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Pebble Morphogenesis of the Cretaceous Conglomerates from the Abeokuta Formation near the Oluwa River, Eastern Dahomey Basin, Southwestern Nigeria

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 552.5
DOI: 10.17794/rgn.2021.5.9

Original scientific paper

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Abstract
Pebbles taken from the bed of the Cretaceous Abeokuta Formation paraconglomerate near the Oluwa River were used to infer the depositional setting and the nature of the source area, through the integration of bivariate and ternary (sphericity-form and Zingg diagrams) analyses. Deposition in a river environment is indicated by the high sphericity values, ranging from 0.59 to 0.88 (average 0.70). Also, bivariate plots of the maximum projection sphericity (ψ_p) vs. oblate-prolate index (OPI) and flatness index (FI) vs. maximum projection sphericity (ψ_p) point to the domination of fluvial processes. Dominantly elongated, compact elongated, compact and compact-bladed pebbles are typical for sedimentary regime with prevalence of fluvial over beach processes. Co-existence of various pebbles shapes (mainly disc, rod-, and sphere-shaped), despite of the similar, predominantly quartz composition, may occur due to the different clast fabrics. This heterogeneity also indicates various transport distances and water energies, pointing to the multiple source areas.

Keywords:
Cretaceous; paraconglomerate; pebble morphometry; depositional processes; Abeokuta Formation; Nigeria

1. Introduction

The Abeokuta Formation is composed of conglomerates and sandstones, exposed along the Ore-Ode Aye Road in the southwestern part of Nigeria, and also forms the basal stratigraphic unit of the eastern Dahomey (Benin) Basin (**Okosun, 1990**). It unconformably overlies the Precambrian Basement Complex of Nigeria (**Obaje, 2009**). The formation is well exposed near the Oluwa River, which is located 6.4 kilometers to the north of Ode-Aye (see **Figure 1**).

Several authors have carried out sedimentological studies on the Abeokuta Formation (**Nton, 2001; Okosun, 1990; Ikhane et al., 2013; Madukwe, 2016**), but they did not apply the pebble morphometric approach, a method previously successfully applied in some other research areas in Nigeria (**Nwajide and Hoque, 1982**; **Olugbenro and Nwajide, 1997**; **Nton and Adamolekun, 2016**; **Ocheli et al., 2018; Bankole et al., 2020**). The aim of this study is to apply the pebble morphometric analyses to interpret the nature of the source area and the depositional environment of Abeokuta conglomerates exposed near the Oluwa River.

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1.1. Geology of the area

The Abeokuta and Araromi Formations are two lithostratigraphic formations that make up the Cretaceous sequence of the eastern Dahomey Embayment (**Figure 2; Okosun, 1990**). The Abeokuta Formation is mostly composed of unconsolidated sands with grey shale, mudstone, silt, and clay intercalations (**Okosun, 1990**; **Obaje, 2009**). These deposits are dated from the late Albian to the Santonian (**Okosun, 1990**). Dark grey and black shales with sandstone, limestone, marl, siltstone, and glauconite shale interbeds make up the Araromi Formation (**Obaje, 2009**).

The Paleocene Imo Shale/Ewekoro Formation, the Eocene Oshosun and Akinbo formations, the Oligocene-Miocene Ilaro Formation, and the Miocene-Quaternary Benin Formation are all Paleogene-Neogene deposits of the eastern Dahomey (Benin) Basin (**Figure 2**; **Ogbe, 1972**; **Olabode, 2006**). The Imo Shale is made up of laminated and calcareous grey, dark grey, and black shale with occasional white to brown sands (**Okosun and Alkali, 2012**), while the Ewekoro Formation consists of limestone with thin bands of sand, shale, and marl (**Okosun and Alkali, 2012**).

Flaggy grey and black shales, as well as clay, make up the Akinbo Formation (**Ogbe, 1972; Olabode and Adekoya, 2007**). The Ewekoro and Akinbo formations are

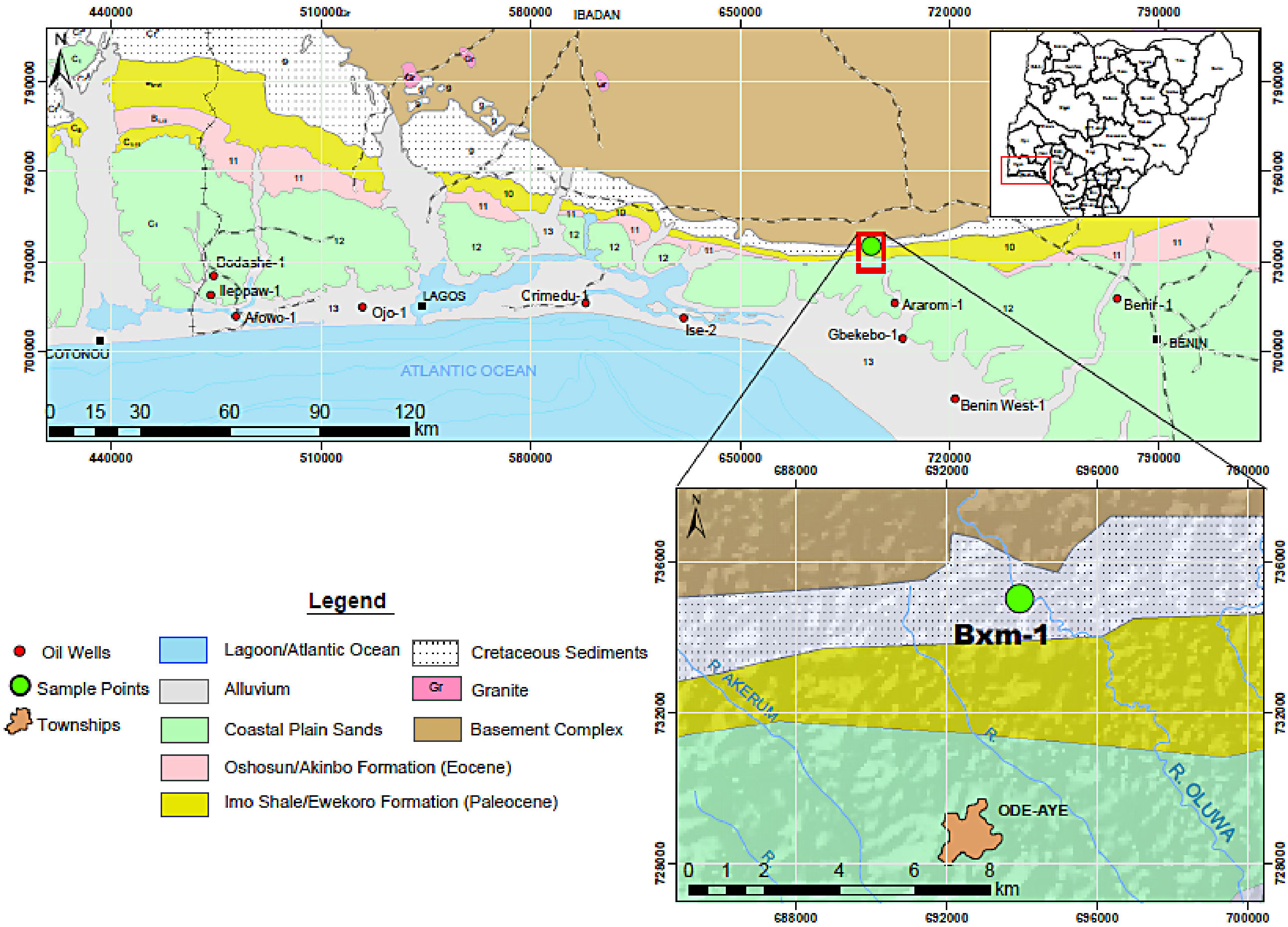


Figure 1: (A) Simplified geological map of the eastern Dahomey (Benin) Basin (after **Murat 1969**; **Oluwajana *et al.* 2021**), **(B)** with position of the exposed outcrop section

