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Geologos 29, 1 (2023): 21–31
https://doi.org/10.14746/logos.2023.29.1.02

GEOLOGOS

Morphometric analysis of pebbles in verification of transport processes and interpretation of palaeoenvironment: A case study from the Ogwashi Formation (Oligocene), Niger Delta Basin, Nigeria

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Abstract

The present paper discusses a palaeoenvironmental interpretation of the Oligocene Ogwashi Formation (Niger Delta Basin, Nigeria) through morphometric analysis of pebbles, a research method essentially depending on the quantitative evaluation of pebble size and shape which change during transport processes in a range of depositional environments. The relationship of bivariate and ternary-diagram plots of independent functions was determined from freshly exposed sandstone sections in quarries at Ibusa, near Asaba, Nigeria. The grain size of pebbles ranges from fine (11.00 mm) to very coarse (41.33 mm), with a mean size of 21.05 mm (coarse pebbles). A bivariate plot of the flatness index *vs* maximum projection sphericity index shows 37% of the pebbles to fall within a beach (marine) environment, and 33% within a fluvial environment; the remaining 30% are uncertain. The maximum projection sphericity index *vs* oblate-prolate index bivariate plot indicates that 47% of pebbles fall within a marine environment and 22% within a fluvial environment, while the remaining 31% are uncertain. The sphericity-form ternary diagram plot shows that the pebbles primarily comprise bladed, platy, very bladed and very platy of near-equal proportions with minor elongate and very elongate stones, which suggests that the pebbles are diverse in origin. The sphericity-form bivariate plot indicates that the pebbles are largely of disc and blade shapes with a minor number of spherical and rod shapes. The near-equal proportion of pebbles in different segments of the bivariate and ternary diagram plots, and the wide distribution of the pebble grain sizes and shapes suggest the Ogwashi Formation is composed of redeposited sediments that likely were transported and deposited in a mix of marine and fluvial settings with possible transitional environments. In other words, the pebbles can be interpreted as marine-influenced fluvial sediments in marginal-marine settings.

Keywords: grain morphometry, sandstone facies, bivariate plot, ternary diagram, mixed environments, Oligocene sediments

1. Introduction

The Ogwashi Formation is an outcropping stratigraphical unit that forms part of lateral equivalents in subsurface successions of the Niger Delta Basin. This formation is defined as a continental depositional unit of Oligocene–Miocene age that forms the upper stratigraphical unit of the Niger Delta Basin in its northern part (Short & Stauble, 1967), and spans into the Anambra Basin. It is reported to attain a thickness of about 250 m (Simpson, 1955; Reyment, 1965; Nwajide, 1980).

The Ogwashi Formation was previously referred to as the Ogwashi-Asaba Formation. A fresh section of this unit is well exposed by extensive quarrying activities and gully erosion at the town of Ibusa, some tens of kilometres north-west of Onitsha (Fig. 1), while other areas are covered by a few metres of lateritic soil development. The formation is composed of predominantly sandy beds, alternating with lignite seams and a few beds of clay (Short & Stauble, 1967; Kogbe, 1976; Nwajide, 1980). Recent workers have reinterpreted the sediments of the Ogwashi Formation at different exposures in the region based on the basis of detailed lithofacies analysis and interpretation. They have reported that the formation consisted of tidally influenced coastal plain deposits, which comprised fluvio-estuarine channels, tidal channels, tidal flats, coastal plain channels and coastal floodplain mud (e.g., Ejeh et al., 2015; Ekwenye et al., 2015; Ekwenye & Nichols, 2016). The fluvio-estuarine channel deposit overlies an erosional surface and is composed of high-energy conglomerate and coarse-grained sandstone facies (Ekwenye & Nichols, 2016). Some other workers have also interpreted the depositional environments of the various lithofacies of the Ogwashi Formation on the basis of geochemical analysis (e.g., Ejeh et al., 2015; Madukwe & Bassey, 2015; Adeoye et al., 2016). Ejeh et al. (2015) and Adeoye et al. (2016) suggested that this formation was developed in fluvio-deltaic to shallow-marine environments. Conversely, Madukwe and Bassey (2015) concluded that the sediments of the Ogwashi Formation were deposited in a continental environment. The sandstone and conglomerate of this unit are defined as a mixture of quartz arenites and sub-litharenites with a low content of heavy minerals (Ekwenye et al., 2015; Overare & Osokpor, 2020).

