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ORIGINAL PAPER

Pebble morphometric analysis as signatures of the fluvial depositional environment of the Katberg Formation near Kwerela River around East London, Eastern Cape Province, South Africa

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Abstract

Pebbles were collected along the Katberg Formation sandstone beds next to Kwerela River (R63) near East London. During the study of pebble morphology, calculations were made to derive values that were used for bivariate plots to confirm the depositional environment of the Katberg Formation. Bivariate plots of MPs against OP showed that 79% of pebbles fall in fluvial environment, whereas 21% of pebbles fall in the beach environment. The plot of flatness index versus sphericity index shows that 87% of pebbles have a sphericity of greater than 0.65 falling into fluvial environment and 13% falling into a beach environment. The average morphometric indices indicated the dominance of river pebbles with an average sphericity of 0.73, which is above 0.65 and considered the limit of sphericity belonging to fluvial environment. The occurrence of a small proportion of beach pebbles suggests that the river reached the marginal marine environment during its flow. The river pebbles have the lowest roundness, highest sphericity index, and neutral Oblate-Prolate Index. Based on calculated indices, it is evident that the pebbles of the Katberg formation were shaped in fluvial environment. Majority of the pebbles yielded a bladed compact shape with a dominating sphericity index symptomatic of fluvial sediments. All the bivariate plots illustrate fluvial depositional environment for the sediments of the Katberg Formation.

Keywords Pebbles · Morphometric · Fluvial environment · Katberg · Karoo

Introduction

The Katberg Formation is defined as an arenaceous formation that occupies 35% of the stratigraphy in the Beaufort Group in the south-eastern part of the Main Karoo Basin (Stavrakis 1979). The Katberg Formation forms the upper part of the Tarkastad Subgroup, Beaufort Group, Karoo Supergroup (Table 1). In the south, it is considered to have been deposited in an alluvial fan by braided stream environments, due to the moderately coarse grain size, lateral extent and thickness of sandstone beds, the presence of up to 15 cm pebbles, the massive beds and the absence of well-developed fining upward cycles (Smith et al. 1993; Catuneanu et al. 1998; Catuneanu et al. 2005; Johnson et al. 2006). The Katberg Formation is well exposed along the Kwerela River, which is located just few kilometres north of East London, South Africa. Lithological sections were identified along the R67 road, sampled, and described to interpret the paleo-depositional environment, using an integration of lithofacies data and pebble morphology. Palaeocurrent direction stipulates a south-east provenance with the abundance of planar cross-bedding and apparent absence of the longitudinal bars, confirming the braided stream depositional environment within the sandstones (Smith 1993). During the deposition of Katberg Formation, the source area was elevated and disturbed by the tectonism that led to incomplete sequence deposition of Katberg Formation under arid climate (Stavrakis 1979). The pebbles within the sandstones of the Katberg Formation have never been studied and published; thus, this study is aimed at discussing the pebble morphology within

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Table 1 The lithostratigraphy of Karoo Supergroup (Johnson et al. 2006)

Period	Group	Formation	Member	Lithology	Max. thickness (m)
Jurassic	Drakensberg	Drakensberg		Basalt, Pyrocl-astic deposits	1400
	Stormberg	Clarens		sandstone	300
Triassic		Elliot		Red,mudstone, sandstone	500
		Molteno		Coarse Sandstone Gray & Khaki Shale Coal Measures	450
	Beaufort	Burgersdorp		Red Mudstone Sandstone Light Gray Sandstone Gray Shale	1000
		Katberg		Light Gray Sandstone Red mudstone	900
			Palingkloof	Red Mudstone	50
		Balfour		Light Gray Sandstone	
Permian			Elandsberg	Sandstone Siltstone	700
			Barberskrans	Light Gray Sandstone Khaki-Shale	100
			Daggaboersnek	Gray-Shale Sandstone Siltstone	1200
			Oudeberg	Light Gray Sandstone Khaki Shale	100
		Middleton		Gray and Black shale Light gray sandstone Red mudstone	1500
		Koonap		Gray Sandstone Shale	1300
	Ecca	Waterford		Sandstone Shale	800
		Fort Brown		Shale Sandstone	1500
		Ripon		Sandstone Shale	1000
		Collingham		Gray Shale Yellow Claystone	30
		Whitehill		Black-Shale Chert	70
		Prince Albert		Khaki Shale	120
Carboniferous	Dwyka	Elandsvlei		Diamicite, Tillite,	750

Katberg sandstone beds to confirm the depositional environment. Morphometric studies have been used for palaeoenvironmental reconstruction (Okon et al. 2018). They have also been successfully utilized to discriminate between beach and river gravels (Stratten 1974). It is noteworthy to highlight that study provenance and depositional environment have been conducted in sedimentological research by means of geochemistry of sediments, but not too much of these studies focused on the morphometric analysis of pebbles, especially in the Katberg Formation. Even if researchers use pebble counts of lithology, the information provided by a pebble count can be subject to potentially large number of processes and circumstances (Lindsey et al. 2007). Count of a large number of pebbles (at least a hundred) can give an insight on the depositional environment; thus, pebbles collected for this study have been discriminated according to their lithology, and their long, intermediate, and short axes have been measured in order to ascertain the fluvial regime that prevailed during the deposition of the Katberg sediments in and around East London.

From the summary of pebble morphometric analysis, it appears that the dominant forms are bladed and platy indicating a beach environment, but results from majority of used analysis (Flatness Ratio, Flatness Index, Elongation Ratio, Maximum Projection Sphericity Index (Fig. 3), Oblate-Prolte Index) are all symptomatic of a fluvial environment.

Review of geology of the Katberg Formation and study area location

The Katberg Formation sandstones form a part of a thick succession of about 900 m (Table 1), is mostly arenaceous, and belongs to the Tarkastad Subgroup, Beaufort Group, Karoo Supergroup (Johnson 1976). However, the thickness increases near East London to 1238 m towards the North (Krummeck 2013). It is mainly characterized by interbedded fine- to medium-grained sandstones and mudstones that show lateral to downstream accretion from channel bars. The sandstone lithologies are associated by channel lags overlain by intraformational conglomerates and calcareous-nodule conglomerates. The main sedimentary structures in Katberg lithologies include horizontal lamination, partying lineations, cross-beddings, soft sediment deformations, massive beds with well-developed sole marks, and heavy mineral laminae that occur frequently (Bordy et al. 2009). The mudstones contain shallow and smooth erosional surfaces, parallel surfaces marked by sand fill desiccation cracks at several levels, and sometimes intercalated with irregular patches of very fine sandy-clay siltstones. These features noticed by Bordy et al. (2009) correspond to the previously noted by SACS (1980) and Hiller and Stavrakis (1984) that suggest a relatively high energy braided fluvial setting under relatively warm, dry climatic conditions.

The continental sedimentary rocks of the upper Beaufort Group, Tarkastad Subgroup of the Karoo Supergroup of early to middle Triassic age are mainly baked by numerous dolerite intrusions of the Karoo Dolerite Suite of early Jurassic age (Stavrakis 1979). Hence, the sandstones have been baked to quartzite and hornfels, reducing their fossil potential; thus, no fossils have been recorded within these thermally metamorphosed country rocks (Almond 2013).

The Katberg Formation forms a regionally extensive, sandstone-rich bottom part of the Tarkastad Subgroup with a maximum thickness of 900 m, dominated by feldspars and lithic grains. The sandstone is fine to medium grained in most areas but it turns to be coarse to pebble size along coastal exposures near East London where the dominant lithology is sandstone (Johnson 1976; Hiller and Stavrakis 1984; Neveling 2002; Johnson et al. 2006). The Katberg sandstone can be recognized and traced throughout the larger exposed areas within the main Karoo Basin as described by Johnson (1976), Hancox (2000), Johnson et al. (2006), Smith et al. (2002), until it becomes hard to differentiate the Katberg Formation from the conformably overlying Burgersdorp Formation in the northward direction due to the decreasing sandstone-mudstone ratio. At some localities, it was found that dominant sediments can be prominent weathering pale buff to grayish, tabular, or ribbon-shaped sandstones (Almond 2015). The intraformational conglomerates (Fig. 5b) are commonly known as parabreccias, are about 1 m thick, and contain mudrock pebbles and reworked calcrete nodules. Spheroidal carbonate concretions can reach 10 cm in diameter, are common, and can occur from place to place (Stavrakis 1979).

