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Textural characteristics, mode of transportation and depositional environment of the Stormberg Group in the Eastern Cape, South Africa: evidence from grain size and lithofacies analyses

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Abstract

The Stormberg Group comprises the Molteno, Elliot and Clarens formations and is one of four stratigraphical groups that make up the Karoo Supergroup in South Africa. The group is the highest unit in the Karoo Basin, representing the final phase of preserved sedimentation. The major problem with the Stromberg Group is that the mode of transport, hydrodynamic energy conditions and depositional environment are still poorly understood. For the present paper, grain size and lithofacies studies on selected sandstones from the Molteno, Elliot and Clarens formations were performed so as to elucidate their textural characteristics, depositional processes, sedimentation mechanisms and hydrodynamic energy conditions and to discriminate different depositional environments. The statistical parameters of grain size distribution (mean grain size, standard deviation, skewness and kurtosis) show that the sandstones are predominantly unimodal, fine grained, moderately well sorted, mesokurtic and near symmetrical. The bivariate diagrams of the aforementioned statistical parameters demonstrate that river and aeolian dune had the greatest impact on the depositional environments. Likewise, the C-M pattern (Passega diagram) shows that the sandstones were mostly deposited through tractive current process. Furthermore, the C-M diagram reveals the prevalence of rolling, suspension and graded suspension modes of sediment transportation. Seventeen sedimentary lithofacies were identified and grouped into seven lithofacies associations. These lithofacies associations indicate braided channel, overbank and swamp deposits for the Molteno Formation, alluvial fan/floodplain and playa deposits for the Elliot Formation and aeolian deposits for the Clarens Formation.

Keywords: Grain size distribution, textural parameters, lithofacies classification, hydrodynamic energy conditions, Triassic, Jurassic

1. Introduction

Grain size distribution is one of the most important properties of sediment particles because the sizes of grains in a specific deposit reveal hydrodynamic energy as well as the transportation and depositional processes. Grain size analysis is a method of determining the variations in grain sizes of a lithified rock or loose deposit sample. In view of differences in erosional processes, transportation and deposition histories, sediments are laid down in different environments and thus have varying particle sizes.

As a result, grain size analysis is an important tool for environmental reconstruction because it can reflect changes in water energy and depth in depositional environments (Amaral & Pryor, 1977).

Folk (1974) and Folk & Ward (1957) depicted some of the statistical parameters used to explain particle size distributions. Mean grain size, sorting, skewness and kurtosis are examples of statistical parameters. These parameters can be presented in the form of histograms, cumulative frequency curves and bivariate scatter plots. Many researchers (Moiola & Weiser, 1968; Passega, 1972; Friedman, 1979; Duck, 1994) have used bivariate scatter plots to demarcate areas where deposits from specific environments can be plotted. The mean grain size, sorting and skewness of sediments are determined by their grain size distribution, erosion processes and transportation history (Folk, 1966). According to Reid & Dunne (1996), fluctuations in the flow regime affect sediment supply and transport, whereas sediment mobilisation alters channel morphology. The sedimentation process in the fluvial system must be evaluated in order to determine the type of channel system.

Similarly, sedimentary facies is defined as any restricted part of a designated stratigraphical unit that exhibits characteristics that differ significantly from those of the unit's other parts (Baiyegunhi & Liu, 2021). Middleton (1978) emphasised that the most important factor in facies analysis was to combine observations made on their spatial relations and internal characteristics such as sedimentary structures with comparative information from other well-studied stratigraphical units. Reading (1996) and Miall (1996) noted that, in order to estimate/interpret depositional environments accurately, it is necessary to determine the relationship of facies to one another as well as to identify the facies that tend to occur together rather than to analyse individual or isolated facies. The term 'facies association' refers to a group of facies that occur together and are thought to be genetically or environmentally related (Reading, 1996; Boggs, 2006).

The Stormberg Group is an informal stratigraphical division name that refers to three formations: the Molteno, Elliot and Clarens formations (Fig. 1). The group is thought to range in age from the Early Triassic (Olenekian) to the Early Jurassic (Pliensbachian). These estimates are based on geological dating methods such as stratigraphical position, lithostratigraphical and biostratigraphical correlations and palynological analyses (Christie, 1981; Johnson, 1991; Hancox, 2000). The lithostratigraphy of the Stormberg Group can be clearly identified in most parts of the Central-South African Karoo basins (Johnson et al., 2006). This group was deposited during the Cape Fold Belt's final unloading phase (Smith et al., 1993). The Molteno, Elliot and Clarens units have the greatest thicknesses in the main Karoo Basin, the Mid-Zambezi and the Cabora Bassa (Johnson et al., 1996). At the base of the succession is the Molteno Formation, which comprises a northward-thinning wedge of clastic sedimentary rocks (Turner, 1975). Geographically, this formation covers an area of approximately 25,000 km^2 and forms an oval-shaped basin that extends from the Northern-Eastern Cape Province into Lesotho, KwaZulu Natal and the Free State (Turner, 1983).

Much research has been focused on the Dwyka, Ecca and Beaufort groups of the Karoo Supergroup, and relatively few previous studies have been carried out on the Stormberg Group. Recent basinal investigations have shown differences in the stratigraphical sequence, palaeocurrent direction, sedimentary structures, petrographical composition, depositional setting during basin formation and developmental processes (Catuneanu et al., 1998). In the Eastern Cape Province, the Upper Triassic/Lower Jurassic succession from the Molteno to Elliot up to the Clarens formations reveals a gradual aridification trend from braided rivers to semi-arid fluvial/playa conditions to aeolian dune conditions (Johnson, 1976). The Eastern Cape holds the thickest and most complete succession of the Stormberg Group rocks of the Karoo Basin. The sedimentary succession of the Stormberg Group in the Eastern Cape consists mostly of sandstones, shales and mudstones, with subordinate siltstones. There are still not many sedimentological details recorded for lithofacies characteristics and grain size parameters of the Stormberg Group. In order to fill the gap, grain size statistical and lithofacies analyses of the Stormberg Group were performed and interpreted in order to unravel the depositional environment of this group. The present study provides the first comprehensive grain size analysis of sandstones from the Stormberg Group. The calculated statistical parameters and Passega C-M diagram are used to highlight aspects of the transportation and depositional conditions that the sediments underwent, as well as relate them to particular depositional environments.

2. General geology and stratigraphy of the Karoo Supergroup

The Main Karoo Basin is a large sedimentary depository in South Africa located north of the Cape

Fold Belt (Catuneanu et al., 1998). The basin formed within the "continental interior of southwest Gondwana" and covers up to 700,000 km^2 (Catuneanu et al., 2005), but it was broader or wider during the Permian, representing approximately 117 myr of sedimentation spanning from about 300 Ma to 183 Ma (Johnson et al., 1996). The Karoo Basin encompasses the Gondwana succession of glacial, marine, deltaic, fluvial and aeolian sedimentary units capped by Jurassic basalts and covers nearly half of South Africa's surface area (Cole, 1992). According to Rubidge (1995) and Catuneanu et al. (1998), the Karoo strata accumulated within an intra-cratonic, retro-arc foreland basin, and a variety of processes influenced the depositional settings via different climatic regimes. All of the tectonic activity occurred as a result of the subduction of the Palaeo-Pacific plate beneath the Gondwanan plate, which caused basinal subsidence and facilitated the formation of the adjacent Cape Fold Belt, which served as the provenance area for basin sediments (Smith et al., 1993). During the Carboniferous–Middle Permian, the glaciers that covered the Karoo Basin began to recede, resulting in high sedimentation that filled the basin in a deep-water environment (Catuneanu et al., 1998). As the glaciation process came to an end, the climate gradually warmed, the basin began to shallow, and sedimentation continued as fluvial-lacustrine and then aeolian deposits (Catuneanu et al., 1998).

In increasing order of age, the Karoo Supergroup is divided into five lithostratigraphical groups, namely the Drakensberg, Stormberg, Beaufort, Ecca and Dwyka. The first unit of the Dwyka Group was laid down as the supercontinent drifted over the South Pole. This group is the result of glaciation and consists mainly of tillites and associated clastic sedimentary rocks (Johnson, 1991). The Ecca Group formed between the Upper Carboniferous Dwyka Group and the Upper Permian–Middle Tri-

Table 1. Stratigraphical subdivisions of the Karoo Supergroup in the Eastern Cape (after Johnson et al., 2006).