separated by glauconitic rock bands and phosphatic beds (**Enu and Adegoke, 1988**). Phosphate-bearing, greenish-grey or beige clay and shale with interbeds of sandstone make up the Oshosun Formation, which unconformably overlies the Akinbo Formation (**Okosun, 1998**).

The Ilaro Formation is composed of large, yellowish, weakly cemented fine to coarse cross-bedded sandstones, clays, and shales with occasional thin bands of phosphate beds that overlie the Oshosun Formation (**Madukwe et al., 2016**). The Benin Formation consists of cross-bedded, poorly sorted sandstones with estuarine to continental characteristics (**Kogbe, 1974**; **Nton et al., 2006**).

2. Methods

The outcrop description and logging, sampling and data analyses are discussed below.

2.1. Outcrop description and logging

The geographic coordinates of the studied outcrop are 06°38'49''N and longitude 004°45'16''E, near the Oluwa River, southwestern part of Nigeria (see **Figures 1, 2 and 3**). The outcrop section is underlain by the Precambrian Basement Complex rock, upon which deposition of basal conglomerate and sandstone occurred (see **Figure 3**). The Precambrian Basement Complex rock is highly weathered (see **Figure 3**), and unconformably overlain by 0.20 - 1.00 meters of basal conglomerate. The basal conglomerate comprises weakly imbricated quartz pebbles held together by a clayey and/or sandy matrix. Weathered, coarse-grained, poorly sorted sandstone overlying the paraconglomerate is 0.80 - 1.2 meters thick.

2.2. Sampling

An outcrop section exposed near the Oluwa River was carefully examined and described. One hundred and sixty-eight (168) unbroken pebble size clasts were randomly picked from the exposed section. The study involved measurement of the orthogonal axes of the pebbles which includes the long (D_L), the intermediate (D_I) and the short axes (D_S). The clast diameter size (φ) and the roundness (R) of the pebbles were also measured. Data from the measurement of these axes (D_L, D_I, and D_S) were used to compute the form indices, namely the coefficient of flatness (CF), the elongation ratio (ER), the maximum projection sphericity (ψ_p), and the oblate-prolate index (OPI) of each pebble (see **Tables 1 to 5**).

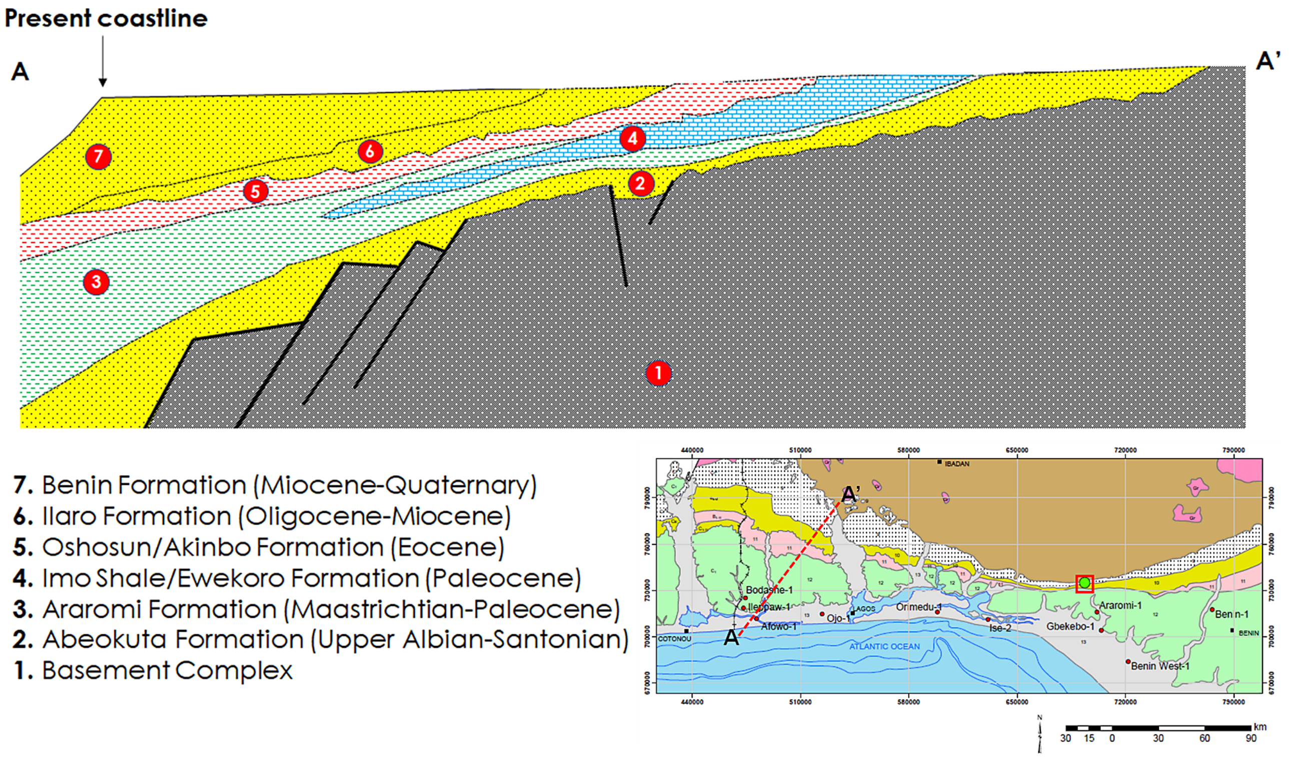


Figure 2: Representative northeast-southwest stratigraphic sketch section across part of the Eastern Dahomey (Benin) Basin, with the position and age of local formations (modified after **Petters, 1982** and **Ajayi, 1995**). The location of the cross-section (modified after **Murat, 1969**; **Ehinola and Oluwajana, 2016**)

