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Application of Multivariate Geochemical Principles in Assessment of Organic Matter Potentiality; A Case Study of The Eocene Ameki Formation, Northern Depobelt of The Niger Delta Basin, Se Nigeria

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Abstract

Multivariate statistical methods were applied to hydrocarbon source rock evaluation of outcrop samples from the Eocene Ameki Formation in the Niger Delta. The statistical tools; Pearson's correlation, linear regression, cluster and factor analysis were deployed in the source rock characterization and also used in establishing the correlation between the assessed parameters (S1, S2, HI, S1 + S2, QI, BI, PI, TOC) and the impact of changes in the T_{max} and R_o% on the assessed parameters.. Rock Eval pyrolysis results revealed that the average Total Organic Carbon of the lignite is 39.44 wt%, while those of the shales range is 3.62 wt%. Petroleum Source Potential (S1 + S2) for the lignite has an average of 23.39 kg HC/t, while the shale is 75.51 kgHC/t. Hydrogen Index values for the lignites has an average 133.69 HC/gTOC, while those of the shales 191.5HC/gTOC. Tmax values for the shale range from 378^{0}C - 435^{0}C , while for lignites from 376^{0}C to 432^{0}C.The lignite and shale facies are predominately of type II/III mixed oil and gas prone and Type III gas prone kerogen type, which contain excellent organic matter that are generally immature to marginally mature . The application of Pearson's correlation and linear regression analysis indicated a clear and strong correlation between TOC vs S_2, TOC vs HI, S_1 vs S_2, and Ro vs Tmax. The hierarchical cluster analysis using the Ward method and factor analysis of the source parameters revealed the existence of three distinct source rock types within the study area, with vary qualities and maturity levels.

***Keywords**: Source rock; Rock Eval analysis; Multivariate statistical; Niger Delta Basin.*

1. Introduction

The demand for hydrocarbon as an energy source has encouraged sedimentary basin and hydro carbon source rock studies in both the offshore and onshore domains aimed to discover new oil and gas pools, while the old ones are reassessed for additional oil and/or gas pools. The Eocene Ameki Formation is the outcropping equivalent of the subsurface Agbada Formation in the Niger Delta Basin. The hydrocarbon source potentials for this formation have not been fully investigated, hence this study. The Niger Delta is situated in the Gulf of Guinea (Fig. 1). The basin is a rift triple junction related to the opening of the southern Atlantic which evolved in the Late Jurassic to the Cretaceous and is considered among the world's most examined delta provinces. The Basin covers an area of 75,000 km^2, comprised of 9000–12,000 m of clastic sediments [1].

The Eocene Ameki Formation is the outcropping equivalent of the subsurface Agbada Formation in the Niger Delta Basin [2]. The outcrops occur in a broad belt running in a southeast trend from NW of Onitsha, Awka and Orlu Divisions to Umuahia/Bende area in Southeastern Nigeria. This Formation consists of two lithological units; a lower part of fine to coarse grain sandstones interbedded with calcareous shales and thin shelly limestone and an upper part dominated by fine of fine, grey-green sandstone, siltstone, sandy fossiliferous clays, and sandstones.

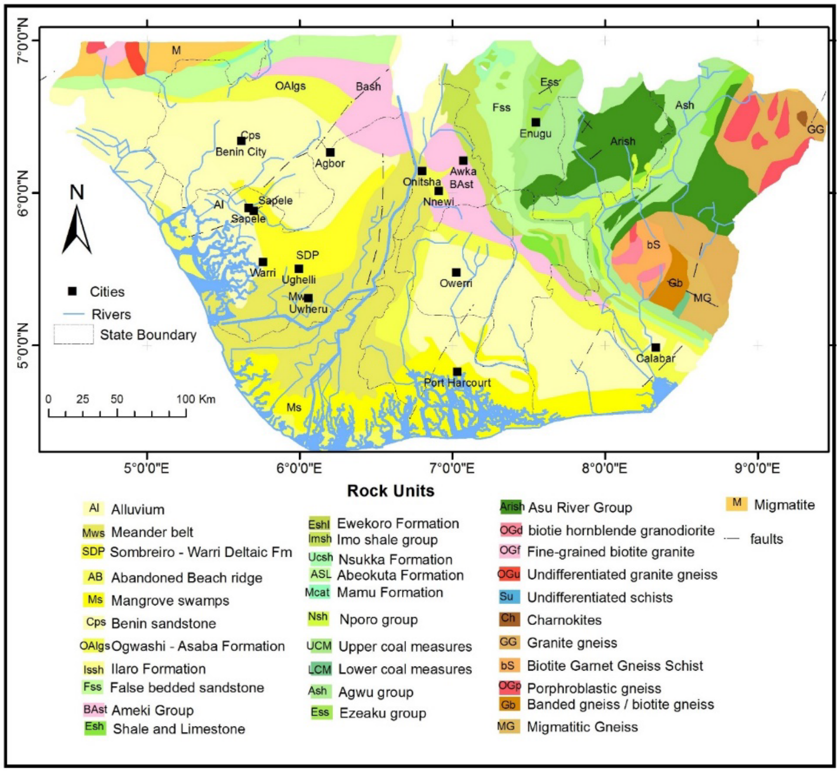

Figure 1. Geologic map of south-eastern Nigeria, showing the Niger Delta (redrawn and modified after Nigerian Geological Survey Agency, 2009 [3])

The study area lies within the Northern up dip fringes of the Niger Delta which lies between latitude $5^0$55′′0N and 6^0 10′0″ N and longitude $6^0$35$^{''0}$E and 6^o55′0″ E. Some of the major towns within the study area include: Nnewi town, Ogbunike, Oba and exposures along Onitsha- Enugu express way. The locations are accessible by footpaths and shallow streams and marked with several small hills especially in the Nnewi area. The outcrop sections are accessible by foot path. They are exposed in quarries, stream channels and roadcut sections.

2. Methodology

Analysis of forty eight samples of thirty-three (33) shales and fifteen (15) lignites were carried out using Rock Eval pyrolysis analytical process. The procedure involved the transfer of sample to be analyzed into a furnace where they are heated initially at 300°C for three minutes in an atmosphere of helium to release the free hydrocarbons (S_1). Pyrolysis of the bound hydrocarbons to give the S_2 peak followed immediately as the oven temperature was ramped up rapidly to 550°C at the rate of 25°C/min. Both the S_1 and S_2 hydrocarbon peaks were measured using a flame ionization detector (FID). A splitting arrangement permitted the measurement of the S_3 peak (carbon dioxide) by means of a thermal conductivity detector (TCD). The instrument automatically recorded the temperatures corresponding to the maximum of the S_2 peak i.e Tmax values. An in-built computer processed the raw data to generate the values corresponding to the respective Rock-Eval indices.

