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Research Article

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Sedimentary facies, stratigraphy, and depositional environments of the Ecca Group, Karoo Supergroup in the Eastern Cape Province of South Africa

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Abstract: The stratigraphy of the Ecca Group has been subdivided into the Prince Albert, Whitehill, Collingham, Ripon, and Fort Brown Formations in the Eastern Cape Province, South Africa. In this article, we present detailed stratigraphic and facies analyses of borehole data and road-cut exposures of the Ecca Group along regional roads R67 (Ecca Pass), R344 (Grahamstown-Adelaide), R350 (Kirkwood-Somerset East), and national roads N2 (Grahamstown-Peddie) and N10 (Paterson-Cookhouse). Facies analysis of the Ecca Group in the study area was performed to deduce their depositional environments. Based on the lithological and facies characteristics, the stratigraphy of the Prince Albert, Whitehill, Collingham, and Fort Brown Formations is now subdivided into two informal members each, while the Ripon Formation is subdivided into three members. A total of twelve lithofacies were identified in the Ecca Group and were further grouped into seven distinct facies associations (FAs), namely: Laminated to thin-bedded black-greyish shale and mudstones (FA 1); Laminated black-greyish shale and interbedded chert (FA 2); Mudstone rhythmite and thin beds of tuff alternation (FA 3); Thin to thick-bedded sandstone and mudstone intercalation (FA 4); Medium to thick-bedded dark-grey shale (FA 5); Alternated thin to medium-bedded sandstone and mudstone (FA 6); and Varved mudstone rhythmite and sandstone intercalation (FA 7). The FAs revealed gradually change of sea-level from deep marine (FA 1, FA 2, FA 3 and FA 4, FA 5, and FA 6) to prodelta environment (FA 7). This implies that the main Karoo Basin was gradually filling up with Ecca sediments, resulting in the gradual shallowing up of the water depth of the depositional basin.

Keywords: stratigraphy, lithofacies, depositional environment, Ecca Group, Karoo Supergroup

1 Introduction

The Karoo is a semi-arid region, located in the southeast in southern Africa, and contains the thickest and complete stratigraphic sequence among the Late Carboniferous – Early Jurassic aged basins that formed in Gondwana [1]. The main Karoo Basin of South Africa covers some 300,000 km^2 and represents about 120 Ma of sedimentation spanning from about 300 to 180 Ma; the Karoo rocks cover two-third of the area of South Africa [2]. It is traditionally thought to be a retro-arc foreland basin [3,4] that developed in front of the Cape Fold Belt in response to crustal shortening and thickening as a result of the Late Paleozoic-Early Mesozoic subduction episode of the palaeo-Pacific plate beneath the Gondwana plate [5,6]. The beginning of sedimentation in the Karoo is placed in the Late Carboniferous (about 300 Ma) after a major inversion tectonics event that occurred along the southern margin of the supercontinent and resulted in the assembly of Pangea [7]. Sedimentation in the main Karoo Basin continued across Gondwana until the Early Jurassic (about 183 Ma) when formation of the Karoo large igneous province (i.e. dolerite intrusions, basalt extrusion) took place.

The Karoo Basin underwent episodes of subsidence and sedimentation within the interior of Gondwana [8,9], with depocentres changing from a passive continental margin in the Early Paleozoic to a landlocked foreland basin during the Permo-Triassic [10]. To date, there is

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controversy on the development of the Karoo Basin and several models have been proposed for the formation of the basin. The interpretation of the evolution and tectonic setting of the Karoo Basin varies from a transient hypothetical mantle plume related model [11]. The basin was reported to be a retro-arc foreland basin formed as a result of shallow angle subduction of the palaeo-Pacific plate underneath the Gondwana supercontinent [4,12,13]. Likewise, the basin was interpreted as a sag-like basin, with subsidence during the deep-water phase of the basin controlled by mantle flow over a complex arrangement of basement blocks [8,9]. In addition, the basin was envisaged to be an extensional back-arc basin formed due to oblique subduction of the palaeo-Pacific plate under western Gondwana [14], to a thin-skinned fold belt that developed from collisional tectonics and distant subduction to the south [15].

