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Modal composition and tectonic provenance of the sandstones of Ecca Group, Karoo Supergroup in the Eastern Cape Province, South Africa

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Abstract: Petrography of the sandstones of Ecca Group, Karoo Supergroup in the Eastern Cape Province of South Africa have been investigated on composition, provenance and influence of weathering conditions. Petrographic studies based on quantitative analysis of the detrital minerals revealed that the sandstones are composed mostly of quartz, feldspar and lithic fragments of metamorphic and sedimentary rocks. The sandstones have an average framework composition of 24.3% quartz, 19.3% feldspar, 26.1% rock fragments, and 81.33% of the quartz grains are monocrystalline. These sandstones are generally very fine to fine grained, moderate to well sorted, and subangular to subrounded in shape. In addition, they are compositionally immature and can be classified as feldspathic wacke and lithic wacke. The provenance characteristics suggest the influence of plutonic and metamorphic terrains (meta-magmatic arc) as the main source rock with minor debris derived from recycled sedimentary rocks. The latter revealed that the compositional immaturity of the sandstones is a result of weathering or recycling and short transport distance. The weathering diagrams and semiquantitative weathering index indicate that the Ecca sandstones are mostly from a plutonic source area, with climatic conditions ranging from arid to humid. The detrital modal compositions of these sandstones are related to back arc to island and continental margin arc. These results, therefore, support previous studies that infer foreland basin setting for the Karoo Basin.

Keywords: Petrography, provenance, tectonic setting, Ecca Group, Karoo Basin

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1 Introduction

Mineral modal composition analysis can be used to characterize and classify sedimentary rock types and to trace provenance of source materials. Sedimentary provenance study is to use measurements of compositional and textural properties of sediments to deduce the characteristics of source areas [1]. The purpose of sedimentary provenance study is to use siliciclastic rocks to reveal the provenance or source area of the sediments, tectonic setting of the sedimentary basins and the associated geological processes responsible for the deposition of the sediments [2–4]. The composition of clastic sedimentary rock is a function of a complex interactions between several factors that include the nature and mineral composition of the source rocks, source area weathering, diagenesis and tectonism [5]. Tectonic setting of the sedimentary basin is thought to have general control on the composition of sedimentary rocks. This is due to the fact that different tectonic environments have distinctive mineral composition characteristics and they are characterized by distinctive sedimentary processes [6]. Therefore, sedimentary rocks, especially sandstones, have been used to deduce 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 [5, 7–10]. The use of framework mineral composition (detrital modes) to determine the tectonic setting of sandstones was first proposed by [11] and has since undergone considerable modification and improvement such as the introduction of single-grain analysis [8, 12–16].

The Ecca Group of Karoo Supergroup is a sedimentary rock sequence that accumulated between the Late Carboniferous Dwyka Group and the Late Permian-Middle Triassic Beaufort Group [17]. This sedimentary succession outcrops in the Eastern Cape Province of South Africa and it comprises mainly of mudstones, siltstones and sandstones (Figure 1). According to [18], the Carboniferous-Permian Ecca Group sediments were intruded by dolerite sills and dykes (at about 180 Ma) during a period of prolonged magmatic activity that intruded much of the southern African subcontinent. The sandstones of the Ecca Group in the study area have not been studied previously in detail to classify the sandstones as well as determine their tectonic provenance. Previous studies carried out on the Ecca Group by several researchers mainly focused on the stratigraphy, lithofacies analysis, depositional environment, impact of dolerite intrusions and shale gas potential of the Ecca Group [7, 17, 19–24]. However, the source(s) of Ecca sediments are still not-well understood. This study was undertaken to interpret the sandstone petrography in order to characterize the detrital sediments of the Ecca Group and to deduce its provenance in the southeastern Karoo Basin of South Africa.

2 Geological setting

The Karoo Supergroup is well preserved in the Main Karoo Basin of South Africa. It covers approximately 700, 000 km^2 of South Africa land mass [22, 25]. During the Permian, it was much more extensive, covering parts of present-day Lesotho, Swaziland, and Mozambique [17, 22]. The basin is a retro-arc foreland setting that developed behind an inferred magmatic arc and fold thrust belt in relation to the Late Paleozoic-Early Mesozoic subduction episode of the palaeo-Pacific plate beneath the Gondwana plate [21, 26]. However, [27] gave a different interpretation for the tectono-sedimentary evolution of the Karoo Basin by subdividing it into a pre-foreland phase and a foreland phase. The pre-foreland phase that comprises of the Dwyka, Ecca and lower Beaufort Group was formed within the continental interior of Gondwana as a result of vertical movement of rigid blocks and intervening crustal faults. The foreland Karoo Basin (consisting of the upper Beaufort Group) developed in response to the uplift of the Cape Fold Belt during the Early Triassic [27]. Furthermore, [27] documented that the sedimentary fill in the Cape and Karoo basins are made up of several unconformity-bounded mega-sequences. These mega-sequences revealed that each basin episode is made up of three phases of evolution, involving crustal uplift, fault controlled subsidence and prolong periods of regional subsidence in which faulting was subordinate.

Ref. [28] proposed that the subsidence was partially controlled by dynamic topography (mantle flow) in relation to the subducting slab. The subsidence was due to mantle flow but becomes complicated as a result of variation or different degrees of foundering of the basement blocks [27]. During the Ecca time, these basement blocks may possibly have behaved or acted as a buried basin boundary and might have influenced the position of the shelf edge just as to a passive margin [27]. Tectonism and climate are the two main allogenic controls that influenced the sedimentary fill of the Karoo Basin [17, 21, 22, 29]. During the Karoo time, the tectonic regimes changed from mainly flexural in the south, in response to processes of subduction, accretion and mountain building along the Panthalassan (palaeo-Pacific) margin of Gondwana, to extensional in the north, in response to processes of spreading along the Tethyan margin of Gondwana. [17] further documented that the tensional episodes initiated during the Karoo time led to the development of early Tethyan spreading centre. This continued to control deposition in the Karoo Basin until the break-up of Gondwana in the Middle Jurassic. The fluctuations in tectonic and climatic conditions from the southern to the northern part of Africa during the Karoo time have led to significant changes in the lithostratigraphic characteristics of the Karoo sequence across the African continent. Consequently the stratigraphy of Karoo Supergroup in the northern (distal) region differs from those in the southern (proximal) region. [30] reported that the observed stratigraphic variation within the basin reveals different tectonic/evolutionary history across the flexural hinge line of the foreland system.

A detailed and continuous sedimentary succession of Permo-Triassic Karoo Supergroup clastic sediments outcropped along the southern margin of Gondwana, South Africa [17, 20, 21, 28–31]. The succession is approximately 12 km thick in the southeastern part of the Main Karoo Basin towards the eastern end of the Karoo Trough [22, 31]. 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 2). The term Ecca was suggested by Rubidge in [17] for the dominant argillaceous sedimentary strata that are exposed along the Ecca Pass, near Grahamstown in the Eastern Cape Province, South Africa. Hence, the term “Ecca” used outside the main Karoo Basin is sometimes questionable or inappropriate, because the rock types could be completely different. The absolute age of the Ecca Group is not well-constrained and most age determinations and correlations rely on fossil wood biostratigraphy and palynology [32]. The Karoo sedimentary sequence was subsequently intruded by several Early Jurassic dolerite sills and dykes (about 183 Ma), with the widest and thickest sills located within the Ecca Group [33]. Sedimentation in the Karoo succession is capped by the basaltic lavas of the Drakensberg Group, which can be linked to the breakup of Gondwana during the Middle Jurassic [34]. [35] disagree with the use of Stormberg Group in a formal lithostratigraphic scheme due to insufficient unifying lithologic features. However, it is used here for the sake of convenience. The sedimentary succession suggests that the depositional environment changes in the basin from glacial to deep marine, then deltaic, fluvial, playa lacustrine and finally aeolian [34]. This research work only focused on the Permian Ecca Group. Deep and shallow water environments with a cool climate predominated during the Ecca times, with coal forming in alluvial fan, fan delta and fluvial systems of the upper Ecca formations [19].

