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STRATIGRAPHY, SEDIMENTARY FACIES AND DIAGENESIS OF THE ECCA GROUP, KAROO SUPERGROUP IN THE EASTERN CAPE, SOUTH AFRICA

By

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DECLARATION

I, Nonhlanhla Nyathi, hereby declare that the research described in this dissertation was carried out in the field and under the auspices of the Department of Geology, University of Fort Hare, under the supervision of Professor K. Liu and Prof. O. Gwavava.

This dissertation and the accompanying photographs represent original work by the author, and have not been submitted, in whole or in part, to any other university for the purpose of a higher degree. Where reference has been made to the work of others, it has been dully acknowledged in the text.

N. NYATHI Date signed: 12/04/2014

Place signed: Alice

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ABSTRACT

This is a MSc research project, and is aimed at the new insight on the stratigraphy, sedimentary facies, diagenesis and depositional environments of the Ecca Group, Karoo Supergroup in the Eastern Cape Province. Methodologies used in this research include field investigation, stratigraphic logging, thin-section microscope study, X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) analyses.

The stratigraphy of the Ecca Group is divided into five formations, namely the Prince Albert Formation, Whitehill Formation, Collingham Formation, Rippon Formation and the Fort Brown Formation from bottom upward. Based on the field investigation and laboratory correlation, the Prince Albert, Whitehill, Collingham, and Fort Brown Formations can each be subdivided into two new members, i.e. lower member and upper member; whereas three new members have been proposed for the Rippon Formation, i.e. lower, middle and upper members.

The Ecca Group sediments were accumulated in various depositional environments, from bottom of deep marine environment, passed through the middle of deltaic environment, and ended in a lacustrine environment. The Prince Albert Formation, Whitehill Formation and the Collingham Formation were all deposited in a deep marine basin, whilst the Rippon Formation was laid down in a deltaic environment. As the climate gradually became warmer and drier, the top Fort Brown Formation was lastly deposited in a lacustrine environment. The stratigraphic succession of the Ecca Group constitutes a perfect regression sequence, indicating that the marine water gradually retreated and the sea-level gradually dropped.

The rocks in the Ecca Group are mainly terrigenous sandstone and mudstone with some coarse grain-sized siliciclastic rock of conglomerate. The sandstones are dominated by feldspathic graywackes with minor quartz-wackes, and there are no arenites in the Ecca Group. Whereas the mudstones are dominated by grayish mudrocks and black shales, purer claystone was found in the turbidite facies of the Collingham Formation, which probably has economic significance for the future since the reserve is quite large.

Optical microscope, XRD and SEM analyses demonstrated that the minerals in the Ecca Group include detrital minerals of quartz, orthoclase, microcline, plagioclase, biotite, muscovite; and clay minerals (smectite, kaolinite, illite and sericite). These minerals constitute the rock framework grains and cements whereas; the authigenic minerals of calcite

and hematite were formed during diagenesis. Accessory minerals such as rutile and zircon are the heavy minerals present in the strata, and occur only in a small amount.

Based on the lithologies, sedimentary structures and sequence stacking patterns, ten sedimentary facies have been recognised, namely 1) Grayish laminated and thin bedded shale facies, 2) Grayish laminated shale and intercalated chert facies, 3) Grayish rhythmite facies (all the three facies above were deposited in deep marine water); 4) Flat and lenticular bedded graywacke facies, 5) Grayish alternating mudstone and sandstone facies, 6) Dark organic rich mudstone facies, 7) Fossil bearing mudstone facies, 8) Laminated and thin bedded black mudstone with lenticular siltstone facies, 9) Interbedded grayish sandstone and mudstone facies (above Facies 4-9 were deposited in deltaic environment and appeared in the Rippon Formation); and 10) Varved rhythmic mudstone facies, which occurs only in the Fort Brown Formation and represents lacustrine sediments.

Four types of cements have been identified in the rocks of the Ecca Group, including quartz, smectite, calcite and feldspar cements. The first three cement types are the major cement types, whilst the feldspar cement is minor and occurs only locally.

Recrystallisation in Ecca sediments includes quartz, feldspar, clay mineral recrystallisation and conversion from smectite and kaolinite to illite and then to sericite. Replacement involves calcite replacing quartz, feldspar and clay matrix; accompanied by albitization, i.e. albite replacing other feldspar minerals in a deep burial environment. Dissolution in the Ecca Group involved calcite and kaolinite dissolving and leaching, which created more pore-space and increased porosity.

The sediments of the Ecca Group went through three stages of digenesis, namely the early stage, the late stage and the up lift stage which led the rocks being exposed on the Earth’s surface and being weathered. In each stage, some minerals became unstable, then replaced by a more stable mineral suitable for the new diagenetic environment. Precipitation of cements and formation of authigenic minerals mostly occurred in the early diagenetic stage, which led the soft sediments becoming a hard rock; whilst recrystallisation, replacement, and dissolution took place mostly in the later diagenetic stage due to increase of temperature and pressure resulting from increase of burial depth.

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CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

The Ecca Group generally consists of five formations, namely, the Prince Albert Formation, Whitehill Formation, Collingham Formation, Rippon Formation and the Fort Brown Formation respectively. The group sequence accumulated between the Late Carboniferous Dwyka Group and the late Permian–Middle Triassic Beaufort Group (Catuneanu et al., 2005) and it consists of mudstones, siltstones and sandstones which Johnson (1976) concurred with. And according to Cadle et al. (1993), deep and shallow water environments with a cool climate predominated during the Ecca times.

According to Bamford (2004) the Prince Albert is noted for having dark green grey shale with some graded silt layers, whilst the Whitehill Formation has carbonaceous shale (which weathers white) intercalated with chert bands and lenses which are dense and dark in colour. The Collingham Formation has rhythmites of mudstone, shale and siltstone with a greyish-green colour, whereas the Rippon Formation shows massive greywackes, arenites, mudstone and carboniferous shale. The Fort Brown Formation has dark or greyish shale and siltstone, with well-developed laminations of probably lacustrine deposits.

Sole clasts, micro-cross lamination and current lineation are the three types of sedimentary structures that have been used to provide reliable palaeo-current information in the Ecca Group(Kingsley (1977). According to Kingsley (1977), the uniform distribution of current directions in the Ecca Group implies the existence of one large mountainous source area to the south and south east of the current coast line during the Permian-Triassic times.

1.2. PROBLEM STATEMENT

Different stratigraphic formations were established for the Ecca Group, especially through the works Kingsley (1977) and Johnson (1976), however, without detailed information about the vertical lithological variations. In terms of sedimentology studies carried out on the Ecca Group, rock types and sedimentary structures were identified, but not in great detail to clearly depict the different sedimentary facies; and no diagenetic pathways were deduced for the minerals.

1.3. AIMS AND OBJECTIVES OF THE PROJECT

The aims of this investigation were to measure the stratigraphic section and to establish the stratigraphic sequence of the Ecca Group, study the lithology, sedimentary facies and diagenesis of the sediments and deduce the depositional environments of the Ecca Group in the study area in Eastern Cape.

The related tasks of investigation in this study included to:

- Measure the stratigraphic sections and establish the stratigraphic sequence of the Ecca Group in the study areas;
- Distinguish different rocks types and recognize their petrographic characteristics;
- Establish of different types of sedimentary facies in the stratigraphic succession;
- Study the sedimentary structures occurring in the sequence in order to ascertain the depositional environments and the hydrodynamic conditions during the deposition of sediments;
- Investigate the diagenetic textures, cement types and the diagenetic environments of the Ecca Group;
- Establish of the burial history and fluid flow episodes of the sediments in order to restore the diagenetic history/pathway of the Ecca Group.

1.4. LOCATION OF THE STUDY AREAS

The study area is located along the Regional Road R67 from Grahamstown to Fort Beaufortin the Eastern Cape Province, South Africa. This research was targeted at the Ecca Group of the Karoo Supergroup, which is well exposed to the roadside of the R67 and shows a continuous stratigraphic thickness of 1363.67m. Supplementary sections of the Ecca Group were also studied along the N2 Road from East London to King William’s Town and along the N6 Road from Gonubie to Macleantown (marked as A-B) in the Eastern Cape shown in Figure

1.1. The rocks of the Ecca Group are clearly exposed along the road cuttings, which mean that, there is easy accessibility of the study areas.

Figure 1.1 location of research area within the marked area (Modified from Google Maps).

1.5 METHODOLOGY

Methodology involved in this project includes field and laboratory work.

1.5.1. FIELD WORK

The field work was done by carefully observing and recording data. Different sedimentary features were described, measured and photographed and where possible, rock samples for analysis were collected. Field exposures of the Ecca Group are easily accessible and data documented during the visits to the study area involved:

- Identifying the different lithologies and their mineral compositions;
- Measuring thicknesses of the stratigraphic units;
- Identifying the rock colours and sedimentary structures;
- Identifying fossil types and variations within the strata;
- Recording the changes in grain size, grain sorting and roundness;
- Establishing sedimentary facies and facies associations;
- Recognizing hydrodynamic conditions and depositional environments;
- Identifying and describing palaeocurrent marks.

The data were used to deduce the stratigraphy of the Ecca Group, and also to identify and describe the sedimentary facies. The equipment used during field work included a camera, hammer, tape measure, global positioning system (GPS), knife, grain-size charter, hand lens and compass.

1.5.2. LABORATORY WORK

Laboratory work was done to confirm some of the field findings and also to discover possibly new attributes that were not visible to the naked eyes especially with regard to mineralogy. Proper identification of the rock minerals was of great significance with regard to diagenetic studies. Thin sections for microscopy, scanning electron microscope (SEM), and x-ray diffraction (XRD) were used for the detailed laboratory analysis and the methods were combined for accurate results.

1.5.2.1. THIN SECTIONS FOR MICROSCOPE STUDY

Eighty thin sections were made and analysed by using the petrographic light microscope. With low and high magnification variations, authigenic and detrital minerals were identified using their optical properties. Photographs of the different minerals and their petrological textures were studied to ascertain the rocks types, grain size variation, grain sorting and roundness, and mineral compositions.

1.5.2.2. SCANNING ELECTRON MICROSCOPE (SEM)

The scanning electron microscope was used on the basis that it has a wide range of magnification for the identification of fine grained minerals; with the aid of Energy Dispersive X-Ray (EDX) technic, chemical compositions can also be identified. SEM was used to photograph the distribution of clay minerals, both detrital and authigenic and also in the study of the effects of cements and grain coating on porosity. The rock samples were coated with carbon prior to the analysis. The scanning electron microscope used is the Jeol JSM-6390LV model with a voltage of 15KV and the secondary electron detector.

1.5.2.3. X-RAY DIFFRACTION (XRD)

This technique is best on the principle that each crystalline substance produces its own unique diffraction pattern, thus providing a fingerprint of the individual components to enable identification of the mineralogical make-up of a rock. The method was used to reveal the mineral compositions of the mudrocks and sandstones found in the Ecca Group especially with the identification of the unknown minerals and the fine grain sized. The D8 Advance Model was used for the XRD analysis and the machine had a maximum speed of 30 rotations per minute with a 2θ range of between 5 and 70.

CHAPTER 2. GEOLOGICAL SETTING

2.1 GEOLOGICAL BACKGROUND

The Main Karoo Basin forms the thickest and stratigraphically most complete mega-sequence of several depositories of Permo-Carboniferous to Jurassic aged sediments in south western Gondwana Continent (Catuneanu et al., 1998). The maximum preserved thickness of this mega-sequence, according to Smith (1990), is adjacent to the Cape Fold Belt, exceeding 6km in thickness, with the sedimentary succession reflecting changing environments from glacial to deep marine, deltaic, then fluvial and aeolian.

The sedimentary fill of the Karoo Basin accumulated under the influence of tectonics and climate changes. Catuneanu et al. (2005) indicate that the tectonic regimes during the Karoo time varied from dominantly flexural in the South, in relation to processes of subduction, accretion and mountain building along the margin of the Gondwana continent. Climate fluctuations also left a mark on the stratigraphic record, showing evidence of a general shift from marine to delta, to river and desert conditions (Keyser, 1966).

2.2 THE MAIN KAROO BASIN

2.2.1 THE TECTONIC SETTING OF THE MAIN KAROO BASIN

The Karoo Supergroup is a thick succession of sedimentary rocks that accumulated in a large intra-cratonic retroarc foreland basin in South-western Gondwana (Smith, 1995). According to Damiani (2004), the Karoo Basin of South-western Gondwana formed as a retroarc foreland basin brought about by the collision of the Palaeo-Pacific plate and the Gondwana plate as pictured in Figure 2.1.

The interior position of the basin was controlled by the re-activation of the Late Proterozoic Cape Conductive Belt in which the sediments of the Cape Supergroup had previously accumulated (Turner, 1999; Figure 2.2). The Karoo succession accumulated within several tectonically controlled depositories, under which different climatic regimes resulted in an almost continuous record of intra-cratonic sedimentation from the Late Carboniferous (300 Ma) to Early Jurassic (190Ma).

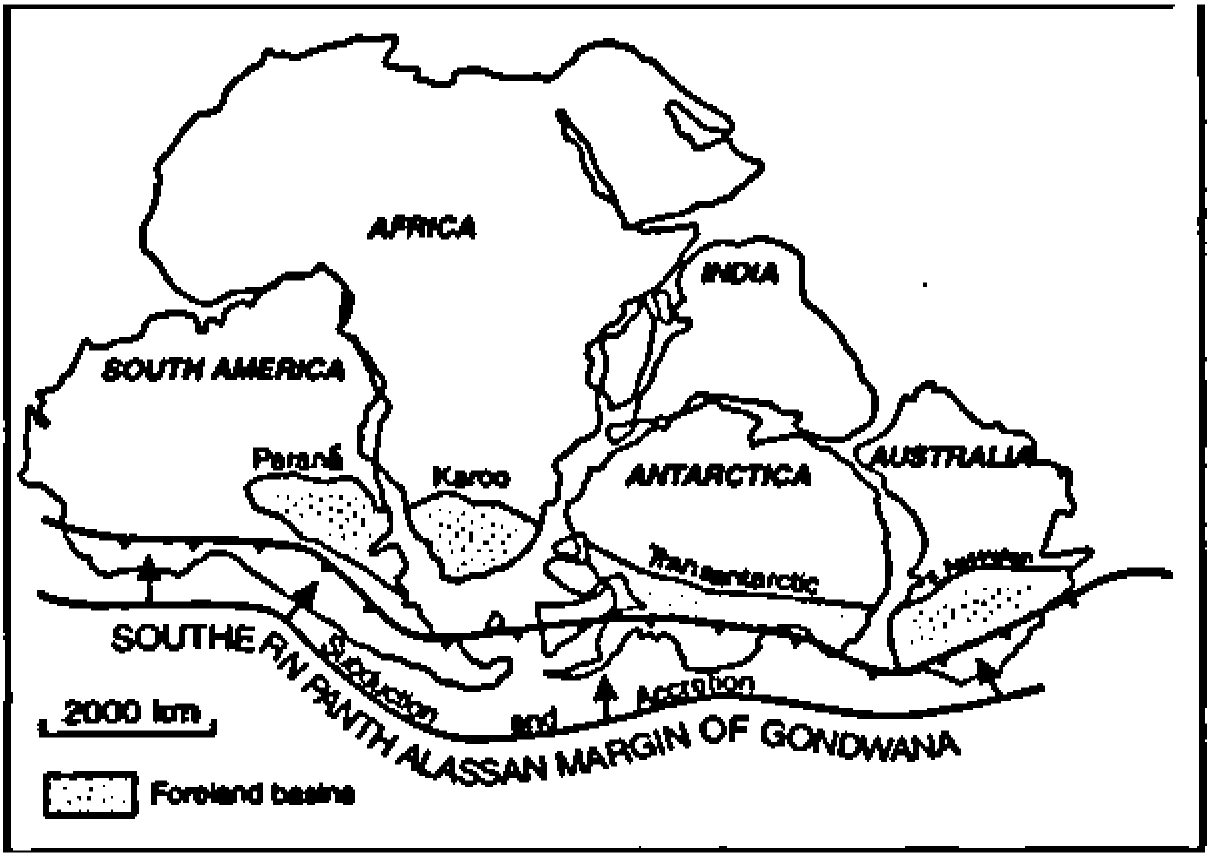

Figure 2.1 Reconstruction of the Karoo Basin and the Gondwanaland Continent in the late-Palaeozoic Period (Turner, 1999).

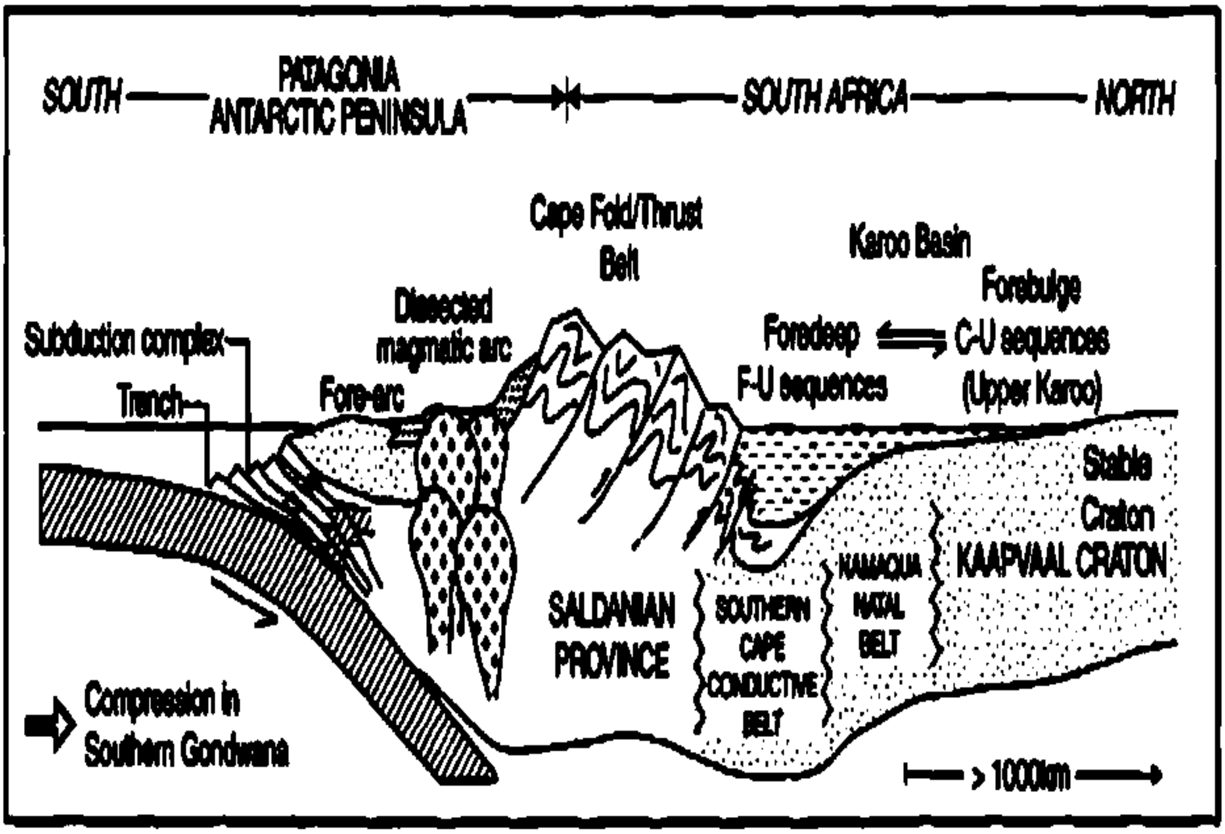

Figure 2.2Generalised foreland basin model of the Karoo basin during the Triassic Period, showing the location of the foredeep and forebulge parts of the basin in relation to the Cape Fold Belt, and the inferred position of the arc and subduction zone (Turner, 1999).

2.2.2 ARCHITECTURE OF THE MAIN KAROO BASIN

The Main Karoo Basin becomes thinner from the south to the north as shown in Figure 2.3. This idea is also supported by Catuneanu et al. (2005) who describe the Molteno Formation as northerly thinning. It is because of this architecture that the Basin is observed as having proximal facies in the south west and distal facies in the north east as shown in Table 2.1. From the information given in the above mentioned table, the Whitehill Formation and the Pietermaritzburg Formation consist of the same facies, however, due to their proximal and distal positions have different names.

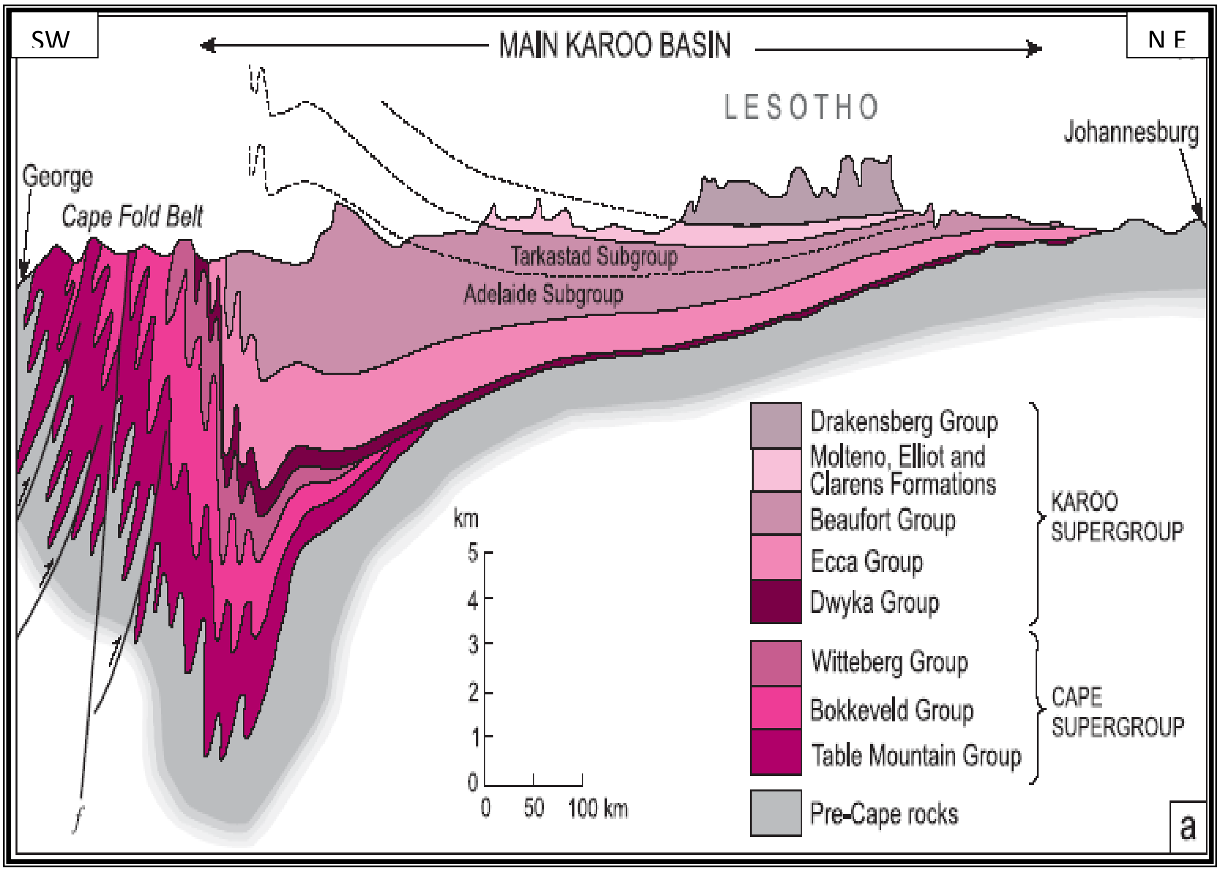

Figure 2.3 Section view of Karoo Supergroup (Johnson et al., 1997).

Table 2.1 Distal and proximal Formations of the Karoo Supergroup (After Catuneanu et al., 1998)

TIME PERIOD	PROXIMAL FACIES (SW)			DISTAL FACIES(NE)
Middle Jurassic, volcanics	DRAKENSBERG GROUP			
Late Triassic–Early Jurassic	STORM-BERG GROUP		Clarens Fm	
			Elliot Fm	
			Molteno Fm	
Late Permian-Middle Triassic	BEAUFORT GROUP	Tarkastad Subgroup		
		Burgersdorp Fm		Driekopppen Fm
		Kartberg Fm		Verykerskop Fm
		Adelaide Subgroup		
		Tekloof Fm (W)	Balfour Fm (C)	Normandien Fm (N)
		Abrahamskraal Fm (W)	Koonap / Middleton Fms (C)	
Permian	ECCA GROUP	Fort Brown Fm		Volkrust Fm
		Rippon / Collingham Fms		Vryheid fm
		Whitehill Fm		Pietermaritzburg Fm
		Prince Albert Fm		
Late Carboniferous-late Permian	DWYKA GROUP			

2.2.3 STRATIGRAPHY

The Late Carboniferous-Early Jurassic succession of Karoo Supergroup is distinctly different in lithology and sedimentary environment (Catuneanu et al., 2005). According to Visser and Dukes (1979), these tectono-stratigraphic units are preserved as both fining upwards and coarsening upwards megacycles, forming the basis of the litho-stratigraphic sequence. The succession is stratigraphically divided into five groups, which are, in ascending stratigraphic order, the Dwyka (Late Carboniferous), Ecca (Early Permian), Beaufort (Late Permian–Middle Triassic), Stormberg (Late Triassic–Early Jurassic) and Drakensberg Groups (Middle Jurassic, volcanics) (Damiani, 2004)as shown in Table 2.2, with their aerial distribution depicted in Figure 2.4. The Drakensberg lavas are believed to have terminated sedimentation in the Basin in the Middle Jurassic (Smith, 1990), which represented the process of breaking up of the Gondwana Continent.

Damiani (2004) alluded that the section broadly represents deposition in glacial, marine and terrestrial environments. Catuneanu and Elango (2001) further explained that the deeper marine facies of the Dwyka and Early Ecca Groups accumulated during the under-filled phase of the foreland system, whilst the shallow marine facies of the late Ecca Group correspond to the filled phase of the basin, which was followed by an overfilled phase dominated by fluvial sedimentation. As Damiani (2004) deduced, from the Late Permian onwards, non-marine sediments were laid down and were provenanced mainly from the rising Cape Fold Mountains along the southern periphery with episodic tectonics in the source area, coupled with fore-deep subsidence, resulting in deposition on large prograding alluvial fans. Catuneanu et al. (2005) envisage that the main Karoo Basin stratigraphy is however complex and this complexity was related to the mode of origin, deep marine water and shallow marine turbidites and submarine fan deposits from specific source areas.

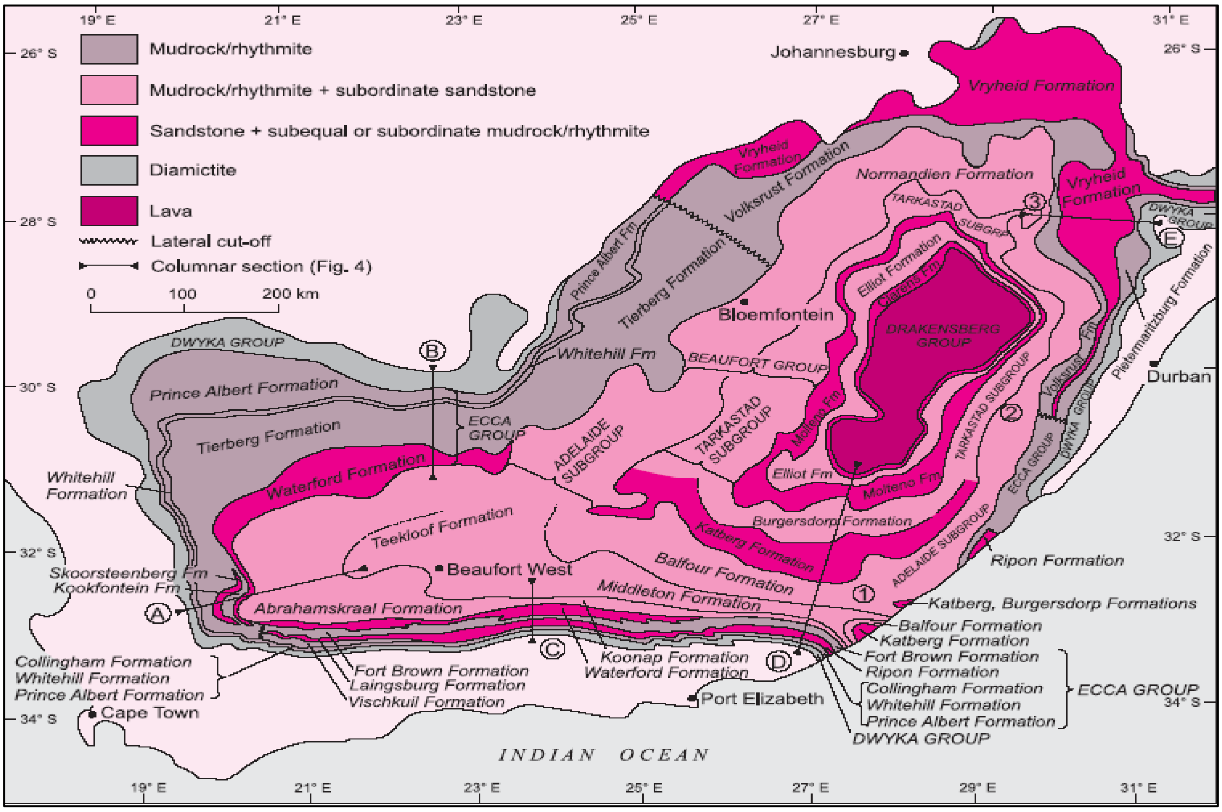

Figure 2.4 Areal distributions of litho-stratigraphic units in the Main Karoo Basin (Johnson et al., 1996).

According to Smith (1995), below the Permo-Triassic boundary, the sediments comprise of drab greenish grey mudrocks with a few multi-storied, laterally accreted fine grained sandstone bodies; and above this boundary, the strata changes into reddish brown mudrocks with numerous thin ribbon sandstone bodies and more continuous sheet sandstones. These changes came as a result of the change in depositional environments from marine to fluvial at the Permo-Triassic boundary which separates the Ecca Group from the Beaufort Group. As Smith (1995) further explained, the changes in fluvial style in the Karoo Basin at the end of the Permian were triggered by a pulse of thrusting in the southerly source area dated at about 247 Ma, which brought about rapid progradation of a large sandy braided fan system (Katberg sandstone Formation) into the central parts of the Karoo Basin.

Table 2.2 Bio-stratigraphy of the Karoo Supergroup (After Rubidge, 2005).

PERIOD	GROUP	FORMATION EAST OF 24^0 LONGITUDE	ASSEMBLAGE ZONE
Jurassic	Drakensberg	Drakensberg	
	Stormberg	Clarens	
Triassic		Elliot	
		Molteno	
	Beaufort	Burgersdorp	Cynognathus
		Katberg	Lystrosaurus
Permian		Balfour	Dicynodon Cistecephalus
		Middleton	Tropidostoma Pristerognathus
		Koonap	Tapinocephalus Eodicynodom
	Ecca	Water Ford*	
		Fort Brown	
		Ripon	
		Collingham	
		Whitehill	
		Prince Albert	
Carboniferous	Dwyka	Elandsvlei	

*: does not occur in the study area.

2.2.3.1 DWYKA GROUP

Johnson (1976) explained that the Karoo Supergroup commenced with the Dwyka Tillite, which is a 700m thick diamictite unit. Johnson et al. (1996) indicated that in the Main Basin, the Dwyka Group extends from the Late Carboniferous to the Early Permian. Catuneanu and Elango (2001),concur with this and explained that the initiation of the Dwyka sedimentation is estimated at about 300 Ma, following a 30 million years stratigraphic break after the end of the Visean when the sedimentation in the Cape Basin was terminated. According to Catuneanu and Elango (2001), the deeper marine glacial facies of the Dwyka Group, including those of the early Ecca Group, accumulated during the under-filled phase of the fore-land basin. In the south, as Catuneanu et al. (1998) explained, the Dwyka succession has a uniform character with lateral continuity of layers suggesting that deposition from floating ice within a large marine basin was the dominant process. Bamford (2004) also concurred with this idea when he explained that the tillites are uniform and laterally extensive, having formed in a glacial marine environment with deposition from both grounded and floating ice, with the latter being dominant.

In general, there are seven lithofacies that have been identified in the Dwyka Group. According to Johnson et al. (2006), the facies include the massive diamictites, stratified diamictites, massive carbonate-rich diamictites, conglomerate facies, sandstone facies, mudrock with drop-stone facies and lastly the mudrock facies. Johnson et al. (2006) noted that the massive diamictite facies consist of highly compacted diamictite, generally clast rich, with rounded to angular, frequently striated clasts up to 2m across, commonly reflecting the composition of the underlying or surrounding rocks, hence can be explained as lodgement or melt out deposits.

According to Visser (1991), the stratified diamictite facies of the Dwyka Group consist of argillaceous diamictite containing sub-rounded to rounded extra-basinal clasts as much as 3m across. The stratification contains faint bedding planes within the diamictite as well as thin inter-bedded mudrock beds and laminae. Johnson et al. (2006) explained that these stratified diamictites were formed by sediment gravity flows, although intermittent reworking of sub-glacial diamictons and rain-out of glacial debris also occurred during deposition.

The mudrock with drop-stone facies consists primarily of rhythmite, and angular to rounddetrital stones varying from small to large (maximum ± 1m across) are commonly found deforming the rhythmite (Visser, 1991). The facies represents deposition in a distal iceberg zone. The mudstone with drop stone facies is different from ordinary mudstone facies in the sense that mudstone facies does not have any kinds of detrital stones, but consist of greenish grey mudstone and black pyrite shale (Visser, 1991).

The massive sandstone diamictite facies are as called because of the thick sandstones (up to about 30m). Von Brunn (1994) described these facies in the Dwyka Group as consisting of either very fine to medium grained, massive to ripple-laminated or medium to coarse grained, trough cross bedded, immature sandstones. The ripple laminated sandstones have been interpreted as turbidite deposits, whereas the trough cross bedded sandstones, represent traditional fall-out from subaqueous outwash streams.

There are also the massive carbonate-rich diamictite facies which Visser (1991) described as the clast poor diamictites containing thin carbonate beds of less 5cm, stringers and concretions forming thick facies units. These facies formed from the rain-out of debris, with the carbonate probably originating by crystallization from interstitial waters.

Theconglomerate facies contain, as the name suggests, pebbles and boulders within fine sediments. The facies ranges from single layered boulder beds to poorly sorted pebble and granule conglomerate, with boulder beds interpreted as lodgement deposits, whereas the poorly sorted conglomerates are a product of water reworking of diamictons by high density sediment gravity flows (Johnson et al., 2006).

2.2.3.2 ECCA GROUP

The Ecca Group is a sequence that accumulated between the Late Carboniferous Dwyka Group and the late Permian–Middle Triassic Beaufort Group, occupying most of the Permian time of the Karoo Supergroup (Catuneanu et al., 2005). However, according to Bamford (2000), the absolute age of the Ecca Group is not perfectly constrained as most age determinations rely on fossil wood biostratigraphy. The term Ecca is suggested by Rubidge (in Catuneanu et al., 2005) for argillaceous sedimentary strata exposed in the Ecca Pass, near Grahamstown in the Eastern Cape Province, South Africa. Therefore, to use the term outside the main Karoo Basin is sometimes questionable as rock types could be totally different. The Ecca Group comprises of mudstones, siltstones, sandstones, minor conglomerates and coal. Cadle et al. (1993) explained that 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 formation.

The group is believed to be about 3000m thick in the Southern part of the main Karoo Basin. Johnson (1976) concurred with this idea when he explained that the Ecca Group consists of sandstone and subordinate mudrock with a total thickness of 2000-3000 m. The Ecca Group generally consists of five formations, namely, the Prince Albert Formation, Whitehill Formation, Collingham Formation, Rippon Formation and the Fort Brown Formation respectively. According to Bamford (2004) the Prince Albert is noted for having dark green grey shale with some graded silt layers, whilst the Whitehill Formation has carbonaceous shale (which weathers white) intercalated with chert bands and lenses which are dense and dark in colour. Johnson et al. (1996) envisaged that the black carbonaceous shale of the Whitehill Formation distinguishes it from the underlying and overlying shale units in the Main Karoo Basin. Phosphatic and siliceous rocks probably formed by chemical or biological processes under reducing conditions in areas where upwelling of cold water occurred; and this upwelling current may have enhanced a rich marine life, which supplied the organic materials trapped in the bottom mud (Parrish and Curtis, 1982). The Collingham Formation has rhythmites of mudstone, shale and siltstone with a greyish-green colour, whereas the Rippon Formation shows massive greywackes, arenites, mudstone and carboniferous shale. The Fort Brown Formation has dark or greyish shale and siltstone, with well-developed laminations of probably lacustrine deposits. It is most probable that the Prince Albert and Whitehill Formations were formed in a reducing deep water marine environment, whilst the Collingham Formation is a deep water turbidite deposit. The Rippon Formation was formed in a shallow marine to deltaic environment whilst the Fort Brown Formation was formed in a broad continental margin of lacustrine environment.

According to Kingsley (1977), sole clasts, micro-cross lamination and current lineation are the three types of sedimentary structures that have been used to provide reliable palaeo-current information in the Ecca Group. According to Kingsley (1977), the uniform distribution of current directions in the Ecca Group implies the existence of one large mountainous source area to the south and south east of the current coast line during the Permian-Triassic times.

2.2.3.3 BEAUFORT GROUP

Most of the continental deposits of the Karoo Supergroup are grouped in the aerially extensive Beaufort Group which formed from the much greater volume of the sediments that were produced from the fast rising Cape Fold Belt. The sediments prograded diachronously northward in rivers that flowed across the floor of the former brackish to freshwater basin down a 500km long piedmont flank into a westward sloping axis of sediment transport (Johnson et al, 1997). Further explained is that, after about 15 million years of deposition, the piedmont wedge reached an estimated thickness of about 6km at the south part of the Karoo Basin. The Beaufort Group thins northwards due to the youngling of the Ecca and Beaufort boundary and the deeper erosion of the Beaufort strata that happened before the deposition of the Late Triassic Molteno Formation. The mud and sand in the Beaufort Group are commonly red due to the well-drained, highly oxidized fluvial slope on which they were deposited; as well as due to the onset of warm and seasonal global temperature increase. As Johnson et al. (1996) explained; red and greenish mudrocks are common in the upper Beaufort Group, reflecting an increase in sub-aerial exposure under oxidizing conditions. Bamford (2004) also explained that the Beaufort Group deposits indicate river systems down grading to braided rivers and meandering streams as the regional climate dried up and basins filled with sediments from the Cape-Fold Belt.

The Beaufort Group is exposed almost over the entire Karoo basin and is intruded by dolerite sills and dykes. The dolerite intrusions are not all of the same rock type; varing from being olivine rich through tholeiitic to granophyres. When considering the minerals within the rocks, dolerites are also noted by differences in colours (Karpeta and Johnson, 1979), with sills showing grading through olivine, hyperite into gabbro. The proportion of dolerite to country rock is seen to vary in the formations. This could be attributed to the fact that some areas experienced much of magmatic activity than the other areas. The sediments on the contact of dolerite intrusions have been indurated or recrystallised, which led to the formation of hornfels.