The Karoo Supergroup is stratigraphically divided into five main groups, namely, Dwyka, Ecca, Beaufort, Stormberg, and Drakensberg groups, respectively. The geometry of the sedimentary fill is reported to be a wedge shape, which is usually associated with foreland successions [12]. This sedimentary fill comprises of the Dwyka (Late Carboniferous – Early Permian; ~302–289 Ma), Ecca (Early – Late Permian; ~289–253 Ma), Beaufort (Late Permian – Triassic; ~253–237 Ma), and the Stormberg Group (Late Triassic – Early Jurassic; ~230–183 Ma). The palaeoenvironmental settings of the Karoo Supergroup revealed changing climatic conditions as Gondwanaland drifted from high latitudes towards the equator [8], varying from glacial and partly marine in the Dwyka Group, to marine in the Ecca Group, then to fluvial and aeolian in the overlying Beaufort and Stormberg Groups, respectively [10,16]. During the deposition of the Dwyka and Ecca Groups, an interior seaway transgressed the Karoo Basin, but it totally regressed from the confines of the preserved basin at the end of Ecca time interval [12]. Stratigraphy of the Ecca Group has been previously investigated on a regional scale by several authors [13,16–20]; this led to the subdivision of the Ecca Group into the Prince Albert, Whitehill, Collingham, Ripon, and Fort Brown Formations. These formations outcrop in the study area (Figure 1) and despite the fact that there is relatively lack of detailed paleontological information in the rocks of the Ecca Group, stratigraphic correlations can still be established based on physical characteristics of the rocks like similarities in lithology, colour, thickness, and sedimentary structures that are manifested in the rocks.

The exposure quality of the Ecca Group is considerably better along road cuttings and easily accessible when compared to outcrops in private farms and game reserves. Thus, in this study, we carried out a detailed stratigraphic analysis on the road-cut exposures of the Ecca Group along regional roads R67 (Ecca Pass; Grahamstown-Fort Beaufort), R344 (Grahamstown-Adelaide), R350 (North of Kirkwood-Somerset East), and national roads N2 (Grahamstown-Peddie) and N10 (Paterson-Cookhouse) (Figure 1) in order to reveal the lateral and vertical changes in lithological features within each formation of the Ecca Group, subdivide the formations into informal members based on the lithological features, and correlate the measured stratigraphic sections in the area. The reason for subdividing the existing stratigraphy into informal members is to provide a more detailed information about the main characteristics of lithologies of the Ecca Group, their thicknesses, associated sedimentary structures, and any perturbations of the early basin floor. Due to insufficient information on the facies analysis of the Ecca Group, the depositional environment of the group is still debatable or not fully established to date. Hence, this research work is also undertaken to provide detailed sedimentary facies analysis of the Ecca Group in the Eastern Cape Province of South Africa. In this article, we provide a more detailed information on the main characteristics of lithologies, sedimentary structures, and vertical sequence patterns and depositional environments of the Ecca Group. The result or dataset presented in this article could be used to tease out an interpretation of the sedimentary history, evolution of the basin, and the advancing clastic margin which would have a higher scientific impact by looking at these correlation panels and discussing the trends seen.

