Lithofacies characteristics and depositional environment interpretations of the Permian Ecca Group in the Eastern Cape, South Africa

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Abstract

The Ecca Group is a sedimentary rock sequence that formed between the Late Carboniferous Dwyka Group and the Late Permian-Middle Triassic Beaufort Group. To determine the nature of their depositional environments, a detailed sedimentary facies analysis of the Ecca Group was performed. Fourteen lithofacies were discovered and classified into seven distinct facies associations. Based on the lithological and facies characteristics, it is inferred that the Prince Albert and Whitehill Formations represent deep marine plain/floor pelagic deposits, whereas the overlying Collingham Formation represents continental slope turbidite. The Ripon Formation, which has three informal members (Lower, Middle, and Upper Members) represents continental slope midfan deposits. The Fort Brown Formation is made up of prodelta deposits. Sedimentological and sequence stratigraphic evidence revealed that the Ecca Group gradually changed upward from deep marine to shallow marine environments, and then to a prodelta lacustrine environment, implying that the Main Karoo Basin was gradually filling up with Ecca sediments.

Introduction

The Main Karoo Basin of South Africa is the thickest and most complete sequence in the Southwestern Gondwana Continent, composed of several depositories of Permo-Carboniferous to Jurassic-aged sediments (Catuneanu et al., 1998) and has been interpreted as a retro-arc foreland basin (Johnson et al., 2006). Sedimentation in the basin continued across Gondwana until the supercontinent rifted in the Middle Jurassic around 183 Ma, resulting in the various Karoo-age successions (Catuneanu et al., 2005). The Karoo Basin sedimentary fill, which includes the Dwyka (Late Carboniferous-Early Permian), Ecca (Permian), Beaufort (Late Permian-Triassic), and Stormberg Groups (Late Triassic-Early Jurassic), accumulated as a result of tectonic and climatic changes (Catuneanu et al., 2005). Rubidge (1858; in Catuneanu et al., 2005) coined the term "Ecca" to describe argillaceous sedimentary strata that outcropped along Regional Road R67 (Ecca Pass) near Grahamstown in South Africa's Eastern Cape Province. As a result, using the term "Ecca" outside of the main Karoo Basin is sometimes questionable because the rock types could be completely different. The base of the Ecca Group is defined at the top of the Dwyka Group's glaciogenic succession, with varied sequences dominated by mudstones, siltstones, and sandstones, with occasional conglomerates and coal (Smith, 1993). The group is thought to have reached a thickness of about 3000 m in the southern part of the Main Karoo Basin.

Nicholaus Steno introduced the term "facies" into geology in 1669. The term "facies" is derived from the Latin word "facia," which means the external appearance or appearance of something. Gressly (1838) defined "facies" as the totality of a stratigraphic unit's lithological and paleontological aspects. However, since 1838, many geologists have used the term in various ways or contexts. The main debate about using the term is whether it only applies to a specific set of characteristics, as opposed to Gressly's use of stratigraphically unconfined rock bodies

(1838). However, whether the term should be used purely for descriptive (i.e., mudstone facies) and interpretative purposes (i.e., fluvial facies) (Middleton and Hampton, 1976; Reading, 1978) is debatable. A sedimentary facies is a body of sedimentary rock with specific petrological, compositional, and sedimentary characteristics or features that reveal the environmental conditions under which the rock was formed (Reading and Levell, 1996; Boggs, 2001).
A sedimentary facies description entails identifying and documenting all of the characteristics that can be defined by lithology, color, grain size, texture, fossil content, and sedimentary structures or mineral compositions. Sedimentary facies are typically divided into two groups: lithofacies and biofacies. Lithofacies is concerned with visible mineralogical or petrological characteristics such as color, grain size, sedimentary structures, and mineral compositions, whereas biofacies is concerned with biological characteristics such as fossil contents. The process or set of processes that prevail in the depositional environment can be deduced by identifying facies associations. The processes that exist or are present in the depositional environment resulted in depositional environment characteristics; thus, there is a connection between facies associations and the depositional environment. However, several sub-environments may exist within a single depositional environment, indicating that facies can vary within a single depositional environment, reflecting the change from one sub-environment to the next within the same depositional environment. As a result, adjacent environments can be represented by adjacent facies, and the manner in which these facies interact with one another is always revealed in the characteristics of the facies (Nyathi, 2014). This study sheds new light on the detailed sedimentary facies analysis of the Ecca Group in the Eastern Cape of South Africa (Figure 1). The research relies on the integration of sedimentological data, such as lithology, sedimentary structures, and vertical sequence patterns, to refine sedimentary processes and depositional paleoenvironments.

Methodologies

In the study area, road-cut exposures of the Ecca Group were examined in outcrops (Figure 1). Stratigraphic sections were measured in the field using a tape measure, and lithologies and sedimentary structures were identified and investigated. For each individual unit, field data such as lithology, colour, grain size, mineral composition, and sedimentary structures were collected. A modified version of Miall's (1988a, 1988b, 1996) lithofacies classification scheme was used to analyze the stratigraphic formations. The scheme is built around a two-part lithofacies coding system. The first letter represents lithology (G, gravel, S, sand, and F, fine), while the second letter represents the distinct sedimentary structure or texture of each lithofacies. In this study, a facies is a restricted lithofacies with specific sedimentary structures that constitutes a part of a stratigraphic unit with characteristics that differ significantly from other parts of the unit and is attributed to depositional features that point to a specific depositional process or combinations of processes. On a small scale, each stratigraphic member or formation is associated with a distinct sedimentary facies based on its lithological characteristics and sedimentary structures. The description of the individual facies is consistent with the work of Miall (1977), Miall (1995), Bordy and Catuneanu (2001), and Bordy et al (2005). Facies association was deduced from the individual facies since individual facies cannot completely reconstruct or interpret the type of depositional environment and conditions that existed during the deposition of the sediments. The identified lithofacies types were grouped into facies associations (FA) and were then used to interpret or deduce the possible depositional palaeoenvironments. A laboratory microscope study of thin sections was also used to aid in the identification and differentiation of different lithofacies, specifically the rock texture, grain size, and mineral compositions.