Period	Supergroup	Group	Formation	Lithology	Maximum thickness (m)
Jurassic	Karoo	Drakensberg		Basalts, pyroclastics	1400
		Stormberg	**Clarens**	**Sandstones**	**300**
Triassic			**Elliot**	**Red mudstones, siltstones, sandstones**	**500**
			Molteno	**Coarse sandstones, grey-khaki shales, coal seams**	**450**
		Beaufort	Burgersdorp	Red mudstones, light-grey sandstones, grey shales	1000
Permian			Katberg	Light-grey sandstones, red mudstones, grey shales	900
			Balfour	Red mudstones, light-grey sandstones	50
				Sandstones, siltstones	700
				Light-grey sandstones, khaki shales	100
				Grey shales, sandstones, siltstones	1200
				Light-grey sandstones	100
			Middleton	Grey & black shales, light-grey sandstones, red mudstones	1500
			Koonap	Grey sandstones, shales	1300
		Ecca	Waterford	Sandstones, shales	800
			Ford Brown	Shales, sandstones	1500
			Ripon	Sandstones, shales	1000
			Collingham	Grey shales, yellow claystones	50
			Whitehill	Black shales, cherts	70
			Prince Albert	Khaki shales	120
Late Carboniferous - Early Permian		Dwyka	Mbizane & Elandsvlei	Diamictites, tillites, shales	750

assic Beaufort Group (Catuneanu et al., 2005). Mudstones, siltstones, sandstones, minor conglomerates and coal make up the Ecca Group. The Upper Permian–Middle Triassic Beaufort Group is composed of fluvio-lacustrine rocks (Johnson et al., 2006), mostly sandstones with minor mudrock intercalations (Katemaunzanga & Gunter, 2009).

The Stormberg Group is an informal stratigraphical division name that refers to three formations: the Molteno, Elliot and Clarens Formations (Table 1). These formations have been thought to represent a transition from humid to arid climates, as well as from fluvial to aeolian deposits (Catuneanu et al., 1998). This group was deposited during the Cape Fold Belt's final unloading phase (Smith et al., 1993). The variation of lithological features has resulted from changes in aridification trends within the Karoo Basin. The Upper Triassic Molteno Formation overlying the Beaufort Group was laid down in broad perennial braided river systems under warm to humid conditions (Hancox, 2000; Bordy et al., 2005), resulting in the formation of conglomerate, sandstone, shale and mudstone, as well as coal seams (Johnson, 1976). The Elliot Formation that followed is a typical red bed that was deposited via floodplain-playa sedimentation. The semi-arid climate and high salinity resulted in the formation of red-brownish mudstone and sandstone (Johnson et al., 1996). Bordy et al. (2005) reported that the argillaceous Elliot Formation had formed under semi-arid conditions by high and low sinuosity fluvial systems. The Clarens Formation's aeolian dune complexes were deposited as a result of progressive aridification (Smith et al., 1993; Johnson et al., 2006).

According to Smith et al. (1993), the end of Karoo sedimentation was caused by the continental flood basalts of the Drakensberg Group, which marked the beginning of Gondwana breakup. The upliftment of the Cape Fold Belt was a major event sedimentary environmental history in the Karoo Basin, as it became the provenance area of the Molteno, Elliot and Clarens formations (Bordy et al., 2004a). The South African Committee for Stratigraphy (SACS, 1980) stated that there are no unifying lithological features in the various units of the Stormberg Group that distinguish them from the other geological groups of the Karoo Basin. The Committee also proposed abandoning the use of the term 'Stormberg' as a group title to describe formally the lithostratigraphy of the Molteno, Elliot and Clarens formations (Kent & Hugo, 1978).

3. Material and methods

A field investigation was conducted to exposures of the Stormberg Group in the Eastern Cape. A few outcrops were selected for the present study (Fig. 1), covering the areas of Indwe, Elliot, Rossouw, Dordrecht and Barkly East. Greater parts of the Molteno Formation are exposed in areas around Indwe, where coal is mined in the Eastern Cape Province. Much of the Clarens Formation sandstones and aeolian sand dunes are exposed in the Barkly East area. Fifteen representative different sandstones types were collected during fieldwork and at least three thin sections were prepared per sample. The selected sandstones (four from the Molteno Formation, six from the Elliot Formation, and five from the Clarens Formation) were labelled with the prefixes M, E and C to represent the Molteno, Elliot and Clarens Formations, respectively. At least two samples were collected from each formation at different locations (Fig. 1), and at least one sample was selected and thin sections were prepared in each of these areas. The thin sections of various sandstone types were chosen based on differences or variations in grain size distribution and textural characteristics. For instance, at least one thin section was chosen to represent a specific facies, and the sample size was large enough to represent both the finest and coarsest component under consideration adequately. The representative samples share many of the same properties as the targeted formation, so data generated from the sample will represent more than just the sample from which it was obtained, namely the entire formation in the study area.

The lithofacies analysis is based on integration of sedimentological data such as lithology, colour, grain size, mineral compositions, bedding characteristics and sedimentary structures. A modified version of Miall's (1977, 1985, 1996) lithofacies classification and coding was used for the facies analysis. The identified lithofacies types were classified into facies associations (FAs), which were then used to interpret or deduce possible depositional palaeoenvironments. For the grain size analysis, 45 representative thin sections of different sandstone types from the Molteno, Elliot and Clarens Formations were selected systematically to cover textural variations (i.e., grain size, shape and arrangement). The grain size, textural parameters and statistical relationships of the selected sandstones were investigated. The grain sizes were measured on thin sections using a petrographical microscope with a calibrated eyepiece. A minimum of 400 grains were measured per thin section using the traditional method of measuring the

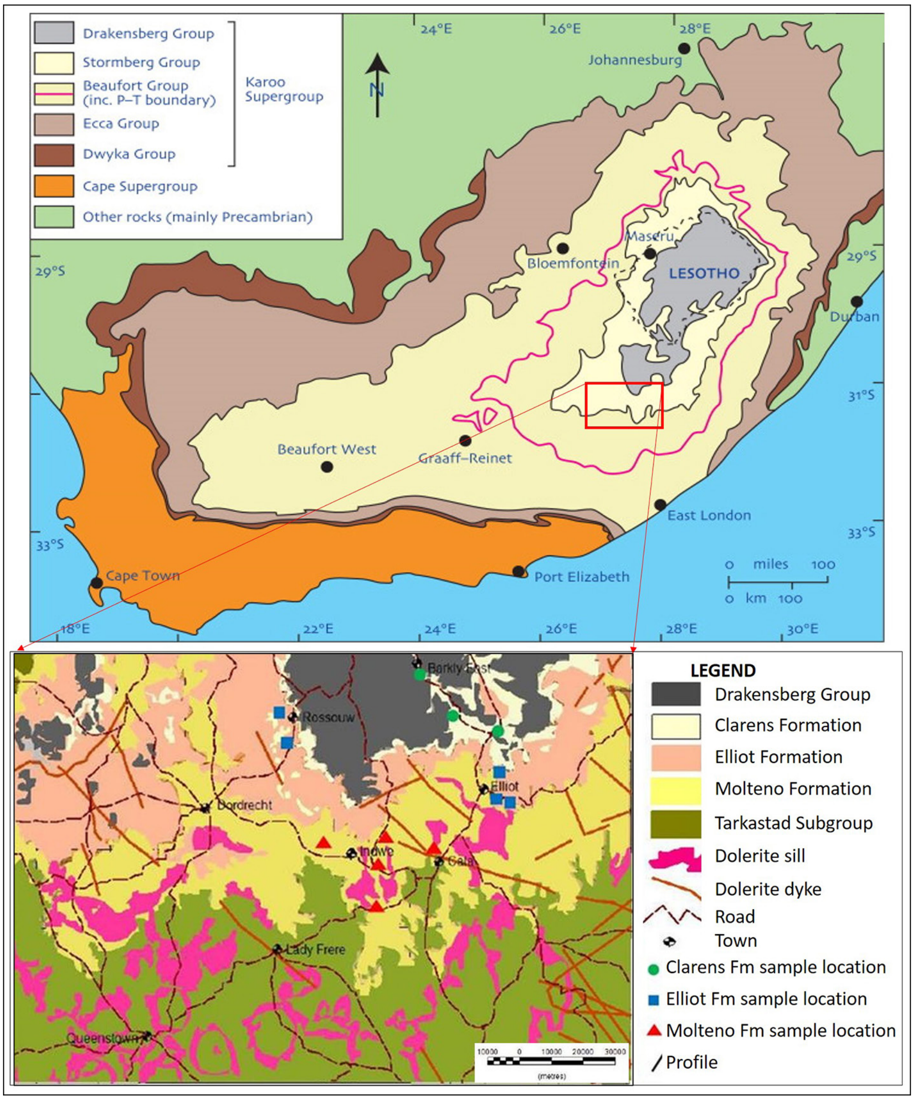

Fig. 1. Geological map showing the study area and areal distributions of lithostratigraphical units in the Main Karoo Basin (after Johnson et al., 1996; Catuneanu et al., 1998).

longest axis of the grain. The grain size dimensions were then converted to normal sieve grain sizes as proposed by Friedman (1958, 1961). Folk & Ward (1957) calculation equations were used to calculate the statistical parameters of grain size distribution. Because grains in sedimentary rocks have a wide range of size distributions, the frequencies of grain size ranges were calculated, and the Udden-Wentworth grade scale was used to determine grain size classes (Wentworth, 1929).