2 Stratigraphic framework

The stratigraphy of the main Karoo Basin is complex and this complexity is related to its mode of origin and varied depositional environments such as deep-marine mudstone, shallow marine turbidite, and submarine fan deposit from specific source areas [7]. The Permian Ecca Group overlies the Upper Carboniferous to Lower Permian Dwyka Group and underlies the Upper Permian-Middle Triassic Beaufort Group [7]. The base of the Ecca Group is defined at the top of the glacial-marine succession of the Dwyka Group (Figure 2), predominantly of mudstones, siltstones, and sandstones, with occasional conglomerates and coal [22]. The deeper marine facies of the Dwyka and lower Ecca Groups accumulated during the under-filled phase of the Karoo foreland system, while the shallow marine facies of the upper Ecca Group matched with the filled phase of the basin and was subsequently followed by fluvial-dominated overfilled phase [18]. The stratigraphy of the Karoo Supergroup in the northern (distal) region differs from

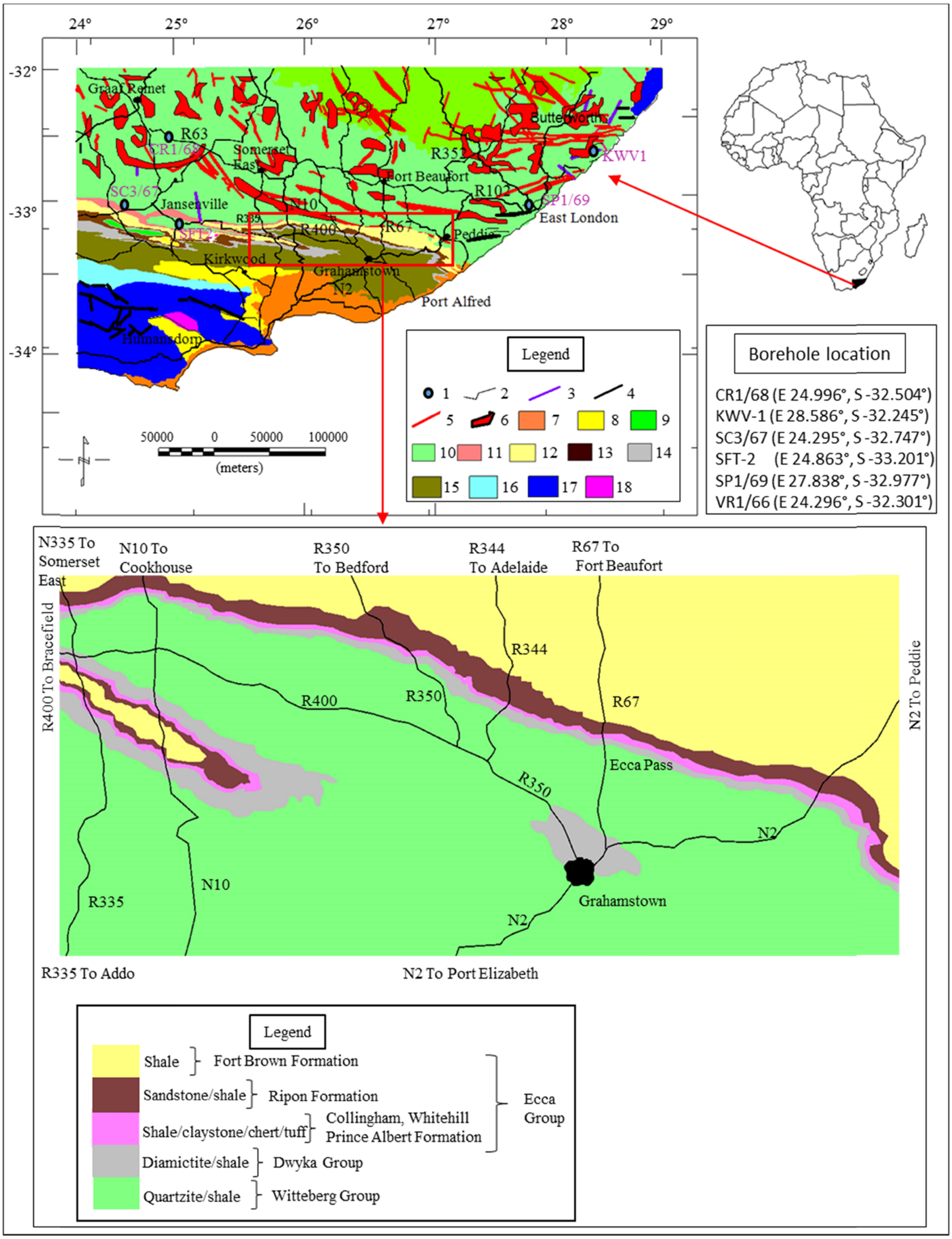