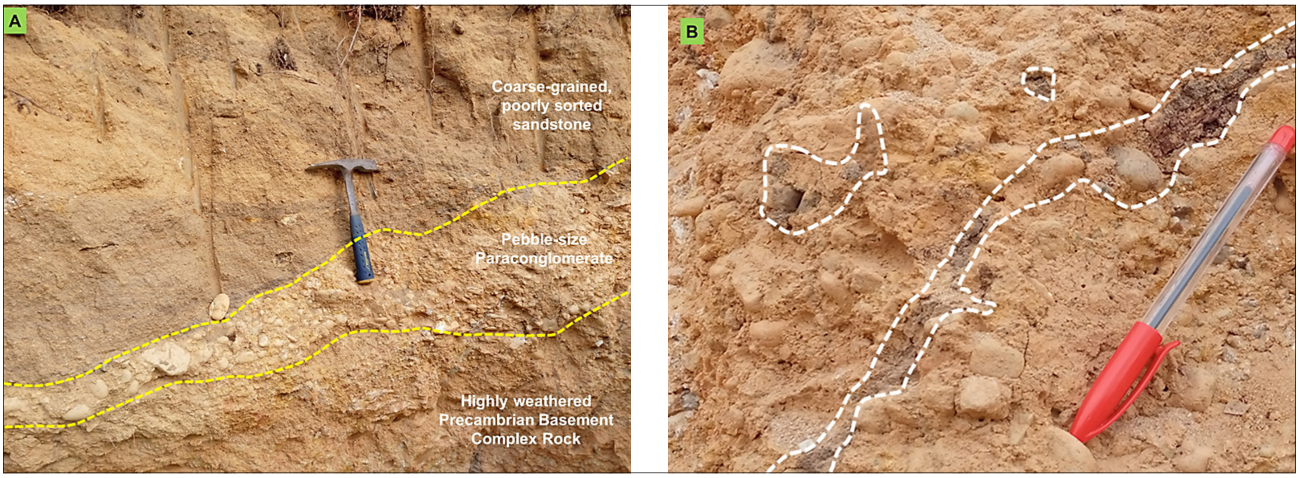


Figure 3: (A) Outcrop exposure near the Oluwa River showing highly weathered Precambrian basement complex rock, overlain by a matrix-supported pebble size conglomerate and coarse-grained sandstone units. (B) A close-up on the matrix-supported conglomerate: each pebble surrounded by matrix. In some instances, the matrix is stained with heavy oil (in the dotted mark)

2.3. Data Analysis

The coefficient of flatness (CF) was determined using **Equation 1** (**Lutig, 1962**).

$$\text{coefficient of flatness (CF)} = \frac{Ds}{Dl} \text{ x } 100 \qquad (1)$$

Where:

D_L represents the long axis of selected pebbles,

D_S represents the short axis of selected pebbles.

Equation 2 was used to determine the elongation ratio (ER) of the selected pebbles (**Lutig, 1962; Sames; 1966**).

$$\text{elongation ratio (ER)} = \frac{DI}{Dl} \qquad (2)$$

Where:

D_L represents the long axis of selected pebbles,

D_I represents the intermediate axis of selected pebbles.

Table 1: Results of the pebble morphometric study of the Cretaceous Abeokuta Formation

s/n	D_L	D_I	D_S	D_S/D_L	D_I/D_L	D_S/D_L	D_L-D_I	D_L-D_S	OPI	ψ_p	FI	Roundness (R)
1	6.5	4.9	3.3	50.77	0.75	0.67	1.6	3.2	0	0.7	75.38	45
2	5.8	4.9	3.6	62.07	0.84	0.73	0.9	2.2	-1.46	0.77	77.59	80
3	7.6	5.5	3.4	44.74	0.72	0.62	2.1	4.2	0	0.65	72.37	35
4	4.5	4	3.3	73.33	0.89	0.83	0.5	1.2	-1.14	0.85	84.44	20
5	5.5	4.5	3.5	63.64	0.82	0.78	1	2	0	0.79	81.82	75
6	4.4	3.7	2.7	61.36	0.84	0.73	0.7	1.7	-1.44	0.77	77.27	60
7	4.8	3.9	2.8	58.33	0.81	0.72	0.9	2	-0.86	0.75	77.08	40
8	4.9	3.3	2.2	44.9	0.67	0.67	1.6	2.7	2.06	0.67	77.55	30
9	3.7	3	2	54.05	0.81	0.67	0.7	1.7	-1.63	0.71	72.97	33
10	3.6	2.9	2	55.56	0.81	0.69	0.7	1.6	-1.13	0.73	75	55
11	5.5	4.2	2.5	45.45	0.76	0.6	1.3	3	-1.47	0.65	69.09	40
12	5.1	3.8	2.4	47.06	0.75	0.63	1.3	2.7	-0.39	0.67	72.55	58
13	4.9	3.8	2.4	48.98	0.78	0.63	1.1	2.5	-1.23	0.68	71.43	43
14	4.1	3.3	2.2	53.66	0.8	0.67	0.8	1.9	-1.47	0.71	73.17	40
15	3.6	3.2	2.5	69.44	0.89	0.78	0.4	1.1	-1.96	0.82	80.56	88
16	4	3.1	2	50	0.78	0.65	0.9	2	-1	0.69	72.5	48
17	4.3	3.2	2	46.51	0.74	0.63	1.1	2.3	-0.47	0.67	72.09	45
18	5.1	4	2.5	49.02	0.78	0.63	1.1	2.6	-1.57	0.68	70.59	38
19	4	3.2	2.2	55	0.8	0.69	0.8	1.8	-1.01	0.73	75	75
20	5	3.5	2.3	46	0.7	0.66	1.5	2.7	1.21	0.67	76	42
21	3.8	3	1.9	50	0.79	0.63	0.8	1.9	-1.58	0.68	71.05	70
22	4.3	3.3	2	46.51	0.77	0.61	1	2.3	-1.4	0.66	69.77	36
23	4.1	3.4	2.4	58.54	0.83	0.71	0.7	1.7	-1.51	0.75	75.61	30
24	4.3	3.4	2.2	51.16	0.79	0.65	0.9	2.1	-1.4	0.69	72.09	60
25	4.7	3.7	2.4	51.06	0.79	0.65	1	2.3	-1.28	0.69	72.34	40
26	3.7	3.1	2.3	62.16	0.84	0.74	0.6	1.4	-1.15	0.77	78.38	65
27	4.4	3.6	2.4	54.55	0.82	0.67	0.8	2	-1.83	0.72	72.73	46
28	3.4	2.7	1.8	52.94	0.79	0.67	0.7	1.6	-1.18	0.71	73.53	35
29	4	3.2	2.1	52.5	0.8	0.66	0.8	1.9	-1.5	0.7	72.5	42
30	3.4	2.9	2.1	61.76	0.85	0.72	0.5	1.3	-1.87	0.77	76.47	65
31	4	3.2	2.1	52.5	0.8	0.66	0.8	1.9	-1.5	0.7	72.5	58
32	4.5	3.6	2.3	51.11	0.8	0.64	0.9	2.2	-1.78	0.69	71.11	38
33	3.8	3	1.9	50	0.79	0.63	0.8	1.9	-1.58	0.68	71.05	38
34	4.5	3.3	2	44.44	0.73	0.61	1.2	2.5	-0.45	0.65	71.11	33
35	4.3	3	2.4	55.81	0.7	0.8	1.3	1.9	3.3	0.77	86.05	35

The maximum projection sphericity (ψp) of the pebbles describes particle behaviour and is defined mathematically as the ratio between the maximum projection area of a sphere with the same volume as the particle (**Boggs, 1987**). The maximum projection sphericity (ψ_p), according to **Sneed and Folk (1958)**, was defined using **Equation 3** and was calculated for each selected pebble.

maximum projection sphericity

$$(\psi_p) = \sqrt[3]{\frac{Ds^2}{D_L D_I}} \tag{3}$$

Where:

D_L represents the long axis of selected pebbles,

D_I represents the intermediate axis of selected pebbles,

D_S represents the short axis of selected pebbles.