However, the sedimentary rocks of the Ogwashi Formation have also been studied through sedimentological pebble granulometric analysis in order to interpret its palaeoenvironment and depositional setting. Pebble morphometric analysis is a sedimentological approach that has been successfully applied by several workers for deciphering the palaeoenvironments and depositional settings of similar formations and basins in Nigeria and other parts of the world (e.g., Sames, 1966; Hubert, 1968; Dobkins & Folk, 1970; Nwajide & Hoque, 1982; Gale, 1990, 2021; Olugbenro & Nwajide, 1997; Ogala et al., 2010; Widera, 2010; Okoro et al., 2012;

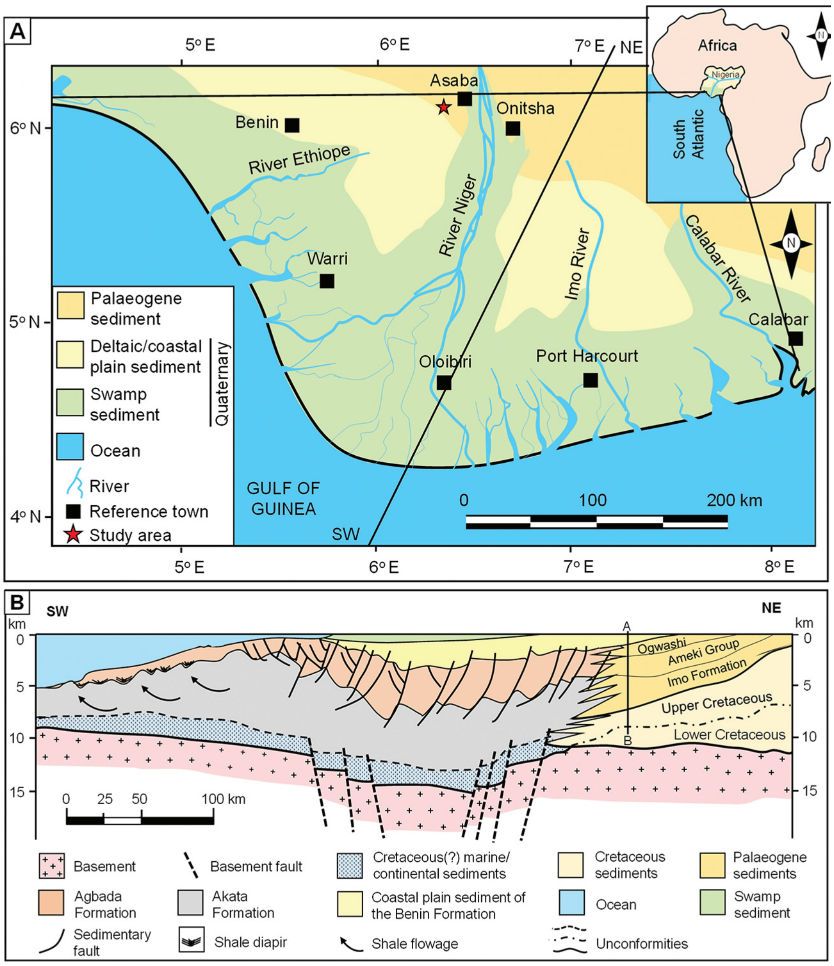

Fig. 1. Location map of the study area. **A** – A simplified regional geological surface map of the Niger Delta Basin showing the location of the studied outcrop (marked as a red star) in the northern delta area (reprinted from Ogbe, 2021); **B** – A schematic NE–SW cross-section through the Niger Delta Basin in south-eastern Nigeria (reprinted from Ogbe, 2021; Ogbe & Osokpor, 2021); note the position of the vertical line AB depicting stratigraphical successions in the Niger Delta Basin; for a detailed stratigraphy see Figure 2.

Nton & Adamolekun, 2016; Ocheli et al., 2018; Madi & Ndlazi, 2020; Oluwajana et al., 2021). Similarly, Odumodu and Israel (2014) and Onyemesili and Odumodu (2019) used this sedimentological approach with eroded pebbles in the interpretation of the Ogwashi Formation and concluded that the sediments of this unit formed in a fluvial environment.

The various sedimentological and geochemical approaches applied by previous workers suggested different depositional environments for the formation of sediments of the Ogwashi Formation. Especially the pebble morphometric analysis provided a wider interpretative deviation than the other studies. Therefore, it is of note to enhance the interpretation of the depositional environment of the Ogwashi Formation by the application of the pebble morphometric analysis. In the present paper, this is achieved through the use of pebbles in stratified sandstone units in outcrops. Thus, application of this research method would seem to be necessary to affirm the interpretations outlined in previous studies. The major goal of the present study is to improve interpretations of the palaeoenvironments represented by Ogwashi Formation strata. An attempt will be made to achieve this by using various computational and graphic techniques to interpret the processes of transport, deposition and provenance of the sediments studied. Generally, the present study is based on the general ideas of field geology and quantitative data analysis. This may be applicable to interpreting the depositional environments of surface and subsurface sediments in similar geological and depositional settings.

