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Morphometric Studies of Pebbles from Ewen Area, Calabar Flank, Southeastern Nigeria: Implications for Paleoenvironmental Reconstruction

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Authors' contributions

This work was carried out in collaboration between all authors. Author EEO designed the study, wrote the protocol and the first draft of the manuscript. Authors MOA and RAO managed the literature searches and performed the statistical analysis of the study. All authors read and approved the final manuscript.

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ABSTRACT

Morphometric parameters of unbroken quartz pebbles recovered from the basal section of Awi Formation exposed around Ewen area, southeastern Nigeria were studied for paleoenvironmental reconstruction. The study involved the determination of the roundness and measurement of the three orthogonal axes (long, short and intermediate) for about 200 pebbles. The pebbles were selected from 20 points across four exposed sections of the Awi Formation around Ewen village. The roundness was determined using the standard roundness chart. The results show that the pebbles are sub-rounded to sub-angular and predominantly compact-bladed. The mean values for the following morphometric parameters: Flatness index, elongation ratio, maximum projection sphericity index and oblate-prolate (OP) index are 0.57, 0.78, 0.74 and 15.65 respectively. These values are in agreement with those of modern fluvial pebbles. This result was integrated with the deductions from bivariate plots of roundness against elongation ratio and sphericity against OP index and they all inferred the deposition of the conglomeratic sandstones in a fluvial setting with subordinate transitional setting.

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1. INTRODUCTION

The Awi Formation consists conglomerates, sandstones and mudrocks belonging to the basal section of the sedimentary succession of the Calabar Flank, southeastern Nigeria. The textural characteristics of sediments are an invaluable tool for characterizing their depositional processes and environment of deposition [1-3].

Morphometric characteristics of sedimentary grains depend on the initial shape as the particles were liberated from their parent rock and the antecedent properties of the depositing medium. Hence, they yield invaluable information about the energy conditions and the environment of deposition [4-8]. The character (form and roundness) of the pebbles, depends on their physical strength as well as the effective distance of travel from their source (parent rock). Pebble morphometry have been utilized with good success in the discrimination between modern (known environments) beach and river gravels [9-14]. This makes the morphometric parameters (size and shape) of the pebbles significant in reconstructing ancient sedimentary environment. Shape indices as paleoenvironmental indicators of quartzite rich rocks have been the subject of considerable discussions among experts [15-20] and the result have greatly aided interpretations from basin analysis to identification of valuable placer deposits.

Initial studies on the lithostratigraphy of the Awi Formation were carried out by ([Reyment [21] and Adeleye and Fayose [22]). Much studies on the provenance and depositional environment have also been carried out by various workers [23-26] and their studies have centred on sand size distributions as well as geochemistry of the sediments. Heretofore, not much exist in the literature on the detailed lithofacies description and sequence stratigraphy of the Awi Formation except for the few studies by Boboye and Okon [27] Itam et al. [28]; Essien et al. [29]. Their studies focussed on the sedimentological characteristics of some road cuts exposed along Calabar - Ikom highway and those of Abbiati area in the far eastern part of the Calabar Flank near Mfamosing Village. This study focuses on the conglomeratic facies of the Awi Formation exposed across 4 locations around Ewen village (Fig. 1) southeastern Nigeria; an area that has previously never been described.

2. GEOLOGICAL SETTING

The Calabar Flank is a NW-SE trending basin in the southeastern Nigeria located in the southern part of the Oban Massif. It is delimited to the west by the Ikpe platform and to the east by the Cameroon Volcanic Line. To the south, the Calabar hinge line separates it from the north-eastern portion of the Niger Delta (Fig. 2). Its origin is closely associated with the breakup and subsequent separation of Africa and South America about 120-130Ma ago [31-32]. Suggestions about the tectonic model that led to the break-up of the Gondwanaland is supported in the literatures as “the mantle – plume concept” [32]. This process was summarized by (Onuoha and Ofoegbu [33]) as resulting from crustal stretching and upwelling of mantle materials, rifting and subsidence due to isostatic compensation, injection of mantle materials, formation of oceanic crust and finally, deposition of continental and marine sediments with further subsidence. The basin architecture of the Calabar Flank is characterized by horst and graben structures which are believed to have ultimately controlled sedimentation in the Basin [31,30,34].

Sedimentation began in the Calabar Flank with the deposition of fluviatile-deltaic sandstones, mudrocks and grits/conglomerates of the Awi Formation in Neocomian to Albian times. This was succeeded by the first marine incursion into the southern Nigeria during the Mid-Albian times represented by the Mfamosing Limestones deposited in a wide variety of environments including beaches, shallow shelf, tidal creeks, bays and lagoons [35]. Further deepening and influx of the siliciclastic sediments gave rise to the Ekenkpon Shale in the Cenomanian-Turonian times. The New-Netim marls Formation consisting of marls and calcareous shales of Coniacian age [30] is separated from the Late Campanian- Maastrichtian Nkporo Shales by the Santonian deformational episode (Fig. 3). These structures favoured vertical movements, and subsequent eustatic sea level changes governed the distribution of sedimentary successions in the basin [31,30,37].