Equation 4 is used to determine oblate-prolate index (OPI) (**Dobkins and Folk, 1970**).

$$\text{oblate-prolate Index (OPI)} = \frac{10(\frac{Dl - DI}{Dl - Ds} - 0.50)}{Ds / Dl} \tag{4}$$

Table 2: Results of the pebble morphometric study of the Cretaceous Abeokuta Formation

s/n	D_L	D_I	D_S	D_S/D_L	D_I/D_L	D_S/D_L	D_L-D_I	D_L-D_S	OPI	ψp	FI	Roundness (R)
36	4.5	3.1	2	44.44	0.69	0.65	1.40	2.50	1.35	0.66	75.56	53
37	5.9	2.5	2.1	35.59	0.42	0.84	3.40	3.80	11.09	0.67	93.22	30
38	4.5	3	2	44.44	0.67	0.67	1.50	2.50	2.25	0.67	77.78	35
39	5	3	2	40.00	0.60	0.67	2.00	3.00	4.17	0.65	80.00	32
40	4.5	3	2	44.44	0.67	0.67	1.50	2.50	2.25	0.67	77.78	36
41	4	3	1.9	47.50	0.75	0.63	1.00	2.10	-0.50	0.67	72.50	40
42	2.8	2.4	1.8	64.29	0.86	0.75	0.40	1.00	-1.56	0.79	78.57	37
43	3.4	2.7	1.8	52.94	0.79	0.67	0.70	1.60	-1.18	0.71	73.53	40
44	4	2.7	1.8	45.00	0.68	0.67	1.30	2.20	2.02	0.67	77.50	38
45	3.5	2.7	1.8	51.43	0.77	0.67	0.80	1.70	-0.57	0.70	74.29	43
46	4.2	3.1	2.1	50.00	0.74	0.68	1.10	2.10	0.48	0.70	76.19	55
47	3.3	2.4	1.7	51.52	0.73	0.71	0.90	1.60	1.21	0.72	78.79	50
48	3	2.5	1.8	60.00	0.83	0.72	0.50	1.20	-1.39	0.76	76.67	35
49	3.5	2.7	1.7	48.57	0.77	0.63	0.80	1.80	-1.14	0.68	71.43	70
50	3.5	2.7	1.8	51.43	0.77	0.67	0.80	1.70	-0.57	0.70	74.29	33
51	3.3	2.6	1.8	54.55	0.79	0.69	0.70	1.50	-0.61	0.73	75.76	34
52	3.4	2.4	1.8	52.94	0.71	0.75	1.00	1.60	2.36	0.74	82.35	52
53	4.4	2.5	1.7	38.64	0.57	0.68	1.90	2.70	5.27	0.64	81.82	48
54	3.7	2.8	2	54.05	0.76	0.71	0.90	1.70	0.54	0.73	78.38	83
55	3.5	2.7	1.8	51.43	0.77	0.67	0.80	1.70	-0.57	0.70	74.29	55
56	3.6	2.7	1.6	44.44	0.75	0.59	0.90	2.00	-1.13	0.64	69.44	38
57	3.5	2.8	1.8	51.43	0.80	0.64	0.70	1.70	-1.72	0.69	71.43	37
58	3.5	2.7	1.7	48.57	0.77	0.63	0.80	1.80	-1.14	0.68	71.43	30
59	3	2.5	1.9	63.33	0.83	0.76	0.50	1.10	-0.72	0.79	80.00	45
60	3.5	2.6	1.6	45.71	0.74	0.62	0.90	1.90	-0.58	0.66	71.43	35
61	2.9	2.3	1.5	51.72	0.79	0.65	0.60	1.40	-1.38	0.70	72.41	31
62	3.8	2.6	1.7	44.74	0.68	0.65	1.20	2.10	1.60	0.67	76.32	33
63	3.1	2.5	1.7	54.84	0.81	0.68	0.60	1.40	-1.30	0.72	74.19	40
64	3	2.4	1.7	56.67	0.80	0.71	0.60	1.30	-0.68	0.74	76.67	38
65	4	2.7	1.8	45.00	0.68	0.67	1.30	2.20	2.02	0.67	77.50	35
66	3.2	2.5	1.6	50.00	0.78	0.64	0.70	1.60	-1.25	0.69	71.88	25
67	3.5	2.4	1.6	45.71	0.69	0.67	1.10	1.90	1.73	0.68	77.14	29
68	3.3	2.5	1.8	54.55	0.76	0.72	0.80	1.50	0.61	0.73	78.79	36
69	3.5	2.7	1.7	48.57	0.77	0.63	0.80	1.80	-1.14	0.68	71.43	48
70	3.2	2.5	1.6	50.00	0.78	0.64	0.70	1.60	-1.25	0.69	71.88	34

Where:

D_L represents the long axis of selected pebbles,

D_I represents the intermediate axis of selected pebbles,

D_S represents the short axis of selected pebbles.

The **Equation 5** was applied in calculating the flatness index (FI) of each selected pebble (**Illenberger, 1991**)

$$\text{flatness index (FI)} = \frac{\left(D_L - D_I + Ds\right)}{D_L} \qquad (5)$$

Where:

D_L represents the long axis of selected pebbles,

D_I represents the intermediate axis of selected pebbles,

D_S represents the short axis of selected pebbles.

The calculated values obtained from **Equations 1, 2, 3, and 4** were used to construct bivariate and ternary plots. The pebble roundness (R) was estimated using the visual charts of **Powers (1953)**. Pebble forms were thereafter plotted using Tri-plot version 1.3 (**Graham and Midgley, 2000**). The **Zingg (1935)** classification plot was used to categorize the pebbles into descriptive shape fields defined by **Sneed and Folk (1958)**.