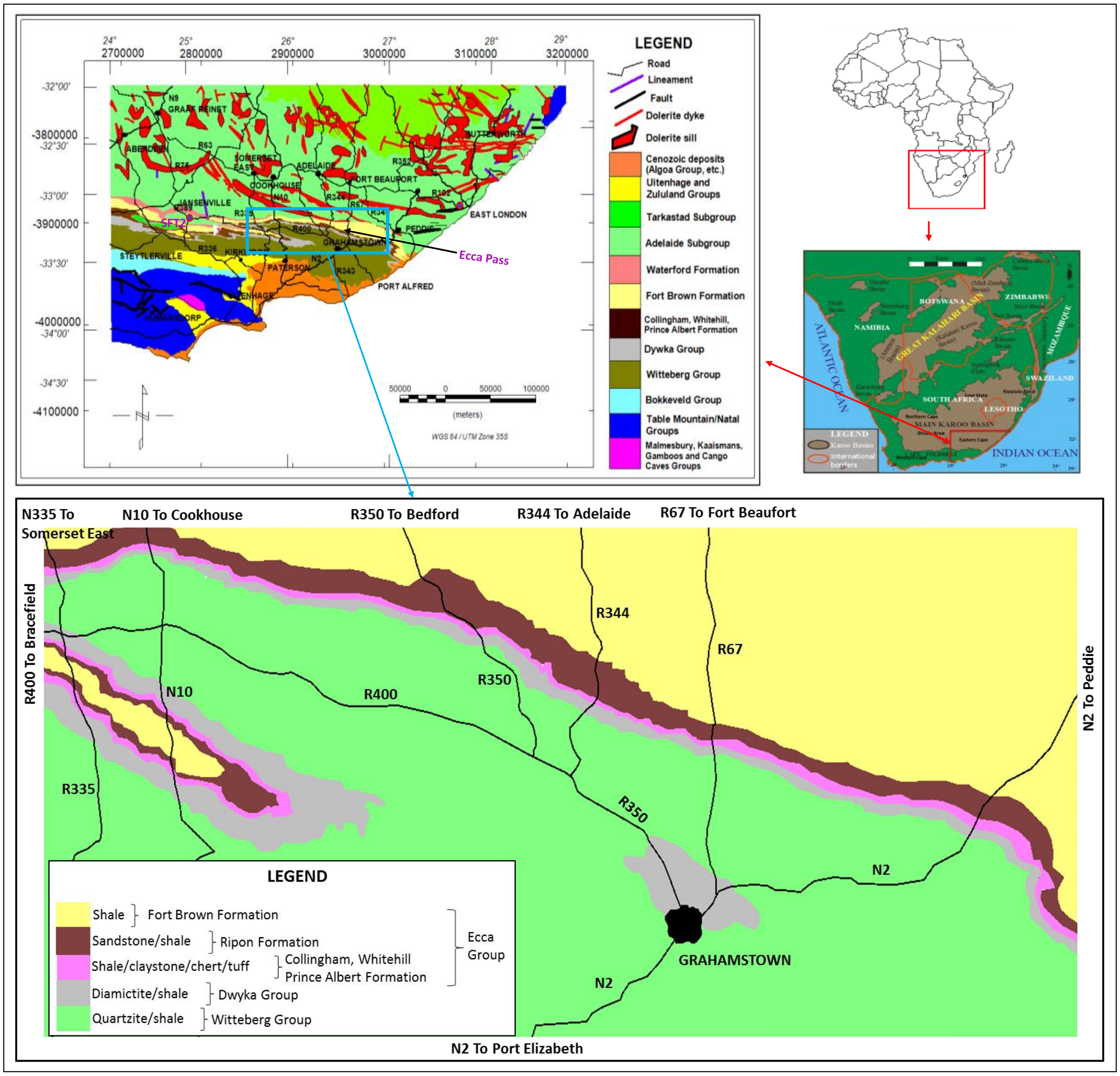

Figure 1. Geological map of the study area showing the position of the outcrops (after Council for Geoscience, 1995).

Lithofacies and facies associations

Fourteen lithofacies were identified in the Ecca Group in the study area (Figure 1). The stratigraphy of the Ecca Group in the study area is presented in Figure 2. The characteristics of these lithofacies are depicted in Table 1 and Figures 3 and 4. Seven distinct facies associations were recognized and interpreted based on the identified lithofacies type, internal and external geometry in the formations. The characteristics of the facies associations (FA) are summarized in Table 2.

Table 1. Lithofacies identified in the Ecca Group.

Facies Code	Facies	Sedimentary Structures

SFt	Thin to medium bedded, fine grained sandstone interbedded with laminated shale	Trough cross-bedding, and sometimes with deformational structures
SFm	Thin to medium bedded, very fine to fine grained sandstone alternated with thin bedded mudstone	Horizontal lamination, micro-cross lamination, current ripple cross-lamination, wavy lamination, graded bedding
Slt	Greyish lenticular and thin bedded, fine grained sandstones	Lenticular bedding
Srl	Ripple cross-laminated, fine grained sandstone	Ripple marks, sometimes with climbing ripple marks and low angle cross- lamination
Fc	Black thin to medium bedded carbonaceous mudstone	Rich organic carbon or carbonized plant debris
Fbm	Dark thin bedded bioturbated mudstone	Roots, bioturbation
Fls	Greyish laminated to thin bedded shale	Laminated to thin bedded, pencil cleavage with occasional trace fossil (a type of ichnogenera)
Fms	Greyish laminated to thin bedded mudstone and lenticular siltstone	Laminated, thin bedded, low angle cross bedding, deformational convolute bedding, folding structures
Frh	Greyish laminated mudstones rhythmite	Fine lamination to thin bedded, with laminae consisting of alternating light and dark coloured mudstone layers
Fsc	Greyish laminated shale intercalated with minor lenticular chert	Fine grained, thin laminated with lenticular bedding
Fbc	Black chert	Thin bedded, layers of shale separate the chert beds
Fsm	Laminated shale intercalated with mudstone and lenticular siltstone	Horizontally laminated, lenticular bedding, rich in organic carbon and iron sulphide (pyrite).
Fss	Black laminated to thin bedded shale with lenticular siltstone	Well laminated to thin bedded (at less than 8 cm for a single layer), lenticular bedding, sometimes with minor fine sandstone lenses and very small ripples
Ftb	Greyish mudstone and claystone	Varve bedded, fine lamination, micro-ripple laminations, climbing ripple lamination, convolute lamination and erosional wave mark structures, occasionally with faint striation and feebly grade bedding
Fts	Dark-grey medium to thick bedded shale	Medium to thick bedded, massive beds sometimes faintly laminated and graded

Table 2. Interpretation of the facies association in the Ecca Group.