The Beaufort Group is subdivided into the Adelaide Subgroup and the Tarkastad Subgroup. The lower Adelaide Subgroup consists of the Balfour Formation with the Palingkloof, Elandsberg, Barberskrans, Daggaboersnek and the Oudeberg Members, the Koonap Formation and the Middleton Formation. As Viser (1995) explained, the lower Beaufort Group consists of dark grey, green and red mudstone alternating with fine grained sandstone, with the base of the group consisting of an upward coarsening deltaic sequence, whereas stacked upward-fining fluvial cycles and flood plain mudrocks, with thin crevasse splay sandstones, commonly present in the rest of the succession. The Tarkastad Subgroup which forms the upper part of the Beaufort Group, consists of the Katberg and Burgersdorp

Formations that are restricted to the southern margins of the Karoo Basin from south of Queenstown to north of Aliwal North (Rubidge, 1995).

According to Bamford (2004), the Balfour Formation is a fining upward sequence of green-grey sandstones with bands of darker mudstones,deposited when braided rivers graded upwards into meandering stream systems. However, according to Smith (1995), the major coarsening upward cycle begins in the Balfour Formation and ends at the top of the Katberg Formation. The Koonap Formation consists of greenish silty-mudstones and sandstones in a fining upward sequence deposited when a high energy braided river system graded into a lower energy meandering river system (Bamford, 2004). The Middleton Formation has dark red and green grey mudstones interbedded with sandstones in an overall fining upward sequence. The upper member of the Balfour Formation is characterized by red and maroon mudrocks as opposed to the dark grey and greenish grey mudrocks of the underlying strata. The predominantly argillaceous unit gradually coarsens upwards into the arenaceous Katberg Sandstone Formation which is composed of fine to medium grained pinkish grey sandstone with subordinate greenish grey mudstone (Smith, 1995).

In the Early Triassic times, there was a tectonic rejuvenation of source area that led to steeper gradients and a sharp increase in the supply of coarser grained detritus. Therefore, alluvial fans developed in areas adjacent to the source terrain and river channels became braided, depositing only sands that formed the Katberg Sandstone, mud and silt was carried down further into the distal parts of the flood plain to form the Burgersdorp Formation. As tectonic changes occurred, climatic conditions were also changing, and it was these climatic changes that influenced stream types. For instance, between the late Permian and early Triassic Periods, there was a change to warmer climatic conditions after having had glaciations of the early to middle Permian.

The lowest Beaufort Group sediments were deposited in warm temperate to humid conditions, but later on deposition occurredin increasingly arid conditions. Hence the Tarkastad Subgroup corresponds to the Early Triassic Lystrosaurus and Cynognathus tetrapod zones (Rubidge, 1984).

According to Bamford (2004), the Katberg Formation is thick and laterally extensive and has light olive grey, coarse grained sandstone with transverse and longitudinal macro-forms containing horizontal and trough cross bedding. The tabular sheet sandstones of the Katberg

Formation are vertically superimposed and separated by erosion surfaces lined with intra-formational mud pebble conglomerates (Smith, 1995).

The Burgersdorp Formation is a thick, upward fining unit of olive grey, medium to coarse grained sandstones overlain by dark red siltstones and mudstones. It conformably overlies the Katberg Formation. As emphasized by Hancox (1998), the Burgersdorp Formation consists predominantly of thick, fining upward units of olive grey, fine to medium grained sandstones overlain by red-maroon coloured siltstones and mudstones, with the fining upward sequence and represents a mixed load meandering river and floodplain deposits which preserve a fauna assignable to the Cynognathus Assemblage Zone.

2.2.3.4 STORMBERG GROUP

The Stormberg Group is made up of the Molteno, Elliot and Clarens Formations from bottom upward respectively. A major stratigraphic gap corresponding to the late Anasian Ladinian separates the Stormberg Group from the underlying Tarkastad Subgroup (Cole, 1992),thus, the gap represents the erosional or non-depositional boundary between the Stormberg and the Beaufort Groups.

The Molteno Formation consists of the Bamboesberg Member, Indwe Member, Mayaputi Member, Qiba Member and Tsomo Member (Figure 2.5). According to Hancox (1998), the Formation has a maximum thickness of 600m in the Southern outcrop and gradually thinner northward. Bamford (2004) explained that the sandstones are tabular sheets of medium to coarse grained sediments with horizontal and cross stratified macro-forms that formed in a braided stream environment on a vast braid plain. Turner (1975) supported this idea when he indicated that the deposition of the Molteno Formation was predominantly by bed-load dominated rivers flowing across extensive braid plains. Siltstone, mudstone and coal occur, but coal is far less abundant than the coal in Ecca Group, and these deposits are interpreted as the fills of abandoned channel tracts and within ponded bodies of water on the braid plain (Turner, 1975).

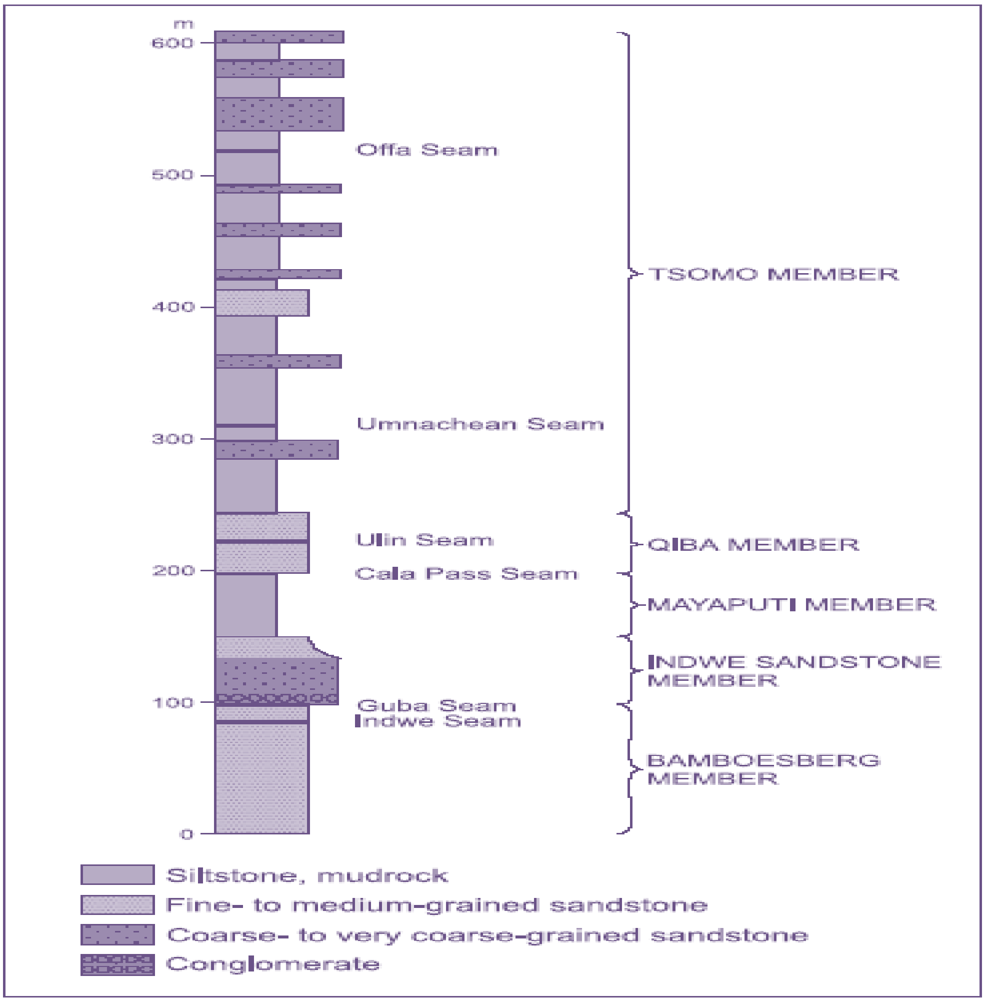

Figure 2.5 Typical section of the Molteno Formation in the southern outcrop area (Christie, 1981).

The Elliot Formation is a fluvial deposit of playa nature. The formation comprises an alternating sequence of mudrock and subordinate fine to medium grained sandstone with a maximum thickness of about 500m in the South Foredeep area (Visser and Botha, 1980). The Formation was deposited when the climate was changing to arid conditions hence the reddish mudstones.

The top formation in the Stormberg Group is the Clarens Formation, deposited in a desert environment and shows high dip angle cross-bedding structures. The climate was progressively drying and warming, as indicated by fine grained aeolian sand dunes and associated playa lakes; as well as the sheet floods and ephemeral stream deposits (Beukes, 1970). According to Bamford (2004), creamy-yellow fine grained sandstones, sandy siltstones and mudstones and some coarse grained sandstones are found in the formation.

2.2.3.5DRAKERNSBERG GROUP

This group has no sedimentary deposits, but is composed of pure mafic volcanic rocks, basaltic in nature with minor felsic rhyolite in later stage. According to Johnson et al. (1996), volcanic activity produced the basaltic lavas along the Drakensberg Mountain Range that covered a large area of central South Africa and Lesotho. The volcanic activity terminated the sedimentation of the Karoo Supergroup and signified the breaking up of the Gondwana Continent.

CHAPTER 3. STRATIGRAPHY

3.1 INTRODUCTION

A considerable amount of work has been done on the Ecca Group stratigraphy as portrayed in Chapter 2. The different stratigraphic formations have been properly investigated, however, the difference between the previous work and this new work lies on the fact that each and every formation has been broken down into smaller rock units and therefore, was produced with more detailed information about the vertical lithological variations and the stratigraphic columns of the different rock units of the Ecca Group. There has so far been no published stratigraphic column or columns of the Ecca Group along the Road R67 from Grahamstown to Fort Beaufort. Therefore this study provides new insight into the Ecca Group, particularly the aspects of the stratigraphy, petrology, sedimentary facies and depositional environments of the Ecca Group.

3.2 THE PRINCE ALBERT FORMATION

The Prince Albert Formation crops out at longitude 26° 13′ 43″ S and latitudes 26° 37′ 59″E along the R67 Road from Grahamstown to Fort Beaufort, and is the basal Formation of the Ecca Group. The Formation disconformably overlies the Dwyka Group and is also disconformably overlain by the Whitehill Formation. The formation has a thickness of 120 meters along the road cuttings, and consists of laminated and thin bedded dark gray mudstone at the bottom and the khaki shale and mudstones at the top (Figure 3.1). The khaki colour of the rocks was the result of strong weathering due to tectonic uplift and exposure to atmospheric conditions thereby obscuring the original gray-black colour of the fresh rocks. However, in the upper most parts of the formation, iron oxide led to the red colouration of the well laminated shale. The rocks contain significant amount of iron-rich minerals which include illite, pyrite and chlorite which produce haematite after weathering. Haematite is found as a cement mineral in the lenticular siltstones of the rock sequence whilst the other named minerals are constituents of the matrix.

The mudstones at the bottom of the Prince Albert Formation are either well laminated or thin bedded (less than 10cm for a single layer). Bottom sea currents reworked the laminated sediments and resulted in the occurrence of thin beds. The action of bottom currents coarsened the clay grain size of the thin beds. Both the fine grain size of the sediments and the well developed lamination indicate a deep water deposition, presumably a deep marine environment, such as a restricted deep marine plain, while the pyrite-rich sediments indicate a reducing environment. The well developed lamination and the pyrite-rich phenomenon, may also be indicative of a very slow rate of deposition and a scarce source of supply of sediments as the lamination are between 1mm and 3mm in thickness. At the bottom of the formation, the argillaceous rocks have a steep inclination because of the deformation by the fault that occurs in the Collingham Formation. The rocks have a dip angle of 35^{o} and a dip direction of 20^{o}. At the top of the formation the red stained shales are also folded due to the tectonic faulting. Regardless of the folding, the lamination is well maintained (Figure 3.2). In general, both the folding and faulting had no effect on petrography and the depositional processes of the rocks.

Figure 3.1 Well laminated and thin bedded shales in the Prince Albert Formation. The khaki colour of the shale was due to weathering, and the original colour of the shale was grayish black or greenish black. Showing also lenticular siltstone layers in the shale dominated sequence.

Figure 3.2 Folded well laminated red stained shale of the Prince Albert Formation.

The Prince Albert Formation can be divided into two members, the lower gray mudstone member and the upper khaki mudstone member. The lower gray mudstone member consists of the thin bedded and dominant well laminated dark-grey shale, whilst the upper khaki mudstone member is composed of khaki-brownish mudstones. The members are clearly distinguished in Figure 3.3 depicting the stratigraphy of the Prince Albert Formation. The lower gray mudstone member and the upper khaki mudstone member are named after the main lithologies as there are no locality towns or village names to be used.

GROUP	FORMATION	MEMBER.	UNIT NO.	LITHOLOGY: CLAY	SILT	FINE SAND	MED SAND	COARSE SAND	CONGLOMERATE	THICK-NESS (M)	CYCLOTHEM	SEDIMENRY STRUCTURES	LITHOLOGY
ECCA GROUP	PRINCE ALBERT FORMATION	UPPER MEMBER	2							15.1		Lamination Folding	The Upper Prince Albert Member consists of folded and well laminated dark-grey shale that now has a reddish-brown colour due to weathering of iron-bearing minerals. Lenticular siltstone beds are found intercalated within the shales. It is also folded due to tectonic movement.
		LOWER MEMBER	1							104.9		Lamination Crumbling Thin bedding	The Lower Prince Albert Member consists of thin bedded and well laminated dark-grey shale that has been obscured by a khaki colour due to weathering after exposure to the Earth's surface. The khaki colour now typifies the rocks at the bottom of the Prince Albert Formation. The shale is strongly crumbled due to fine grain-size and purer clay mineral content. The formation disconformably overlays the Dwyka Group diamictite and is also disconformably overlain by the Whitehill Formation. The topography of the outcrop of the shales is very low since it is rich in soft clay minerals and crumbed due to lamination.

Figure 3.3 Stratigraphy of the Prince Albert Formation.

3.3 THE WHITEHILL FORMATION

The Whitehill Formation rests disconformably on the Prince Albert Formation and is disconformably overlain by the Collingham Formation (Figure 3.4). There is a gradational transitional zone between the Prince Albert and the Whitehill Formations. The gradational zone is shown by slight changes in rock colour and lithology for about one meter at the top of the Prince Albert Formation. The distinguishing feature of the Whitehill Formation is the predominant black shale inter-bedded with black chert. The black chert is silica, which is hard and resistant to weathering, and is darker in colour than the shale which is susceptible to weathering and develops a grayish white colour after weathering (Figure 3.5). The existence of the carbon rich shale together with the chert indicates that the chert may be of organic origin, and the siliceous ooze that led to the formation of chert in the depositional environment was released from the decaying organic rich materials. The organic materials and the reducing deep sea environment therefore both attributed to the dark gray colour of the rocks. Some of the silica that precipitated in the rock sequence was incorporated in the claystones, increasing the hardness of the rocks.

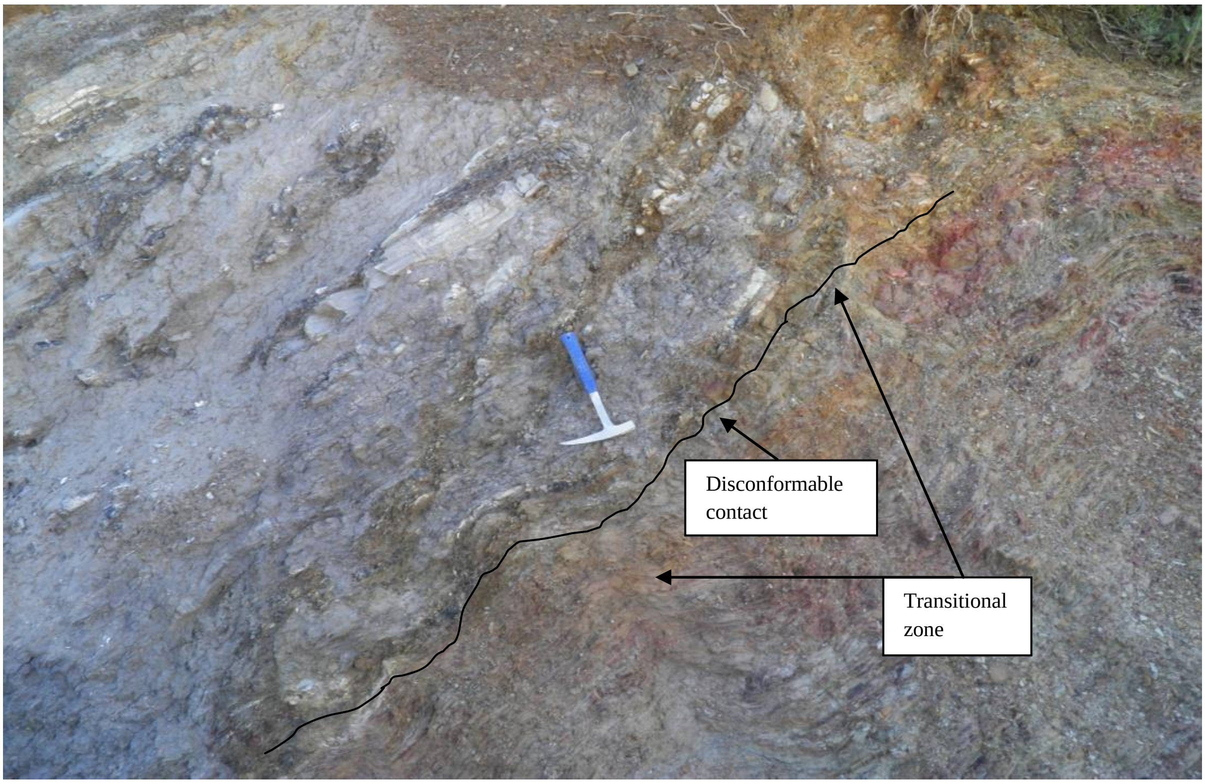

Figure 3.4 Disconformable contact between the Prince Albert Formation and the Whitehill Formation.

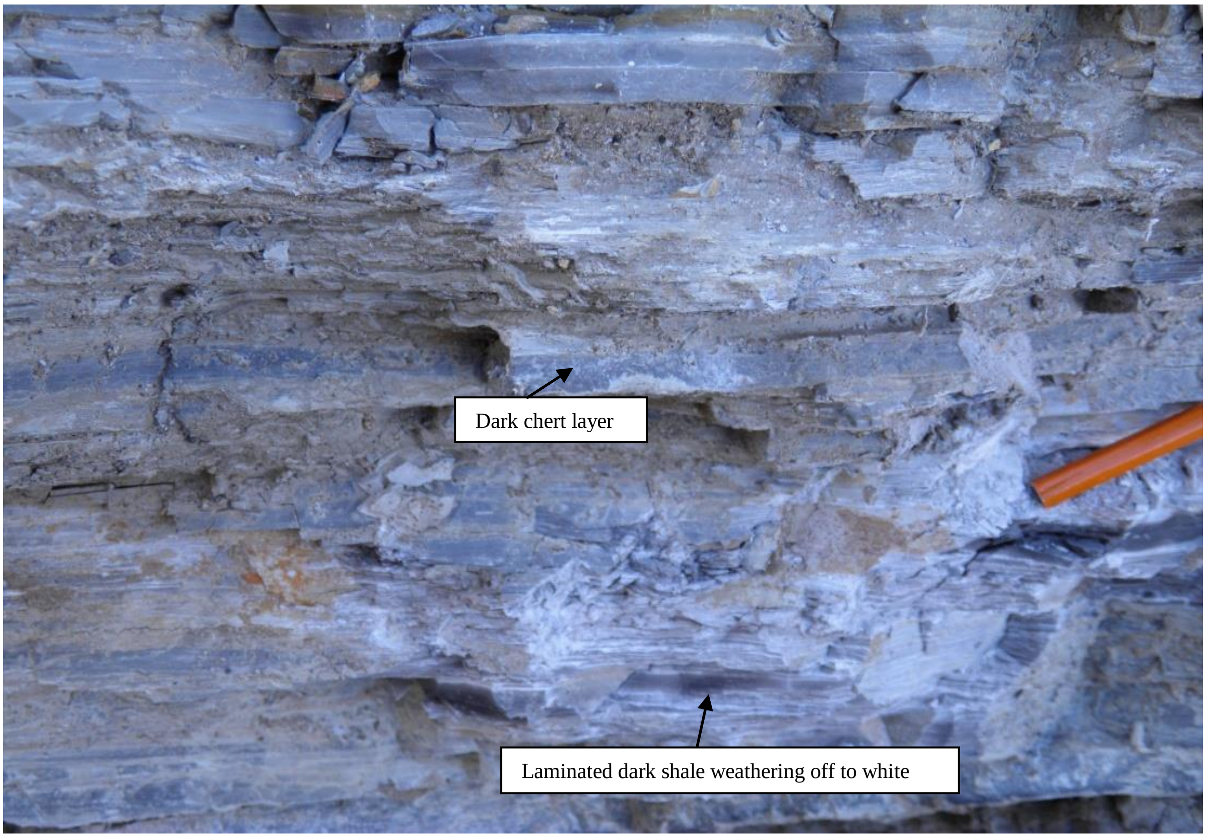

Figure 3.5 Laminated shale layers intercalated with chert layers.

The Whitehill Formation is 25.2m thick, but is broken into two parts by a normal fault (Figure 3.6), which was influenced by another major reverse fault cutting through Collingham Formation. The foot wall in the lower part of the formation is 15.1m thick whilst the hanging wall is 10.1 m thick in the upper part of the formation. Therefore, the thickness of the stratigraphy could not be established. There is a clear difference between the lower part of the formation and the upper part. In the upper part of the formation, chert layers are prevalent and also longer and thicker (up to 6m in length). The lamination of the shale is very thin and well developed at 1-2mm laminae or less because of the very fine nature of the clay sediments. Higher in the formation, chert layers are not only minor, but also shorter and thinner. The claystones are laminated and thin bedded in appearance. Due to the coarser grained clay sediments, the lamination is thicker than that at the bottom of the formation, (up to 5mm in thickness for the individual layers). Incorporated in the thin bedded rocks is silt material, indicating that higher energies resulted in the transportation of silty sediments into the depositional basin and also in the re-working of the laminated sediments leading to the formation of the thin bedded siltstone. For both parts, the thickness of the chert layers ranges from 1cm to 10cm.

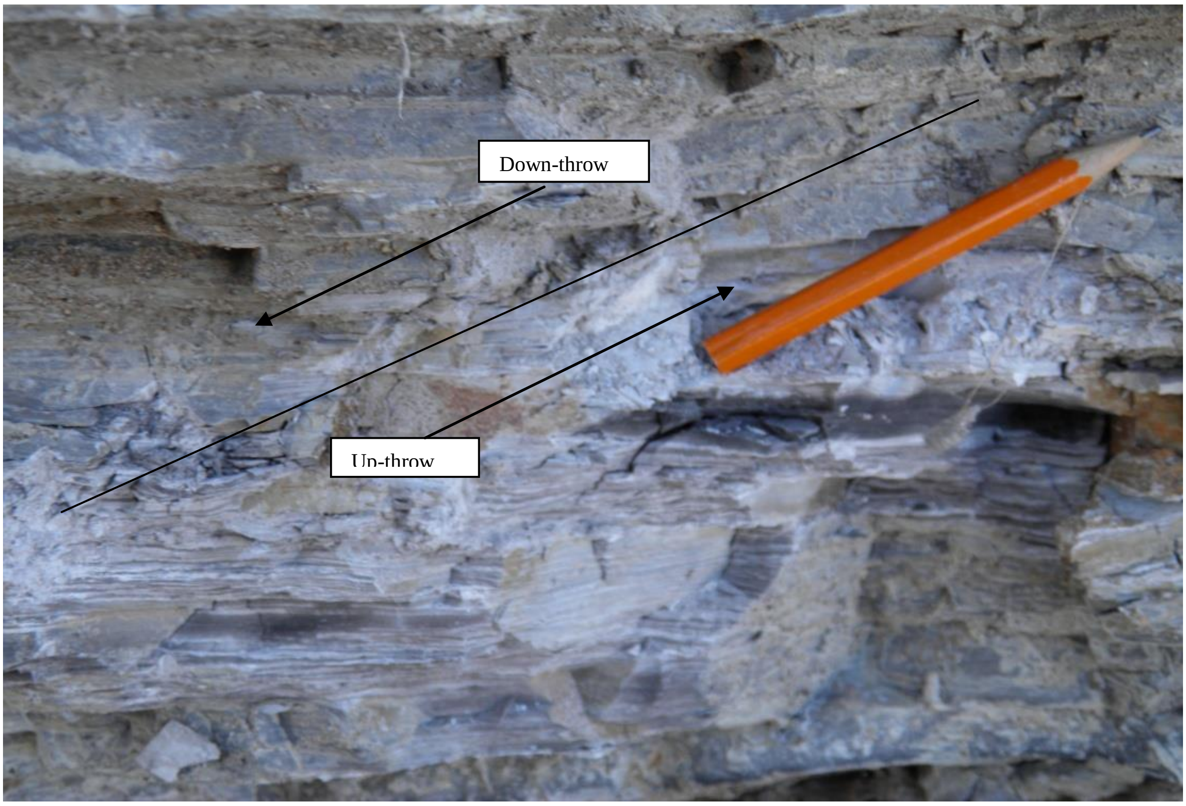

Figure 3.6 Anormal fault cutting across the Whitehill Formation.

The detailed stratigraphy of the Whitehill Formation is presented in Figure 3.7 with the lower black shale-chert member and the upper gray mudstone member. The two members are separated by a normal fault line. The lower black shale-chert member has laminated black shale intercalated with thin bedded black chert layers, with the black shale weathering to give a grayish whitish colour. The upper gray mudstone member has well laminated shale and thin bedded fine to silt grained mudstone with minor chert layers.

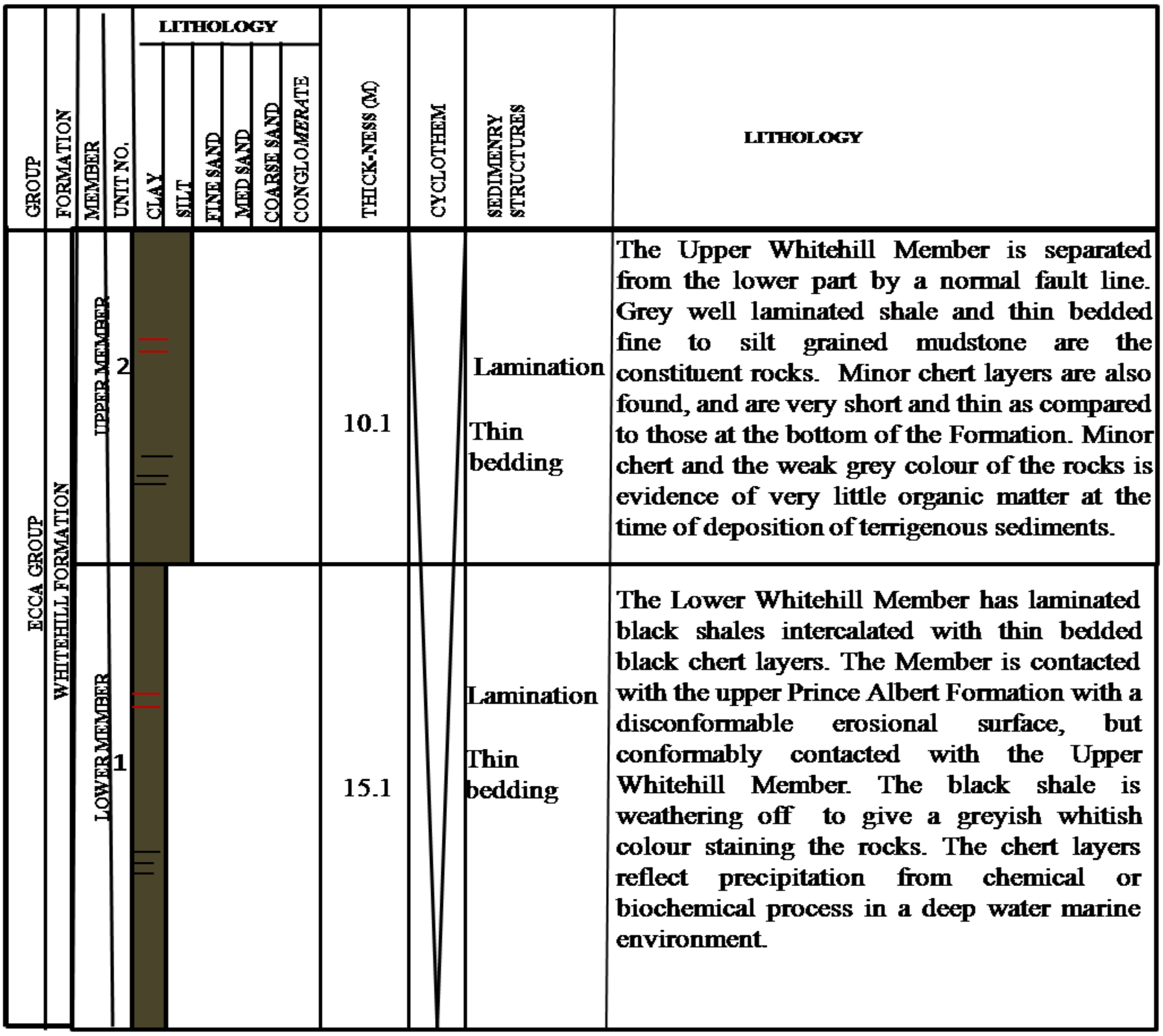

Figure 3.7 Stratigraphy of the Whitehill Formation.

3.4 THE COLLINGHAM FORMATION

The Collingham Formation rests conformably on the Whitehill Formation and is disconformably overlain by the Rippon Formation. The formation is consists of dark grayish or dark greenish shales and thin bedded claystones with a total thickness of 55.2m. The Collingham Formation is divided into two parts by a fault line that runs through it. The footwall has a thickness of 35.1m whilst the hanging wall measures at 20.1m. In general, the formation has beds thicker than those of the Whitehill Formation (ranging from 1cm to 15cm thick), indicating a much quicker deposition. The footwall has thin and tabular mudstones with the bedding scale ranging from 1cm to 12cm in thickness (Figure 3.8). The thicker beds have coarser grain size whilst the thinner beds are finer grained.

Figure 3.8 Thin bedded mudstones of the Collingham Formation.

The hanging wall has thin to medium beds that are near horizontal with thicknesses between 2.5cm and 10cm and many vertical joints. Alternated hard and soft layers are interbedded together (Figure 3.9). The mudstones are the hard and dark coloured layers with a relatively coarser grain size; whereas the soft and light coloured layers are relatively fine grained claystones. The soft beds are well laminated with a pure clay mineral composition which results in their flakiness and crumble characteristics. Micro-ripple lamination and climbing ripple lamination structures are found in the dark hard mudstone layers, but not in the soft claystone layers. The alternated layer structure has typical rhythmite rock features, indicating that the deposits were turbidite sediments in origin and probably formed in marine continental slope environment. The purer claystone layers were deposited in relatively quieter water period whereas the hard mudstone layers were formed in a slightly agitated water period, reflecting that the water energy fluctuated during the deposition of sediments. Other sedimentary structures of importance on the mudstones layers include slumping and recumbent folding structures. The occurrence of this stratigraphic is horizontal (Figure 3.9) to inclined (Figure 3.8) with a deep angle of 28^o and a dip direction of 36^o due to late tectonic influence.

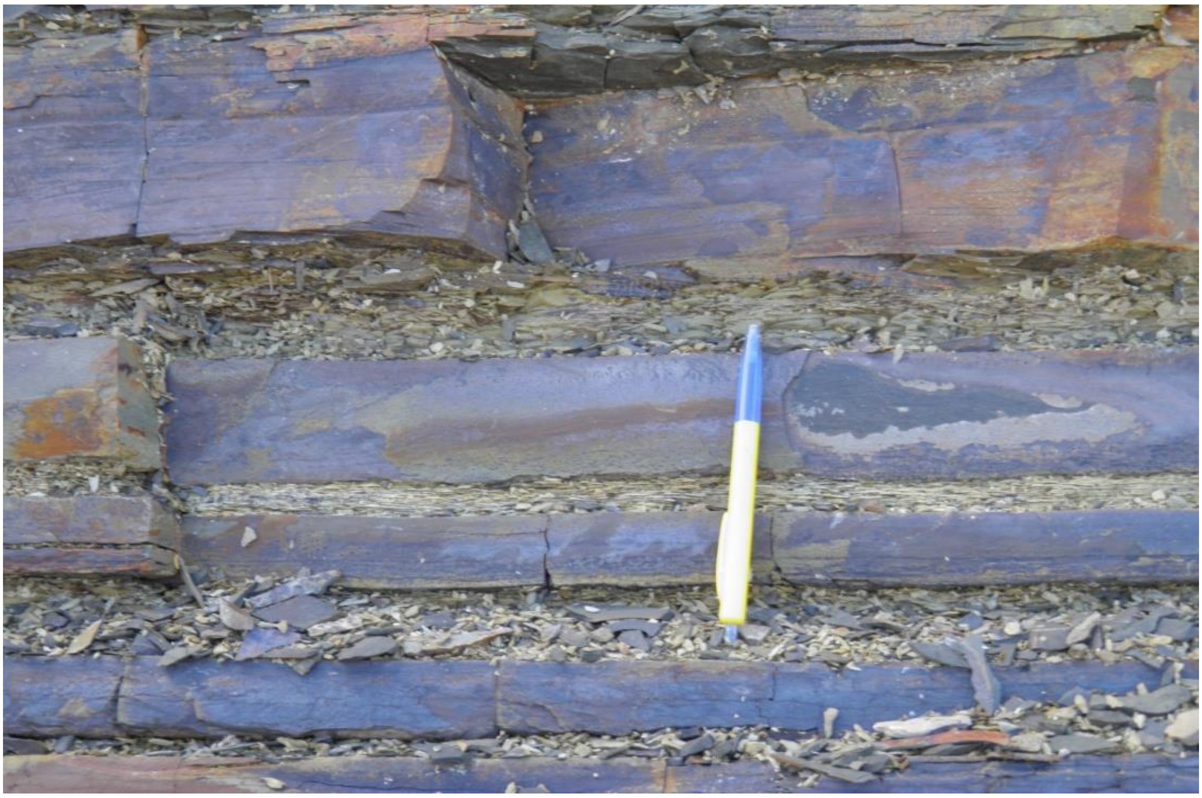

Figure 3.9 Well developed horizontal rhythmite of claystone (soft and light coloured) alternated with mudstone (hard and dark coloured). The claystone is purer and thus crumbles more than the mudstone. Lamination structures can be seen in the finer mudstone. Micro-ripple lamination appeared in the relative coarser and thicker mudstone layers, which is a typical sedimentary structure for turbidite sediments.

The stratigraphy of the Collingham Formation can be divided into members; the lower gray mudstone member and the upper black rhythmite member. The lower gray mudstone member is composed of thin bedded claystone and siltstone and well laminated shale overlaying the Whitehill Formation. The upper black rhythmite member differs from the lower member in that it has dark-black rhythmite depicting multiple cyclotherms of repeated couplets of claystone and mudstone (Figure 3.10).

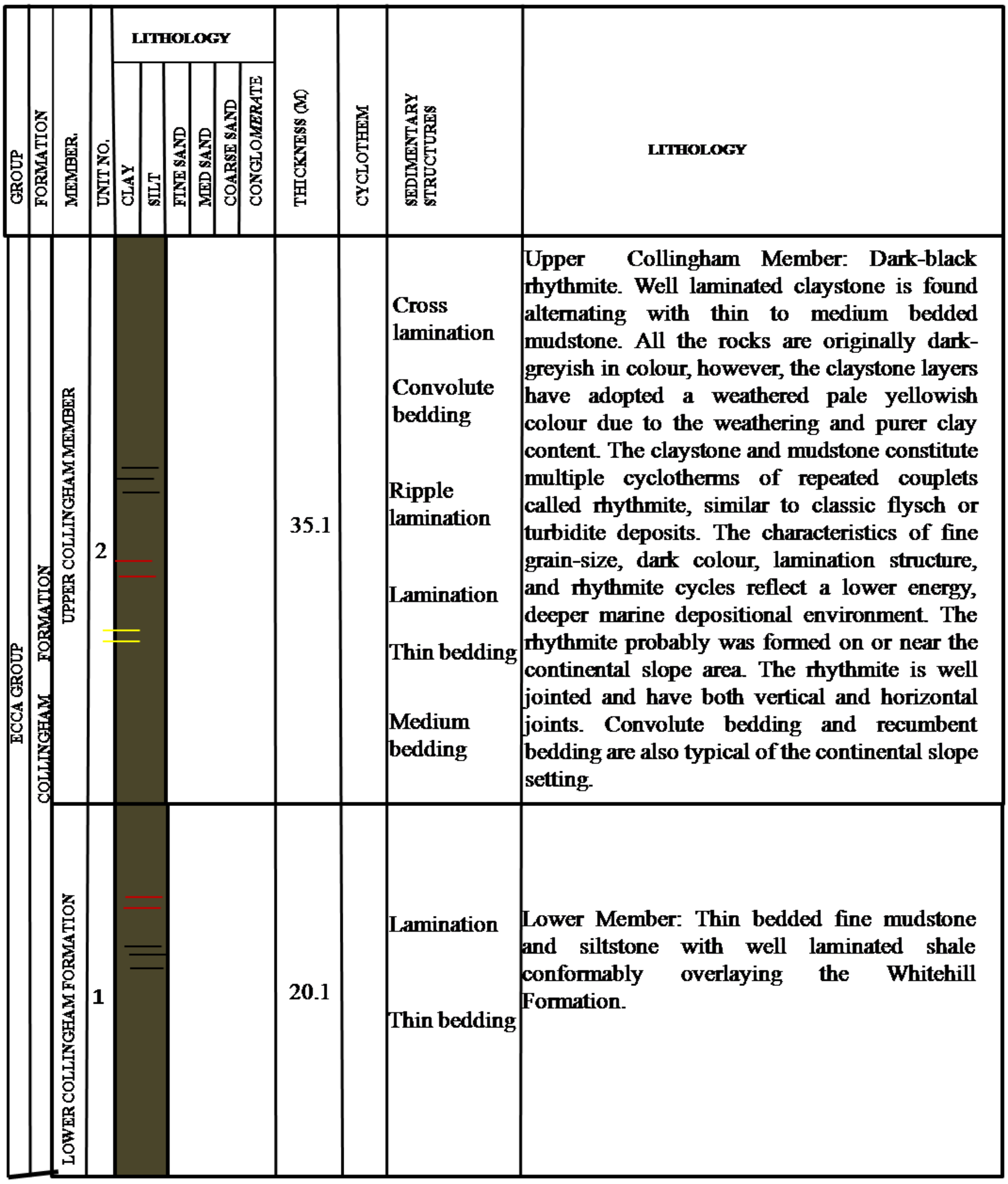

Figure 3.10 Stratigraphy of the Collingham Formation.

3.5 THE RIPPON FORMATION

The Rippon Formation disconformably overlays the Collingham Formation (Figure 3.11) and the formation has a mean thickness of 813.07m. Sandstones and mudstones constitute the rocks of the formation. The sandstones are predominantly graywacke and in general, silicification in the Rippon Formation is much strongly developed than in any other formations in the Ecca Group. The beds vary from thin to thick, ranging between 0.3m and 48.1m in thickness for an individual bed. In some instances, there are no bedding planes that can be identified leaving the sandstones as massive bedded rocks.