The lithofacies study suggests that the Katberg Formation consists mainly of six lithofacies in association with sandstone and mudstone facies based on the terminology of Miall (1977, in Stravrakis, 1980) as follows: *Fm* mudstone, massive *Fl* mudstone, laminated *Sml* massive sandstone deposited under lower flow regime conditions, *Sr* ripple cross-laminated sandstone, *Sp* planar cross-bedded sandstone, *St* trough cross-bedded sandstone, *Sh* horizontally bedded sandstone, and *Sm2* semi-massive sandstone with in-phase wave cross-bedding (upper flow regime).

Pebble occurrence of the Katberg Formation in the study area lies within latitudes E 28°0′15″ to E27°59′53″ and longitudes S32°50′36″ to S32°50′52″. Two red lines in Fig. 1 in the south eastern part of the Eastern Cape Province delineate a zone in which falls the study area. This zone has been zoomed in Fig. 2, which shows a detailed lithostratigraphy and the Kwelera River flowing through the Katberg Formation.

Methods

Basics of morphometric study of pebbles

A pebble morphometric investigation depends on various independent and dependent functions (Fig. 3). As an independent function, the coefficient of flatness ratio (FR), elongation ratio (ER), Maximum Projection Sphericity Index (MPSI), Oblate-Prolate Index (OPI), roundness (%), and pebble form have been used as indices for the determination of environment of deposition (Table 2). As dependent variables, scatter plots of Maximum Projection Sphericity Index (MPSI) versus Oblate-Prolate Index (OPI), roundness (%) versus elongation ratio (ER), and geometric form diagram have been used in determining the environment of deposition (Ikoro et al. 2014). Formulae for the above mentioned variables are represented in Table 3. The energy and

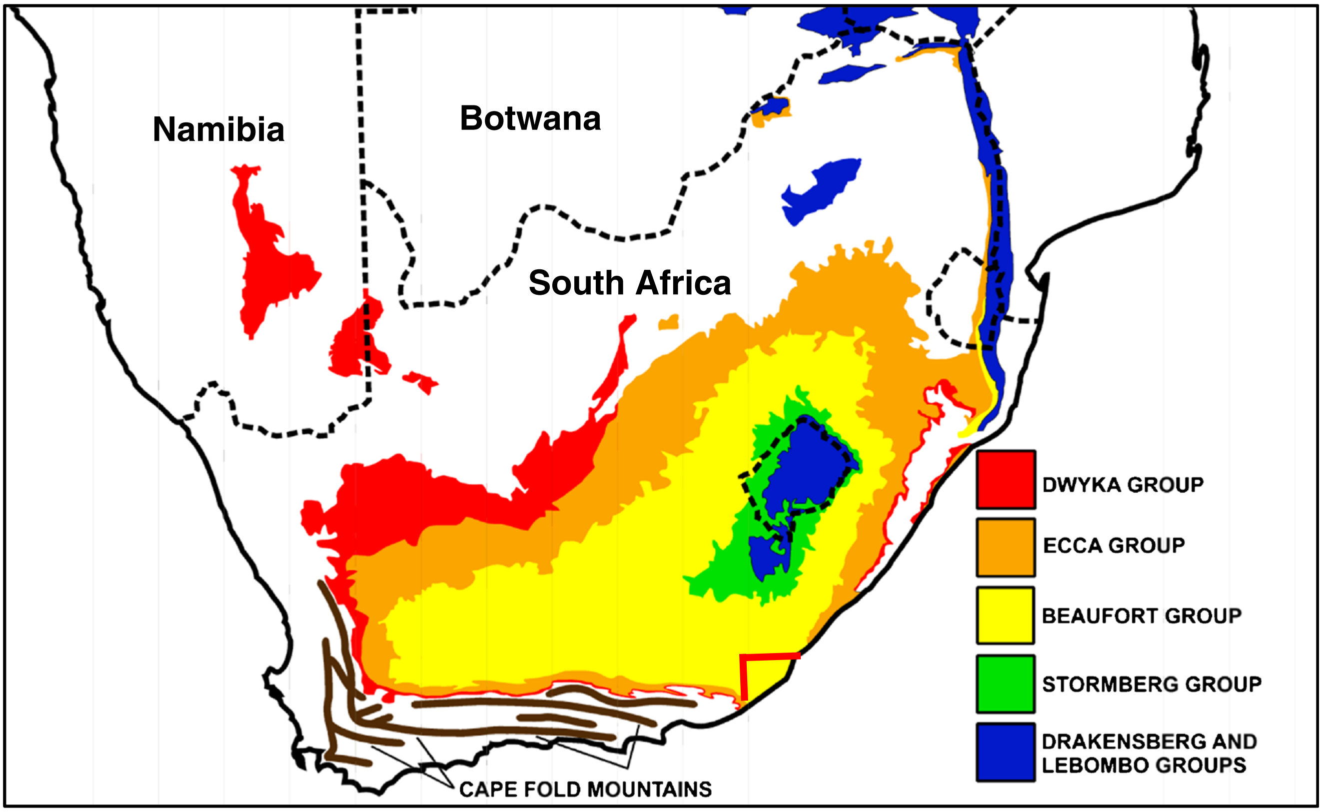

Fig. 1 Geology map of South Africa, the area delineated by two red lines in the south eastern part has been zoomed in with a detailed lithostratigraphy in Fig. 2

conditions within river system differ from one river to another. Therefore, the grain size characteristics of sediments may show variation within different parts of the same environment setting. Grain size distribution reflects processes, depositional environment, and sediment transport processes (Flemming 2007; Kanhaiya et al. 2017). In any case, grain size data is considered as one of the existing tools for environmental interpretation although it cannot be used alone to define the depositional environment of the pebbles (Boggs 2006). Therefore, it is useful to classify pebbles collected in the field according to the Wentworth scale (Table 2) to enlighten on the nature of the river that deposited the sediments and estimate the distance they travelled as well as the water velocity that deposited the sediments of Katberg Formation.

The sedimentary history and the hydrodynamic context can be derived from the shape of particles. Particle shape will depend on many factors: particle size, mode and duration of transport, energy of the transporting medium, and nature and extent of post-depositional weathering, history of sediment transport, and deposition (Bluck 1967). Shapes of pebbles found on the sandstone of the Katberg Formation were studied and evaluated in order to confirm the known depositional environment.

Materials and methods

A maximum of 100 pebbles were collected on top of the eroded sandstone bedding along the sandstone beds next to Kwerela River (R63) to be used during the study of pebble morphology. Some of them were directly removed using a hammer from the sandstone beds. They were selected according to their perfection, while broken pebbles were officially eliminated. The calculation process (Table 5) started by measuring their longest axis (L), intermediate axis (I), and shortest axis (S) using a calliper. Three-dimensional analyses of individual irregularly shaped particles generally involve measuring the principal axes of a triaxial ellipsoid (Fig. 4) to approximate particle shape (Fig. 2). The longest axis (L) is presented by (a), intermediate axis (I) presented by (b), and shortest axis(S) presented by (c). Mean size calculation was done to classify the collected pebbles according to Wentworth scale (Table 2). Calculation of flatness and sphericity was useful to plot a sphericity plot diagram to classify the pebbles according to their depositional environment, either beach or fluvial (Figs. 8 and 9). Hydrodynamic behavior of particles in the river was estimated and elongation was derived to deduce the shape of the pebbles (Fig. 7) according to Sneed and Folk (1958). The travelling distance can be estimated based