3. Results and discussion

3.1. Organic richness

The TOC is the first screen for measuring organic richness and is a necessary requirement for sediments to generate oil or gas. According to [4-5], the TOC values between 0.5 and 1.0% indicate a fair source-rock generative potential, TOC values varying from 1.0 to 2.0% reflect a good generative potential whilst values between 2.0 and 4.0% refer to a very good generative potential, and rocks with TOC greater than 4.0% are considered to have excellent generative potential. The Organic geochemical results for TOC of the analyzed samples of the Eocene sediments shows that the lignite samples range from 3.15 to 60.36 wt%, with an average of 39.4 %, while those of the shale range from 0.39 to 11.25 wt% with an average of 3.62 wt%.The TOC for fifteen (15) lignites in the study areas ranges from 3.18 to 17.1 wt% with an average TOC value of 11.88 wt% (Table 1), while those of the thirty-three (33) shale sample ranges from 0.39 to 60.36 wt% with an average TOC value of 17.8 wt%. The highest concentrations of organic carbon are present in the shales. Most of the samples have TOC values in excess of 2.0 wt% and such level of organic enrichment are considered as very good source rocks for hydrocarbon generation [4]. The results also showed a random pattern of organic matter distribution within the sections.

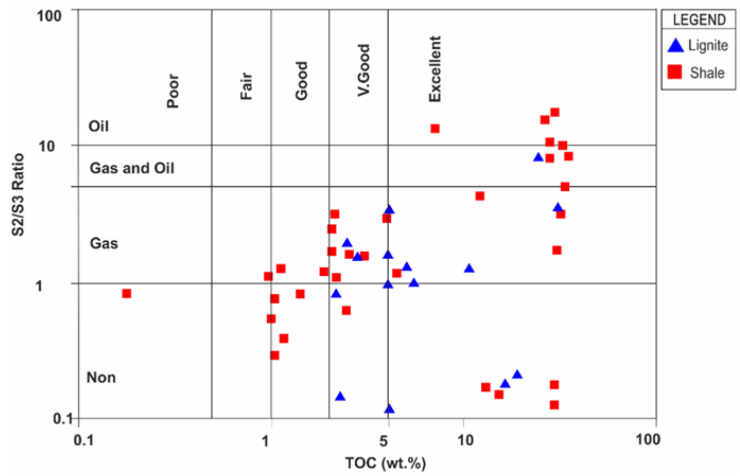

Figure 2. Plot of S2/S3 VS TOC of the studied shales and lignites

Table 1. Rock- Eval data from the study area.

SN	ID	LITH	TOC	S1	S2	S3	S1 + S2	Tmax	HI	OI	PI	Ro	QI	BI
1	KN 4M	shale	3.98	0.18	0.41	2.78	0.59	376	10	70	0.3	-0.39	0.15	0.05
2	KN 5B	Lignite	54.2	3.41	149.86	15.77	153.27	431	276	29	0.02	0.6	2.83	0.06
3	KN 5T	lignite	53.95	4.93	203.94	17.44	208.87	433	378	32	0.02	0.63	3.87	0.09
4	KN 8B	Shale	5.7	4.43	167.7	16.32	172.13	427	301	29	0.03	0.53	3.09	0.08
5	KN 8T	Shale	7.15	4.48	171.53	17.36	176.01	435	300	30	0.03	0.67	3.08	0.08
6	KN 16T	Lignite	22.15	3.16	46.2	10.49	49.36	424	209	47	0.06	0.47	2.23	0.14
7	KN 16B	Lignite	17.1	2.15	32.03	8.5	34.18	420	187	50	0.06	0.4	2	0.13
8	KN 15T	Dark Shale	2.37	0.3	2.15	1.67	2.45	414	91	71	0.12	0.29	1.03	0.13
9	KN 15B	Dark Shale	2.15	0.33	2.06	0.83	2.39	408	96	39	0.14	0.18	1.11	0.15
10	KN 19T	lignite	45.5	5.18	260.77	10.52	265.95	431	573	23	0.02	0.6	5.85	0.11
11	KN 19B	lignite	41.9	6.67	162.23	10.7	168.9	416	387	26	0.04	0.33	4.03	0.16
12	KN 18T	shale	5.65	0.76	7.41	3.21	8.17	417	131	57	0.09	0.35	1.45	0.13
13	KN 18B	shale	5.6	0.66	6.69	3.43	7.35	414	119	61	0.09	0.29	1.31	0.12
14	KN 17M	Laminated Shale	3.74	0.18	0.43	2.35	0.61	378	11	63	0.3	-0.36	0.16	0.05
15	KN 17B	Laminated Shale	7.75	3.6	45.25	6.88	48.85	425	255	39	0.07	0.49	2.75	0.2
16	KN 24T	lignite	47.5	6.77	252.73	11.57	259.5	432	532	24	0.03	0.62	5.46	0.14
17	KN 24B	lignite	47.85	7.48	256.99	17.71	264.47	429	537	37	0.03	0.56	5.53	0.16
18	KN 23T	shale	7.74	2.12	11.84	4.55	13.96	432	153	59	0.15	0.62	1.8	0.27
19	KN 23B	Shale(coaly)	11.25	1.49	13.58	5.05	15.07	421	121	45	0.1	0.42	1.34	0.13
20	KN 29B	lignite	22.53	7.39	118.06	4.44	125.45	417	524	20	0.06	0.35	5.57	0.33
21	KN 31B	lignite	60.36	6.49	176.66	21.4	183.15	417	293	35	0.04	0.35	3.03	0.11
22	KN 30B	shale	5.25	1.07	14.47	2.68	15.54	422	276	51	0.07	0.44	2.96	0.2