Certain standard statistical measures are usually described for grain size distribution in clastic sedimentary rocks, and these can be subdivided into four main parameters, including the graphic mean, graphic standard deviation, graphic skewness and graphic kurtosis. Detailed information on or definitions of the aforementioned statistical parameters are documented in Boggs (2006). These statistical parameters were calculated using the equations published by Folk & Ward (1957). Following that, different bivariate scatter plots of the statistical parameters were plotted and used to differentiate between depositional settings. Furthermore, Passega's (1964) modified C-M pattern was used to deduce modes of transportation and depositional processes.

4. Results and interpretation

4.1. Stratigraphy

The Molteno Formation consists mainly of coarse feldspathic sandstones, greyish mudstones and greyish-black shales. The sandstone beds range between 0.5 and 8 m in thickness and are mostly khaki in colour. The sandstone beds have erosional bases, thus marking the beginning of each vertical cyclothem. The sandstones were observed to be mostly massive, although some trough cross-bedded sandstones were noted. The measured successions indicate multiple fining-upward cycles.

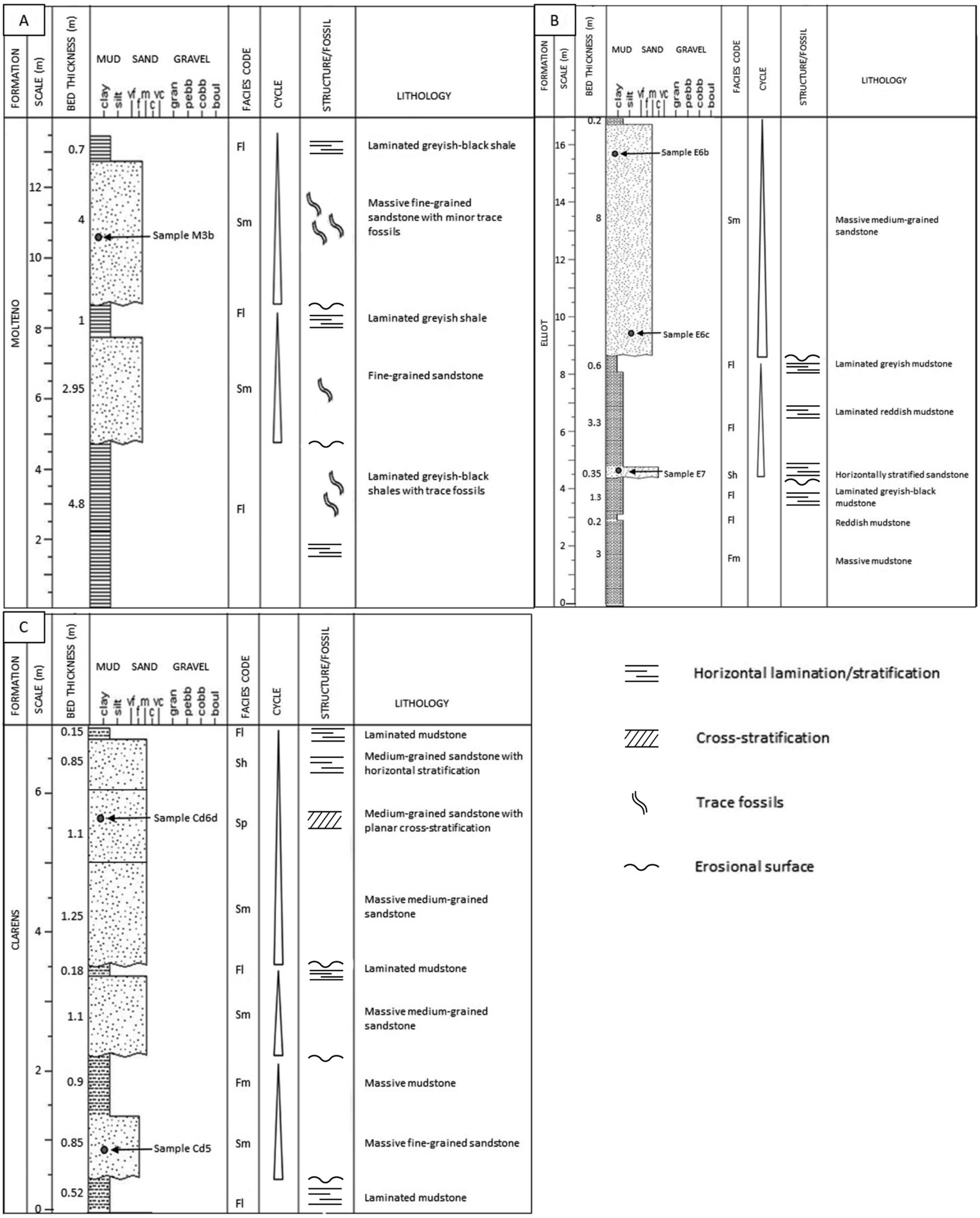

Fig. 2. Examples of logs from the Molteno, Elliot and Clarens formations in the study area.

The Elliot Formation unconformably overlies the Molteno Formation and reaches a thickness of about 480 m. It is composed mostly of fine- to medium-grained khaki-greyish sandstones and, at some locations, reddish sandstones, massive reddish mudstones and laminated greyish shale. The sandstones are often normally graded and calcareous. Calcareous nodules and thin calcareous beds often occur within the mudstones and sandstones. The sandstones often display cross-stratification, ripple cross-lamination and scour-and-fill structures with lag at their bases. Weakly developed mudcracks were observed on the sandstone beds, and the mudstone beds also contained some mudclasts. Alternation of mudstones and fine-grained sandstones has been found locally. In comparison to the sandstones, the mudstone beds are much thicker, up to 1.65 m. Fining-upward megacycles (averaging thickness: 8.5 m) were observed at all outcrops. Thirteen fining-upward megacycles of alternating sandstone and mudstone beds were observed near Elliot Town with an estimated total thickness of over 100 m.

The Clarens Formation is the youngest formation of the Stormberg Group and is characterised by massive planar-bedded sandstones and fossil sand dunes deposited as aeolian and ephemeral playa-lake sediments. This formation is mostly dominated by sandstones, which are wind-blown sand dunes of coastal and desert environments. Dunes have heaped-up crests with their pinnacles parallel to the wind direction (longitudinal dunes) or perpendicular ones (transverse dunes). Because of their wind-blown nature, these aeolian sandstones are extremely well sorted. Most of the sandstones observed in the study area are fine-to medium-grained and well sorted. Greyish mudstones and matrix-supported conglomerates are also observed within the formation. Characteristic logs for the Molteno, Elliot and Clarens formations are presented in Figure 2.

4.2. Lithofacies

Ten different types of lithofacies were observed in outcrops of the Molteno, Elliot and Clarens formations; lithofacies identified are presented in Table 2.

4.2.1. Matrix-supported conglomerate lithofacies (Gm)

The matrix-supported conglomerate facies (Gm) occurs in the Molteno and Clarens formations. The conglomerate beds are characterised by poor sorting and polymictic pebble compositions such as quartzite, sandstone, mudstone and rock fragments. The matrix is composed of clay, silt and fine sand material and takes more than 50% of the rock volume (Fig. 3A). The conglomerates are light greyish-brown in colour, as they are mostly dominated by clay. The bed thickness varies from 0.5 to 1.5 m and is mostly massive. The pebbles range up to 60 mm in diameter. The roundness is variable, from sub-rounded to sub-angular in shape. Most often the tops of beds are erosive. This conglomerate lithofacies is mostly dominant in the basal parts of the Molteno Formation. The matrix-supported conglomerate facies is generally intercalated with coarse-grained sandstone.

Table 2. Facies classification and coding (modified after Miall, 1996).

Lithofacies	Lithofacies code
Matrix-supported conglomerate	Gm
Massive sandstone	Sm
Trough cross-stratified sandstone	St
Planar cross-stratified sandstone	Sp
Low-angle cross-stratified sandstone	Sl
Ripple cross-laminated sandstone	Sr
Horizontally laminated sandstone	Sh
Massive mudstone	Fm
Laminated shale	Fl
Organic-rich mudstone and shale	FC

4.2.2. Massive sandstone lithofacies (Sm)

The massive-bedded sandstone facies is present in all formations and is composed of well-sorted, fine- to medium-sized grains but with no visible structures within the beds (Figs 3B, 4F, I). The thickness of the sandstone beds varies between approximately 1 and 6 m, averaging about 3 m in a unit. Occasionally, these sandstone beds have only a few faint structures, and microlaminations can be observed. Hence, the massive sandstone facies can be described as homogeneously massive bedded.

4.2.3. Low-angle cross-stratified sandstone lithofacies (Sl)

The low-angle cross-stratified sandstone lithofacies is very common within the Molteno and Elliot formations (Figs 3C, 4C). This lithofacies is represented by medium- to coarse-grained pale greyish sandstones. The beds are characterised by elongate sandstone bodies interbedded with mudstone beds as well. The bed thickness ranges from 8 to 64 cm, and the whole rock package can be up to 40 m. The width of the lenticular bed may reach 35 m. The base of a bed is usually erosional.