In the study area, the Ecca Group can be subdivided into five formations, namely, Prince Albert, Whitehill, Collingham, Ripon, Fort Brown and Waterford Formations [20]. These formations are partially correlative to the Pietermaritzburg, Vryheid and Volkrust Formations in the north-east of the basin [21]. The marine claystone and mudstones of the Prince Albert Formation were deposited on the top of diamictites of the Dwyka Group in the southern part of the basin [21]. This was followed by the carbonaceous shale of the Whitehill Formation. Subsequently, the Collingham Formation that is made up of persistent grey shales alternating with yellow-claystones, as well as the sandstones and shales of the Ripon, Fort Brown and Waterford Formations were deposited in the submarine fans, shelf and delta environments, respectively [7]. The Dwyka and Ecca Groups were deposited during the seaway transgression into the interior part of the southern Karoo Basin [37]. The change from deep marine to shallow marine during the lower Ecca time led to regression of the Ecca sea towards the southeast [38]. Afterwards, at the end of Ecca time, the complete regression that occurred from the limits of the preserved basin led to the formation of a fully non-marine environment resulting in the accumulation of the fluvio-lacustrine Beaufort Group [30, 34].

3 Methodology

A total of one hundred and twenty four (124) sandstone samples were collected from outcrops of the Ecca Group within the Eastern Cape Province (Figure 1). Thirty-five (35) representative thin sections of different types of sandstone and siltstone were prepared and studied under optical microscope and applied to modal composition analysis. In this study, comparative abundance of the main mineral constituents were determined by counting at least 500 points per thin section using the methods of [12] and [8]. Each thin section was analysed in accordance with the Gazzi-Dickinson's traditional point-counting method 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 advocated by [6, 8, 12]. Constituent minerals of the sandstones were classified into monocrystalline quartz, polycrystalline quartz, K-feldspar, plagioclase, lithic fragments (volcanic and sedimentary lithic fragments), accessory minerals and matrix. In order to classify the sandstones, framework detrital modes of the sandstones were normalized or recalculated to 100% (Table 3–5) and ternary diagrams of Q-F-L (quartz-feldspar-lithic fragments), Qm-F-Lt (monocrystalline quartz-feldspar-total lithic fragments) and Qt-F-L (total quartz-feldspar-lithic fragments) were plotted. Classifications of the sandstones were based on the methods adopted by [1, 8, 41–43]. Petrographic compositions of the Ecca sandstones are presented in Table 4. The Whitehill Formation of the Ecca Group is mainly made up of shale and chert. Therefore, the formation was not studied for modal compositional analyses. Clay minerals within the sandstone units and the whole rock analysis were determined by X-ray diffraction (XRD). The XRD result was used to confirm the petrographic framework. The X-ray diffraction measurements were performed on a Bruker XRD D8 Advance (Model: V22.0.28) at a room temperature of 25° and the samples were scanned at 2° 2θ per minute from 2° to 70° (wavelength of 1.5406).

4 Results

4.1 Sandstone petrography and texture

Detrital framework grains of the Ecca sandstones include quartz, feldspars, rock fragments, matrix and accessory minerals. The matrix is made of clay minerals and minor detrital silts. The sandstones are very fine to fine grained, subangular to rounded shapes, and poor to well sorted (Table 1). The amount of quartz, feldspar and rock fragments range from 18.4-31.8%, 10.6-34.4% and 14.8-32%, respectively (Table 4). The shape of quartz grains are mostly subangular to sub-rounded. Monocrystalline quartz (Qm) and polycrystalline quartz (Qp) grains are both present, with the monocrystalline quartz grains making up to 81.33%

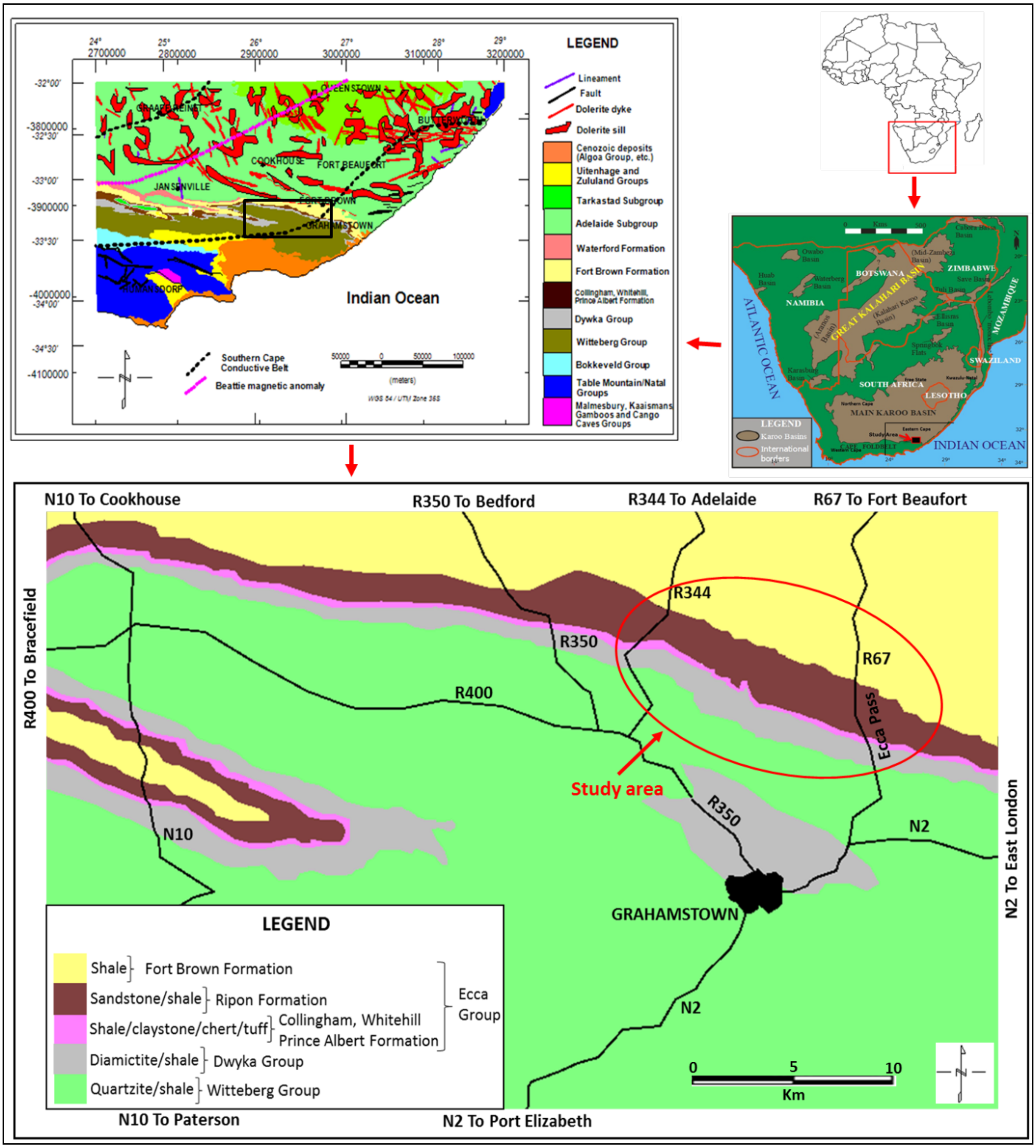


Figure 1: Geological map of the study area (After [20]).

of the total quartz grains in the samples analysed (Figure 3 and 4). Alkali feldspar (orthoclase and microcline) and plagioclase feldspar (albite) are the feldspar minerals present in the thin sections, with alkali feldspar and albite being the most dominant. The amount of feldspar grains range from 10.6-34.4%, averaging 19.41% of the total grains in the samples. Both monocrystalline and polycrystalline feldspar grains are present. The feldspar grains generally range from sub-angular to sub-rounded and some are partially replaced or altered to sericite. In few cases, they are altered to kaolinite, illite, muscovite or replaced by calcite. Albite and orthoclase are the dominant feldspar minerals occurring in both twinned and untwinned forms. About 70% of the plagioclase shows twinning, while others appear to be untwinned. Microcline only occurs in minor quantities and are completely absent in some samples. Albite grains are mostly elongated and shows parallel twinning, while those of microcline shows cross-hatch twin-