Figure 3.11 Disconformable contact between the Rippon Formation at the top and the Collingham Formation at the bottom. The top beds are slightly inclined compared to the bottom beds, indicating a disconformity or lower angle unconformity.

The rocks of the Rippon Formation contain numerous upward coarsening cycles of well laminated mudstones and sandstones (Figure 3.12). The repeated cycles were influenced by flooding and lack there-of, in the delta plain river channels as climatic conditions gradually changed. When the sediment load overcame the carrying capacity of the delta plain, coarse sediments were deposited onto the mouth bars of the delta front. Tides and currents re-worked the sediments at the mouth bars leaving them mostly structure-less, only being massive and thin bedded and also lenticular bedded. The mudstones accumulated from suspended fine materials, allowing lamination to form. Due to pelagic and hemi-pelagic conditions that can prevail in the flood plains of delta plains, the mudstones observed in the study area have an increased carbon content compared to the sandstones.

Figure 3.12 Floodplain deposits represented by the alternating sandstones and mudstones.

The basal unit of the Rippon Formation consists of graywackes with a thickness of up to 50m. The rocks have 7 cycles of alternating thin and thick beds. The thicknesses of the beds are between 2.2m and 12.3m. Typical for all sandstones, the sediment grains are sub angular to sub round and imbedded in a clay matrix that makes the rocks very hard. The rocks also have a high percentage of feldspar with matrix minerals that include smectite, illite, chlorite and kaolinite. The sandstones have horizontal bedding planes and joints and also calcite concretions (Figure 3.13).

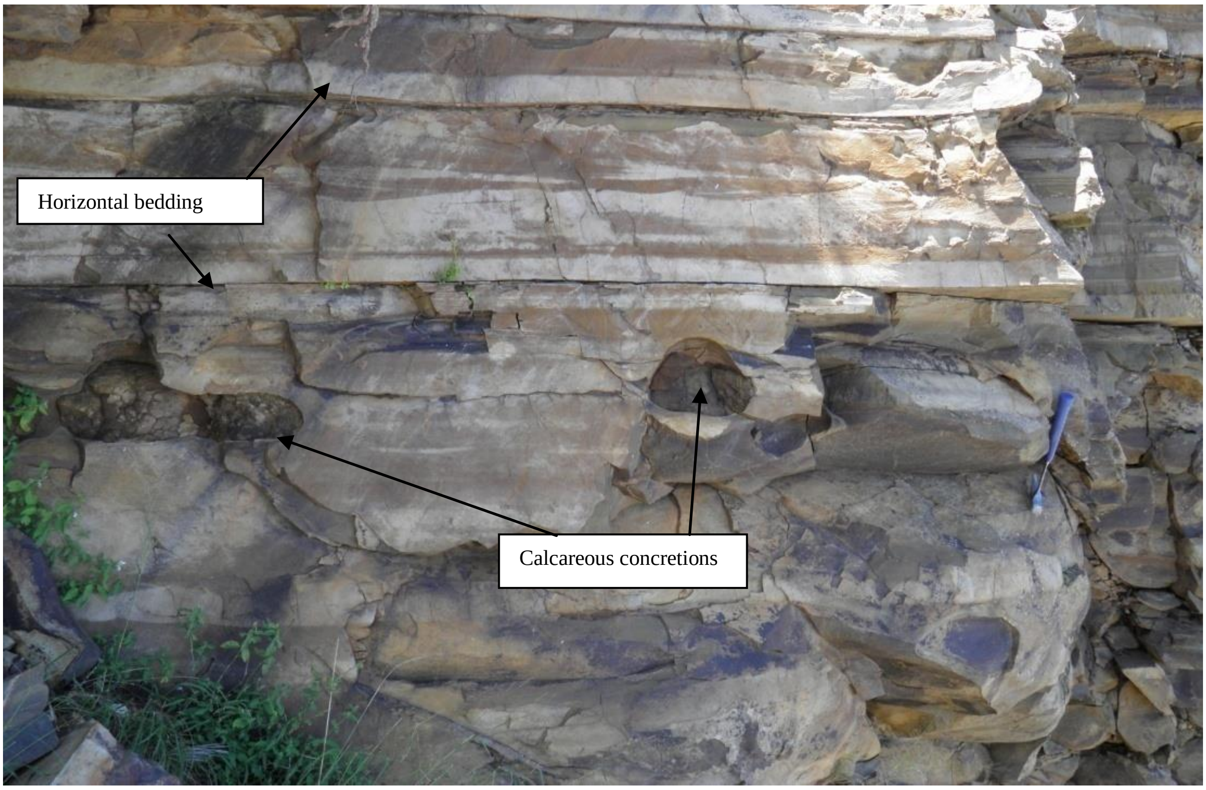

Figure 3.13 Well developed horizontal bedding, lenticular bedding (upper middle), calcite concretions, and joints on the graywackes in the basal unit of the Rippon Formation.

The presence of siltstone facies in the mudstones stand out to verify the increase in hydraulic energy in the depositional environment because of flooding. Sedimentary structures that can be identified on the mudrocks include ribose structures, convolute bedding and low angle cross bedding.

There are three members that the Rippon Formation can be divided into (Figure 3.14). The lower graywacke-mudstone member is 138.07m thick and consists of thin to thick bedded graywackes overlain by alternating shale and sandstone rocks. The middle gray mudstone-sandstone member (515.5m in thickness) is also composed of thin to thick bedded sandstones (generally thicker than in the lower member) overlain by alternating sandstones and shale produced during delta regression. The upper black mudstone-sandstone member consists of alternating sandstone and shale overlain by interbedded sandstone and mudstone with a thickness of 259.5m.

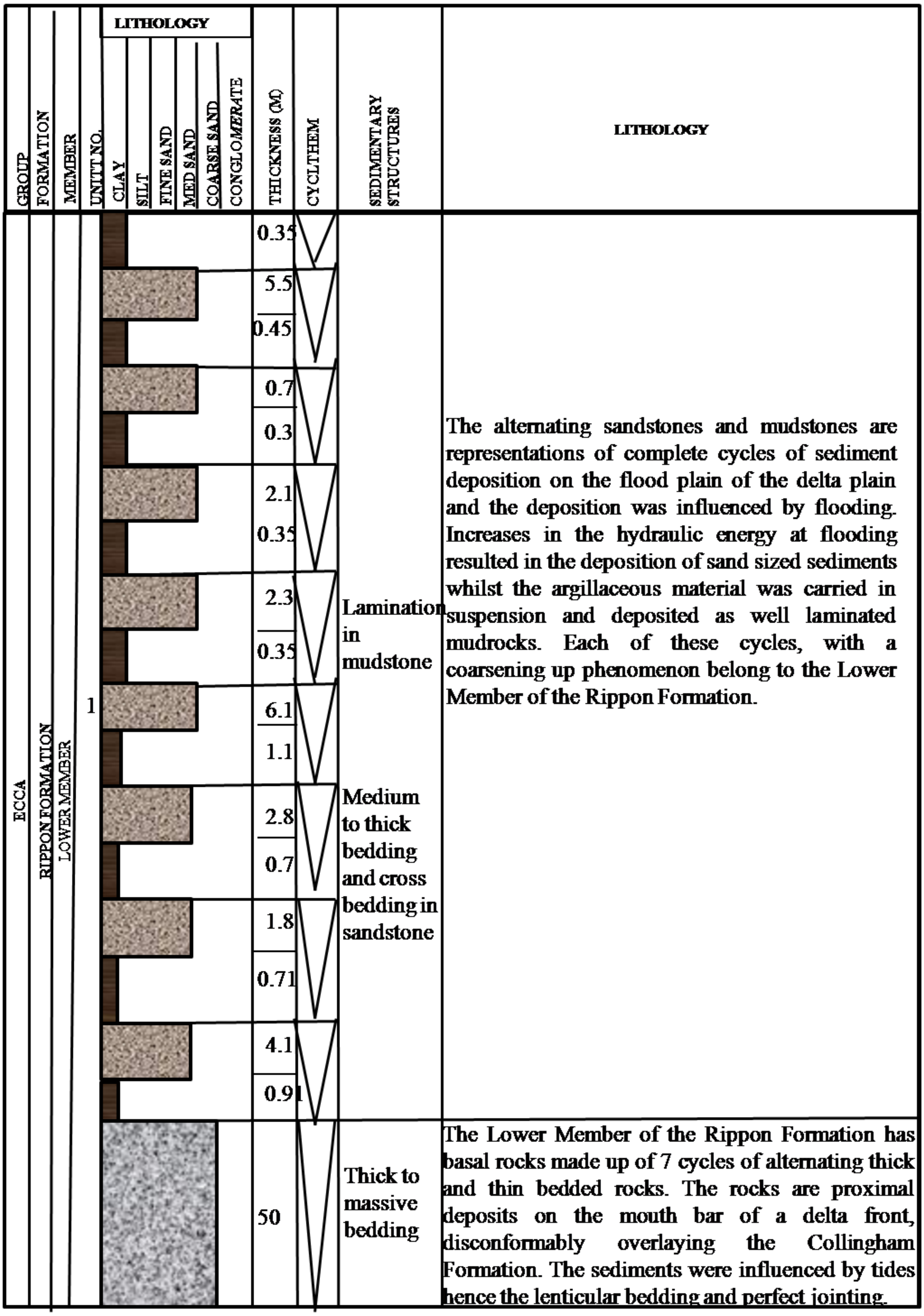

Figure 3.14 Stratigraphy of the Rippon Formation.

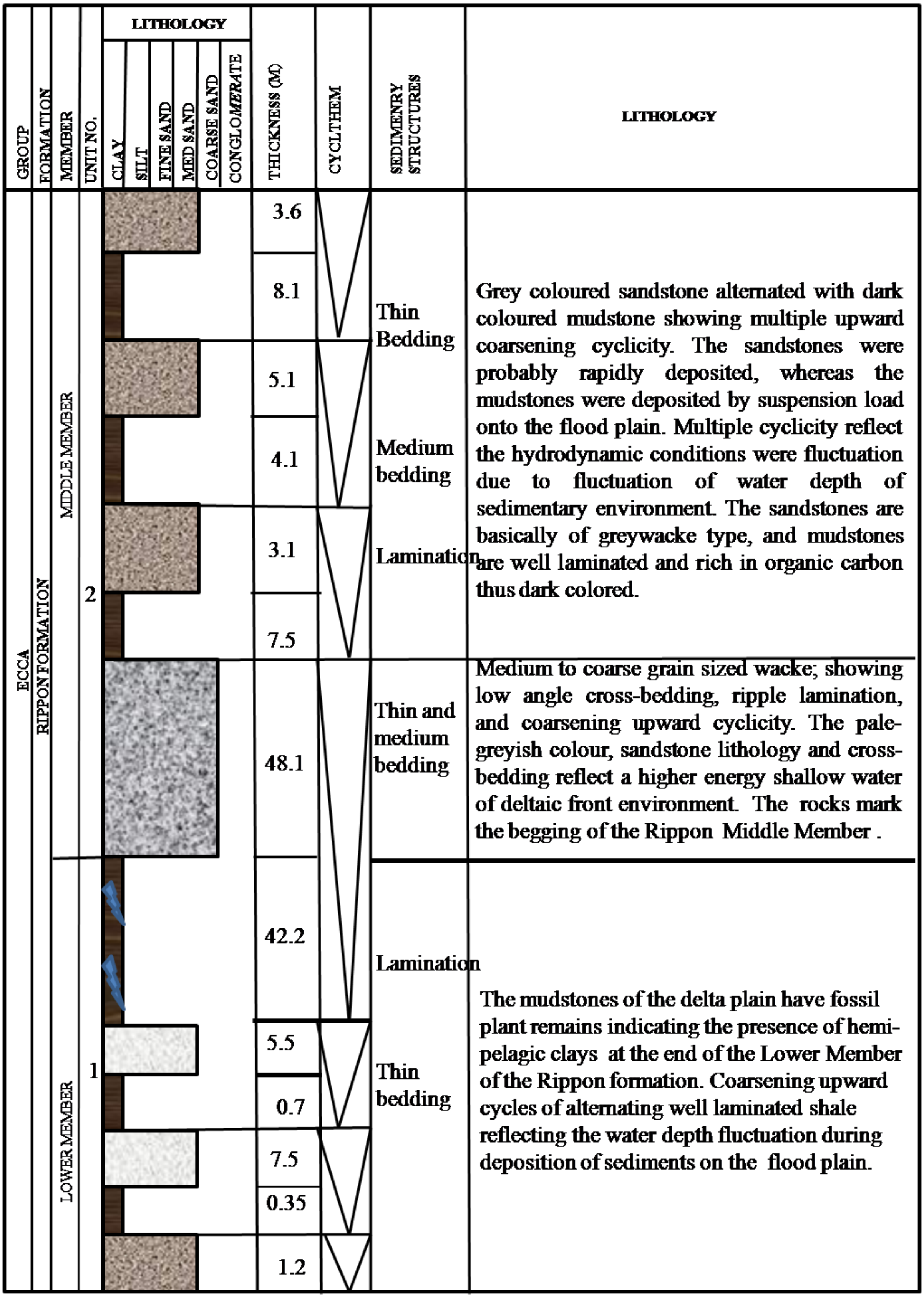

Figure 3.14 Stratigraphy of the Rippon Formation Continued.

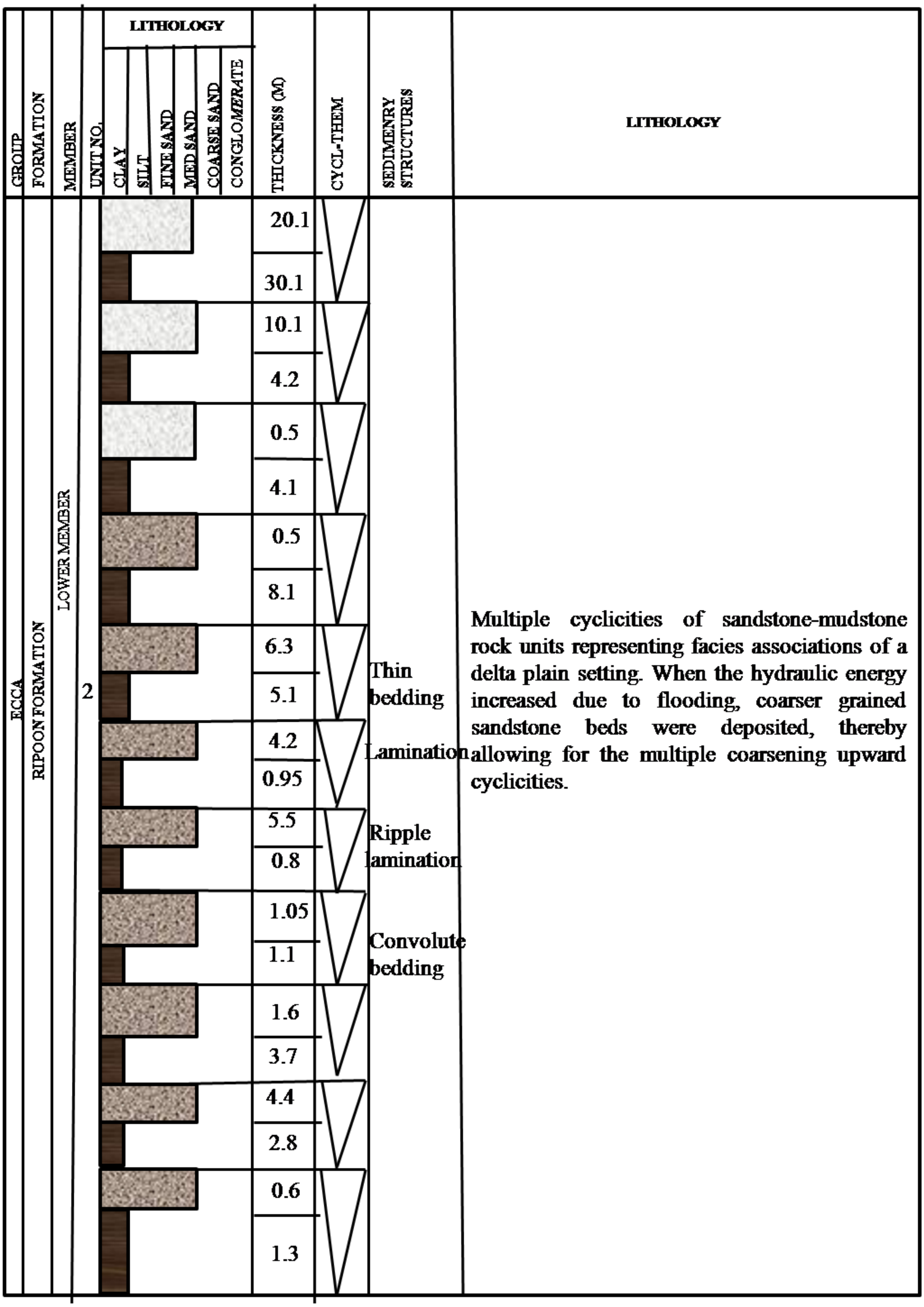

Figure 3.14 Stratigraphy of the Rippon Formation Continued.

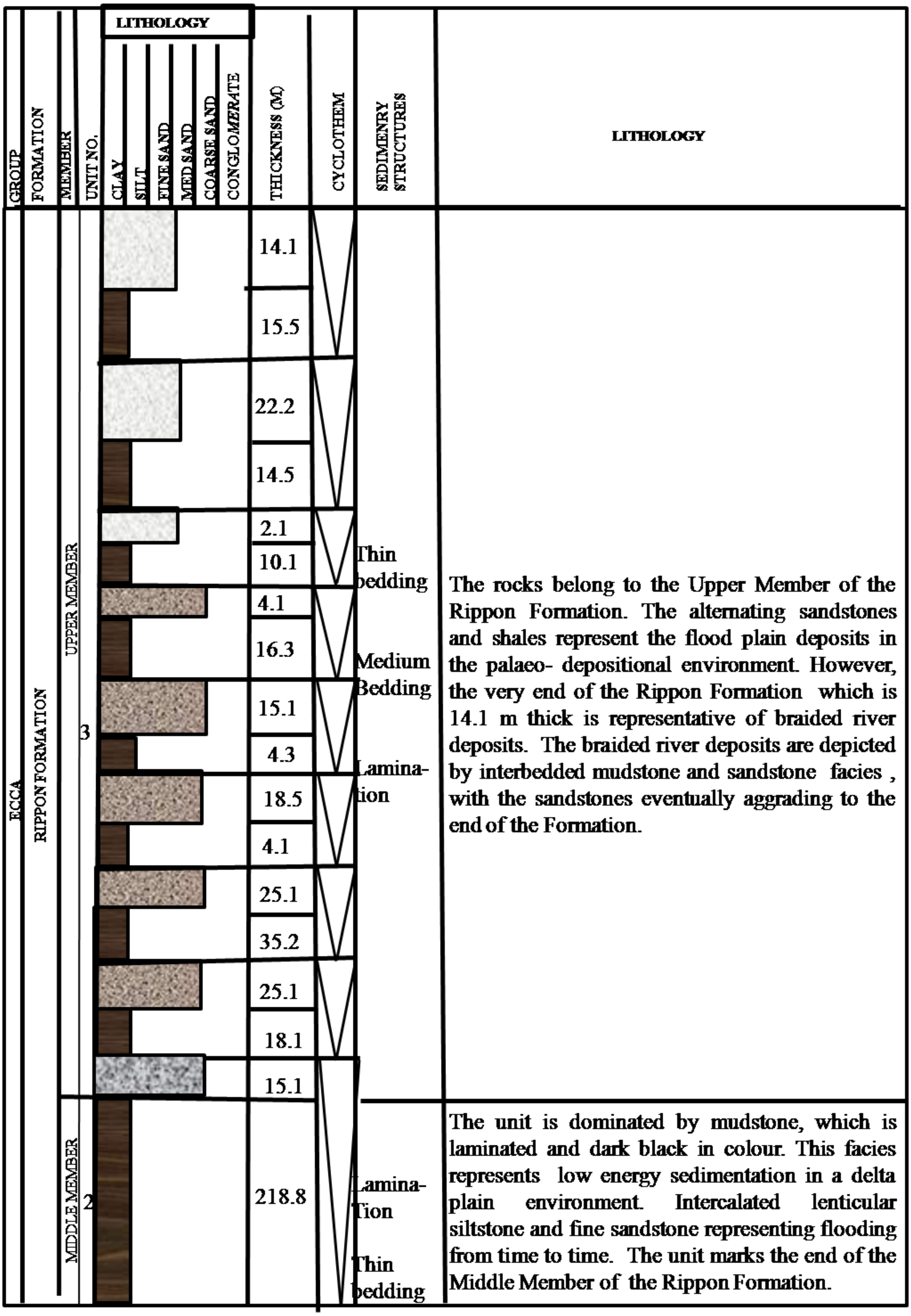

Figure 3.14 Stratigraphy of the Rippon Formation Continued.

3.6 THE FORT BROWN FORMATION

The Fort Brown Formation is divided into two members with a total thickness of 350.2m. The formation accumulated in a lacustrine environment since there are well developed varve rhythmite structure and seat-earth layers. The shift in the depositional environments of the Ecca Group, from a deep marine water environment to a delta environment and lastly to a lacustrine environment, clearly documented the change in climatic conditions in the depositional basin.

Two members have been established for the Fort Brown Formation, the lower gray varved rhythmite member and the upper mudstone-sandstone member. The lower gray varved rhythmite member consists of thin bedded grayish brown and well laminated rhythmites of mudstone, intercalated with a subordinate lenticular sandstone layer of about 10m in length imbedded within the mudstone sequence. The varved rhythmites are presented light and dark colour layers with a thickness of less than 2 millimetres. The thin layers (Figure 3.15) have resulted in the crumbling of the rocks of the study area. The upper mudstone-sandstone member has more sandstone beds compared to the lower member. The increase in the number of sandstone beds indicates the shallowing of the lacustrine environment in which the sediments of the Fort Brown Formation accumulated. The shallowing of the basin water continued to the overlying strata of the Beaufort group, which is dominated by fluvial sediments as the basin was finally closed.

The stratigraphy of the Rippon and Fort Brown Formations is presented in Figure 3.16, marking the end of the Ecca Group at longitude 33^{o} $10^{'}$ $54^{''}$S and latitude 26^{o} 36′ 54″Ealong the Road R67 from Grahamstown to Fort Beaufort.

Figure 3.15 Varve rhythmite facies of the Fort Brown Formation. Centimetre thick light coloured mudstone alternated with dark coloured mudstone, representing deposition of summer and winter seasonal changes.

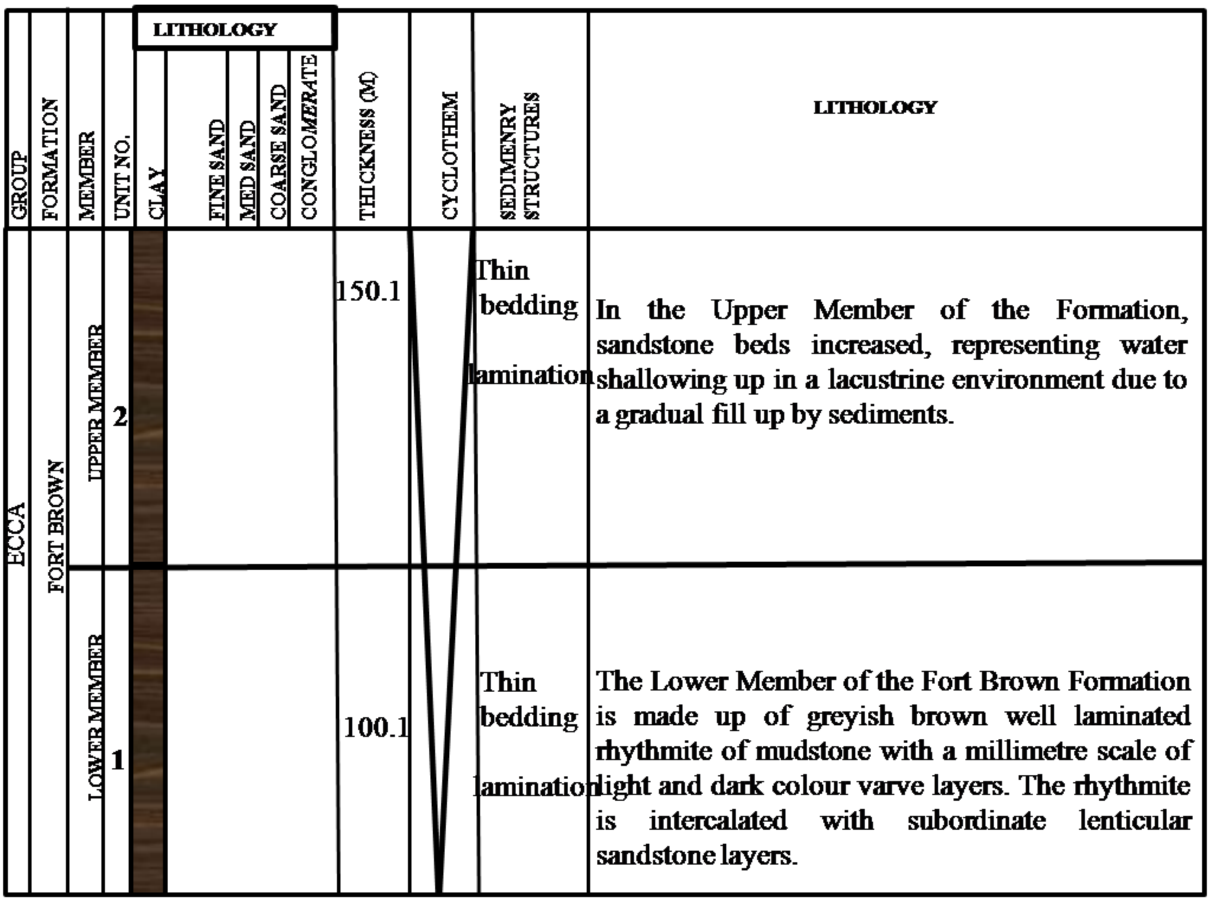

Figure 3.16 Stratigraphy of the Fort Brown Formation.

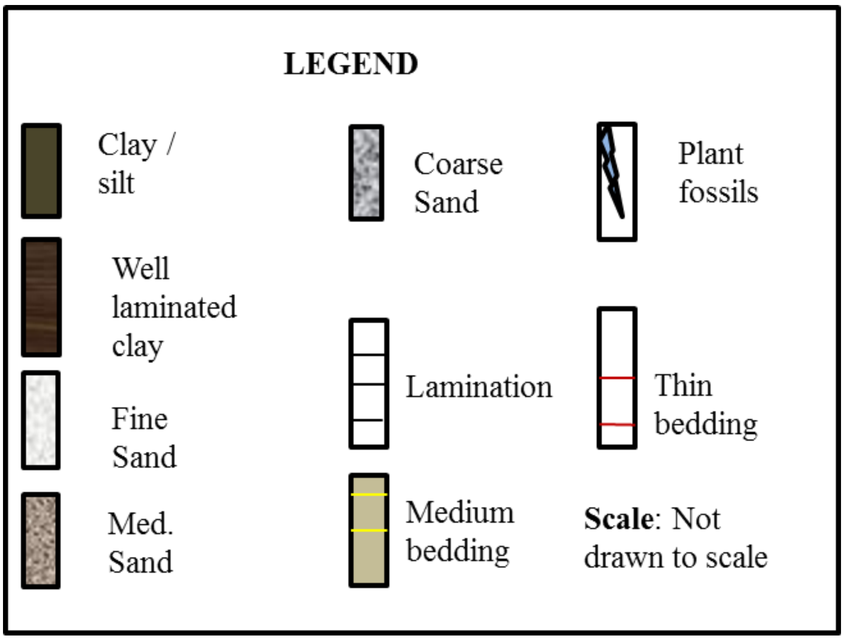

Figure 3.17 Legend for the stratigraphy of the Ecca Group

CHAPTER 4. PETROGRAPHY

4.1 INTRODUCTION

Detrital mineral grains that make up sedimentary rocks are derived from already existing metamorphic, igneous and sedimentary rocks. Some of these minerals are distinctive minerals which lead to the better understanding of their source areas. As sediments are transported from their source to the point of deposition, physical and chemical processes act upon them which in-turn influence the resultant rocks. According to Williams et al. (1954), a few detrital types of sediment components can point clearly to a particular source, but the composition of any detrital sediment reflects the character of its source. However, as Williams et al. (1954) further explained, many minerals may be altered or completely destroyed; therefore, sediments never have exactly the same mineral composition as their parent rock.

Minerals much more resistant to either physical or chemical changes are better preserved compared to those which are easily eroded and turned into more stable counter parts. The resilient minerals become the primary minerals in the rocks, whilst the weaker are reduced to minute particles then form the matrix. Although chemical changes can result in some changes on the detrital sediments, it is usually the physical processes that play a major role on the changes that occur. The sediments are altered in size, shape and level of sphericity. As the distance travelled by the sediments increases, the level of sorting, and the physical and chemical maturity is also drastically increased.

4.2 ROCK TYPES OF THE ECCA GROUP

Argillaceous rocks are prevalent in Prince Albert and Whitehill Formations, while arenaceous rocks (sandstones) compose a large part in the Rippon and Fort Brown Formations.

4.2.1 Classification of sandstones

The sandstones are flood plain, delta and tidal deposits with the same mineral composition. Their classification was based on the classification by Pettijohn et al. (1987) (Table 6.1).

Table 4.1 Classification of sandstones based on Pettijohn et al. (1987).

<table>
<tr><td colspan="2">Matrix , i.e., fine terrigenously derived minerals, e.g., clay minerals</td><td colspan="2">Matrix prominent >15%</td><td colspan="3">Matrix of fine terrigenous silt or clay absent or scanty (<15%)</td></tr>
<tr><td rowspan="5">**Sand fraction**</td><td rowspan="2">Feldspar exceeds rock fragments</td><td rowspan="4">**Graywackes**</td><td rowspan="2">Feldspathic graywackes</td><td colspan="2">Arkosic sandstones</td><td rowspan="4">**Quartz arenite**</td></tr>
<tr><td>Arkose</td><td>Sub-arkose or feldspathic sandstones</td></tr>
<tr><td rowspan="2">Rock fragments exceed feldspar</td><td rowspan="2">Lithic graywackes</td><td colspan="2">Lithic sandstones</td></tr>
<tr><td>Sub-graywacke</td><td>Proto-quartzites</td></tr>
<tr><td>Quartz content</td><td colspan="2">Variable; generally <75%</td><td><75%</td><td>>75%</td><td>>95%</td></tr>
</table>

4.2.1.1 Graywackes

The rocks of the Ecca Group were basically classified as graywackes. The characteristic feature of these rocks was the dominance of matrix as compared to the sand sized grains (Figure 4.1) although some rock samples were moderately sorted. The framework grains were always quartz, feldspar and lithic grains.

According to Tucker (2001), there are two possible origins of the matrix; fine grained sediment deposited along with sand fraction and diagenetic alteration of unstable lithic grains to produce a pseudomatrix. The latter is the most accepted opinion because of the presence of authigenic clay minerals caused by diagenetic alteration of detrital relicts. In the graywackes, clay minerals were separated from sand by turbidity currents hence could not be deposited together with the sand fraction.

The wackes were further divided into feldspathic graywackes, quartz graywackes and lithic graywackes and the groups had varieties within them.

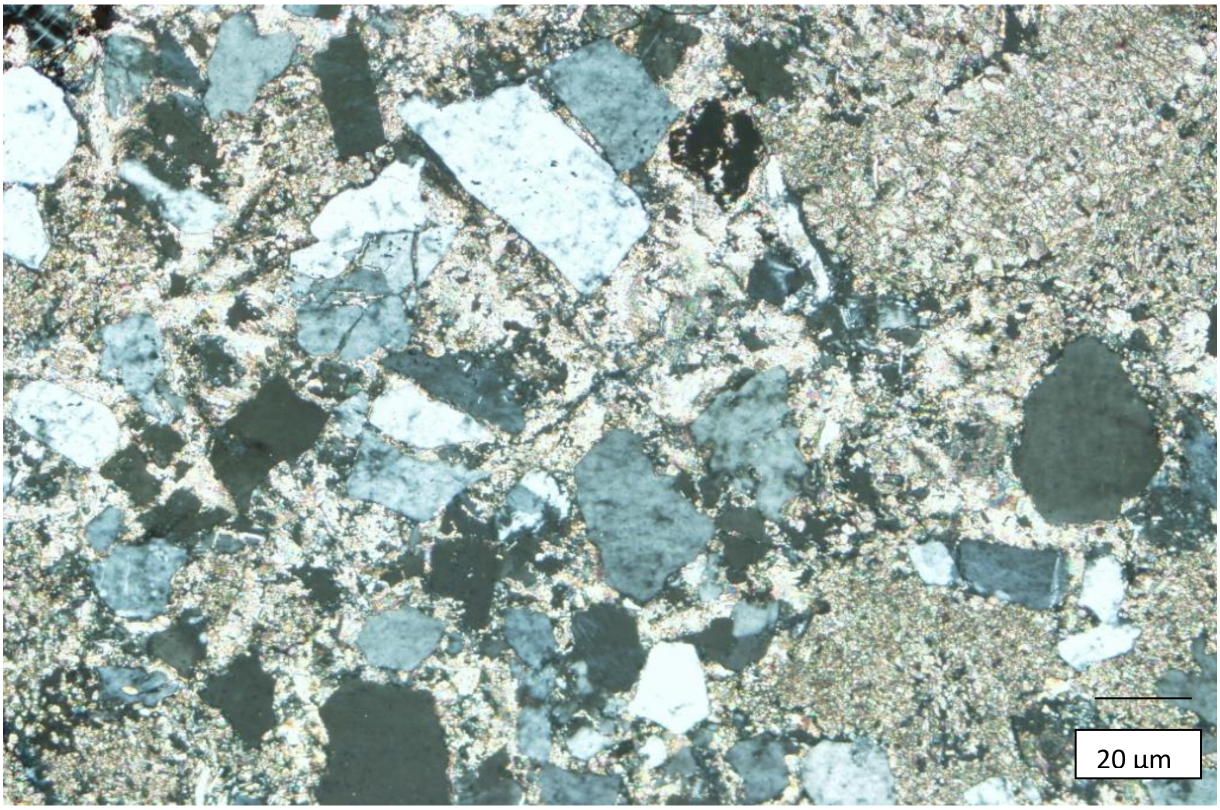

Figure 4.1 Thin section photomicrograph of a typical graywacke. The rock is characterised by poor sorting of angular and subround quartz, feldspar and lithic particles in a fine matrix.

4.2.1.1.1 Feldspathic graywackes

The rocks were also referred to as arkosic wackes. Feldspar grains were most dominant as compared to the lithics. In all of the rock samples, quartz content was generally high. Calcic and pottasic detrital feldspars had a high occurrence indicating the chemical immaturity of the rocks, having been deposited at close proximity to the sediment source. The varieties of the feldspathic graywackes are shown in Figure 4.2, Figure 4.3 and Figure 4.4.

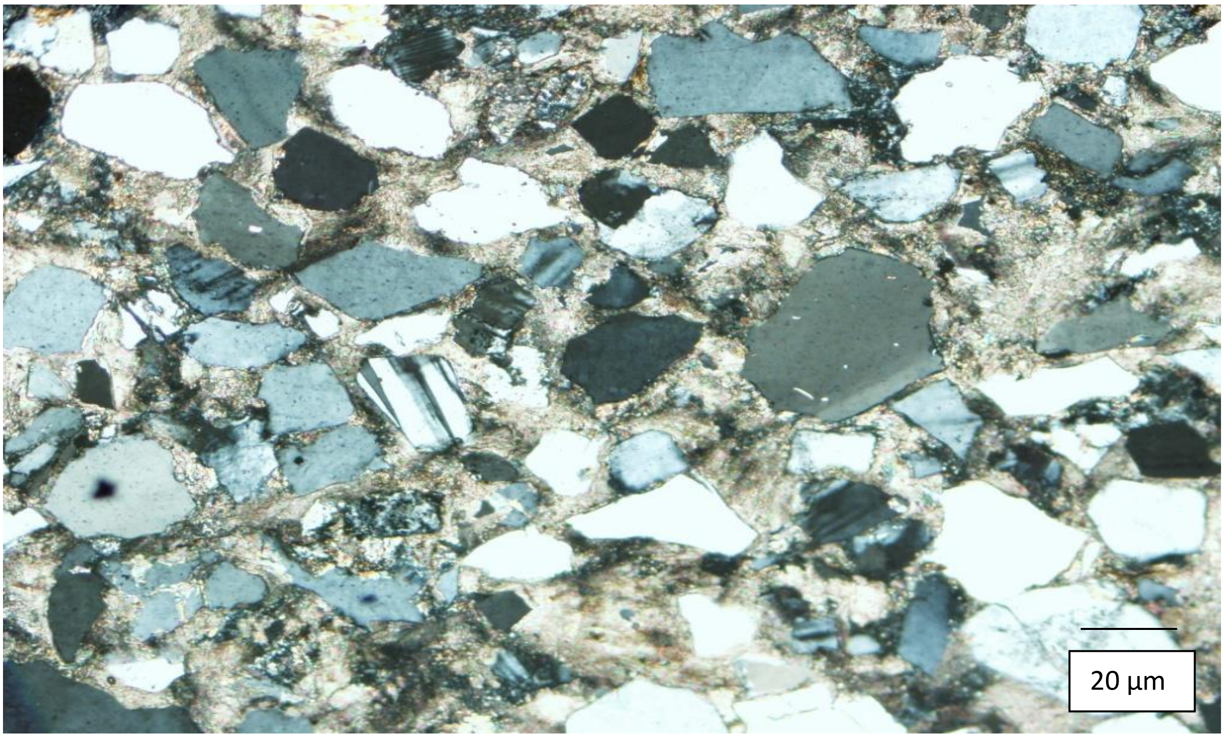

Figure 4.2 A thin section photomicrograph of a typical feldspathic greywacke which consists chiefly of quartz, feldspar and rock fragments in a fine grained sericite matrix. The grains are moderately sorted and subround.