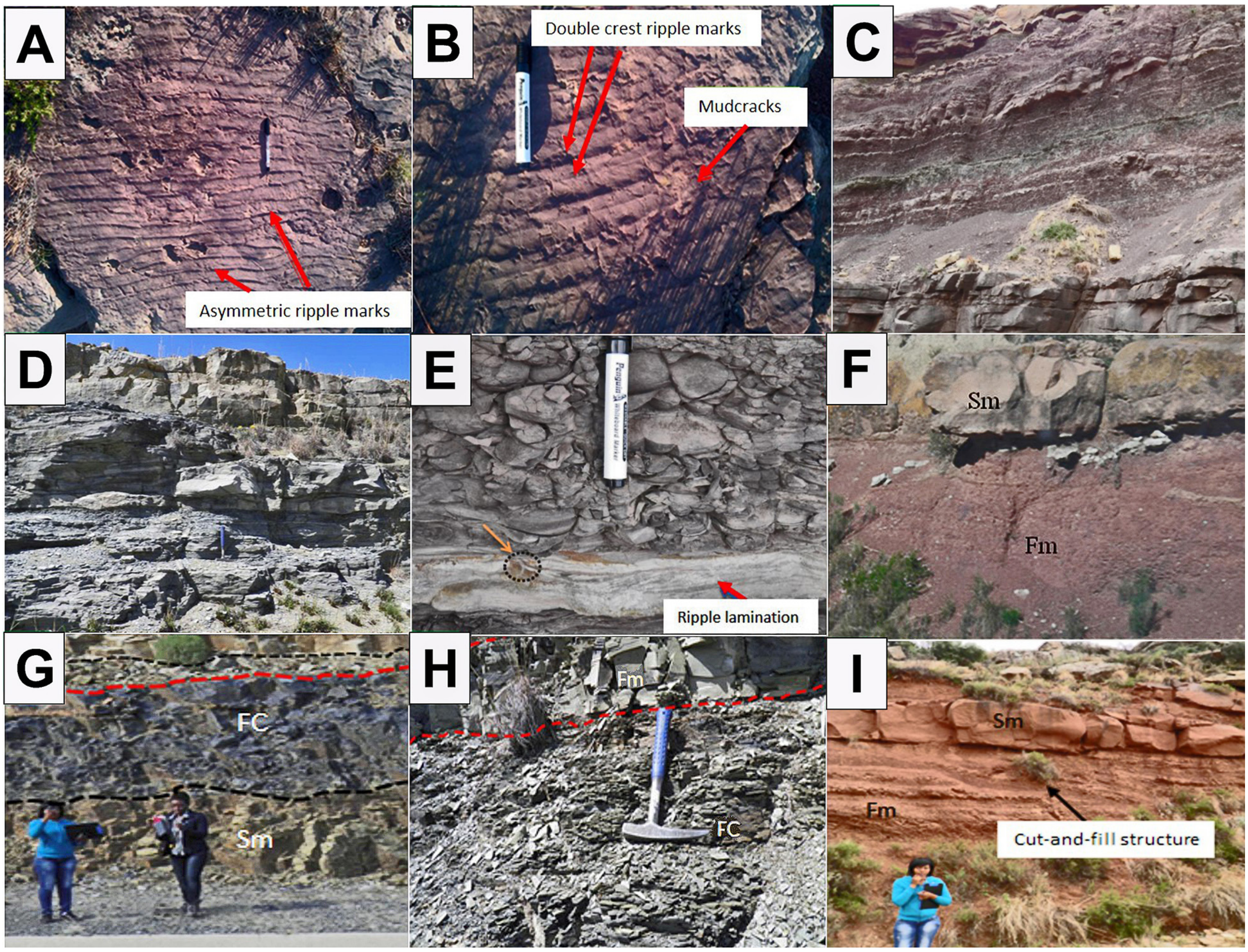

Fig. 3. Photographs of lithofacies. **A –** Conglomerate with very small, sub-angular to sub-rounded pebbles within a fine-grained matrix (Clarens Formation); **B –** Massive and horizontally stratified sandstone alternating with laminated shale (Elliot Formation); **C –** Massive and laminated mudstone alternating with low-angle, cross-stratified sandstone (Elliot Formation); **D –** Planar cross-stratified sandstone alternating with mudstone (Elliot Formation); **E –** Trough cross-stratified sandstone (Molteno Formation); **F –** Large-scale planar cross-stratified sandstone (Clarens Formation); **G –** More than 5-m-thick sandstone of Caved Rock (Clarens Formation) – the fossil aeolian dune; **H –** Horizontally laminated sandstone (Molteno Formation).

4.2.4. Planar cross-stratified sandstone lithofacies (Sp)

The planar cross-stratified sandstone has been observed only in the Clarens Formation (Fig. 3D). The large-scale planar cross-stratified sandstones are typical cover rocks of the Clarens Formation in areas around Barkly East. The planar cross-stratified sets range in thickness from 0.5 to 2 m. Although solitary sets do occur, the cosets Sp are the most common. Sets are usually tabular or wedge shaped, with their bases being slightly erosive with low relief or non-erosive. Grain size and sorting characteristics are generally similar to those of the trough cross-bedded sandstone facies (St). In some areas, the bed sets are bound by erosional surfaces at their bases. Likewise, the cross-stratification is tangential with the bed bases at an angle of less than 20°. These beds have reactivation surfaces.

4.2.5. Trough cross-stratified sandstone lithofacies (St)

The trough cross-stratified sandstone facies (St) is composed of trough-shaped (occasionally wedge-shaped) sets that range up to thickness of 2 m. It has been observed that generally, the trough set thickness tends to increase with grain size. Trough cross-stratification in the Molteno Formation is mostly present within the medium- to coarse-grained sandstones. However, large-scale trough cross-stratified sandstone has been observed in the Elliot Formation and bed thicknesses vary between 2 and 5 m.

4.2.6. Horizontally stratified sandstone lithofacies (Sh)

The horizontally stratified sandstone facies is present in both the Molteno and Clarens formations (Fig. 3B). The sandstone beds reach up to 2 m in thickness and their colours alternate between brown and khaki. These sandstones are medium- to coarse-grained.

4.2.7. Ripple cross-laminated sandstone lithofacies (Sr)

The ripple cross-laminated sandstone facies (Sr) is not common within outcrops in the study area and occurs only locally within the Molteno Formation. This lithofacies appears in medium- to coarse-grained sandstones. Ripples in the sandstone facies occur as asymmetrical ripples (Fig. 4E). Some mud