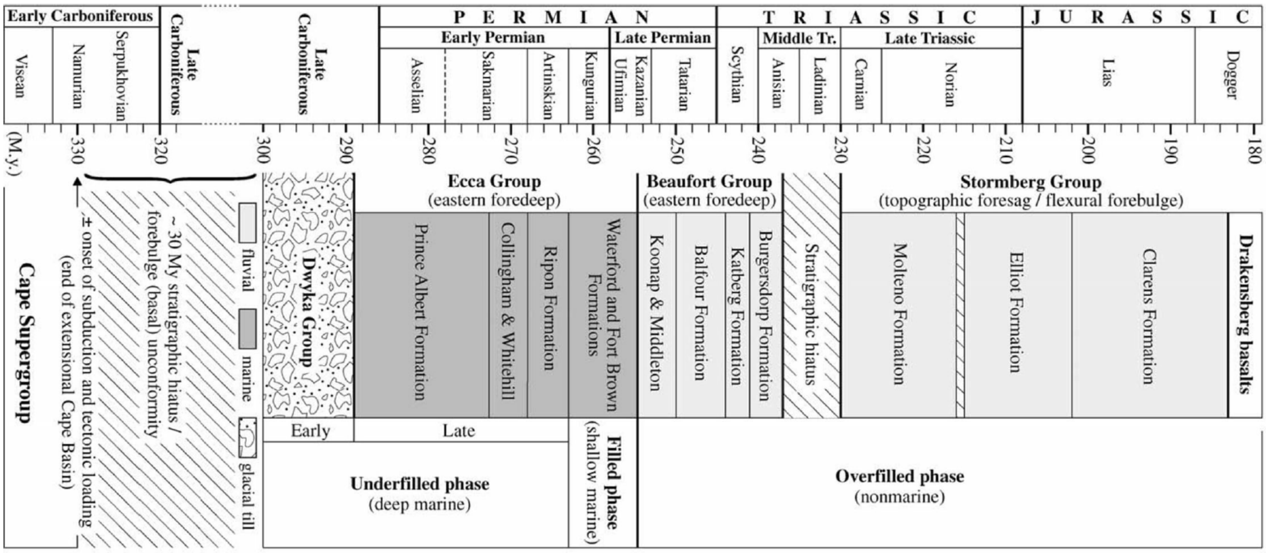


Figure 2: Stratigraphy and its subdivisions in the Main Karoo Basin of South Africa [36].

ning. The orthoclase grains are mostly cloudy in colour, but sometimes, they show simple twinning with perthite texture. Rock fragments that were identified are metamorphic, sedimentary and igneous in nature, and constitute an average of about 19.51% of the total grains. Mica, hematite, garnet, rutile and zircon are the accessory minerals. Muscovite and biotite are the mica in the sandstones, with muscovite occurring more frequently than biotite. Some of the muscovite grains are stained or invaded by chlorite. The detrital muscovite grains that are not altered or changed have an elongated flaky shape with parallel cleavage. The framework grains are bound together by both cement and matrix. Sericite, kaolinite and smectite are the most commonly observed matrix. Quartz and calcite cements are the main types of cements in the sandstones.

4.2 Mineralogy and modal composition

The XRD analyses of the sandstones are given in Table 2. The most abundant minerals include quartz (20-32%) and plagioclase (10-30%), while the dominant clay minerals are kaolinite/illite (4-18%), chlorite (4-13%) and sericite/calcite (20-39%). Quartz, feldspar, illite, sericite and muscovite were formed through recrystallisation, whereas kaolinite was formed through the dissolution of K-feldspar. In addition, kaolinite was also observed as having replaced muscovite grains and in some cases, illite formed through the replacement of feldspar grains. The identified heavy minerals are hematite, garnet and zircon and they all exist in traces. The modal compositions of the Ecca sandstones are presented in Tables 3–5.

5 Interpretation

5.1 Petrography and mineralogy

The rock are dominantly feldspathic and lithic wackes, with textural data indicating very fine to fine grain sizes, poor to well sorted, subangular to subrounded shapes and sometimes rounded. Ecca sandstones showed relatively high percentage of feldspar, lithic fragments and matrix (> 15%), indicating short transport distance and quick burial. The average contents and characteristics of different quartz and feldspar grains in these sandstones show igneous, metamorphic and pre-existing sedimentary rock sources. These have been proven by overall variation in the relative abundance of different types of quartz and feldspar grains. Quartz and feldspar grains are both polycrystalline and monocrystalline, indicating that they were not fully separated by long transportation, which is consistent with the immature nature of the rocks. Based on the genetic and empirical classification of the quartz types [43], monocrystalline quartz grains are mainly plutonic, hydrothermal and recycled sedimentary sourced, whereas polycrystalline quartz grains are recrystallized and stretched metamorphic types. The dominance of monocrystalline quartz grains show that the sediments were mostly derived from a granitic source [47].

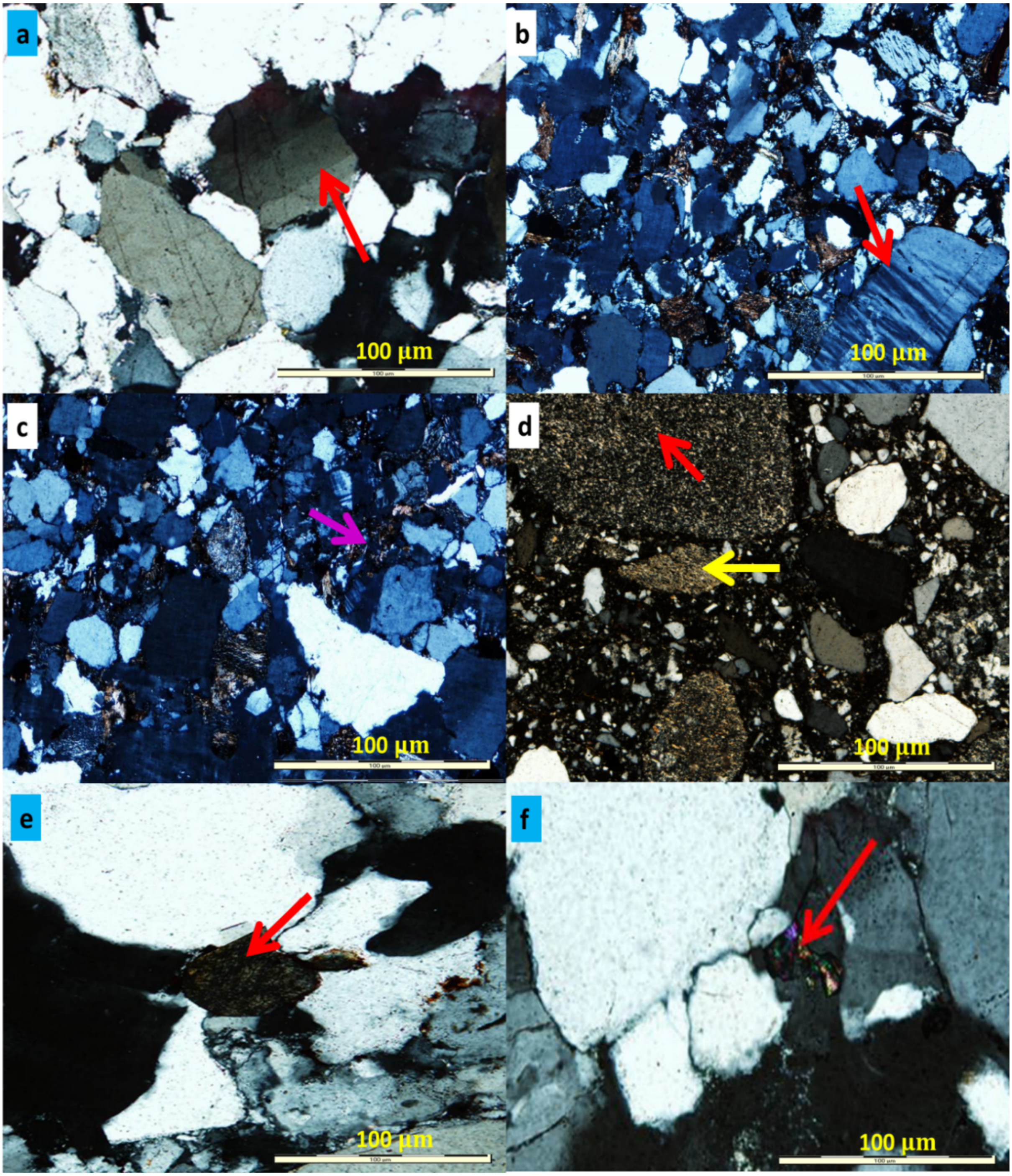


Figure 3: Photomicrographs of Ecca sandstones showing: (a) Quartz grain with undulose extinction (red arrow). (b) Feldspar lithic with perthitic texture (red arrow). (c) volcanic lithics (arrow) grains. (d) Laminated mudstone lithic (red arrow) and sedimentary lithics (yellow arrow). (e) Zircon mineral grain (red arrow). (f) Rutile mineral grain (red arrow).