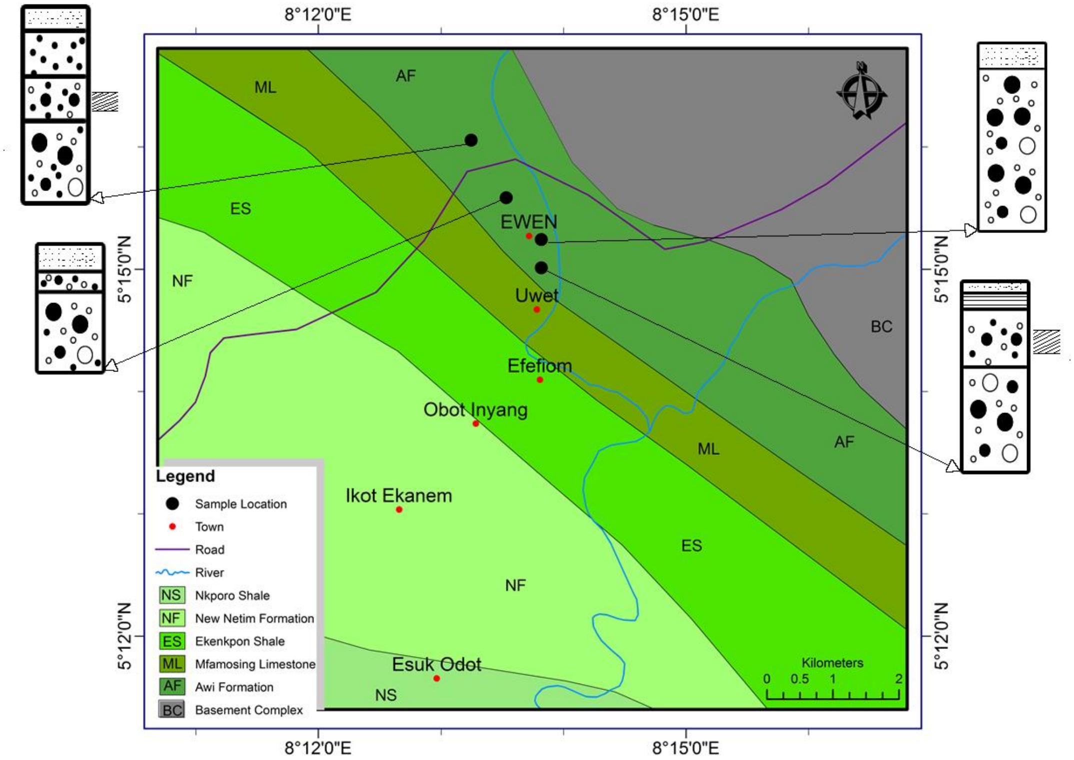

Fig. 1. Geological map of Ewen and environs showing the sample locations

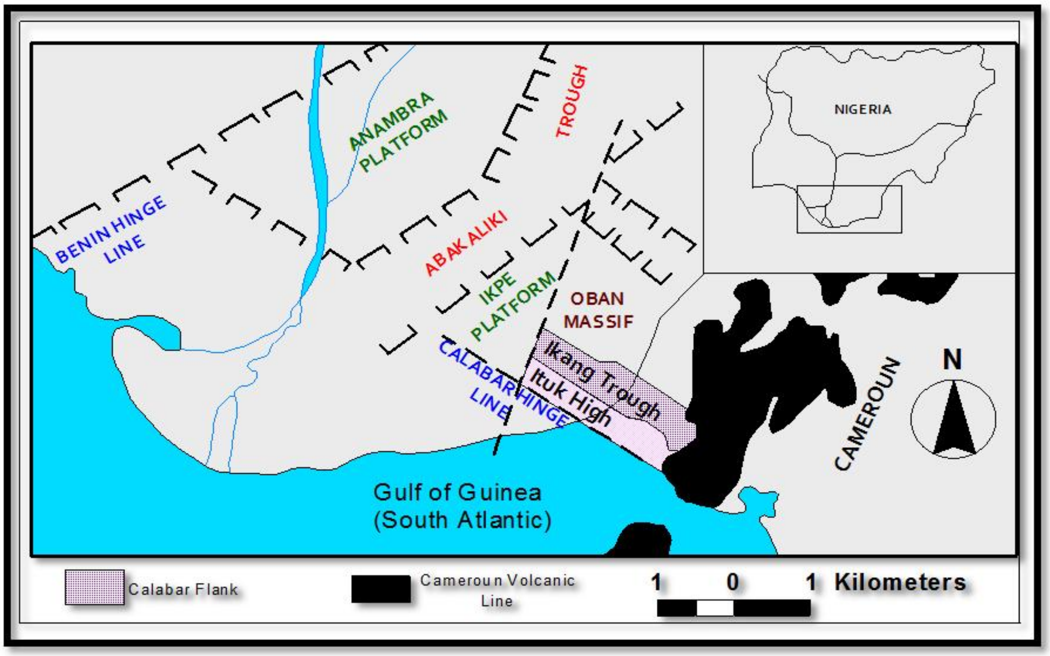

Fig. 2. Map of southern Nigeria showing the tectonic elements and geographic location of the Calabar flank with respect to the Benue trough (modified from Nyong and Ramanathan [30])

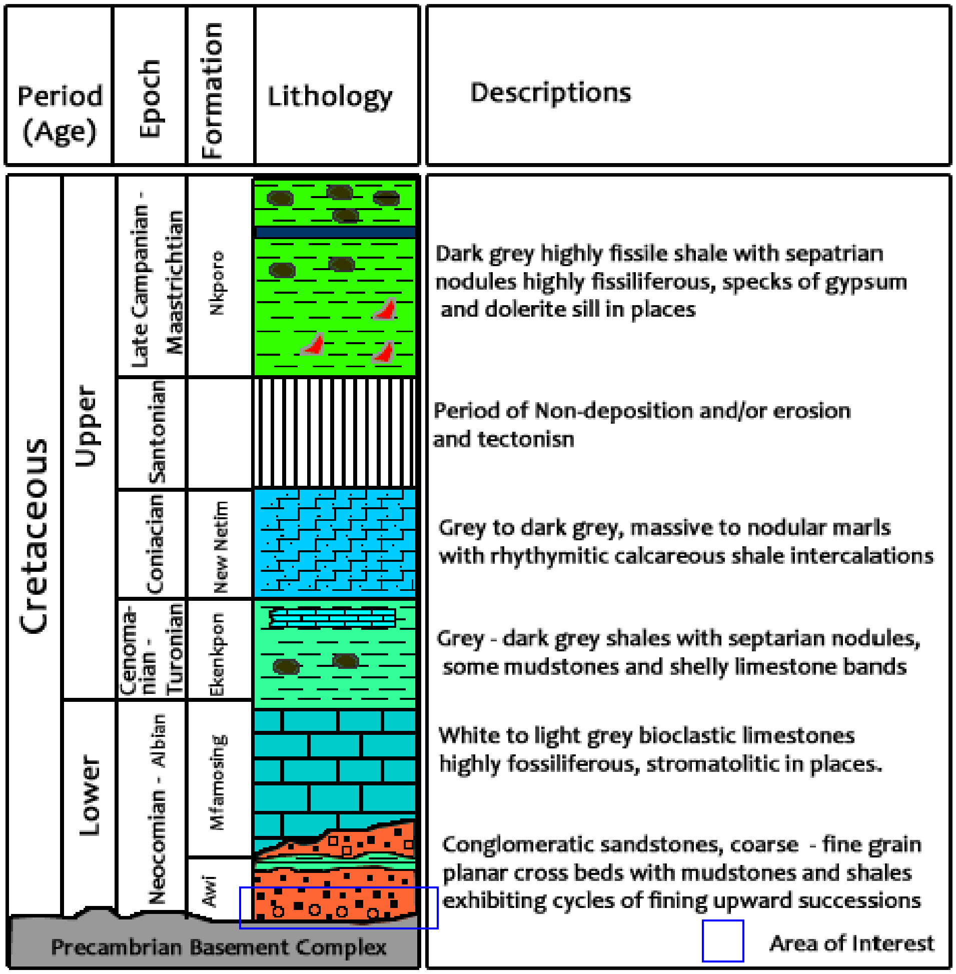

Fig. 3. Stratigraphic chart for the Calabar Flank (Okon et al. [36])

3. METHODOLOGY

The Awi Formation is exposed along new road cut sections and constitutes a significant non-conformity between the basement rocks of the Oban Massif and the sedimentary succession of the Calabar Flank. Four different locations around Ewen and its environs (Fig. 1) were visited, properly logged and described (Fig. 4). At each location 50 unbroken quartz pebbles were collected in 5 batches of 10 each. The analysis was carried out with the mean form of at least 10 pebbles taken from each sampling station. In each case 5 sets per sample location representing 50 pebbles for the four locations visited.

