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Petrography, modal composition and tectonic provenance of some selected sandstones from the Molteno, Elliot and Clarens Formations, Karoo Supergroup, in the Eastern Cape Province, South Africa

Abstract: The Late Triassic - Early Jurassic non marine clastic sediments of the Molteno, Elliot and Clarens Formations were studied to deduce their mineralogy and tectonic provenance. The study is based on road-cut exposures of the formations in the Eastern Cape Province of South Africa. Petrographic studies based on quantitative analysis of the detrital minerals shows that the clastic sediments (mostly sandstones) are predominantly made up of quartz, feldspars, and metamorphic and igneous rock fragments. Among the main detrital framework grains, quartz constitutes about 62-91%, feldspar 6-24% and 3-19% of lithic fragments. The sandstones can be classified as both sub-litharenite and subarkose. Although, most of the sandstones (> 70 %) plotted in the sub-litharenite field. Petrographic and XRD analyses revealed that the sandstones originated from granitic and metamorphic rock sources. The QFL (Quartz-feldspar-lithic fragments) ternary diagrams indicate that the sandstones were derived from recycled or quartzose source rocks reflecting a craton interior or transitional continental setting which probably came from the Cape Fold Belt. This possibly revealed that most of the sandstones might have been derived as a result of weathering and erosion of igneous and metamorphic rocks in the Cape Supergroup. The study has revealed the depositional environments, and provide a basis for the description and interpretation of the sedimentology of the Molteno, Elliot and Clarens Formations.

Keywords: Petrography, modal analyses, sandstones, tectonic provenance, Karoo Basin

1 Introduction

Sedimentary rocks, particularly sandstones, are commonly used to construe provenance and to identify ancient tectonic settings since clastic detrital components preserve detailed information on the provenance, sediments transportion and the interaction of physical and chemical processes [1, 2]. Petrography of sandstones reveal more on the provenance of the detritus despite the fact that their original compositions are influenced by processes such as weathering, transportation and diagenesis [3]. [4] documented that other factors like source area characteristics, orogenesis, multicycling, storage pathways and/ or leaching also contribute to the formation of clastic sediments. Provenance analysis is done to determine the parent source rock constituencies of sediments as well as palaeogeographic conditions under which the sediments were formed. [5] highlighted that provenance encompasses all factors that facilitate the production of sediments. As documented by [3], tectonic setting of the sedimentary basin is believed to have an overall control on the composition of sedimentary rocks. Owing to the fact that, different tectonic environments have specific mineral composition characteristics which are unique to a particular sedimentary processes. Provenance studies enable the determination of sediment characteristics which are derived from measurements of compositional and textural properties and can then be supplemented by information from other investigations ([6] in [7]). With the aid of petrographic analysis, it becomes possible to understand and

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reconstruct the palaeodepositional history of sedimentary rocks.

The Karoo is a semi-desert region of southern Africa with vast distribution of sedimentary rocks. The sedimentary part of the Karoo Basin fill consists of the Dwyka (Westphalian-Early Permian), Ecca (Permian), Beaufort (Permo-Triassic) and Stormberg Groups (Late Triassic-Early Jurassic) (Figure 1; Table 1). Recent basinal investigations have shown differences in the stratigraphic sequence, palaeocurrent direction, sedimentary structures, petrographic composition, depositional setting during the basin formation and developmental processes [7, 8]. Geographically, the Molteno, Elliot and Clarens Formations covers an area of approximately 25,000 km^2 and forms an oval shaped basin that extends from the Northern-Eastern Cape Province of South Africa into Lesotho, KwaZulu Natal and Free State in South Africa [9]. In the Eastern Cape Province, the Upper Triassic/Lower Jurassic succession from the Molteno Formation up to Clarens Formation reveals a gradual aridification trend from braided rivers to semi-arid fluvial/playa, and subsequently aeolian dune conditions [10]. Based on the palaeogeographic condition and basin tectonic structure, the Eastern Cape Province of South Africa is believed to have the thickest and most completed succession of the Molteno, Elliot and Clarens Formations sediments of the Karoo Basin [11]. In the study area, the Molteno, Elliot and Clarens Formations are considered to represent a transition from humid to arid climate and from cratonic sedimentation to active volcanic eruption [11]. These formations recorded the developmental history of the Karoo Basin and the breakup processes of the Gondwana continent. Previously, there have not been much detailed studies to examine the petrography, modal composition, tectonic provenance and depositional history of these formations in relation to the basin development. Hence, till date, the mineralogical composition, classifcation and source(s) of sandstones of the Molteno, Elliot and Clarens Formations are still not-well understood. This study was undertaken to interpret the sandstones petrography in order to characterize the sandstones of the Molteno, Elliot and Clarens Formations and to infer their provenance in the southeastern Karoo Basin of South Africa.

2 Generalized Geology and Stratigraphy

The word "Karoo" was coined from the Main Karoo Basin of South Africa to describe sedimentary fill of all basins
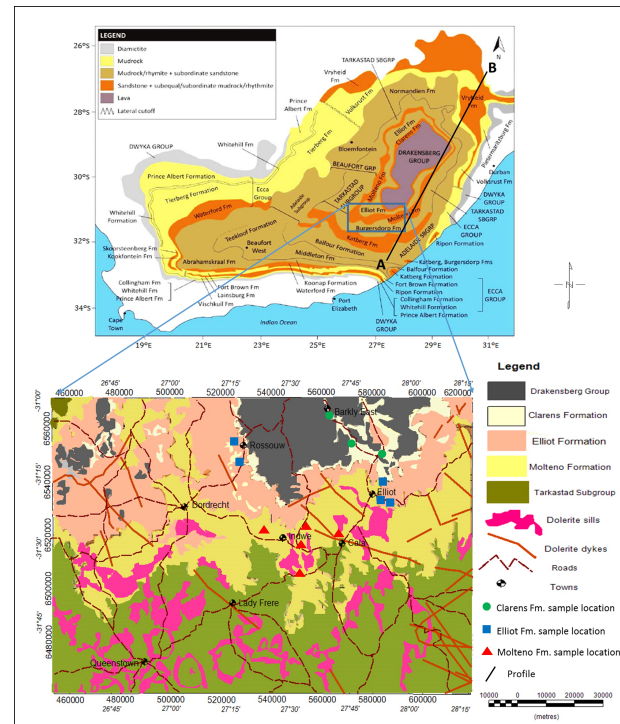
Figure 1: Geological map of the preserved Karoo Basin showing the outcrop distribution of the main lithostratigraphic units of the Karoo Supergroup and location of the study area (After [8]). The cross-section transect in the upper map connects the proximal (south) to the distal (north-east) facies. The profile (A-B) connects the proximal (south) to the distal (north-east) facies in the area studied by [8] and depicted in Figure 2.