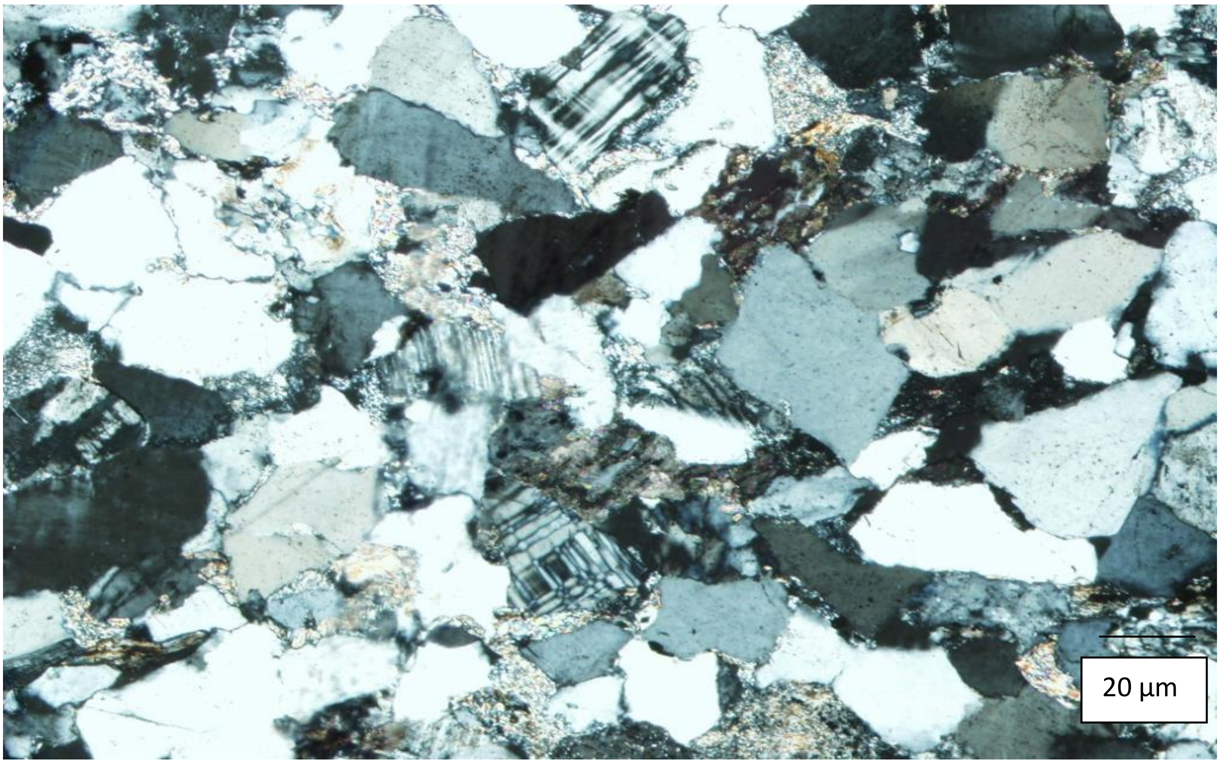

Figure 4.3 Photomicrograph of a feldspathic graywacke. It is moderately sorted with angular and subangular shaped quartz, feldspar and lithic grains.

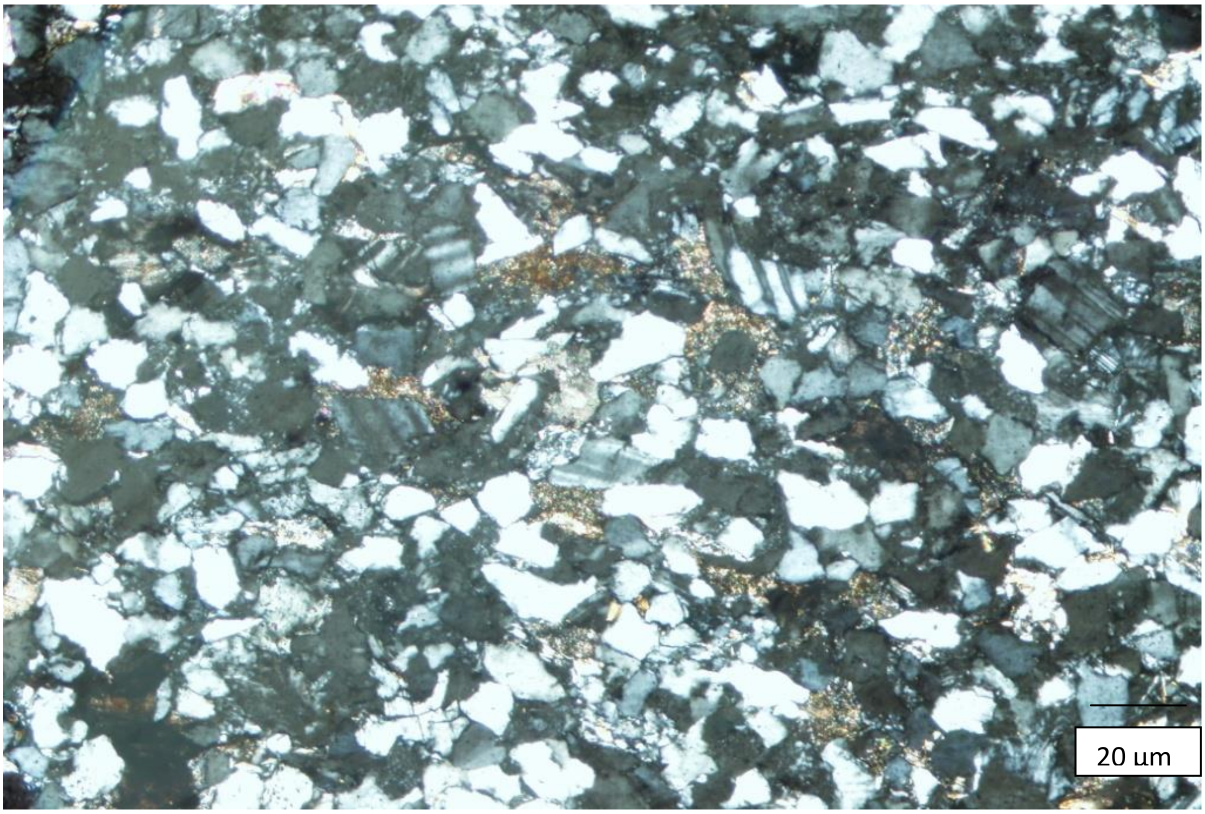

Figure 4.4 A thin section photomicrograph of a fine grained feldspathic graywacke. The rock is also moderately sorted.

4.2.1.1.2 Quartz graywackes

The rocks had a similar mineralogical composition to the feldspathic graywackes. The only difference lies in the dominance of quartz sand sized grains compared to feldspar and lithic grains (Figure 4.5). Quartz grains are the most durable when sediments undergo reworking during transportation.

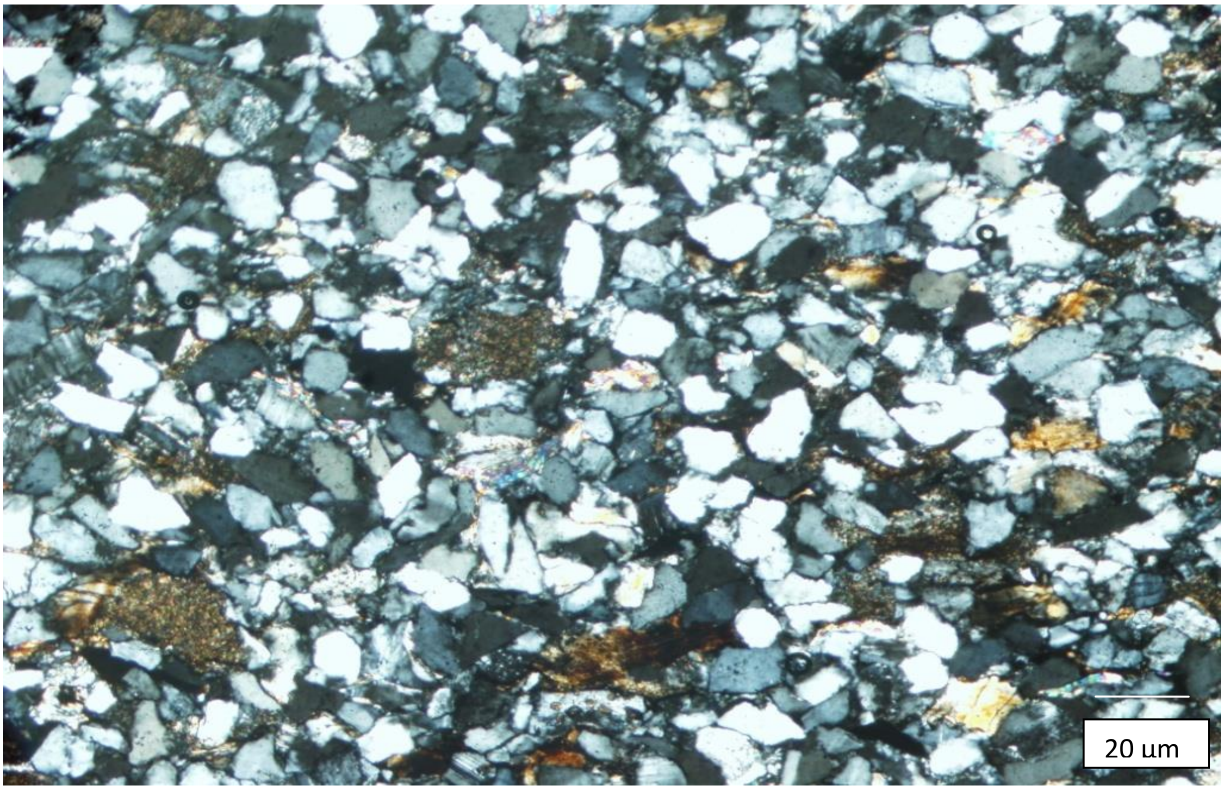

Figure 4.5 Thin section photomicrograph of a quartz graywacke. The rock lacks feldspar grains and is moderately sorted with subangular to subround quartz grains and lithic fragments.

The quartz rich graywackes were formed as a result of the deposition of sediments mostly derived from sedimentary sources. Considering that the mineral sediments had undergone reworking at first deposition, only the quartz grains could withstand further alteration when compared to the other mineral grains. The rocks are also reasonably sorted; therefore, the rocks have moderate textural and mineralogical maturity.

4.2.1.1.3 Lithic graywackes

The rocks have a high rock fragment content compared to feldspar although they generally had a wide range of composition with regard to grain types. The rock fragments were derived from mudrocks, low grade metamorphic and volcanic rocks. Micas and quartz grains could also be identified in the rocks. The amount of matrix in the rock samples was generally low when compared to the other types of graywackes. In some rock samples, feldspar minerals occurred in considerable amounts, hence the rocks could be referred to as feldspathic lithic wackes.

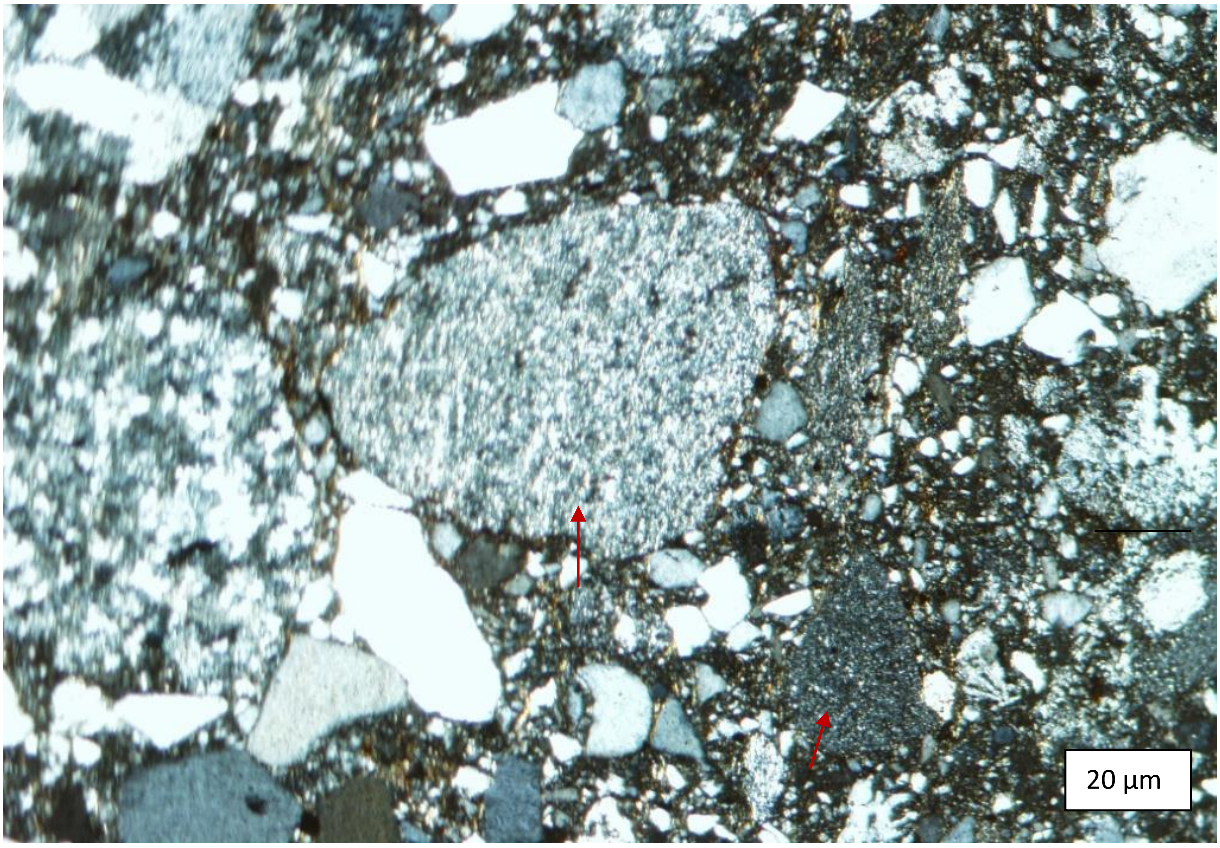

Figure 4.6 Thin section photomicrograph of a volcanic graywacke of the Ecca group; volcanic fragments indicated by arrows.

Volcanic graywackes had a considerable amount of ferromagnesian minerals due to the high presence of volcanic materials. The ferromagnesian minerals were easily identified by their dark colour under the microscope. Figure 4.6 shows a typical volcanic graywacke due to the high content of volcanic lithics.

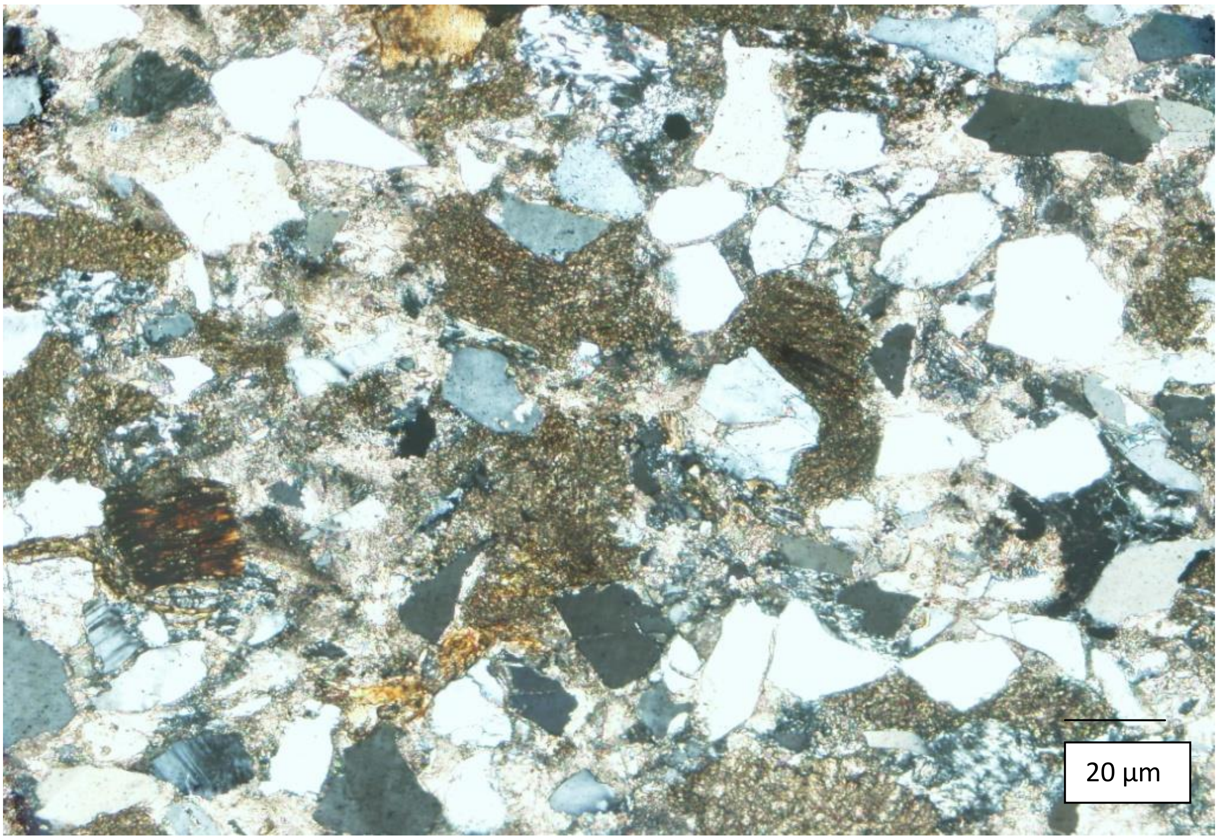

Figure 4.7 thin section photomicrograph of a lithic graywacke. The rock has a sedimentary rock source. It is moderately sorted with subangular to subround detrital grains of feldspar, quartz and sedimentary rock lithics.

Figure 4.7 shows lithics derived from sedimentary sources. The sedimentary rocks were generally sandstones and shales. Graywackes with lithics from sedimentary sources had high quartz content whilst those with volcanic lithics were observed as having lower quartz content and the quartz grains were also smaller in size.

4.2.2 Sedimentary structures in the Ecca Group sandstones

4.2.2.1 Lenticular bedding

The heterolithic facies phenomenon occurs in the sandstones of the Rippon Formation (Figure 4.8). Lenses of mud are found occurring within the sand sediments, a common feature for tidal deposits. The mud sediments probably invaded the sand deposits during fluctuations in sediment supplies and low water strengths. The mud ripples may be the muddy matrix that was separated from the sand sediments by tidal action.

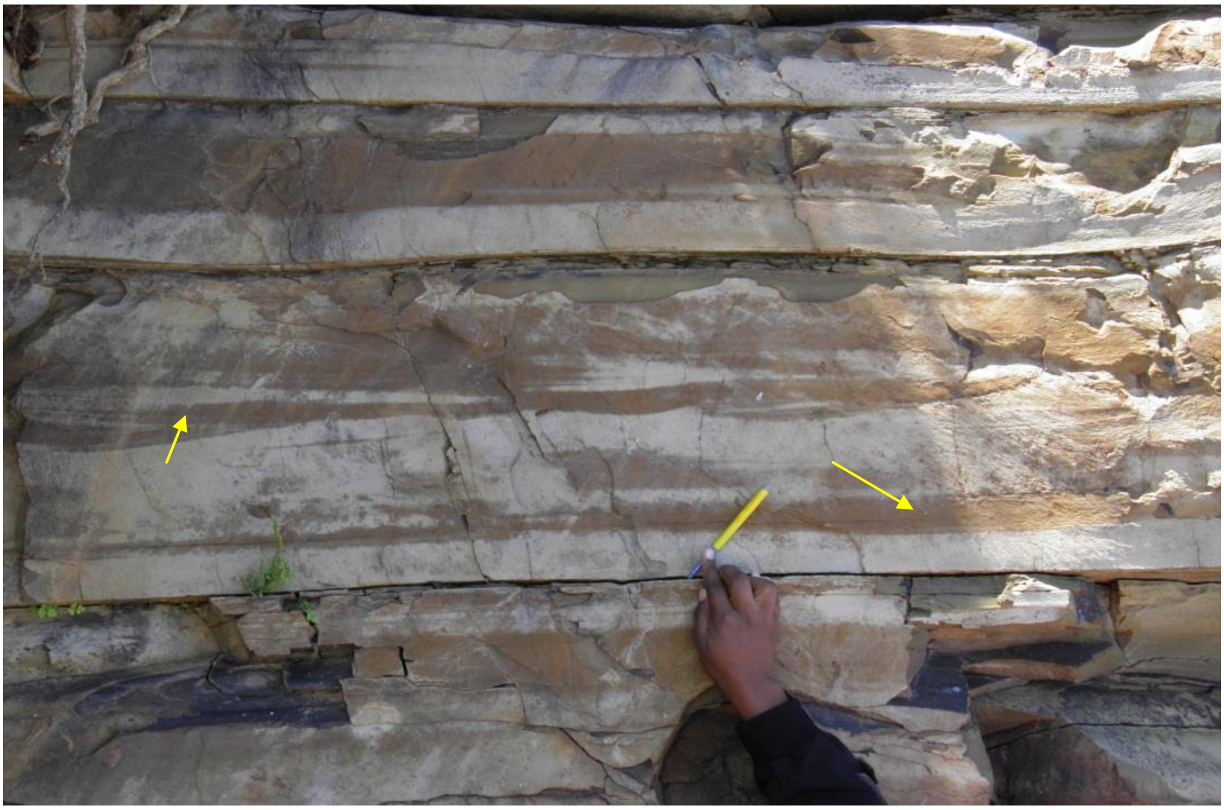

Figure 4.8 Sandstone rock with lenticular bedding (shown by arrows).

4.2.2.2 Tabular bedding

Horizontal bedding in the rocks was mostly as a result of deposition of suspended sediments. Low density tidal currents and a slow moving sediment load could have also been another cause of the planar bedding of the sandstones. The beds are of various thicknesses and are visibly separated from each other. Thin, medium and thick beds can be recognised. The thin beds measure between 1cm and 1m whilst the medium beds measure between 1m and 30m. The thick beds have a thickness of more than 30m.

Figure 4.9 Sandstone rock with planar bedding (shown by arrows).

4.2.2.3 Node clasts

The sole marks (Figure 4.10) were observed at the bottom surfaces of the coarser grained sandstones which were overlying fine grained mud sediments. The fine grained sediments either had uneven loading or were also affected by currents resulting in the formation of depressions which were later filled up by the coarser sediments. The mudstones of the Collingham Formation are turbidite deposits, the currents could have resulted in the uneven surfaces which were then later filled up by sand rich sediments of the overlaying Rippon Formation.

Figure 4.10 Node clasts at the bottom surface of a sandstone rock.

4.2.3 Classification of argillaceous rocks

The rocks are mainly composed of detritus clay and silt size particles with some chemically precipitated cements and organic material. Quartz and feldspar are the common minerals with calcite, haematite and organic matter also being of great influence in the rocks. The rocks accumulated in deep ocean water, continental slope, delta plains and lakes. Although found in low energy environments, in some instances, mudrocks were found trapped within high energy rocks as lenticular beds.

The rocks were grouped based on their particle size and origin. In terms of particle size, the rocks were divided into:

1. **Siltstones**

   Siltstones composed of particles that range between0.062mm and 0.0039mm (i.e. 4-8 Ø).

2. **Claystones**

These rocks have particle sizes that are less than0.0039mm (i.e. > 8 Ø) and >75% clay.

3. **Mudstones**

   Mudstones are generally rocks that consist of both clays (> 50%) and silt size grains.

With reference to the places of origin deduced in the stratigraphy chapter, the mudrocks were classified as;

- **Non marine mudrocks**

  The rocks were mainly associated with fluvial and lacustrine depositional environments. The rocks were in most cases over bank deposits hence associated with floodplains and lakes and have a fining upward phenomenon. Climate, chemistry of waters and organic productivity played a major role in the variations of the mudrocks.

- **Marine mudrocks**

  These rocks were deposited at the delta front, continental slope and off shore marine shelf. The rocks were affected by tides and turbidites and other current processes, hence mostly derived from suspended sediments. The rocks are dark grey in colour, a function of both high organic content and the reducing environments.

- **Black shales and Organic rich mudrocks**

  The rocks contain between 3% and 10% of organic matter. The rocks were found occurring in lakes, flood plains and delta front. The depositional zones at some point became oxygen deficient and anoxic, resulting in the decomposition of organic matter by bacteria. With increase in anoxic conditions, the rocks became darker in colour.

4.2.4 Sedimentary textures of the Ecca Group argillaceous rocks

4.2.4.1 Fissility

The rocks of the Ecca Group have a fissility texture (Figure 4.11) allowing the rocks to break along laminae planes. Thefissility of the shale is as a result of the high organic content, the alignment of clay particles and presence of laminae. The rocks were all deposited in low energy environments which allowed for the preservation of the laminae.

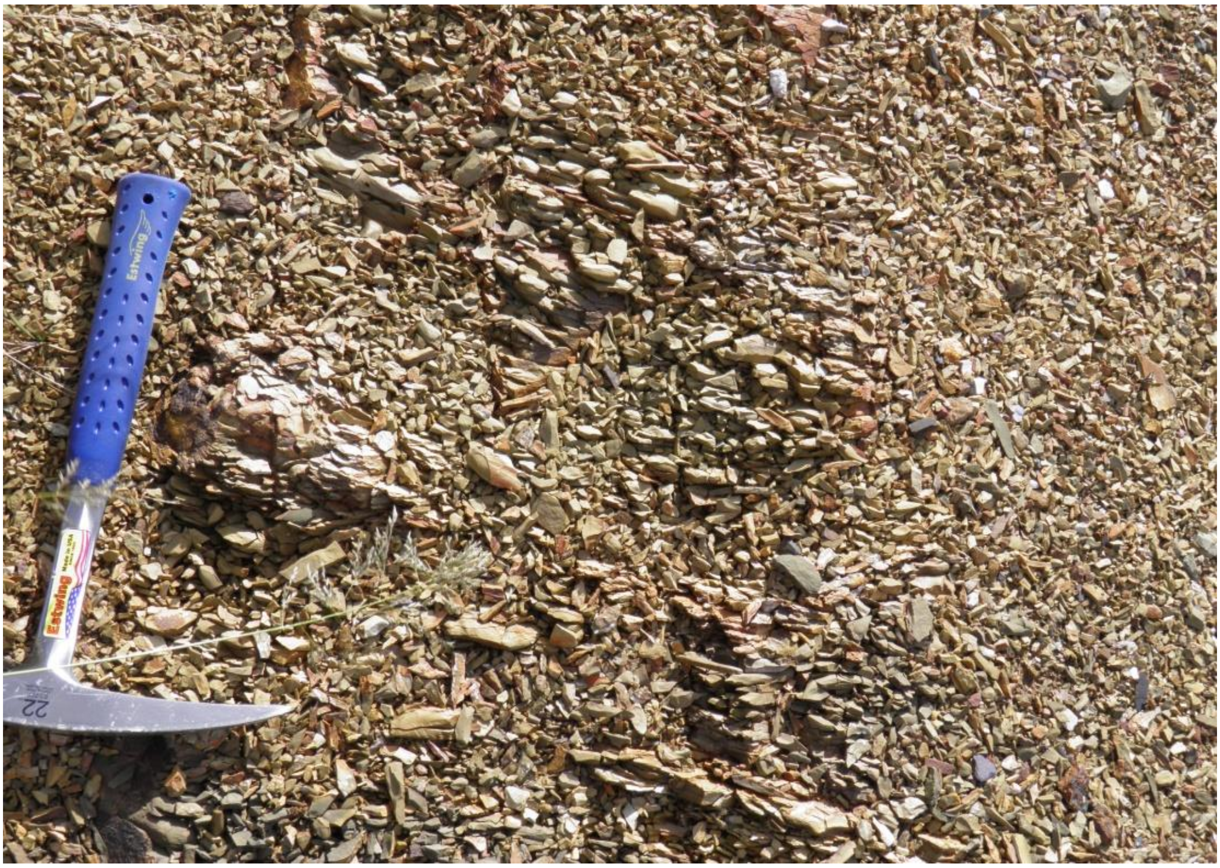

Figure 4.11 The crumbling of shale along lamination planes.

4.2.4.2 Orientation of minerals parallel to bedding

The texture was detected in thin sections. The texture was effected by settling and compaction allowing the clay and silt grains to lie parallel to the lamination of the rocks as shown in Figure 4.12.

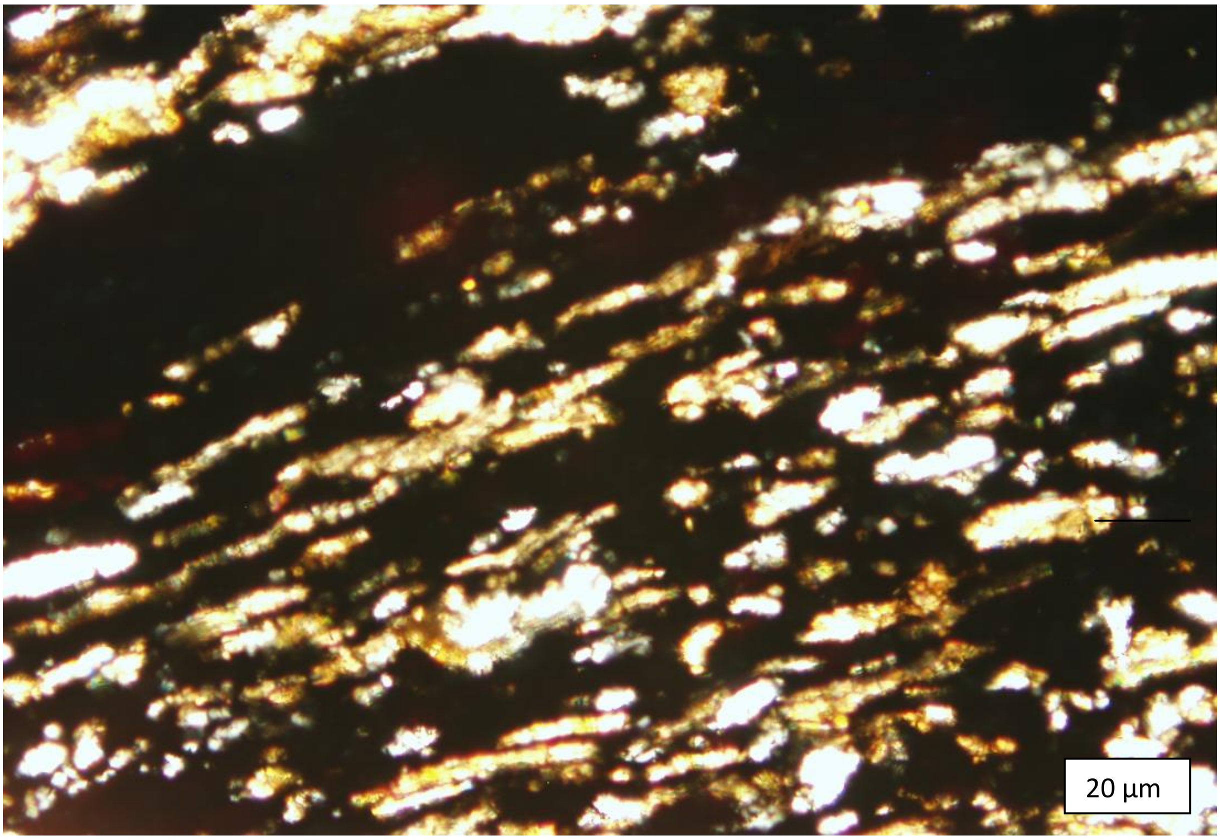

Figure 4.12 Thin section photomicrograph depicting mineral grains lying parallel to the lamination planes.

4.2.5 Sedimentary structures in the Ecca Group argillaceous rocks

4.2.5.1 Lamination

This was the most common rock texture in the mudstones (Figure 4.13). The structures were due to the deposition of suspended clay minerals. At instances, turbidity currents led to the destruction of the structures where lamination did not occur on the mudrocks.

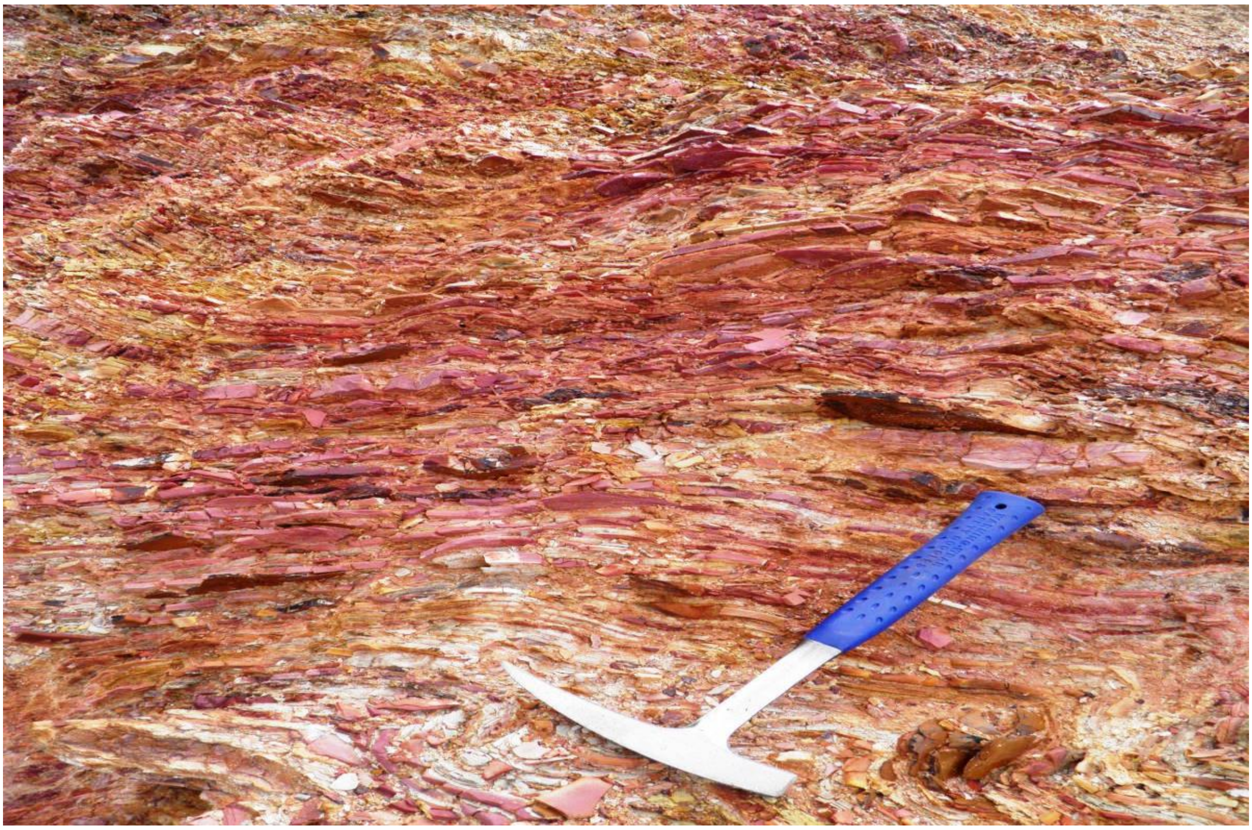

Figure 4.13 Well laminated shale. The red staining is due to iron oxide produced during the weathering and leaching on the surface.

Varves (Figure 4.14) which are another kind of lamination can also be observed and the structures formed in a lacustrine environment with seasonal deposition of sediments. Whenever there was a high inflow of water, coarser sediments were also transported into the basin, whilst the finer sediments were deposited from suspension during periods when the water inflow was low.

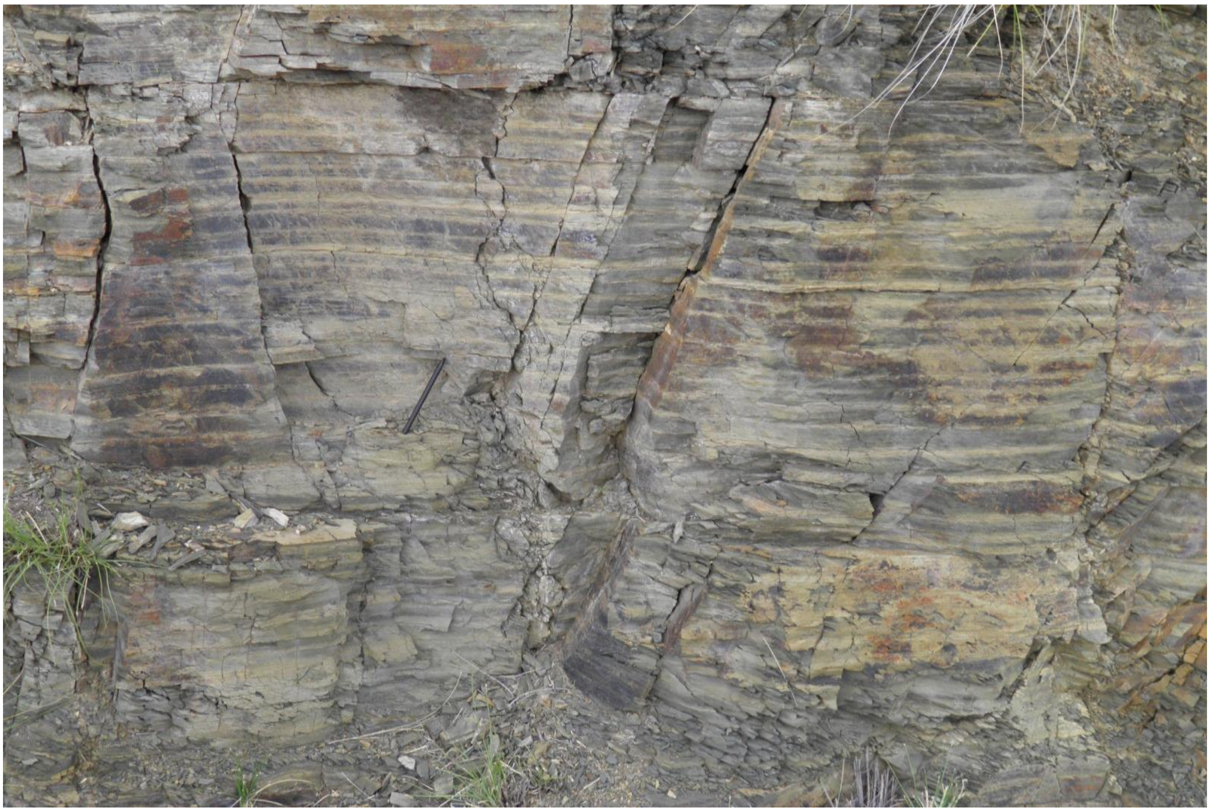

Figure 4.14 Varved rhythmite deposits of lacustrine origin. Showing alternating light coloured mudstone and dark coloured mudstone, each with a centimetre thickness.

4.2.5.2 Low angle cross bedding

Cross bedding (Figure 4.15) was formed by lateral movements of silt sized sediments on clayey sediments. The presence of currents increased the water energy in the depositional environment allowing for silt sediments to be deposited.

Figure 4.15 Siltstone intercalated within mudrock. The siltstone shows low angle cross bedding.

4.2.5.3 Convoluted bedding

This texture developed when the sediments were still wet, before lithification occurred. The structures in Figure 4.16 occurred at the uppermost part the bed. The texture was as a result of dewatering processes. Differential liquefaction and lateral-vertical intrastratal flow and shearing of sediments by currents result in water escape features such as convolute bedding.