During the process, imbrications were analysed and their back azimuth were used here to approximate the paleocurrent direction. While sampling, freshly broken pebbles and those with lithologic in-homogeneities were discarded. The selected pebbles were washed and numbered appropriately according to their group identity. They were then subjected to axial measurement of the long, short and intermediate axes using the Vernier calliper and their values tabulated. The record was used to determine the various morphometric parameters including: maximum projection sphericity index (MPSI), elongation ratio (ER), flatness index (FI) and oblate-prolate index (OPI). The form of the pebbles was also determined using the ternary method of Sneed and Folk [38]. Roundness of the pebbles were estimated using the Power [39] roundness chart and its accuracy was ensured with direct measurement of the roundness of randomly selected pebbles using the well-established roundness equation as outlined in Wadell [40] Krumbein [41] and Cheel [42]. Table 1 outlines the formulae used for the calculation of the morphometric indices.

4. RESULTS AND DISCUSSION

The result for the mean of the 20 batches of pebble morphometric parameters is presented in Table 2. The pebbles are notably massive and crudely bedded held together by sandy matrix (matrix supported), the clast diameter range from 2.63 – 3.40 cm (Fig. 5a), the sorting is poor and pebble grains are weakly imbricated. In some studied sections, the effect of post depositional tectonics was observed with brecciated ferruginized layer admixed with sub-rounded pebbles (Fig. 5b). These features suggest lad deposits and conform to Miall [43] facies classification “Gm”. Regarding the clast sphericity, roundness and “Oblate – Prolate” Indexes, the parametric values of an average of 10 pebbles [13] was used in the analysis. The formula proposed by Sneed and Folk [38] was adopted because it was established comparing the volume of the particle with its maximum projection area which naturally opposes the direction of motion.

This according to them is more behaviouristic of the equidimensionality of the pebbles with its experimental error of ±0.021 sphericity units.

Table 1. Formulae used in computation of pebble morphometric parameters

S/No	Formula	Reference
1	Maximum Projection Sphericity Index **(MPSI)** = $\{S^2/LI\}^{1/3}$	Sneed and Folk, 1958
2	Elongation Ratio, (ER) = I/L	Lutig, 1962; Sames, 1966
3	Flatness Ratio **FR = S/L**	Lutig, 1962
4	Flatness Index = (L – I + S) / L	Illenberger 1992
5	Oblate – Prolate Index, $OPI = \frac{10\left(\frac{L-I}{L-S} - 0.50\right)}{S/L}$	Dobkins and Folk 1970
6	Roundness = [(∑r)/nR]	Wadell 1932

Table 2. Result for the mean values of 20 batches of pebble morphometric parameters for Awi formation

S/N	L	S	I	S/L	Elongation (I/L)	L-I	L-S	LI	S2	OPI	MPS	FI	Roundness	Form name
L1/B1	2.80	1.63	2.31	0.58	0.83	0.49	1.17	6.47	2.66	-0.74	0.74	76.04	0.38	CB
L1/B2	2.67	1.44	2.26	0.54	0.85	0.41	1.23	6.03	2.06	-1.95	0.70	69.22	0.4	CB
L1/B3	3.04	1.82	2.30	0.60	0.76	0.74	1.22	6.97	3.29	0.69	0.78	84.39	0.43	CB
L1/B4	3.17	1.71	2.47	0.54	0.78	0.70	1.46	7.83	2.92	-0.46	0.72	75.74	0.41	CB
L1/B5	2.63	1.39	2.02	0.53	0.77	0.61	1.24	5.29	1.93	-0.24	0.71	76.28	0.34	CB
L2/B6	2.82	1.60	2.12	0.57	0.75	0.70	1.23	5.98	2.54	0.43	0.75	81.54	0.46	CB
L2/B7	2.68	1.69	2.04	0.63	0.76	0.64	0.99	5.46	2.86	2.21	0.81	87.77	0.45	CB
L2/B8	3.40	1.63	2.43	0.48	0.71	0.97	1.77	8.23	2.64	-0.03	0.68	75.99	0.47	CB
L2/B9	2.68	1.58	2.26	0.59	0.84	0.43	1.11	6.04	2.48	0.02	0.74	77.55	0.42	CB
L2/B10	2.63	1.66	2.04	0.63	0.78	0.59	0.97	5.34	2.76	0.50	0.80	85.88	0.39	CB
L3/B11	2.69	1.57	2.00	0.58	0.74	0.69	1.12	5.38	2.46	0.97	0.77	82.54	0.41	CB
L3/B12	2.97	1.52	2.06	0.51	0.69	0.92	1.46	6.10	2.30	0.14	0.72	80.89	0.41	CB
L3/B13	2.75	1.45	2.23	0.53	0.81	0.52	1.31	6.13	2.09	-0.69	0.70	71.91	0.44	CB
L3/B14	2.76	1.63	2.19	0.59	0.79	0.57	1.13	6.02	2.66	0.15	0.76	80.43	0.44	CB
L3/B15	2.97	1.53	2.32	0.52	0.78	0.65	1.44	6.89	2.34	-0.21	0.70	72.98	0.47	CB
L4/B16	2.38	1.31	1.85	0.55	0.78	0.53	1.07	4.40	1.72	-0.04	0.73	76.95	0.38	CB
L4/B17	2.49	1.45	1.97	0.58	0.79	0.52	1.04	4.91	2.10	0.003	0.75	79.66	0.44	CB
L4/B15	2.49	1.47	1.88	0.59	0.76	0.61	1.02	4.68	2.16	0.53	0.77	83.62	0.39	CB
L4/B19	2.55	1.56	2.05	0.61	0.80	0.50	0.99	5.23	2.43	0.64	0.78	82.88	0.44	CB
L4/B20	2.55	1.48	1.90	0.58	0.75	0.65	1.07	4.85	2.19	0.80	0.77	84.30	0.42	CB
Mean	2.75	1.55	2.13	0.57	0.78	0.62	1.20	5.91	2.43	-0.74	0.74	76.04	0.42	-