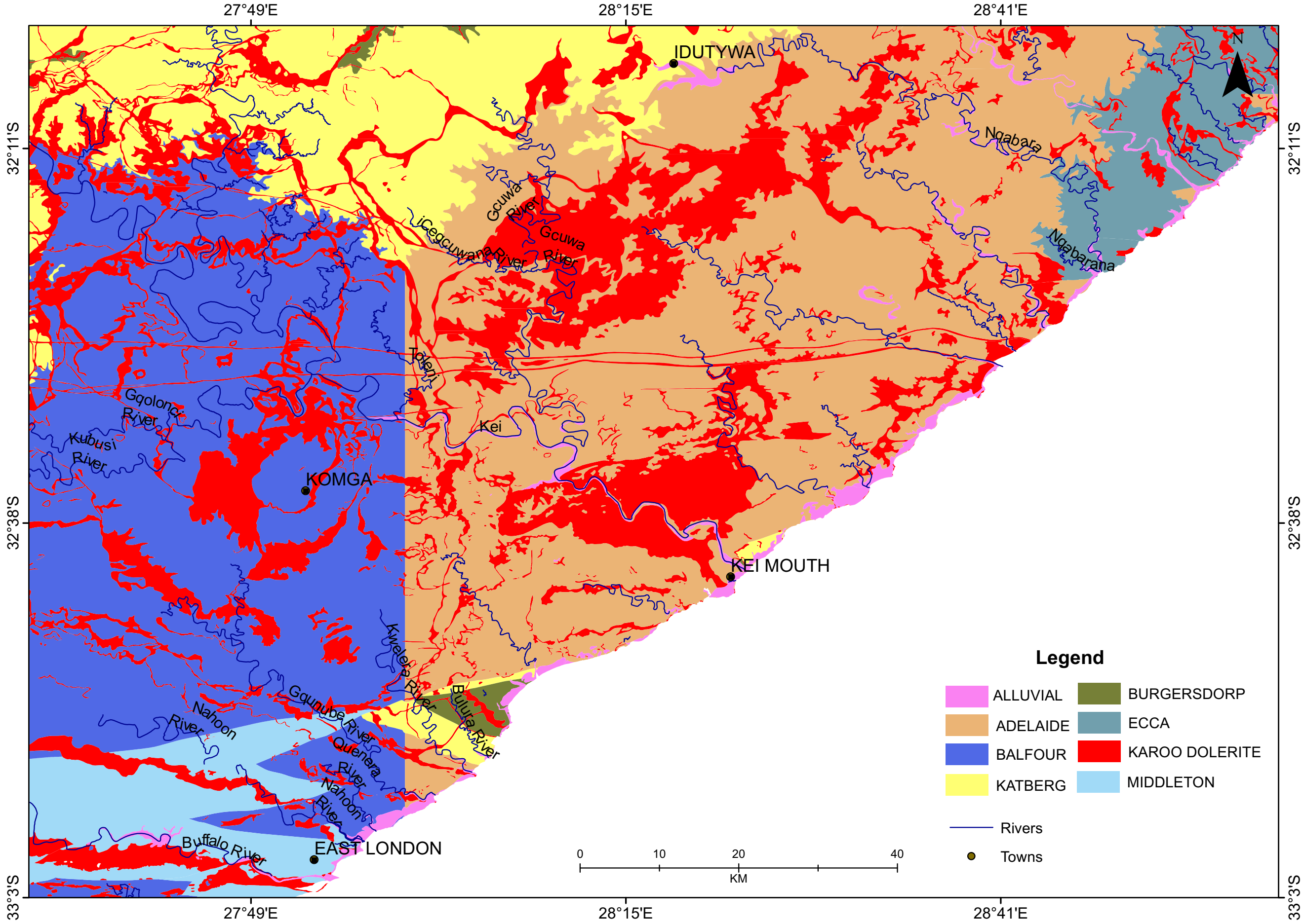

Fig. 2 Geology map of the south eastern part of the Eastern Cape Province in South Africa showing the study area

on the roundness and sphericity of the pebbles. A pie chart was used to show the percentages of the pebble lithology present in the study area (Fig. 6).

The mean values of length (l), width (i), thickness (S), mean size, flatness, elongation, sphericity, and OP Index were calculated from the 100 pebbles. The lithology of pebbles was identified to be mainly composed of quartzite, sandstone, and granite.

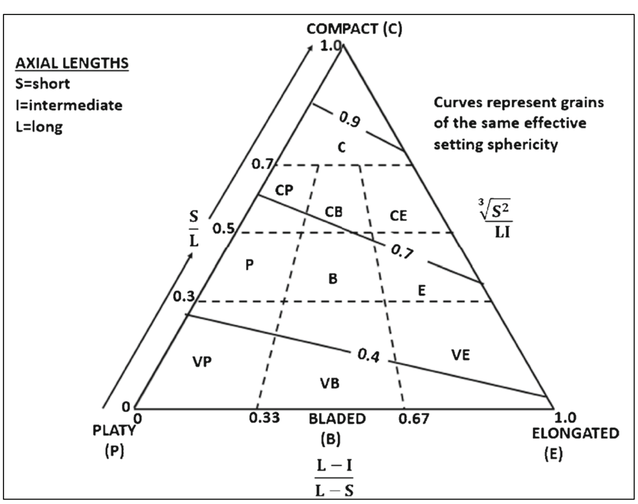

Fig. 3 Sphericity-form diagram of Sneed and Folk (1958) (from Lewis and McConchie 1994)

Results

Field observations

The sandstone beds are almost equal in thickness (Fig. 4a) indicating that they were deposited by the river that carried a same load of sediments, with the same hydrodynamic processes, over equal periods of time. The massive sandstone beds contain a narrow intraclast conglomerate (Fig. 5b) bed with a thickness of 30 cm, with some angular clast of mudstones "mud drapes" and some few well rounded pebbles. In the Katberg Formation, no true conglomerate has been identified before. At some places isolated, rounded pebbles occur within the feldspar-rich sandstone (arkose) beds of the Katberg Formation (Fig. 5c), while some pebbles occur in quartzose sedimentary beds forming a stone line (Fig. 5d). If sedimentary strucutres like cross-bedding were not seen in the Katberg

Table 2 Widely used Udden-Wentworth grain-size scale proposed to better differentiate coarse sediment (after Chesworth 2008; Folk 1954, 1974; Folk et al. 1970)

PARTICLE LENGTH (dI) km	m	mm	ϕ	GRADE	CLASS	FRACTION Unlithified	FRACTION Lithified
1075			-30	very coarse	Megalith	Megagravel	Mega-conglomerate
538			-29	coarse			
269			-28	medium			
134			-27	fine			
67.2			-26	very fine			
33.6			-25	very coarse	Monolith		
16.8			-24	coarse			
8.4			-23	medium			
4.2			-22	fine			
2.1			-21	very fine			
1.0	1048.6		-20	very coarse	Slab		
0.5	524.3		-19	coarse			
0.26	262.1		-18	medium			
	131.1		-17	fine			
	65.5		-16	very coarse	Block		
	32.8		-15	coarse			
	16.4		-14	medium			
	8.2		-13	fine			
	4.1	4096	-12	very coarse	Boulder	Gravel	Conglomerate
	2.0	2048	-11	coarse			
	1.0	1024	-10	medium			
	0.5	512	-9	fine			
	0.25	256	-8	coarse	Cobble		
		128	-7	fine			
		64	-6	very coarse	Pebble		
		32	-5	coarse			
		16	-4	medium			
		8	-3	fine			
		4	-2		Granule		
		2	-1	very coarse	Sand	Sand	Sandstone
		1	0	coarse			
		0.50	1	medium			
		0.25	2	fine			
		0.125	3	very fine			
		0.063	4	coarse	Silt	Mud	Mudstone or Shale
		0.031	5	medium			
		0.015	6	fine			
		0.008	7	very fine			
		0.004	8		Clay ↓ ?		
		0.002	9				
		0.001	10				
		0.0005	11				
		0.0002	12				
		0.0001	13				

Formation near Kwelera River, nevertheless, trough cross-beddings have been found in the same Katberg Formation that crops out at the East London Beach (Fig. 5e). Sole marks having a unique trend direction of current flow were found in the Katberg sandstones near the Kwelera River (Fig. 5f). In relation to these sole marks, during quiet times, fine partcicles