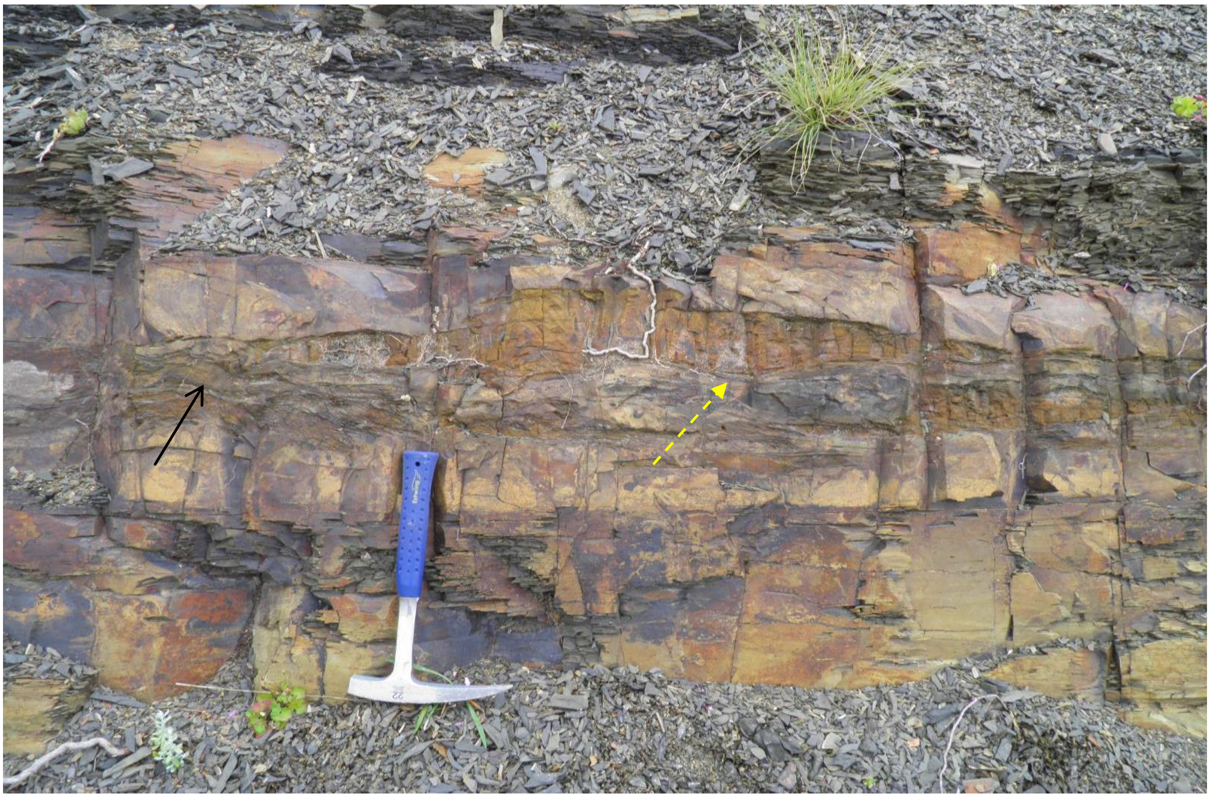

Figure 4.16 Convoluted bedding (black arrow) and ripple marks (yellow arrow) on mudstone.

4.2.5.4 Ripple marks

The undulations on the surface of the silt sediments were recognised in the study area. The asymmetrical undulations were produced perpendicular to the direction of flow. The waves truncated the surfaces of the ripples due to their continued action, washing off the crests of the ripples; in general, ripples have a low preservation potential (Figure 4.17).

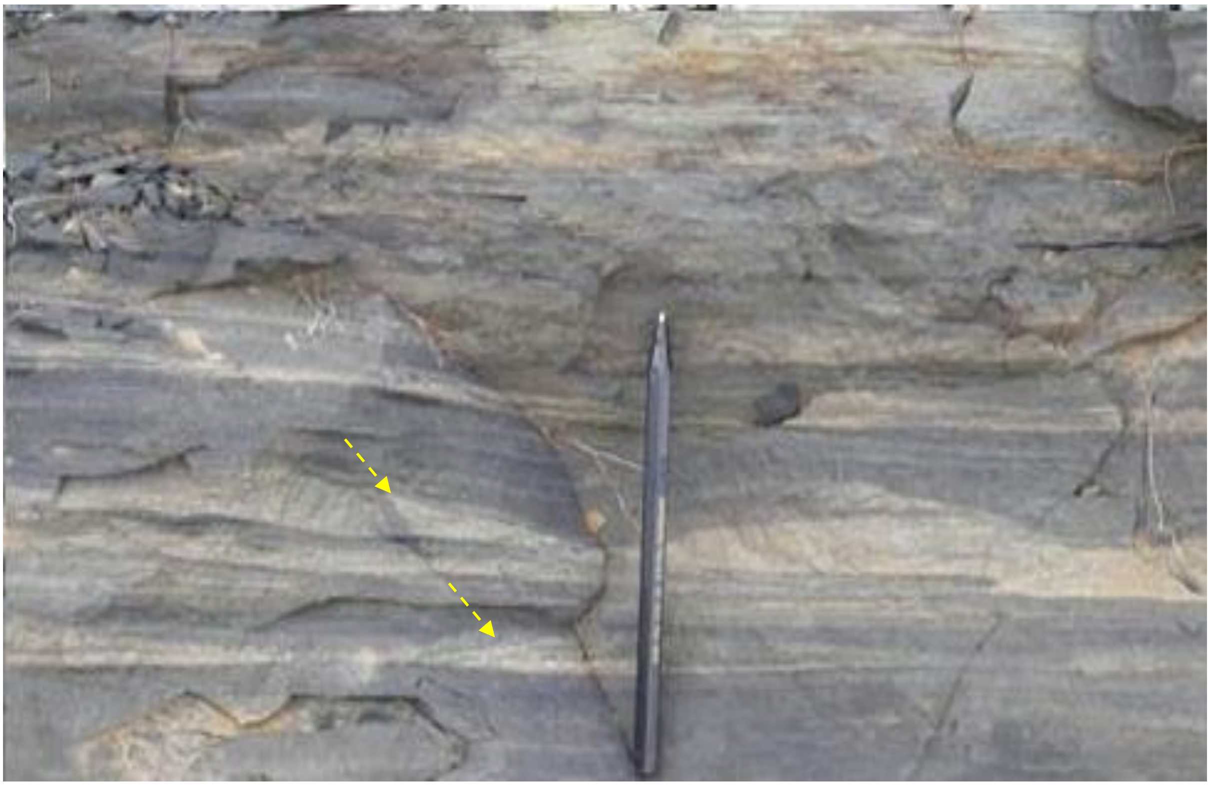

Figure 4.17 Siltstone intercalated within mudrock. The siltstones have ripple marks at their top surfaces (arrow).

4.2.5.5 Trace fossils

The trace fossils could have been left by animals that lived in the fine sediments. Workdone on the Ecca Group from a different location of study by Almond (2013); the fossil marks were described as burrows of ichnogenus *Chondrites* which include endichnial branching feeding burrows typically associated with quiet water and low oxygen environments. The conclusion was made due to the similarities between Figure 4.18 and Figure 4.19 taken from the main study area and from the work done by Almond (2013) respectively.

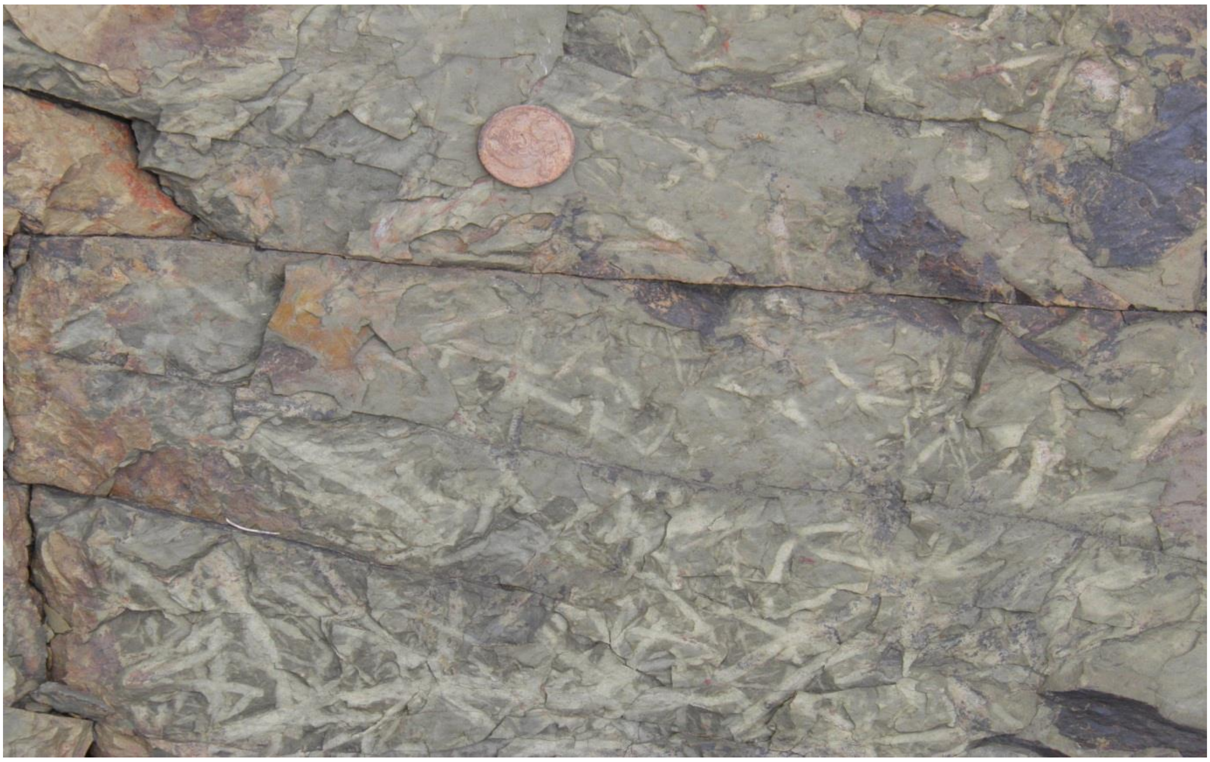

Figure 4.18 Burrows of the ichnogenus *Chondrites*.

Figure 4.19 Plant-like branching burrow system of the ichnogenus *Chondrites* within the mudrocks of the Ecca Group. The thicker "stem" of the burrow is c. 3 mm wide. Cited from Almond (2013) for comparison.

CHAPTER 5. MINERALOGY AND CHEMICAL ANALYSIS

5.1 INTRODUCTION

A mineral is an element or chemical compound that is normally crystalline and that has been formed as a result of geological processes (Nickel, 1995). From the definition, it can be deduced that a mineral is a naturally occurring element or compound with a specific internal structure in the arrangement of its atoms. Commonly, minerals are solid substances that are stable under normal temperatures. Although there are numerous minerals that have been discovered, minerals can be distinguished from each other using their physical properties which in most cases are influenced by their chemical compositions and physical properties. The chemical compositions are therefore definite in nature although slight changes may be observed occurring in the crystal lattices. The physical properties used for differentiating the different minerals usually include luster, colour, streak, cleavage, hardness and cleavage or partings.

5.2 MAJOR MINERALS IN THE ROCKS OF THE ECCA GROUP

In the Ecca Group, various minerals were distinguished using the scanning electron microscope (SEM) and X-Ray diffraction (XRD). The various identified minerals are mainly framework minerals, matrix minerals, micas and heavy minerals.

5.2.1 Framework minerals

5.2.1.1 Quartz

Quartz is differentiated by being colourless under the microscope, with first order white-greyish interference colours. The quartz grains in the rocks are either detrital or authigenic. Authigenic quartz grains appear in two forms, as syntaxial overgrowths (Figure 5.1) or as euhedral prismatic crystals observed under the SEM and light microscope, albeit occurring only in minor quantity. The authigenic quartz grains can be observed clean, clear under the light microscope and found directly associated with feldspar and mica dissolution. The dissolution of feldspar to illite allowed for the formation of authigenic quartz and this feature was determined in SEM. The recrystallisation of the matrix also resulted in the formation of authigenic quartz (Figure 5.2).

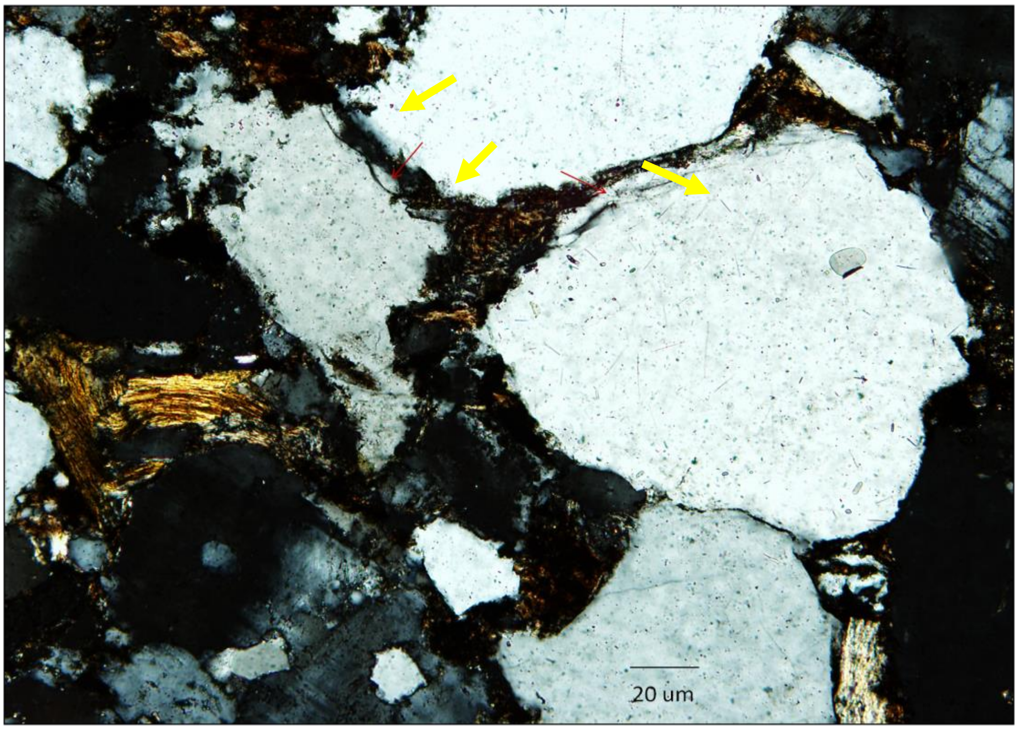

Figure 5.1 Thin section photomicrograph of quartz grains and the overgrowth parts of the quartz (yellow arrow).

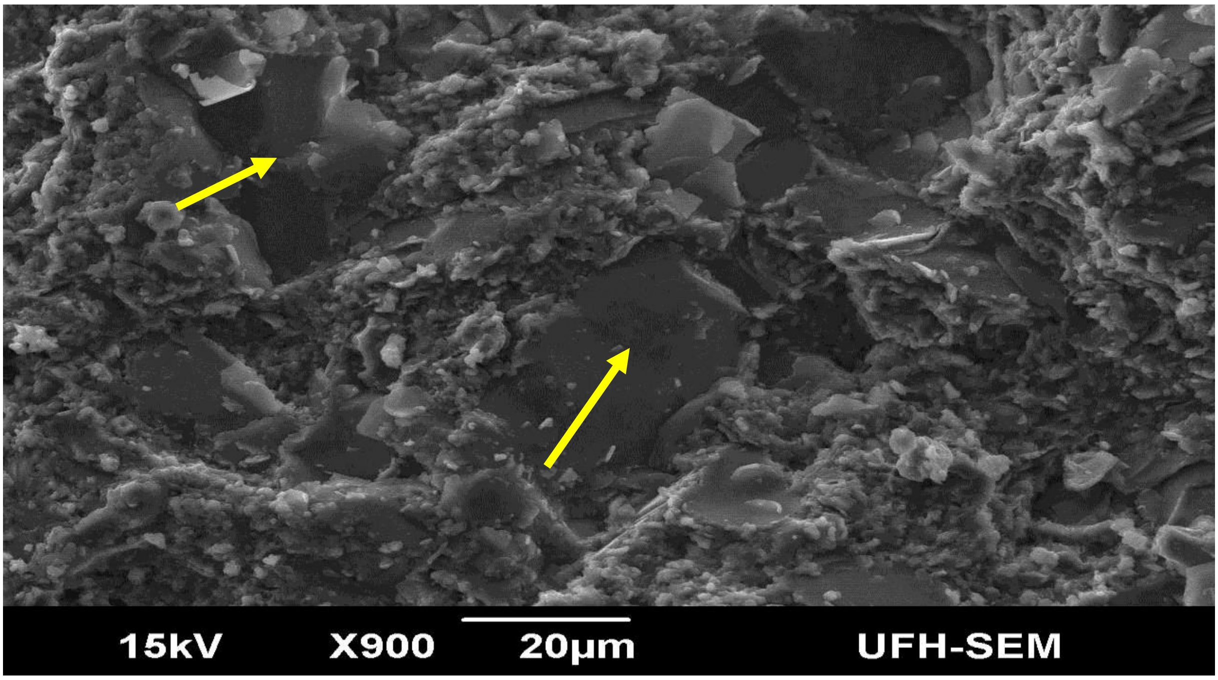

Figure 5.2 Scanning electron photomicrograph showing euhedral quartz grains (arrows).

Both monocrystalline and polycrystalline quartz (Figures 3 and 4) that exhibit intercrystalline suturing are found in the rocks. Whilst some of the monocrystalline quartz grains display undulatory extinction (Figure 5.5), others have uniform extinction. Undulatory extinction indicates that different mineral parts have different orientations due to deformation, causing extinction at different positions. The polycrystalline grains are minor as compared to the monocrystalline quartz grain, which infers instability in depositional environments. The polycrystalline grains have a random sorting of both big and smaller grains grouped together, indicating the existence of quartz rich rocks at the sediment source whilst some of the polycrystalline quartz grains are elongated.

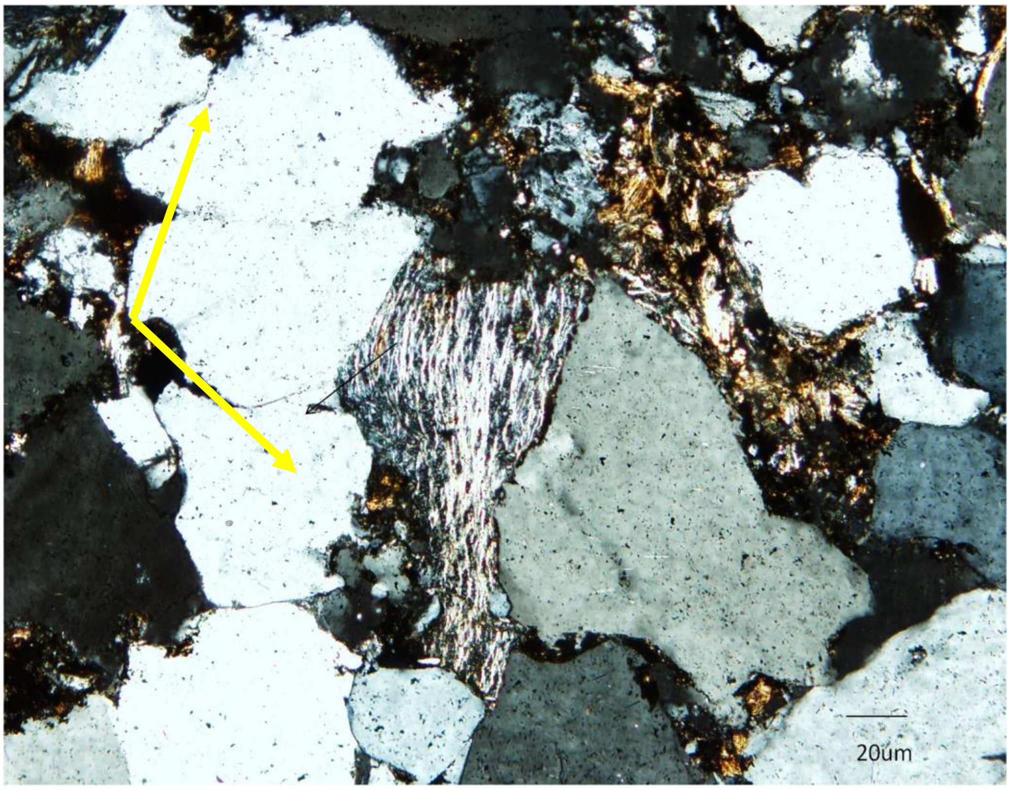

Figure 5.3 Thin section photomicrograph of polycrystalline quartz consisting of five quartz grains, with concave convex texture.

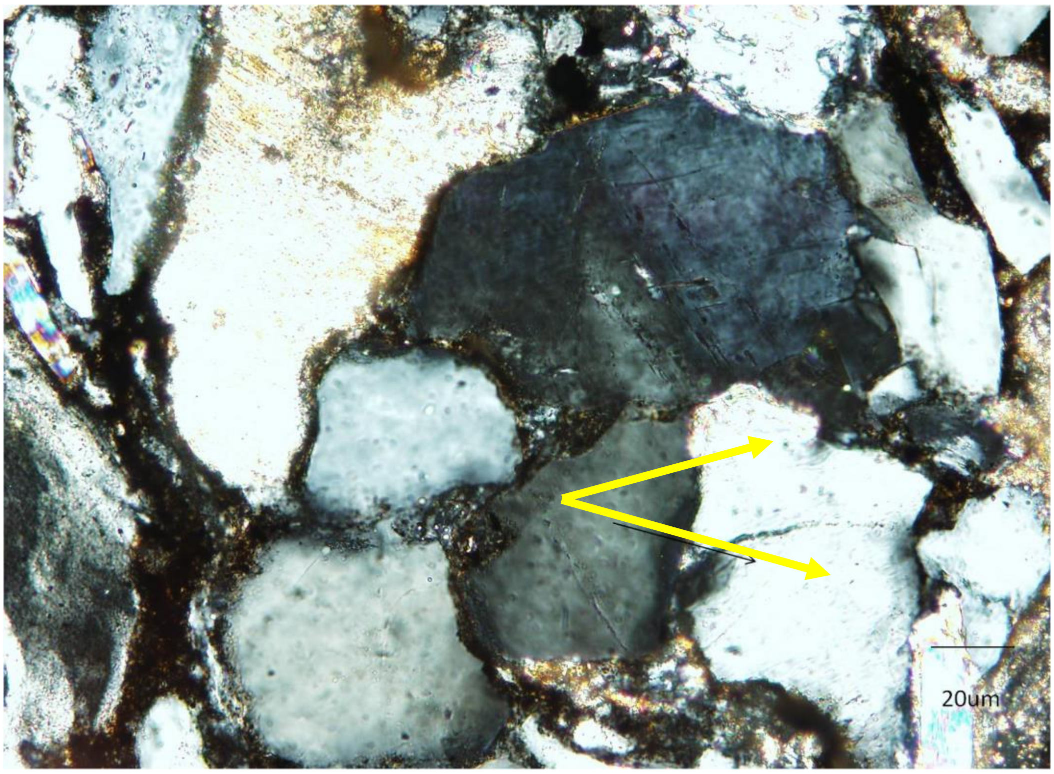

Figure 5.4 Thin section photomicrograph of polycrystalline quartz with two quartz grains (arrows).

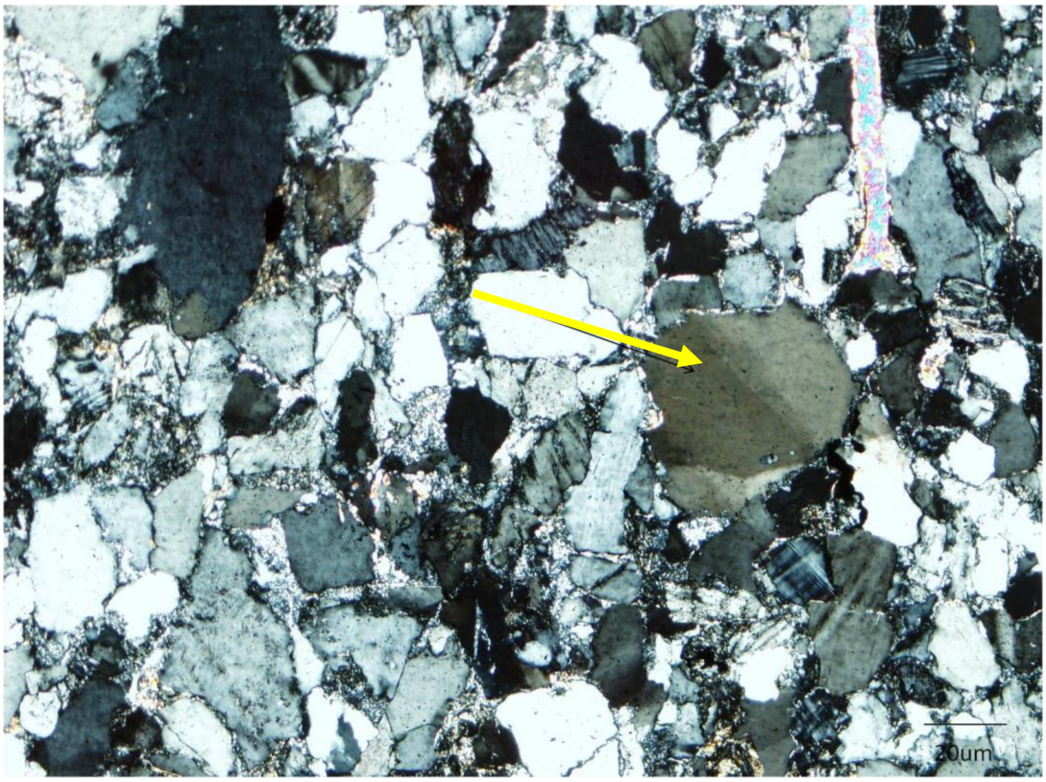

Figure 5.5 Thin section photomicrograph depicting undulatory extinction observed on a monocrystalline quartz grain.

5.2.1.2 Feldspar

Feldspar occurs in both detrital and authigenic forms. Plagioclase, microcline and orthoclase are the feldspar minerals present in thin sections and were identified by their low birefringent and interference colours. Microcline however, is always found in minor quantities where it exists and in some rock samples was not present, whilst plagioclase and orthoclase are always the dominant feldspar minerals. Plagioclase occurs mostly elongated and is clearly distinguished by its polysynthetic or albite twining of vague black and gray stripes whilst microcline clearly displays its cross hatch twining although in some cases the hatch twinning was poorly developed (Figure 5.6). The polysynthetic twining is both equant and unequant suggesting different source areas. Orthoclase can be noted as cloudy, with some grains showing simple twinning or a perthitic texture. In some instances, the potassium feldspar is also easily identified by its sericitisation. On rotation of the microscope stage, zonation on some grains of plagioclase and orthoclase can be observed. Some feldspar grains have a perthitic texture (Figure 5.7). Perthite forms as a result of slow cooling and the minerals are common in sediments from plutonic sources. Plutonic rocks form when magma cools deep below the earth surface and as result plutonic rocks have large grains. When alkali feldspar is of intermediate composition, K-rich and Na-rich domains get separated from one another forming the lamellae during slow cooling.

Both monocrystalline and polycrystalline feldspar grains are found in the rocks of the Ecca Group. The polycrystalline feldspars consist of feldspar grains in varied sizes grouped together. The grains of the feldspars are subangular to subround. The minerals are susceptible to alteration, to sericite, illite, kaolinite (Figure 5.8), muscovite and calcite. Dissolution textures were also identified. In general, feldspars are unstable in sedimentary environments.

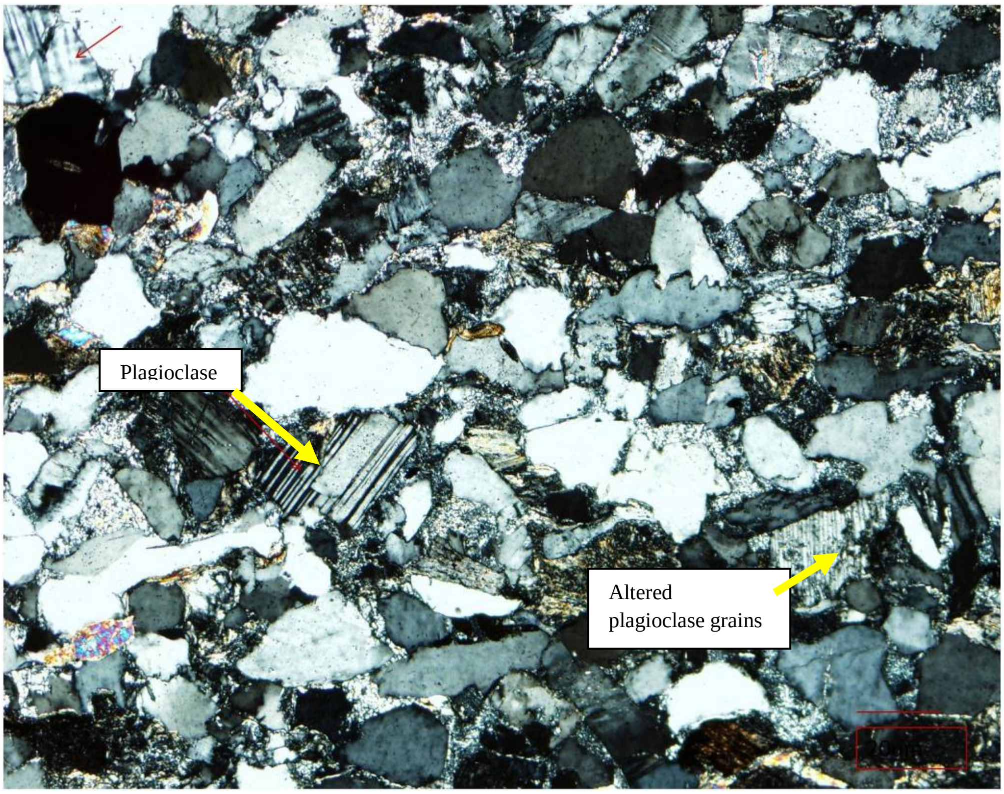

Figure 5.6 Thin section photomicrograph showing plagioclase feldspar grains.

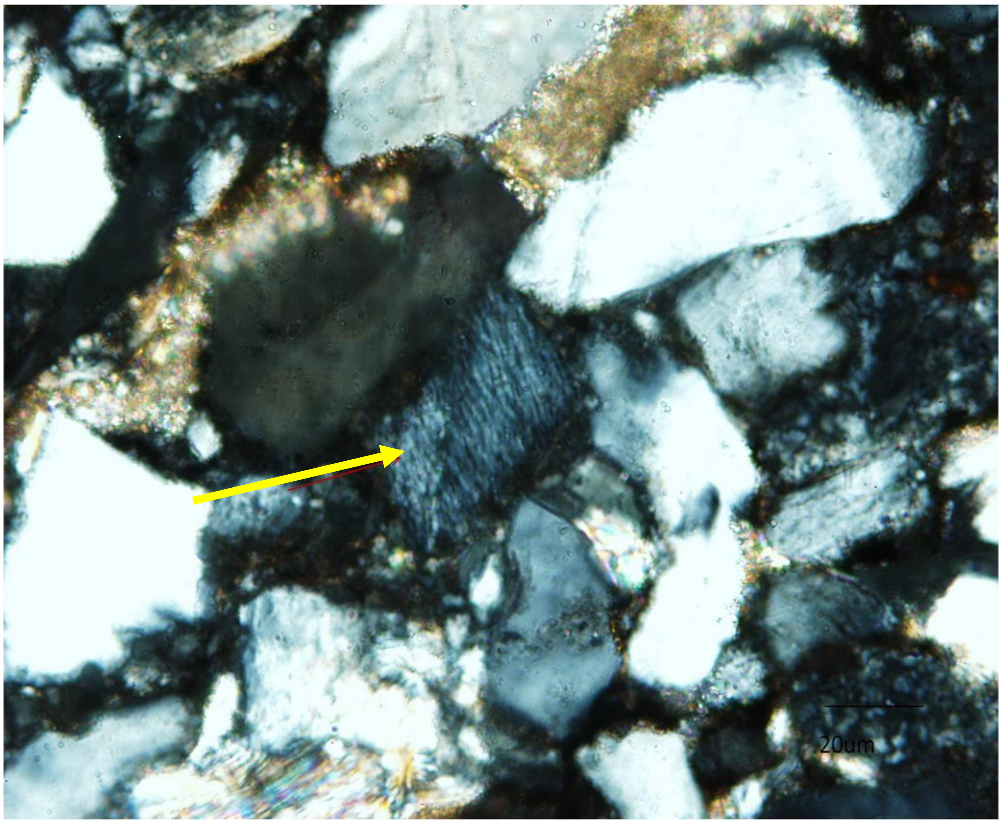

Figure 5.7 Thin section photomicrograph of perthitic feldspar (arrow).

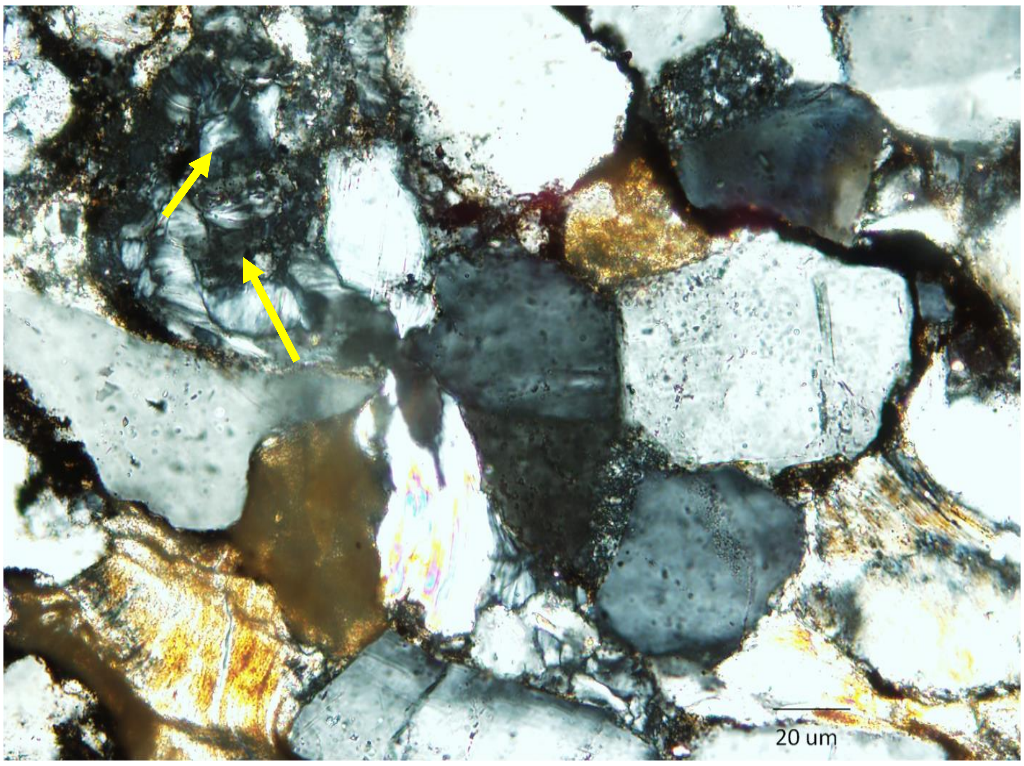

Figure 5.8 Thin section photomicrograph depicting feldspar grains undergoing alteration to kaolinite vermicules (arrows).

5.2.1.3 Lithics

Besides the polycrystalline quartz shown in Figure 5.9 and large feldspar grains shown in Figure 5.10, other lithics were observed. With the exclusion of the polycrystalline quartz, lithics are believed to be unstable in sedimentary environments, however, when present; they are the best provenance indicators for the sediments (Figure 5.11). Lithic fragments identified were volcanic, metamorphic, sedimentary and igneous in nature, inferring that the sediments were derived from volcanic, metamorphic, sedimentary and igneous regions (Table 5.1).

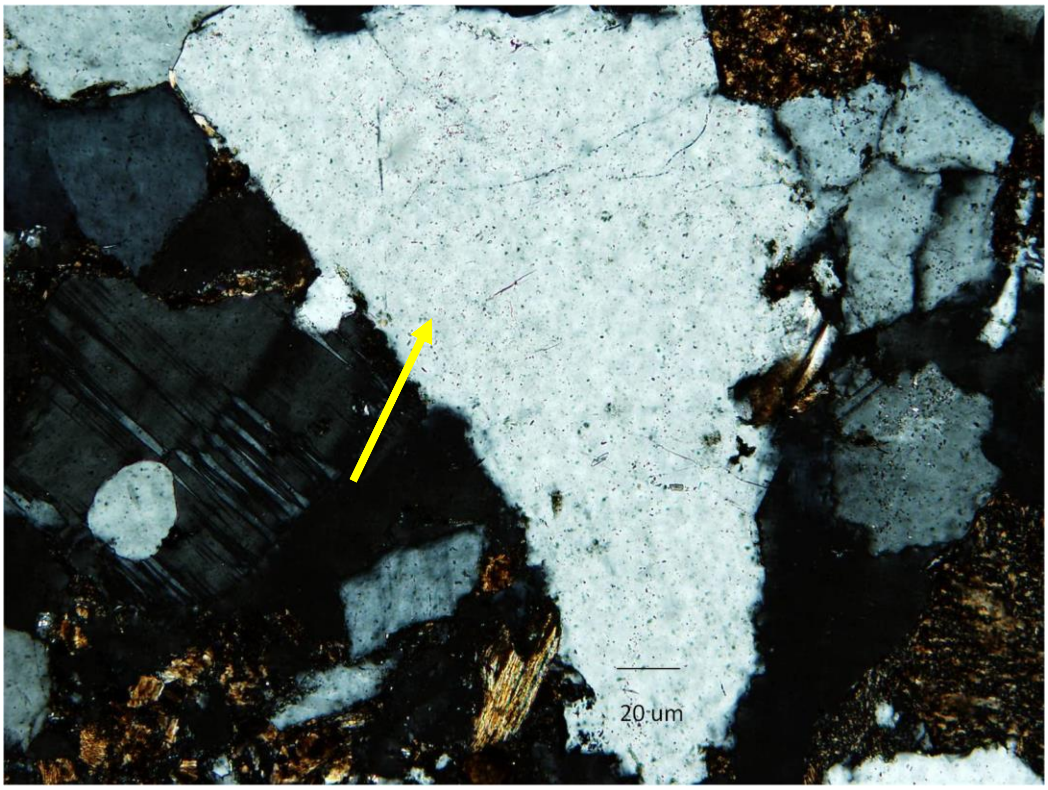

Figure 5.9 Thin section photomicrograph of quartz lithic (arrow)with small quartz and feldspar grains.