Figure 1: Geological map of the study area showing the position of the outcrops as well as boreholes (after [21]). Note: In the insert map; 1. Borehole; 2. Road; 3. Lineament; 4. Fault; 5. Dolerite dyke; 6. Dolerite sill; 7. Cenozoic deposits; 8. Uitenhage and Zululand Groups; 9. Tarkastad Subgroup; 10. Adelaide Subgroup; 11. Waterford Formation; 12. Fort Brown Formation; 13. Collingham, Whitehill, and Prince Albert Formations; 14. Dwyka Group; 15. Witteberg Group; 16. Bokkeveld Group; 17. Table Mountain and Natal Groups; 18. Malmesburg, Kaaismans, Gamboos, and Congo Caves Groups. The final depth of boreholes CR1/68, KWV-1, SC6/67, SFT-2, SP1/69, and VR1/66 are approximately 3,750, 2,353, 2,400, 300, 3,760, and 2,800 m, respectively.

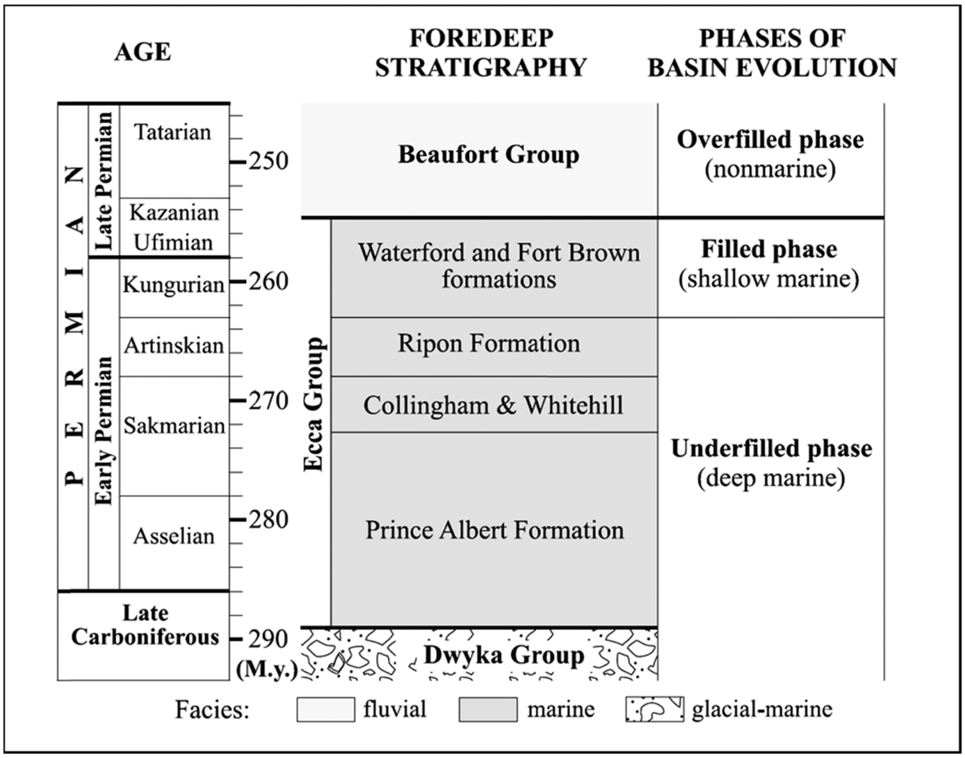

Figure 2: Summary of the main stratigraphic subdivisions of the Ecca Group [12].

those in the southern (proximal) region. The stratigraphic variation within the basin reveals different tectonic/evolutionary history across the flexural hinge line of the foreland system [12]. They further explained that a deep-marine depositional environment must have controlled the processes of sedimentation in the south, which led to the accumulation of the glacial-marine Dwyka tillite with dropstones, as well as the basin floor pelagic sediments of the lower Ecca Group.