of akin age across Gondwana. The Main Karoo Basin is a large sedimentary depository lying north of the Cape Fold Belt in South Africa. The bulk of the Karoo strata occurs in the Main Karoo Basin, with maximum preserved thickness of about 12 km along the southern margin of the basin [8, 11]. The basin developed within the continental interior of southwest Gondwana and covers up to 700, 000 km^2 [12, 13]. But it was much more extensive during the Permian [14] and represents about 117 Ma of sedimentation spanning from 300 Ma to 183 Ma [15]. In addition, the basin is underlain by a stable basement comprising the Kaapvaal Craton in the north [8, 16], the Namaqua-Natal Metamorphic Belt (NNMB) in the south [17] and the Cape Fold Belt (CFB) along its southern margin [11]. The Main Karoo Basin is a unique type of basin of all the Karoo basins in southern Africa because it contains the thickest and stratigraphically most complete mega-sequence of several depositories of the Permo-Carboniferous to Jurassic age sediments in southwestern Gondwana continent [8].

The Karoo depositional cycle and palaeoenvironments commenced with Late Carboniferous glacial deposits of

Table 1: Lithostratigraphy of the Karoo Supergroup in the Eastern Cape Province as compiled by the Council for Geoscience [11].

SUPERGROUP	GROUP	SUBGROUP	FORMATION	MEMBER	LITHOLOGY	MAXIMUM THICKNESS (m)
KAROO			Drakensberg		Basalt, Pyroclastic Deposits	1400
			Clarens		Sandstone	300
			Elliot		Mudstone, Sandstone	500
			Molteno		Sandstone, Shale, coal	450
	BEAUFORT	TARKASTAD	Burgersdorp		Mudstone, Sandstone, Shale	1000
			Katberg	Palingkloof	Mudstone, Sandstone, Shale	900
		ADELAIDE	Balfour	Palingkloof	Mudstone, Sandstone, Shale	50
				Elandsberg	Sandstone, Silt	700
				Barberskrans	Sandstone, Shale	100
				Daggaboersnek	Sandstone, Silt, Shale	1200
				Oudeberg	Sandstone, Shale	100
			Middleton		Sandstone, Shale, Mudstone	1500
			Koonap		Sandstone, Shale	1300
	ECCA		Waterford		Sandstone, Shale	800
			Fort Brown		Shale, Sandstone	1500
			Ripon		Sandstone, Shale	1000
			Collingham		Shale, Claystone	30
			Whitehill		Black Shale, Chert	70
			Prince Albert		Khaki Shale	120
			Dwyka		Diamictite, Tillite, Shale	750

the Dwyka Group, followed by the Permian Ecca Group which contains significant hydrocarbon deposits associated with the deltaic and lacustrine environments [11]. The Middle Permian-Middle Triassic Beaufort Group lies above the Ecca Group, and it is composed of fluvio-lacustrine rocks [11]. The Late Triassic Molteno Formation overlies the Beaufort Group, and it was deposited under warm to humid conditions in broad perennial braided river systems [18, 19]. The argillaceous Elliot Formation that overlies the Molteno Formation was deposited by high and low sinuosity fluvial systems under semi-arid climatic conditions [19]. Progressive aridification led to the deposition of the aeolian dune complexes of the Clarens Formation on the Elliot Formation [11, 20]. The end of the Karoo sedimentation was brought about by the continental flood basalts of the Drakensberg Group which marked the initiation of the Gondwana breakup [20]. [8, 21] are of the view that the Karoo sediments were accumulated within an intracratonic retro-arc foreland basin and a number of processes influenced the depositional settings through different climatic regimes. The tectonic activities that took place were in response to the subduction of the Paleo-Pacific plate beneath the Gondwanan plate, and this triggered basinal subsidence which facilitated the building of the adjacent Cape Fold Belt that served as the provenance for the basin sediments [20]. The glaciers that covered the Ka-

roo Basin during the Late Carboniferous-Middle Permian Period started retreating resulting in high sedimentation which filled the basin in a deep-water environment [8]. As the glaciation process stopped, climate gradually became warmer, the basin began to shallow (thins northward, producing a highly asymmetrical basin) as shown on the cross sectional view (Figure 2) and sedimentation continued as fluvial-lacustrine and then aeolian deposits [8].

The Stormberg Group is an informal stratigraphic division name, which is collectively made up of three formations, namely, Molteno, Elliot and Clarens Formations. The South African Committee for Stratigraphy [22] highlighted that there are no unifying lithological features in the various units of the Stormberg Group which distinguishes them from all the geological groups of the Karoo Basin. The Committee further suggested discontinued use of "Stormberg" as a group title to formally describe the lithostratigraphy of the Molteno, Elliot and Clarens Formations [23]. [24] is of the opinion that the Stormberg Group sediments form a unique tectono-sedimentary sequence which lies between the Beaufort and Drakensberg Groups and was deposited north of the Cape Fold Belt as a direct result of the sediment production by the Cape Fold Belt. The Molteno Formation was deposited within braided river channels and resulted in the formation of conglomerate, sandstone, shale and mudstone as well as coal seams [10, 25]. [26] divided the Molteno Formation into 3 members; the basal Boesmanhoek Member, the Indwe Sandstone Member and the upper the Kramberg Member. [27], in his studies of the Molteno Formation considered the Indwe Sandstone to be a regionally extensive unit and this view was supported by [25] when he identified the Indwe Sandstone Member as a lithostratigraphic marker horizon of regional importance, and it is the only unit which has been formally defined by the South African Committee for Stratigraphy [22]. The overlying Elliot Formation is typical red bed, and was deposited through floodplain – playa sedimentation. The semi-arid climate and high salinity of these floodplain/playa resulted in the formation of red-brownish mudstone and sandstone [28]. Analysis of the Elliot sandstones revealed two contrasting geometries resulting from different fluvial depositional styles. The lower parts of the formation was be interpreted as deposits of meandering river systems and the upper parts deposited through ephemeral fluvial processes [29]. The Clarens Formation that overlies the Elliot Formation represents the final stage of the aridification process. It consists of sandstones and sandy siltstones formed from aeolian processes [8, 10]. The Clarens Formation contains a central zone that indicates a true desert condition which is dominated by an aeolian dune environment and the

westerly wind transported the sand [28]. [30] documented that towards the final stage of deposition of the Clarens Formation, the climate became fairly moderate and wet desert processes of stream and sheet flood became more dominant [8]. The Clarens Formation is overlain by the basaltic lavas of the Drakensberg that forms the top of the Karoo sequence, and is believed to have terminated sedimentation within the basin in the Middle Jurassic [11].
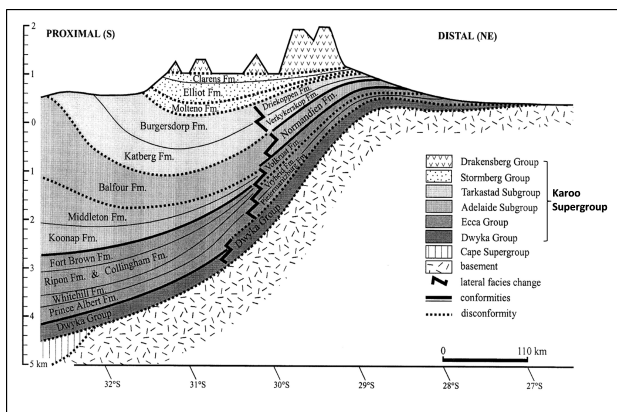
Figure 2: Stratigraphic cross-section of the Karoo Supergroup along the profile shown in Figure 1 [8].