SN	ID	LITH	TOC	S1	S2	S3	S1 + S2	Tmax	HI	OI	PI	Ro	QI	BI
23	KN 26B	Shale	2.53	0.9	7.05	1.2	7.95	427	279	47	0.11	0.53	3.14	0.36
24	KN 37B	shale	6.72	0.93	3.9	4.09	4.83	408	58	61	0.19	0.18	0.72	0.14
25	KN 36B	lignite	57.6	6.06	77.09	26.43	83.15	410	134	46	0.07	0.22	1.44	0.11
26	KN 46T	Shale	5.34	0.83	3.61	3.31	4.44	413	68	62	0.19	0.27	0.83	0.16
27	KN 45B	Lignite	59.56	10.48	306.38	13.11	316.86	417	514	22	0.03	0.35	5.32	0.18
28	KN 49T	Shale	2.57	3.23	32.25	1.48	35.48	415	143	7	0.09	0.31	1.57	0.14
29	KN 50T	Lignite	56.62	7.1	137.19	20.65	144.29	410	242	36	0.05	0.22	2.55	0.13
30	KN 52B	Lignite	3.94	0.34	3.43	1.09	3.77	411	87	27	0.09	0.238	0.96	0.09
31	KN 54M	Shale	1.48	0.09	0.4	0.69	0.49	403	26	46	0.18	0.094	0.33	0.06
32	KN 54T	Shale	1.59	0.1	0.54	0.73	0.64	401	34	45	0.16	0.058	0.4	0.06
33	KN 55B	Lignite	3.15	0.29	2.43	1.05	2.72	409	77	33	0.11	0.202	0.86	0.09
34	KN 56B	Shale	0.39	0.05	0.17	0.19	0.22	408	42	49	0.24	0.184	0.56	0.13
35	KN 56T	Shale	1.45	0.1	0.53	0.45	0.63	402	36	31	0.16	0.076	0.43	0.07
36	KN 59B	Shale	1.14	0.08	0.38	0.47	0.46	400	33	41	0.17	0.04	0.4	0.07
37	KN 59T	Shale	2.99	0.27	2.69	0.9	2.96	420	89	30	0.09	0.4	0.99	0.09
38	KN 62B	Shale	2.64	0.24	3.15	0.72	3.39	424	119	27	0.07	0.472	1.28	0.09
39	KN 62T	Shale	2.51	0.23	2.95	0.93	3.18	424	117	36	0.07	0.472	1.27	0.09
40	KN 64	Shale	1.17	0.04	0.45	0.62	0.49	406	38	53	0.08	0.148	0.42	0.03
41	KN 74B	Shale	1.09	0.07	0.51	0.45	0.58	409	46	41	0.12	0.202	0.53	0.06
42	KN 74 T	Shale	1.2	0.08	0.4	0.63	0.48	405	35	56	0.17	0.13	0.4	0.07
43	KN 80B	Sandy Shale	1.79	0.1	0.69	0.76	0.79	406	38	42	0.13	0.148	0.44	0.06
44	KN 80T	Shale	1.46	0.07	0.42	0.79	0.49	410	28	54	0.14	0.22	0.34	0.05
45	KN 81	Shale	1.31	0.06	0.38	0.62	0.44	403	28	46	0.15	0.094	0.34	0.05
46	KN 83	Shale	2.53	0.13	1.08	0.98	1.21	412	42	38	0.11	0.256	0.48	0.05
47	KN 85B	Shale	8.81	1.61	25.74	1.64	27.35	424	292	18	0.06	0.472	3.1	0.18
48	KN 85T	Shale	4.07	0.33	4.34	1.29	4.67	415	106	31	0.07	0.31	1.15	0.08

3.2. Organic quality

The results obtained from the rock-Eval pyrolysis revealed that the amount of free hydrocarbon (S_1), and the generated hydrocarbons (S_2) through thermal cracking of non-volatiles are on the average, following the characterization model by 14 with the highest S_2 value recorded in KN24 for lignites, while for the shales were observed in sample KN 4M. S1 values range from 0.07 to 7.48 mg HC/gTOC for the shales, while for the lignites ranged from 0.41 to 10.48 mg HC/gTOC. Generally, S_1 values greater than 1mg HC/g TOC in any organic rock is indicative of hydrocarbon shows [6]. S_2 values, ranging from 0.42 to 256.99 mg HC/g TOC which is indicative of the remaining potential of kerogen in the source rock to generate petroleum at higher temperatures is relatively high. The high S_2 values compliment the high TOC values recorded in most samples.

3.3. Kerogen type

The organic matter type is a key important parameter in evaluating source rock potential and has important influence on the nature of the hydrocarbon products [7-9]. It is very important to determine the kerogen types of the source rocks as they have a first-order control on the hydrocarbon products after maturation. The analyzed samples of the Eocene sediments are characterized by high hydrogen index values ranging from 10 – 255 HC/gTOC (mean = 109.67HC/gTOC) for the shales, while the lignites ranges from 187 – 573 HC/gTOC (mean = 368HC/gTOC). Plot of Hydrogen Index (HI) against Oxygen Index (OI) on the Van Krevelen diagram [9-10]. The Van Krevelen maturation tracks for kerogen has shown that some samples from Ekwulu, Ugunzu, Nnewi and Ogbanelu shales plot into the Type II kerogen organic matter which are mostly terrestrial in origin and mostly oil and gas prone, while others are predominantly of Type III gas prone kerogen type.

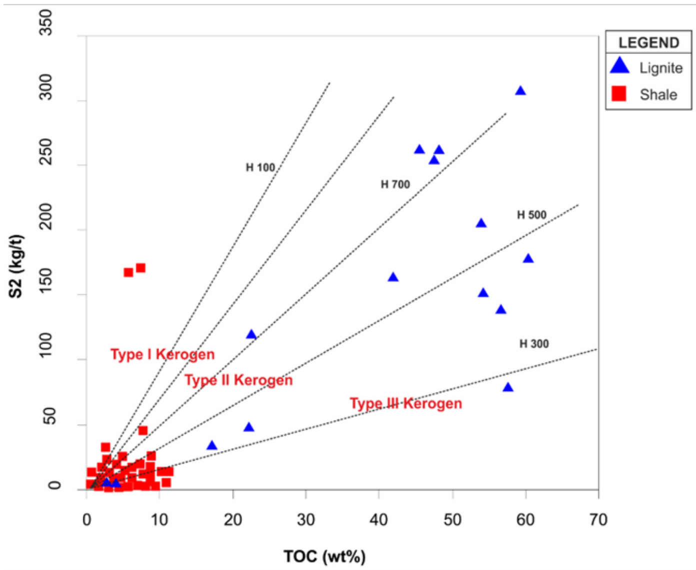

Figure 3. Hydrogen yield (S_2kg/t) versus total organic carbon (TOC wt %) of the studied organic rock used for evaluation of the source rock kerogen type