Table 3: Results of the pebble morphometric study of the Cretaceous Abeokuta Formation

s/n	D_L	D_I	D_S	D_S/D_L	D_I/D_L	D_S/D_L	D_L-D_I	D_L-D_S	OPI	ψ_p	FI	Roundness (R)
71	3	2.4	1.7	56.67	0.80	0.71	0.60	1.30	-0.68	0.74	76.67	54
72	2.8	2.2	1.5	53.57	0.79	0.68	0.60	1.30	-0.72	0.72	75.00	32
73	3.4	2.6	1.8	52.94	0.76	0.69	0.80	1.60	0.00	0.72	76.47	60
74	2.8	2.2	1.4	50.00	0.79	0.64	0.60	1.40	-1.43	0.69	71.43	38
75	2.6	2.1	1.4	53.85	0.81	0.67	0.50	1.20	-1.55	0.71	73.08	32
76	2.7	2.3	1.7	62.96	0.85	0.74	0.40	1.00	-1.59	0.78	77.78	15
77	3.4	2.8	2	58.82	0.82	0.71	0.60	1.40	-1.21	0.75	76.47	33
78	3	2.4	1.6	53.33	0.80	0.67	0.60	1.40	-1.34	0.71	73.33	37
79	2.8	2.2	1.4	50.00	0.79	0.64	0.60	1.40	-1.43	0.69	71.43	27
80	3	2.4	1.7	56.67	0.80	0.71	0.60	1.30	-0.68	0.74	76.67	46
81	3	2.3	1.5	50.00	0.77	0.65	0.70	1.50	-0.67	0.69	73.33	37
82	3	2.4	1.7	56.67	0.80	0.71	0.60	1.30	-0.68	0.74	76.67	45
83	4	2.2	1.6	40.00	0.55	0.73	1.80	2.40	6.25	0.67	85.00	30
84	3	2	1.7	56.67	0.67	0.85	1.00	1.30	4.75	0.79	90.00	32
85	3	2.3	1.6	53.33	0.77	0.70	0.70	1.40	0.00	0.72	76.67	45
86	4.4	2.2	1.7	38.64	0.50	0.77	2.20	2.70	8.15	0.67	88.64	39
87	2.4	2	1.6	66.67	0.83	0.80	0.40	0.80	0.00	0.81	83.33	70
88	3.9	2.2	1.6	41.03	0.56	0.73	1.70	2.30	5.83	0.67	84.62	38
89	2.7	1.8	1.5	55.56	0.67	0.83	0.90	1.20	4.50	0.78	88.89	38
90	4	2.2	1.6	40.00	0.55	0.73	1.80	2.40	6.25	0.67	85.00	30
91	3.3	2.2	2	60.61	0.67	0.91	1.10	1.30	5.71	0.82	93.94	52
92	2.4	1.6	1.1	45.83	0.67	0.69	0.80	1.30	2.52	0.68	79.17	48
93	1.9	1.5	1	52.63	0.79	0.67	0.40	0.90	-1.06	0.71	73.68	34
94	3.6	1.8	1.5	41.67	0.50	0.83	1.80	2.10	8.57	0.71	91.67	45
95	2.5	1.9	1.3	52.00	0.76	0.68	0.60	1.20	0.00	0.71	76.00	34
96	2.4	1.8	1.4	58.33	0.75	0.78	0.60	1.00	1.71	0.77	83.33	60
97	2.9	2	1.3	44.83	0.69	0.65	0.90	1.60	1.39	0.67	75.86	33
98	2.4	2.2	1.9	79.17	0.92	0.86	0.20	0.50	-1.26	0.88	87.50	35
99	1.7	1.3	0.9	52.94	0.76	0.69	0.40	0.80	0.00	0.72	76.47	33
100	4.2	1.9	1.5	35.71	0.45	0.79	2.30	2.70	9.85	0.66	90.48	39
101	2.5	1.8	1.2	48.00	0.72	0.67	0.70	1.30	0.80	0.69	76.00	35
102	2.6	2.1	1.7	65.38	0.81	0.81	0.50	0.90	0.85	0.81	84.62	38
103	2.9	2.2	1.3	44.83	0.76	0.59	0.70	1.60	-1.39	0.65	68.97	38
104	2.5	1.6	1.1	44.00	0.64	0.69	0.90	1.40	3.25	0.67	80.00	36
105	2.9	1.7	1.2	41.38	0.59	0.71	1.20	1.70	4.98	0.67	82.76	28

3. Results

The clast diameter size (φ) of the pebbles generally ranges from -3.5 to 5.5 and the average roundness (R) value for the pebbles is 39.96 (see **Tables 1 to 5**). The results of pebble morphometric analysis (see **Tables 1 to 5**) indicate that the oblate-prolate values of the studied pebbles range from -1.96 to 12.15 with a mean value of 0.98 (see **Tables 1 to 5**). Over 90% of the pebbles have oblate-prolate index (OPI) values greater than -1.5, suggesting a fluvial environment (**Dobkins and Folk, 1970**). The pebbles' elongation ratio ranges from 0.69-0.85. The maximum projection sphericity (ψ_p) of the pebbles obtained from the exposed outcrop varies from 0.59 to 0.88, with a mean value of 0.70. The percentage of pebbles with maximum projection sphericity (ψ_p) values greater than 0.65 is 92%, indicating a fluvial setting. The flatness index (FI) values range from 68.18 to 96.00, with a mean FI value of 77.50. All the measured pebbles have flatness index (FI) values greater than 45% (see **Tables 1 to 5**), suggesting deposition by fluvial-influenced processes.

The values obtained from the calculation of oblate-prolate index (OPI), maximum projection sphericity (ψ_p) and flatness index (FI) are in concordance, suggesting

Table 4: Results of the pebble morphometric study of the Cretaceous Abeokuta Formation