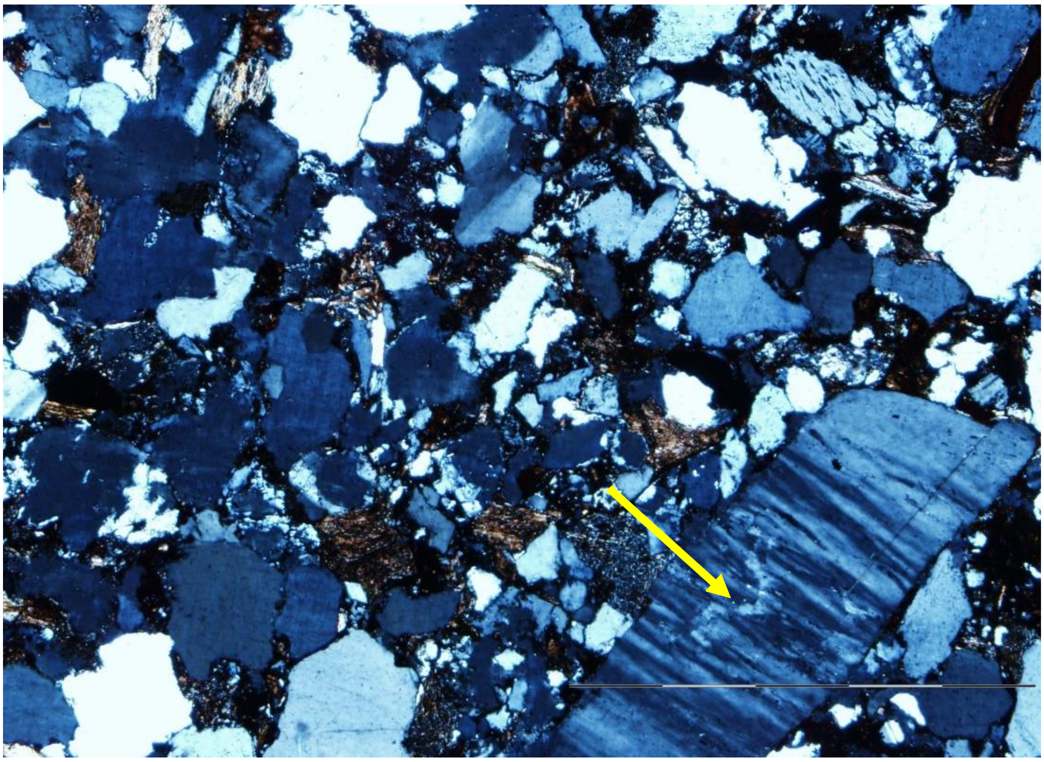

Figure 5.10 Thin section photomicrograph of feldspar lithic with perthitic texture (arrow).

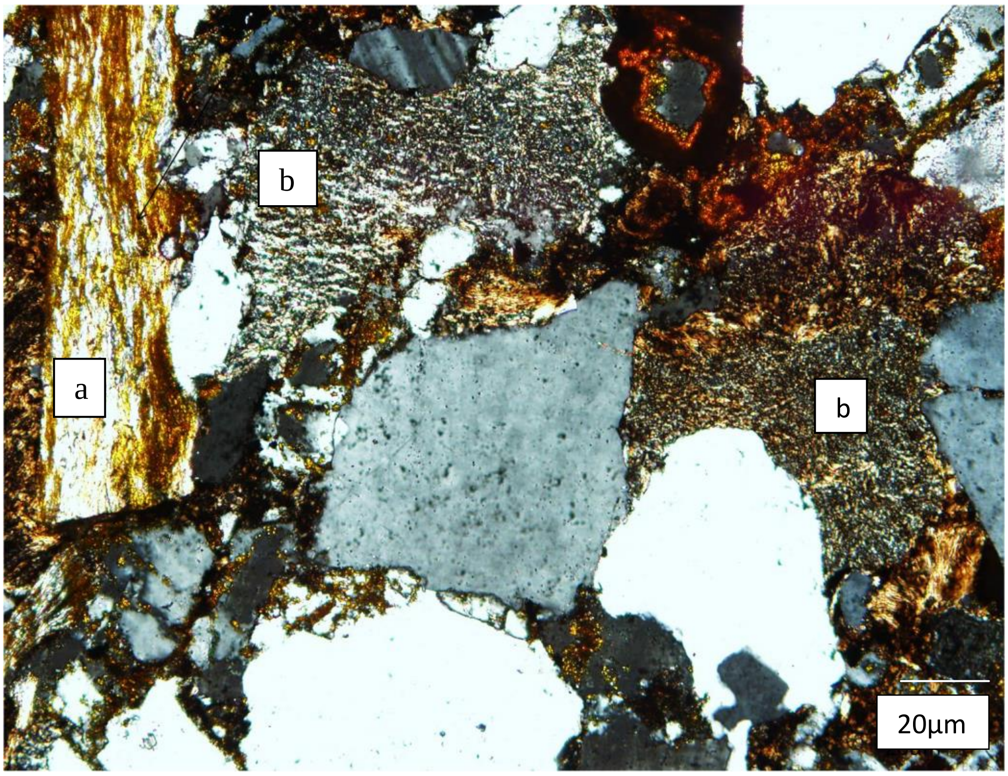

Figure 5.11 Thin section photomicrograph of laminated mudstone lithic (a) and volcanic lithics (b). Also shown is dark brown heamatite cement at the top.

Table 5.1 Minerals and their possible provenances

Type of sediment	Provenance
Polycrystalline quartz, coarse grain-sized	Metamorphic
monocrystalline quartz	Igneous and metamorphic
Plagioclase with albite twinning	Igneous and metamorphic
Zoned albite	Volcanic
Orthoclase	Igneous and metamorphic
Microcline	Igneous and metamorphic
Tuffaceous material	Volcanic

5.2.2 Matrix

The matrix minerals were observed under both the light microscope and the SEM. The minerals were either detrital or diagenetic. The diagenetic matrix minerals formed through the recrystallisation of the matrix, the alteration of framework grains or precipitation. Sericite, kaolinite, smectite and illite are the matrix minerals in the rocks. The named minerals, illite (Figure 5.12) and sericite formed through recrystallisation, whilst kaolinite formed through the dissolution of the detrital potassium feldspar. Kaolinite was also observed as having replaced muscovite grains and in some instances, illite also formed through the replacement of feldspar grains (Figure 5.13).

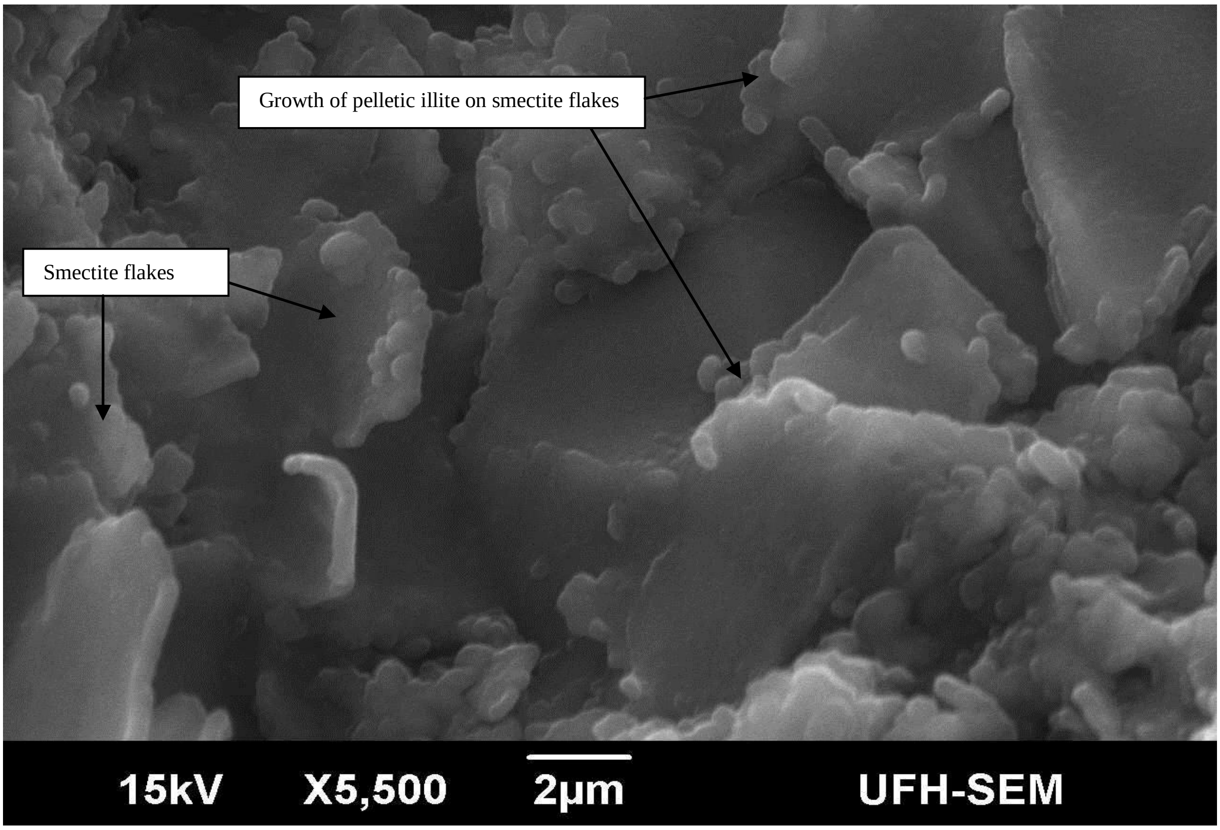

Figure 5.12 Scanning electron photomicrograph depicting the growth illite on smectite flakes.

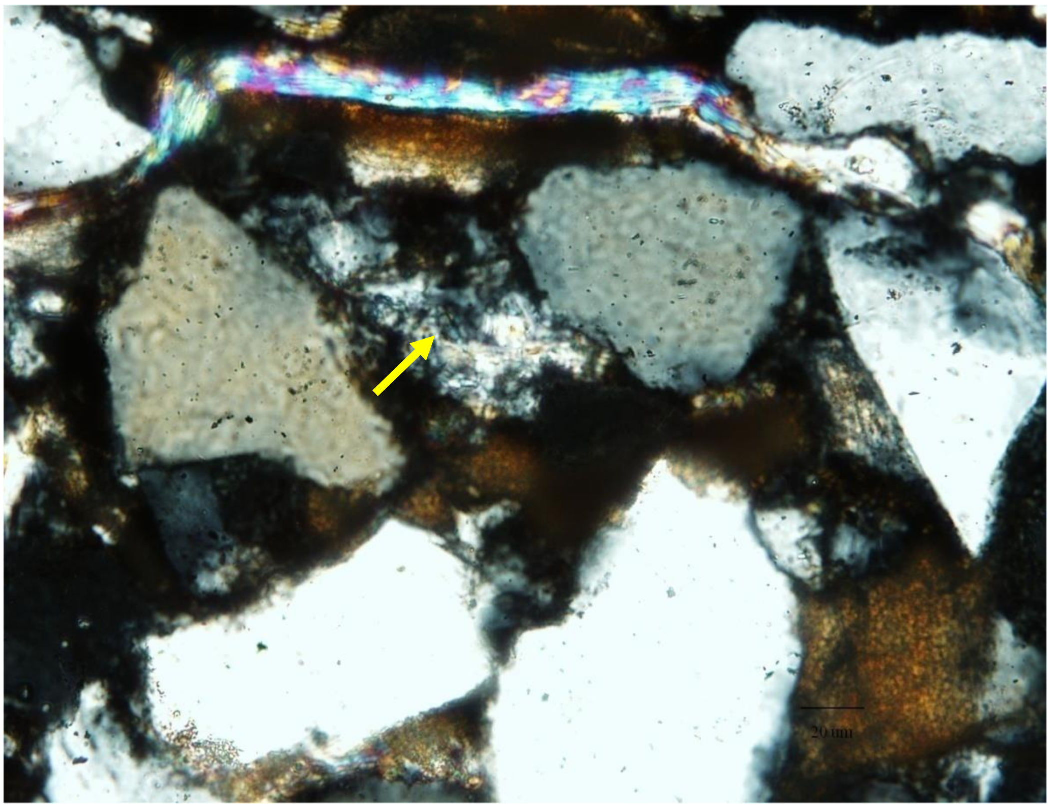

Figure 5.13 Thin section photomicrograph of a feldspar grain that has been altered to illite, with some feldspar relicts that still can be seen (arrow). The long coloured mineral is detrital muscovite.

The transformation of smectite to illite as temperatures increased was observed by SEM, from the growth of single illite pellets on smectite to their nucleation (Figure 6.12). Smectite has curved flake or platy box-work shapes with illite growing from its surfaces allowing for the mixed illite-smectite layers to form. According to Hurst and Irwin (1982), fibrous or hairy illite can frequently coalesce to form a platy morphology.

Figure 5.14 shows silt sized grains in the midst of clay matrix.

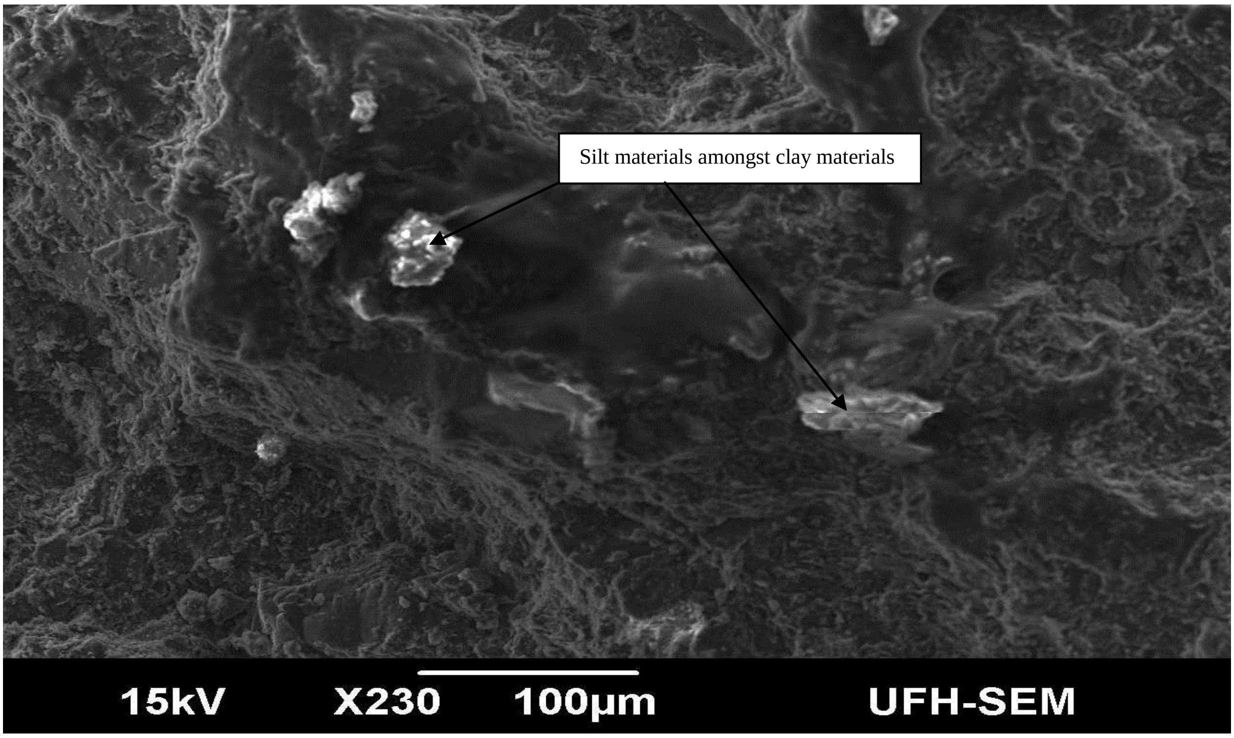

Figure 5.14 Scanning electron photomicrograph of silt-sized minerals amongst clay matrix.

The presence of the clay minerals was also proved by the XRD results shown below in Figure 5.15.

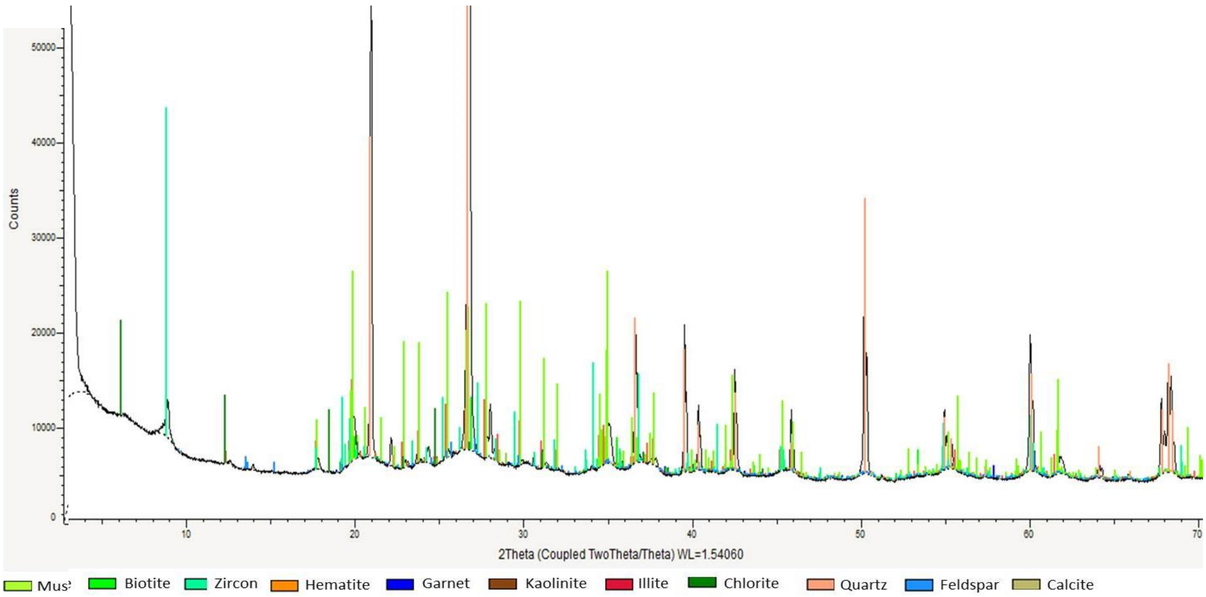

Figure 5.15 X-ray diffraction patterns proving the presence of quartz, feldspar and clay minerals. Sample was taken from the Whitehill Formation. Note: different colour represents different mineral in the picture.

5.2.3 Micas

Muscovite was identified in the thin sections of the rock samples in the Ecca Group. The mineral was amongst the common detrital accessory framework minerals, easily identified by its perfect cleavage and the high second to third order interference colours of yellow, red and blue (Figure 5.16). However, under uncrossed polarisers, the mica grains are colourless and clear. Muscovite occurs more frequently as compared to biotite. This is due to the fact that muscovite is chemically more stable than biotite in the depositional environment thus has better chances of being preserved.

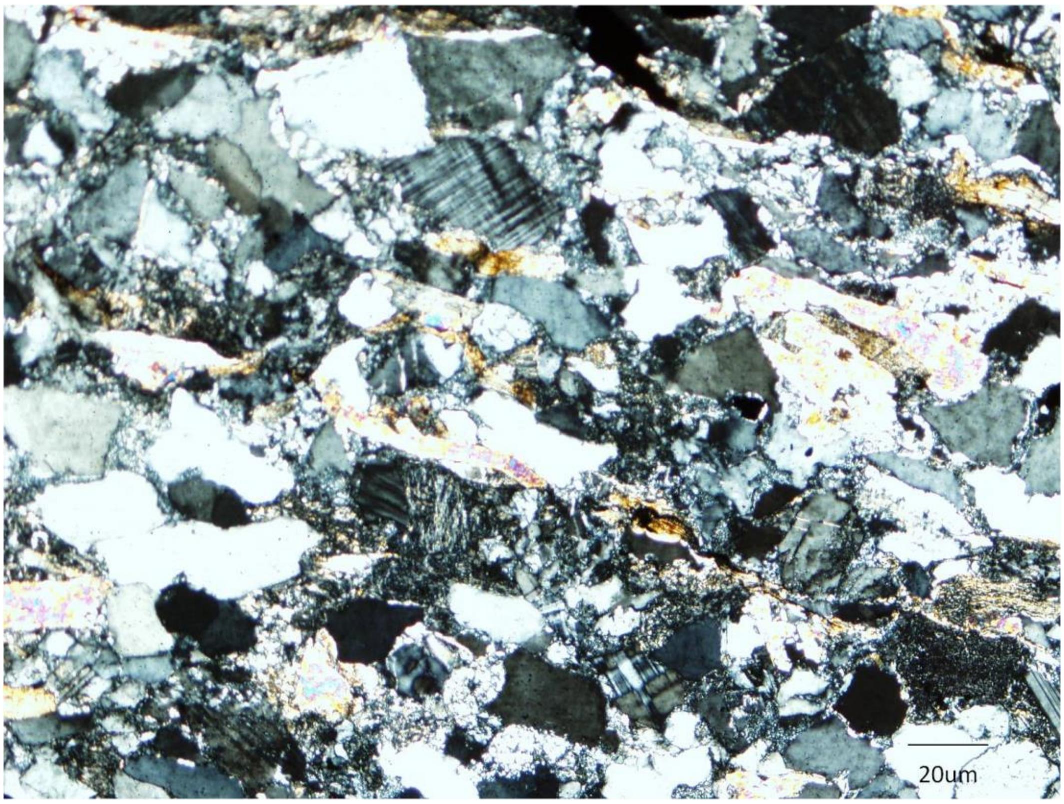

Figure 5.16 Thin section photomicrograph of biotite and muscovite (arrows) in the rock sample of the Ecca Group.

The mineral grains of muscovite were invaded by chlorite although the chlorite mineral itself was never identified as granular. According to Reed et al. (2005), chlorite appears in rocks as a minor constituent associated with altered detrital muscovite. The un-altered detrital muscovite grains have an elongated flaky shape with clearly visible boundaries. The mica minerals also occur in the matrix as a result of recrystallisation of clay minerals whilst some of other mica formed through the alteration of feldspar. Fracturing of some of the detrital grains explains that the recrystallisation was as a result of high pressures exerted by the overburden. According to Greensmith (1978), micaceous minerals are partly derived from the breakdown of unstable silicates in the source areas and are clastic whilst the rest are diagenetic, with loading accelerating the post depositional change of the unstable grains.

5.2.4 Heavy Minerals

Heavy minerals were identified by using microscopy and X-Ray Diffraction (SEM) (Figure 5.17). The heavy minerals include heamatite, pyrite, garnet and zircon. The minerals however, only exist in minor quantities. Their presence in the rocks gives a firm confirmation to the fact that source of the Ecca Group sediments was mainly metamorphic and igneous rocks.

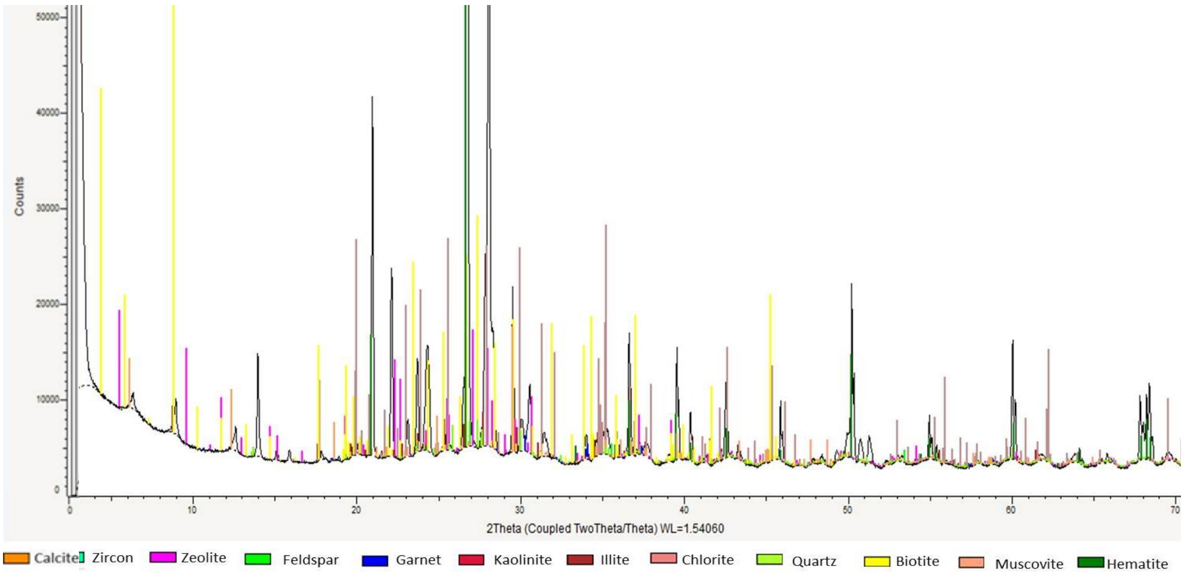

Figure 5.17 X-ray diffraction results proving the presence of zeolite, garnet and heamatite as the heavy minerals found in the rocks of Fort Brown Formation.

5.3 SEM-EDX CHEMICAL ANALYSIS

Chemical analysis was done based on the EDX results. The results are as indicated in Figure 5.18 and Figure 5.19 and Tables 5.2 and Table 5.3.

The elements were identified using SEM-EDX in the rock samples. Mg, Al, Si, K and Fe have a high content. According to Cox et al. (1974), the chemical compositions of sedimentary rocks are greatly varied because they derive their sediments from a wide range of sources and sedimentary processes are also extremely efficient in separating elements from each other hence allowing for rocks of widely differing compositions to be formed.

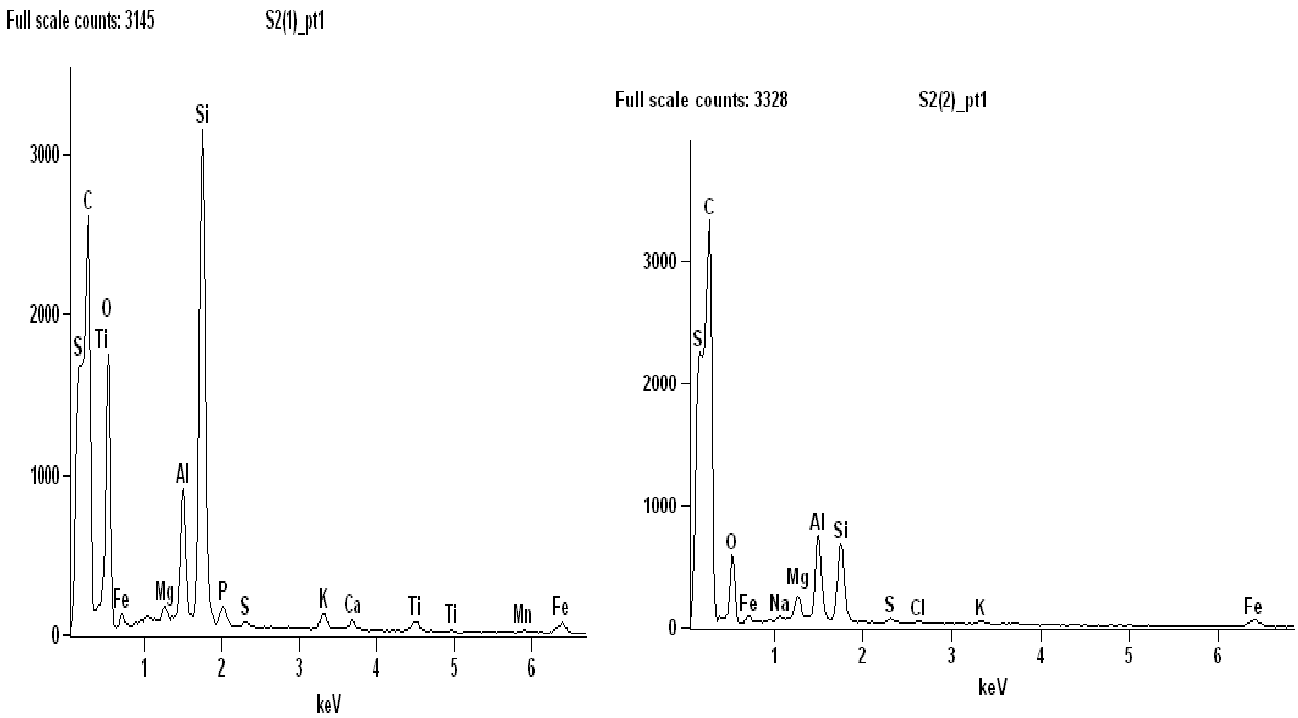

Figure 5.18 SEM-EDX results showing presence of silicate mineral elements (Ca, Al, Mg, Na and K) and also elements for heavy minerals rutile and ilmenite (Ti) for sandstone samples. The carbon peak was due to carbon coating.

Table 5.2 Elements in the sandstone samples.

Compound %	C	O	Mg	Al	Si	P	S	K	Ca	Ti	Mn	Fe	Na	S	Cl
sample S2(1)	40.80	29.62	0.32	3.91	17.18	0.85	0.25	1.06	0.76	1.27	0.54	3.44	----	----	----
Sample S2(2)	58.92	19.76	1.73	5.82	6.43	----	0.41	0.73	---	----	----	5.69	0.16	0.41	0.34

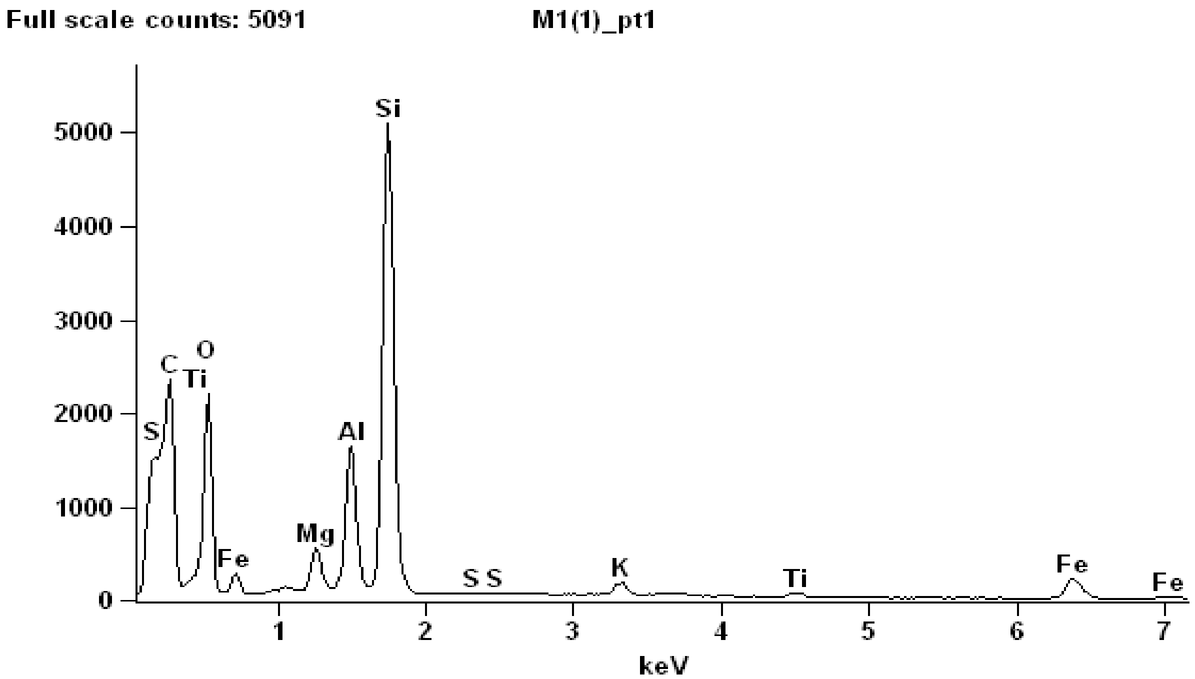

Figure 5.19 SEM-EDX results for mudstone sample, showing dominant clay mineral elements (Al, Si, Mg and K) and probably also ilmenite or rutile (Ti). The C peak was due to carbon coating and should not be taken into consideration.

Table 5.3 Elements in the mudstone sample.

Compound %	C	O	Mg	Al	Si	S	K	Ti	Fe
Sample M1(1)	34.93	25.73	1.74	5.87	21.71	0.07	1.25	0.67	8.04

Al and Si are the common elements that constitute silicate minerals and the majority of the minerals in rocks are silicate in nature. Silicate minerals include illite, muscovite, biotite, kaolinite, chlorite, zircon and feldspar. Fe, Al and K are common constituents of clay minerals in the rocks. K is also found in potassium feldspars. Ca rich feldspars are the weakest when compared to other types of feldspars meaning that they have a very low durability in the depositional environment and the plagioclases in general are prone to diagenetic alterations. Once they are found occurring in greater amounts, the sediments would have been deposited at close proximity. Some of the released Ca at the break down of plagioclase was precipitated as calcite. The phenomenon of close proximity of deposition of the sediments can also be explained by the high K content to Na. Na rich feldspars are more durable than those which are K rich. The shorter the distance travelled from the source, the better preserved will be the K-feldspars. The alteration of smectite to illite also led to the increase in Na in the sediments and as depicted in SEM results, illite is one of the dominant clayey minerals in the rocks of the Ecca Group.

The presence of Ti on the EDX results implys the occurrence of ilmenite or rutile in the rocks as they are titanium rich minerals, which occur as heavy minerals in the rocks.

5.4 CONCLUSION

As noted under thin sections, kaolinite is dominant in the Rippon Formation sandstones that formed in a deltaic environment whilst illite is more dominant in the Prince Albert Formation where a deep marine environment existed. Although diagenetic processes may have played a role in the distribution of the minerals, the rate of sedimentation and the environmental conditions also contributed to nature of the sediments. As explained by Millot (1970), weathered materials which are deposited slowly can migrate far out into the sea and be transformed through recrystallisation into illite whilst kaolinite is deposited as large crystals along the coast where it would be able to grow by diagenetic processes. The above conclusion is well illustrated in the model (Figure 5.20) Smoot (1960).

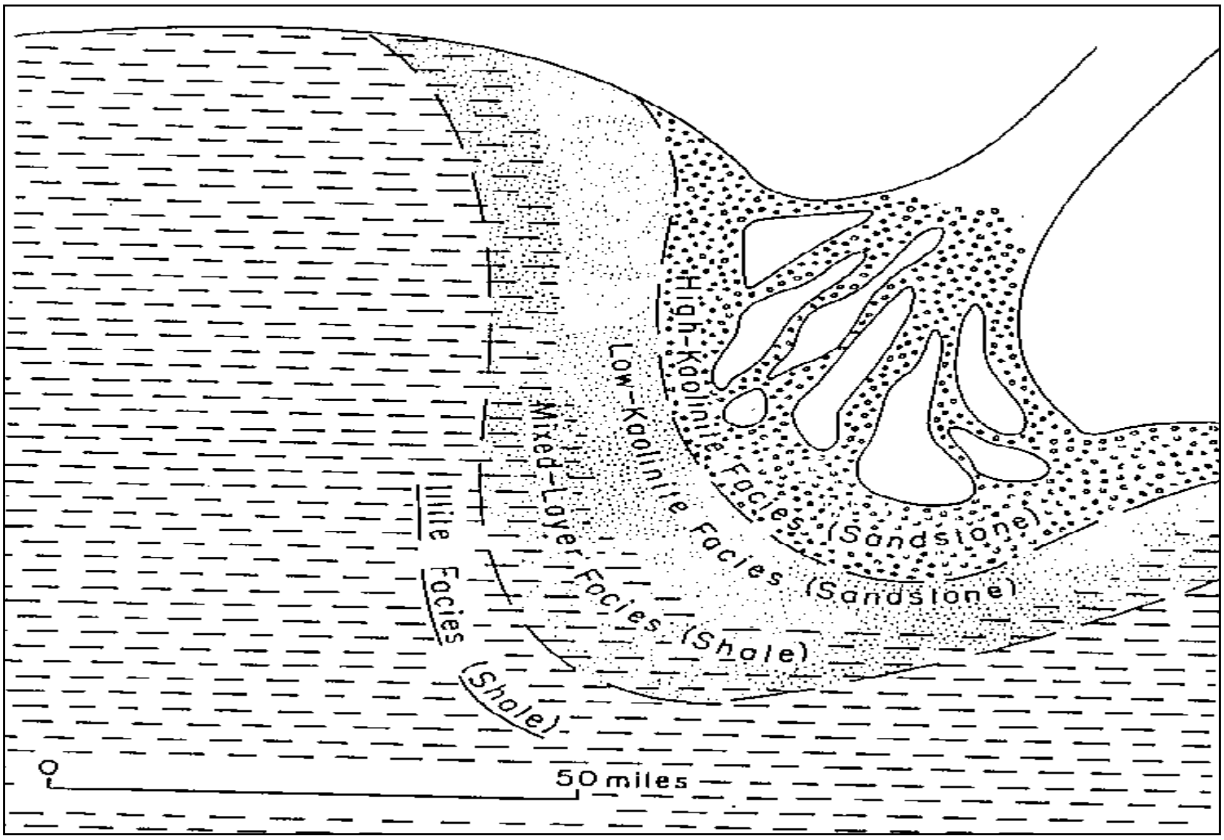

Figure 5.20 Idealized distributions of clay minerals as a function of facies (Smoot 1960).

The occurrence of illite and kaolinite was also identified in XRD analysis as shown by peak strength (heights) in Figures 5.21 and 5.22.

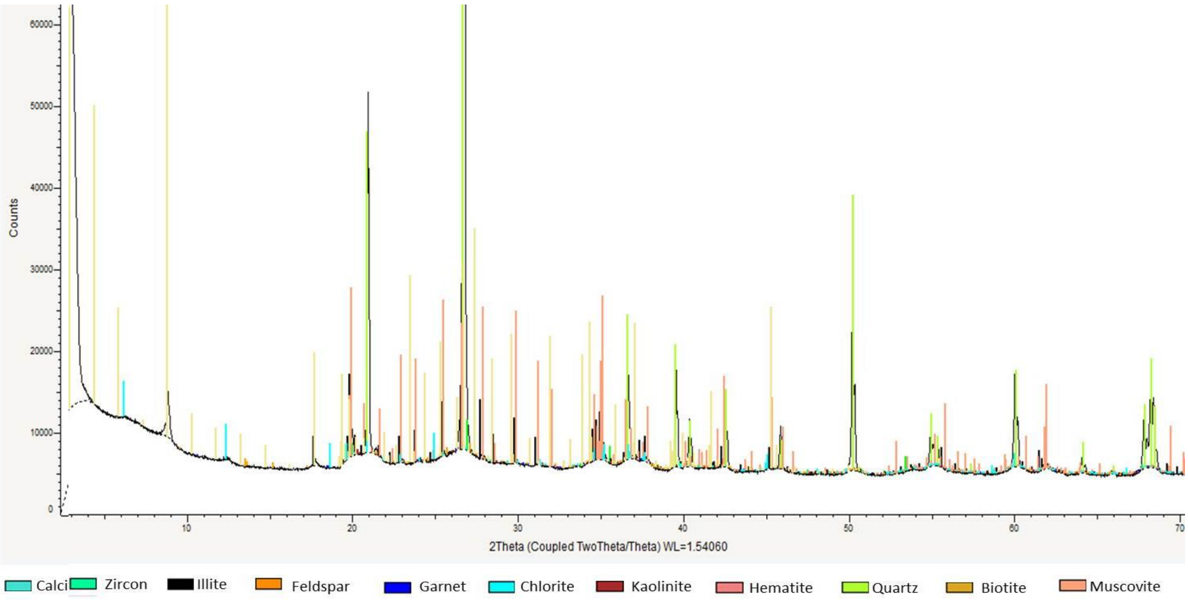

Figure 5.21 X-ray diffraction patterns of the shale from the Prince Albert Formation of deep marine environment, showing a high presence of illite as compared to kaolinite.