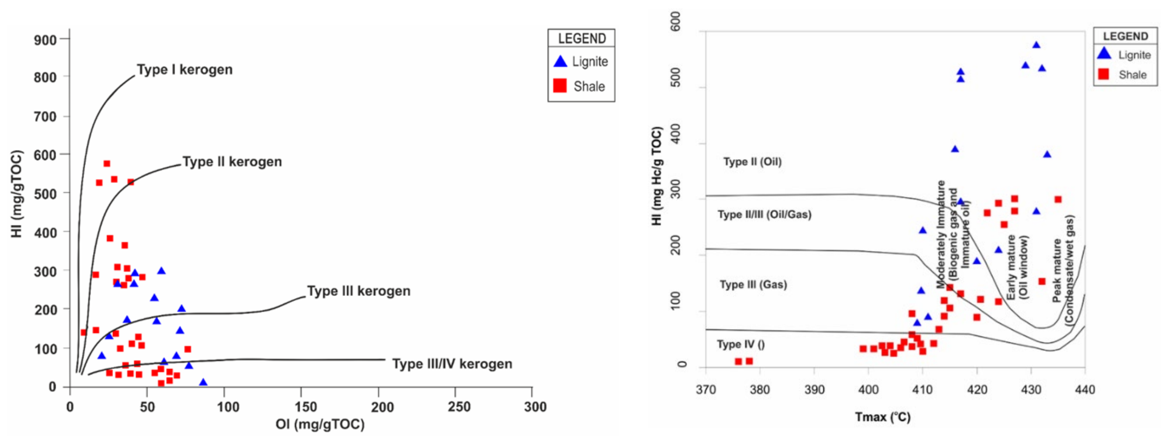

Figure 4. Plot of Hydrogen index versus Tmax and the Van Krevalen's diagram showing the kerogen types

3.4. Thermal maturity

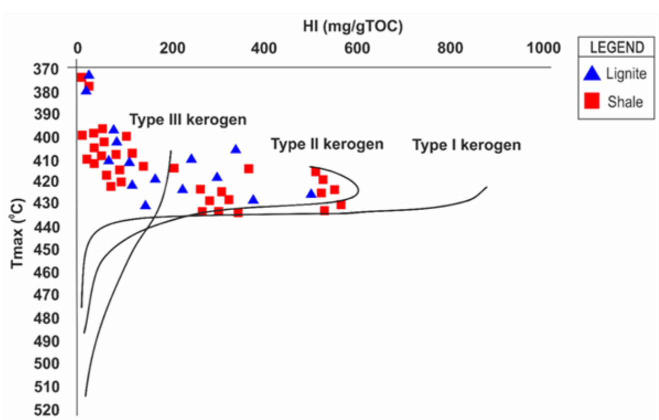

Figure 5. Tmax (°C) against Vs HI plots

Tmax values for the shale samples ranges between 376^{0}C - 432^{0}C (mean = 409.4^{0}C), while the lignites range from 427^{0}C to 435^{0}C (mean = 427.8^{0}C). This suggests that the shales are mostly still within the immature, but marginally matured in parts, 14 and 19 suggested that at Tmax 435ºC, rocks with HI above 300mg HC/g TOC will produce oil; those with HI between 300 and 150 will produce oil and gas; those with HI between 150 and 50 will produce only gas; and those with HI less than 50 are inert. Plot of hydrogen index against Tmax (Fig. 5) confirm the immature to marginal maturity status of the Eocene sediments.

3.5. Geo statistics

3.5.1. Pearson correlation and linear regression

To investigate the relation between the assessed parameters (S_1, S_2, S_1 + S_2, HI, QI, BI, PI, TOC) of petroleum potentiality and to investigate the impact of changes in the T_{max} and R_o% on these parameters, Pearson's correlation, spearman correlation (Table 2 and 3) and linear regression analysis (Table 4) principles were applied. The plot of S2 vs. TOC showed a strong correlation, hence S2 is contributed from TOC. A clear and strong correlation was observed between TOC vs HI, S1 Vs S2, and Ro vs Tmax. Whereas, the plotting of Tmax vs. HI, Ro Vs S2, and Ro Vs HI showed no significant trend (Figure 6). Two different trends were observed in the cross plot of S1 vs. S2 (Fig.6 c) which might be attributed to the compositional difference in organic material.

Table 2. Pearson correlation matrix

	TOC	S1	S2	S3	S1+S2	Tmax	HI	OI	PI	Ro	QI	BI
TOC	1											
S1	0.9	1										
S2	0.9	0.91	1									
S3	0.95	0.81	0.77	1								
S1+S2	0.91	0.91	1	0.78	1							
Tmax	0.48	0.45	0.51	0.42	0.51	1						
HI	0.74	0.86	0.89	0.61	0.89	0.66	1					
OI	-0.45	-0.49	-0.5	-0.25	-0.5	-0.45	-0.54	1				
PI	-0.65	-0.63	-0.64	-0.57	-0.64	-0.81	-0.71	0.63	1			
Ro	0.48	0.45	0.51	0.42	0.51	1	0.66	-0.45	-0.82	1		
QI	0.73	0.86	0.88	0.6	0.88	0.66	1	-0.53	-0.71	0.67	1	
BI	0.09	0.36	0.16	0.06	0.17	0.44	0.51	-0.11	-0.23	0.45	0.54	1

Table 3. Spearman correlation matrix

	TOC	S1	S2	S3	S1+S2	Tmax	HI	OI	PI	Ro	QI	BI
TOC	1											
S1	0.9	1										
S2	0.9	0.91	1									
S3	0.95	0.81	0.77	1								
S1+S2	0.91	0.91	1	0.78	1							
Tmax	0.48	0.45	0.51	0.42	0.51	1						
HI	0.74	0.86	0.89	0.61	0.89	0.66	1					
OI	-0.45	-0.49	-0.5	-0.25	-0.5	-0.45	-0.54	1				
PI	-0.65	-0.63	-0.64	-0.57	-0.64	-0.81	-0.71	0.63	1			
Ro	0.48	0.45	0.51	0.42	0.51	1	0.66	-0.45	-0.82	1		
QI	0.73	0.86	0.88	0.6	0.88	0.66	1	-0.53	-0.71	0.67	1	
BI	0.09	0.36	0.16	0.06	0.17	0.44	0.51	-0.11	-0.23	0.45	0.54	1

Table 4. Linear regression equation for estimating the relationship between each measured hydrocarbon parameters