Facies association (FA)	**Facies code**	**Formation**	**Interpretation of depositional environments**
FA 1: Shale and mudstones intercalated with siltstones	Fls, Fss	Prince Albert	Deep marine environment Mainly deep sea basin sediments
FA 2: Carbonaceous shale, mudstone with subordinate chert and sandstone	Fsc, Fbc, Fsm	Whitehill	Deep marine environment More restricted part of the deep marine (Deep sea floor)
FA 3: Mudstones rhythmite with thin bedded mudstone and lenticular siltstone	Ftb, Fss	Collingham	Deep marine environment. Distal turbidites mixed with falling tuff on the continental slope
FA 4: Greyish medium bedded sandstone intercalated with laminated mudstone	Slt, SFt	Ripon	Deep marine environment. Distal turbidites on the continental slope
FA 5: Dark-grey medium to thick bedded mudstone and siltstone	Fts, Fc		Deep marine environment. Pelagic sediments
FA 6: Thin to medium bedded sandstone Alternated with thin bedded carbonaceous mudstone	Fc, Fbm, Fms, SFm		Deep marine environment. Mainly proximal turbidites

FA 7: Varved mudstone rhythmite intercalated with siltstone and sandstone	Frh, Srl	Fort Brown	Deep marine environment Prodelta deposits

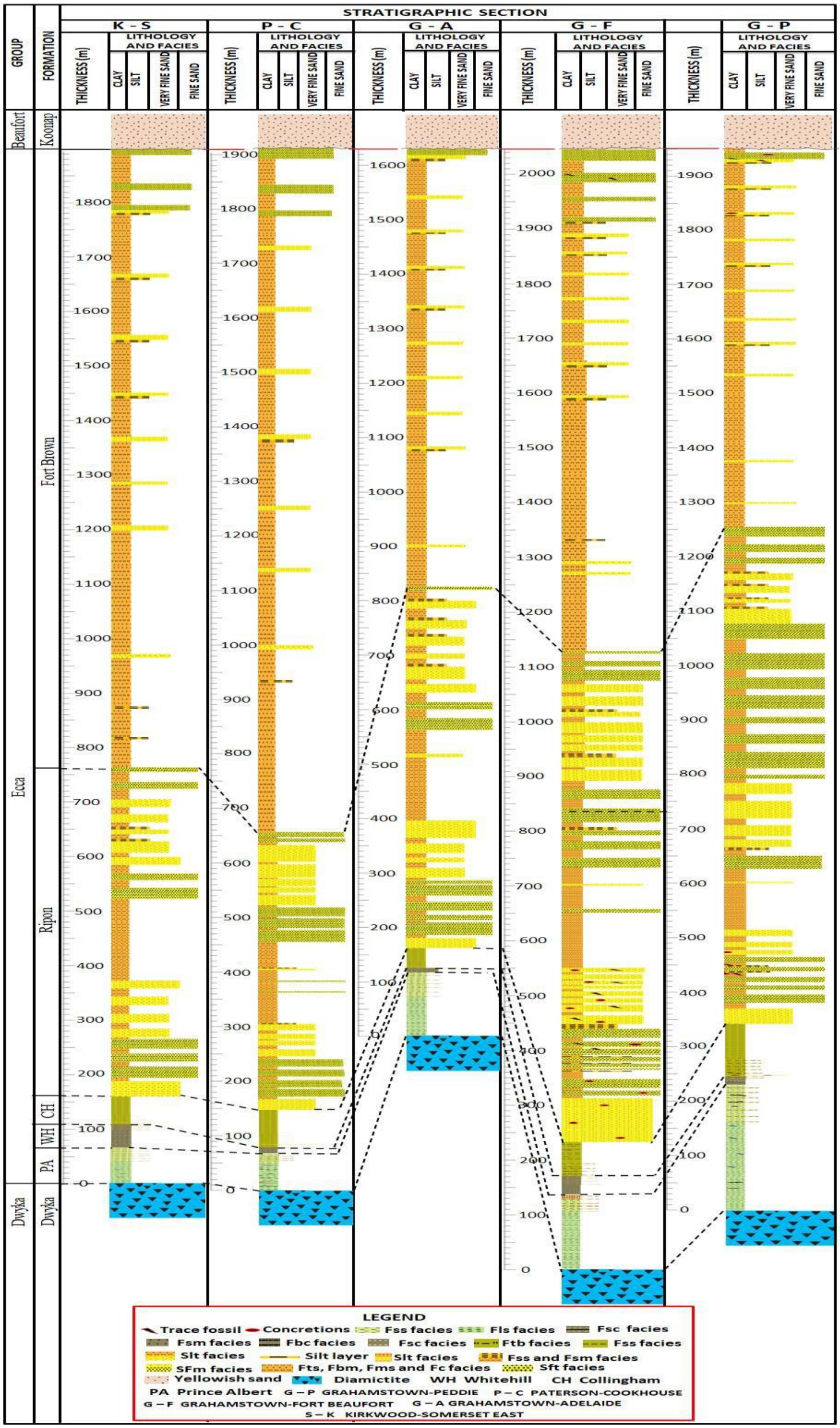

Figure 2. Stratigraphic correlation of the Ecca Group within the study area.