On the other hand, [48] documented that such grains could have been formed due to disaggregation of the original polycrystalline quartz during high energy or long distance transport from the metamorphic source. Some of the polycrystalline quartz grains have three or more crystals with straight to slightly curved intercrystalline boundaries, which possibly suggest that they were derived from plutonic igneous rocks and metamorphic rocks [43, 49]. Though some monocrystalline and polycrystalline quartz grains exhibit undulatory extinction and occasional in-

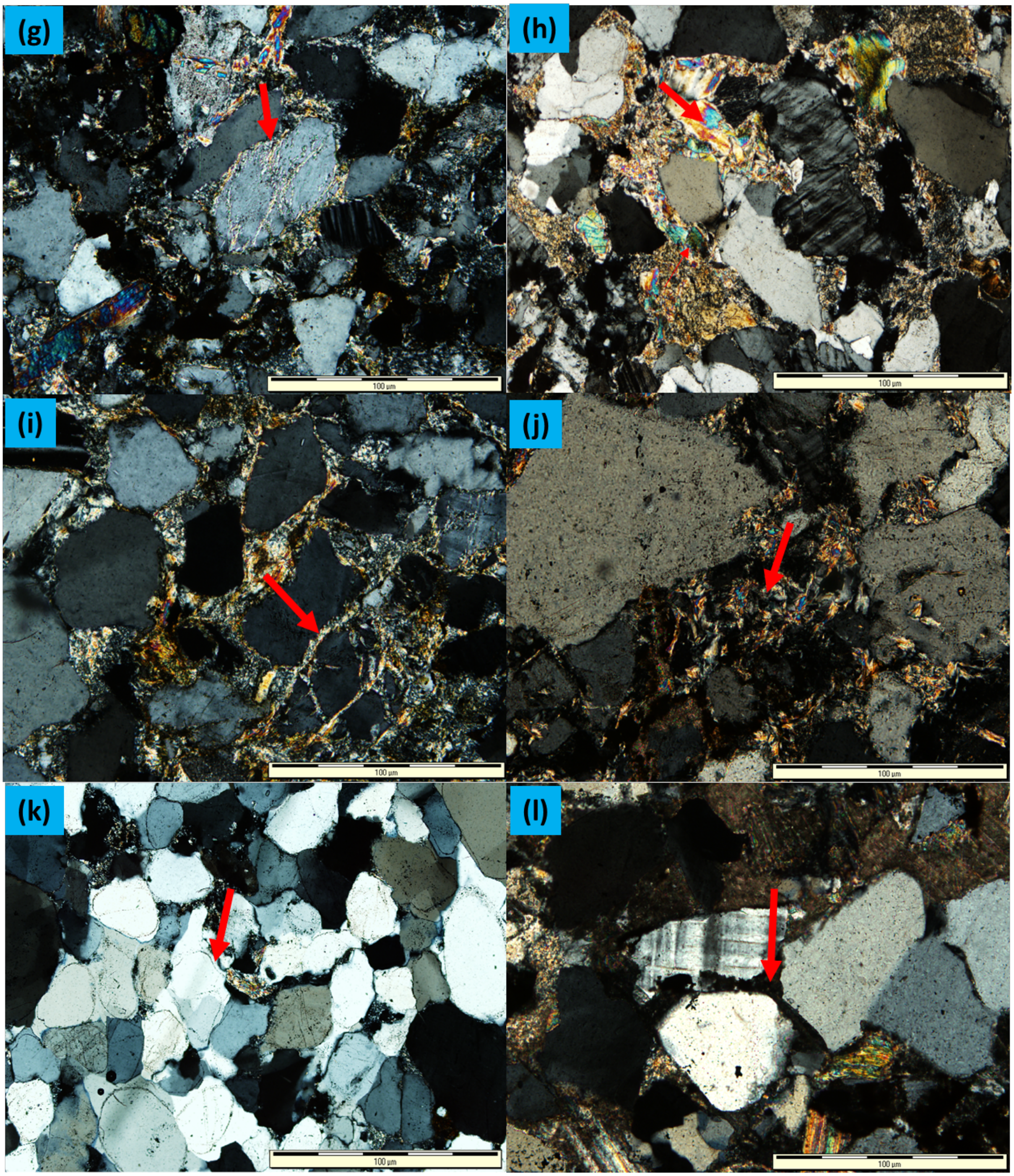


Figure 4: Photomicrographs of Ecca sandstones showing:(g) Partial replacement of feldspar grain by clay minerals (red arrow). (h) Recrystallization of clay matrix into muscovite (red arrow). (i) Pore lining clays (red arrow). (j) Recrystallization of clay matrix to illite (red arrow). (k) Quartz overgrowths (red arrow). (l) Dissolution along grain boundaries (red arrow).

tercrystalline suturing, which indicate metamorphic rock source (Figure 2b), other monocrystalline quartz grains have uniform extinction, unstrained and shows overgrowth. In few cases, the quartz grains contain muscovite, rutile needle and zircon inclusions within the crystalline grains, which suggest an igneous or metamorphic rock source [47, 50]. The presence few pure fragments of feldspar grains in some of the sandstones probably indicate igneous source, whereas the altered feldspar grains point to a metamorphic source [47]. The existence of micro-

Table 1: Textural characteristics of the lithofeldspathic sandstones from the Ecca Group.

s Formation	Sample	Mean grain size (φ)	Verbal grain-size	Roundness	Sorting
Fort Brown	FB 6	2.48	Fine sand	Subrounded	Moderately well sorted
	FB 5	2.04	Fine sand	Rounded	Well sorted
	FB 4	2.19	Fine sand	Subrounded	Well sorted
	FB 3	2.03	Fine sand	Subangular	Moderately well sorted
	FB 2	3.07	Very fine sand	Subrounded	Moderately well sorted Well
	FB 1	2.13	Fine sand	Rounded	sorted
Ripon	RP 19	3.04	Very fine sand	Subrounded	Well sorted
	RP 18	2.39	Fine sand	Subrounded	Well sorted
	RP 17	2.89	Fine sand	Rounded	Well sorted
	RP 16	3.13	Very fine sand	Subrounded	Well sorted
	RP 15	3.01	Very fine sand	Rounded	Very well sorted
	RP 14	2.97	Fine sand	Subrounded	Very well sorted
	RP 13	2.57	Fine sand	Rounded	Well sorted
	RP 12	2.47	Fine sand	Rounded	Well sorted
	RP 11	2.09	Fine sand	Subangular	Moderately well sorted Well
	RP 10	2.44	Fine sand	Subangular	sorted
	RP 9	2.27	Fine sand	Subrounded	Well sorted
	RP 8	2.92	Fine sand	Subrounded	Well sorted
	RP 7	2.04	Fine sand	Rounded	Well sorted
	RP 6	3.17	Very fine sand	Subangular	Moderately well sorted Well
	RP 5	2.94	Fine sand	Rounded	sorted
	RP 4	3.12	Very fine sand	Subangular	Moderately well sorted Well
	RP 3	2.96	Fine sand	Subrounded	sorted
	RP 2	2.78	Fine sand	Subrounded	Well sorted
	RP 1	2.41	Fine sand	Subrounded	Well sorted
Collingham	CH 5	3.13	Very fine sand	Subrounded	Moderately well sorted
	CH 4	3.27	Very fine sand	Subrounded	Moderately well sorted
	CH 3	3.34	Very fine sand	Subangular	Moderately well sorted Well
	CH 2	3.11	Very fine sand	Rounded	sorted
	CH 1	2.82	Fine sand	Subrounded	Moderately well sorted
Prince Albert	PA5	2.68	Fine sand	Subangular	Poorly sorted
	PA4	2.49	Fine sand	Subangular	Poorly sorted
	PA3	2.51	Fine sand	Angular	Poorly sorted
	PA2	2.21	Fine sand	Subangular	Poorly sorted
	PA1	2.55	Fine sand	Subangular	Poorly sorted

cline suggest that the source rock is of low grade metamorphic terrain and alkali-rich granites. The orthoclase and perthite in the sandstones possibly point to plutonic and metamorphic provenances. However, the percentage of alkali feldspar in the sandstones is small compared to other detrital components. Generally, mica is derived from metamorphic and igneous sources [1]. The relative abundance of muscovite and biotite in the sandstones suggest that the source rock is micaceous in nature, possibly of felsic igneous rocks or metamorphic rocks.