3 Material and Methods

A total of ninety (90) sandstones samples were collected from outcrops of the Molteno, Elliot and Clarens Formations within the Eastern Cape Province (Figure 1). Fifteen (15) representative thin sections of different types of sandstones were prepared and studied under optical microscope and applied to modal composition analysis. The selected sandstones (four samples from the Molteno Formation, six samples from the Elliot Formation and five samples from the Clarens Formation) were labelled with prefixes M, E and C to represent samples from the Molteno, Elliot and Clarens Formations respectively. Four to six samples for each formation might look not sufficient to adequately characterize each of these formations due to heterogeneity of sedimentary sequences. Nevertheless, an attempt was made to collect reasonably representative samples to represent the geologic deposit that is the object of study. Samples for each formation was collected at different locations (Figure 1) and in each of these areas, at least one sample was selected and thin section prepared. The selected 15 representative thin sections of different types of sandstone were chosen based on difference or variation in

lithology, grain-size distribution, textural characteristics, sedimentary facies, and petrographic composition (mineralogy). For example, at least one thin section was selected to represent a particular facies and the sample size was large enough to represent adequately the finest and coarsest component under consideration. The representative samples possess many of the same characteristics as the targeted formation such that data generated from the sample will represent more than just the sample from which they were obtained, but extended to the entire formation in the study area. The comparative abundance of the main mineral components was determined by counting a minimum of 400 points in each thin section based on the Gazzi-Dickinson's method and the nomenclature suggested by [31]. The modal composition analysis (point-counting) was carried out using an Olympus BX51 microscope equipped with an Olympus DP72 digital camera. An evenly spaced counting grid was employed to traverse the thin section, and mineral grains under the grid nodes were counted. The grids were equally spaced in such a way that each grid exceeds the average grain size in order to avoid counting an individual grain more than once. Framework constituents were determined using the nomenclature proposed by [1, 3, 32]. Mineral constituents of the sandstones were categorized into monocrystalline quartz, polycrystalline quartz, K-feldspar, plagioclase, lithic fragments, accessory minerals and matrix. Quartz, K-feldspar, Ca-feldspar, lithic fragments, mica and heavy minerals were all accounted for and used for modal analysis, while the matrix, cement, and other authigenic accessory minerals were only counted but excluded for modal analysis. So as to classify the sandstones, framework detrital modes of the sandstones were recalculated to 100 % and Q-F-L (Quartz-feldspar-lithic fragments) ternary diagrams were plotted. In this study, the Q-F-L ternary diagrams proposed by [33, 34] were used to classify the sandstones as well as infer their provenance(s). In addition, mineralogical composition of the sandstones was determined by X-ray diffraction (XRD) and used to confirm or support the petrographic framework.

4 Results

4.1 Sandstone petrography

4.1.1 Quartz

The most dominant mineral which constitutes large percentage of the detrital grains in the sandstones is quartz.

Table 2: Framework parameters of detrital modes (After [3]).

A	Quartzose Grains	(Qt = Qm + Qp)
		Qt = Total quartz grain
		Qm = Monocrystalline quartz grain
		Qp = Polycrystalline quartz grain
B	Feldspar Grains	F = (P+K)
		F = Total feldspar grain
		P = Plagioclase feldspar grain
		K = Potassium feldspar grain
C	Unstable Lithic Fragments	L = Lv + Ls, Lithics
		Lv = Volcanic / meta-volcanic lithic fragment
		Ls = Sedimentary/metasedimentary lithic fragment
D	Total Lithic Fragments	Lt = (L+ Qp), Total lithics
		Lc = Extra basinal detrital lime-clasts (not included in L or Lt)

The total quartz content in the sandstones of the Molteno, Elliot and Clarens Formations range between 72-86%, 70-87% and 66-90% respectively. Both monocrystalline and polycrystalline quartz grains are present in the sandstones, with the monocrystalline quartz, averaging 75%, 78%, and 74% in the Molteno, Elliot and Clarens Formations respectively. Some of the monocrystalline grains tend to show undulose extinction. The monocrystalline quartz grains mostly have sub-rounded to sub-angular shape (Figure 3a). The quartz grains occasionally have secondary overgrowths that precipitated around the original detrital grain boundary (Figure 3b). Recrystallized quartz mostly from metamorphic origin occurs mainly as polycrystalline, composite grains of sub-equant to equant shape while stretched metamorphic quartz is mostly platy to elongate. [40] concluded that quartz grains with non-undulatory extinction most likely originated from non-metamorphic rocks, whereas the grains with undulatory extinction came from metamorphic rock source. On the other hand, significance The individual grain shows almost sub-parallel to parallel orientation and sutured boundaries (Figures 3c and 3d). The polycrystalline quartz grains also show sub-rounded to sub-angular nature with moderate sphericity. As documented by [35], "Strongly undulose and finely polycrystalline quartz grains are indicative of metamorphic source rocks, but quartz grains of plutonic and volcanic origin are characteristically strain free".
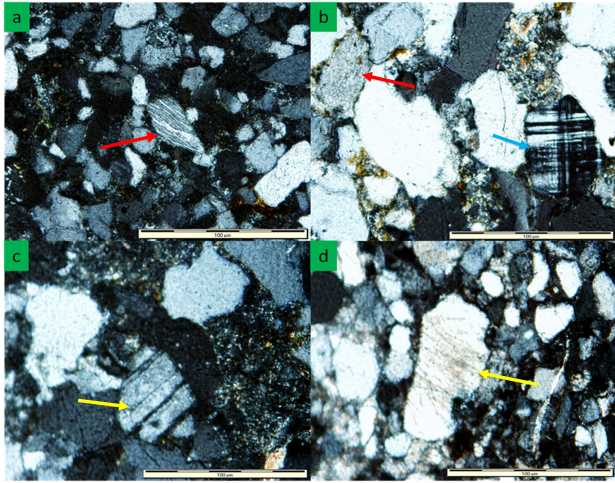
4.1.2 Feldspar