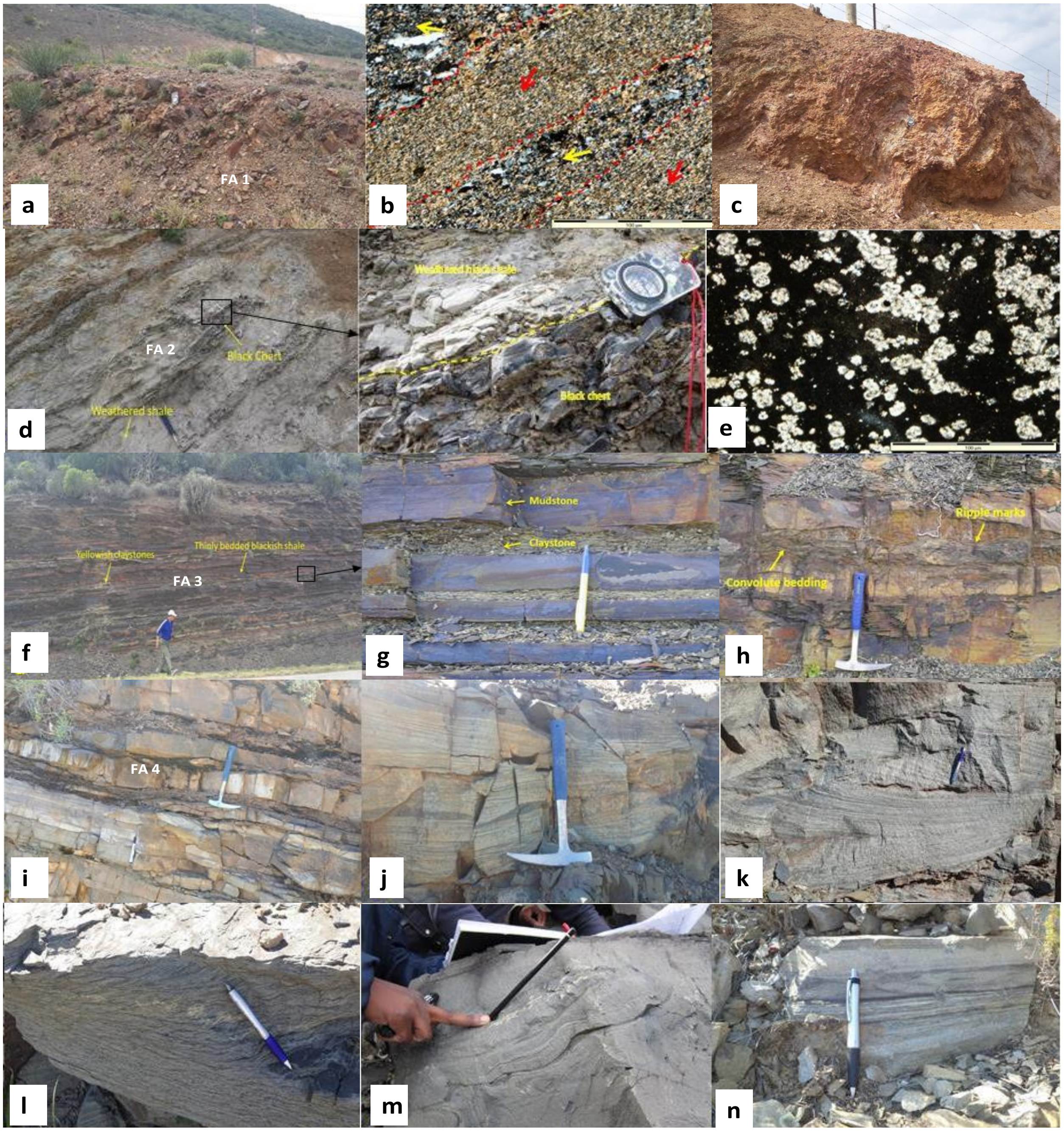

Figure 3. (a) Outcrop photograph showing laminated to thin mudstone and lenticular siltstone (Fss) in the upper part of Prince Albert Formation; (b) Thin section photomicrograph of mudrock showing claystone (red arrows) and siltstone (yellow arrows, more than half are clays) layers; (c) Outcrop photograph showing folded well laminated red stained shale in the upper part of Prince Albert Formation along the Ecca Pass; (d) Outcrop photograph showing laminated greyish shale with subordinate lenticular black chert (Fsc facie); (e) Thin section photomicrograph of mudrock showing dark micrite and white chalcedony nodules in the Whitehill Formation; (f) Outcrop photograph of Collingham Formation showing greyish mudstone and claystone turbidite (Ftb) along Ecca Pass; (g) Outcrop photograph of Collingham Formation showing laminated or thin bedded greyish black mudstone layers and softer yellowish bentonite claystone layers which were thought to be ash-fall tuffs; (h) Convolute bedding and ripple marks in the mudstone of the Collingham Formation along the Ecca Pass; (i) Outcrop photograph showing sandstone intercalated with shale of SFt; (j) Horizontal and faint cross lamination in the sandstone of SFt; (k) Trough cross bedded sandstone of SFt; (l) Climbing laminated sandstone of SFt; (m) Convolute bedding in the mudstone-siltstone of SFt; (o) Plane parallel lamination in the sandstone of SFt.