Table 3 Morphometric indices with their formulae used during calculations

Morphometric indices	Formulae	Author
Flatness ratio	S/L	Luttig 1962
Elongation	I/L	Luttig 1962
Maximum projection sphericity index	$(S^2/LI)^{1/3}$	Sneed and Folk 1958
Oblate-Prolate index	10 [(L-I)/(L-S)-(0.50)]/S/L	Dobkins and Folk 1970
Roundness	Visual estimation	Sames 1966

settle out of the suspension in water building up a layer of mud. Then, when a strong current flows over the mud surface, the surface of the mud is removed easily by erosion before depositing sand on top. The current erodes the mud cracks in the mud, which are filled by sand. During lithification, when sand lithifies into sandstone, casts of holows and other marks are preserved at the bottom of the sandstone beds, called sole structures. Predominant structures found in the study area are mainly thrust faults (Fig. 3g, h). According to the Andersonian theory of faulting, the least principal stress σ_3 should be vertical and the maximum principal stress σ_1 and intermediate stress σ_2 should be horizontal. Mass loss by attrition increases with particle velocity but is weakly dependent on particle size; thus, small pebbles tend to travel fast and are deposited later in the suspenssion compared to larger pebbles. This type of pebble occurrence is dominant within the Katberg sandstone beds, which indicates that the Katberg Formation was indeed deposited by braided channels that existed during Permo-Triassic times where the climatic conditions were dry ams warm. It was indicated that the lowermost part of the Katberg formation was deposited under oscillating wet to dry conditions, and this occurred throughout the earliest Triassic (Pace et al. 2009). Moreover, sanstones of the Katberg Formation also accumulated in arid conditions that corresponded to the mass extinction (Ward et al. 2005). Multilateral fluvial deposits were found in the Katberg Formation (Gastaldo and Rolerson 2008) displaying interfluvial wet paleosols as a concrete evidence of seasonally dry conditions (Pace et al. 2009). It is evident that the Katberg Formation was deposited under arid climatic conditions with ephemeral braided channels draining a source that was predominated by granitic, metamorphic, and alkaline rocks (Smith 1995). This confirms again the variety of pebbles examined in this study.

Katberg pebble morphometric analysis

The pebble's lithology was identified to be mainly composed of quartzite, sandstone, and granite (Table 5). The majority of pebbles are quartzitic in composition, which is common for river pebbles that have travelled for a long distance. During transportation, unstable minerals like feldspars are lost during transportation, and quartz grains tend to dominate due to their resistance to weathering. From Fig. 8, 79% of pebbles fall in the fluvial environment, whereas 21% fall in the beach environment. The average morphometric indices indicated an average sphericity of 0.73, this mean value of sphericity is above 0.65, which is the limit of sphericity belonging to fluvial environment. All pebbles with sphericity less than 0.65 belong to the beach environment. The occurrence of beach pebbles in Katberg Formation may be an indication that the sediments were deposited in an environment shared between river and beach tidal zone since the majority of them show a bladed form as indicated in sphericity-form diagram of Fig. 7. The average pebble size is 31.18 mm which, as indicated above,

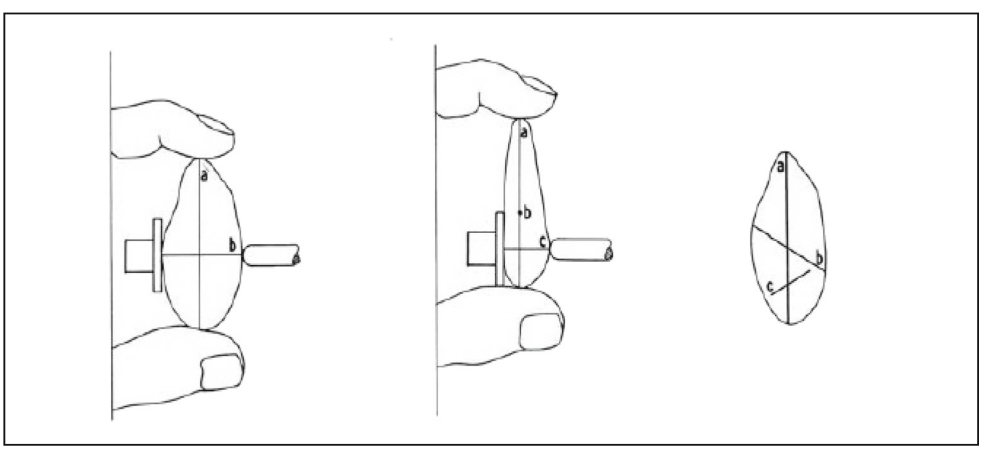

Fig. 4 Concept and measurement of pebble diameter (adopted from Krumbein 1941 in Pettijohn 1957). The two-dimensional particle shape (ab) is generally considered to be a function of attrition and weathering during transport whereas three-dimensional shape is more closely related to particle lithology

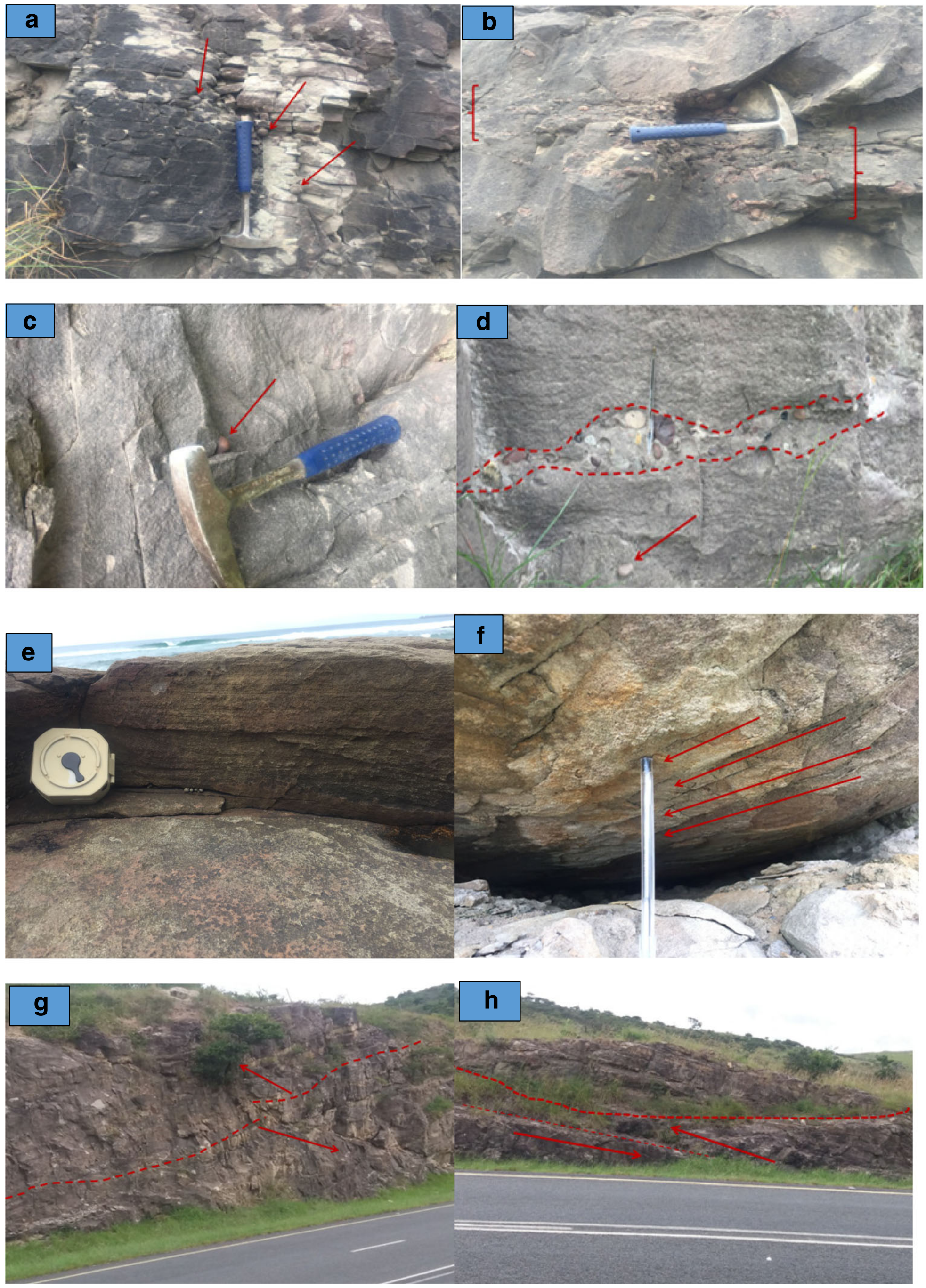

Fig. 5 Some isolated well round pebbles (**a**), deposited by braided streams. Intraclast conglomerate in the Katberg Formation sandstone (**b**), an isolated rounded pebble within the feldspar-rich sandstone bedding of the Katberg Formation (**c**). Pebbles could be traced through a stone line (**d**). Trough-cross and planar-cross bedding (**e**), sole marks at the base of sandstone layer (**f**). Reverse faulting cutting across the Katberg sandstones (**g**, **h**)

and according to Udden-Wentworth (Table 2), can be categorized as coarse to very coarse. With this average size, it can be clearly said that boulders or cobbles in the Katberg Formation are yet to found.