Parameters	Regression equation	R^2
TOC versus S2	S2 = -8.07 + 3.70TOC	0.813*
TOC versus HI	HI = 79.739 + 0.53TOC	0.55*
S2 versus S1	S1 = 0.62 + 0.03S2	0.82*
Ro versus HI	HI = 31.49 + 474.98Ro	0.44 NS
Ro versus S2	S2 = -4.72 + 200Ro	0.26 NS
Ro versus Tmax	S2 = 397.81 + 55.38Ro	1.0*
Tmax versus HI	HI = -3368+ 8.55Tmax	0.43 NS
BI versus HI	HI = 35.17 +1197.41BI	0.26 NS
Ro vs BI	BI = 0.08 + 0.14Ro	0.18 NS
Tmax versus BI	HI = -0.90+ 0.002Tmax	0.18 NS
Tmax versus QI	QI = -34.5+ 0.09Tmax	0.44 NS
Ro vs QI	QI = 0.40 + 4.9Ro	0.44 NS

*R^2 = Coefficient of determination, * Significant at $p < 0.05$, NS = Not significant.*

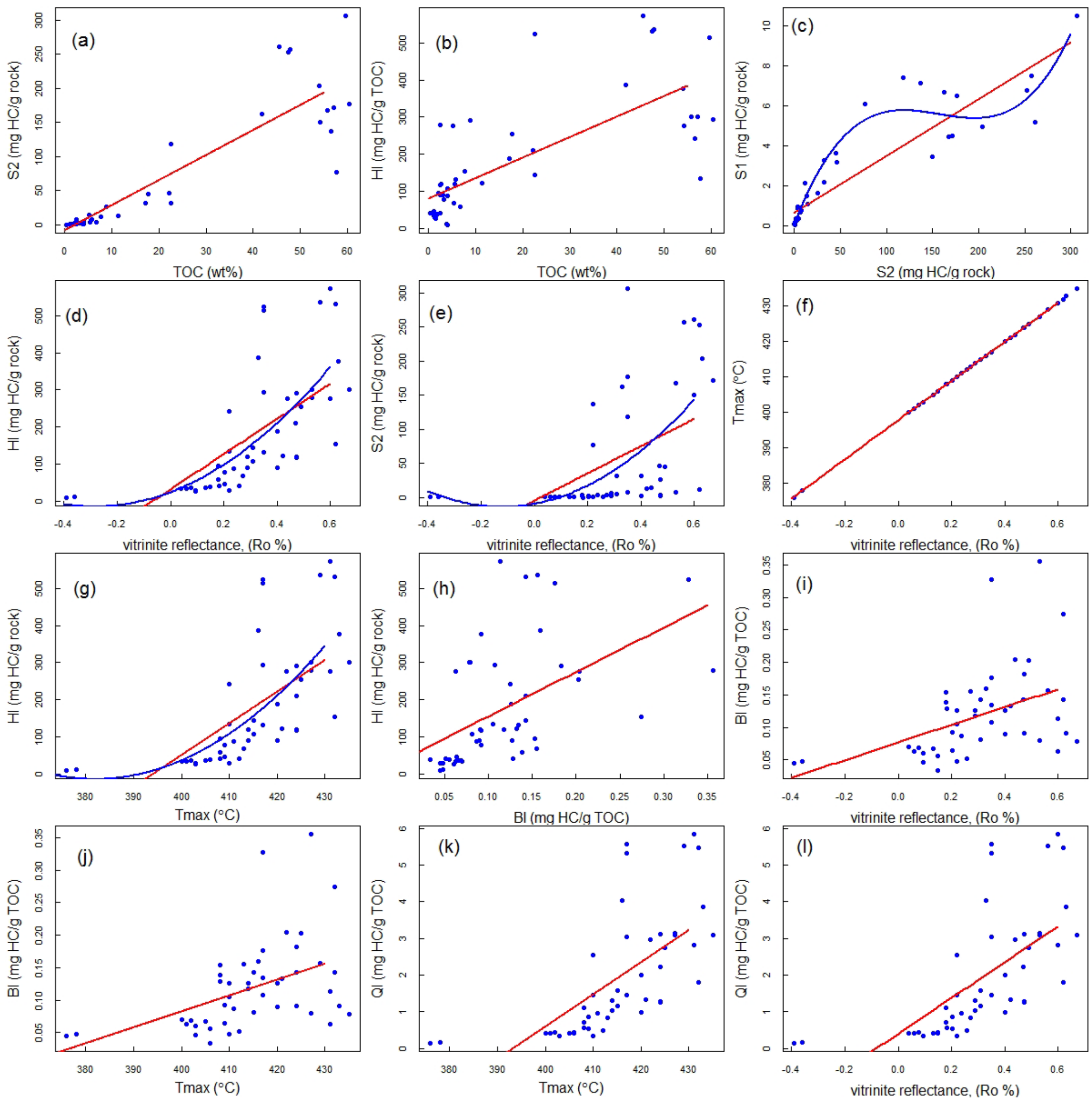

Figure 6. Pearson's correlation coefficient and linear regression between the measured parameters and thermal maturity (Ro% and Tmax)

4.1. Hierarchical clustering

Hopkins statistic is computed to show that the dataset is amenable for clustering if its <0.5. The Hopkins statistic computed for this data set has a value of 0.17 which indicates that this cluster analysis is possible. Figure 7 is an elbow plot that shows the optimal number of clusters that can be generated from the dataset is three (3). Agglomerative clustering/nesting (Agnes) using ward method of linkage was applied on the dataset and Figure 8 presents the resulting dendrogram.

4.2. Factor analysis (Principal Component Analysis – PCA)

Principal component analysis is a dimension reduction technique that attempt to capture most of the information in the original dataset of high dimension, and summarize it in a few new variables (PCs) which are linear combination of the original variables [10]

The extracted eigen values explaining the information captured by the principal components (PCs) is given in Table 5, and Fig. 9 is a scree plot that shows the proportion of information in each PC.