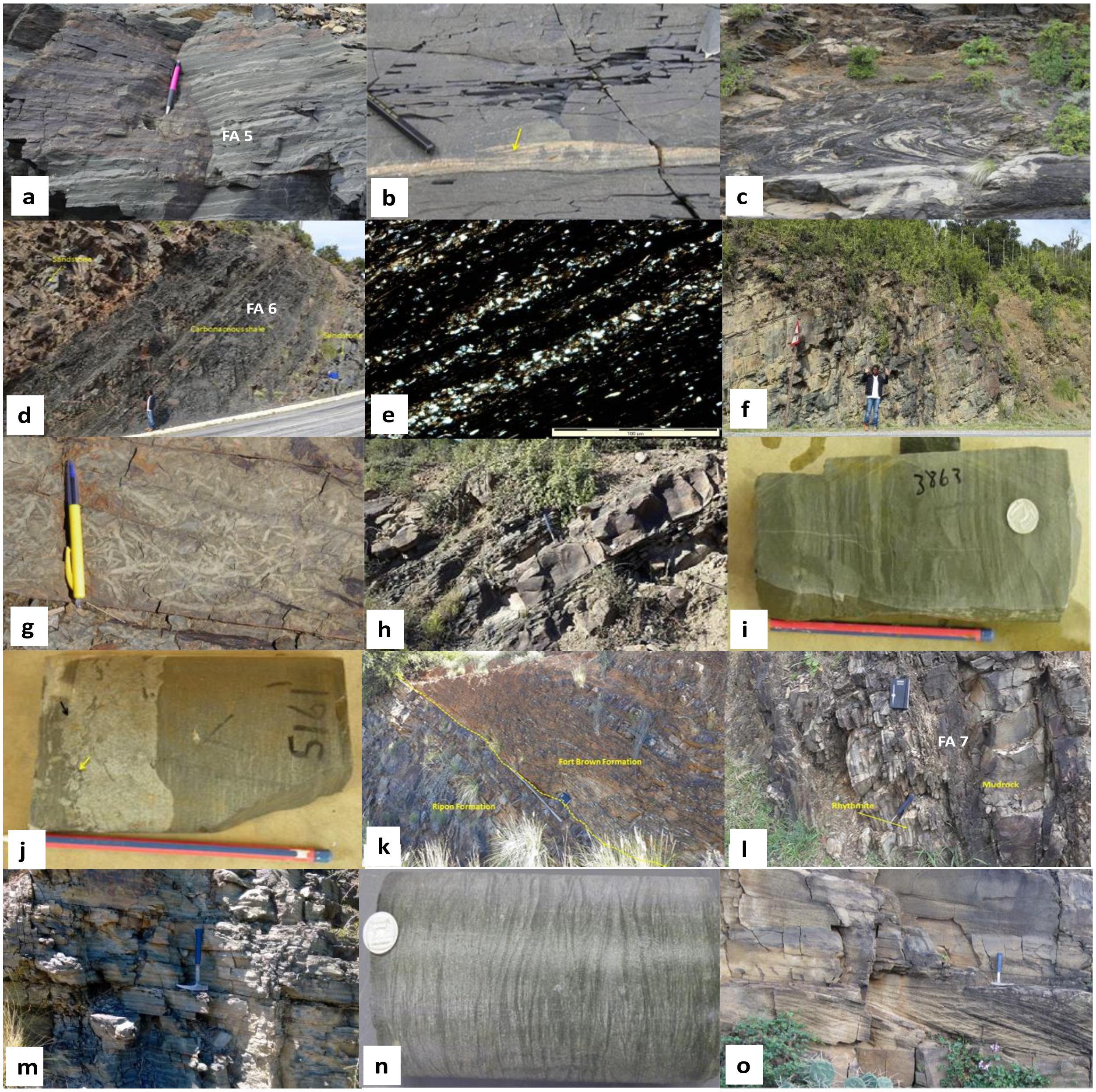

Figure 4. (a) Outcrop photograph showing laminated to thin bedded mudstone (dark colour) intercalated with lenticular siltstone (light colour) (Fms facies); (b) Low angle cross bedding on the lenticular siltstone (arrow) of Fsm facies; (c) Recumbent deformation structures in the greyish mudstone of the Ripon Formation; (d) Outcrop photograph showing dark laminated organic carbon-rich shale with sandstone; (e) Thin section photomicrograph showing carbonaceous shale with mineral grains lying parallel to the lamination planes; (f) Black medium to thick bedded mudstone (Fts) in the Wonderfontein Shale Member of the Ripon Formation; (g) Outcrop photograph showing mudstones of the Fbm facies in the Ripon Formation; (h) Outcrop photograph showing thin to medium bedded sandstone alternated with thin bedded mudstone; (i) Wavy laminated sandstones of SFm; (j) Erosional surface (arrow) in the bottom of sandstone (white) and burrows on the mudstone (dark); (k) Sharp contact between the Fort Brown Formation and the underlying Upper Mudrock-Sandstone Member of the Ripon Formation along national road N10 between Paterson and Cookhouse (Olifantskop Pass); (l) Greyish mudstones rhythmite intercalated with mudrock layers along the Ecca Pass; (m) Photograph showing Frh facies of the Fort Brown Formation along Eca Pass; (n) Wavy ripple-lamination in the sandstone beds of the Upper Member of Fort Brown Formation; (o) Greyish cross-bedded sandstones with wave-ripple marked surface.

Shale and mudstones intercalated with siltstones (FA 1): FA 1 is made up of Fls and Fss facies. It is grayish in color and has a coarsening upward sequence, with the Fls facies forming the lower part and the Fss facies forming the upper part. The contact between Fls and Fss is sharp, but in a few cases it is gradational. FA 1 reaches a maximum thickness of about 145 m along the Ecca Pass, with an average thickness of 131 m in the Eastern Cape Province. FA 1 is interpreted as deep-sea pelagic sediments. The lateral extent, well-developed lamination, fine-grained homogenous nature, as well as the absence of current structures and sandstone intercalation in the FA 1 point to deposition in a relatively deep, undisturbed large body of water environment, possibly a deep sea basin or abyssal plain.

Carbonaceous shale, mudstone with subordinate chert and sandstone (FA 2): FA 2 is approximately 42 m thick in the road cut exposure along the Ecca Pass and 28.6 m thick on average in outcrop exposures in the Eastern Cape Province. It is made up of Fc, Fsc and Fsm facies. The Fc, Fsc, and Fsm facies make up the basal, middle, and upper parts of FA 2, respectively. As a result, they exhibit a coarsening upward sequence. The Fsc and Fsm facies predominate in FA 2, and in a few cases, the Fsm facies contains possible water escape or deformation structure. Fc and Fsc make gradational contact, whereas Fc and Fsm make a sharp contact. The presence of organic carbon in FA 2 suggests that the deep-sea basin was anoxic or under reducing conditions. The chert layers suggest a chemical or biochemical precipitation in a deep sea environment. The black colour, fine-grain size, and laminated structure in FA 2 indicate deposition by suspension sedimentation in a low-energy, deep marine environment, presumably a deep sea floor or deep sea plain environment. Thus, FA 2 represents deep marine or pelagic basin deposits.