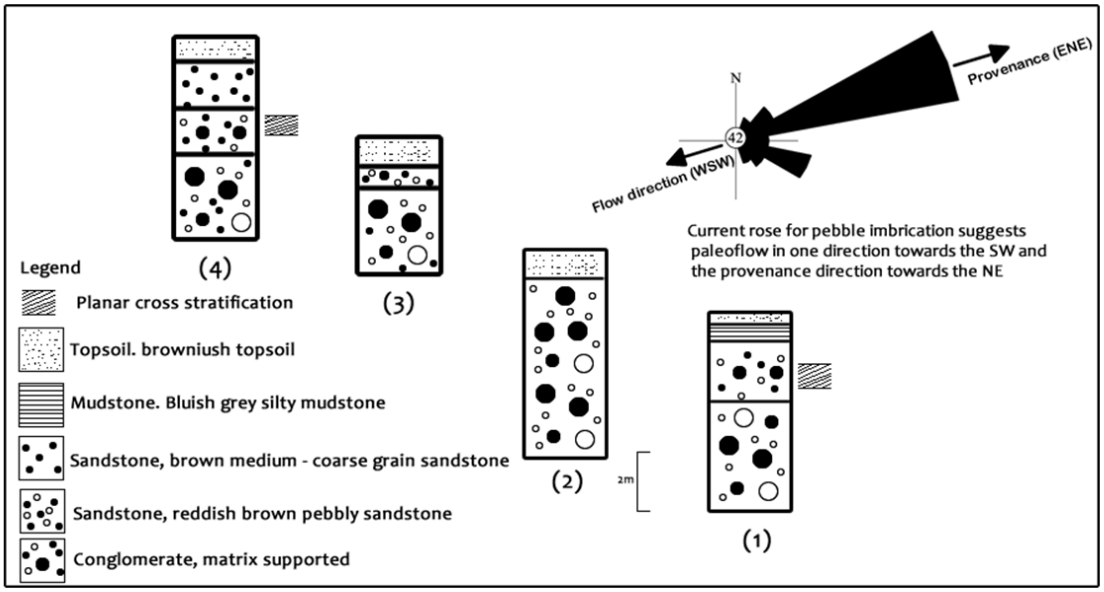

Fig. 4. Lithologic log for the sample area

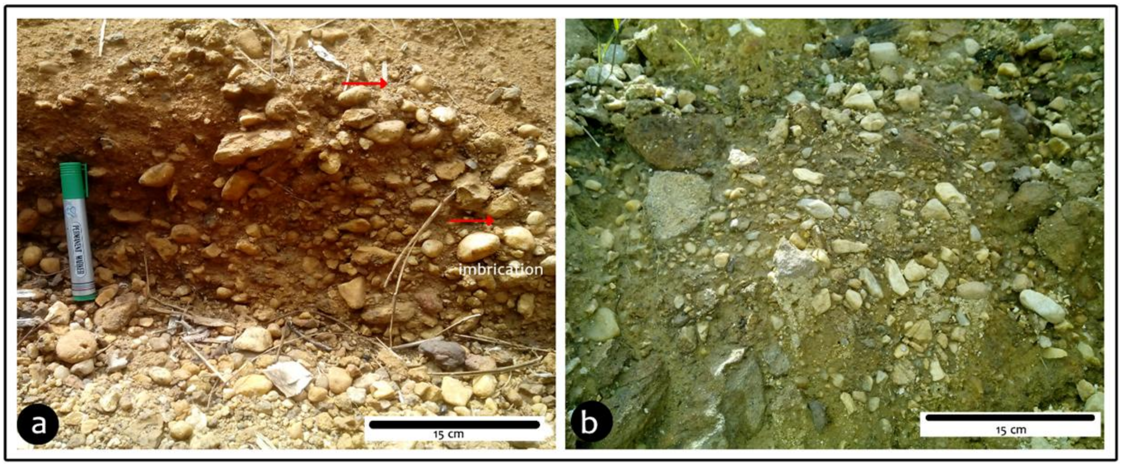

Fig. 5. (a) Photograph of matrix-supported conglomerate showing clast imbrication, red arrow showing the prevailing current direction. (b). Admixture of brecciated rock units with sub-rounded pebbles