Morphometric interpretation derived from 100 pebbles indicates that dominant shapes are bladed and platy. All the morphometric indices obtained from measurements of length, width, and thickness in millimeter revealed a fluvial environmental indication as shown in Tables 4 and 5. OP Index has an average of 2.25 which is greater than − 1.5, a limit for fluvial pebbles. The maximum projection sphericity index of the Katberg Formation pebbles appears to have a higher value. Probable beach sediments are indicated by some individual pebbles with Oblate-Prolate Index and maximum projection sphericity values of less than − 1.5 and 0.65, respectively.

Flatness index for fluvial pebbles is greater than 45%, so 79% of pebbles had flatness index greater than 45% indicating fluvial origin, average is 52.97 common for fluvial pebbles. All of these indices in Table 5 confirmed the fluvial origin. On the basis of indices, it is evident that the pebbles were shaped

Table 4 Summary of pebble morphometric analysis

Morphometric indices	Average	Environmental indications
Length (l) mm	41.86	Fluvial
Width (i) mm	29.72	Fluvial
Thickness (S) mm	21.97	Fluvial
Mean size	31.18	Fluvial
Elongation ratio	0.72	0.6–0.9 fluvial
Flatness ratio	0.53	< 0.45 fluvial
Maximum projection Sphericity	0.73	< 0.65 fluvial
OP-index	2.25	≤ 1.5 fluvial
Plot of flatness ratio (FR) versus maximum projection sphericity	87% fluvial and 13% beach	Fluvial
Plot of MPS against OP	79%fluvial and 21% beach	Fluvial
Dominant pebble forms	bladed, platy	Beach

in fluvial environment. All the bivariate plots illustrate the dominance of the fluvial depositional environment for the sediments of the Katberg Formation. Some pebbles were traced in a small stone line (Fig. 5d) in the sandstone with more than 90% quartz content. Pebbles deposited by turbidiry currents or other gravity flow processes become oriented with their long axis mainly parallel to the flow direction, although orientation in some deposits can be random like in this case (Fig. 5d). When pebbles are imbricated and appear having any given dip direction, the flow direction would be opposite to the dip direction of these pebbles. Imbricated pebbles were not found, this has made almost impossible to derive the flow direction.

Discussion

A depositional environment can be defined in terms of physical, chemical, biological, or geomorphic variables (Reineck and Singh 2012). The quartzite pebbles within the Katberg sandstone originated from the Cape Fold Belt. The intensification of the Cape Fold Belt tectonics dated at 229 ± 5 Ma (Hälbisch et al. 1983). Strong uplift associated with Cape Fold Belt orogeny at the beginning of the Triassic led to the influx of medium-grained, pebbly, bed-load fluvial sandstones of the Katberg Formation (Selley 1997). Other findings indicate that the Katberg sandstones can be seen from the Kidd's Beach near East London; in this area, the Katberg sandstones are coarse-grained with scattered pebbles of various rock types, mainly of quartz and quartzite. These pebbles indicate derivation from the Cape Fold Belt that was uplifted and eroded (Norman 2013). Granite pebbles in the East London area have probably a distal source. The Falkland Islands were identified as distal source of orthogneiss pebbles (Veevers et al. 1994). It is noteworthy to mention that it cannot be possible that larger pebbles were derived from the erosion of Dwyka Tillite (Stavrakis 1980); no striated pebble was found near East London. Isolated rounded pebbles occurring within the feldspar-rich sandstone (arkose) beds of the Katberg Formation might be indicative of abrasion and attrition changes that characterize sediments carried by mountain rivers from an eroding landscape (Attal and Lavé 2009). According to our findings, the Katberg Formation has two types of conglomerates (intraformational and extraformational). Intraclast conglomerates such as those seen in Fig. 5b have been also evidenced by other researchers (Catuneanu et al. 2005). Thus, the rounded pebbles (e.g., Fig. 5d) that have travelled for a long distance that originates from another source and were cemented by a sandy matrix forming a consolidate rock. This type of rock would be classified as extraformational conglomerate. This extraformational conglomerates are polymictic because of different lithology of pebbles and point to a fluvial deposit (e.g., Osborne 1991). The dominant pebble lithologies are quartzite, followed by sandstone, and granite, in the order of dominance as indicated in pie chart (Fig. 6). It is not quite sure about the age of the pebbles found in the study area; it is possible that they are post-Devonian according to Hiller and Starvakis (1980). Besides, one might question the findings of these two researchers about the lithology of pebbles. They indicated that pebbles of reworked silicified wood of post-Devonian age occur within the Katberg sandstones in the proximal outcrop area near East London. However, these reworked silicified wood pebbles might have been found elsewhere; our findings prove that mainly quartzite pebbles were identified besides the few sandstones and granites pebbles. The mean size of pebbles (31.8 mm) is indicative of moderate to high flow competence (Tankard et al. 1982). This study indicates that most of the pebbles were deposited in a fluvial regime. This finding corroborates the works of Dobkin and Folk (1970)