Mudstones rhythmite with thin bedded mudstone and lenticular siltstone (FA 3):
FA 3 is made up of the Ftb and Fss facies. Gradational contact exists between the Ftb and Fss facies. FA 3 depicts a fining upward sequence, with the Ftb facies at the bottom and the Fss facies at the top. In road cut exposure along the Ecca Pass, FA 1 reaches a maximum thickness of about 60 m, with an average thickness of 64 m in the Eastern Cape Province. FA 3 is interpreted as the suspension settling of mudstones intermixed with distal turbidites on the continental slope. The laterally extensive individual beds, fine-grained characteristics, and absence of current structures in the FA 3 point to deposition in relatively deep water, probably a deep-sea basin. The regular alternation of thin bedded mudstones and claystones (Ftb) represents a classic rhythmite facies, implying that the deposits were most likely turbidite sediments. The turbidity current that transported the sediments into the deep basin is thought to have been non-channelized or to have spread across a wide front from a depositionally active prograding slope, as proposed by Kingsley (1977), rather than moving along the channels.

Greyish medium bedded sandstone intercalated with laminated mudstone (FA 4): FA 4 is made up of Slt and SFt facies. It is greyish in colour and covers the Lower Member (Pluto Vale Member) of the Ripon Formation. FA 4 is composed of greyish lenticular and thin bedded sandstone facies (Slt) at the base, and thin to medium bedded sandstone interbedded with laminated mudstone facies (Slt) at the top (SFt). The contact between Slt and SFt facies is sharp. FA 4 is interpreted as lower continental slope distal outer fan turbidites (lobe region). The presence of depositional and deformational structures in FA 4 such as current ripple lamination, convolute bedding, and graded bedding indicates that the sandstone beds are of turbidity-current origin. The presence of thick convolute bedding in the basal sandstone bed indicates a rapid rate of deposition; the thickness of the overlying sandstone beds increases just above the bed where convolute bedding occurred, indicating a rapid rate of sediment supply from the source area. Turbidity currents or a large river system are thought to have eroded/transported the pelagic sediments down the slope. The general thickening upward sequence of FA 4 also suggests that the depositional lobe prograde, as marginal facies in depositional lobes are expected or thought to be thinner bedded than those near the lobe's apex.

Dark-grey medium to thick bedded mudstone and siltstone (FA 5):
The Middle Member (Wonderfontein Shale Member) of the Ripon Formation largely consists of dark-grey, medium- to thick bedded mudstone and siltstone (FA 5). FA 5 is made up of Fts and Fc facies and dark-grey colour is due to their enrichment in organic carbon. The homogenous shale in FA 5 split perfectly along well-defined bedding planes. FA 5 signifies pelagic sedimentation or low-energy periodic sedimentation with low-density turbidity current deposition (moderate depth setting) on the middle-upper continental slope. Kingsley (1977) reported that FA 5 marks a recession in the supply of sediments, possibly during a period of small transgression of the southern basin edge. The parallel horizontally laminated shale suggests turbulent suspension in a relatively deep water environment with frequent hydrodynamic energy variation. Decreased organic-carbon content in FA 5 points to increased clastic dilution as well as an increased rate of consumption by benthic organisms.

Thin to medium bedded sandstone alternated with thin bedded carbonaceous mudstone (FA 6): The Upper Member (Trumpeters Member) of the Ripon Formation is composed of FA 6, which includes the facies Fc, Fbm, Fms, and SFm. FA 6 is generally greyish-black in color, with Fc and Fbm, Fms, and SFm facies in the basal, middle, and upper parts, respectively. The SFm facies encompasses the majority of the Trumpeters Member in the Ripon Formation (FA 6). The majority of the mudstones are thinly bedded and contain plant fossils. The thickness of mudstone beds increases from about 0.4 m in the lower part of FA 6 to about 4.3 m in the upper part. In most cases, the upper and lower boundaries between the mudstone and sandstone are sharp and occasionally irregular. The alternation of sandstone and mudstone beds indicates that deposition occurred under fluctuating energy conditions. Laminations and flat beds in mudstones indicate calm waters and slow sediment settling, whereas thin to medium beds in sandstone layers indicate rapid deposition and high water energy during deposition. The presence of parallel laminated shale in FA 6 indicates that the sediments were most likely deposited in floodplain environments with frequent variations in hydrodynamic energy. The presence of carbonaceous mudstone indicates that vegetation grew slowly in the depositional environment. The trace fossils/burrows may point to shallow waters in the depositional basin, allowing plants to thrive in the presence of sunlight. The organic carbon-rich shale and mudstone were able to accumulate in the flood plain swamps. The medium-bedded mudstone in FA 6 was formed by the aggrading of the braided streams, which resulted in the deposition of thick, fine-grained sandstone in the river channel. FA 6 is interpreted as proximal turbidites on the continental shelf.

Varved mudstone rhythmite intercalated with sandstone (FA 7): FA 7 makes up the entire Fort Brown Formation. It is made up of variegated, well-laminated, thin-bedded greenish-grey mudstone rhythmite (Frh) with minor sandstone intercalation (Srl). The Frh facies dominates the lower part of FA 7, while mudstones are intercalated with the Srl facies in the upper part of FA 7. As a result, they exhibit a coarsening upward sequence. Furthermore, the thickness of the sandstone layers increases upward. The upper part of FA 7 contains several finely laminated siltstones and a few medium-bedded sandstones. The seasonal freezing of the lake and the regular alternation of layers of light (coarser) and dark (finer) sediments (varved rhythmite) may indicate a fluctuating sedimentary supply. The FA 7 is believed to have been deposited in a freshwater lacustrine environment due to the existence of a well-developed varved rhythmite structure and seat-earth layers. The abundance of finely laminated siltstone in the upper part of FA 7 points to continuous sedimentation from suspension settling. Consequently, the intercalated sandstone beds were deposited during periods of high energy floods when there was an influx of fresh fluvial sediments. It is believed that, in places where there was sufficient sand, ripple marks were formed and these rippled sandstone lenses point to periodic influxes and depositions of current-borne sediment that were later affected by wave action. The sediments must have been deposited below the wave base because wave-formed rippled marks are only found in the upper part of FA 7. The presence of wave ripples in the upper part of FA 7, as well as the general coarsening upward sequence of FA 7, all point to slightly more proximal turbidites in the prodelta setting and basin shallowing as a result of continued sediment accumulation or deposition. FA 7 could be prodelta lacustrine deposits.