The identified clay minerals (kaolinite, smectite, illite, sericite and chlorite) possibly exist in the rock either as detrital grains or diagenetic minerals. The detrital nature of the framework grains and the presence of lithic fragments, thus, render the rocks to be terrigenous in origin. From the observed lithics and heavy minerals

Table 2: Semi-quantitative XRD estimates for some of the Ecca sandstone mineralogy in the Eastern Cape Province. PA: Prince Albert sandstone, CH: Collingham sandstone, RP: Ripon sandstone and FB: Fort Brown sandstone, tc: trace, - : not detected.

Sample	PA 1	PA 2	CH 1	CH 2	RP 1	RP 2	FB 1	FB 2
Plagioclase (%)	15	10	13	12	19	25	30	26
Microcline (%)	tc	2	-	4	-	-	2	1
Quartz (%)	20	24	30	32	28	32	29	31
Kaolinite/illite (%)	14	18	11	13	7	5	6	4
Chlorite (%)	8	6	13	10	10	8	5	4
Mica (%)	4	3	4	5	1	2	2	1
Sericite/calcite (%)	31	39	28	23	34	25	20	24
Talc/pyrophyllite (%)	-	-	-	tc	tc	2	5	8
Smectite (%)	7	5	-	-	-	-	-	-
Hematite (%)	tc	tc	tc	tc	tc	tc	tc	tc
Garnet (%)	tc	tc	tc	tc	tc	tc	tc	tc
Zircon (%)	tc	tc	tc	tc	tc	tc	tc	tc
Zeolite (%)	-	-	-	-	-	tc	tc	tc

Table 3: Framework parameters of detrital modes [6, 46].

Parameter	Explanation
Q	Quartz (Qm + Qp)
Qp	Polycrystalline quartz
Qm	Monocrystalline quartz
Qt	Total quartzose grains (Qm + Qp)
P	Plagioclase feldspar
K	Potassium feldspar
F	Total feldspar grains (P + K)
Lv	Volcanic-metavolcanic rock fragments
Ls Lm	Sedimentary rock fragments Metamorphic lithic fragments
Lsm	Metasedimentary lithic fragments
L	Unstable (Siliciclastic) lithic fragments (Lv + Ls + Lsm)
Lt	Total siliciclastic lithic fragments (L + Qp)

and the nature of quartz and feldspar minerals, it can be inferred that the provenances of the sediments were derived mostly from igneous and metamorphic rock sources, rarely from sedimentary rock source. Furthermore, the relative abundance of monocrystalline quartz, zoned albite and tuffaceous material in the Collingham Formation also point to the existence of volcanic rocks in the sediment source area. Under the microscope, illite is more dominant in the Prince Albert and Collingham Formation where a deep marine environment existed, whereas kaolinite is dominant in the sandstones of Ripon and Fort Brown Formations that formed in a deltaic environment. Though diagenetic processes may have played a role in the distribution of these minerals, the rate of sedimentation and the environmental conditions also contributed to nature of the sediments. [51] documented that weathered materials which are deposited slowly can migrate far out into the sea and be transformed through recrystallisation into illite, while kaolinite was thought to have been deposited as large crystals along the coast where it would be able to grow by diagenetic processes. The distribution of these minerals puts further emphasis on the nature of the depositional environments, which is well represented in the model proposed by Smoot in [51]. Based on the model depicted in Figure 5, it can be infer that indeed the Prince Albert and Collingham Formations were deposited in deep marine water environment, whereas Ripon and Fort Brown Formations were deposited in shallow marine waters under the influence of deltaic processes.

Table 4: Modal compositions of the lithofeldspathic sandstones from the Ecca Group.

SAMPLE	Qt (%)	Qm (%)	Qp (%)	F (%)	L (%)	Lt (%)	Mx (%)	Acc (%)	Normalized (100 %)					
									Qm-F-Lt (%)			Qt-F-L (%)		
									Qm	F	Lt	Qt	F	L
FB 6	27.4	21.6	5.8	32.0	17.6	23.4	18.6	4.4	28.05	41.6	30.4	35.6	41.6	22.9
FB 5	24.2	20.6	3.6	34.4	18.6	22.2	20.2	2.6	26.7	44.6	28.8	31.4	44.6	24.1
FB 4	31.8	27.8	4.0	26.4	20.4	24.4	17.2	4.2	35.4	33.6	31.0	40.5	33.6	26.0
FB 3	29.2	27.4	1.8	26.2	29.2	31.0	13.6	1.8	32.4	30.8	36.6	34.5	31.0	34.5
FB 2	30.6	26.2	4.4	26.2	16.8	21.2	21.4	5.0	35.6	35.6	28.8	41.6	35.6	22.8
FB 1	28.4	23.8	4.6	32.8	14.8	19.4	20.8	3.2	31.3	43.1	25.5	37.4	43.2	19.5
R 19	18.6	15.8	2.8	17.2	26.2	29.0	31.2	6.8	25.5	27.7	46.8	30	27.7	42.3
R 18	17.8	15.2	2.6	12.8	18.2	20.8	33.6	17.6	31.1	26.2	42.6	36.5	26.2	37.3
R 17	23.0	19	4.0	20.6	29.6	33.6	23.4	3.4	26.0	28.1	45.9	31.4	28.1	40.4
R 16	23.0	14.2	8.8	20.8	24.0	32.8	25.6	6.6	20.9	30.7	48.4	33.9	30.7	35.4
R 15	21.4	20.2	1.2	23.2	16.6	17.8	34.0	4.8	33.0	37.9	29.1	35.0	37.9	27.1
R 14	24.4	20.0	4.4	18.4	26.4	30.8	24.8	6.0	28.9	26.6	44.5	35.3	26.6	38.2
R 13	27.2	20.4	6.8	19.2	18.6	25.4	30.4	4.6	31.4	29.5	39.0	41.9	29.5	28.6
R 12	30.0	25.4	4.6	16.8	20.8	25.4	26.8	5.6	37.6	24.9	37.6	44.4	24.9	30.8
R 11	24.8	21.6	3.2	17.2	23.2	26.4	32.4	2.4	33.1	26.4	40.5	38.0	26.4	35.6
R 10	21.6	15.6	6.0	16.4	25.4	31.4	32.2	4.4	24.6	26.0	49.5	34.1	25.9	40.1
R 9	20.8	15.2	5.6	11.4	17.2	22.8	42.2	8.4	30.8	23.1	46.2	42.1	23.1	34.8
R 8	19.6	15.0	4.6	14.8	29.6	34.2	34.0	2.0	23.4	23.1	53.4	30.6	23.1	46.3
R 7	25.6	17.6	8.0	23.0	31.6	39.6	16.8	3.0	21.9	28.7	49.4	31.9	28.7	39.4
R 6	18.4	11.2	7.2	20.0	22.4	29.6	32.4	6.8	18.4	32.9	48.7	30.3	32.9	36.8
R 5	27.4	22.0	5.4	21.2	32.0	37.4	17.2	2.2	27.3	26.3	46.4	34	26.3	39.7
R 4	29.0	25.0	4.0	20.6	25.6	29.6	21.4	3.4	33.2	27.4	39.4	38.6	27.4	34.0
R 3	23.0	18.2	4.8	11.8	20	24.8	41.2	4.0	33.2	21.5	45.3	42.0	21.5	36.5
R 2	30.2	23.8	6.4	23.2	24.8	31.2	16.2	5.6	30.4	29.7	39.9	38.6	29.7	31.7
R 1	26.8	21.8	5.0	19	16.4	21.4	30.6	7.2	35.0	30.6	34.4	43.1	30.6	26.4
CH 5	31.6	26.4	5.2	16.8	19.6	24.8	25.6	6.4	38.8	24.7	36.5	46.5	24.7	28.8
CH 4	24.6	19.2	5.4	19	17.8	23.2	35.2	3.4	31.2	30.9	37.8	40.1	30.9	29.0
CH 3	28.6	26.2	2.4	20.4	18.0	20.4	28.4	4.6	39.1	30.5	30.5	42.7	30.5	269
CH 2	30.4	24.8	5.6	15.8	21.4	27.0	20.8	11.6	36.7	23.4	39.9	45.0	23.4	31.7
CH 1	27.8	21.2	6.6	12.8	20.6	27.2	32.0	6.8	34.6	20.9	44.4	45.4	20.9	33.7
PA 5	19.4	15.8	3.6	10.8	18	21.6	42.6	9.2	32.8	22.4	44.8	40.3	22.4	37.3
PA 4	23.2	20.4	2.8	13.8	18.6	21.4	34.0	10.4	36.7	24.8	38.5	41.7	24.8	33.5
PA 3	20.4	16.8	3.6	10.6	21.0	24.6	42.2	5.8	32.3	20.4	47.3	39.2	20.4	40.4
PA 2	23.8	19.2	4.6	12.8	16.0	20.6	35.0	12.4	36.5	24.3	39.2	45.3	24.3	30.4
PA 1	18.4	17.2	1.2	15.6	17.0	18.2	41.2	7.8	33.7	30.6	35.7	36.1	30.6	33.3

Table 5: Mean modal compositions of sandstones of the Ecca Group.