2. Geological setting

The Niger Delta Basin is bounded to the east by the Calabar flank (the subsurface extension of the Oban Massif), to the west by the Benin flank (the subsurface extension of the West Africa Shield), to the north by the post-Abakaliki Anambra Basin and to the south it opens into the Atlantic Ocean (Murat, 1972). The Lower Cretaceous Abakaliki, Upper Cretaceous Anambra and Cenozoic Niger Delta basins form the southern Nigeria sedimentary basin (Fig. 2). The tectonic and sedimentary evolution of these basins was related and developed progressively (Short & Stauble, 1967; Nwajide, 2013).

The Paleogene older stratigraphical units of the Cenozoic Niger Delta Basin outcrop in the northern part of the basin (Figs 1, 2). The outcropping stratigraphical successions comprise four lithostratigraphical units, i.e., the Imo Formation, the Ameki Group (comprising the Ameki, Nanka and Nsugbe formations), the Ogwashi Formation and the Benin Formation. The Imo Formation has an average thickness of ~1,000 m and forms the oldest sedimentary succession of the Cenozoic Niger Delta Basin that unconformably overlies the Anambra Basin (Figs 1B, 2; see Simpson, 1955; Reyment, 1965; Short & Stauble, 1967; Petters, 1991; Nwajide, 1980; Arua, 1986; Ekwenye et al., 2015). The Imo Formation is composed of blue-grey shales with sand lenses, fossiliferous limestones and marls. It is the mappable equivalent of the subsurface Akata Formation, which is the source rock of the petroleum system of the Cenozoic Niger Delta Basin (Figs 1B, 2; see Reyment, 1965; Short & Stauble, 1967; Nwajide, 2013; Ekwenye et al., 2015; Osokpor & Ogbe, 2019). The Ameki Group conformably overlies the Imo Formation with a thickness that ranges from 1,400 to 1,900 m. It is composed mainly of sandstone facies and minor siltstone, heteroliths, thin shelly limestone and calcareous clay intercalations (Fig. 2; see Reyment, 1965; Nwajide, 1980; Arua, 1986; Nwajide, 2013; Ekwenye et al., 2015; Ogbe & Osokpor, 2021). The Ogwashi Formation overlies the Ameki Group and is composed of alternating coarse sandstone facies, siltstone and clays with thin to thick (up to 6 m) lignite seams (Figs 1B, 2; see Kogbe, 1976; Ogala, 2012; Nwajide, 2013; Ekwenye & Nichols, 2016). The Ameki Group and Ogwashi Formation are the mappable equivalents of the subsurface Agbada Formation that constitutes the reservoir rock of the petroleum system of the Cenozoic Niger Delta Basin (Short & Stauble, 1967).

The Neogene Benin Formation overlies the Ogwashi Formation and forms the youngest stratigraphical unit of the basin (Fig. 2). It is composed of coastal plain sands with lenses of clay and mud (Tattam, 1944; Simpson, 1955; Short & Stauble, 1967). The Benin Formation is about 2,000 m thick at the depocentre developed both at outcrop and in the subsurface. This formation occupies an extensive area in southern Nigeria (Figs 1B, 2; see Reyment, 1965; Short & Stauble, 1967; Nwajide, 1980; Arua, 1986; Nwajide, 2013).

3. Material and methods

3.1. Outcrop field sampling

Measurements of the external transporting agency medium of pebble size, orientation, shape and roundness are important in order to determine the environment of deposition of clastic strata in sedimentary basins. Such an approach is generally