Depositional environment

Detailed analysis of the fourteen lithofacies types and seven identified facies associations in the Ecca Group clearly point to three main depositional environments, namely, deep marine, shallow marine and lacustrine depositional environments. The deep marine environment consist of deep plain sediments (FA 1: Shale and mudstones intercalated with siltstones, Prince Albert Formation), restricted deep-basin with hydrothermal silica (chert) sediments (FA 2: Carbonaceous shale, mudstone with subordinate chert and sandstone, Whitehill Formation), continental slope turbidite deposits (FA 3: Mudstones rhythmite with thin bedded mudstone and lenticular siltstone, Collingham Formation), distal outer fan turbidites on the lower continental slope (FA 4: Greyish medium bedded sandstone intercalated with laminated mudstone, Lower Member of the Ripon Formation) and pelagic sediments on the middle - upper continental slope (FA 5: Dark-grey medium to thick bedded mudstone and siltstone, Middle Member of the Ripon Formation). The shallow marine environment is made up of continental shelf-proximal turbidites (FA 6: Thin to medium bedded sandstone alternated with thin bedded carbonaceous mudstone, Upper Member of the Ripon Formation). The lacustrine environment consists of more proximal turbidites in the prodelta setting or distal turbidites (FA 7: Varved mudstone rhythmite intercalated with sandstone). The Ecca sequence shows a progressive change upwards from a deep-water marine environment (basin plain-continental slope) to a shallow marine environment (continental shelf), and finally to a freshwater lacustrine environment.

From the bottom up to the top of the Ecca succession, it is believed that the Prince Albert (FA 1) and Whitehill (FA 2) Formations were deposited in a deep-water marine environment. The latter was deposited in a more restricted part of the deep marine water, thus allowing the chert layers in the carbonaceous shale of FA 2 to develop. The source of the silica for the chert formation probably came from underwater hydrothermal or volcanic silica. The overlying Collingham Formation (FA 3) is interpreted as the suspension settling of mud intermixed with distal turbidites on the continental slope. The classic rhythmite facies in FA 3 indicate that the deposits are of turbidite origin and formed in a reducing environment, most likely on a marine continental slope. This Ecca turbidite sequence is thought to have experienced a major volcanic event; thus, the mudstone and bentonite claystone turbidite were accumulated on the basin floor. The presence of volcanic materials in FA 3 points to volcanic activity near the source area and leads to the formation of bentonitic claystone. These volcanic materials are thought to ash-fall in the sea due to the fact that the thin layers of the volcanic materials can be traced over a relatively long distance. If the materials were deposited by a turbidity current, they would have intermixed with other detrital materials. But since the yellowish material retained its pure volcanic nature (not intermixed), it is believed to be of ash-fall origin. The distal turbidites and volcanic ash layers in FA 3 is the only layer of the Ecca Group that can be directly linked to the volcanism with evidence of active volcanic ash. There is possibility that these tuff beds are products of the Permian silicic-andesitic and volcanoes (Veevers et al., 1994; Wickens, 1994). Paleocurrent, thickness and provenance studies by Kingsley (1977) also indicate that the Ecca sequence was sourced from the south-southeast and deposited in an east-west trending Karoo Basin.

The sandstone of the Lower Member (Pluto Vale Member) of the Ripon Formation (FA 4) is interpreted as distal turbidites on the lower continental slope. Most of the member is occupied by FA 4 due to slumping of sediments over a wide area. The multiple cyclicity of alternating sandstone and mudstone layers in FA 4 points to the fact that the turbidites are essentially related to autocyclic processes like fan progradation or recession and lobe-switching, among others (Walker, 1978). The overlying shale unit (Wonderfontein Shale Member) of the Ripon Formation (FA 5) represents low-energy sedimentation in a continental slope environment. This indicates a decrease in sediment supply, possibly as a result of a period of minor transgressions along the Karoo Basin's southern edge. The shallow marine environment is mainly made up of proximal turbidites on the continental shelf (FA 6, Upper Member of the Ripon Formation), while the lacustrine environment consists of freshwater lacustrine deposits (FA 7, Fort Brown Formation). The varve rhythmite in the lower part of FA 7 is believed to represent lake (lacustrine) deposits that were formed as a result of aggradation and possibly some progradation during successive floods. A well-developed varve is distinguished by the regular alternation of varve layers of light and dark sediments, which exhibit typically varved rhythmite layer structure, indicating a fluctuation of seasonal sediment supply and deposition.

Kingsley (1977) documented that this flooding period is noted by the gradual increase in the rate of sedimentation as well as the shallowing of the environment when a fast or rapid regression or regressive episode occurs, which is characterized by the presence of relatively shallow-water muds, silts and sands. The abundance of finely laminated siltstone intercalated in mudstone in the upper part of FA 7 points to sedimentation from suspension settling shifting to traction settling, and the intercalated sandstone beds were deposited during periods of high-energy floods when there was an influx of fluvial sediments. The upward movement of sandstone interbeds, the presence of wave ripples, and the general coarsening upward sequence all point to more proximal sedimentation and shallowing of the basin as a result of continued sediment accumulation or deposition. The Beaufort Group, which overlies the Ecca Group, is primarily composed of sandstones with minor shale. It is believed that the group was deposited in a fluvial environment and could be linked to the continuous dropping or retreating of the water as a result of sea-level dropping in the Karoo Basin. Thus, the depositional environment subsequently changed from a marine setting to deltaic and then continental inland fluvial environments. This also agrees with the findings of Catuneanu and Elango (2001) that the deeper marine facies of the early Ecca Group were accumulated during the under-filled phase of the foreland system, whereas 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 of the Beaufort Group.