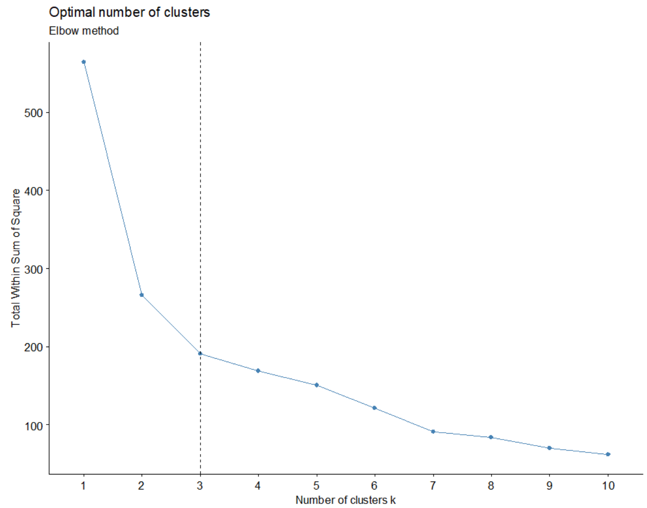

Figure 7. Elbow plot showing the optimal number of clusters that can be generated from the dataset

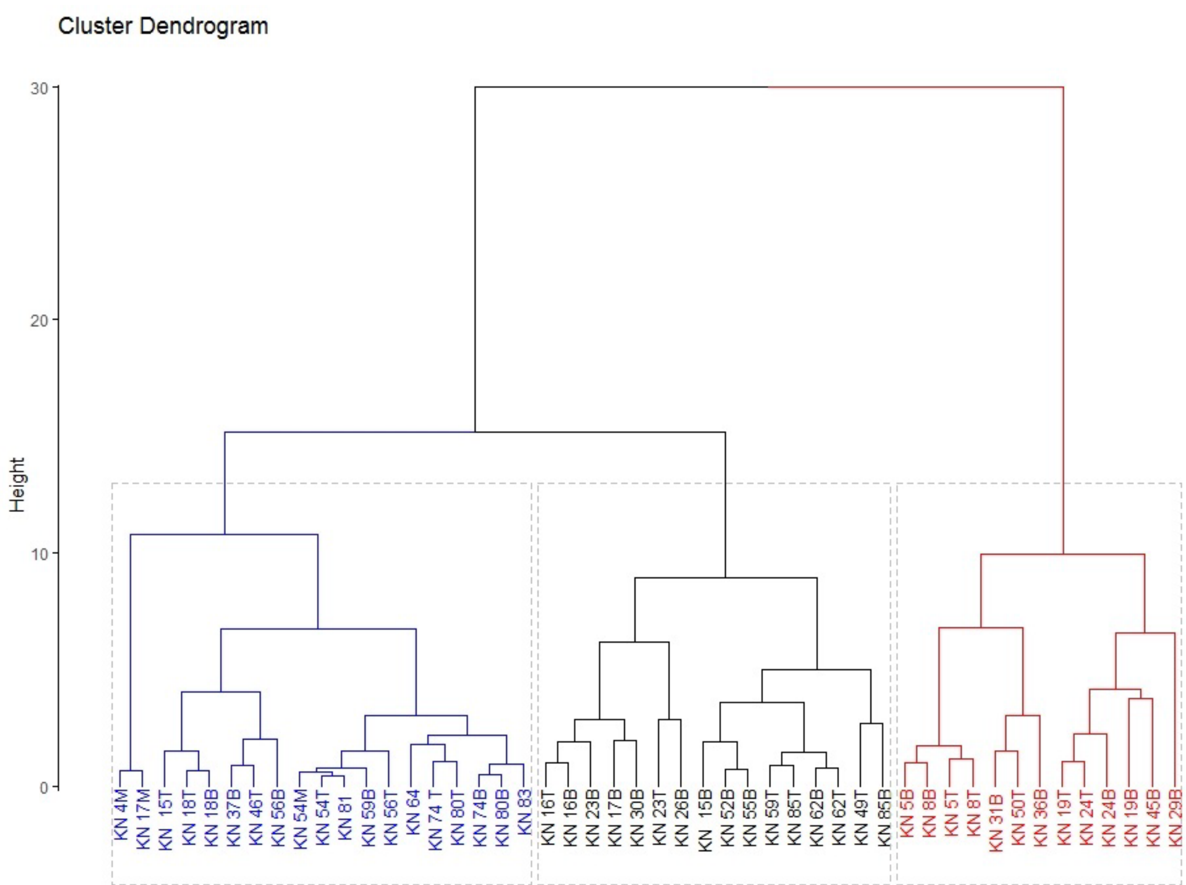

Figure 8. Dendrogram showing the result of hierarchical cluster analysis of the Eocene source rocks

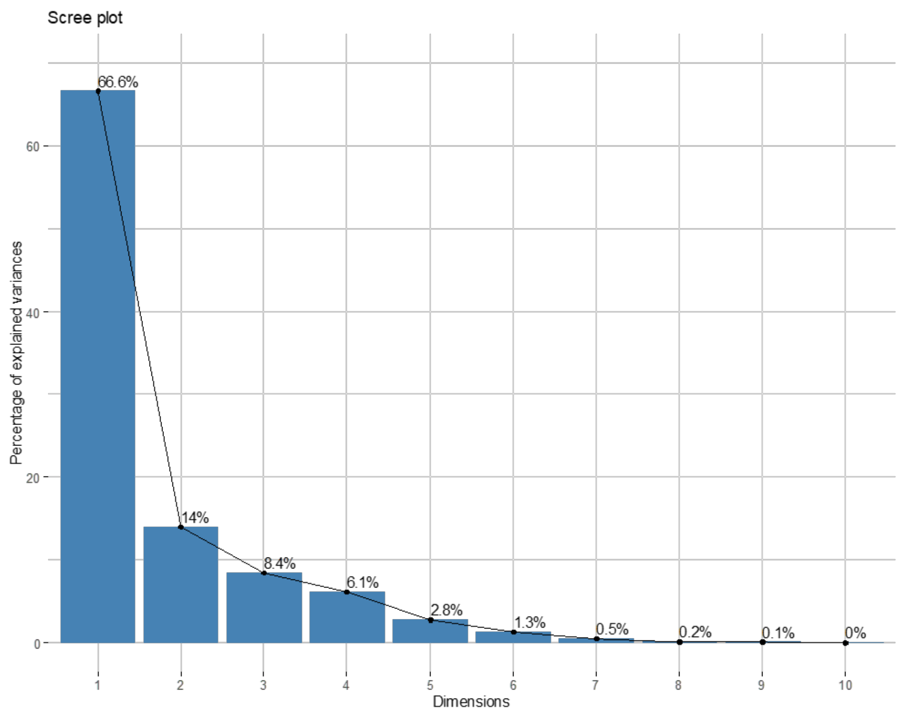

Figure 9. Scree plot showing contributions made by the PCs

It can be seen that the first two (2) principal component capture about 80.6% of the information in the original dataset and subsequent analysis and interpretation will be based on this two PCs. Table 7 shows the correlation of the variables with the first and second PC. Values of correlation above 0.6 is considered high, and hence TOC, S1, S2, S1 + S2, S3, GP, Tmax, PI, and Ro are the major contributors to the first PC because of their high positive correlation with it, while HI and OI contribute negatively to the first PC, and Tmax, Ro, and BI all have negative contributions to PC2 Figure 10 is the correlation factor map which present the relationship of the original variables and the principal components in form of correlation circle. Figure 11 shows the classification of the samples based on their PC scores.

