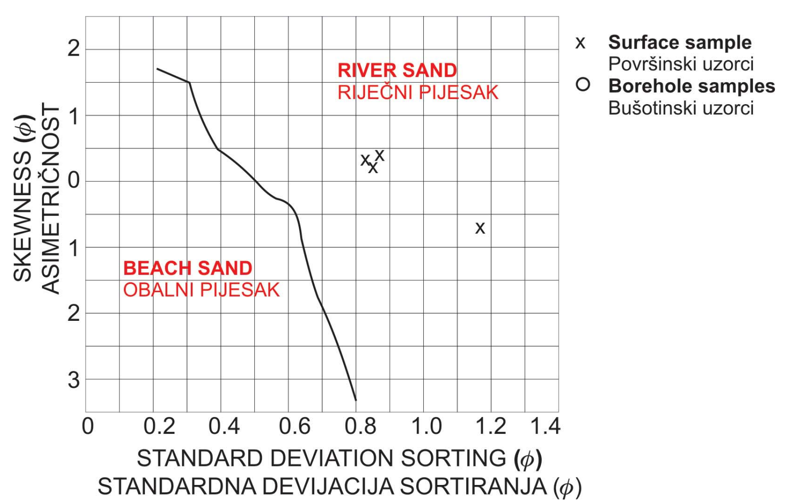

Fig. 5. Bivariate plot of graphic skewness versus graphic standard deviation (after ref.[19])
Sl. 5. Dvomjerni prikaz grafičke asimetričnosti nasuprot grafičke standardne devijacije (prema ref.[19])

(Figures 5 and 6) is that the sandstones were deposited in a palaeo-fluvial environment. The presence of argillaceous, arenaceous and carbonaceous materials within the same formation connotes an association of sediments formed in varying local environments including those of the alluvial fan, delta, prodelta and swamp environments.

The cyclic fining upward sequence of the Ogwashi-Asaba Formation sediments appears to be of a local extent which suggests migration of a river channels across its floodplain.[9] Therefore the sequence owes its cyclicity to channel switching (avulsion) as the river migrates/aggrades over its floodplain.[31] The occurrence of both fining and coarsening upward sequences results from a fluvio-delta deposition, triggered by a gradual progradation of a river over the delta.[39] The upper delta plain tends to favour accumulation of coal but with wide variation in thickness and is prone to channel cut off; a process significant for the occurrence of lignite in this formation, which are in all places bordered by mudstones. The lignite beds and disseminated carbonaceous detritus were contemporaneously formed in palaeo-swamp.[40] The extensively mudstones of the overbank floodplain indicates deposition in subaerial conditions.

However, the coal facies contradicts a wholly oxidizing (acidic) condition, rather there was a variation in oxidation–reduction potential (Eh) of the environment. A highly reducing condition must have prevailed in the swamps among meanders and in the inter-channel areas of the delta. TOC values of the lignites are higher than 1% which indicate an anoxic environment of deposition.[11] In such environment, bottom water masses are depleted of oxygen; a situation predominant in peat swamps due to poor water circulation and intense biological degradation which restrict respiration to anaerobic bacteria/microbes.

In order to assess the type of depositional environment for the lignites, maceral data are evaluated in the light of different swamp types and the resulting dominant maceral thus illustrated with Teichmuller[44] and coal facies diagram.[15] The swamp and moor types described by Teichmuller[44] is based on the premise that characteristic plants occur in each swamp type and their remains can be identified petrographically by maceral and lithotype analysis. The huminite-liptinite-inertinite plot for lignites in the study area indicates a reed marsh swamp deposition (Figure 7). The environment characterization based on the plot of tissues preservation index (TPI) and gelification index (GI) suggests their formation in a marsh or lake swamp environment. Earlier sedimentological studies have emphasized the dominance of paralic (fluvial and deltaic) environment for lithofacies of the coal. These environments are believed to be dominated by alternating high and low ground water table which facilitated the growth of reed (marsh) swamps in lower inland delta plain.[4,32]

4.2.5. Hydrocarbon source potential

The dominant vitrinite maceral when compared with the kerogen type on the van Krevelen diagram of Tissot et al.[45] shows predominance of type III kerogen which is dominantly gas generating. This is supported by the fact that the dominant vitrinite group is derived from lignin and cellulose containing plant organic matter with potential for generating gas. The liptinite maceral corresponds to type II organic material that is transformed into type II kerogene, which has potential to generate both oil and gas. The inertinite maceral group which corresponds to