Table 5 Pebble morphometric analysis result of 100 samples

Pebble no.	Length L (mm)	Width I (mm)	Thickness S (mm)	Mean size = (L + I + S)/3	Flatness = S/L	Elongation = I/L	S/I	(L-I)/(L-S)	Flatness = (S/L)100	Sphericity	OP index	Sed. Environ	Lithology
1	60	38	28	42.00	0.47	0.63	0.74	0.69	46.67	0.70	4.02	Fluvial	Sandstone
2	42	35	22	33.00	0.52	0.83	0.63	0.35	52.38	0.69	− 3.21	Fluvial	Quartzite
3	35	33	20	29.33	0.57	0.94	0.61	0.13	57.14	0.70	− 7.86	Fluvial	Quartzite
4	42	23	21	28.67	0.50	0.55	0.91	0.90	50.00	0.77	8.67	Fluvial	Quartzite
5	37	33	24	31.33	0.65	0.89	0.73	0.31	64.86	0.78	− 4.12	Fluvial	Quartzite
6	45	30	21	32.00	0.47	0.67	0.70	0.63	46.67	0.69	2.68	Fluvial	Sandstone
7	44	36	25	35.00	0.57	0.82	0.69	0.42	56.82	0.73	− 1.69	Fluvial	Quartzite
8	52	30	25	35.67	0.48	0.58	0.83	0.81	48.08	0.74	6.75	Fluvial	Quartzite
9	52	45	37	44.67	0.71	0.87	0.82	0.47	71.15	0.84	− 0.71	Fluvial	Quartzite
10	47	35	25	35.67	0.53	0.74	0.71	0.55	53.19	0.72	0.97	Fluvial	Quartzite
11	32	26	16	24.67	0.50	0.81	0.62	0.38	50.00	0.68	− 2.68	Fluvial	Sandstone
12	55	44	40	46.33	0.73	0.80	0.91	0.73	72.73	0.87	5.00	Fluvial	Quartzite
13	38	36	23	32.33	0.61	0.95	0.64	0.13	60.53	0.73	− 7.86	Fluvial	Quartzite
14	52	35	28	38.33	0.54	0.67	0.80	0.71	53.85	0.76	4.46	Fluvial	Quartzite
15	20	18	17	18.33	0.85	0.90	0.94	0.67	85.00	0.93	3.57	Fluvial	Quartzite
16	39	33	27	33.00	0.69	0.85	0.82	0.50	69.23	0.83	0.00	Fluvial	Quartzite
17	44	30	24	32.67	0.55	0.68	0.80	0.70	54.55	0.76	4.29	Fluvial	Quartzite
18	41	37	23	33.67	0.56	0.90	0.62	0.22	56.10	0.70	− 5.95	Fluvial	Quartzite
19	39	28	19	28.67	0.49	0.72	0.68	0.55	48.72	0.69	1.07	Fluvial	Sandstone
20	60	34	40	44.67	0.67	0.57	1.18	1.30	66.67	0.92	17.14	Fluvial	Sandstone
21	32	22	26	26.67	0.81	0.69	1.18	1.67	81.25	0.99	25.00	Fluvial	Quartzite
22	28	24	17	23.00	0.61	0.86	0.71	0.36	60.71	0.75	− 2.92	Fluvial	Quartzite
23	53	41	28	40.67	0.53	0.77	0.68	0.48	52.83	0.71	− 0.43	Fluvial	Sandstone
24	50	33	23	35.33	0.46	0.66	0.70	0.63	46.00	0.68	2.78	Fluvial	Quartzite
25	40	29	19	29.33	0.48	0.73	0.66	0.52	47.50	0.68	0.51	Fluvial	Sandstone
26	84	35	45	54.67	0.54	0.42	1.29	1.26	53.57	0.88	16.21	Fluvial	Sandstone
27	33	27	17	25.67	0.52	0.82	0.63	0.38	51.52	0.69	− 2.68	Fluvial	Quartzite
28	32	25	17	24.67	0.53	0.78	0.68	0.47	53.13	0.71	− 0.71	Fluvial	Sandstone
29	46	34	30	36.67	0.65	0.74	0.88	0.75	65.22	0.83	5.36	Fluvial	Quartzite
30	46	29	23	32.67	0.50	0.63	0.79	0.74	50.00	0.73	5.12	Fluvial	Sandstone
31	44	28	22	31.33	0.50	0.64	0.79	0.73	50.00	0.73	4.87	Fluvial	Sandstone
32	32	25	17	24.67	0.53	0.78	0.68	0.47	53.13	0.71	− 0.71	Fluvial	Quartzite
33	38	28	15	27.00	0.39	0.74	0.54	0.43	39.47	0.60	− 1.40	Beach	Quartzite
34	47	30	28	35.00	0.60	0.64	0.93	0.89	59.57	0.82	8.46	Fluvial	Quartzite
35	43	27	12	27.33	0.28	0.63	0.44	0.52	27.91	0.50	0.35	Beach	Quartzite
36	46	30	25	33.67	0.54	0.65	0.83	0.76	54.35	0.77	5.61	Fluvial	Quartzite
37	51	40	19	36.67	0.37	0.78	0.48	0.34	37.25	0.56	− 3.35	Beach	Quartzite
38	38	30	25	31.00	0.66	0.79	0.83	0.62	65.79	0.82	2.47	Fluvial	Quartzite
39	40	18	18	25.33	0.45	0.45	1.00	1.00	45.00	0.77	10.71	Fluvial	Quartzite
40	54	33	22	36.33	0.41	0.61	0.67	0.66	40.74	0.65	3.35	Beach	Sandstone
41	40	31	15	28.67	0.38	0.78	0.48	0.36	37.50	0.57	− 3.00	Beach	Granite
42	41	34	15	30.00	0.37	0.83	0.44	0.27	36.59	0.54	− 4.95	Beach	Sandstone
43	42	29	20	30.33	0.48	0.69	0.69	0.59	47.62	0.69	1.95	Fluvial	Quartzite
44	35	20	19	24.67	0.54	0.57	0.95	0.94	54.29	0.80	9.38	Fluvial	Quartzite
45	55	37	35	42.33	0.64	0.67	0.95	0.90	63.64	0.84	8.57	Fluvial	Sandstone
46	39	26	16	27.00	0.41	0.67	0.62	0.57	41.03	0.63	1.40	Beach	Sandstone

Table 5 (continued)

Pebble no.	Length L (mm)	Width I (mm)	Thickness S (mm)	Mean size = (L + I + S)/3	Flatness = S/L	Elongation = I/L	S/I	(L-I)/(L-S)	Flatness = (S/L)100	Sphericity	OP index	Sed. Environ	Lithology
47	40	23	10	24.33	0.25	0.58	0.43	0.57	25.00	0.48	1.43	Beach	Quartzite
48	46	43	20	36.33	0.43	0.93	0.47	0.12	43.48	0.59	− 8.24	Beach	Sandstone
49	31	30	20	27.00	0.65	0.97	0.67	0.09	64.52	0.75	− 8.77	Fluvial	Quartzite
50	54	35	21	36.67	0.39	0.65	0.60	0.58	38.89	0.62	1.62	Beach	Sandstone
51	37	27	20	28.00	0.54	0.73	0.74	0.59	54.05	0.74	1.89	Fluvial	Quartzite
52	55	27	18	33.33	0.33	0.49	0.67	0.76	32.73	0.60	5.50	Beach	Quartzite
53	46	35	17	32.67	0.37	0.76	0.49	0.38	36.96	0.56	− 2.59	Beach	Quartzite
54	39	35	20	31.33	0.51	0.90	0.57	0.21	51.28	0.66	− 6.20	Fluvial	Quartzite
55	39	35	30	34.67	0.77	0.90	0.86	0.44	76.92	0.87	− 1.19	Fluvial	Quartzite
56	37	22	20	26.33	0.54	0.59	0.91	0.88	54.05	0.79	8.19	Fluvial	Quartzite
57	57	43	30	43.33	0.53	0.75	0.70	0.52	52.63	0.72	0.40	Fluvial	Quartzite
58	49	26	33	36.00	0.67	0.53	1.27	1.44	67.35	0.95	20.09	Fluvial	Sandstone
59	39	24	17	26.67	0.44	0.62	0.71	0.68	43.59	0.68	3.90	Beach	Sandstone
60	35	20	16	23.67	0.46	0.57	0.80	0.79	45.71	0.72	6.20	Fluvial	Quartzite
61	52	34	24	36.67	0.46	0.65	0.71	0.64	46.15	0.69	3.06	Fluvial	Quartzite
62	42	26	19	29.00	0.45	0.62	0.73	0.70	45.24	0.69	4.19	Fluvial	Sandstone
63	46	23	19	29.33	0.41	0.50	0.83	0.85	41.30	0.70	7.54	Beach	Sandstone
64	37	26	18	27.00	0.49	0.70	0.69	0.58	48.65	0.70	1.69	Fluvial	Quartzite
65	42	33	18	31.00	0.43	0.79	0.55	0.38	42.86	0.62	− 2.68	Beach	Sandstone
66	44	27	20	30.33	0.45	0.61	0.74	0.71	45.45	0.70	4.46	Fluvial	Sandstone
67	37	55	20	37.33	0.54	1.49	0.36	− 1.06	54.05	0.58	− 33.40	Beach	Quartzite
68	40	32	22	31.33	0.55	0.80	0.69	0.44	55.00	0.72	− 1.19	Fluvial	Sandstone
69	41	30	23	31.33	0.56	0.73	0.77	0.61	56.10	0.75	2.38	Fluvial	Quartzite
70	34	25	20	26.33	0.59	0.74	0.80	0.64	58.82	0.78	3.06	Fluvial	Quartzite
71	49	35	20	34.67	0.41	0.71	0.57	0.48	40.82	0.62	− 0.37	Beach	Quartzite
72	27	23	19	23.00	0.70	0.85	0.83	0.50	70.37	0.83	0.00	Fluvial	Granite
73	28	24	14	22.00	0.50	0.86	0.58	0.29	50.00	0.66	− 4.59	Fluvial	Sandstone
74	44	30	23	32.33	0.52	0.68	0.77	0.67	52.27	0.74	3.57	Fluvial	Quartzite
75	30	20	13	21.00	0.43	0.67	0.65	0.59	43.33	0.66	1.89	Beach	Quartzite
76	25	18	13	18.67	0.52	0.72	0.72	0.58	52.00	0.72	1.79	Fluvial	Sandstone
77	40	29	28	32.33	0.70	0.73	0.97	0.92	70.00	0.88	8.93	Fluvial	Quartzite
78	43	37	24	34.67	0.56	0.86	0.65	0.32	55.81	0.71	− 3.95	Fluvial	Quartzite
79	48	28	22	32.67	0.46	0.58	0.79	0.77	45.83	0.71	5.77	Fluvial	Quartzite
80	55	36	25	38.67	0.45	0.65	0.69	0.63	45.45	0.68	2.86	Fluvial	Quartzite
81	52	33	23	36.00	0.44	0.63	0.70	0.66	44.23	0.68	3.33	Beach	Quartzite
82	50	30	29	36.33	0.58	0.60	0.97	0.95	58.00	0.82	9.69	Fluvial	Sandstone
83	46	23	20	29.67	0.43	0.50	0.87	0.88	43.48	0.72	8.24	Beach	Sandstone
84	62	52	36	50.00	0.58	0.84	0.69	0.38	58.06	0.74	− 2.47	Fluvial	Sandstone
85	51	29	28	36.00	0.55	0.57	0.97	0.96	54.90	0.81	9.78	Fluvial	Quartzite
86	36	24	11	23.67	0.31	0.67	0.46	0.48	30.56	0.52	− 0.43	Beach	Quartzite
87	35	27	19	27.00	0.54	0.77	0.70	0.50	54.29	0.73	0.00	Fluvial	Quartzite
88	34	33	28	31.67	0.82	0.97	0.85	0.17	82.35	0.89	− 7.14	Fluvial	Quartzite
89	40	18	20	26.00	0.50	0.45	1.11	1.10	50.00	0.82	12.86	Fluvial	Quartzite
90	35	31	20	28.67	0.57	0.89	0.65	0.27	57.14	0.72	− 5.00	Fluvial	Quartzite
91	44	25	23	30.67	0.52	0.57	0.92	0.90	52.27	0.78	8.67	Fluvial	Sandstone
92	28	17	15	20.00	0.54	0.61	0.88	0.85	53.57	0.78	7.42	Fluvial	Quartzite