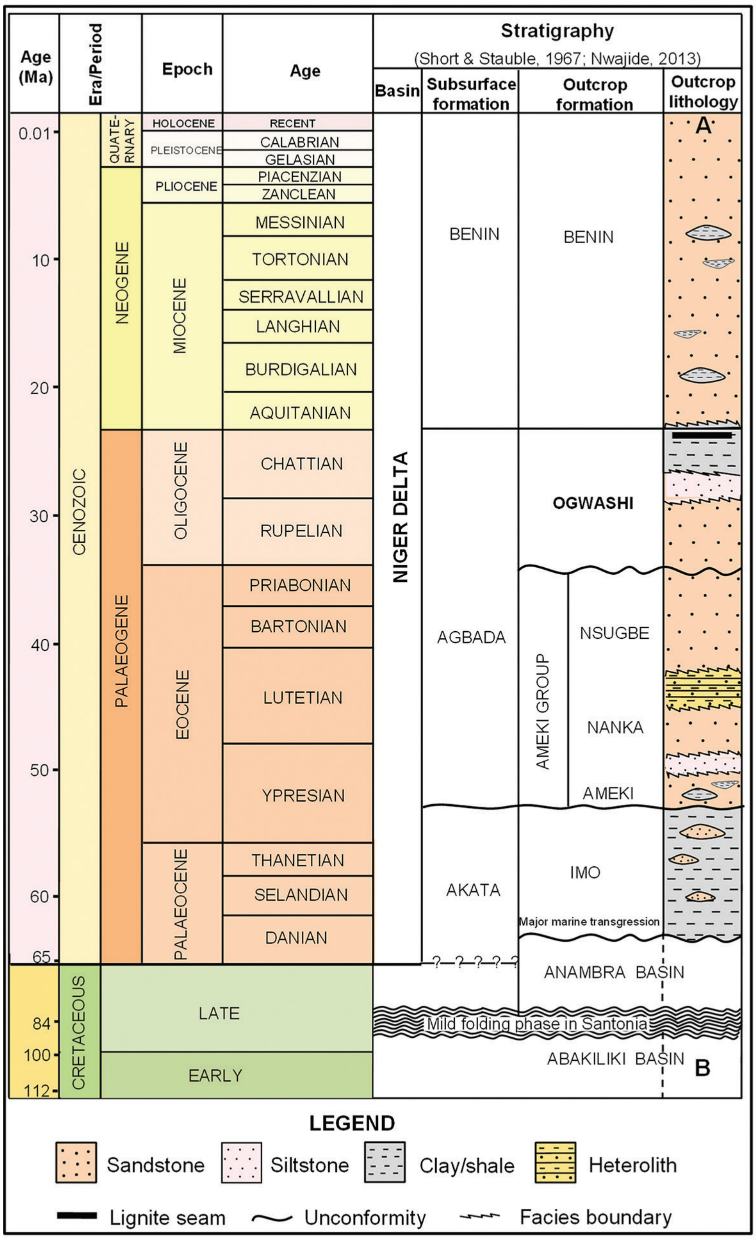

Fig. 2. The chronostratigraphical position of the Cenozoic succession of the Niger Delta Basin outcropping in south-eastern Nigeria (Ogbe & Osokpor, 2021). See Figure 1B for the vertical line AB that cuts across the southern Nigeria basins.

referred to as pebble morphometric analysis. The interpretation of results of such an analysis largely depends on the sedimentary facies features of these deposits in outcrops, grain size of particles studied (pebble size) and their morphometric independent and dependent functions (Sneed & Folk, 1958; Lutig, 1962; Sames, 1966; Dobkins & Folk, 1970; Madi & Ndlazi, 2020).

A total of 100 quartz pebbles were obtained from outcrops of the Ogwashi Formation, which comprises a sandstone, siltstone, mudstone and shale succession with a mixture of various pebble grain sizes and shapes (Figs 3–6). The sections were exposed due to sand quarrying activities at Ibusa in the northern part of the Niger Delta Basin. The pebbles were largely found in strata of sandstone bodies, while some occurred in the basal parts of the individual strata as lag deposits that are laterally extensive across the study area (Fig. 4). The pebbles are essentially subrounded to rounded quartzitic sediments.

During sampling of quartz pebbles and preparing these sediments for morphometric measurements, those with clear and fresh breaks/cracks and other lithologies were discarded. This procedure was aimed at eliminating the apparent size and shape of the pebbles, and thus the obtained parameters/indices did not affect the interpretation of the results. The pebbles were collected across various strata at outcrops of the Ogwashi Formation studied (Figs 3–6).

Fig. 3. Field photograph of an outcrop of the Ogwashi Formation around the town of Ibusa near Asaba, showing pebble distribution and other depositional features.

3.2. Field data analysis

The three-dimensional principal axes of the selected pebbles were analysed: the shortest axis (D_S), the intermediate axis (D_I) and the longest axis (D_L) of individual pebbles. They were measured with the aid of a veneer caliper. The various measured dimensions, D_S, D_I, and D_L values were then put in established equations, and independent functions (Eqs. 1–6) proposed by previous researchers (i.e., Sneed & Folk, 1958; Lutig, 1962; Sames, 1966; Dobkins & Folk, 1970; Stratten, 1974; Illenberger, 1991). In this way, the key morphometric parameters/indices of the examined pebbles were calculated (Table 1 in Appendix). These parameters include the coefficient of flatness index (FI), elongation ratio (ER), maximum projection sphericity index (MPSI), oblate-prolate index (OPI) and pebble form (PF). The range and mean size (MS) values of the selected pebbles were calculated and classified according to the Wentworth grain size scale (Table 1 in Appendix, Fig. 7).