Formation	Qm	Qp	L	Mx	Acc	Qt	F	Lt
Fort Brown	24.57	4.03	19.57	18.63	3.53	28.6	29.67	23.6
Ripon	18.80	5.02	23.61	28.76	5.52	23.82	18.29	28.63
Collingham	23.56	5.04	19.48	28.4	6.56	28.6	16.96	24.52
Prince Albert	17.88	3.16	18.12	21.28	9.12	21.04	12.72	21.28

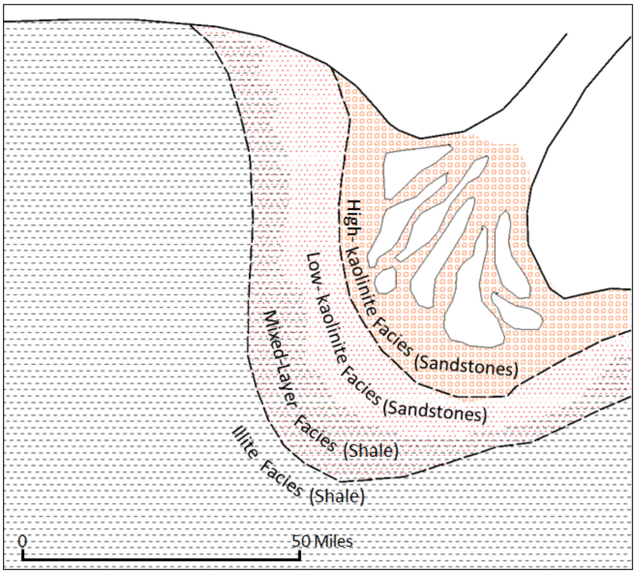


Figure 5: Idealised distributions of clay minerals as a function of facies, as proposed by Smoot in [51].

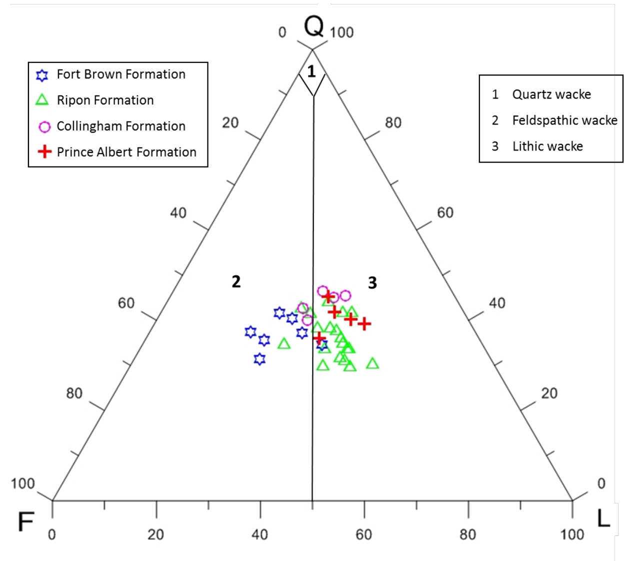


Figure 6: Q-F-L ternary plot of the data presented in Table 4, showing classification of the Ecca sandstones (After [40, 42]).

5.2 Sandstone classification

The most effective and commonly used methods for sandstone classification integrate both texture and mineralogy [2, 8, 39–44, 65]. Matrix minerals, which could have been introduced or diagenetically formed, are often taken into consideration. Folk's classification revealed vital information about provenance with the rock's name reflecting details of its composition as proven and documented by [45]. Based on the method of [1, 41], the Ecca sandstones can be classified as wacke or greywacke. The characteristic feature of the greywacke is the dominance of matrix (> 15 % matrix; Table 6). The Ecca greywacke can be further subdivided into feldspathic and lithic greywacke based on the framework grains (quartz, feldspar and lithic). This petrographic subdivision is supported by the QFL ternary classification scheme of [8, 43], in which the samples plotted as both feldspathic and lithofeldspathic sandstones (Figures 6–8). In the feldspathic graywackes,feldspar grains were most dominant as compared to the lithics, whereas in the lithic graywacke, percentage of the rock fragments are higher than those of the feldspars. However, the lithic graywacke generally have a wide range of composition with respect to grain types.

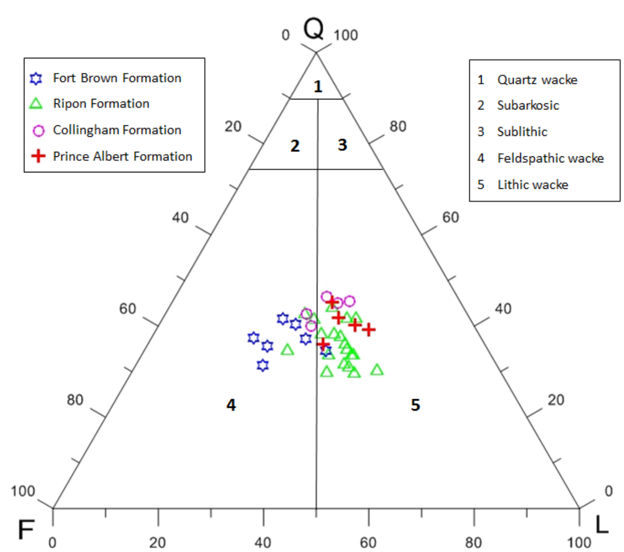


Figure 7: Q-F-L ternary plot of the data presented in Table 4, showing classification of sandstones from the Ecca Group in the Eastern Cape Province (After [43]).

Table 6: Classification of sandstones based on [1].

	Matrix, i.e., fine terrigenously derived minerals, e.g., clay minerals		Matrix prominent (>15%)	Matrix of fine terrigenous silt or clay absent or scanty (< 15%)		
Sand fraction		Greywacke		Arkosic sandstones		Quartz arenite
	Feldspar exceeds rock fragments		Feldspathic greywacke	Arkose	Sub-arkose or feldspathic sandstones	
				Lithic sandstones		
	Rock fragments exceed feldspar		Lithic greywacke	Sub-greywacke	Proto-quartzite	
	Quartz content		Variable; generally < 75%	< 75%	> 75%	> 95%

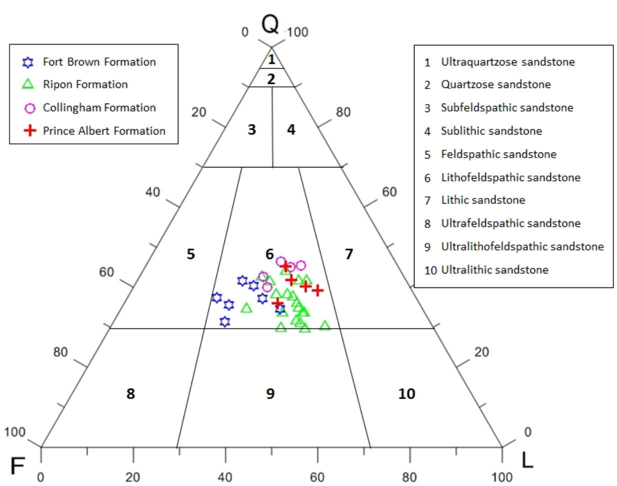


Figure 8: Q-F-L ternary plot of the data presented in Table 4, showing mineralogical classification of the Ecca sandstones (After [8]).

6 Discussion

6.1 Tectonic setting

Provenance studies of sandstone is mainly based on the assumption that different tectonic environments contain distinctive characteristic rock types [6]. Several researchers [8, 10, 12, 52] have linked detrital sandstone compositions to different provenance types (i.e. stable cratons, basement uplifts, magmatic arcs and recycled orogens) using the Qt-F-L and Qm-F-Lt ternary diagrams. The average compositions of sandstone suites sourced from different plate tectonic environments controlled provenance terranes, tend to plot within discrete and separate fields on Qt-F-L and Qm-F-Lt diagrams [12]. These plots have also been attempted for the Ecca sandstones to discriminate between the different kinds of tectonic settings. In the Qt-F-L ternary diagram (after [12]), the Ecca sandstones plotted in the dissected arc and recycled orogen field (Figure 9). This is an indication that the sediments' source were derived from recycled orogeny and magmatic arc provenances. Within recycled orogens, sediment sources are mainly sedimentary with minor volcanic rocks, partly metamorphosed and exposed to erosion by orogenic uplifted fold-belts [8, 12].