The form is used to examine the three-dimensional characteristics of the particle as is reflected by the various parameters that shaped it during transportation to the point of deposition. According to [38] their end points are responsible for limiting the system of dimensional variation of the parameters; whether they are prolate-spheroid (one long axis, two short axes), oblate-spheroid (two long axes, one short one) or sphere (all axes equal). The sphericity – form diagram (Fig. 6) of [Sneed and Folk [38] was used to determine the form for the pebbles. The result show that the pebbles are predominantly compact – bladed and range from sub-angular to sub-rounded with high sphericity. This points to the fact that there is little variation in the shape of the grains across the stratigraphic sections sampled and thus possibly similar depositional process was responsible to shappen the clasts. Fluvial transported clasts tend to be compact - compact bladded than beach clasts. Dobkins and Folk [13] noted this in their study of the Tahiti beach sediments, where they pointed out that the back and forth motion of wave action and the wave swash was responsible for flattening the pebbles.

The maximum projection sphericity index (MPSI) together with disc-like and rod-like geometrical pebbles was the approach used to determine the degree to which the pebbles approach the shape of a sphere. In this study, the sphericity ranges from 0.68 to 0.81, with a mean value of 0.74. High values of sphericity indicate that the degree to which the grains intercept (hydraulic behaviour of the sediments) each other during transportation in the fluid was high.

The formula proposed by Sneed and Folk [38] was adopted for sphericity determination because it was initially established for comparing the volume of particles with their maximum projection area which naturally opposes their directions of motion. Since projection sphericity is an indicator of the hydraulic behaviour of the particle during transport, it approximates based on the geometry of the particles in a medium with characteristics volume and /or density peculiarities of the settling rate of the particles.

The plot of MPSI versus OPI and that of FI versus MPSI (Fig. 7, 8) have been used also to distinguish beaches from river processes [13]. Sames [25] also pointed out the rare significance and suitability of quartz pebbles (compared with cherts and other rock types) having high resistance to wear for morphometric research amongst all sedimentary rocks. His studies successfully pointed out that most fluvial pebbles tend to be more elongated than their littoral counterparts. In this study elongation ration range from 0.69 – 0.85 with an average of 0.78. Although this is an indication of fluvial process of transportation, the environmental determination plot (Fig. 9) of Sames [25] was further utilized to confirm it. Oblate – Prolate index, defined as the measure of the closeness of the intermediate (I) axis to the long (L) axis was computed and values for OPI in this study range from -1.95 to 2.21 with an average of 0.14 (Table 1). OPI presents a useful parameter that distinguishes the various forms/shapes of pebbles [13,19].