$$\mathrm{MS} = \frac{D_S+D_I+D_L}{3} \tag{1}$$

$$\mathrm{FI} = \frac{D_S}{D_L} \tag{2}$$

$$\mathrm{ER} = \frac{D_I}{D_L} \tag{3}$$

$$\mathrm{MPSI} = (D_S^{\,2}/D_I * D_L)^{1/3} \tag{4}$$

$$\mathrm{OPI} = \frac{10\left(\frac{D_L-D_I}{D_L-D_S} - 0.5\right)}{\frac{D_S}{D_L}} \tag{5}$$

$$\mathrm{PF} = \frac{D_L-D_I}{D_L-D_S} \tag{6}$$

The various relationships of the derived pebble morphometric parameters, e.g., flatness index (FI) *vs* maximum projection sphericity index (MPSI) and MPSI *vs* oblate-prolate index (OPI) were used to construct bivariate plots (Fig. 7A, B). The combination of ER, FI and PF parameters was used to plot a ternary diagram and bivariate plot (Fig. 7C, D). In the present study we employed the various equations (independent functions) and their various relationship plots (dependent functions) to verify palaeoenvironment interpretations of the sediments studied, together with the provenance, transport and depositional processes of these.

4. Results

4.1. Outcrop descriptions

The studied outcrops are located near Ibusa, within the Northern Depobelt of the Niger Delta Basin. Exposures are available thanks to sand quarrying activities, and the average thickness of the outcrop is about 15 m. The deposit outcropping comprises different clastic rock facies: shale, mudstone, siltstone, sandstone and conglomerate. Sandstones are the most widely distributed sedimentary rocks in the study area. In some successions, the sandstones contain dispersed granules but also very coarse-grained (11–41.34 mm) pebbles (Figs 3–6).

Within other sedimentary units, thin layers with pebbles occur across the study area. Planar-bedding and trough cross-bedding are widespread depositional structures found in the studied outcrops (Figs 3, 4, 6), and sporadically deposits with a massive structure were also documented (Fig. 5). The pebbles were often clasts in sandstone beds. In some cases, the pebbles, especially those interpreted as channel lag deposits, dip in northeasterly and northwesterly directions. Long axes of the pebbles appeared to be oriented in northeasterly–southwesterly and northwesterly–southeasterly directions, respectively.

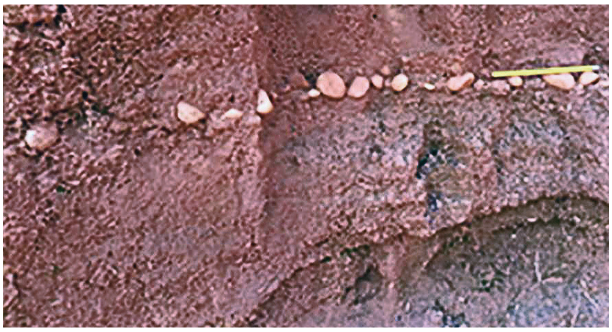

Fig. 4. Pebbles of the Ogwashi Formation as a lag deposit in the study area. The long axes of the pebbles show orientation in a similar direction.

Fig. 5. Field photograph of the Ogwashi Formation showing an admixture of pebbles with various sizes as clasts in sandstone facies.

Fig. 6. Field photograph of the Ogwashi Formation highlighting a trough cross-bedded pebbly sandstone.

4.2. Pebble morphometric analysis

The studied pebbles are quartz grains of conglomeritic sandstone and conglomerate of the Ogwashi Formation. The results of pebble dimension measurements show that the long axes of the studied pebbles range from 14 to 49 mm, with an average value of 30.17 mm; the intermediate axes range from 9 to 44 mm, with an average value of 21.92 mm; the shortest axes range from 4 to 28 mm, with an average value of 11.05 mm, and their mean size ranges from 11.00 to 40.33 mm, with an average value of 21.05 mm (Table 1 in Appendix). The pebble morphology calculated from the indices and the roundness data show that the flatness index (FI) varies from 16.67 to 92.86%, with a mean value of 52.25%. The elongation ratio (ER) ranges from 0.38 to 0.97, with an average value of 0.73. The maximum projection sphericity index (MPSI) ranges from 0.28 to 0.81, with a mean value of 0.57. The oblate-prolate index (OPI) ranges from –24.65 to 4.89, with an average value of –2.44, while the flatness index (FI) ranges from 21.42 to 96.55, with an average value of 64.26 (Table 1 in Appendix).