Ternary plot of Qm-F-Lt after [10] shows that the samples fall in the transitional arc, dissected arc and mixed fields (Figure 10). In contrast, this suggests that the primary or host rock where the sandstones were derived are solely of magmatic arc provenance. As documented by [8], within active magmatic arcs, sediment sources are predominantly in the volcanic cover capping the fold belt and in granitic plutons of the arc roots. Minor debris is thought to have been derived from bounding envelopes of metamorphic rock and adjoining sediments cover. Sands that are derived from this environment tend to produce a spectrum of lithofeldspathic and feldspatholitic types of which the compositions are usually scattered across the central part of Q-F-L plot, as evidenced in Figure 9. The Qt-F-L ternary plot after [53] indicate that the sandstones are of magmatic arc provenance, which comprises of dissected, renewed and matured magmatic arc provenances (Figure 11). Figure 12 shows that the sandstones plotted in the mixed and plutonic to volcanic sources of the [10] discrimination fields. Again, this is an indication that the sediments' source were derived from plutonic and volcanic sources. The detrital modal compositions of the Ecca sandstones are related to strike slip (SS), back arc to island (BA) and continental margin arc (CA) settings (Figure 13) [52]. This also agrees with the work of [8] in which they documented that arkosic sands (feldspathic wacke) predominantly derived from plutons of magmatic arcs are gradational. This sand has similar composition and characterisitcs with those sands derived from basement uplifts that expose granite and gneiss elsewhere within continental blocks. Generally, the Q-F-L provenance data indicate influence of plutonic, volcanic and metamorphic terrains as the main source rock with minor debris derived from recycled sedimentary rocks. The lithic wackes are characteristically volcanoplutonic sands derived from dissected arcs where erosion has exposed batholiths underneath volcanic cover. On the other hand, the feldspathic wackes with less lithic sands are thought to have been derived from the transitional arc.

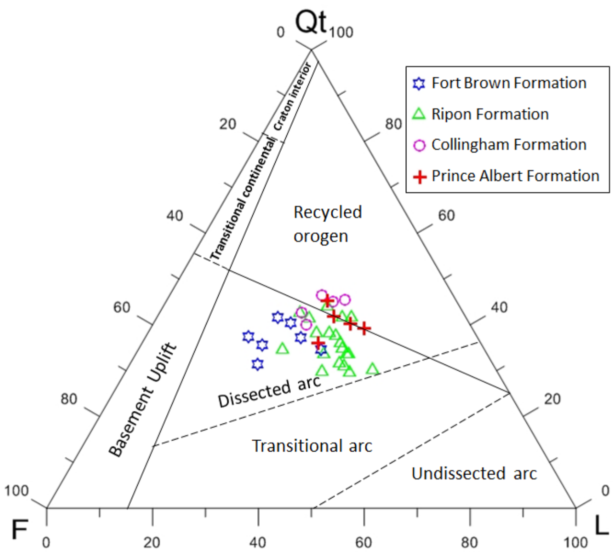


Figure 9: Qt-F-L ternary plot of the data presented in Table 4 showing provisional subdivisions of the Permian Ecca sandstones, according to inferred provenance type (After [12]).

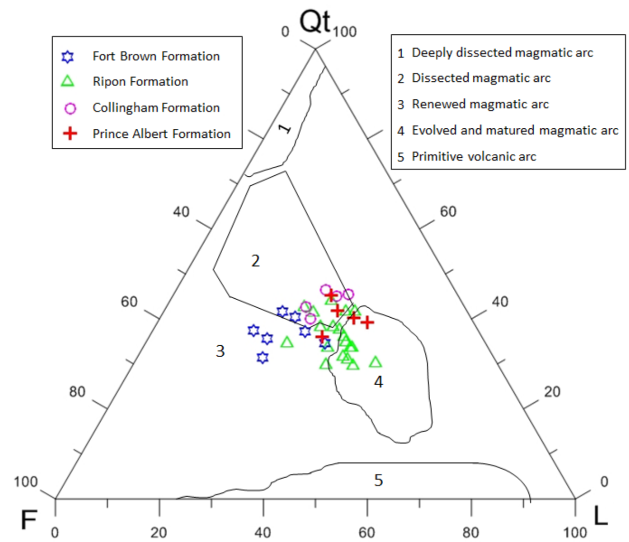


Figure 11: Ecca sandstone modal data (Table 4) plot on the Qt-F-L diagram used to discriminate between provenance types of magmatic arc, as proposed by [53].

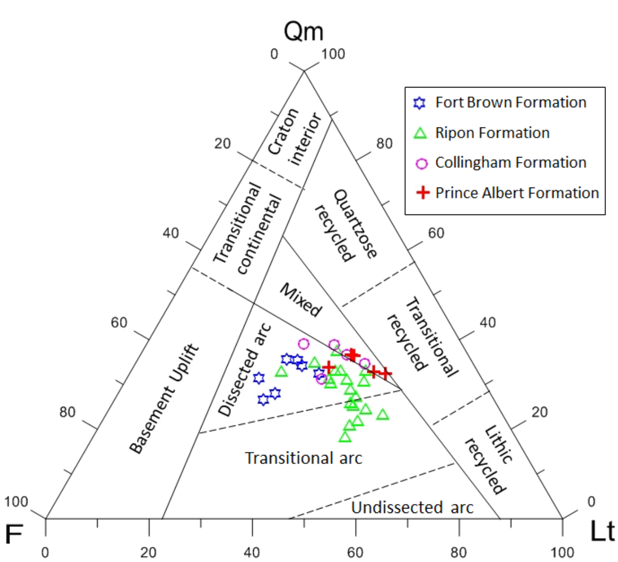


Figure 10: Qm-F-Lt ternary plot of the data presented in Table 4 showing provenance of the Permian Ecca sandstones (After [10]).

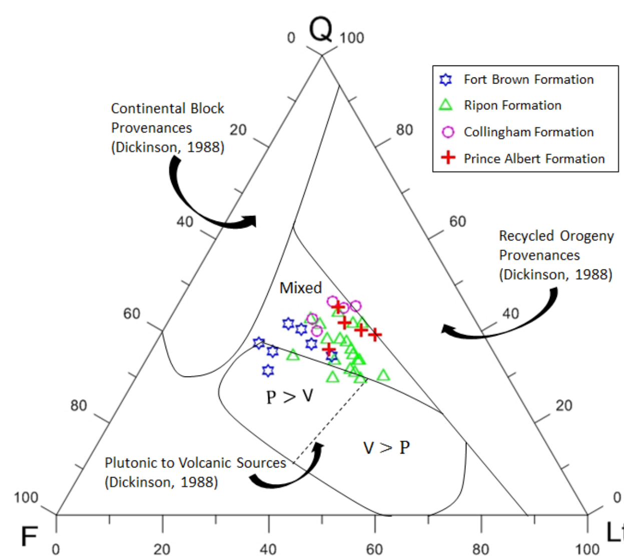


Figure 12: Ecca sandstone modal data (Table 4) plot on the Q-F-L diagram of [8]. Provenance field boundaries are taken from [10].

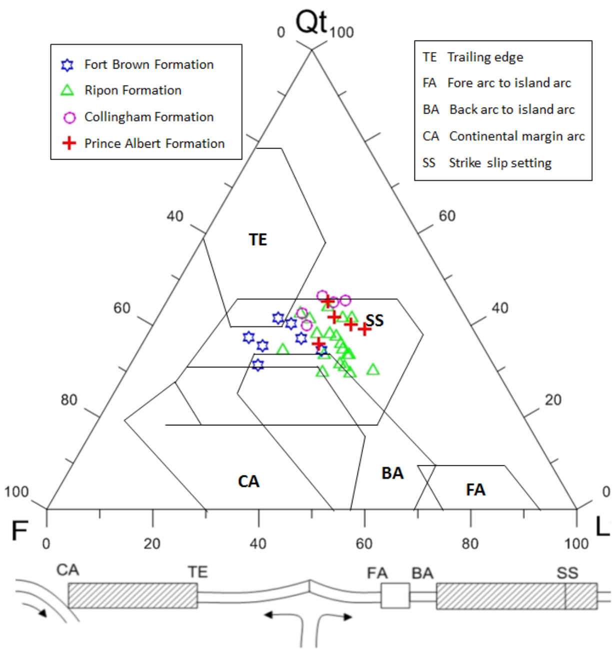


Figure 13: Qt-F-L ternary plot of the data presented in Table 4 showing tectonic provenance of the Ecca sandstones, in accordance to the schemes proposed by [52].