s/n	D_L	D_I	D_S	D_S/D_L	D_I/D_L	D_S/D_L	D_L-D_I	D_L-D_S	OPI	ψ_p	FI	Roundness (R)
106	2.4	1.6	1.1	45.83	0.67	0.69	0.80	1.30	2.52	0.68	79.17	48
107	3	2.3	1.5	50.00	0.77	0.65	0.70	1.50	-0.67	0.69	73.33	52
108	2.3	1.9	1.4	60.87	0.83	0.74	0.40	0.90	-0.91	0.77	78.26	38
109	2.5	1.7	1.1	44.00	0.68	0.65	0.80	1.40	1.62	0.66	76.00	45
110	2.1	1.6	1.1	52.38	0.76	0.69	0.50	1.00	0.00	0.71	76.19	25
111	2	1.5	1	50.00	0.75	0.67	0.50	1.00	0.00	0.70	75.00	85
112	2.2	1.7	1.2	54.55	0.77	0.71	0.50	1.00	0.00	0.73	77.27	29
113	2.9	2.1	1.3	44.83	0.72	0.62	0.80	1.60	0.00	0.66	72.41	30
114	2.2	1.7	1.1	50.00	0.77	0.65	0.50	1.10	-0.91	0.69	72.73	52
115	2.7	2	1.2	44.44	0.74	0.60	0.70	1.50	-0.75	0.65	70.37	43
116	3.1	2.1	1.4	45.16	0.68	0.67	1.00	1.70	1.95	0.67	77.42	37
117	2	1.5	1	50.00	0.75	0.67	0.50	1.00	0.00	0.70	75.00	40
118	2.6	1.9	1.2	46.15	0.73	0.63	0.70	1.40	0.00	0.67	73.08	43
119	2	1.6	1.2	60.00	0.80	0.75	0.40	0.80	0.00	0.77	80.00	42
120	2.5	1.9	1.3	52.00	0.76	0.68	0.60	1.20	0.00	0.71	76.00	35
121	3	2	1.3	43.33	0.67	0.65	1.00	1.70	2.04	0.66	76.67	46
122	3.1	2.3	1.4	45.16	0.74	0.61	0.80	1.70	-0.65	0.65	70.97	35
123	2.5	1.9	1.3	52.00	0.76	0.68	0.60	1.20	0.00	0.71	76.00	42
124	3	2.2	1.6	53.33	0.73	0.73	0.80	1.40	1.34	0.73	80.00	28
125	2.5	2	1.5	60.00	0.80	0.75	0.50	1.00	0.00	0.77	80.00	35
126	2.3	1.8	1.4	60.87	0.78	0.78	0.50	0.90	0.91	0.78	82.61	28
127	2.5	1.8	1.2	48.00	0.72	0.67	0.70	1.30	0.80	0.69	76.00	28
128	2.7	2	1.3	48.15	0.74	0.65	0.70	1.40	0.00	0.68	74.07	28
129	3.8	1.8	1.4	36.84	0.47	0.78	2.00	2.40	9.05	0.66	89.47	33
130	2.5	1.9	1.2	48.00	0.76	0.63	0.60	1.30	-0.80	0.67	72.00	30
131	2.5	2.2	1.8	72.00	0.88	0.82	0.30	0.70	-0.99	0.84	84.00	35
132	1.9	1.4	1	52.63	0.74	0.71	0.50	0.90	1.06	0.72	78.95	35
133	3.3	1.8	1.3	39.39	0.55	0.72	1.50	2.00	6.35	0.66	84.85	40
134	1.8	1.3	1	55.56	0.72	0.77	0.50	0.80	2.25	0.76	83.33	25
135	1.9	1.4	1.1	57.89	0.74	0.79	0.50	0.80	2.16	0.77	84.21	32
136	3	1.7	1.2	40.00	0.57	0.71	1.30	1.80	5.56	0.66	83.33	20
137	2.2	1.7	1.1	50.00	0.77	0.65	0.50	1.10	-0.91	0.69	72.73	45
138	2.9	2	1.3	44.83	0.69	0.65	0.90	1.60	1.39	0.67	75.86	35
139	2.8	2	1.6	57.14	0.71	0.80	0.80	1.20	2.92	0.77	85.71	25
140	2.9	2.3	1.5	51.72	0.79	0.65	0.60	1.40	-1.38	0.70	72.41	35
141	2.3	1.7	1.2	52.17	0.74	0.71	0.60	1.10	0.87	0.72	78.26	28

the prevalence of fluvial processes (**Dobkins and Folk, 1970; Stratten, 1974; Anyiam *et al*., 2017**). The plot of flatness index (FI) against maximum projection sphericity (ψ_p) (see **Figure 4**) and maximum projection sphericity (ψ_p) against the oblate-prolate index (OPI) (see **Figure 5**) was used also to distinguish beaches from river processes (**Dobkins and Folk, 1970; Okon *et al*., 2018**). The bivariate plots of flatness index (FI) vs. maximum projection sphericity (ψ_p) (see **Figure 4**) and maximum projection sphericity (ψ_p) vs. oblate-prolate index (OPI) (see **Figure 5**) revealed that most of the pebbles are located in the fluvial field.

4. Discussion

4.1 Depositional environment

The roundness (R) of pebbles is a function of transport and tends to increase downstream from rivers to beaches (**Sneed and Folk, 1958; Lutig 1962; Sames**

Table 5: Results of the pebble morphometric study of the Cretaceous Abeokuta Formation

s/n	D_L	D_I	D_S	D_S/D_L	D_I/D_L	D_S/D_L	D_L-D_I	D_L-D_S	OPI	ψ_p	FI	Roundness (R)
142	2.1	1.6	1.2	57.14	0.76	0.75	0.50	0.90	0.97	0.76	80.95	25
143	2	1.5	1.1	55.00	0.75	0.73	0.50	0.90	1.01	0.74	80.00	23
144	2.6	1.6	1.1	42.31	0.62	0.69	1.00	1.50	3.94	0.67	80.77	33
145	1.9	1.5	1.1	57.89	0.79	0.73	0.40	0.80	0.00	0.75	78.95	52
146	1.9	1.5	1	52.63	0.79	0.67	0.40	0.90	-1.06	0.71	73.68	28
147	3	2.3	1.5	50.00	0.77	0.65	0.70	1.50	-0.67	0.69	73.33	30
148	2	1.5	1	50.00	0.75	0.67	0.50	1.00	0.00	0.70	75.00	30
149	2.6	1.7	1	38.46	0.65	0.59	0.90	1.60	1.63	0.61	73.08	31
150	2.2	1.7	1	45.45	0.77	0.59	0.50	1.20	-1.83	0.65	68.18	33
151	3	2	1.1	36.67	0.67	0.55	1.00	1.90	0.72	0.59	70.00	29
152	2.4	1.6	0.9	37.50	0.67	0.56	0.80	1.50	0.89	0.60	70.83	48
153	2	1.5	0.9	45.00	0.75	0.60	0.50	1.10	-1.01	0.65	70.00	48
154	2.5	1.5	1.1	44.00	0.60	0.73	1.00	1.40	4.87	0.69	84.00	35
155	2.5	1	0.9	36.00	0.40	0.90	1.50	1.60	12.15	0.69	96.00	34
156	2.2	1.2	1	45.45	0.55	0.83	1.00	1.20	7.33	0.73	90.91	35
157	2.9	1.3	1	34.48	0.45	0.77	1.60	1.90	9.92	0.65	89.66	42
158	2	1.2	1	50.00	0.60	0.83	0.80	1.00	6.00	0.75	90.00	28
159	1.8	1.4	0.9	50.00	0.78	0.64	0.40	0.90	-1.11	0.69	72.22	42
160	1.9	1.2	0.8	42.11	0.63	0.67	0.70	1.10	3.24	0.66	78.95	25
161	2	1.4	0.9	45.00	0.70	0.64	0.60	1.10	1.01	0.66	75.00	27
162	2.2	1.2	0.9	40.91	0.55	0.75	1.00	1.30	6.58	0.68	86.36	28
163	1.8	1.1	0.8	44.44	0.61	0.73	0.70	1.00	4.50	0.69	83.33	33
164	2	0.9	0.7	35.00	0.45	0.78	1.10	1.30	9.89	0.65	90.00	25
165	1.8	1.3	0.8	44.44	0.72	0.62	0.50	1.00	0.00	0.65	72.22	40
166	2.4	1.3	1	41.67	0.54	0.77	1.10	1.40	6.86	0.69	87.50	32
167	2.1	1.4	0.9	42.86	0.67	0.64	0.70	1.20	1.94	0.65	76.19	35
168	2.1	1.2	0.9	42.86	0.57	0.75	0.90	1.20	5.83	0.69	85.71	31

1966; Dobkins and Folk 1970). Flatter pebbles migrate down the beach more than spherical pebbles (**Humbert, 1968; Pettijohn, 1975**). This means that the roundness (R) value suggests deposition under a fluvial-influenced process (**Okoro *et al*. 2012; Anyiam et al., 2017**).