Table 5 (continued)

Pebble no.	Length L (mm)	Width I (mm)	Thickness S (mm)	Mean size = (L + I + S)/3	Flatness = S/L	Elongation = I/L	S/I	(L-I)/(L-S)	Flatness = (S/L)100	Sphericity	OP index	Sed. Environ	Lithology
93	30	22	18	23.33	0.60	0.73	0.82	0.67	60.00	0.79	3.57	Fluvial	Sandstone
94	33	25	17	25.00	0.52	0.76	0.68	0.50	51.52	0.70	0.00	Fluvial	Quartzite
95	40	36	30	35.33	0.75	0.90	0.83	0.40	75.00	0.85	− 2.14	Fluvial	Quartzite
96	37	20	28	28.33	0.76	0.54	1.40	1.89	75.68	1.02	29.76	Fluvial	Sandstone
97	36	24	18	26.00	0.50	0.67	0.75	0.67	50.00	0.72	3.57	Fluvial	Quartzite
98	30	29	18	25.67	0.60	0.97	0.62	0.08	60.00	0.72	− 8.93	Fluvial	Quartzite
99	24	14	11	16.33	0.46	0.58	0.79	0.77	45.83	0.71	5.77	Fluvial	Quartzite
100	30	20	16	22.00	0.53	0.67	0.80	0.71	53.33	0.75	4.59	Fluvial	Sandstone
Average	41.86	29.72	21.97	31.18	0.53	0.72	0.75	0.60	52.97	0.73	2.25		

who used binary diagram of MPSI versus OP Index to characterize depositional environments.

The mean value of sphericity index is above 0.65, which is the limit of sphericity belonging to fluvial environment (Stratten 1974). According to Hubert (1968), the elongation ratio values for fluvial environment range from 0.6 to 0.9. Almost 79% of the calculated values have an average elongation ratio of 0.72, indicating that the fluvial environment was predominant for the analyzed Katberg pebbles (Fig. 7).

The high value of MPSI of the Katberg Formation pebbles dovetails the findings of Dobkins and Folk (1970) and Hubert (1968) who pointed out that the maximum projection sphericity of pebbles is generally higher for fluvial environment (river) than for beaches. Most of the pebbles fall into the fluvial environment (Figs. 8 and 9).

Flatness index for fluvial pebbles such as the one in the present study is greater than 45; Okoro et al. (2012) quoting Stratten (1974) indicated that the % of flatness ratio can be used to discriminate between fluvial and beach pebbles, a value of more than 45% is indicative of fluvial pebbles. The majority of pebbles fall in the fluvial environment; however, those who fall in the beach environment highlighted in Figs. 8 and 9 may be indicative of swash, which is also characterized by trough cross-bedding (e.g., Bezzera et al. 2015).

The pebbles were carried by water flowing down the mountains and deposited on top of the sandstone beds in the south of East London. The sandstone pebble occurrence forms a stone line (Fig. 3 d), and this stone line is undoubtedly of fluvial origin. This may also confirm the arid climate during the Permo-Triassic times; indeed, a stone line may have resulted from the redistribution and concentration of gravel by surface water flows and associated colluvial activity related to dry climate (Mukerjee 1993). Most of the pebbles are well rounded and bladed in shape, as indicated in the sphericity form diagram of Fig. 7. Their roundness in shape indicates that they were transported over a longer distance. During transportation, their edges were destroyed through the process of abrasion and attrition. The abundance of quartzite pebbles indicates the stability of quartz as a dominating minerals in terms of resistance to abrasion throughout the transportation.

Conclusions

It appears that the dominant forms are bladed, all analysis (Flatness Ratio, Flatness Index, Elongation Ratio, Maximum Projection Sphericity Index, Oblate-Prolte Index) used in this study point to a fluvial environment. The plot of Sphericity Index versus Flatness Index shows that 87% of pebbles have a sphericity of greater than 0.65 falling into fluvial environment

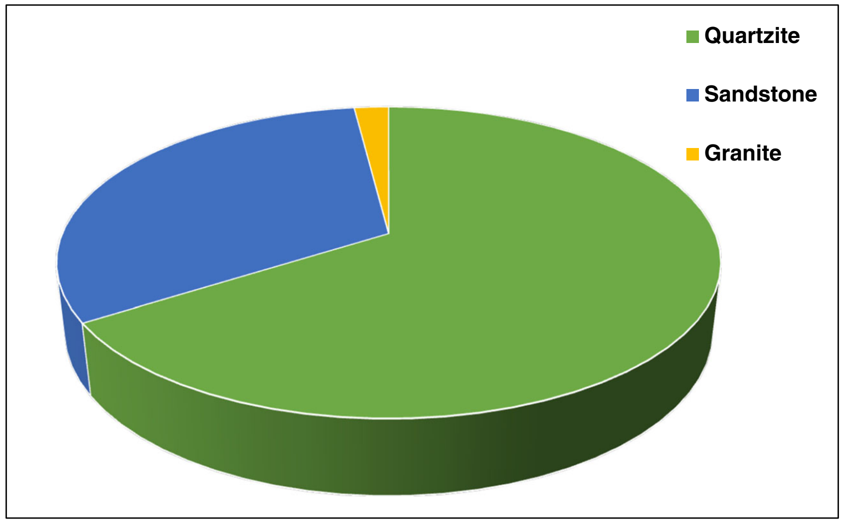

Fig. 6 A pie chart representing lithologies of pebbles found in sandstone beds of Katberg Formation: quartzite = 66%, sandstone = 32%, and granite = 2%

and 13% falling into a beach environment. The mixture of large number of pebbles indicative of fluvial environment and small number of pebbles indicative of beach environment may be explained by the proximity of Katberg formation sediments cropping out around the Kwelera River to the Indian Ocean. Besides, the Katberg Formation also crops out at the East London beach and can undoubtedly be correlated with sediments near the Kwelera River. The shoreline demarcating the beach and fluvial environment is yet to be discovered. It is known that the Katberg Formation consists of fluvial deposits (Gastado et al. 2013; Hiller and Stavrakis 1984; etc.) and as well as indicated in this study (sole marks and bivariate plots), but this seemingly uncommon admixture of two palaeo-environments (fluvial pebbles and beach pebbles) in the Katberg sediments might indicate synchronous deposits. Pebbles originating from the Cape Fold Belt and even Falkland Islands were transported in a fluvial environment, and other pebbles were carried in a swash up the beach. This two modes of transportation resulted in a cross shore sediment exchange. As the percentage of what would be considered as