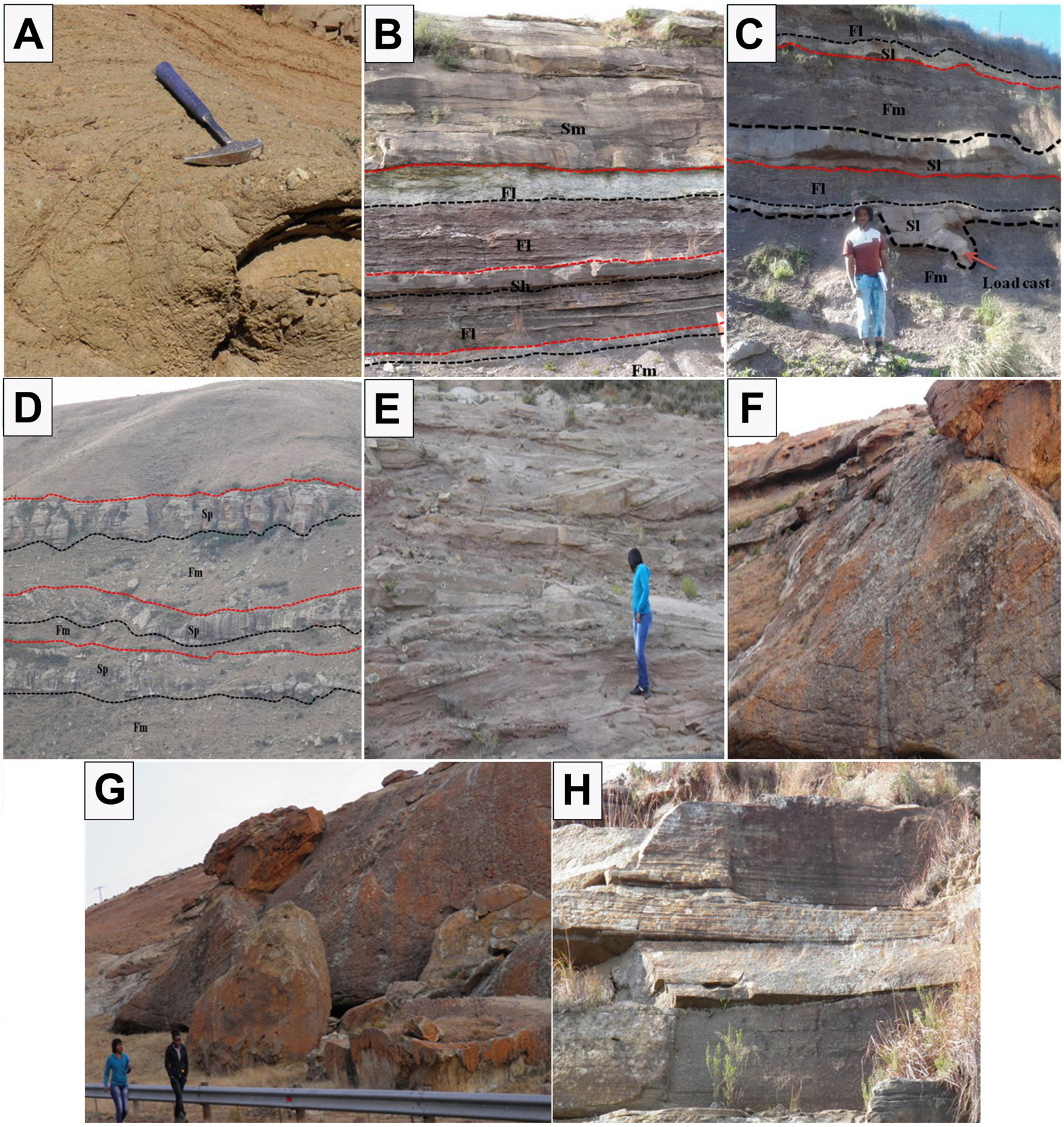

Fig. 4. Photographs of lithofacies. **A, B –** Ripple-laminated sandstone (Molteno Formation); **C –** Low-angle cross-stratified sandstone interbedded with reddish mudstone (Elliot Formation); **D –** Organic-rich shale with massive sandstone intercalation (Molteno Formation); **E –** Greyish laminated mudstone with ripple lamination (blue arrow) and deformed bedding (orange arrow) in siltstone (Elliot Formation); **F –**Massive sandstone and mudstone intercalation (Clarens Formation); **G, H –** Organic-rich mudstone and shale (Molteno Formation); **I –** Massive sandstone and mudstone (Clarens Formation).

cracks that are poorly developed can also be observed together with the ripple marks. The ripples tend to form at an angle with each other, and when they are well developed, the angle between them will be approximately 90°.

4.2.8. Mudstone lithofacies (Fm)

The mudstone lithofacies is observed in all formations (Figs 3D, 4F, I), being greyish-reddish in colour and often interbedded with some sandstone layers. The reddish mudstones are the most dominant within the Elliot Formation, and it is from these facies that the former name "Red Beds" was derived. Most often these mudstones are massive. The red mudstone beds are very thick, ranging to up to 2 m. Load cast structures occurred at the bases of the beds, where gravity caused the denser sandstone to sink down into the less dense mudstone, forming bulging structures. The less competent mudstone deformed upwards and occupied the spaces created by the sinking sandstone.

4.2.9. Laminated shale lithofacies (Fl)

The laminated shale facies is present in all formations and is dark grey to blackish in colour and displays parting (Figs 3B, C, 4D). The shale beds reach an approximate thickness range of 0.7–5.0 m. The shale facies commonly occurs between sandstone beds.

4.2.10. Organic-rich mudstone and shale lithofacies (FC)

The organic-rich mudstone facies are fissile and contain traces of coal lenses from the lithification of organic material (Fig. 4G, H). The organic-rich mudstone bed is covered by a trough cross-stratified, coarse-grained arkosic sandstone bed.

4.3. Grain size statistics

The four statistical parameters used to depict the textural characteristics of strata of the Molteno, Elliot and Clarens formations are the median, mean (Mz), standard deviations (σ_I), skewness (Sk_I) and

Table 3. Grain size statistical parameters of samples from Molteno, Elliot and Clarens formations.

Formation	Sample no	Median (phi)	Mode (phi)	Mean (phi)	Sorting (phi)	Skewness	Kurtosis	Interpretation
Clarens	C9	2.30	2.50	2.28	0.48	−0.15	1.01	Fine-grained, well-sorted, coarse-skewed, mesokurtic
	C11	2.25	2.50	2.28	0.49	0.11	1.01	Fine-grained, well-sorted, fine-skewed, mesokurtic
	C18	1.45	1.50	1.47	0.35	0.20	0.93	Medium-grained, well-sorted, fine-skewed, mesokurtic
	Cd5	2.20	2.50	2.20	0.43	0.06	0.92	Fine-grained, well-sorted, nearly symmetrical, mesokurtic
	Cd6b	2.40	3.00	2.32	0.50	−0.28	0.87	Fine-grained, well-sorted, coarse-skewed, platykurtic
Elliot	E6a	2.35	2.50	2.37	0.55	0.04	0.96	Fine-grained, moderately well-sorted, nearly symmetrical, mesokurtic
	E6c	1.50	1.50	1.60	0.58	0.22	0.84	Medium-grained, moderately well-sorted, fine-skewed, platykurtic
	E6d	1.35	1.50	1.33	0.45	−0.03	0.82	Medium-grained, well-sorted, nearly symmetrical, platykurtic
	E7	2.45	2.50	2.48	0.45	0.09	1.02	Fine-grained, well-sorted, nearly symmetrical, mesokurtic
	E17b	2.35	3.00	2.33	0.44	−0.04	1.23	Fine-grained, well-sorted, nearly symmetrical, leptokurtic
	E17c	1.80	2.00	1.78	0.45	−0.06	0.82	Medium-grained, well-sorted, nearly symmetrical, platykurtic
Molteno	M1	1.45	1.00	1.47	0.38	0.01	0.85	Medium-grained, well-sorted, nearly symmetrical, platykurtic
	M2c	2.30	2.50	2.30	0.48	0.02	1.06	Fine-grained, well-sorted, nearly symmetrical, mesokurtic
	M4	1.65	2.00	1.65	0.49	0.00	1.01	Medium-grained, well-sorted, symmetrical, mesokurtic
	Md1	0.75	1.00	0.80	0.51	0.15	0.90	Coarse-grained, moderately well-sorted, fine-skewed, mesokurtic

kurtosis (KG). The sandstone grain size parameters of mean, sorting, skewness and kurtosis for the Molteno Formation have an average of 1.56, 0.47, 0.05 and 0.09, respectively. Samples from the Elliot Formation have average mean, sorting, skewness and kurtosis value of 1.98, 0.49, 0.04 and 0.95, respectively, while those from the Clarens Formation have an average of 2.11, 0.45, –0.01 and 0.95, respectively. The frequency diagrams show that the majority of samples range between 0.5 to 4 phi classes