The plot of roundness (R) vs. elongation ratio (ER) for the Abeokuta Formation pebbles (see **Figure 6**) shows that the bulk of the pebbles occur in the fluvial field (**Sames, 1966; Figure 6**). Most of the measured pebbles are plotted in the fluvial field, indicating the dominance of fluvial processes, and the occurrence of some proportion of beach pebbles suggests that the river reached the marginal marine environment during its flow (**Figure 6; Madi and Ndlazi, 2020**). The integration of the pebble morphometric data and bivariate plots reflects a fluvial depositional environment for pebbles of the Cretaceous Abeokuta Formation.

4.2 Character of the source area

The majority of the measured pebbles plotted on the bivariate plot of Zingg (1935), fall on the disc, spheroid, and rod fields (see **Figure 7**). Spheres and rollers are transported more readily than blades and discs having the same mass, thus owing to preferential transport of spheres and rollers, downstream changes in pebble form may occur in rivers (**Boggs, 1987**). Homogeneous rocks (massive limestones, dolomites, quartzites, or marbles) form sphere and disc pebble shapes (**Barudžija et al., 2020**). The rod-shaped pebbles were formed from highly cleaved or schistose rocks (**Tucker, 2003**). The distribution of pebbles shapes of mainly disc-, rod-, and sphere-shaped may reflect different clast fabrics and indicating multiple sources (e.g., **Sremac et al., 2018**; **Barudžija et al., 2020**).

The compact (C), compact platy (CP), compact bladed (CB), and compact elongated (CE) pebbles are diagnostic of fluvial environments; platy, bladed, and elongated pebbles are diagnostic of a transitional environment; while very platy, very bladed, and very elongated are diagnostic of marine (beach) environment (**Ocheli et al., 2018**). The compact, compact platy, compact bladed, and compact elongated pebbles constitute 2%, 0% and

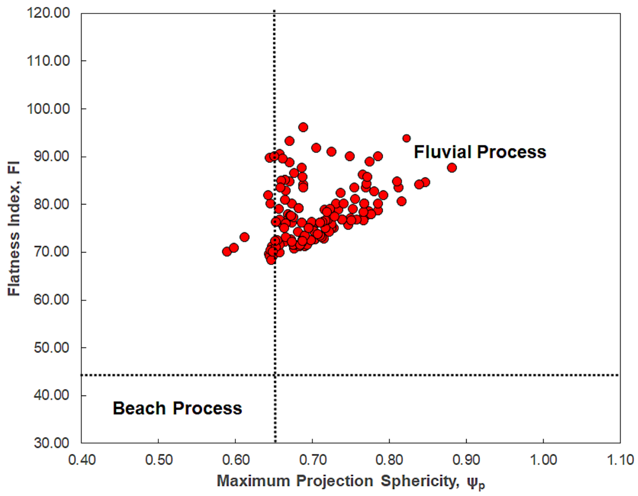
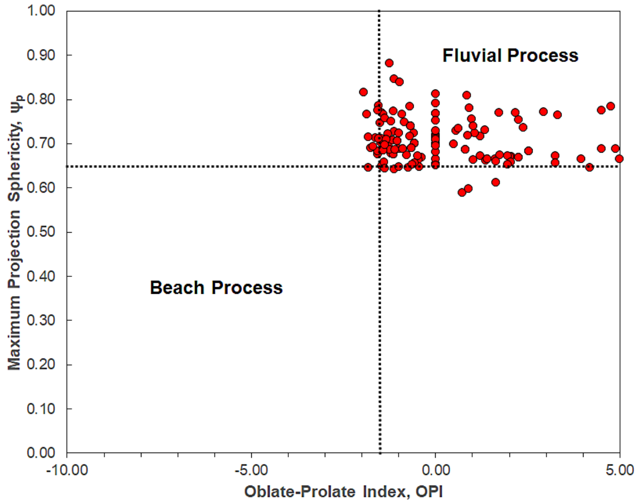


Figure 4: Bivariate plot of flatness index (FI) against maximum projection sphericity (ψ_p) (**Dobkins and Folk, 1970**), with measured values for pebbles from the Abeokuta Formation



42.26%, respectively. The percentages of points that correspond to platy, bladed, and elongated fields are 0%, 40.48%, and 13.10% respectively, while none of the pebbles fall in very platy, very bladed, and very elongated fields. The plots on the ternary diagram of **Sneed and Folk (1958)** indicate that the pebbles of the Abeokuta Formation fall on the fluviatile-transitional depositional environment field (see **Figure 8**).

The present study has shown that the high proportion of fluvial plots indicates the dominance of fluvial processes, and the occurrence of some proportion of beach pebbles suggests that the river reached the marginal marine environment during its flow. This study has shown the reliability of using the pebble morphometric approach in deciphering a depositional environment and source area. The outcome of this study is consistent with the results of previous authors (**Omatsola and Adegoke, 1981; Ikhane et al., 2013; Madukwe, 2016**).

5. Conclusions

The Cretaceous Abeokuta Formation exposed near the Oluwa River consists of paraconglomerate and coarse-grained poorly sorted sandstone. The morphometric analysis of the pebbles from the paraconglomerate strata allows the following conclusions to be made on the source area, transport process, and depositional settings.

Figure 5: Bivariate plot of maximum projection sphericity (ψ_p) against oblate-prolate index (OPI) (**Dobkins and Folk, 1970**), with measured values for pebbles from the Abeokuta Formation

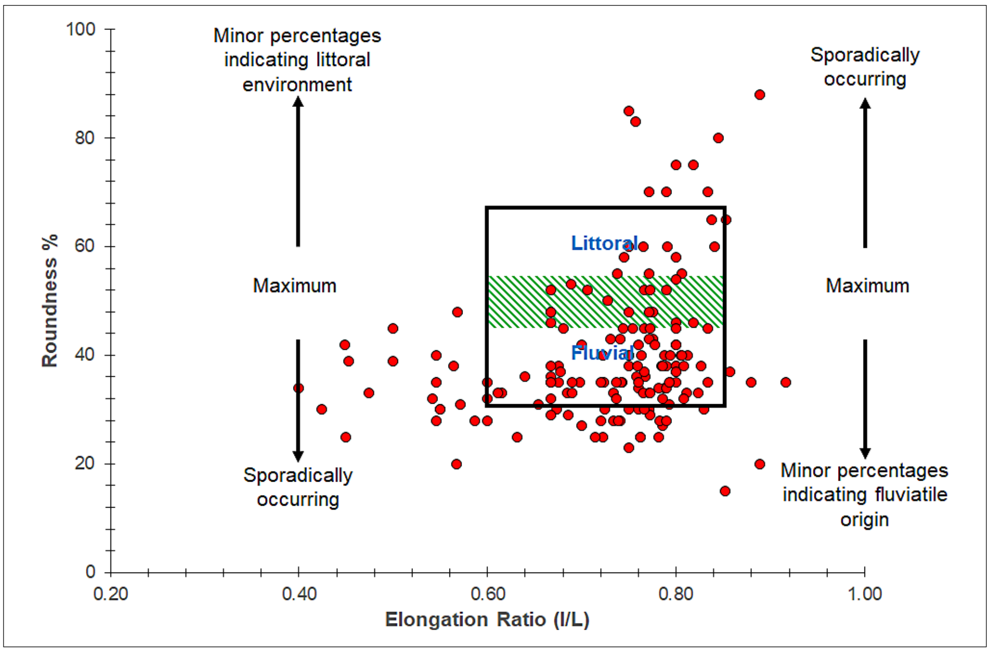


Figure 6: Plot of roundness (R) against elongation ratio (ER) (**Sames, 1966**), with measured values for pebbles from the Abeokuta Formation