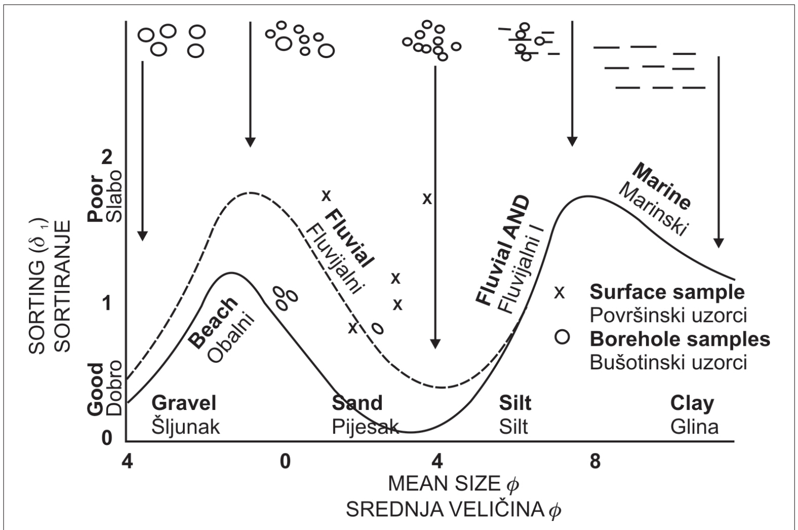

Fig. 6. Plot of sorting versus mean size (ref.[18])
Sl. 6. Prikaz sortiranja nasuprot srednje veličine (ref.[18])

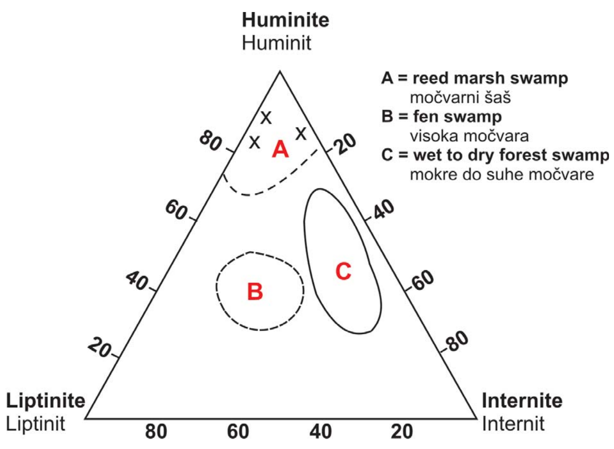

Fig. 7. Huminite-liptinite-inertinite plot for the Ogwashi Asaba lignites (adapted from ref.[44])

Sl. 7. Graf huminit-liptinit-internit za Ogwashi Asaba lignite (modificirano prema ref.[44])

type IV kerogen that is considered as "dead source rock" is composed mainly of recycled or oxidized organic materials. It can therefore be concluded from maceral composition of the samples from the study area that the kerogen is mainly type III which is formed from humic organic matter derived from terrestrial plant material having a continental source with very little contribution from marine organic matter.

The chemical nature of different kinds of maceral in relation to the thermal history of a basin is an important aspect in predicting its oil and gas occurrence.[11] The level of maturity can be determined by correlating kerogen type with corresponding maceral group.[30] Type III kerogene within catagenesis stage is characterised by vitrinite reflectance (Ro) of 0.5 to1.35, and temperature between 150 and 200 °C.[43]

5. RESULTS REVIEW AND CONCLUSIONS

The Anambra Basin in SE Nigeria is made up of Cretaceous to Miocene sediments with the Ogwashi-Asaba Formation capping the basin in the research area. The study area covers Ibusa, Azagba-Ogwashi, Okpanam and Asaba regions. Three main lithofacies are described. These are lignite, sandstone, and mudstone. Grain size analysis shows that the sandstones are dominantly coarse to medium grained and of mainly bimodal distribution. They also exhibit near symmetrical to very fine skewness. This implies that the velocity of current that deposited the fine sediments was lower than the prevalent velocity. Generally, the sands showed moderate to poor sorting and predominance of sedimentary rock fragments which indicates a brief transport history from a high relief. The sediments display mesokurtic to leptokurtic behaviour, which is diagnostic of reworked sediment. Bivariate plots of skewness against sorting and sorting against mean size show fluvially transported sands in a continental environment.

The sandstones are texturally, chemically and mineralogically immature as they are poorly to moderately sorted with a high argillaceous content of greater than 5% and low SiO_2/Al_2O_2 ratio having a mean of 3.80, as well as a low Q/F+R value in the range of 0.14 to 2.61. It was inferred from the rounded to subrounded quartz grains and their overgrowths that the sediments are a second cycle type.

The occurrence of clastic carbonaceous sediments, coupled with ferrugunisation of the clastics signifies co-existing oxidizing and reducing conditions in the depositional environment. Reducing condition must have prevailed in the swamps of the meander system and abandoned peat swamps of the upper deltaic plain, thus enhancing the formation of lignites with high TOC values. However oxidation in the main channel of the meander led to the redness of the sandstones and clay (or mud) observed in most of the study area. Both fining and coarsening upward sequences displayed by the sandstones depicts a fluvio-deltaic deposition.

An elucidation of the various sub-environments has been deduced based on critical assessment of the various lithofacies. The basal conglomerates are taken to be channel lag deposit overlain by decreasing sand size clastics of the point bar as the velocity of deposition wanes. The mudstones are proven to be the product of low velocity of deposition on the floodplain and ox-bow lakes. The associated lignites are typical sediments in marsh or swamp environments.

TOC analysis of the lignites showed that they are quite rich in terrigenous organic matter as exemplified by the dominance of vitrinite macerals over liptinite and inertinite groups. This maceral corresponds to type III kerogen and as such have every potential to generate gas. Therefore the lignites are coal gas-bearing, an unconventional source rock.

6. References

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