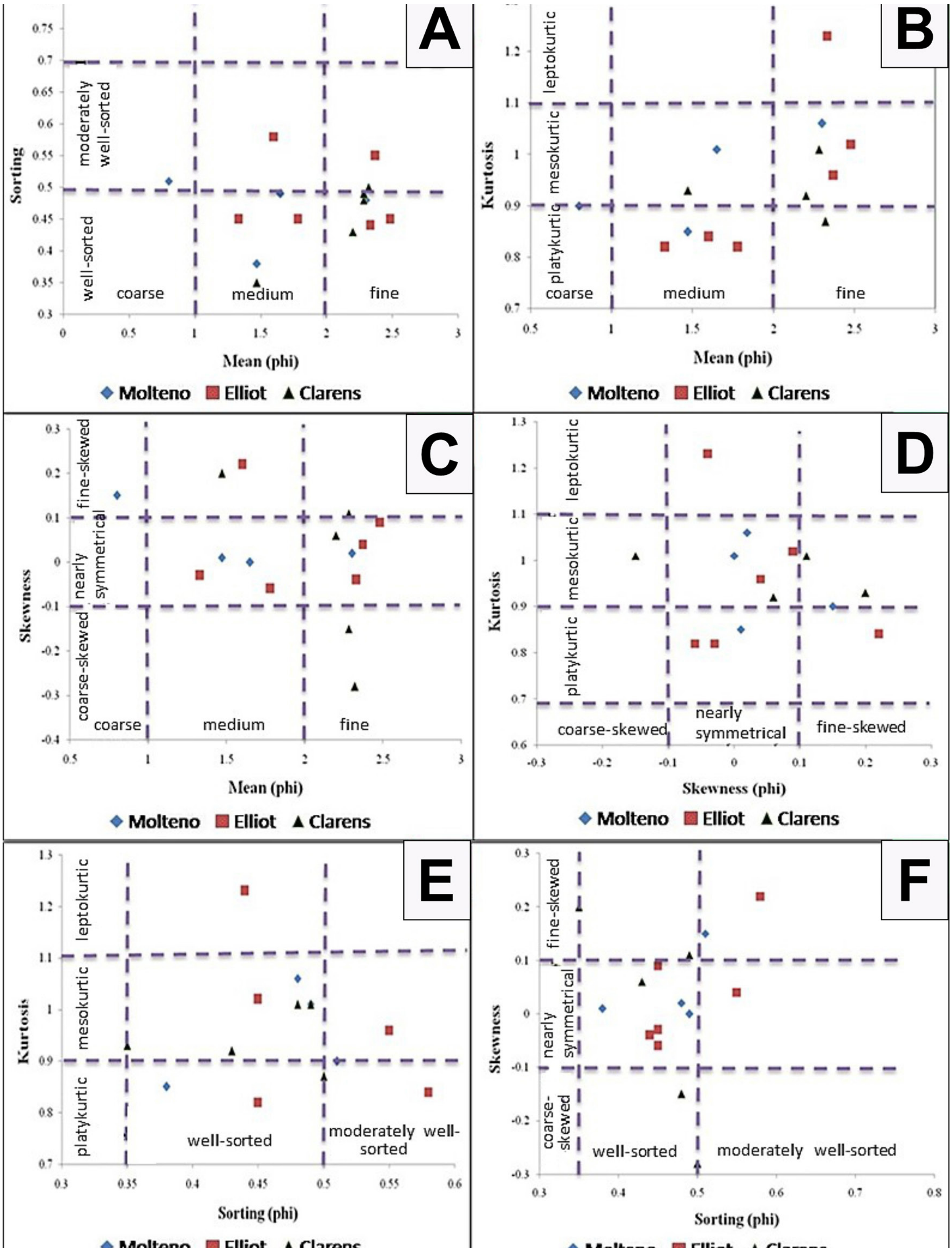

Fig. 5. Bivariate scatter plots showing relationships between grain size parameters (background diagram after Tanner, 1991).

on the Udden-Wentworth grade scale, indicating coarse- to fine-grained distribution. The result of the statistical/textural characteristics is presented in Table 3, and the bivariate diagram is shown in Figure 5.

4.4. Depositional processes and environments

4.4.1 Bivariate scatter plots

The bivariate scatter plots of the statistical parameters (i.e., mean, skewness and kurtosis) have been successfully used to decipher the depositional processes and settings (Stewart, 1958; Friedman, 1961, 1967; Moiola & Weiser, 1968). The bivariate plot of the mean *vs* skewness is best used to distinguish between river processes, dune processes and wave processes. Moiola &Weiser (1968) acknowledged that Friedman's (1961) discriminating boundary does manage to separate clearly between modern inland dunes and river sands. The bivariate plot of the mean *vs* skewness (Fig. 6) shows that the majority of the samples lie within the aeolian process, followed by the river process environment. Aeolian processes involve wind erosion, transportation and deposition of sediment. Particles are moved by the wind as a result of a combination of direct wind shear stress and atmospheric turbulence. Creep, saltation and suspension are the three most common modes of sediment transport by wind. The mode of transport depends primarily on the ratio between particle settling velocities (i.e., particle size and wind shear stress and turbulence intensity). Wind-transported particles can be weathered grains entrained from a rock's surface, but the majority of the particles come from loose materials. Aeolian processes create a number of distinct fea-

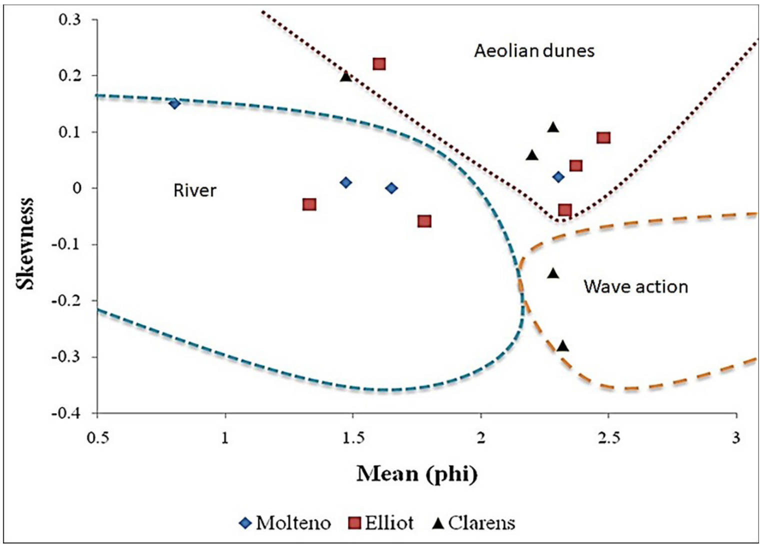

Fig. 6. Bivariate scatter plots of mean grain size *vs* skewness; boundaries after Stewart (1958), Friedman (1961) and Moiola & Weiser (1968).

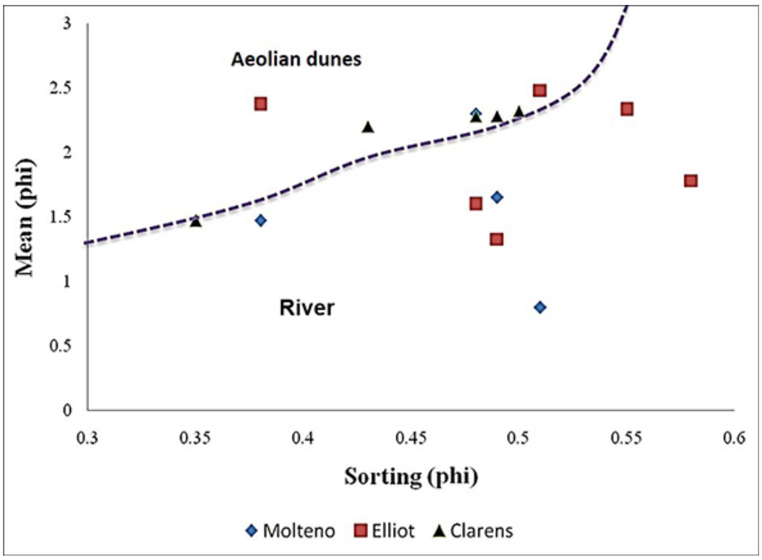

Fig. 7. Bivariate scatter plot of standard deviation *vs* mean grain size; boundary after Friedman (1961).

tures through both erosion and deposition of sediment (clay, silt and sand), such as sand dunes and loess deposits. They largely depend on other geological agents, such as rivers, glaciers and waves, to supply sediment for transport. The majority of the Elliot Formation samples and some from the Clarens Formation lie within the aeolian process, and these sandstones can be interpreted as aeolian dunes. Likewise, the bivariate plot of the standard deviation (sorting) *vs* mean shows that about 54% of the samples fall within the fluvial environment, with the remaining 46% within the aeolian one (Fig. 7). This phenomenon could be caused by the continuous transition of depositional environmental conditions (aridification process) that occurred during the deposition of the sediments of these three formations. The distinct red colour is due to the presence of haematite derived from the pre-existing soils that results in a reddish coating being formed around the sediment grains.

4.4.2. C-M pattern (Passega diagram)

C-M plots were introduced by Passega (1957) as a mechanism to evaluate the hydrodynamic forces at work during deposition of sediments. The plot shows the relationship between "C," which is the coarsest one percentile value of the grain size distribution in microns, and "M," which is the median value in microns on the log-probability scale. These parameters were selected because the coarse fraction of a sediment is more representative of the depositional agent than the fine fraction (Passega, 1964).

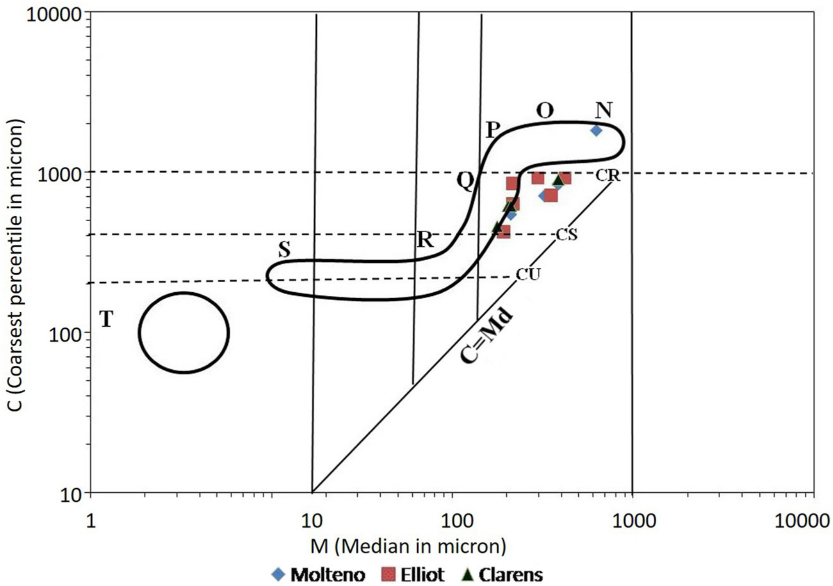

Fig. 8. C-M diagram of the sandstones from the Molteno, Elliot and Clarens formations (background field after Passega, 1964). T – pelagic suspension, S-R – uniform suspension, Q-R – gradual suspension, Q-P – suspension and rolling, P-O – rolling and suspension, O-N – rolling.CU – limit for the maximum grain size transported in uniform or homogeneous suspension, CS – the maximum grain size transported in graded suspension, CR – the minimum grain size transported by rolling (with some contribution of suspension).