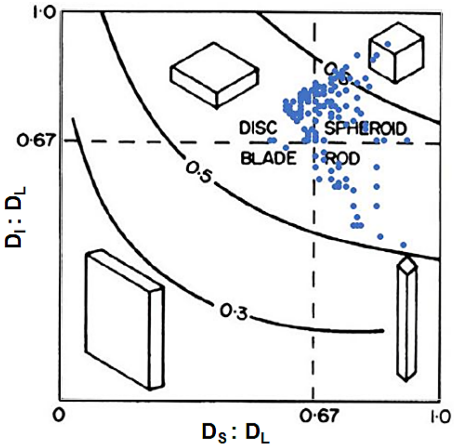


Figure 7: Zingg's classification of pebble shapes showing lines of equal sphericity (**Lewis and McConchie, 1994**). The curves denote clast of the same sphericity. The blue spots represent the results for the measured pebbles.

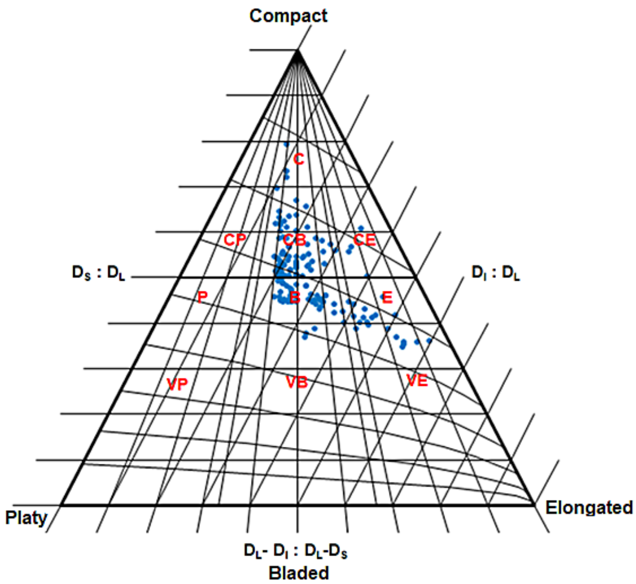


Figure 8: Triangular diagrams showing the descriptive classes of **Sneed and Folk (1958)**, where C = Compact, CP = Compact Platy, CB = Compact Bladed, CE = Compact Elongated, P = Platy, B = Bladed, E = Elongated and VP = Very Platy, VB = Very Bladed, VE = Very Elongated. The blue spots represent the results for the measured pebbles.

1. The mean pebble form indices and average sphericity of 0.70 indicate the deposition under a fluvial setting.
2. The maximum projection sphericity (ψ_p) vs. oblate-prolate index (OPI), flatness index (FI) vs. maximum projection sphericity (ψ_p), and coefficient of flatness (CF) vs. roundness (R) are bivariate graphs also indicative of a fluvial environment.
3. Bivariate and ternary plots of pebbles obtained from the bed of the Cretaceous Abeokuta Formation support the deposition in a river system.
4. Most of the pebbles yielded elongated, compact elongated, compact, and compact-bladed forms, indicative of the dominance of fluvial processes over beach actions.
5. The scattered distribution of pebble shapes of mainly disc-, rod-, and sphere-shaped pebbles reflects different clast fabrics, indicating multiple sources.

Acknowledgement

The research was done when the first author was on sabbatical at the Life and Earth Sciences Institute, Pan African University at the University of Ibadan in Ibadan, Nigeria. We thank Prof. Olugbenga Ehinola, Dr. Olugbenga Boboye, and Dr. Christopher Adeigbe of the Department of Geology, University of Ibadan, Ibadan, Nigeria for sharing their thoughts on the exposed outcrop section of the Abeokuta Formation. Reviews by Olajide Adamolekun, anonymous reviewers, together with editorial comments helped improve the quality of this manuscript.

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Croatian abstract, key words, author(s) contribution and acknowledgement (if necessary).

SAŽETAK

Morfogeneza valutica krednih konglomerata formacije Abeokuta, okolica rijeke Oluwa, istočni dio bazena Dahomey, jugozapadna Nigerija

Valutice iz podine kredne formacije Abeokuta predstavljaju parakonglomerate. Uzorkovani su iz okolice rijeke Oluwa s ciljem opisivanja taložnih uvjeta i izvorišnoga područja. Istraživani su dvovarijantnim i ternarnim dijagramima (oblika sferičnosti i Zinggovim). Na riječno taloženje upućuje visoka sferičnost u rasponu 0,59 – 0,88 (srednja vrijednost 0,70). Usporedba dvovarijantnih dijagrama maksimalne sferičnosti (ψp), spljoštenosti i izduženosti te zaravnjenosti uputila je na dominantno riječni okoliš. Posljedica su izdužene, kompaktne i oštre valutice nastale u dominantno riječnim uvjetima, s manjim utjecajem procesa okoliša plaža. Različiti oblici valutica (pretežito diskoidni, štapićasti i sferni), iako su uglavnom pretežito svi izgrađeni od kvarca, imaju različit uzorak. Takva heterogenost upućuje na različitu udaljenost prijenosa, energiju vode i višestruka izvorišta materijala.

Ključne riječi:
kreda, parakonglomerati, morfometrija valutica, taložni procesi, formacija Abeokuta, Nigerija

Authors' contributions

Oladotun Afolabi Oluwajana (Ph.D., Senior Lecturer, Petroleum Geologist, Sedimentologist) as the main contributor, coordinated the field study, sampling, data analysis, interpretation of the pebble morphometric results, and presentation of the results. **Charles Ugwu Ugwueze** (Ph.D., Senior Lecturer, Sedimentologist) analyzed and interpreted the pebble morphometric results. **Ovie Benjamin Ogbe** (Ph.D., Lecturer I, Petroleum Geologist, Sedimentologist) assisted in the interpretation of the results and contributed to the geology of the basin. **Kehinde Egunjobi** (M.Sc. Junior researcher, Sedimentologist) performed the field study.