Table 6. Eigenvalues and proportion of explained variance/information by each principal component (PC)

Principal component	Eigenvalue	Variance %	Cumulative variance %
PC 1	8.0	66.6	66.6
PC 2	1.7	14.0	80.6
PC 3	1.0	8.4	89.0
PC 4	0.7	6.1	95.2
PC 5	0.3	2.8	98.0
PC 6	0.2	1.3	99.3
PC 7	0.1	0.5	99.8
PC 8	0.0	0.2	99.9
PC 9	0.0	0.1	100.0
PC 10	0.0	0.0	100.0
PC 11	0.0	0.0	100.0
PC 12	0.0	0.0	100.0
PC 13	8.0	66.6	66.6

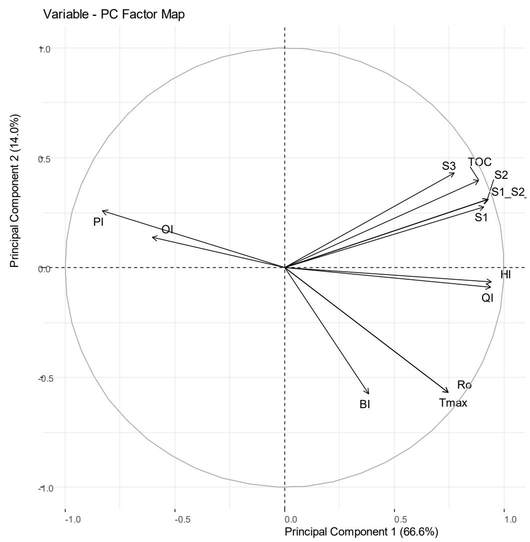

Figure 10. Variable factor map or correlation circle between the PCs (central dashed lines) and the variables (arrows; length is proportional to correlation strength, and direction is proportional to sign)

Table 7. Correlation between the principal components (PCs) and the original variables

Parameter	PC 1	PC 2	Parameter	PC 1	PC 2
TOC	**0.9**	0.4	HI	**0.9**	-0.1
S1	**0.9**	0.3	OI	**-0.6**	0.1
S2	**0.9**	0.3	PI	**-0.8**	0.3
S3	**0.8**	0.4	Ro	**0.7**	**-0.6**
S1 + S2	**0.9**	0.3	QI	**0.9**	-0.1
Tmax	**0.7**	**-0.6**	BI	0.4	**-0.6**

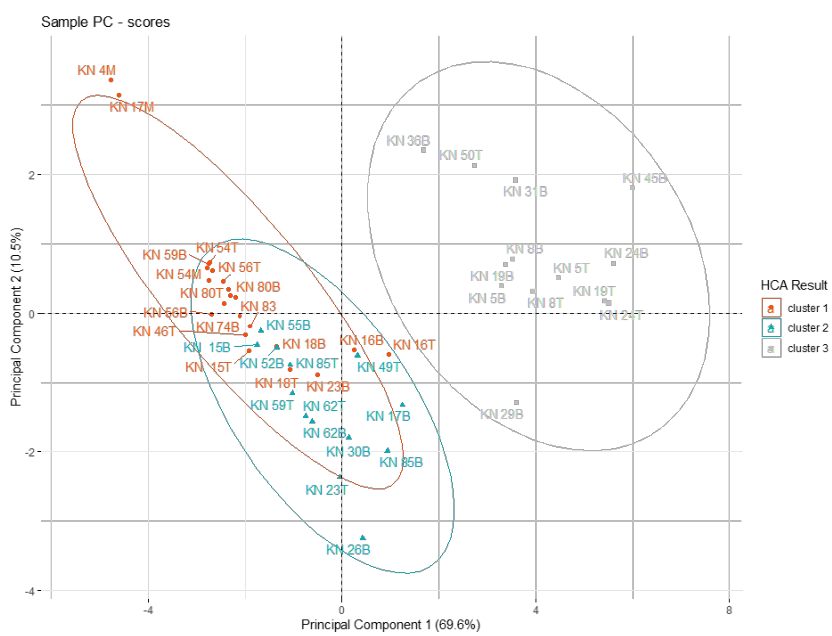

Figure 11. Classification of source rocks in the study area using factor analysis (PCA) Red circle (Low potential), Blue circle (medium Potential), while the black circle (good potential)

5. Discussion of results

The potentials of a source rock can be better understood by critically examining the organic matter dissemination in the sediments. This is linked to the formation of organic-rich, fine-grained sediments through photosynthesis, deposition, and preservation of abundant organic matter. Therefore, the oil source capacity of a possible source rock depends of four factors: quantity, quality, and thermal maturity of kerogen, and expulsion efficiency of the source sequence [11]. The source rock characteristics of the Eocene sediments from this study reveals sufficient amount of organic matter necessary for hydrocarbon generation. However, the organic matter is dominantly composed of type II/III mixed oil and gas prone and Type III gas prone kerogen which contain excellent organic matter that are immatured, but marginally matured in parts, with good potentials to generate hydrocarbons.

5.1. Multivariate analysis

The use of statistical principles in research works enables the scientist to gain a proper understanding of data acquired and its interpretation for optimal use. Geostatistics has become a toolbox of methods useful for attacking a range of problems in geology. The multivariate statistical analysis is the construction of cluster analysis (hierarchical and K-means cluster analysis), Factor analysis, and linear regression and Pearson's correlation.

5.2. The Pearson correlation and linear regression

The relation was established between the assessed geochemical parameters (S1, S2, S1 + S2, HI, QI, BI, PI, TOC) for the petroleum potentiality of the source rocks and used to investigate the impact of changes in the T_{max} and R_o% on these parameters. The plot of S2 vs TOC showed a strong correlation and hence can be inferred that S2 is contributed from TOC. Also clear and strong correlation was observed between TOC values and HI values, S1 values and S2 values, and Vitirnite reflectance values and Tmax. This implies that as one value increases so does the other within the source rocks. This implies that higher Total Organic content in source rocks also results in higher HI values within the study.