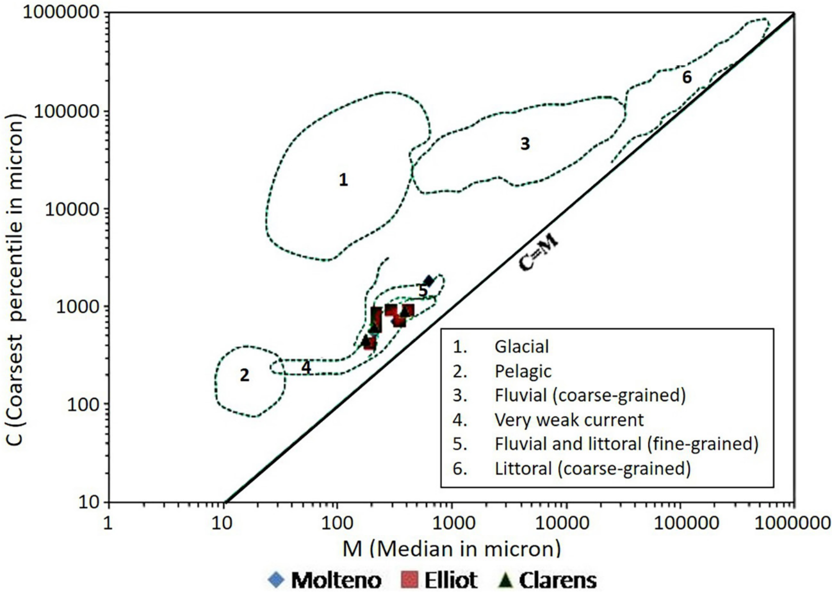

Fig. 9. C-M diagram showing palaeoenvironmental conditions for the sandstones from the Molteno, Elliot, and Clarens formations (background field after Passega, 1964).

The Passega diagram features several fields which are: pelagic suspension (T field), uniform suspension (SR field), gradual suspension (QR field), suspension and rolling (QP field), rolling and suspension (PO field) and rolling (ON field), corresponding to the various transport and sedimentation conditions in the marine, littoral or fluvial domains.

As observed in Figure 8, the majority of samples collected from the three formations are projected in the QR (gradual suspension), QP (suspension and rolling) and PO fields (rolling and suspension). The QP field characterises the main section of a river channel and it also falls within the CS field, which characterises the maximum diameter of grains transported in graded suspension. The samples projected in the PO field, which also represents the CR section, form the lower size limit of grains transported through rolling, and the QR field represents samples deposited by shallow, braided streams and sandbars adjacent to the main currents of larger stream channels. The increase in the C parameter indicates an increase in the energy levels of the depositional environment currents. Thus, from the plot, a sizeable number of samples from the Molteno and Elliot formations are representative of deposition in high-energy settings. Overall, the rolling and suspension of sediments were influenced by turbidity controls, which indicate that the river transportation process was intensive, especially in the main channels. In addition, the C-M plot (Fig. 9) indicates variations in energy conditions, possibly seasonal. From the plot, it can be observed that all the samples are projected between environments 4 and 5, which represent tractive current and beach, respectively. As a rule, the tractive currents transport the sediments by rolling and sliding both along the river bed and the beach. Of course, taking into account all other features of the rocks analysed, the beach environment must be excluded.

4.4.3. Lithofacies Associations (FAs)

Facies associations can be described as a group of facies that occur together and are considered to be genetically or environmentally related to each other. Based on the lithology, mineral composition, rock colour, sedimentary structures and vertical and lateral overlaid relationships of the different facies in the Molteno, Elliot and Clarens formations, seven facies associations and sedimentary environments can be deduced, as shown below.

Lithofacies Association FA1 (Gm + Sm + Sh + St + Sr) was observed in most parts of the Molteno Formation, consisting of the Gm, Sm, Sh, St and Sr lithofacies. The conglomerates are made up of sub-rounded quartzite and mudrock pebbles set in a clayey-silt matrix that is dominant in the bottom parts of the formation. The channel bars are composed of massive sandstones and conglomerates, horizontally stratified, trough cross-stratified and ripple cross-laminated sandstones. Individual beds range in thickness from 0.5 to 2 m and rock successions can reach up to 25 m, showing repeating upward-fining cycles. The massive lithofacies (Sm) was deposited rapidly within large river channels, whereas the rippled sandstone lithofacies formed when water depth and velocity decreased. The horizontally laminated lithofacies (Sh) were laid down as the sand was transported along the channel bottom or on top of the channel bars. The three distinctive bars are longitudinal, transverse and point bars. The trough cross-stratified lithofacies (St) resulted from the scouring of axial channel zones and/or bar tops during flood crest. Interbeds of mudstone lithofacies (Fm/Fl) record the abrupt flow cessation typical of an unstable fluvial regime. FA 1 represents braided river channel deposits.

Lithofacies Association FA 2 (Sr + Fl + Fm) is observed in the Molteno Formation and is composed of fine-grained facies Sr, Fl and Fm, representing low-energy currents. The laminated mudstones are dominated by facies that indicate deposition from suspension load along the overbank, and these mudstone beds tend to form on top of the channel sandstones during channel abandonment. The ripple cross-laminated sandstone lithofacies forms on the erosional surface as the waters shallow up. The FA 2 represents the overbank deposits of braided fluvial system.

Lithofacies Association FA 3 (Fl + Fm + FC) is characterised by organic-rich mudstones and shaly-coal facies (Fl, Fm, and FC). The organic-rich mudstone beds mostly overlie siltstone beds and are capped with sandstones. In the Molteno Formation, the shaly-coal beds progressively form thick coal seams of about 0.5 to 3 m. These facies suggest moderately drained back-swamps with vast vegetation that were periodically inundated by floodwaters. The overlying sandstones and siltstones formed within the crevasse splay during periodic flooding. FA 3 represents swamp, most likely in the distal alluvial fan.

Lithofacies Association FA 4 (Sr + Sm + St + Sl + Sh) is observed within the Elliot Formation. This lithofacies association is composed of fine- to medium-grained sandstones: Sr, Sm, St, Sl and Sh lithofacies. Accumulation of sediments is facilitated by confined flow due to the abundance of water. The migration of distal floodplain facies towards the edges of the basin was facilitated by progressively dry climate conditions. In the distal floodplain, low-energy waters formed during floods and led to suspension settling of the finest-grained sediments. The Sl lithofacies formed due to fluctuations in levels of energy. FA 4 are sand-bed braided channels and braidplain in more distal position to FA 1, perhaps in the middle zone of the alluvial fan.

Lithofacies Association FA 5 (Fl + Fm + Sm) is the most distinct one within the Elliot Formation. The majority of the sediments in this group are reddish in colour. This reddish colour is due to the emergence of a progressively dry climate, hence the predominance of iron oxides reacting with the sediments to give the red colour. Accumulation was due to increased aridity, which resulted in a change in patterns of alluvial sedimentation into ephemeral floodplain playas. These playa deposits are composed mostly of mudstones and fine- to medium-grained sandstones. Horizontal lamination (Fl) is most frequent, especially where the fine clastic sediments are interbedded with sandstone facies. These rock successions mostly show fining-upward trends, and the mudstone beds reaching up to 2 m tend to be much thicker than the sandstone beds due to prolonged suspension settling. The massive sandstone beds (Sm) probably developed in a river channel where sediments were deposited from the flows carrying a large volume of suspended material. These currents experienced a rapid decrease in velocity and the suspended sediments were suddenly laid down, resulting in the massive beds. The massive sandstone facies is believed to have developed in transitional fluvial-to-lacustrine subenvironment. FA 5 represents semi-arid lake/playa deposits.

Lithofacies Association FA 6 (St + Sm + Sp + Sh) covers most parts of the Clarens Formation, the youngest unit of the Stormberg Group. The FA 6 are mostly fine- to medium-grained sandstones with well-sorted grains, forming large-scale tabular cross-stratified lithofacies (St), massive sandstone lithofacies (Sm), as well as horizontally laminated facies (Sh). The large-scale trough cross-bedded sandstone lithofacies displays the characteristics of aeolian accumulation. Grain characteristics (i.e., sorting, frosting, well-rounded shapes) also reveal aeolian depositional processes. The horizontally laminated facies are mostly fine- to medium-grained with erosional bases, overlain by mudstone beds, whilst the large-scale tabular cross-stratified sandstones, which tend to reach heights of up to 6 m, tend to have irregular surfaces. The folded sandstone bodies are derived from the overload of the water-saturated sand, such as in the interdune areas (Bordy & Catuneanu, 2002). FA 6 represents aeolian dune deposits.