Alkali feldspar (orthoclase and microcline) and plagioclase feldspar (albite) are the feldspar minerals present in the sandstones (Figure 4), with plagioclase feldspar being the most dominant. On the average, the feldspar
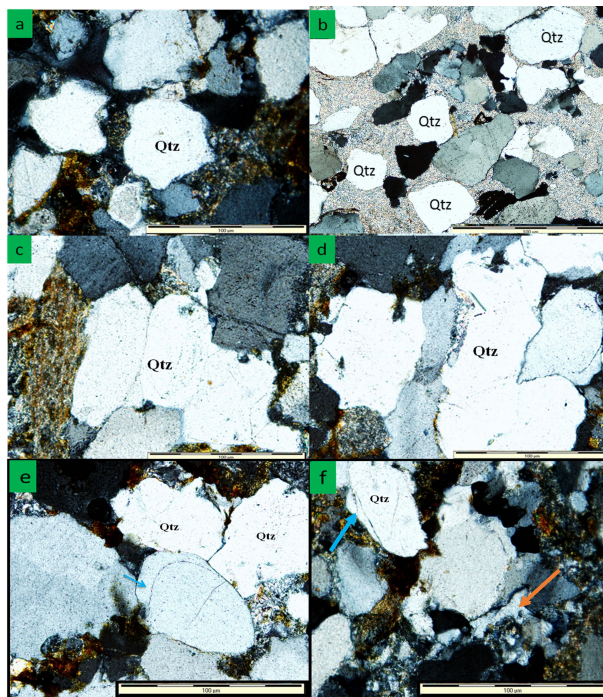
Figure 3: Photomicrograph of quartz grains showing: (a) Sub-angular quartz grains from the Clarens Formation; (b) Sub-rounded quartz grains with overgrowth (arrow) from the Elliot Formation; (c) Polycrystalline quartz grain from the Elliot Formation; (d) Polycrystalline quartz grain with sutured boundaries from the Molteno Formation; (e) quartz overgrowth (blue arrow) within a sandstone from Molteno Formation; (f) Quartz cement (orange arrow) and quartz overgrowth (blue arrow) within a sandstone of Clarens Formation.

minerals in the Molteno, Elliot and Clarens Formations are 13.6%, 11.1% and 14.2% respectively. Monocrystalline and polycrystalline feldspar grains are both present in the sandstones. The feldspar grains are texturally sub-rounded to sub-angular and medium to coarse grained in size. Some of the feldspar grains are partially changed to sericite. Ocassionally, they are changed to kaolinite, illite, muscovite or replaced by calcite. Albite and orthoclase are the dominant feldspar minerals occurring in both twinned and untwinned forms. Most of the plagioclase shows twinning, while others appear to be untwinned. Microcline only occurs in minor quantities and are totally absent in some samples. Albite grains are generally elongated and shows parallel twinning, while the microcline exhibits cross-hatch twinning. The orthoclase grains are usally cloudy in colour. Nonetheless, they ocassionally have simple twinning with perthite texture.

Figure 4: Photomicrograph of feldspar grains showing: (a) K-feldspar grain in the sandstone of the Clarens Formation (red arrow); (b) Microcline (blue arrow) and K-feldspar (red arrow) in the sandstone of the Elliot Formation; (c) Plagioclase (arrow) in the sandstone of the Molteno Formation; (d) K-feldspar grain partially albitized in the sandstone of the Clarens Formation.

4.1.3 Lithic fragments

Lithic fragments constitute only a small fraction as compared to quartz and feldspars. The lithic fragments are made up of metamorphic, sedimentary and igneous rock clasts (Figure 5) and they have an average percentage of 7.9%, 6.73% and 7.9% in the sandstones of the Molteno, Elliot and Clarens Formations respectively. Metamorphic and igneous clasts constitute a larger percentage than volcanic and sedimentary clasts. Metamorphic clasts are mainly shale schist, chert and quartzite, whereas igneous clasts include granitic and granodioritic rock types. Sedimentary rock fragments of sandstone, siltstone and shale constituting a small percentage of the total lithic fragments. These pieces of rocks have been eroded down to sand size and are now sand grains in the sedimentary rock. In addition, The igneous lithic fragments consist mainly of quartz, feldspar and minor alkali minerals that have previously undergone alteration due to auto-hydrothermal reaction. The rock fragments tend to break into their constituent minerals or grains, while argillaceous grains can be squashed, deformed and moulded about the more competent grains.

4.1.4 Clay matrix and cement

The detrital framework grains in the sandstone of Molteno, Elliot and Clarens Formations are bound by matrix of
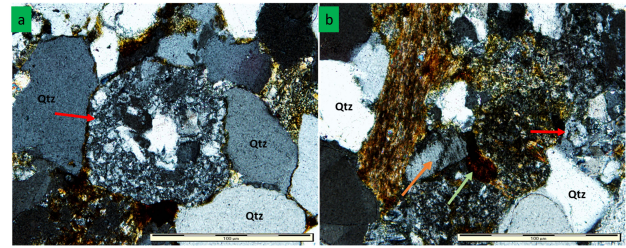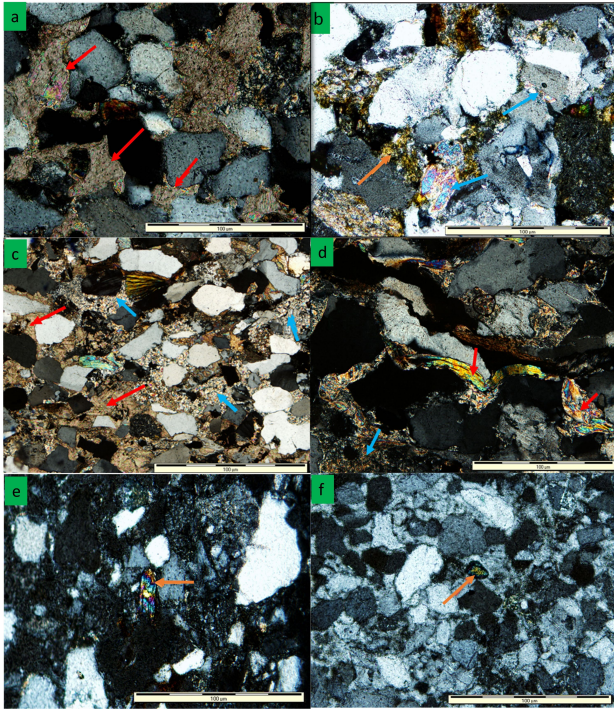

Figure 5: Photomicrograph showing: (a) Metamorphic lithic (red arrow) in sandstone of the Molteno Formation; (b) Igneous lithic (red arrow) in sandstone of the Elliot Formation. Figure 5b also shows partial albitization of clay matrix (orange arrow) and hematite cement (green arrow).

clay minerals, quartz, hematite and calcite (Figure 6a-c). The abundant quartz overgrowths make up much of the quartz cement that precipitate within the pore space between original detrital grains. Clay minerals include smectite, kaolinite, sericite and illite. Recrystallization of the clay matrix is a common phenomenon in the sandstones; for example, smectite gradually changes to illite, then to sericite and finally muscovite. Hematite cement is also common cement type in the sandstones. This cement tends to fill up the pore spaces within the sandstone grains.