The plotting of Tmax vs. HI, Ro Vs S2, and Ro Vs HI showed no significant trend, and a pattern for their correlation could not be established. The implication of no significant correlation observed between HI and T_{max} implies that the highest HI do not occurs at certain maturities, however a strong correlation between (R_o% and T_{max}) are indicative that maturity occurs only at specific stages. A non-correlation was observed between R_o% and S2 (Figure 6 (e). indicating that the S2 values in the study area are not dependent on maturity. Additionally, T_{max} and R_o% were found to be positively correlated which confirms that both Rock–Eval pyrolysis and vitrinite reflectance can be used as indicators of thermal maturity. Two different trends were observed in the cross plot of S1 vs. S2 (Figure 6 (c) which might be attributed to the compositional difference in organic material. This can also be linked to the macerals contents which showed a predominance of Huminite and liptinite materials.

5.3. Cluster analysis

The set of 10 source parameters (R_o%, T_{max}, HI, QI, BI, PI, S1, S2, TOC, S1 + S2) were subjected to hierarchical cluster analysis using the ward method, which was proven to be the most reliable according to the up-to-date organic geochemical investigations. Based on the different HI values, the samples were distinguished into three main clusters: the first one (cluster I) of high HI and TOC values ranging respectively from 134 to 573mg/g and 22.53 to 60.36 mg/g) and the second (cluster II) of HI and TOC values of medium values range from 89 to 292 to mg/g and 2.51 to 22.57, while the third cluster shows lower HI and TOC ranges respectively from 10 to 139 mg/g and 0.39 to 6.72.The variability in the clusters are also significantly observed in other parameters like S1, S2, T_{max} and R_o. The resulting dendrogram (Figure 8.) showed three types of clusters which reflect three types of source rocks. Cluster I that represents the Edo, Ugunzu, Nnewi and Ogbanelu source rocks is found to be a good source rock for oil generation with slightly higher thermal maturation and characterized by HI values ranging from 134 to 573 mgHC/gTOC reflecting that these source rocks were characterized by kerogen type II and II/III. Cluster II represents the Akamili,Oba Akwu and Ekulu which indicate fair source rock types characterized by HI values ranging from to 89 to 292 mgHC/gTOC reflecting kerogen type III ,while cluster III represents characterized by HI values ranging from 10 to 139 mgHC/gTOC reflecting kerogen type IV.

5.4. Factor analysis

To get a more detailed classification of the source rock potential in the study area, a factor analysis of the source parameters was carried out using principle component analysis. According to up-to-date organic geochemical investigations, this method has been shown to be the most convenient. Factor analysis showed that there are three factors affecting the source rocks evaluation potentiality in the study area, factor 1 includes (TOC and S2) which determine the quantity of the organic matter and (R_o% and T_{max}) which determine the thermal maturity of the organic matter. On the other hand, factor 2 includes (HI) which determine the quality of the organic matter. By plotting the ratios of factor 1 vs. factor 2 (Figure 11), three groups of source rocks were observed. By comparing the results obtained by factor and cluster analyses, both methods confirmed the existence of three distinct source rock types with the study area, with the First type showing higher potentials, the second showing medium potentials while the third type displaying very poor qualities and maturity levels.

6. Conclusions

Multivariate statistical methods were applied to hydrocarbon source rock evaluation of outcrop samples from the Eocene Ameki Formation in the Niger Delta Basin to access its hydrocarbon generative potential. The following conclusions were deduced;

1. Source rock investigation using TOC and Rock – Eval pyrolysis was used to evaluate outcrop intervals of the Eocene successions indicate a generally good to excellent amount of organic matter. It is observed that dispersed organic matter in the source rock facies is composed mainly of Type II (oil and gas prone) and Type III (gas prone) kerogen and immature in most, but marginally matured in parts, and this been reported for the first time.
2. Multivariate statistical analysis was applied to evaluate the source rock potentiality and clarify the relationship between petroleum potential and maturity. The results obtained for studied samples were statistically analyzed using cluster analysis (hierarchical and K-means cluster analysis), Factor analysis, linear regression and Pearson's correlation by SPSS. The results obtained for the Pearson's correlation showed a clear and strong correlation was observed between TOC Vs S2, TOC vs HI, S1 Vs S2, and Ro vs Tmax. Whereas, the plotting of Tmax vs. HI, Ro Vs S2, and Ro Vs HI showed no significant trend. The implication of no significant correlation observed between HI and T_{max} implies that the highest HI do not occurs at certain maturities, however a strong correlation between (R_o% and T_{max}) are indicative that maturity occurs only at specific stages. Additionally, T_{max} and R_o% were found to be positively correlated which confirms that both Rock–Eval pyrolysis and vitrinite reflectance can be used as indicators of thermal maturity.
3. Cluster analysis classified the source rocks into three clusters. Cluster I that represents the Edo, Ugunzu, Nnewi and Ogbanelu source rocks is found to be a good source rock for oil generation with slightly higher thermal maturation and characterized by HI values ranging from 134 to 573 mgHC/gTOC reflecting that these source rocks were characterized by kerogen type II and II/III. Cluster II represents the Akamili, Oba Akwu and Ekulu which indicate fair source rock types characterized by HI values ranging from to 89 to 292 mgHC/gTOC reflecting kerogen type III ,while cluster III represents characterized by HI values ranging from 10 to 139 mgHC/gTOC reflecting kerogen type IV.
4. Factor analysis showed that there are three factors affecting the source rocks evaluation potentiality in the study area, factor 1 includes (TOC and S2) which determine the quantity of the organic matter and (R_o% and T_{max}) which determine the thermal maturity of the organic matter. On the other hand, factor 2 includes (HI) which determine the quality of the organic matter. By comparing the results obtained by factor and cluster analyses, both

methods confirmed the existence of three distinct source rock types with the study area, with the First type showing higher potentials, the second showing medium potentials while the third type displaying very poor qualities and maturity levels. There was further correlated to their depositional environment.

This paper reports on parts of the PhD thesis completed by Kennedy Ndeze at the Nnamdi Azikwe University Awka. The authors however take full responsibility for the ideas and interpretations presented in the paper.

Credit authorship contribution statement

Ndeze C. Kennedy: Conceptualization, Validation, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. Okoro A. U: Conceptualization, Validation, Investigation, Resources, Writing - review & editing, Supervision.Haruna K. A: Investigation, Resources, Writing - review & editing.Kalu C.G: Writing - review & editing, Resources.

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