Lithofacies Association FA 7 (Fm + Fl) is common in the Clarens Formation and consists of Fm, and Fl lithofacies formed as massive mudstone beds (loess-like deposits). As wind energy dwindles, fine particles of silt become deposited to form loess-like deposits. The loess-like sediments are thought to have formed as a result of suspension settling from high dust clouds (tens to hundreds of metres above the ground surface). The fine mudstone beds (Fm) are deposited from suspension by aeolian and then by flood (or aeolian) redeposition. These areas can also be identified as floodplains, swamps or shallow lakes which occasionally occurred during the aridification process. The amount of water present during deposition help in determining the colour which the sediments acquire. Deposits in much more exposed floodplains tend to develop a red colouration, whilst those in swampy areas or lakes preserve organic matter thus assuming a greyish colour. Figure 4I shows a reddish coloured mudstone bed which could be an indication of partial oxic conditions of iron-rich deposits. FA 7 may also represent inter-dune small-scale lakes. The lake waters captured aeolian dust and deposited this as mudstone beds. In the higher, dry zones of the dunes, the dust was blown away and could not accumulate.

5. Discussion

The facies and facies associations (Figs 3, 4) indicate a braided channel, braidplain and swamp origin for the Molteno Formation, an alluvial fan/floodplain playa lake and fluvial environments for the Elliot Formation, and aeolian dune and loess-like deposits for the Clarens Formation. The grain size analyses show that the Molteno Formation sandstones are mostly medium- to coarse-grained, commonly moderately to well sorted, near symmetrical and mesokurtic, while the Elliot sandstones are mostly fine- to medium-grained, moderately well sorted, near symmetrical and mesokurtic. The Clarens sandstones are mostly fine-grained, well sorted and also mesokurtic. The positive skewness indicates fluvial or aeolian sediments, while negative skewness indicates a relatively lower-energy environment. The bivariate plots of the mean grain size *vs* skewness and the mean grain size *vs* standard deviation (sorting) reveal that fluvial and aeolian processes were interdependent. Likewise, the Passega C-M diagrams (Figs 8, 9) show that the sandstones formed mainly through tractive current processes. Furthermore, the low-angle stratified sandstone facies formed as a result of variable velocity of unidirectional traction currents. The multiple fining-upward cycles are indicative of numerous falling floods. The sandstone/mudstone intercalations suggest that the flow energy dropped rapidly.

The characteristic logs for the Molteno, Elliot and Clarens formations indicate multiple fining-upward cycles with each cycle distinguished by an erosional surface at the base, which reflected multiple channel shifting (Fig. 2). Based on the observation from the stratigraphical sections it can be noted that the Molteno Formation is dominated by coarse-grained sandstones. These sandstones represent a braided river system which is characteristic of a low-sinuous river where different types of bars and bedforms tend to impede and divert the flow within broad, shallow channels. Deposition occurs along the braided river channels which have banks that are easily eroded for sediment supply. The coarse-grained longitudinal bars (lithofacies Gm) were distinctive barforms there. 3D (highly sinuous) dunes (lithofacies St) are also indicative of intense flows. In the shallow channel zones, rapid flows deposited low-relief dunes (lithofacies Sl) – the transitional bedforms to the upper flow regime, as well as the upper plane bed (lithofacies Sh). The thick mudstone beds indicate prolonged flooding periods whereby the water spilled over the river banks and assembled in the low-lying areas between the river channels. Lithofacies Fm and Fl are representative of sedimentation in response to extensive overbank flooding as well as abrupt cessation of channel flow, i.e., avulsion resulted from powerful flood. The high rate of aggradation favoured the poorly oxidising conditions of the rapidly buried sediments. For this reason they assumed a greyish colour.

The Elliot Formation is characterised by interbedded mudstone and sandstone beds. The multiple cycles within the sections highlight continuous alternating depositional environment between lacustrine and ephemeral rivers. Most of the sandstones represent alluvial fan channel deposits (lithofacies St). Much of the whitish spots in many sandstone beds indicate the presence of traces of organic matter suggesting that the mottles could be a result of reducing processes. The oxidising conditions due to progressing semi-arid environment and a fall in groundwater levels could have been the major factor influencing the changes in the diagenetic environment. The precipitation of the iron-oxides/hydroxides from ground waters caused the reddening. Mudstone units (lithofacies Fl, Fm) within the Elliot Formation are regarded as floodplain fines formed in standing waters of lakes or abandoned channels (Bordy et al., 2004b). Deposition of these mudstones interbedded with the sandstones could have been due to the occurrence of sporadic flooding by ephemeral streams which led to the deposition of fine-grained sediments or aeolian dust. The tabular beds of sandstones and siltstones (Figs 3, 4) are interpreted as crevasse splay deposits. Rhythmically bedded units of sandstone and mudstone are identified as levees formed along the banks of major channels. The matrix-supported conglomerates occurring at the base of some outcrops can be interpreted as products of channel lags of ephemeral streams or aeolian deflation lags. The fine-grained matrix material could have precipitated within the pebbles as a suspension load from sporadic ephemeral streams, reflecting highly fluctuating currents.

Visser & Botha (1980) noted that the aridification trend within the Elliot Formation indicated an initial high-sinuosity stream environment which was subsequently succeeded by excessive flooding, resulting in the formation of alluvial fans. Under these conditions, rivers continued to be braided, as vegetation cover declined and aeolian processes became increasingly important. This results in a large sediment supply to the fluvial system. The aeolian reworking of the surfaces of alluvial fans caused the formation of the lakes and the deposition of playa deposits. During floods the areas built up of fine-grained sediments (clays and silts) have enough high cohesive strength to resist erosion (Bordy et al., 2004a). Other sandy zones undergo deflation and this is how the playa lakes are formed.

Bordy et al. (2004a) noted that the change in fluvial style that took place during the deposition of the Elliot Formation was due not only to climatic changes but also to tectonic control. The boundary between the Lower and Upper Elliot formations was most likely caused by the last stage of orogenic loading of the Cape Fold Belt. The specific lithological feature of the Clarens Formation is the coexistence of large-scale, planar cross-stratified sandstones (lithofacies Sp) and massive, thick-bedded sandstones (Sm). Lithofacies Sp is a record of aeolian dunes, whereas the origin of lithofacies Sm is enigmatic. The massive structure is interpreted as secondary (i.e., post-depositional). According to Eriksson (1986), in modern aeolian deposits, sedimentary structures are not always readily visible, hence they are documented as structureless. This feature is well developed especially in fine-grained and well-sorted sand-sized deposits. The abundance of horizontally laminated sandstones (Sh) can be interpreted as wet inter-dune deposits formed by aqueous reworking of aeolian sand (Bordy & Catuneanu, 2002). Those authors also stated that the horizontally laminated sandstones could be interpreted as fluvially derived strata of non-channelised, intermittent, rapid, shallow flows (i.e., sheetflows). Significant changes of sediment supply and facies development of the Clarens Formation can also be interpreted as an effect of tectonics – the increasing rifting activity prior to Lower Jurassic Karoo volcanism (Holzförster, 2007).

6. Conclusions

Textural studies of the sandstones from the Molteno, Elliot and Clarens formations show that they are mostly fine- to medium-grained and moderately well sorted. The sandstones have unimodal distributions, perhaps indicating that the sediments were sourced from the same provenance. The positive, negative, as well as near-symmetrical distribution indicates frequent fluctuations in energy conditions. The fine-grained nature of rocks indicates that moderately to low-energy conditions dominated. The bivariate plots of the mean grain size *vs* skewness and the mean grain size *vs* standard deviation (sorting) reveal fluvial and aeolian processes were interdependent. Likewise, the C-M pattern (Passega diagram) shows that the sandstones were deposited mainly through tractive current processes.

Seventeen lithofacies were identified and grouped into seven lithofacies associations (from FA1 to FA7). For the Molteno Formation, the lithofacies can be integrated into three lithofacies associations (FA1, FA2 and FA3). Lithofacies association FA1 is made up of Gm+Sm+Sh+St+Sr lithofacies that represent braided river channel deposits, FA2 is made up of Sr+Fl+Fm lithofacies that represent overbank deposits, and FA3 is made up of Fl+Fm+FC lithofacies that represent organic-rich (swamp) deposits. The Elliot Formation contains two lithofacies associations (FA4 and FA 5). Lithofacies association FA 4 consists of Sr+Sm+St+Sl+Sh lithofacies representing alluvial fan/floodplain deposits and FA 5 consists of Fl+Fm+Sm lithofacies representing deposition of playa lakes and fluvial overbank. For the Clarens Formation, the facies can be grouped into two facies associations: FA 6 is made up of St+Sm+Sp+Sh lithofacies, and FA 7 is made up of Fm+Fl lithofacies. Both associations are interpreted as records of environments dominated by aeolian processes.

Sediment deposition of the Stormberg Group took place in a terrestrial environment, changing from fluvial to aeolian. The base of the Stormbeg Group (Molteno Formation) was deposited by rivers under climatic conditions with heavy precipitation. The depositional environment of the Elliot Formation changed to fluvial-lacustrine conditions, as mudstones became more common. The energy of the rivers of that time decreased. The sandstone-dominated Clarens Formation represents aeolian dune fields and inter-dune depressions in a desert environment.

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