4.1.5 Mica and accessory minerals

Mica grains occur as random tiny fragments or elongated flakes (Figure 6d and 6e) ranging between 2% to 6%. Muscovite and biotite are the mica in the sandstones and their average percentage composition reaches up to 4%. Muscovite is chemically more stable than biotite and thus is commonly much more abundant in sandstones. Some of the muscovite grains are stained or invaded by chlorite. The detrital muscovite grains are distinguished by their tabular appearance with individual crystals bent through compaction and deformation around quartz grains. Garnet, rutile, zircon, and magnetite are the accessory (heavy) minerals in the sandstones (Figure 6f). These minerals have long been used in sedimentary petrology to deduce the composition of the source rocks of sediments. The presence of a particular heavy minerals is diagnostic of the certain type of source area or provenance, for example, the presence of garnet, rutile and magnetite would imply derivation from igneous source area, whereas the would imply derivation from igneous source area, possibly reworked sediments. It is possible that a sediment to have been sourced or derived from more than one type of source area.

Figure 6: Photomicrograph showing: (a) calcite cement (red arrow) in sandstones of the Molteno Formation; (b) recrystallization of clay minerals into muscovite (blue arrow) and sericite (yellow crystals, orange arrow) in sandstone of the Elliot Formation; (c) calcite cement (red arrows) and clay matrix (blue arrows) in sandstone of the Clarens Formation; (d) detrital muscovite flakes (red arrows) and recrystallized clay matrix to muscovite (blue arrow) in sandstone of the Elliot Formation; (e) detrital muscovite in sandstone of the Molteno Formation; (f) weathered heavy mineral rutile (arrow) in the sandstone of the Clarens Formation.

4.2 Mineralogy and modal composition

The summary of the mineralogical composition of the sandstones as detected using XRD analysis is presented in Table 3. Prefixes M, E, and C were used to identify samples from the Molteno, Elliot and Clarens Formations respectively. The most abundant minerals are quartz (72-91%) and plagioclase (8-17%). The mica range between 1-11%, while the heavy minerals like rutile, garnet and zircon only occurred in traces. The modal compositions of the sandstones are presented in Table 4.

5 Interpretation and Discussion

5.1 Sandstone petrography and mineralogy

Mineralogical compositions and textural characteristics of the detrital sediments are determined by their parent

Table 3: X-ray diffraction percentage mineralogical abundances (%) in the sandstones of the Molteno, Elliot and Clarens Formations.

Formation	Sample label	Sample location	Quartz	Plagioclase	K-Feldspar	Mica	Calcite	Kaolinite/Chlorite	Laumontite	Smectite	Rutile	Garnet	Zircon	I/S Interstratification
Clarens	C9	BE	76	15	5	3	-	-	-	-	-	tc	tc	-
	C11	BE	76	13	5	2	-	-	4	-	-	tc	-	-
	C18	BE	91	5	-	3	-	-	-	2	tc	tc	tc	-
	Cd5	NE	74	14	8	2	-	-	1	-	tc	tc	-	-
	Cd6b	NE	62	7	4	1	-	-	24	2	tc	-	tc	-
Elliot	E6b	ET	74	10	-	12	-	4	-	-	tc	-	tc	-
	E6c	ET	88	5	-	6	-	6	-	-	-	tc	tc	-
	E7	RO	72	17	-	11	-	-	-	-	tc	tc	-	-
	E17a	RO	75	16	4	1	-	-	-	-	-	-	tc	5
	E17b	RO	82	12	-	6	-	-	-	-	tc	tc	tc	-
Molteno	M3b	NC	90	-	-	7	-	3	-	-	tc	tc	-	-
	M4	ID	73	10	-	7	1	8	-	-	tc	-	-	-
	Md9	NC	75	11	-	9	2	3	-	-	tc	tc	-	-
	M14a	NC	71	8	-	9	-	3	-	-	-	tc	-	8
	M14b	NC	75	11	-	5	5	-	-	-	tc	tc	tc	6

Note: tc: trace, - : not detected, BE: Barkly East, NE; Near Elliot, ET: Elliot town, RO: Rossouw, NC: Near Cala, and ID: Indwe.

Table 4: Modal compositions of sandstones from the Molteno, Elliot and Clarens Formations.

Formation	Sample label	Sample location	Normalised (100%)					
			Qt	Qm	Qp	F	L	Lt = (L + Qp)
Clarens	C9	Barkly East (S 31° 10.525', E27° 46.888')	75.22	73.12	2.10	19.64	5.14	7.24
	C11	Barkly East (S 31° 10.525', E27° 46.888')	79.24	75.54	3.70	16.42	4.34	8.04
	C18	Barkly East (S 31° 13.504', E27° 50.942')	90.43	85.63	4.80	6.05	3.52	8.32
	Cd5	Near Elliot town	77.63	73.33	4.30	19.92	2.45	6.75
	Cd6b	Near Elliot town	66.42	62.82	3.60	9.20	24.38	27.98
Elliot	E6a	Elliot town (S 31° 15.202', E27° 49.579')	85.81	81.11	4.70	8.11	6.08	10.78
	E6c	Elliot town (S 31° 14.411', E27° 49.277')	86.68	83.18	3.50	4.12	9.20	12.70
	E6d	Elliot town (S 31° 10.950', E27° 17.636')	76.28	73.58	2.70	20.66	3.06	5.76
	E7	Rossouw (S 31° 10.950', E27° 17.636')	70.90	66.80	4.10	15.45	13.65	17.75
	E17b	Rossouw (S 31° 13.539', E27° 17.232')	85.68	81.28	4.40	10.32	4.00	8.40
	E17c	Rossouw (S 31° 10.950', E27° 17.636')	87.57	84.37	3.20	8.02	4.41	7.61
Molteno	M1	Indwe (S 31° 27.196', E27° 22.338')	82.09	78.79	3.30	12.94	4.97	8.27
	M2c	Near Cala (S 31° 36.928', E27° 27.932')	86.71	82.41	4.30	8.54	4.75	9.05
	M4	Indwe (S 31° 36.548', E27° 30.974')	72.42	69.72	2.70	8.86	18.72	21.42
	Md1	Indwe (S 31° 36.548', E27° 30.974')	72.52	69.52	3.00	24.00	3.48	6.48