6.2 Weathering of source areas

The abundance of detrital framework grains plotted on ternary diagram gives an effective discrimination between different tectonic settings. It has been used as a vital tool for unravelling the origin and tectonic environment of terrigenous deposits [6, 54]. However, the relationship between sandstone petrofacies (facies distinguished principally by composition and appearance) and tectonic setting does not always hold well due to the influence of other factors (i.e. climate and topographic relief) on mineralogy of the detrital sandstones [55]. Weathering in the source area is one of the most significant processes that does not only affect the sandstone composition but also aid in determining the source rock and climatic condition of the sediment source area. Stronger chemical weathering is usually associated with warm and humid climates, whereas more arid climate is mostly allied with relatively weak chemical weathering. [56, 57] documented that tropical warm and humid climates supported by low relief that led to intense chemical weathering is the most active agent modifying the composition of the original detritital sandstone. Other modifying agents include sediment transport across tectonic boundaries, changing tectonic styles at provenance as well as mixing with other sources, sediment recycling and reworking in depositional environment and diagenesis [58, 59]. The proposed diagrams of [56, 60–62] were used to discriminate sources of metamorphic and plutonic rocks in different climatic conditions.

The relatively high percentage of unstable grains (i.e. feldspar and other rock fragments) point to weak weathering, quite short transport distance and quick burial for the sandstones. The abundance of quartz in all the samples is fairly low which could possibly indicate less weathering in the source area as a result of rapid uplift. The QFL ternary plot after [56] shows that the Ecca sandstones are of plutonic source area, with climatic conditions ranging from arid to humid (Figure 14). However, the bivariate plot after [60] revealed that the climatic conditions varies between semi-arid and semi-humid (Figure 15). This possibly indicate that the parent rocks were situated in both arid and humid climatic setting during the Permian time. The presence of polycrystalline quartz grains that are not elongated nor flattened, but of nearly equant grains with sutured intercrystalline boundaries and non-undulose quartz extinction support a plutonic igneous granitoid source as the dominant source rock under a humid climatic condition [1, 43, 49, 57, 65]. Nonetheless, the presence of monocrystalline quartz with strong undulose extinction and metamorphic rock fragment suggest that some of the sediments were of metamorphic source. In the [61] weathering index wi = c * r (Figure 16) and [63] diagrams (Figure 16), most of the sandstones clustered in the field of wi = 0. This either indicates sedimentation in a high relief with climatic conditions changing between semi arid, temperate, tropical and humid, or in a low to moderate relief under semi arid conditions. [64] reported that the diagrams (Figures 14 and 15) are defined for first-cycle sediments and the effect of recycling and long distance transportation can move or shift the data on the diagrams toward the humid conditions. In a regional context of the evolution of the Ecca Group, our data support the interpretation that the Ecca Group was deposited in a foreland basin generated after the accretion of Gondwana [2, 4, 7, 12, 27, 37, 65].

7 Conclusions

The petrographic study of Ecca sandstones revealed that they are poorly sorted, compositionally immature and can be classified as feldspathic wacke and lithic wacke. The absence of major petrographically distinctive compositional variations in the sandstones perhaps indicate homogeneity of their source. As a result of this, it is inferred that the transportation distance from the source area was quite short and the main mechanism of transportation was

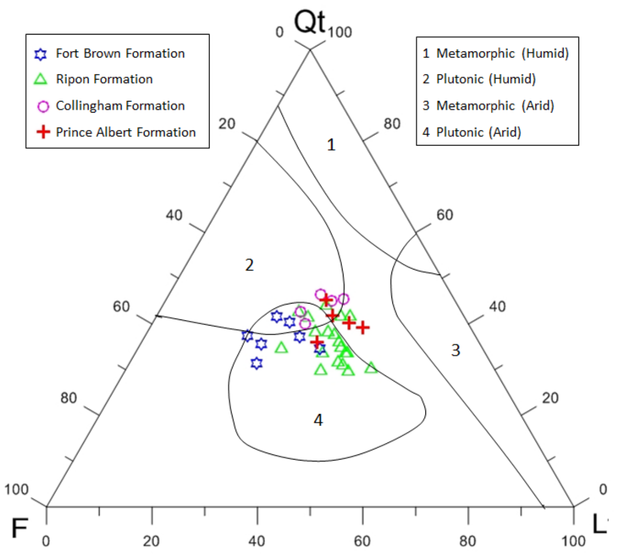
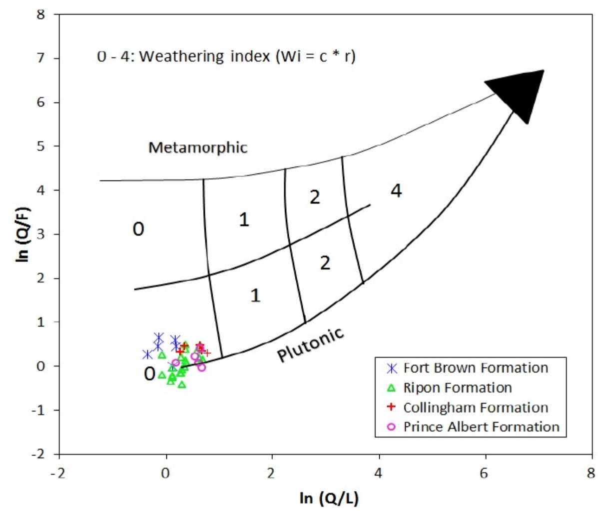


Figure 14: Qt-F-L ternary plot of the data presented in Table 4, showing the effect of climate on the composition of the Ecca sandstones (After [56]).



Semi-quantitative weathering index Wi = c * r			Relief (r) High mountain 0	Moderate hills 1	Low plains 2
(precipitation)	Semi arid and Mediterranean	0	0	0	0
	Temperate subhumid	1	0	1	2
	Tropical humid	2	0	2	4

Figure 16: The effect of climate on the composition of the Ecca sandstones (Table 4) using weathering diagram (After [63]) and semi-quantitative weathering index (After [61]). Q: quartz, F: feldspar, L: rock fragments. Fields 1-4 refer to the semi-quantitative weathering indices defined on the basis of topographic relief and climate as indicated in the table.

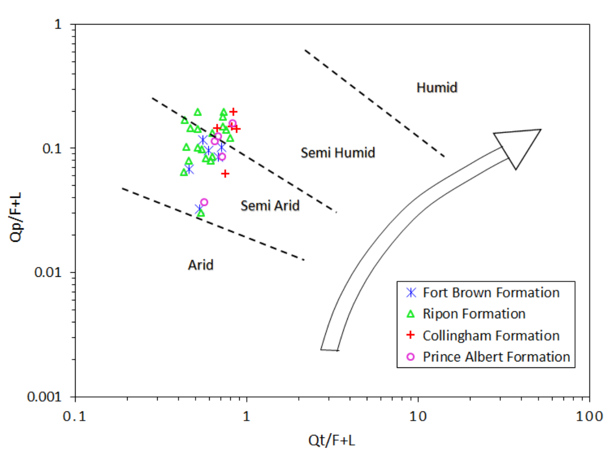


Figure 15: The effect of climate on the composition of the Ecca sandstones (Table 4) using bivariate plot proposed by [60].

by river systems to the basin. Both Petrographic and XRD analyses revealed that the sandstones were derived from granitic, metamorphic and pre-existing sedimentary rock sources.

The QFL ternary diagrams revealed dissected and transitional arc provenance pointing to an active margin and uplifted basement preserving the signature of a recycled provenance. This is an indication that the sandstones werederived from a magmatic arc provenance. Since magmatic provenance include transitional arc and dissected arc, it also shows that the source area of the Ecca sediments had a secondary sedimentary and metasedimentary rocks from a marginal belt that developed as a result of rifting.

The weathering diagrams and semi-quantitative weathering index indicate that the Ecca sandstones are mostly from a plutonic source area, with climatic conditions ranging from arid to humid. In addition, the compositional immaturity of the sandstones is suggested to be due to weathering or recycling and low relief or short transport from the source area. The origin and deposition of the Ecca sandstones are due to low-moderate weathering, recycling of pre-existing rocks, erosion and transportation of debris from the orogeny of the Cape Fold Belt which has been described by Halbich (1992) as a single phase multiple events orogeny.

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