To integrate the independent and dependent functions, the combination bivariate and ternary plots of the various morphometric indices were analysed (Fig. 7). A bivariate plot of flatness index (FI) *vs* maximum projection sphericity index (MPSI) shows 37% of the pebbles fall within a beach (marine) environment, and 33% within a fluvial environment, while the remaining 30% are uncertain (Fig. 7A). The maximum projection sphericity index (MPSI) *vs* oblate-prolate index (OPI) bivariate plot displays that 47% of the pebbles fall within a marine environment and 22% in a fluvial environment, while the remaining 31% are uncertain (Fig. 7B). The uncertain proportions may represent a transitional environment. The sphericity-form ternary diagram analysis documents that about 31% of the forms fall within the bladed (B), 20% within the platy (P), 15% within the very platy (VP) and 13% within the very bladed segments of the plot, while the remaining forms are distributed within the very elongated (VE), elongate I, compact bladed (CB), compacted elongated (CE) and compacted platy (P) segments of the plot (Fig. 7C). The sphericity-form ternary diagram, plotted using the pebble morphometric values, shows a wide range of distribution. The sphericity-form bivariate plot of the studied pebbles taken from the Ogwashi Formation indicates that they are predominately disc shaped (61%), while other pebbles are blade-shaped (20%), rod-shaped (10%) and spheroid-shaped (9%), respectively (Fig. 7D).

5. Discussion

5.1. Pebble morphogenesis for interpretation of depositional settings

Clastic sediments form from the breakdown of pre-existing (igneous, metamorphic and sedimentary) rocks by weathering and transportation through external agencies and from material that forms within the depositional environment (Nichols, 2009). Quartz grains are the commonest and coarser mineral in most clastic rocks. This is attributed to its hardness and high resistance to chemical weathering. Hence, morphometric properties of quartz grains are retained over long distances and for a long-time during transport. The size and shape of clastic sediments have been related to the processes of transport and deposition. It has been shown and proved that pebble morphometric parameters may be helpful, as additional indicators, in deciphering the processes of transport and depositional environment (e.g., Sneed & Folk, 1958; Lutig, 1962; Sames, 1966; Dobkins & Folk, 1970; Stratten, 1974; Gale, 1990, 2021; Widera, 2010; Okoro et al., 2012; Odumodu & Israel, 2014; Ocheli et al., 2018; Madi & Ndlazi, 2020; Oluwajana et al., 2021).

The present study compared the interpreted morphometric indices of pebbles of the Ogwashi Formation in the Niger Delta Basin, with results obtained by Dobkins & Folk (1970) morphometric analysis of pebbles of rivers (fluvial environment) and high- and low-energy beaches (marine environment) around Tahiti-Niu. Those authors concluded that pebbles with an MPSI average value > 0.65 suggested fluvial transport, while an MPSI average value ≤ 0.65 suggested marine, i.e., beach processes of mechanical change of pebble morphology. Thus, the MPSI average value is < 0.65 for more than 70% of the pebbles examined (Fig. 7A, B; Table 1 in Appendix). This suggests that the pebbles were shaped by marine processes. Dobkins & Folk (1970) also concluded that pebbles with an OPI average value ≥ –1.50 corresponded to rivers (fluvial processes), while an OPI average value < –1.50 indicated beaches (marine processes). The OPI average values for 52% of the studied pebbles are < –1.50, and the rest are > –1.50 (Fig. 7A, B; Table 1 in Appendix). Thus, it follows that the pebbles of the Ogwashi Formation are probably a mixture of both river and beach sediments. In other words, this suggests that sediments containing these pebbles may be of fluvial origin and were influenced by marine processes.

In a similar way, Lutig (1962) and Sames (1966) applied a morphometric index, based on the elongation ratio (ER), in order to decipher palaeoenvironments. They reported that pebbles with an ER average value of < 0.70 were characteristic of torrent or fluvial processes, while those ≥ 0.70 indicated marine processes. The pebbles of the Ogwashi Formation analysed here have an ER average value of > 0.70 for 60% of their population, which suggests that the pebbles were probably shaped by marine (beach) processes. Furthermore, the present study adopts the approach of Stratten (1974) and Els (1988), which is based on the FI coefficient. Those authors proposed that pebbles with a FI average value of ≥ 45% indicated fluvial transport, while < 45% was typical of marine (beach) transport. The FI average value of the studied pebbles is > 45% for 60% of the investigated pebbles (Table 1 in Appendix). Thus, this may suggest predominantly a fluvial origin.