Facies model

The facies model is thought to be a general summary of a particular sedimentary process and depositional environment. For the interpretation of depositional environments, internal sedimentary structures, boundary conditions lithofacies, their interrelationships, sequences, and facies associations are taken into account. Likewise, in the studied portions of the southeastern Karoo deposits (Ecca sediments), the sedimentation commenced with the deposition of mudstones intercalated with siltstones and carbonaceous shale subordinate to chert and sandstone in the deep marine environment. On the lower continental slope, this sequence is overlain by mudstone rhythmites with thin bedded mudstone and lenticular siltstone. In addition, the overlying medium-bedded sandstone is intercalated with laminated mudstone, and medium- to thick-bedded mudstone and siltstone are both deposited on the middle to upper continental slope. This sequence is overlain by thin to medium-bedded sandstone alternated with thin-bedded carbonaceous mudstone deposited on the continental shelf (shallow marine environment). Subsequently, the varved mudstone rhythmite intercalated with sandstone (the Fort Brown Formation) accumulated in a lacustrine environment. Herein, a facies model for the depositional environment of the Ecca sediments is expressed as a geographical and depositional process restoration that shows deep marine basin and turbidity dynamics as well as their deposits by using a simplified depositional model for the Ecca sediments in the southeastern Karoo Basin. Most of the Ecca turbidites occurred at the base of the continental slope, resulting in the formation of a turbidite fan complex. The fan was differentiated into an outer fan (distal fan), midfan and proximal fan consisting of hemipelagic sediments that enclose large sandstone bodies resulting from the filling of fan valleys. This was done in accordance with Walker (1978) who attempted to combine the models of Normark (1970) and Mutti and Ricci Lucchi (1972) on the basis of research on facies, facies models and modern stratigraphic concepts. The proposed depositional model for the Ecca sediments in the study area is depicted in Figure 5. The inferred depositional environments are in agreement with the works of several researchers (Johnson, 1991; Kingsley, 1981; Smith, 1995; Johnson, 1996; 2006) that previously documented depositional environments of the Ecca sediments in southern Africa.

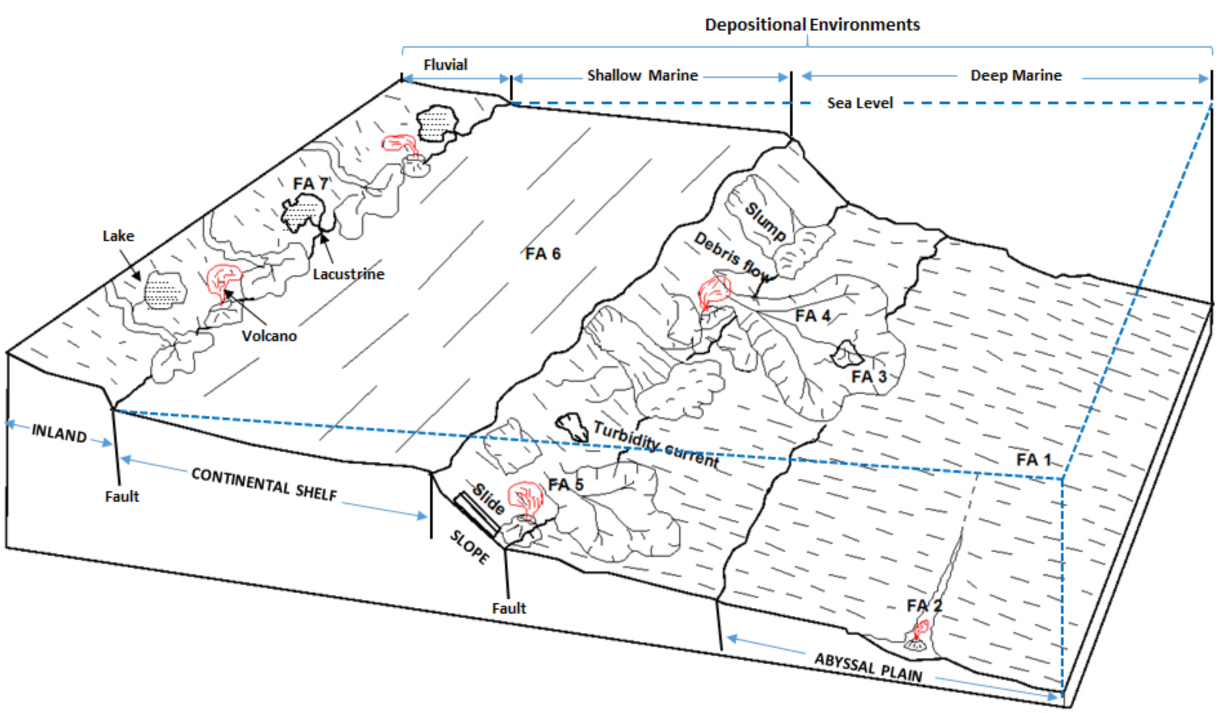

Figure 5. Proposed depositional model for the Ecca sediments in the study area.

Conclusions

The study on the sedimentary facies and depositional environments of the Ecca Group in the Eastern Cape Province of South Africa was performed to give new insight that will enhance the understanding of the sediment characteristics and the depositional environment of the Ecca sequence. The results obtained from this investigation demonstrate detailed facies associations and different depositional environments present within the Ecca Group in the Karoo Supergroup of South Africa. A total of fourteen sedimentary facies and seven facies associations have been identified, which represent the gradual change of sea level from deep marine to shallow and then to lacustrine environments. The seven distinct facies associations (FAs) are: shale and mudstones intercalated with siltstones (FA 1), carbonaceous shale, mudstone with subordinate chert and sandstone (FA 2), mudstones rhythmite with thin bedded mudstone and lenticular siltstone (FA 3), greyish medium bedded sandstone intercalated with laminated mudstone (FA 4), dark-grey medium to thick bedded mudstone and siltstone (FA 5), thin to medium bedded sandstone (FA 6) and varved mudstone rhythmite intercalated with sandstone (FA 7). A detailed examination of lithofacies types and facies assemblages in the Ecca Group reveals four deposition environments, namely the deep marine basin, turbidite, shallow marine, and lacustrine environments, which form a gradually regression sequence as a result of sea-level dropping during basin development processes.

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