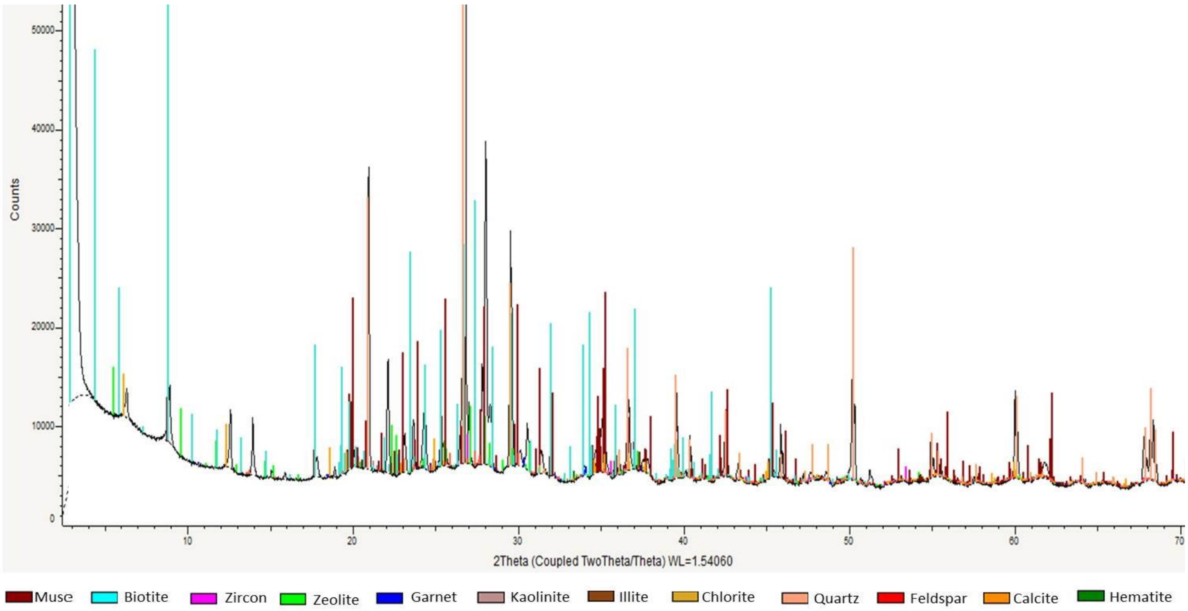

Figure 5.22 X-ray diffraction patterns of the sandstones from the Rippon Formation depicting a high presence of kaolinite as compared to illite.

CHAPTER 6. SEDIMENTARY FACIES

6.1 INTRODUCTION

Sedimentary facies is a unit of rock generated in a depositional environment characterised by specific petrological, sedimentary and compositional properties (Boggs, 2001). Thus, depositional environments generate sedimentary facies, and facies are in-turn a reflection of the conditions of the environment. In order to understand depositional environments, the lithology and sedimentary structures should be identified and their formation processes explained. Within a particular depositional environment, multiple sub-environments can be found. This means that facies can actually vary within a particular environment, reflecting the transition from one sub-environment to the other. Therefore, adjacent facies can be a representation of adjacent environments, and the manner in which these facies relate to each other is always characteristic of facies change or facies shifting. Different characteristics can be dealt with to give different facies studies. Basically, there are two types of facies, i.e. lithofacies and biofacies. When petrological characteristics like colour, grain size and mineralogy are concerned on, lithofacies are observed; whereas when fossil content is concerned, biofacies are recognised.

In the Ecca Group, various rock types were identified, therefore different types of facies could be established. As already noted in Chapter 2, the Ecca Group was mostly deposited in marine environments with a cool climate predominant. The group is predominantly composed of mudstones and shales with some minor siltstones and graywackes.

6.2 LITHOFACIES ANALYSIS

A facies analysis technique was used in the study of the sandstones, siltstones, mudstones and shales of the Ecca Group. After the field observations, ten facies with regard to the lithology and the sedimentary structures were recognized.

Facies 1: Grayish laminated and thin bedded shale facies

The rocks are predominantly well laminated although thin bedding occurs at the base of the unit as shown in Figure 6.1. The rocks were stained by a khaki colour that has obscured the original gray colour after being strongly weathered, therefore, the khaki laminated and thin bedded shale facies occurs exclusively in the Prince Albert Formation. However, higher up in the facies unit, the khaki colour is also obscured by the red iron oxide colour. The presence of iron minerals was proven by SEM-EDX results and the red staining of grains viewed in thin sections under the microscope. Some minerals, like smectite and pyrite, have variable iron elements in them and the iron is released and oxidized when the rocks are exposed to the atmosphere and suffer weathering. The dissolution of hornblende also present in the rocks may again have been another source of iron that led to the red staining of the Prince Albert Formation shales.

Figure 6.1 Weathered laminated khaki shales, with fine siltstone lenses.

The red shales are folded but still maintaining their lamination (Figure 6.2). Right at the top of the Formation, layers of pure magnetite, iron rich sediments and clay rich sediments can also be observed.

Figure 6.2 Laminated red shales facies which were folded due to structural deformation.

Facies 2: Grayish laminated shale and intercalated chert facies

Silicon dioxide precipitated from water to form chert. As the chert occurs as nearly continuous layers and has no clastic texture, it is therefore thought to be a chemical sedimentary rock. In general, many primary chert beds have a marine origin. In the study area, the chert beds are gray in colour and microcrystalline in nature with no conspicuous organic carbon remains. The silica was also incorporated into the mudstones and shales of the formation making them a little harder than the shales of the underlying Prince Albert Formation.

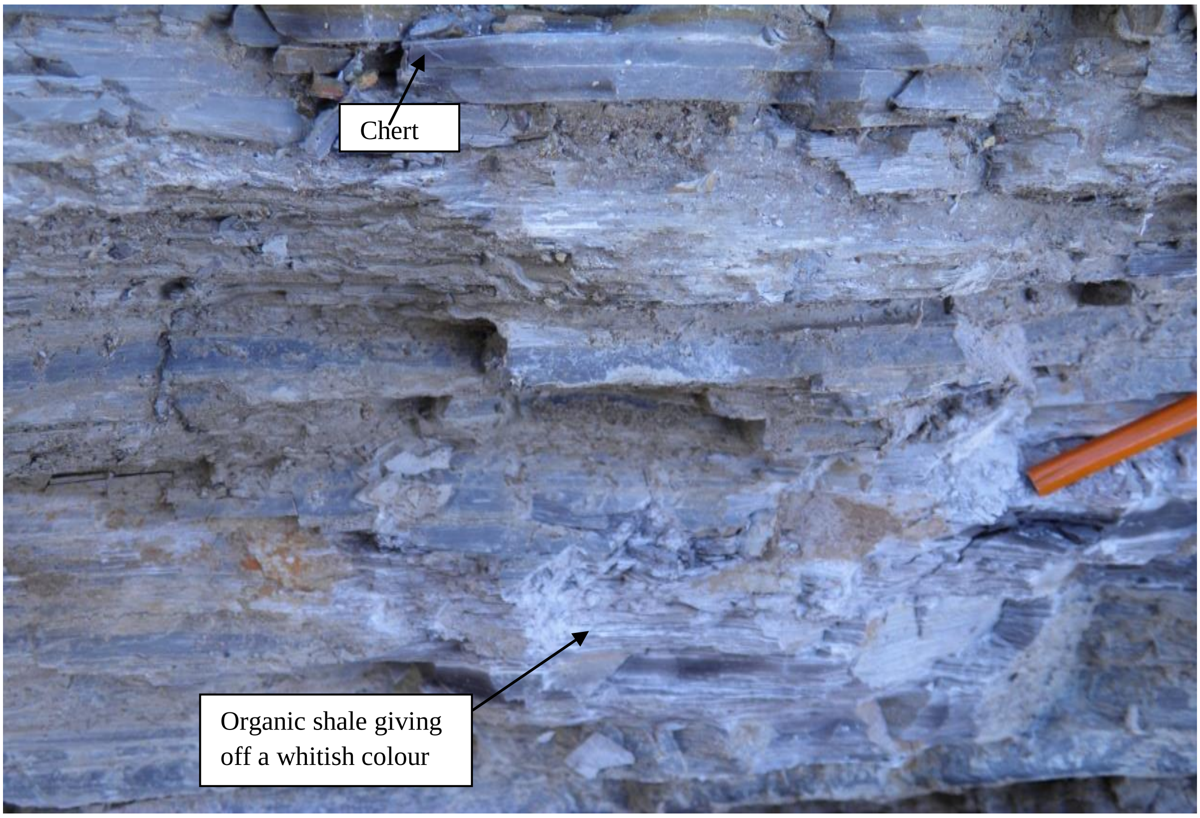

Figure 6.3 Laminated shale intercalated with chert layers. Note: the carbon rich shale giving out a whitish colour after weathering.

Carbon material in the carbon rich shales caused the dark gray colour to form. Buried dead fauna and flora always change to hydrocarbons, and hydrocarbons are dark gray to black in colour. The chert also displays its resistance to weathering as compared to the carbon rich shale that is giving out a white colour as shown in Figure 6.3.

Facies 3: Grayish rhythmite facies

The alternating continuous and parallel layers of claystone and mudstone are typical of the Collingham Formation (Figure 6.4). The mudstone layers are dark gray in colour, well laminated and finer grained whilst the claystone layers are relatively pure in clay mineral composition and are pale yellowish coloured. From under the microscope, volcanic material was observed in the claystones. In general, claystones with trachyte tuff assume a yellowish colour at weathering and in the field of study, the tuff rich clay sediments were easily transformed to kaolinite and secondary quartz. Regardless of being finer grained, the higher silica content in the mudstones renders them harder compared to the tuffaceous thin bedded claystones.

The thin bedding of the mudstones ranges between 2.5cm and 10cm in thickness. In the mudstones, sedimentary structures include convolute bedding and current mark structures. The convolute bedding shown in Figure 6.5 occurs only within a single bed as opposed to affecting a group of beds. The presence of the current mark structures indicated that the water energy was not always quiet at the time of deposition of the thin bedded sediments. The current mark structures have an average length of 30.1cm and amplitude of 11cm and are well depicted in Figure 6.6.

The rhythmite facies is typical of the continental slope turbidity deposits. The low and high water densities due to the presence of the turbidity currents and the lack there-of produced the alternated layers of claystones and mudstones of the Collingham Formation. As sediments accumulated on the continental slope, turbidity currents were created because of the over-loading and sediment instability that was occurring.

Figure 6.4 Convolute bedding in the mudstone (arrow).

Figure 6.5 Erosional current mark structure on the top surface of the mudstone.

Facies 4: Flat and lenticular bedded greywacke facies

The rocks were considered as immature in texture and mineral composition due to consisting of sub-angular to sub-rounded poorly sorted materials and a high percentage of feldspar as compared to the quartz content. The sediments were greatly affected by tidal currents hence the rocks are thin to thick bedded with minimal internal structures of low angle cross bedding. The thickness of the beds increases from the bottom to the top in each unit and ranges between 2.2m and 12.3m. Between the beds, are sharp breaks that are easy to identify.

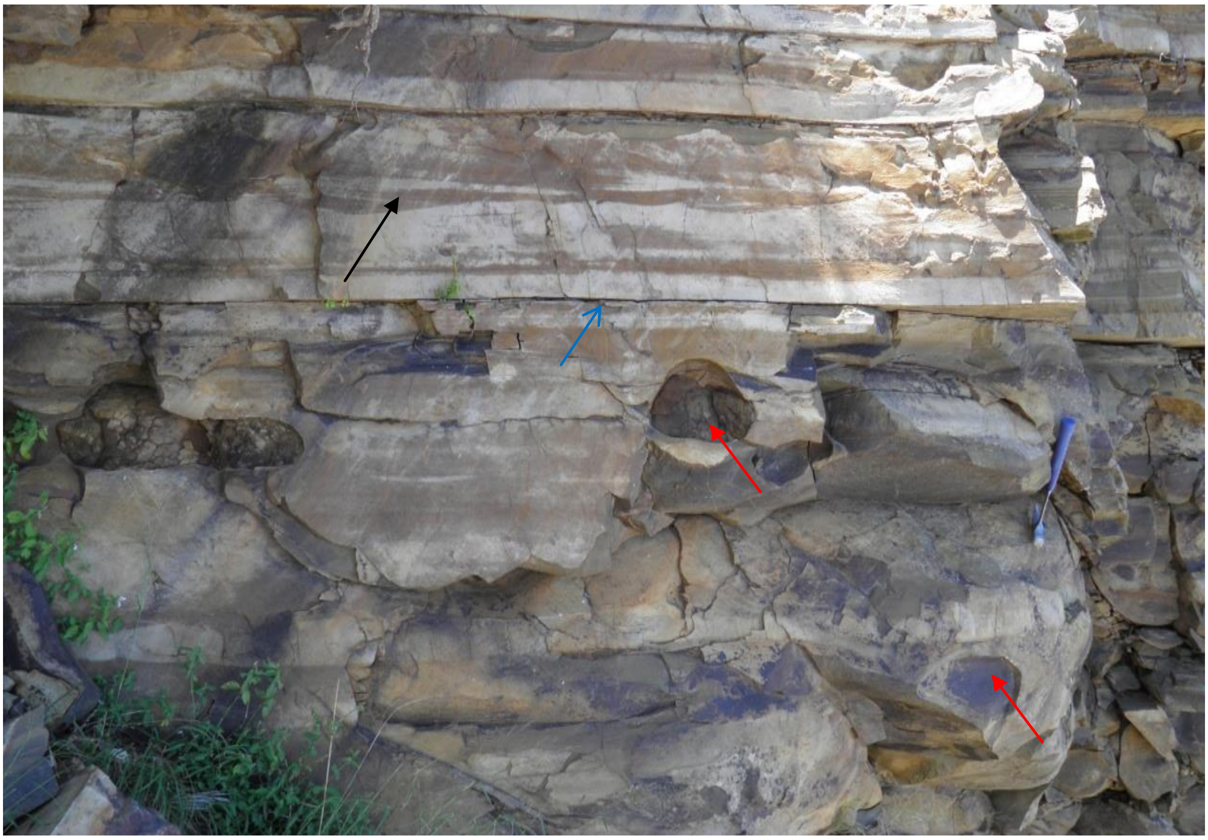

Figure 6.6 Flat and lenticular graywacke with diagenetic nodules. The graywacke shows light colour after weathering, but it was grayish when it was fresh. Flat (blue arrow) and lenticular bedding (black arrow) can be clearly seen at the top of the photo brownish lenticular sandstone alternated with thin bedded light sandstone, also showing calcareous nodules (bottom right with red arrow) in the rock.

The rocks have a high percentage of matrix minerals; as a result, clay matrix can hold the grains tightly together, resulting in the hardness of these rocks which are dipping north east at 32^{o}. The grains consist of quartz, potash feldspar and plagioclase and lithic fragments. The matrix is composed of kaolinite, sericite, illite and smectite. Illite also has a white-greenish colour in the rocks. Nodules are a common feature in the greywacke (Figure 6.6), and mineral replacement of the feldspars to calcium carbonate may also have led to the formation of the nodules in sediments. Calcite concretions can occur commonly within thick bedded and structureless sandstones and the observed concretions in the field of study were mostly spherical in shape with very few of them having an elongated shape. Besides the calcitisation of feldspar, other diagenic changes observed in the rocks included the sericitisation of feldspars, the alteration of feldspar to illite and also the recrystallisation of matrix materials.

The rocks generally have a coarsening upward sequence typical of deltaic deposits. However, the well developed lenticular bedding is indicative of the presence of tides in the shallow marine environment. The tidal effect was envisaged to have been flood related considering that the depositional environment was shallow. Fine sand and clayey sediments were separated from the coarse sediments and were laid out in lenticular beds (Figure 6.6). The brownish colour of the lenticular beds was probably as a result of higher amounts of iron containing minerals as compared to the light colour weathered sandstones and most mudstones contain high amounts of pyrite. The sandstones generally have an irregular jointing pattern with the sub-horizontal joints being the most common and related to the bedding planes. The other joints are steeper, straight and curved and found within the beds and also cutting across the bedding planes.

Facies 5: Alternating grayish mudstone and graywacke facies

The facies in the field are depicted by well laminated shales and medium to very fine grained sandstones (Figure 6.8). The beds were deposited parallel to each other. The thinly bedded graywackes are similar in composition to the flat bedded graywacke facies. The sandstones also lack sedimentary structures with the shales only displaying lamination. The lack of lamination in the sandstones was probably due to quick deposition. The alternating sandstone and mudstone facies was interpreted as flood plain deposits in the lower coastal areas. Sandstones where laid down when heavy floods occurred in the migrating channels which were laden with sediments. The increase in hydraulic energy therefore, allowed for the coarse sediments to be carried off the channels and onto the flood plain whilst the fine sediments accumulated as suspended deposits. The sandstone beds measure between 0.3m and 35.2m and the facies occur over very wide area.

Figure 6.7 Alternating graywacke and mudstone facies.

Facies 6: Dark organic rich mudstone facies

The rocks in the study area have tabular lamination structure indicating a very low rate of deposition, typical of a quiet water environment. In the Rippon Formation, black shales are separated by grey laminated shale and mudstone (Figure 6.8). There may have been persistence of the anoxic conditions leading to the increase in the organic carbon content of the upper black shale layer.

Figure 6.8 Laminated organic carbon rich shale separated by gray shale and mudstone.

Facies 7: Fossil bearing mudstone facies

The gray trace fossil bearing and thin bedded mudstones (Figure 6.10) are also found in the Rippon Formation. The fossils are an indication of shallow waters in the depositional basin, allowing for animals (ichnogenus *Chondrites*) to thrive in the environment. In swamps that form on the flood plains, fossil bearing mudstones are able to accumulate.

Figure 6.9 Burrows in mudstone facies.

Facies 8: Laminated and thin bedded black mudstone with lenticular siltstone facies

The facies covers the largest extent of the Rippon Formation, with a dark grey colour on the shale and mudstones due to rich in carbonaceous material and clay matrix. The depositional environment was affected by currents which brought in the silt materials that are intercalated in the mudstones (Figure 6.10). The siltstones displayed low angle cross bedding (Figure 6.11) and scouring surfaces (Figure 4.17) which were truncated at the top in some instances, decreasing their amplitude. The siltstones surfaces were therefore reworked probably by erosional processes. The laminated and gray mudstones with siltstone interbeds were also deposited on flood plain. In times of weak floods, currents formed due to weakly high hydraulic energy introduced silty material into the depositional basin. In the mudstones, convolute bedding and folding structures (Figure 6.12) were identified as the existing sedimentary structures. However, dewatering structures were sparse.

Figure 6.10 Intercalated mudstone (dark) and lenticular siltstone (light).

Figure 6.11 Low angle cross bedding on the lenticular siltstone facies (arrow).

Figure 6.12 Recumbent deformation structures in the grayish mudstone.

Facies 9: Interbedded grayish sandstone and mudstone facies

Sandstone and mudstone rocks are noted interbedded together in the area of study as can be seen above in Figure 6.13. The laminations of the mudstones are indicative of quiet waters and slow settling of the sediments whilst the thin to thick beds of the sandstone layers was indicative of rapid deposition and high water energy during the deposition. The deposits come across as sheet like bodies, especially considering the manner in which the sandstones are laid out and the rocks have a great lateral extent, typical of braided delta environments. The elongate bodies were formed as a result of lateral migration of the depositional channels. The sandstone beds range between 30cm and 2.5m in thickness whilst the mudstones are mostly very thin bedded. Although the sandstones are originally grayish in colour, they have been weathered white due to the alteration of feldspars to kaolinite, whilst the mudstones are black coloured, thus allowing for the sandstones to stand out in the field from a distance. Although the rocks exist together, the mudstones have a great amount of carbon materials compared to the sandstones. The formation of the thick bedded sandstone at the top of the facies unit was due to braided streams aggrading, resulting in the deposition of thick bedded coarse sediments in the high energy channels.

Figure 6.13 Interbedded mudstone and sandstone facies.

Facies 10: Varved rhythmite facies

The rhythmite facies of the Fort Brown Formation consists of alternating light and dark laminae (Figure 6.14). The alternation is due to compositional changes and also the changes in grain size of the sediments. The dark laminae consist mainly of clay minerals whilst the light laminae are silty. The dark layers are also low energy deposits whilst the light laminae indicate an increase in water strength. Overbank flooding of channels brought sand into the lakes and formed the minor sandstones in the lower parts of the formation, but as the lake filled up, more sandy materials were deposited in the basin, creating a coarsening up sequence. The rhythmites are fresh water lacustrine facies.

Figure 6.14 Varved rhythmite facies.

6.3 CONTINENTAL MARGINS AND DEEP WATER BASINS

From the facies descriptions given above, it can be deduced that the rocks of the Ecca Group were deposited on the continental margins and deep water basins. Sediments deposited in these zones can be affected by numerous sediment gravity flows which include turbidity currents, bottom sea currents, sliding and slumping, of which the results are already indicated above in the facies descriptions. In these depositional areas, pelagic and hemi-pelagic depositions are also common, leading to the formation of carbon rich shale and precipitation of chert and nodules.

Turbidity currents are one of the most significant gravity flows. The currents are either of high density or low density and the resultant effects of the two are always different. Very high energies of gravity flows are associated with high density flows whilst low energies exist in the presence of the low density flows. The higher the energy, the bigger the size of grains that get influenced whilst lower energies only have an influence on fine and medium grained rocks.

6.4 FACIES MODEL

The Lower Ecca Group Formations, namely the Prince Albert Formation, the Whitehill Formation and the Collingham Formation, accumulated in a deep marine environment. The Fort Brown formation is a fresh water lacustrine deposit whilst the Rippon Formation consists of facies that accumulated in the delta plains and fronts of prograding delta (Figure 6.15).

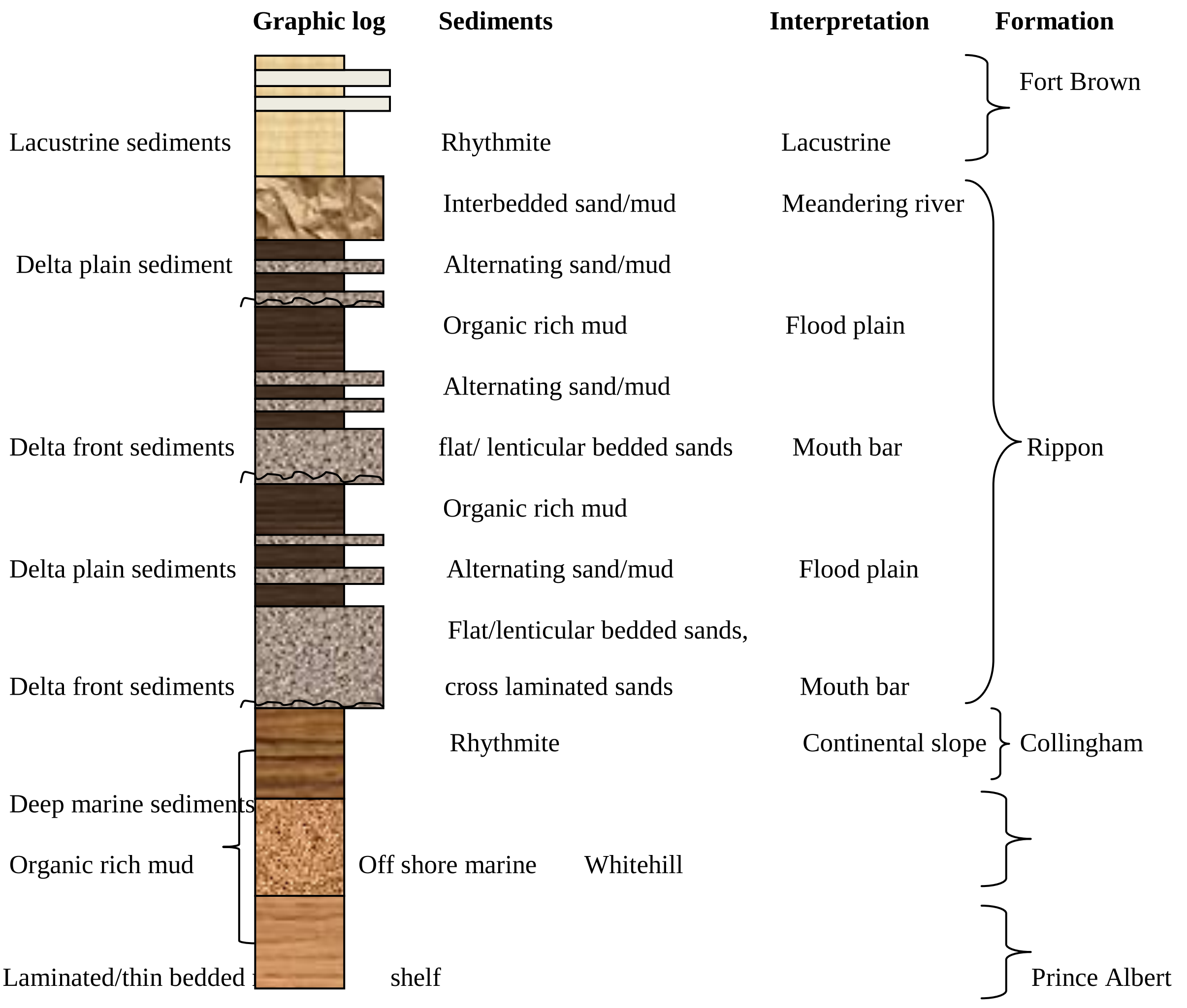

Figure 6.15 Graphic sketch log and interpretation of facies successions produced in deep marine, delta and lacustrine environments of the Ecca Group.

CHAPTER 7. DIAGENESIS

7.1 INTRODUCTION

Berner (1980) defines diagenesis as the total sum of processes that bring about changes in a sediment or sedimentary rock subsequent to deposition in water. The processes maybe physical, chemical and or biological in nature and may occur at any time subsequent to the arrival of particles at the sediment–water interface. The processes always occur above the zone of metamorphism with temperatures of below ~250 degrees Celsius. Certain minerals can be used to determine the upper and lower limits of diagenesis, for instance taking the stable limit temperature of laumontite of 195^{o} – 220^{o} C as the highest temperature of diagenesis, and taking the stable limit temperature of pumpellyite of $>250^{o}$ C as the lowest limiting temperature of metamorphism.

Summarized from Tucker (2001), the processes of diagenesis are mainly compaction, cementation, recrystallisation, dissolution and replacement. Compaction occurs when varied grains are settled together into a tighter and dense mass as a result of water being squeezed out as pore spaces get limited. For dissolution to occur, unstable minerals have to exist in the depositional environment such that when fluids move through the sediments, the unstable minerals dissolve, releasing the ions contained. As for replacement, already existing minerals, when certain conditions prevail, will be converted, the old minerals become unstable and then replaced by stable minerals in the new environment. Cementation is part of the process of lithification of soft sediments, where new minerals are chemically precipitated from pore fluids in sediments or sedimentary rocks. Cementation takes place as water is squeezed out by pressures on the sediments exerted by the weight of overlying sediments. The water is replaced by minerals such as carbonates, silicates, iron oxides, or clays, which bond the sediment particles together into a hard sedimentary rock. A new mineral grows from the matrix during diagenesis, this process is referred to as authigenesis and the newly formed minerals are called authigenic minerals. Therefore, it can be important to establish the paragenetic sequence in order to define the diagenetic process, burial history and fluid flow episodes since certain conditions have to be in existence for the formation of authigenic minerals. Therefore, authigenic minerals are well known to hold information about the diagenetic processes in ancient and modern sediments. The most common authigenic minerals in mudstones and sandstones summarized from Reed et al. (2005) are usually as follows:

1. Quartz
2. Calcite, dolomite, siderite and magnesite
3. Heamatite
4. Clays (kaolinite, illite, montmorillonite, chlorite)
5. Feldspar
6. Phosphate and barite
7. Gypsum
8. Halite and other salts

Important factors that influence diagenesis of rocks, especially the sandstones were identified by Hurst and Irwin (1982) as:-

- Temperature
- Pressure
- Detrital mineralogy
- Pore-water composition
- Sedimentary facies
- Tectonics
- Time

In general, all the factors are interrelated as no one single factor controls diagenesis, for example, the thermal decomposition of a mineral in the presence of an aqueous solution will change the pore-water composition as the mineral decomposes (Hurst and Irwin, 1982). According to Davis et al. (1979), mineralogy and pore-water composition are interpreted being the most important whilst Bjorlykke et al. (1979) consider sedimentary facies and pore-water composition the critical factors. Summarized from Hurst and Irwin (1982), sedimentary facies influence the growth form and distribution of authigenic minerals; for instance, in marine sandstones, kaolinite forms finer grained crystals which are found as pore filling cements. In pore-water composition, the environment of deposition has a fundamental control on the initial pore-water composition in sandstones. The end member compositions of these pore-waters are meteoric and sea water. Meteorically derived water generally has a low pH value and is acidic, whilst the pH value of sea water is maintained between 7.5 and 8.5 and is alkaline. Thus, different levels of acidity have different effects on the stability of newly formed diagenetic minerals in sediments.

7.2 AUTHIGENIC CEMENTATION

Three authigenic cementing types were observed in rock samples. The cements are namely quartz cement, calcite cement and authigenic clay minerals.

7.2.1 Quartz cement

The dissolution of feldspars and micas resulted in the release of silica, thereby providing a silica source for the formation of authigenic quartz. Some quartz cements are also formed through the recrystallisation of the fine matrix minerals whilst others are precipitated. The authigenic quartz exists in the rocks as fine granular quartz cements (Figure 7.1) and as quartz overgrowths (Figure 5.2).

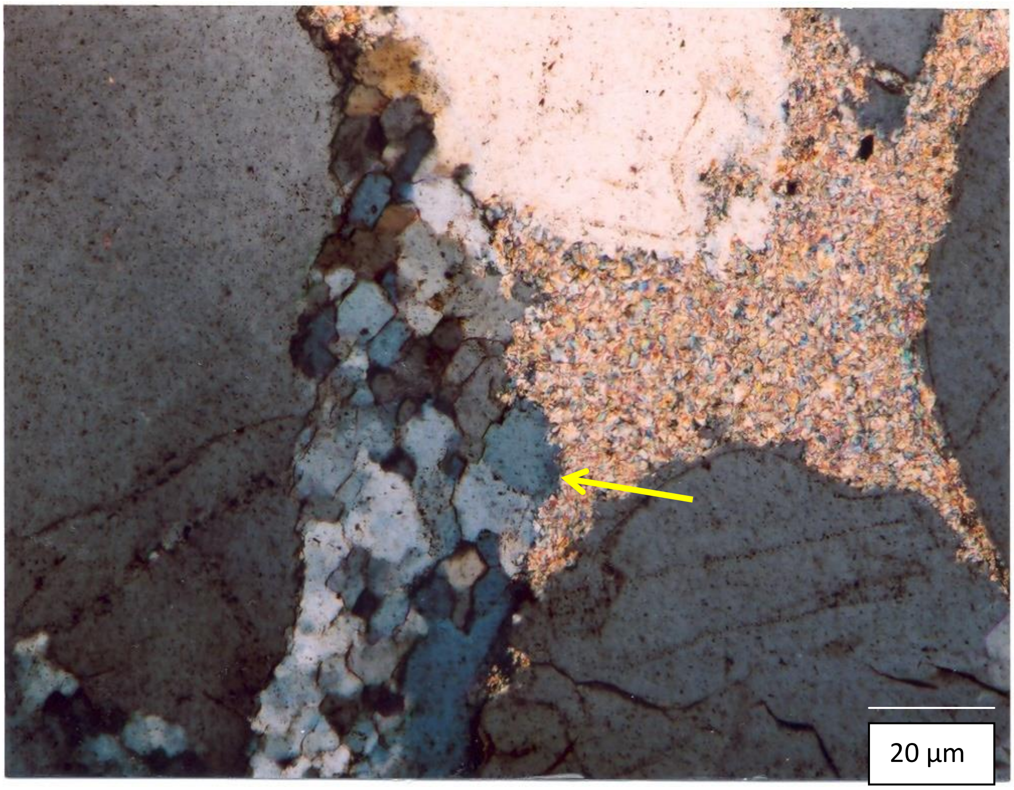

Figure 7.1Thin section photomicrograph showing fine granular quartz cement.

7.2.2 Calcite cement

Calcite is a common cement in siliciclastic rocks and carbonates of sedimentary origin, and particularly for the later. There are two types of calcite cements, i.e. micrite calcite and sparite cement. Micrite calcite is usually formed in quite water low energy environment with a grain-size commonly less than 4 micros, whereas sparite calcite is formed in the active circulation, high energy environment with grain size commonly coarser than 4 micros. In the case of the Ecca Group, the calcite is only a minor type of cement and occurs as secondary cement, i.e. as replacement mineral of clay matrix and framework grains; and filled in the pore-spaces between detrital grains of feldspar and quartz (Figure 7.7).

7.2.3 Clay minerals

Smectite, kaolinite and illite can act as cementation agents; hence the abundance of matrix materials in rocks has rendered the rocks to be very hard in texture. The minerals were identified by their specific characteristic textures in SEM and thin sections. The minerals formed from both the dissolution of potassium feldspars and through the recrystallisation of fine sediments (Figure 7.7). The minerals also formed through the modification of one clay mineral to the other for instance, both kaolinite and smectite were transformed into illite (Figure 7.4).

7.3 RECRYSTALLISATION

Under increased temperatures and pressure, micro-granular and fine grained materials can recrystallise into coarse textures. Existing minerals may retain their original chemistry whilst only increasing in size. In another case, minerals can be completely altered forming new minerals. In the rock samples of the Ecca Group, quartz and feldspar overgrowths were formed through recrystallisation. With regard to clay minerals, illite and sericite recrystallised from both smectite and kaolinite whilst muscovite recrystallised from sericite as temperatures continued to increase. Chlorite was also a product recrystallisation from smectite.

7.3.1 Quartz overgrowth

Quartz overgrowths are not a common phenomenon in all the rock samples of the Ecca Group. Where observed, the overgrowths were easily identified due to the presence of dust rims around the quartz grains as shown in Figure 7.2. The overgrowths had the same optical properties as the detrital grains hence in some instances; it was difficult to distinguish them from the original mineral grains when dust lines were not present.

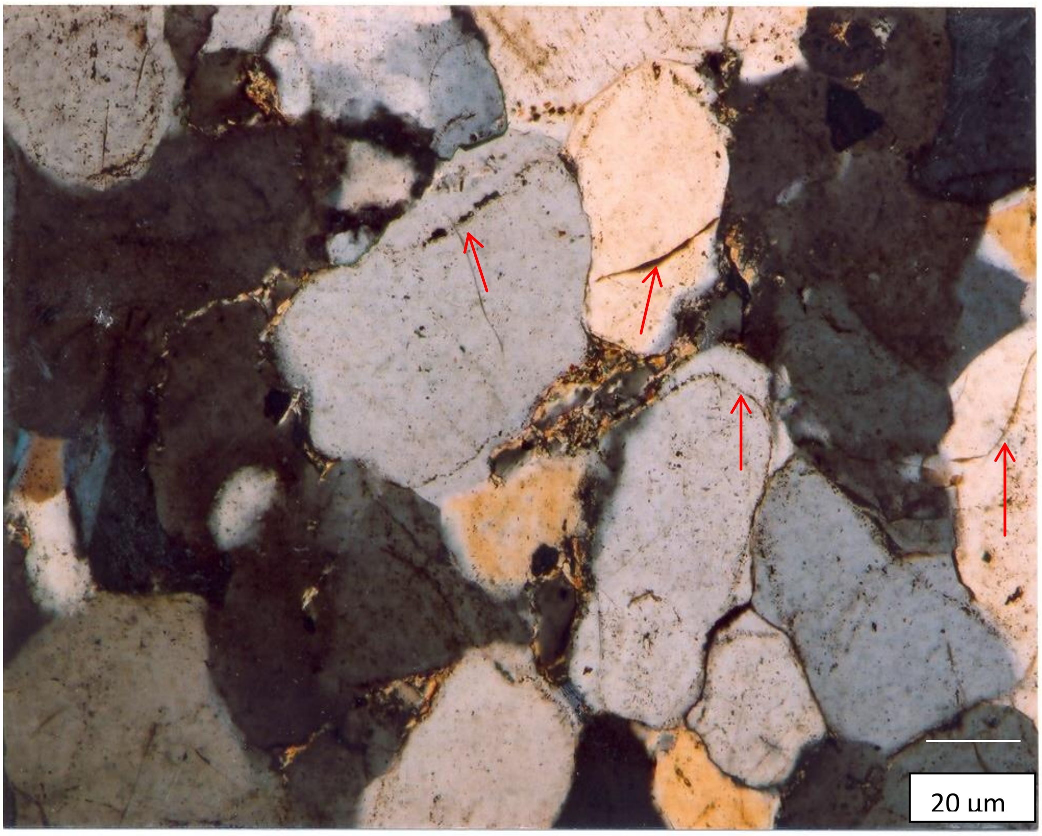

Figure 7.2 Thin section photomicrograph of quartz overgrowths, shown by relict dust lines at boundaries of detrital quartz grains (arrows).

7.3.2 Feldspar overgrowth

The feldspar overgrowths formed as feldspar cements precipitated around the original feldspar grains and enlarged the detrital grains in the rock samples as shown in Figure 7.3. Some overgrowths were also formed through recrystallisation.

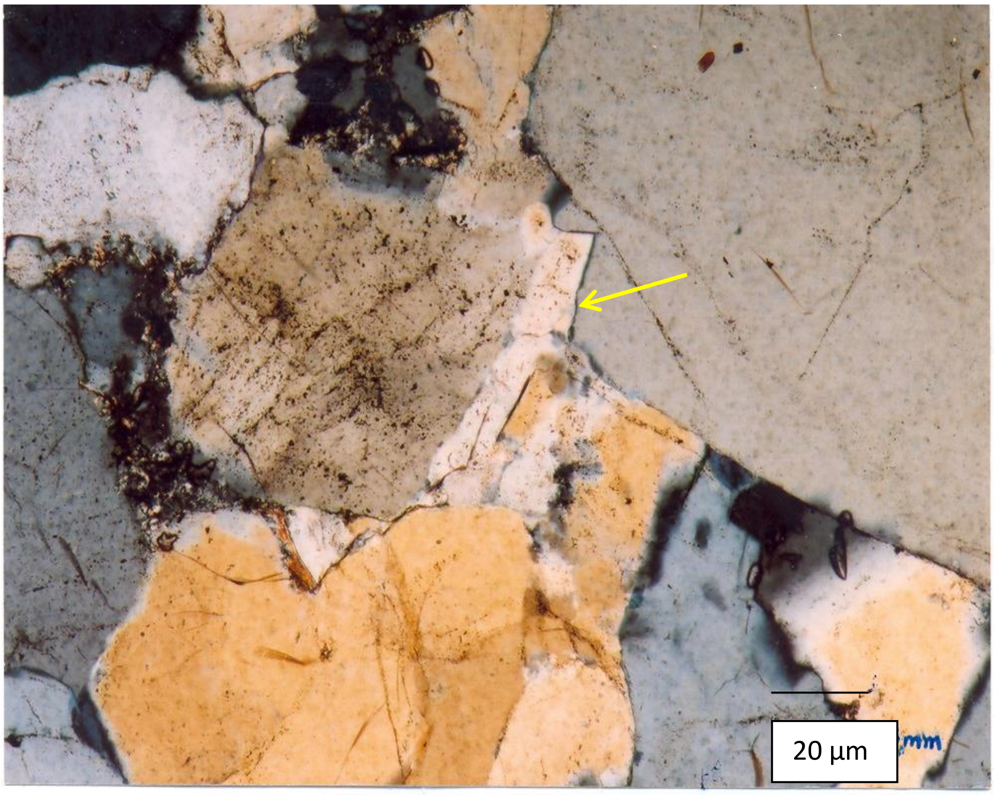

Figure 7.3 Thin section micrograph depicting recrystallised feldspar overgrowths around detrital feldspar grains (arrow).