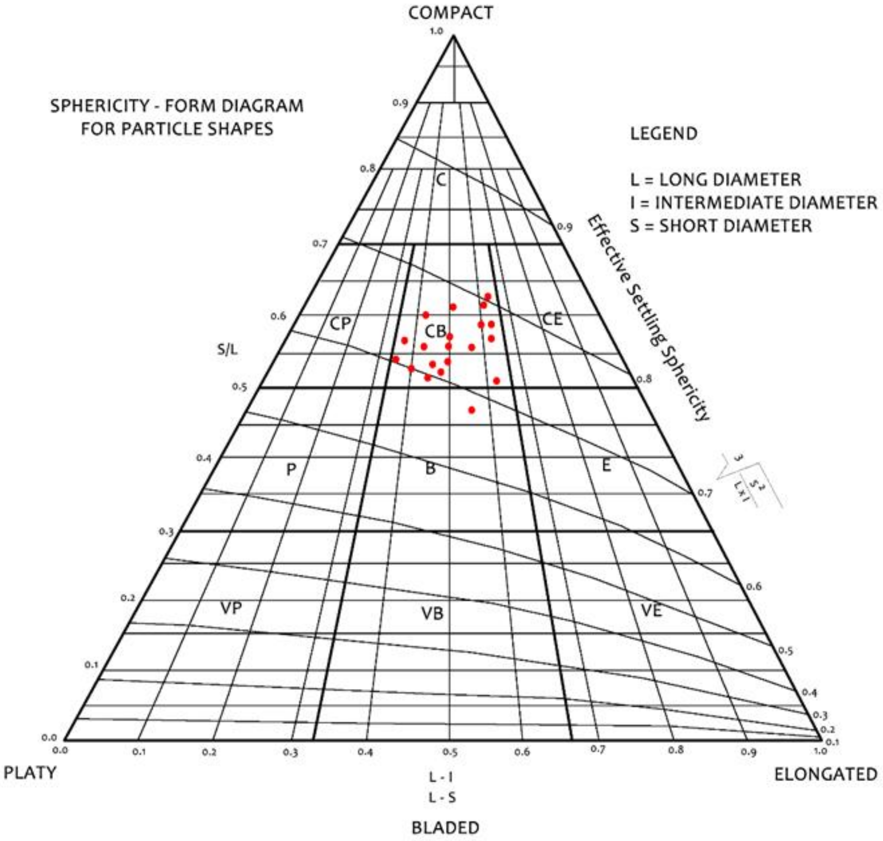

Fig. 6. Spehericity – Form diagram for particle shapes after [38]

Each point represents the mean of 10 pebbles that form a batch. (the letters in upper case defined by the bold lines are used to represent the 10 classes: C=Compact; CP=Compact-Platy; CB=Compact-Bladed; CE=Compact-Elongate; P=Platy; B=Bladed; E=Elongate; VP=Very Platy; VB=Very Bladed; VE=Very Elongate)

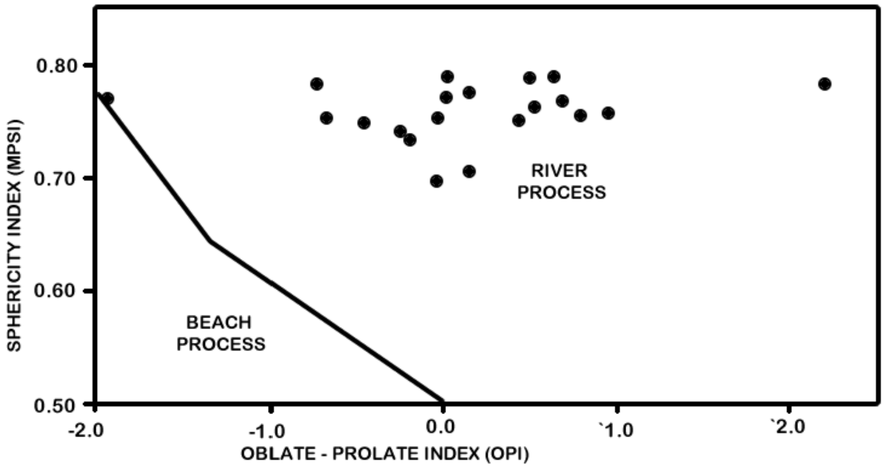

Fig. 7. A plot of MPS versus OPI (fields after Dobkins and Folk, [13])

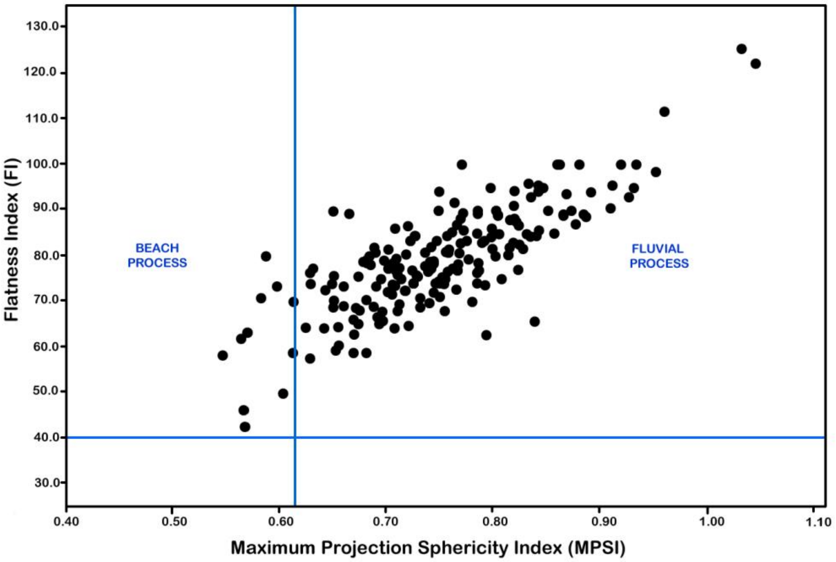

Fig. 8. Plot of flatness index (FI) against maximum projection sphericity index (MPSI) (Fields after [14])

The outlined morphometric parameters that arise from the effect of transportation dynamics contribute largely to the final shape of the pebble and since these operate in different depositional settings, their signature as visualized from the shape of the grain can aid in paleoenvironmental diagnosis. Among these include the initial inherited morphology which depends on the rock type, whether the rock cleaves or fracture when subjected to applied stress and the climatic setting of the source area.