rocks and diagenetic processes that exist at the time of sediment deposition and post-depositional processes after transportation of sediments from their source area to the point of deposition. As the sediments are continuously reworked, some exist as lithic fragments and some become distinctive minerals which assist in identification of parent rock. Physical, chemical, and biologic processes subsequently play important roles in determining the variation in mineralogical composition between parent rock and final sedimentary product. Minerals that are less resistant to physical and chemical effects are either al-

tered or they recrystallize into other minerals, whilst the more resistant minerals end up becoming the more dominant minerals. Distance of transportation overall determines the sediment size, shape, sorting and degree of sorting. The sandstones from Clarens and Elliot Formations are mostly fine to medium grained ranging from moderately well sorted to well sorted, while the Molteno Formation sandstones are mostly medium to coarse grained and moderately well sorted. Bulk detritus of the sandstones from the Molteno, Elliot and Clarens Formations is composed of abundant quartz and lesser amounts of feldspars and lithic fragments. [38] pointed out that given an instance whereby quartz is the abundant mineral in a sample compared to the amounts of feldspar, micas and matrix, this scenario gives an indication of how mature the sediments are in relation to the weathering and transportation. The sandstones showed high quartz content, low content of feldspar, sub-rounded and moderately well sorted grains, perhaps indicate relatively long transport distance from the source area. The unstable mineral of feldspar can not survive long distance as it will be affected (destroyed) by both weathering and erosion. Both quartz and feldspar minerals have polycrystalline and monocrystalline grains, indicating that they were not fully separated by the long transportation. The characteristics of the quartz and feldspar grains in the sandstones shows igneous, metamorphic and pre-existing sedimentary rock sources. [37] reported that the dominance of monocrystalline quartz grains indicate that the sediments are mostly derived from a granitic source. [38] suggested that most monocrystalline quartz grains are as a result of the disaggregation of original polycrystalline quartz (quartzite or vein quartz) during high energy or long distance transportation especially from magmatic and metamorphic sources. Considering the genetic and empirical classification of the quartz types as proposed by [39], monocrystalline quartz grains are primarily plutonic, hydrothermal and recycled sedimentary sourced, whereas polycrystalline quartz grains are recrystallized and stretched metamorphic types. The dominance of monocrystalline quartz grains in the sandstones show that the sandstones were mostly derived from a granitic source [37]. The monocrystalline and polycrystalline quartz grains often shows undulatory extinction and exhibit intercrystalline suturing, which indicate metamorphic source(s) area for the sandstones. In support of this, [40] concluded that quartz grains with non-undulatory extinction are mostly sourced from non-metamorphic rocks, whereas the grains with undulatory extinction came from metamorphic rock source. In few cases, some of the polycrystalline quartz grains have three or more crystals with straight to slightly curved intercrystalline boundaries, and as reported by [39, 41], such quartz grains possibly indicate that they were sourced from metamorphic and plutonic igneous rocks.

[37] documented that pure fragments of feldspar grains in sandstones indicate igneous source area, while altered or stained feldspar grains are mostly of metamorphic source area. Both weathered (altered) and a few pure feldspar grains are observed in the sandstones, indicating that the sandstones are probably sourced from igneous and metamorphic source area. Based on sedimentological, geochemical and paleontological (fossil assemblage) evidences, [42] reported thatthe presence of feldspar in the Molteno Formation implies erosion under cold climatic conditions in an area of high relief. This study as well as [29] highlighted that the detrital feldspars in the sandstones of the Molteno, Elliot and Clarens Formations are mostly plagioclase with very few microcline. The plagioclase grains are commonly twinned on the albite law, while the microcline displays tartan (cross-hatched) twins. The existence of few microcline in the sandstones indicates that the source rock is of low grade metamorphic terrain and alkali-rich granites. The sandstones of the Clarens Formation have higher feldspar content than those of the Molteno and Elliot Formations. This is an indication that the sandstones of the Clarens Formation are less mature than the sandstones of the other two formations, probably due to the presence or existence of dry climate and thus feldspar survived as there was less chemical weathering. These sandstones are mostly dominated by quartz and calcite cements as well as a clay matrix which mostly lines the boundary of grains. This reflected the characteristics of dry and arid climatic conditions during and after the deposition of the Clarens Formation sandstones. [6] documented that micas are mostly sourced from metamorphic and igneous rocks. The relative abundance of muscovite and biotite in the studied sandstones show that the source rock is micaceous in nature, perhaps of felsic igneous rocks or metamorphic rocks. The occurence (in traces) of heavy minerals like rutile, garnet and zircon in the sandsones possibly shows that the sandstones are derived from metamorphic, igneous and sedimentary sources.

The identified clay minerals (kaolinite, smectite, calcite and chlorite) possibly exist in the rock either as detrital grains or diagenetic minerals. The sample (Cd6b) from the Clarens Formation is of much interest as a result of the high laumontite content (about 24%). Laumontite is a secondary mineral formed from alteration of zeolite group minerals. Zeolites occur in lavas and clastic volcanics. It is of hydrothermal origin, lining cavities in igneous rocks [43]. Thick sedimentary beds rich in laumontite are said to have formed by decomposition of analcime

or metamorphism of plagioclase [44]. In most cases, laumontite occurs as an authigenic mineral, cementing sandstones. It forms together with calcite, chlorite after albitization of plagioclase. Since the Clarens Formation caps the sedimentary succession of the Karoo Basin and is also in contact with the volcalnic Drakensberg Group (contains basalt), there is a possibility that the basaltic lava flows that was present during the Triassic time had an effect on the sedimentary beds of the Clarens Formation. Thus, it is inferred that the formation of authigenic laumontite in the sedimentary sequence represents the hydrogenous catagenetic mineralization related to the circulation of heterogeneous alkaline groundwaters within the sedimentary sequence. The heated circulating groundwater that was released during the volcanic eruptions probably mixed with the hydrothermal solution fluids and reacted chemically with plagioclase to form laumontite. Likewise, excessive calcium may also react with silica to produce laumontite, which fills the cracks or fractures (acted as fracture filling fluids). Laumontite has also been found in Archean metamorphic rocks and their coarse detrital reworking products, as well as in basalts and their tuffs [45]. [45] further states that in some areas, laumontite containing sedimentary sequences were accumulated before or after the intrusive or effusive volcanic activity and the processes were almost synchronous in other places.