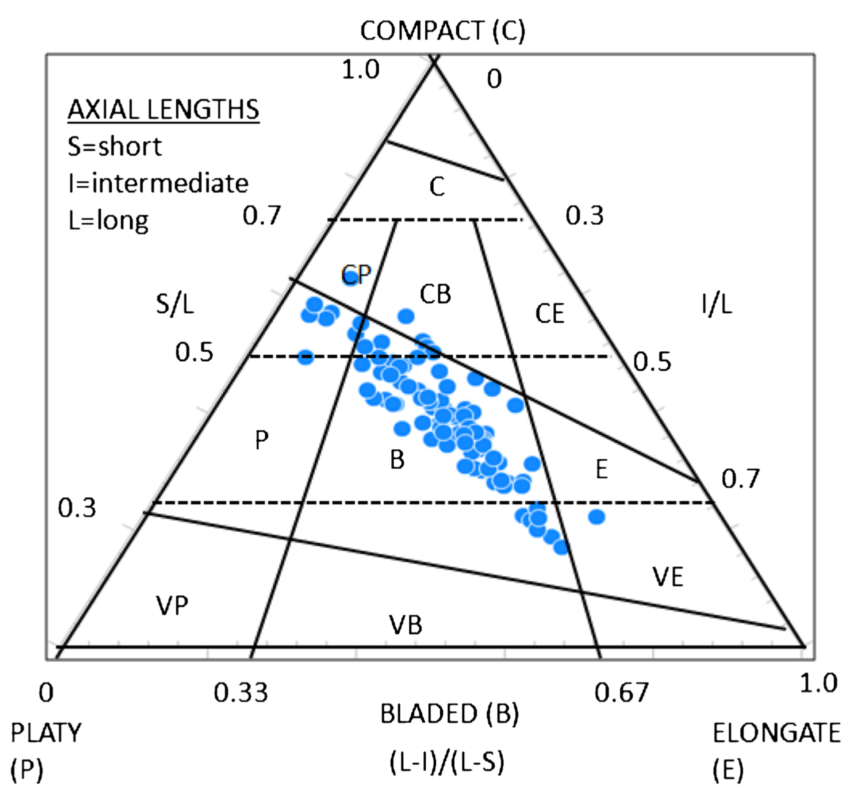

Fig. 7 Sphericity-form diagram for pebbles of Katberg Formation in the study area of East London (adapted from Sneed and Folk (1958))

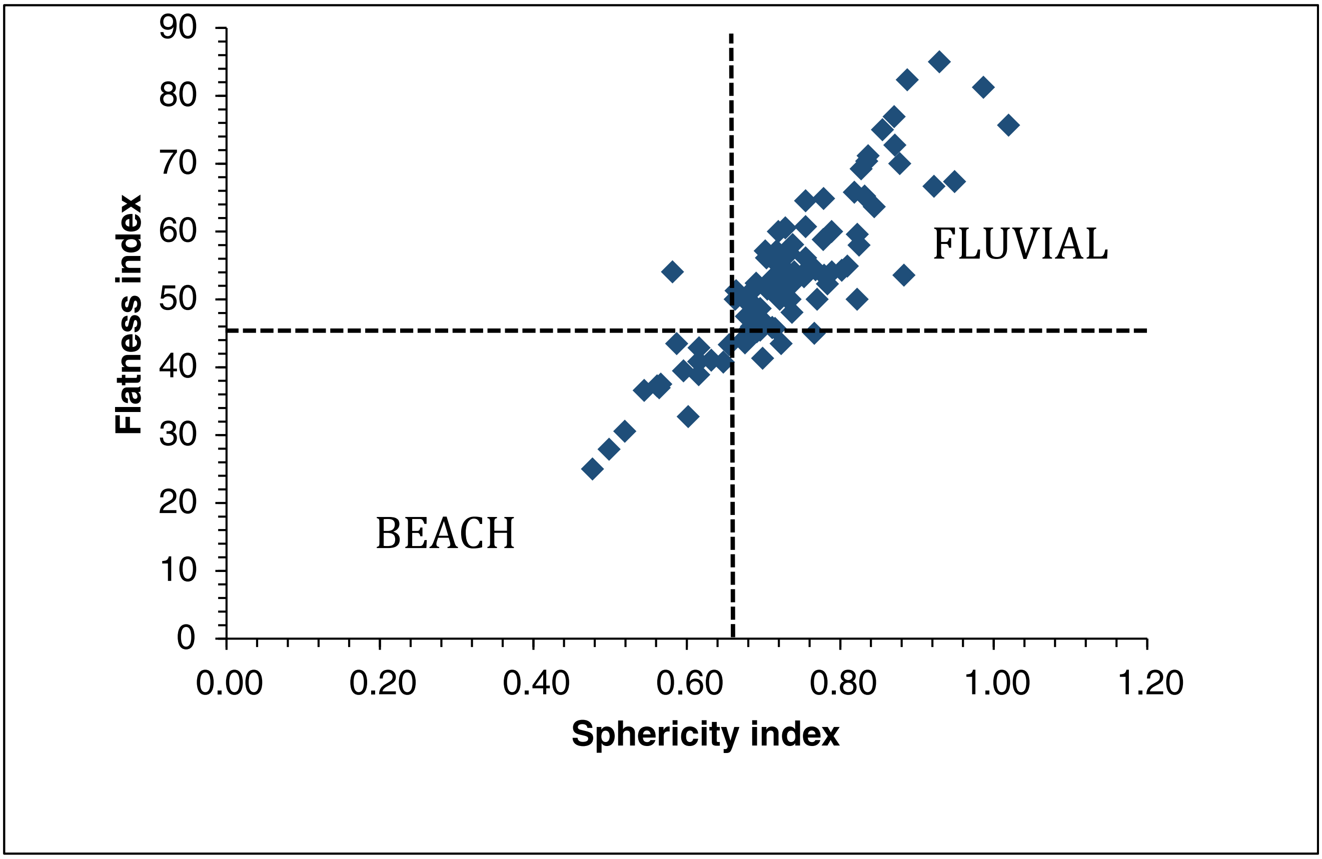

Fig. 8 A bivariate plot of Sphericity Index versus Oblate-Prolate index that shows most of pebbles of the Katberg Formation falls within a fluvial environment

beach pebbles is less significant, the use of morphometric analysis in this study, besides other studies that would use geochemistry and tectonic provenance, confirms that the fluvial palaeo-environmental processes prevailed during deposition of sediments of the Katberg Formation.

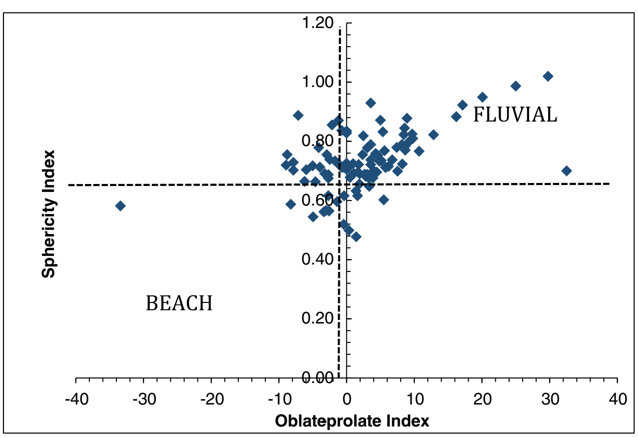

Fig. 9 A bivariate plot of Flatness Index versus Sphericity Index that shows most of pebbles of the Katberg Formation falls within a fluvial environment

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