The occurrence of a near-equal proportion of pebbles in different segments of the bivariate plots suggests that they are most likely a mixture of those of fluvial and beach origin. However, transitional depositional environments are also possible, as indicated by a high proportion of environmentally uncertain pebbles in the plots (Fig. 7A, B). In other words, the studied pebbles of the Ogwashi Formation are interpreted here as fluvial sediments influenced by marginal parts (beach) of marine settings. In contrast, the ternary diagram shows that the pebbles primarily comprise bladed, platy, very bladed and very platy, while minor elongate and very elongate particles occur in almost equal proportions (Fig. 7C). This indicates that the pebbles are diverse in origin. Sneed & Folk (1958) established that compact, compact platy, compact bladed and compact elongate pebbles might be indicative of transport in fluvial environments; platy, bladed and elongate pebbles were characteristic of transitional environments, while very platy, very bladed and very elongate might indicate transport in beach zones (marine environments). Thus, the ternary plot analysis may be indirect evidence, in the absence of other indicators of the sedimentary environment, that the pebbles of the Ogwashi Formation represent mixed depositional environments that consisted of beaches, rivers and fluvial-marine transitional settings.

5.2. Depositional environment

Generally, all results obtained in the present study suggest that the Ogwashi Formation arose primarily in mixed depositional environments, that is, fluvial and marine. Marine-influenced fluvial deposits of a deltaic setting were supposed to be of

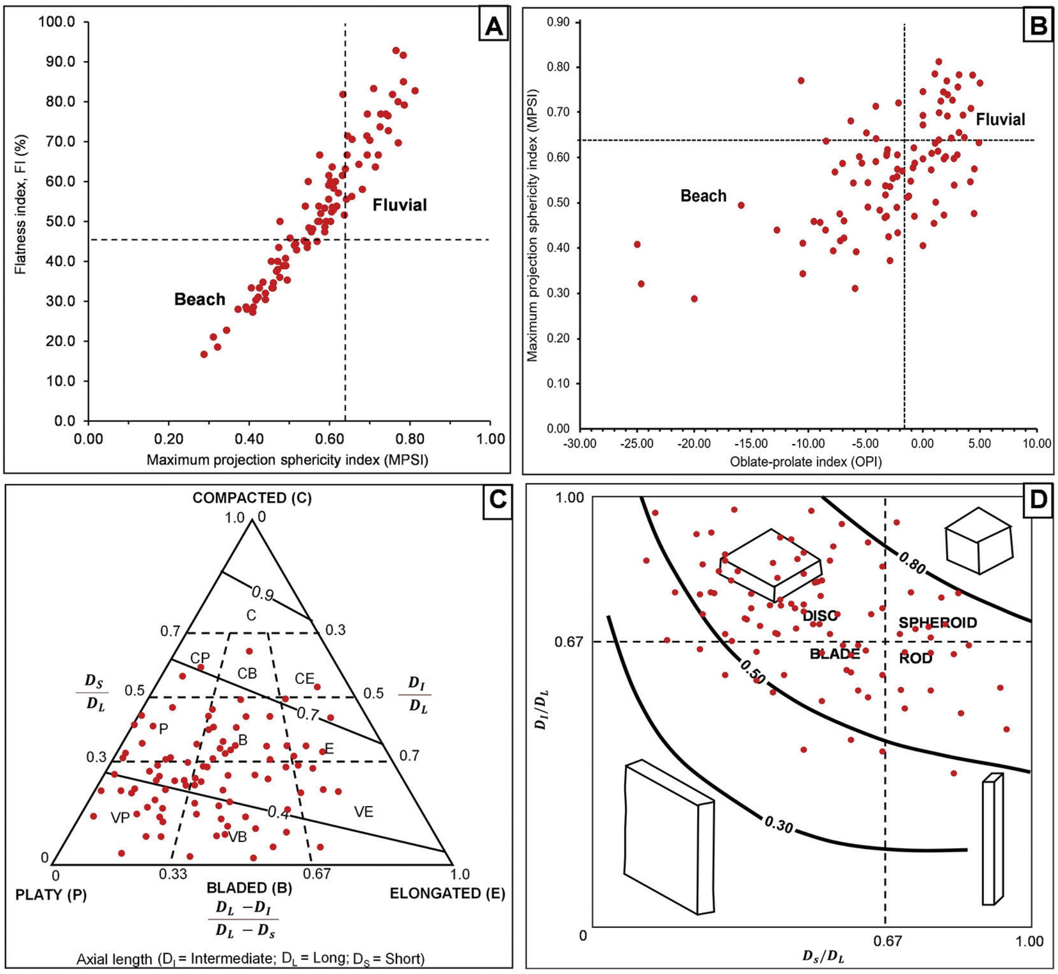

Fig. 7. Morphometric analysis plots for quartz pebbles from the Ogwashi Formation. **A** – Bivariate plot of flatness index (FI) *vs* maximum projection sphericity index (MPSI) (according to Dobkins & Folk, 1970); **B** – Bivariate plot of maximum projection sphericity (MPSI) *vs* oblate-prolate index (OPI) (according to Dobkins & Folk, 1970); **C** – Sphericity-form ternary diagram (according to Sneed & Folk, 1958); **D** – Sphericity-form bivariate plot of pebble shapes showing lines of equal sphericity (according to Lewis & McConchie, 1994); Explanations: B – bladed, C – compact, CB – compact bladed, CE – compact elongated, CP – compact platy, E – elongated, P – platy, VB – very bladed, VE – very elongated, VP – very platy.