5.2 Sandstone classification

The most commonly used and effective methods for sandstone classification integrate both textural characteristics and mineralogy [1, 7, 33, 34, 39]. The Folk's classification scheme unravel important information about provenance with the rock's name showing details of its composition as reported by [46]. The QFL ternary diagrams have been effective in deducing the relationship between plate tectonic settings and sandstone compositions. [3] supported the use of ternary diagrams as a way of providing effective discrimination for different plate tectonic settings, thus enabling tectonic reconstruction of terrigenous deposits. [36] pointed out that given an instance whereby quartz is the abundant mineral in a sample, compared to the amounts of feldspar, micas and matrix, this scenario gives an indication of how mature the sediments are in relation to the weathering and transportation. Based on the classification scheme proposed by [33], the sandstones of the Molteno, Elliot and Clarens Formations can be classified as both sub-litharenite and subarkose (Figure 7). Most of the sandstones (>70 %) plotted in the sub-litharenite field. The QFL ternary diagram proposed by [34] also shows that
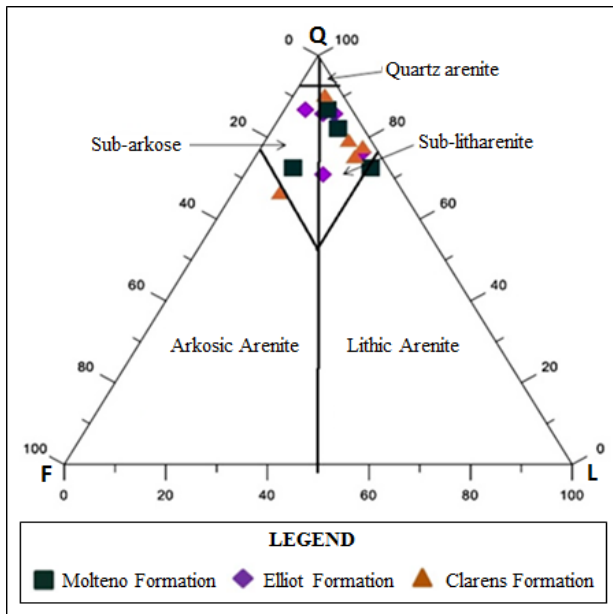

Figure 7: Q-F-L ternary plot of data presented in Table 4 showing classification of sandstones from the Molteno, Elliot and Clarens Formations (After [33]).

about 70% of the sandstones plotted in the sub-litharenite field, while the remaining 30% plotted in the lithic arkose, lithic subarkose, and lithic arenite (Figure 8).
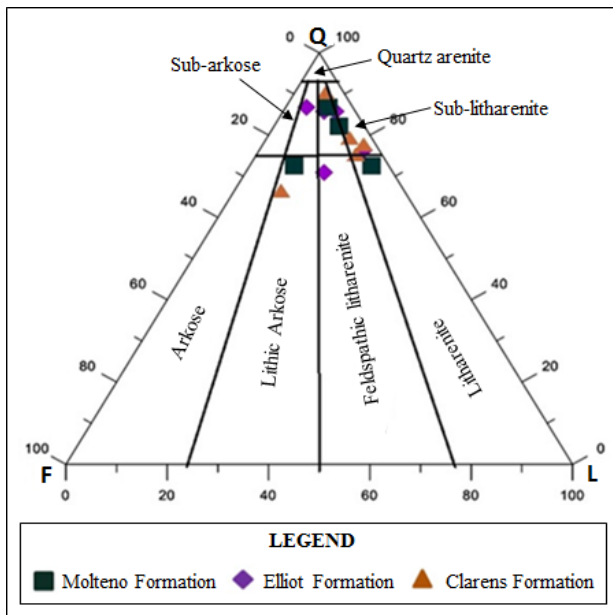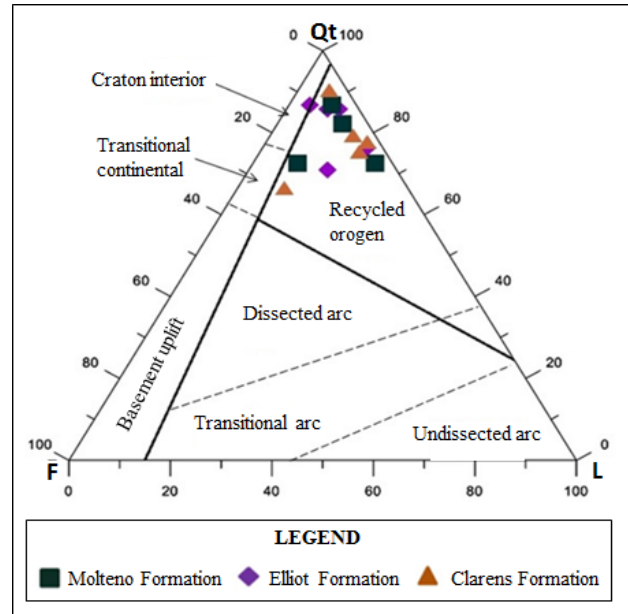

Figure 8: Q-F-L ternary plot of data presented in Table 4 showing classification of sandstones from the Molteno, Elliot and Clarens Formations (After [34]).

5.3 Provenance and tectonic setting

Provenance studies of sandstone are generally founded on the notion that different tectonic environments have distinguishing or unique characteristic rock types [3]. Several researchers like [1, 2, 7, 33, 34, 47] have associated detrital compositions of sandstones to different provenance types (i.e. stable cratons, basement uplifts, magmatic arcs and recycled orogens) using the QFL ternary diagrams. [32] in [7] reported that the average compositions of sandstone suites sourced from different tectonic settings/environments controlled provenance terranes tend to plot within distinct and separate fields on QFL diagrams. The QFL ternary plots proposed by [33, 34] have also been attempted for sandstones from the Molteno, Elliot and Clarens Formations in order to unravel their tectonic settings.

In the Qt-F-L ternary diagram (Figure 9), the sandstones of the Molteno, Elliot and Clarens Formations plotted in the recycled orogen field. This is an indication that the sediments' sources were derived from recycled orogeny. Sandstones derived from subduction complexes or fold thrust belts are mostly associated with recycled orogen [1]. In addition, recycled orogens indicate increasing maturity in mineralogy. As documented by [1, 32], within recycled orogens, sediment sources are mostly sedimentary with minor volcanic rocks, partly metamorphosed and uncovered or exposed to erosion by orogenic uplifted foldbelts. The Qm-F-Lt plot (Figure 10) shows that the sandstones falls within the craton interior, quartzose recycled, transitional continental and mixed zone. Most of the sandstones from the Elliot Formation plotted within the craton interior zone which is mostly associated with quartz arenites. A descriptive table summarizing the results of this study is depicted in Table 5.