7.3.3 Clay mineral recrystallization

Kaolinite and smectite also underwent some transformation, changing into illite. In SEM, the growth and nucleation of illite from smectite is shown as in Figure 7.4. According to Hurst and Irwin (1982), smectite transforms to illite at temperatures ranging from 55- 200^0C. Illitization of kaolinite shown in Figure 7.5 requires an influx of potassium in the presence of higher temperatures. However, although illitic clays were commonly associated with the decomposition of kaolinite, kaolinite decomposition is not always accompanied by illitization nor does kaolinite always decompose when illitic cements form (Hurst 1980). Illite however, maintained the shape of its predecessors at transformation. Illite transformed into sericite and as temperatures continued to increase, sericite was transformed into muscovite which is however, not a clay mineral.

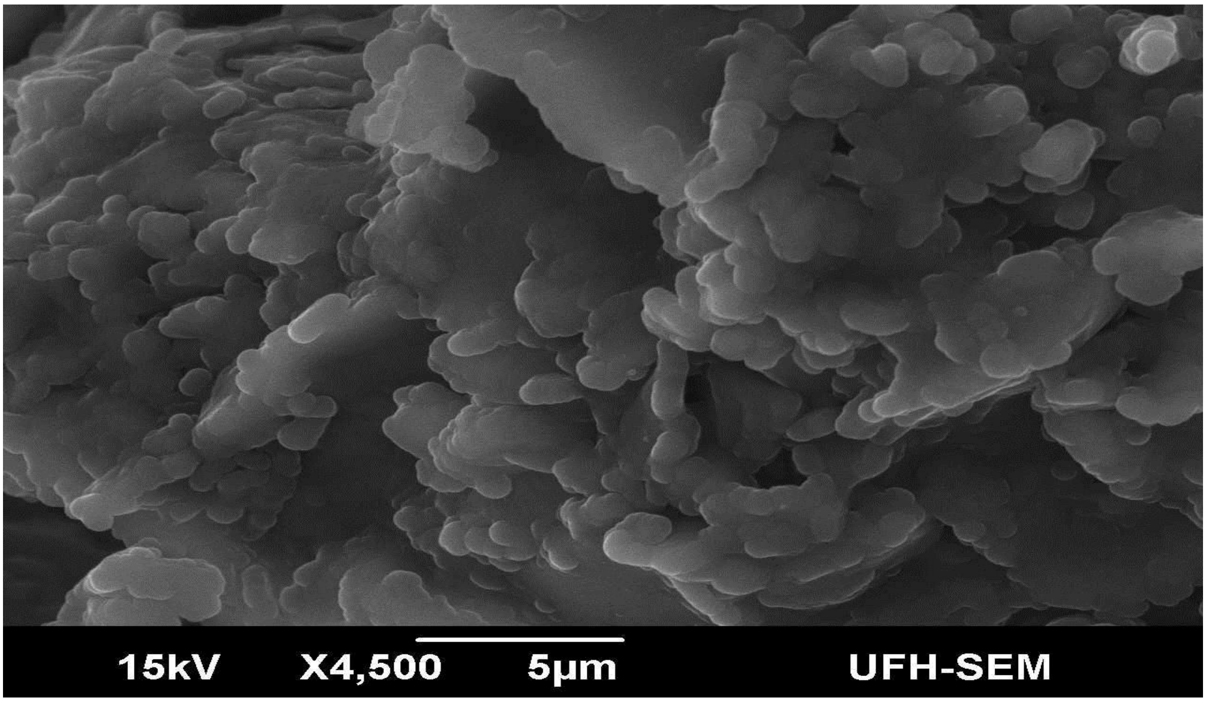

Figure 7.4 Scanning electron photomicrograph depicting recrystallisation of smectite flakes to pelletic and fibrous illite.

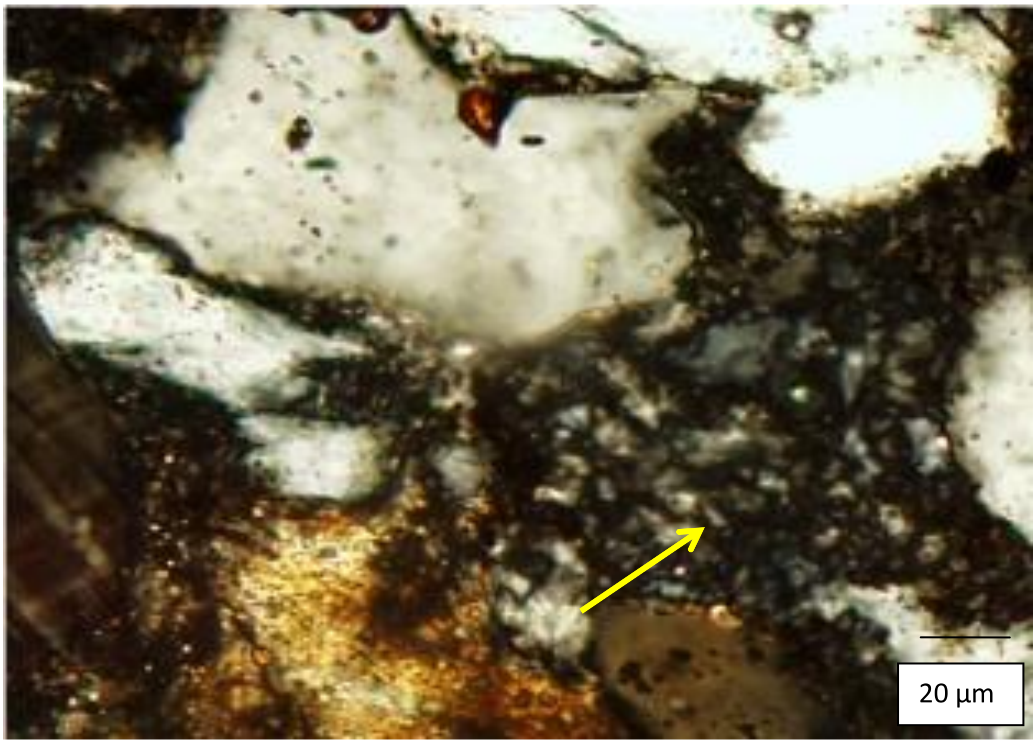

Figure 7.5 Thin section photomicrograph depicting the recrystallisation of kaolinite (arrow).

7.4 REPLACEMENT

The weak and unstable minerals are easily altered. Mineral replacement is very common in rocks that are compositional immature like those found in the Ecca Group which have a high content of feldspar. Feldspars are susceptible to alteration whenever their environmental conditions are changed. In the rocks of the study area, potassium feldspar grains were altered to kaolinite and albite. Some feldspar grains were either completely or partially altered to either kaolinite or albite. However, kaolinite was found to be the most abundant replacement mineral in the sandstone rock samples.

7.4.1 Calcite

Calcite was another of the significant replacement mineral observed in the Ecca Group (Figure 7.6). Calcite replaced both the mud matrix and framework grains. The detrital grains replaced included those of quartz, volcanic fragments and feldspars. The most affected feldspars were potassium feldspar with minor plagioclase.

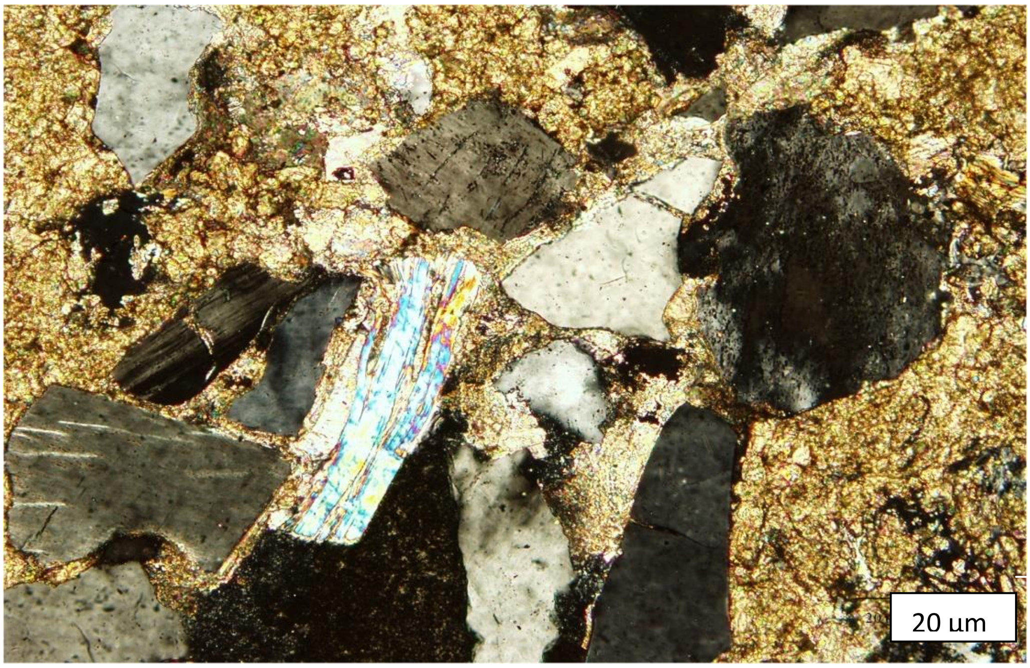

Figure 7.6 Thin section photomicrograph of rhombic shaped calcite cement (yellowish) after the replacement of matrix minerals and framework grains. The framework grains include quartz, feldspar and chloritised biotite (greenish middle).

7.4.2 Authigenic clay minerals

The minerals were identified using electron microscopy. Kaolinite was the most common replacement mineral. It was observed having replaced both the matrix and framework grains of potassium feldspar. Feldspar relicts could still be identified in some instances (Figure 7.7). Illite replacement of feldspar mineral grains also occurred.

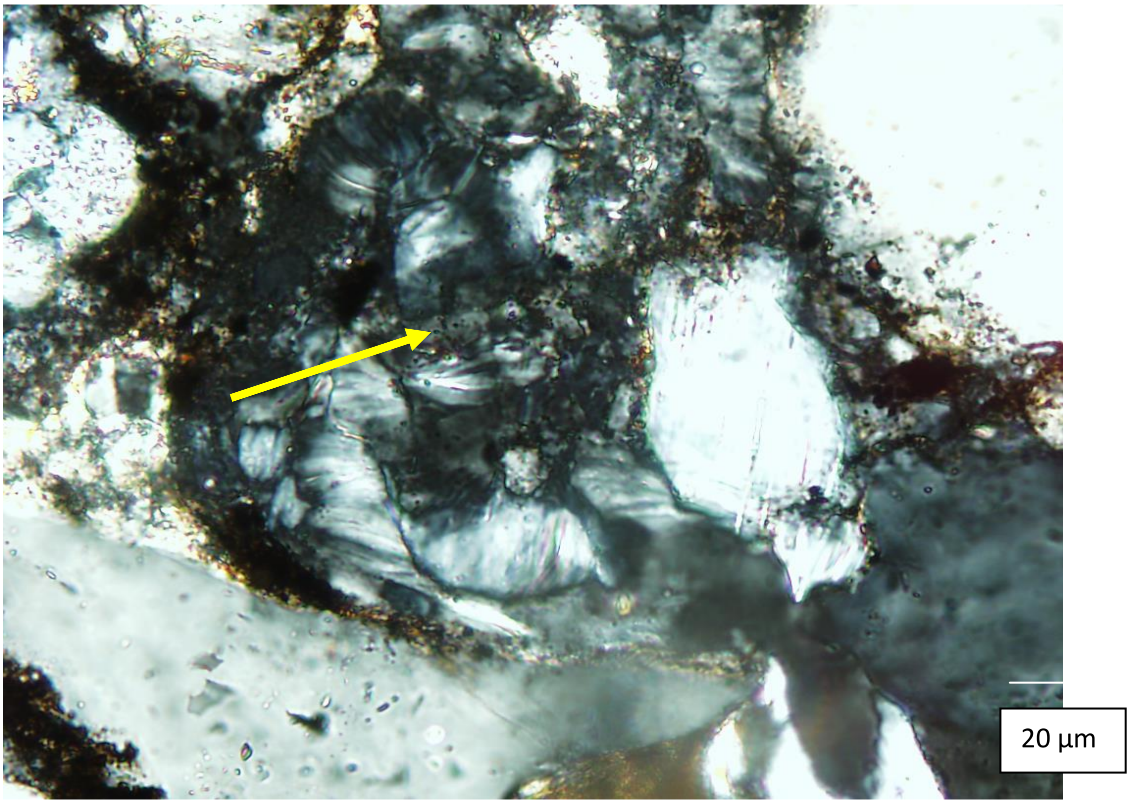

Figure 7.7 Thin section photomicrograph of kaolinite replacement of feldspar, still showing some feldspar relicts.

7.4.3 Albite replacement of K- or Ca-feldspar

Albitisation occurred both directly and indirectly from K-feldspar; indirectly after the replacement of K-feldspar by calcite as an intermediate stage. Albite formed through replacement was revealed by the blocky to tabular sector extinction patterns where incomplete replacement occurred (Figure 7.8). Albite was also observed having equant alternating black and gray and as overgrowths on plagioclase grains.

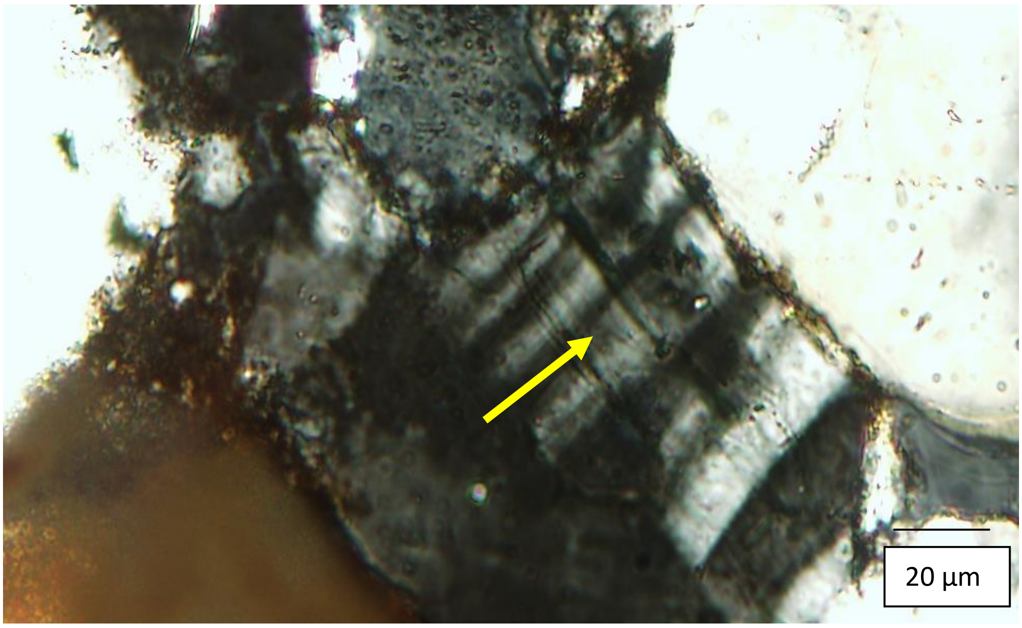

Figure 7.8 Thin section photomicrograph of albitised feldspar grain with a blocky extinction pattern, indicating incomplete replacement of a detrital feldspar grain.

7.5 OVERCOMPACTION AND PRESSURE SOLUTION

The sediments of the Ecca Group were compacted together at burial as is indicated by some point and line contacts between the framework grains. The compaction resulted in the reduction in size of the pore spaces. The heavy over burden that squashed the sediments together led to the fracturing of some of the grains, especially those of the feldspars and muscovite, whilst the other muscovite grains were completely deformed.

Temperatures and pressure increased as the burial depth increased. This allowed for the fine grained recrystallize to coarse grained minerals. Smectite and kaolinite recrystallised to illite whilst muscovite formed from sericite. With regard to the presence of microcline, a low temperature mineral, compared to orthoclase which is a high temperature mineral, the increased temperatures allowed for the conversion of the microcline to albite as the minerals became unstable. The high temperatures also led to the dissolution of some mineral grains at their boundaries as shown in Figure7.9.

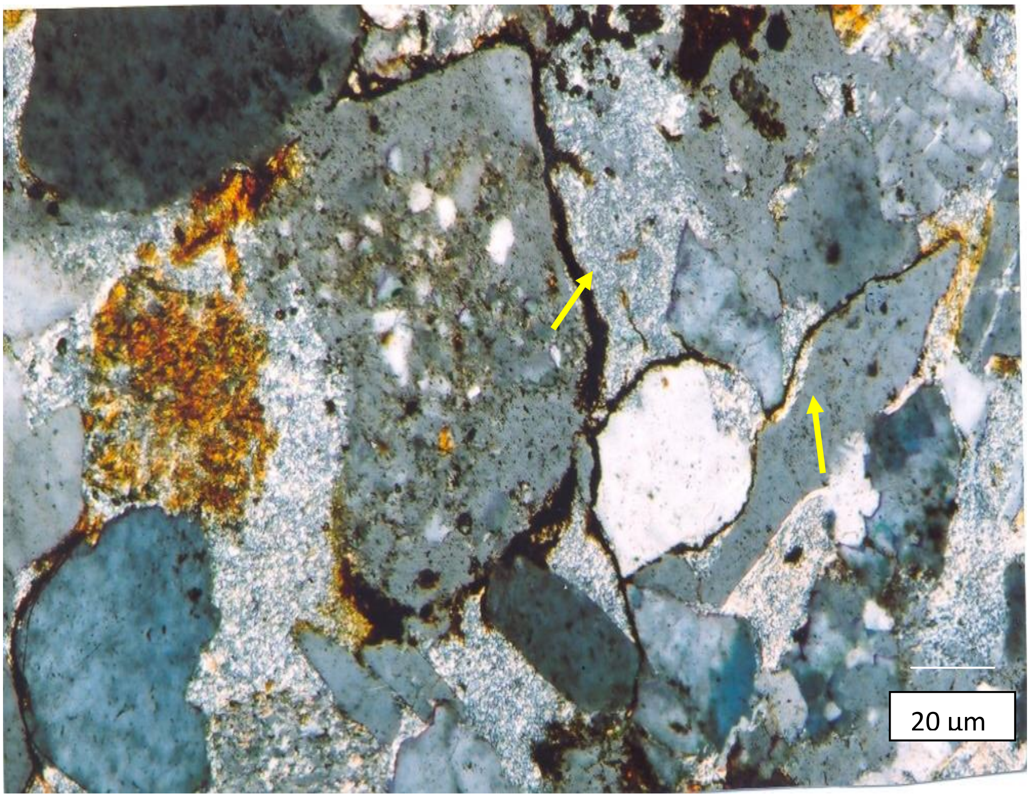

Figure 7.9 Thin section photomicrograph depicting the dissolution texture formed along grain boundaries.

Over-compaction allowed for the suturing and the concave-convex textures on poly-crystalline quartz. However, in the samples of the Ecca Group, a weakly compacted fabric can be observed for the polycrystalline quartz.

7.6 INTERPRETATION OF DIAGENETIC HISTORY

The diagenetic history of the rocks in Ecca Group was inferred following the principal diagenic processes and changes as the main events that occur in siliclastic sedimentary rocks. The processes and changes are summarised in Table 7.1. The processes of diagenesis resulted in the formation of an equilibrium mineral assemblage. According to Dapples (1967), the pH and Eh of the interstitial fluids can be deduced at the same time identifying the progressive changes of the depositional and diagenetic environments.

Table 7.1Diagenetic Processes and Changes in the Ecca Group (the table format follows Boggs, 2001).

	Diagenetic stage	Diagenetic Process	Result
Burial	Early diagenesis	Cementation and replacement	Pyrite (reducing environment) Iron oxide (oxidizing environments); precipitation of quartz and feldspar cement and overgrowths, carbonate cements, authigenic clay minerals.
	Late diagenesis	Physical compaction	Tighter grain packing, porosity reduction and bed thinning.
		Chemical compaction (pressure solution)	Partial dissolution of silicate grains, porosity reduction and bed thinning.
		Cementation	Precipitation of carbonate(calcite) and silica (quartz) cements with accompanying porosity reduction,
		Dissolution by pore fluids	Solution removal of carbonate cements, silicate framework grains, creation of new (secondary) porosity by preferential destruction of less stable minerals.
		Mineral replacement	Partial to complete replacement of some silicate grains and clay matrix by new minerals (e.g. replacement of feldspars and matrix by calcite).
		Clay mineral recrystallisation	Alteration of one kind of clay mineral to another (e.g. smectite to illite, sericite or chlorite, kaolinite to illite or sericite)
Uplift	Uplift and weathering	Dissolution and replacement, oxidation	Solution of carbonate cements, alteration of feldspars to clay minerals, oxidation of iron carbonate minerals to iron oxides, oxidation of pyrite to hematite, solution of less stable minerals (e.g. pyroxenes, amphiboles)

7.6.1 Early diagenesis

At early diagenetic stage, quartz was precipitated in the sandstones of the Ecca Group, coating the detrital grains. According to Lewin (1971), the early occurrence of quartz cements in marine sandstones is related to the decomposition of biogenic siliceous organisms shortly after deposition. The quartz coatings are however of minor quantity in all of the rock samples. Considering the absence of fossil material both in the field and in thin sections of the sandstones, only a considerable amount of siliceous material existed to allow for the precipitation of quartz overgrowths.

Hematite formation in the rocks is another of the early diagenesis processes. Although the iron oxide is rarely a major cement in the mudstone rock samples, the presence of the iron oxide allowed for the colouration of the Prince Albert rocks to be red. At early diagenetic stage, oxidizing conditions in the intrastitial waters existed to allow for the formation of the iron cement. According to Walker (1967), intrastitial solutions are usually the most probable source of iron. Iron rich minerals were the main source of iron for the formation of heamatite.

Precipitation of pyrite is significant process in organic rich sediments as those observed in the Ecca Group. Under reducing conditions, organic matter decomposed to produce bisulphide, which later reacted with dissolved iron or iron rich minerals to form iron sulphide minerals (Berner, 1970). Pyrite, which is an iron sulphide mineral, therefore, accumulated in organic rich, deep ocean water basins.

Glauconite is a clay mineral that formed at early diagenetic stage. Harder (1980) indicated that the formation process occurs at interface between reducing and oxidizing zones in muddy sediments in the presence of Si, Fe, Al and K containing pore fluids. The silica content can be a controlling factor in the formation of glauconite. Regarding that mudrocks had more organic materials as compared to the aranaceous sediments, glauconite exists in in higher amounts in the clayey sediments than in the sandy sediments of the Ecca Group.

Summarized from Hurst and Irwin (1982), the formation of kaolinite in the sediments requires a low pH. Since the sea water is saturated with respect to feldspar and muscovite, only a small amount of kaolinite is likely to form when silicates equilibrate in the marine pore water, a justification for the small percentages of kaolinite in most of the rock samples. In sandstones, authigenic kaolinite may have been produced by the migration of ions in fluids evolved during shale diagenesis and compaction (Foscolos and Powell, 1979). Acidic pore waters produced from CO_2 released during the diagenetic oxidation of organic matter, causes dissolution of carbonate, and thereby allowing for the formation of kaolinite in a low pH diagenetic environment (Burke and Mankin, 1971).

7.6.2 Late diagenesis

Late diagenesis is an important stage in the formation of hard rocks. Dapples (1967) deduced that, at this stage, most of the reactions are favoured by the increase in pressure and pressure. Late diagenesis began with the physical compaction of sediments as the overburden increased. The effects of compaction can easily be identified in both the sandstones and shales. In the shales, the grains developed an alignment parallel to lamination and porosity was reduced due to overloading. In the sandstones, further compaction caused convex-concave grain contacts and suture contacts between grains and secondary porosity was created when the detrital feldspar, rock fragments and muscovite grains were fractured and dissolved.

Increase in pressure due to compaction resulted in the recrystallisation of minerals. High pressures led to dissolution of silicate materials from which some of the silicate minerals recrystallised according to their different recrystallisation points. Authigenic quartz, muscovite, illite, sericite, chlorite and feldspars are the recrystallised silicate minerals observed in thin sections and SEM. Smectite recrystallized to illite and further to chlorite, whilst kaolinite recrystallized to illite. Illite also further changed to sericite, which later recrystallised to muscovite.

According to Dapples (1967), the alteration of clay minerals into mica and the development of well crystallised phyllosilicate minerals generally occur at late diagenetic stage. Biotite recrystallization favoured the presence of a reducing environment whilst muscovite favoured slightly more oxidized interstitial fluids to form. Chlorite formation in rocks is also believed to be associated with mildly reducing environments; therefore, the chlorite invasion of biotite can be understood since both minerals required similar environmental conditions to form.

Calcite precipitation is a late diagenetic process in the Ecca Group. An alkaline environment prevailed with increase in burial depth. Unstable detrital grains released cations to pore-waters, allowing the calcite cements to precipitate in the pore-space or replace feldspar and matrix. In the Ecca Group rocks, replacement was not only restricted to the potassium feldspar, clay matrix and even quartz grains were also partially replaced. When organic materials decayed during diagenetic processes, the CO_2 released also provided carbonate ions for the precipitation of calcite cements.

Partial and complete replacement of potassium feldspars is a common phenomenon in feldspar rich rocks because feldspars are susceptible to alteration in a deep burial environment. In the rocks of the Ecca Group, potassium feldspar was replaced by calcite, with authigenic quartz being released as a by-product. Albite and illite also formed through the replacement of feldspar, particularly the potassium feldspar.

7.6.3 Uplift and weathering

Marine deposited materials are never invaded by large quantities of meteoric waters unless uplifted and subjected to weathering (Hurst and Irwin, 1982). Diagenetic modification in the rocks of the Ecca Group continued at surface and near surface conditions due to uplift and denudation processes since the Mesozoic era. At uplift, the rocks were exposed to acidic rain, which led to the dissolution of some of the carbonate cements and increasing porosity in the sandstones. The mudstones of the Prince Albert Formation also underwent changes after being exposed on the surface. The red pigmentation is change that took place due to exposure to meteoric waters. Smectite mudstones are rich in iron, at breaking down; released iron elements that were oxidized to give the red colour in the mudrocks of the Prince Albert Formation. The red colour was not the original sediment colour but secondary in nature.

A part of kaolinite found in the rocks of the Ecca Group was produced due to weathering of feldspars, however, in minor quantities, perhaps due to the fact that most of the rocks in Ecca Group are argillaceous rocks, which are dominated of clay minerals other than feldspar. The presence of fresh surface-water at uplift was the cause of the kaolinisation of the feldspars. According to Bjorlykke et al. (1979), flushing of sediments by fresh water is widely believed to be an important process in kaolinisation, especially in the kaolinisation of sandstones.

7.6.4 Diagenetic pathway

Table 7.2 below summarises the diagenetic pathway for the precipitation of the diagenetic minerals in the Ecca Group.

Table 7.2 Diagenetic processes and pathway of the Ecca Group.

Diagenetic stage		Early Diagenesis	Late diagenesis	Uplift and weathering
Cement and matrix minerals	Kaolinite			
	Heamatite			
	Smectite			
	Quartz			
	Biotite			
	Illite			
	Sericite			
	Muscovite			
	Chlorite			
	Calcite			
	Albite			
Compaction				
Dissolution				
Fracturing				

7.7 POROSITY

Porosity in sandstones is determined by both primary and secondary pores. Secondary porosity features are common for siliciclastic rocks and form at all burial depths. Compaction of sediments due to the overburden results in the reduction of primary porosity. Carbonate minerals are susceptible to dissolution by acidic water and when this happens; dissolution pores between grains are formed. Lastly, the dissolution of feldspars also leads to the formation of secondary pores. Table 7.3 below summarises the envisaged and observed pore types in the sandstones of the Ecca Group.

Table 7.3 Envisaged and observed primary and secondary pores in the Ecca Group (table format follows Zhu et al., 2008).

	Type of pore	Method of formation	Characteristics
Primary pores	Condense pores	Compaction and contraction between grains	Point-line contact of grains
	Surplus pore	Surplus pore between grains after the cementation of condense pores	Space between grains after filling with carbonate cement
	Matrix micro pore	Pores formed by the sustained function between matrix grains	Pores between authigenic clay minerals
Secondary pores	Dissolution pores in grains	Formed by partly corrosion of grains	Corrosion inside of feldspar grains
	Dissolution pores between grains	Dissolution of cement material	Corrosion of the edge of grains and cements

There are pore spaces in the matrix. The pores are generally small in size even though a few big and elongated ones also exist (Figure 7.10). According to Stalder (1973), the precipitation of authigenic clays such as illite in pore spaces can significantly reduce porosity and permeability of a rock.

The lack of quartz cementation allowed for the preservation of the primary porosity, considering that quartz cementation is best known to be destructive on primary porosity. Calcite is the most dominant cement in the rocks compared to quartz which appears minimal. Calcite cements in general do not fill all pore spaces completely but appear as patches since they partially occupy intergranular pores. As Stalder (1973) explains, the dissolution of detrital minerals or cements is important for the formation of secondary porosity.

Some of the detrital mineral grains of feldspar and muscovite observed in thin sections are cracked. As the burial depth of sediments increased, compression resulted in fracturing.

Fracturing is also evidence of over-compaction which in some case allowed for the reduction in pore space and size, reducing porosity. Although permeability and porosity are not the same, a rock would not be permeable without porosity. The vermiform appearance of kaolinite as seen in thin sections allowed for the increase in secondary porosity.

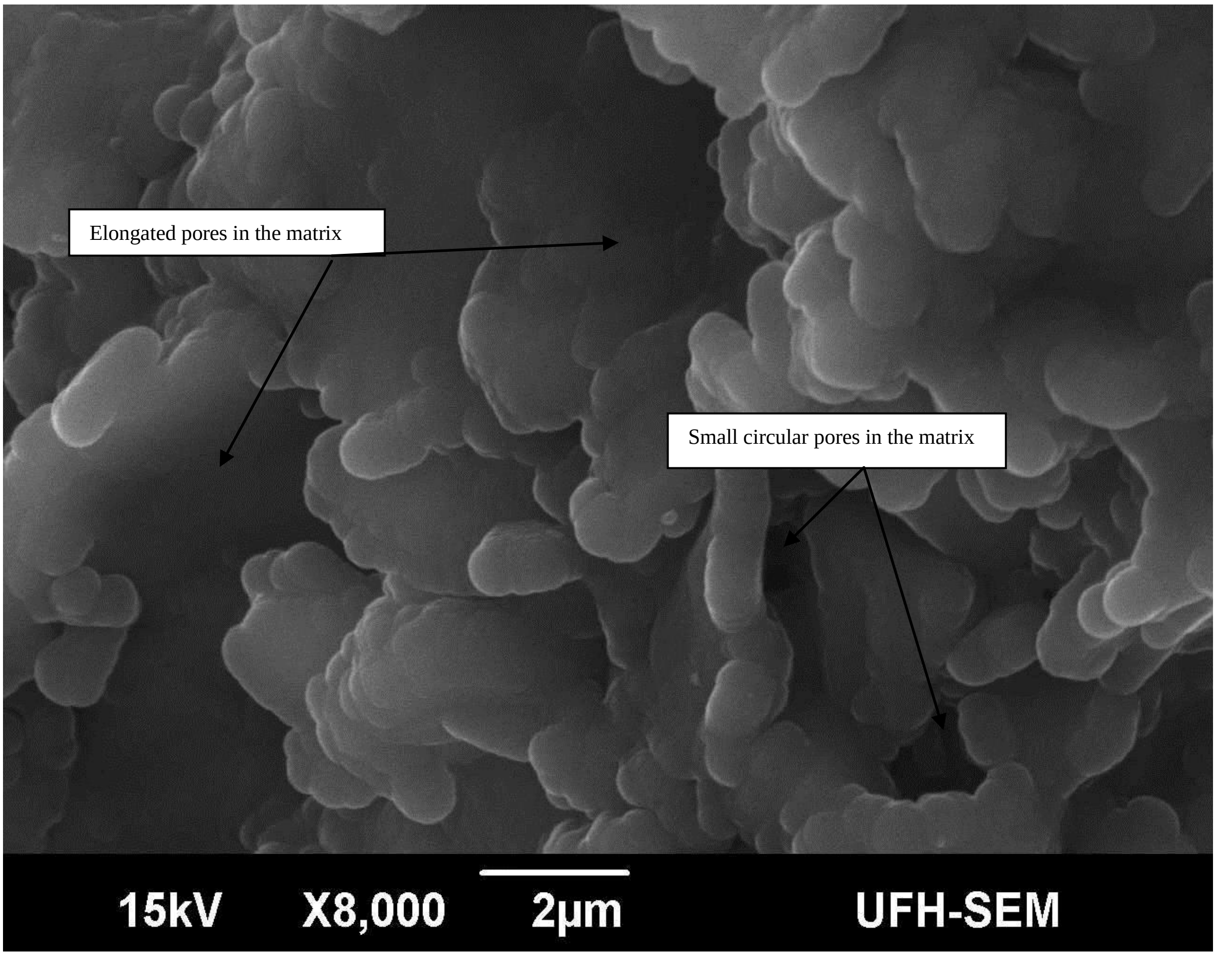

Figure 7.10 Scanning electron photomicrograph showing elongated and rounded pores within the matrix of illite and smectite.

CHAPTER 8. DISCUSSION AND CONCLUSION

8.1 Discussion

Stratigraphy

The stratigraphy of the Ecca Group was divided into five formations, namely the Prince Albert Formation, Whitehill Formation, Collingham Formation, Ripon Formation and the Fort Brown Formation from bottom upward. The thicknesses of the formations were measured and lithologies were studied. Based on the differences of rock colour, lithology, sedimentary structures and sedimentary facies, the Prince Albert Formation can be further divided into lower gray member and upper khaki mudstone member. The lower member has a thickness of 104.9m, consisting of laminated black mudrocks, whereas the upper member has a thickness of 15.1m and composed of thin-bedded khaki brownish shales and siltstone. The Whitehill Formation has a total thickness of 25.2m, which can also be divided into two members. The lower black shale-chert member is 15.1m thick, and composed of laminated-thin bedded black shales interbedded with chert layers; while the upper gray mudstone member consists of grayish well laminated shales intercalated with minor chert layers and is 10.1m thick.

The Collingham Formation was divided into 2 members, i.e. the lower gray mudstone member and upper black rhythmite member. The lower member is 20.1m thick and is made up of grayish-black thin bedded mudstone; whereas the Upper Member is 35.1m thick, and composed of grayish black rhythmites which were deep marine turbidite sediments. The Rippon Formation has a total thickness of 813.07m, and is the thickest formation in the Ecca Group, which was divided into three members; the lower greywacke mudstone member is 138.07m thick and consists of thin to thick bedded graywackes overlain by alternating shales, mudstone and minor sandstones. The Middle Member is measured at 415.5m in thickness and is also composed of thin to thick bedded sandstones overlain by mudstones which represent deltaic sediments and were produced during delta progradation. The upper black mudstone-sandstone member consists of alternating sandstone and shale or mudstone with a thickness of 259.5m. Overlaying the Rippon Formation is the Fort Brown Formation which was divided into two members. The lower gray varved rhythmite member consists of varved mudstone rhythmite with minor sandstone, whereas the upper mudstone-sandstone member consists of mudstone and sandstone, the sandstone becomes dominated upward. The Fort Brown Formation has a total measured thickness of 250.2m, with its lower member measuring at 100.1m and the upper member measured at 150.1m in thickness.

All of the above mentioned stratigraphic members are the proposed members of the Ecca Group, and are proposed for the first time in the studies of the Ecca Group.

Petrology

The petrology of the Ecca Group is mainly all terrigenous rocks with a lack of conglomerates. There are also no carbonate rocks in the group.

Mineralogy

Feldspar, quartz and micas occur as the major minerals in the rocks with lithics also forming part of the framework grains in the sandstones. Quartz and feldspar grains are both polycrystalline and monocrystaline, indicating they were not fully separated by long distance of transportation, which is consistent with the immature nature of the rocks. Hematite, rutile and zircon are the accessory minerals whilst the clay minerals that can be observed in the rocks include kaolinite, smectite, illite and sericite. The minerals exist in the rocks as either detrital grains or diagenetic minerals. The detrital nature of some the minerals and the presence of lithics therefore classify the rocks to be terrigenous in origin. From the observed lithics and heavy minerals and the nature of quartz and feldspar minerals, conclusions can be made that the provenances of the sediments were derived mainly from igneous and metamorphic rock sources.

The mineral compositions in the Ecca Group can be classified into three groups:

- Terrigenous mineral group: quartz, orthoclase, microcline, albite, plagioclase, muscovite, rutile and zircon; the latter two are also called as heavy minerals, which occur as minor minerals;
- Clay mineral group: smectite, kaolinite, illite and sericite;
- Diagenetic mineral group: calcite and hematite.

Sedimentary facies and depositional environments

Based on the characteristics of lithology, sedimentary structures and vertical sequence patterns of the Ecca Group, ten sedimentary facies were identified. In Chapter 2, all the facies were only described as having been deposited in a marine environment. This research further distinguished the deep marine, deltaic and also lacustrine environments.

From bottom upward of the succession of the Ecca Group, it is clear that the depositional environments gradually changed from deep marine water environment (Prince Albert, Whitehill and Collingham Formations) to deltaic environment (Ripon Formation) and then to lacustrine environment (Fort Brown Formation), which implies that the sedimentary basin was gradually filling up with sediments and the water depth of the basin was gradually shallowing. This is also consistent with the evidence that the overlying strata of the Ecca Group, i.e. the Beaufort Group was deposited in a fluvial environment, which was the result of basin water and sea-level continuously retreating or dropping; a marine environment then shifted to a continental inland environment.

Diagenesis

Four types of cements have been identified in the rocks of the Ecca Group, including quartz cement, smectite cement, calcite cement and feldspar cement. The first three cement types are the major cement types, whilst the feldspar cement is only minor and occurs only locally.

Recrystallization in Ecca sediments includes quartz, feldspar, clay mineral recrystallisation and conversion from smectite and kaolinite to illite and then to sericite.

Replacement includes calcite replacement of quartz, feldspar and clay matrix; with albitization, i.e. albite replaced feldspar minerals in a deep burial environment and also illite replacement of feldspar.

Dissolution in the Ecca Group occurred when calcite and kaolinite dissolved and leached; which created pore-space and increased porosity.

The sediments of the Ecca Group went through three stages of digenesis, namely the early stage, the late stage and the up lift stage at exhumation and weathering of the rocks after exposed on the Earth’s surface. In the early stages, precipitation of cements and formation of authigenic minerals mostly occurred, which led to the soft sediments becoming a hard rock. In later diagenetic stage, recrystallization, replacement, overgrowth and dissolution took place as a result of increase of temperature and pressure due to increase burial depth. At up lift stage, leaching, weathering, dissolution and oxidation occurred. Pyrite weathered releasing ions of iron that led to the formation of hematite whilst calcite cement was dissolved by acidic pore waters.

8.2 CONCLUSION

Ecca Group is the main target of shale-gas exploration in South Africa and diagenetic research is pre-requisite for the feasibility studies of the exploration. This is the first time diagenesis studies have been done on the Ecca Group in the research area and further detailed work is necessary in the future.

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