fluvial origin by some previous workers who applied similar research methods (e.g., Odumodu & Israel, 2014; Onyemesili & Odumodu, 2019). However, the present findings only support those earlier statements that suggested that the formation was deposited in mixed environments (e.g., Nwajide, 2013; Ejeh et al., 2015; Adeoye et al., 2016; Ekwenye & Nichols, 2016).

Some of the pebbles can be interpreted as of beach origin, so they could possibly have formed in the swash zone of marine environments. These pebbles are assigned to those sandstones that have a clear trough cross-bedded structure (see Fig. 6). This suggests an area in which the beach face was intermittently exposed to the air, possibly over both long (minutes) and short (seconds) time scales (Elfrink & Baldock, 2002). The pebbles that are indicative of a transitional environment may have formed in a tidally influenced setting. This is ascribed to the pebbly sandstones that are also characterised by tidal imprints such as clay drapes and flaser beddings (see Fig. 3).

5.3. Depositional processes and provenance

The average size with a wide-range distribution of pebbles is suggestive of fluctuating river flow competence from moderate to high (Brush, 1961; Wilcock, 1971; Tankard et al., 1982; Madi & Ndlazi, 2020). On average, the long axes of the studied pebbles in some places are oriented northeasterly-southwesterly and northwesterly-southeasterly directions, and they dip in northeasterly and northwesterly directions, respectively. Infrequently, their long axes are oriented in northeasterly-southwesterly and northwesterly-southeasterly directions in different sections of the outcrop; this may be suggestive of fluvial point bars. It implies that sediments of the Ogwashi Formation in the study area were possibly transported by a meandering river from the north and deposited in a southerly direction, where wave and tidal actions occurred (see Figs 3, 4, 6). Sphericity-form bivariate and ternary diagram plots indicate that the pebbles are largely disc and blade in shape, with a minor amount of sphere and rod shapes (see Fig. 7C, D). This highlights that a larger proportion of the studied pebbles have low sphericity, which suggests that most of them were transported relatively far from their source area or in the beach zone (Bluck, 1967; Widera, 2010; Oluwajana et al., 2021).

The wide distribution of pebble shapes is suggestive of multiple provenances of the sediments (Brush, 1961; Sremac et al., 2018; Barudžija et al., 2020; Oluwajana et al., 2021). The sediments of the Ogwashi Formation may have been redeposited and reworked by wave and tidal actions, as reflected in mixtures of various pebble sizes (Abdulkadir & Abdullatif, 2013; Ogbe & Osokpor, 2021). Generally, the present study affirms that adjacent basement complexes are the source for the sediments that fill the Anambra and Abakiliki basins. Thereafter, these sediments (including the studied pebbles from the Ogwashi Formation) were redeposited and became the main components of the Cenozoic Niger Delta Basin, the development of which has continued from the Thanetian to the present day (see Fig. 2; Nwajide, 2006; Ekwenye et al., 2015; Ogbe & Osokpor, 2021).

6. Conclusions

Morphometric analysis, as a sedimentological tool that largely depends on a quantitative evaluation of grain sizes and shapes to verify transport processes and interpret depositional environments, was used for the Ogwashi Formation (Oligocene) in the Niger Delta Basin. The relationship of various independent and dependent functions, together with the different bivariate and ternary diagram plots, have enabled to indicate the presumably mixed nature of transport and, as a result, of fluvial, marine and tidal origin of the pebbles studied.

In the present paper, pebble formation is roughly interpreted as composed of river gravels, which acquired the present morphological features in marine and tidal environments, that is, on the beach of the Oligocene sea. Most likely, the pebbles came from gravelly rocks of the Anambra and Abakiliki basins.

Finally, the present research results, based on field observations and an analysis of quantitative pebble data, may be applicable when other methods cannot be used. However, they should be considered for verification of transport processes and sediment origin as convincingly determined by other methods, for example, sedimentological analysis, as is the case with pebbles from the Ogwashi Formation studied.

Acknowledgements

We wish to thank all our colleagues who joined in the general geological field mapping exercise and are grateful to two anonymous reviewers for their constructive comments and insightful suggestions, which significantly improved the quality of the paper.

Appendix is available in digital version of the article: http://www.geologos.com.pl/

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Manuscript submitted: 25 October 2022
Revision accepted: 5 December 2022