Several studies including those of [8, 24, 48, 49] have suggested that sediments of the Molteno, Elliot and Clarens Formations were deposited in the Late Triassic-Early Jurassic Period. The deposition occurred after the terminal listric thrusting and epeirogenic uplift of the Cape Fold Belt. During the time of unloading, the Cape sediments were transported into the distal sector which later resulted in the deposition of the Molteno, Elliot and Clarens Formations [50]. The high quartz content of the sandstones is associated with the thrusting and upliftment of the Cape Fold Belt. [51] as well as this study, found out that the rock fragments in the Molteno Formation comprised quartzite and polycrystalline quartz , and are probably derived from metamorphic rocks. The volcanic and plutonic fragments are an indication of magmatic source area. Small tectonic events such as the P7 final phase at

Figure 9: Qt-F-Lt ternary plot of data presented in Table 4 showing provenance of sandstones from the Molteno, Elliot and Clarens Formations (After [33]).
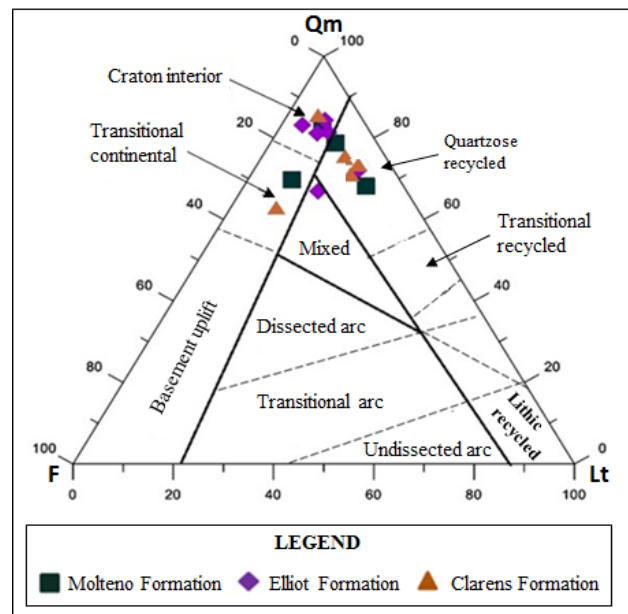
Figure 10: Qm-F-Lt ternary plot of data presented in Table 4 showing provenance of sandstones from the Molteno, Elliot and Clarens Formations (After [34]).

~223 Ma and P8 final phase at ~215 Ma in the Cape Fold Belt also acted as sources of sediments [8, 52, 53]. Much of these events occurred within the Molteno Formation and at the base of the Elliot Formation thereby resulting in forebulge uplift and two subaerial unconformities [50]. [19] reported how the recycled orogen produced the sub-

Table 5: Descriptive table summarizing the results of this study.

	Molteno Formation	Elliot Formation	Clarens Formation
Lithology	Greyish sandstones, mudstone and greyish-black shale	Reddish mudstones and sandstones	White and cream coloured sandstone and minor greyish mudstones with layered calcareous nodules
Sedimentary structure	Sandstones are mostly massive and structureless	Sandstones often display cross bedding, ripple marks and scour and fill structures	Sandstones are mostly massive with large – scale planar cross-beds
Thickness of beds	Sandstone beds are often thicker than the mudstones beds	Mudstone beds are much thicker than the sandstone beds	Sandstone beds are often thicker than the mudstones beds
Cyclotherms	Sandstone beds have an erosional surface beneath them thus marking the beginning of each vertical cyclotherms.	Sandstone beds have an erosional surface beneath them thus marking the beginning of each vertical cyclotherms.	Sandstone beds have an erosional surface beneath them thus marking the beginning of each vertical cyclotherms.
Depositional conditional	Black mudstone and shales are highly rich organic (reducing condition)	Red mudstone and shales are oxidized, giving the reddish-brown colour (oxidizing condition)	Greyish mudstones have low organic content (reducing-oxidizing condition)
Quartz content	72-86%	70-87%	66-90%
Feldspar content	8-24%	5-20%	5-22%
Lithics content	3-18%	4-13%	2-24%
Mica	1-3%	1-12%	1-9%
Grain size	Medium to coarse	Fine to medium	Fine to coarse
Sorting	Moderately well sorted	Moderate to well sorted	Moderate to well sorted
Sandstone classification	Felspathic litharenite, sub-arkose	Felspathic litharenite, sub-arkose	Litharenite, quartz arenite
Depositional environment	Mostly braided river (fluvial) deposits	Mostly alluvial fan channel (fluvio-lacustrine) deposits	Possibly ripple and aeolian (ephemeral streams/dune) deposits
Provenance	Recycled orogen (mostly in quartzose recycled)	Recycled orogen (mostly in craton interior zone)	Recycled orogen (mostly in quartzose recycled)

litharenites and quartzo-feldspathic sandstones of the Elliot Formation, which also occurred within the transitional continental and craton interior sources. [54, 55] proposed that the Archaean granite source, from which the Beaufort Group sediments were derived, also acted as a renewed source area for sediments of the Elliot Formation. The increasing aridity in the transition from the Triassic to Jurassic period most likely contributed to decreased supply of detritus from the Gondwana Orogeny [11]. The observed fine grained sandstones with better sorting were due to increased aridity which promotes the preservation of finer grained sediments thereby reducing the amount of fluvial input. The slightly high feldspar content in the sandstones has a climatic significance which is more closely related to an arid climate where chemical weathering is more restricted [19]. [56] observed that the palaeowind directions for the Clarens Formation indicated that the source regions for the sediments were towards the west, northwest and southwest of the depocentre. Much of the Clarens Formation sediments coincide in age with the end of magmatic activity associated with the Karoo Igneous Province [57]. [58] is of the view that some of the Clarens Formation sediments could have been sourced from the basaltic lavas representing early phases of igneous activity. A large proportion of zircon grains of Pan African age suggest that the rocks formed during the Pan-African Orogeny were the main source area for the sediments of the Clarens Formation [59].

6 Conclusion

The petrographic and mineralogical studies of the sandstones from the Molteno, Elliot and Clarens Formations have revealed that they can be classified as sub-litharenite and subarkose. The aeolian and fluvial sediments appeared to be composed of relatively similar mineral compositions. The absence of major petrographically distinctive compositional variations in the sandstones perhaps suggest a similar sediment source area. The sandstones have high content of quartz (62-91%) and low percentages of feldspar (<15%), thus it is inferred that the sandstones have passed through relatively long transportation distance from the source area. The fairly high feldspar content observed in the sandstones of the Clarens Formation as compared to the Molteno and Elliot Formations indicate dry climatic conditions which supported less chemical weathering and preserved less stable minerals. Petrographic and XRD analyses both revealed that the sandstones were mostly derived from granitic and metamorphic rock sources. The provenance analysis indicates that the sandstones were derived from recycled or quartzose source rocks reflecting a craton interior or transitional continental setting which probably came from the Cape Fold Belt.

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