Also, the intensity of the energy of the depositing agent during transport may result in abrasion and fracturing of the grains as they collide with one another or as they are dragged on the bed during tractive motion. Fluvial transport has been noted to have little effect on the shape and/or sphericity of grain when compared with the effects of beach process leaving the grains more or less equant in terms of their form (sphericity < 0.65, [44]). The distance to which a grain travels also impacts on its degree of roundness. It has been noted that the most rapid change in grain morphology occurs within the first 10 km [45] but the medium through which the grain is transported and the mode of transportation is critical in shaping the grains. Ward [46] noted that shape modifying

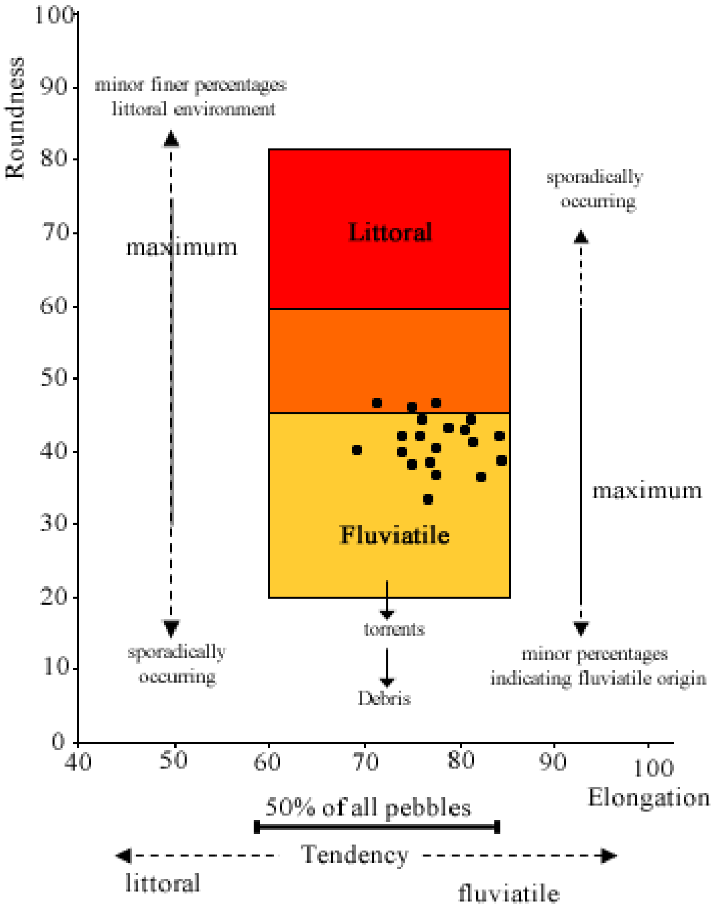

Fig. 9. Environmental determination chart showing distinction between strongly fluvial processes and littoral process (modified after sames [25])

processes in surf zone (beach environment) tend to be complex but statistically regular to the production of more flattened ovoid forms. The pebbles studied showed some crude imbrications and the direction of imbrication (Fig. 4, Fig. 5a) presents a useful insight to the unidirectional nature of the depositing agent, since clast imbrication originates when discoid gravel clasts become oriented in strong flows until they become stable with one of its longer axes dipping upstream. The back-azimuth gives the direction of flow of the depositing agent.

5. CONCLUSION

Pebble morphometric analysis has aided the determination paleoenvironment during the deposition of Awi Formation. The depositional processes (abrasion conditions) responsible for shaping the pebbles and the environment that prevailed during past geological times was characterized from the study of the clast morphology. Fluviatile process with some overlapping littoral influence has been shown to be responsible for the variation in clast morphology of the paraconglomerates (matrix-supported) of Awi Formation. Calibrating this with the fining upwards successions of the section studied and the unidirectional nature of the crudely imbricate pebbles further suggests a typical fluvial setting. It is possible that the jointing, faulting, sheeting and/or exfoliation of the rocks of the Oban Massif, which is believed to be the principal source of the sediments, also accounts for the abundance of vein quartz in the area which was eventually adapted for this study. Within sedimentary settings as this one with paraconglomerates associated with high energy flux during deposition and other typical channel lag deposits are locations of good economic deposits (placer deposits) and in some cases hydrocarbon accumulation. Therefore, besides the significance for pebble morphometry in deciphering paleoenvironments, it also gives clues for potential sites of ore bodies and/or characteristics of some targets for hydrocarbon pools. There are obviously several methods for paleoenvironmental reconstruction using sediments, grain morphology is one. However, care must be taken when reconstructing paleoenvironment because the shape of grains is a result of so many other factors and for effective utilization, a careful study and integration of all other parameters is advised.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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