Sedimentation in the southern region (proximal) of the basin continued with the deposition of the shallow marine deposits that include the shelf and marginal marine facies of the upper Ecca Group. In relation to sediment deposition in the south, sediment aggradation occurred in the northern (distal) region of the basin and in the shallow marine and non-marine environments [12]. It is estimated that the group attained a thickness of about 3,000 m in the southern part of the main Karoo Basin and can be subdivided into five formations, namely, the Prince Albert Formation, Whitehill Formation, Collingham Formation, Ripon Formation, and Fort Brown Formation [20]. The marine clays and mudstones of the Prince Albert Formation were deposited on the diamictites of the Dwyka Group in the southern part of the Karoo Basin [4]. This was followed by the carbonaceous shale of the Whitehill Formation. Subsequently, there is Collingham Formation that is made up of persistent grey shales alternating with yellow-claystones. The sandstones and shales of the Ripon and Fort Brown Formations were deposited on the submarine fans and shelf, respectively [16]. The Dwyka and Ecca Groups were deposited during the seaway transgression into the interior part of the southern Karoo Basin [23]. Nonetheless, at the end of Ecca time, complete regression in the Ecca Group occurred from the limits of the preserved basin [4]. The change from glacial (Dwyka) to post-glacial (lower Ecca) sedimentary environments occurred first in the southwestern part followed by the northern and eastern parts of the Karoo Basin [16]. The deep and shallow water environments with a cold climate prevailed during the Ecca times, with coal forming in alluvial fan, fan delta, and fluvial systems of the formation [24].

3 Materials and method

The area investigated was carefully mapped and the observed sedimentary structures in the outcrops were described and measured and photographs were taken using a digital camera. The thicknesses of the stratigraphic units were measured perpendicular to the strike of the outcrop using a measuring tape. Stratigraphic subdivision of the formations into members was based on similarities in lithological features. Fieldwork was limited to road-cut exposures because of the excellent quality of the road-cut exposures. The stratigraphic section along regional road R67 (Ecca Pass; Grahamstown-Fort Beaufort Road) represents the general succession of the formations of the Ecca Group. However, references will be made to other locations where interesting features and lithological changes are observed. Borehole log studies were also undertaken in order to understand lithostratigraphic correlations and ascertain the thickness change of the Ecca Group across the study area. A total of four boreholes that include the Cranemere borehole (CR 1/68), Springfontein borehole (SP 1/69), the incomplete Vrede borehole (VR 1/66), and Schietfontein borehole (SC 3/67) were logged and stratigraphically correlated. The borehole log for the Vrede borehole (VR 1/66) is not complete or missing, thus lack detailed stratigraphic information, and only the available part of the borehole data could be applied to stratigraphic studies. Generally, the borehole core log descriptions give little information on the sedimentary structures and characteristics of the rocks, therefore they were only used for stratigraphic correlation and thickness determination.

Facies analysis of the stratigraphic formations was carried out using a modified version of lithofacies classification scheme by refs. [25–27]. The scheme is based on a bi-part lithofacies coding system. The first part denotes lithology (G, gravel; S, sand; F, fine), whereas the second letter denotes distinctive sedimentary structure or texture of each lithofacies. In this study, a facies is a restricted lithofacies with specific sedimentary structures and constitutes a part of a stratigraphic unit with characteristics that significantly differ from other parts of the unit and are attributed to depositional features that point to a specific depositional process or combinations of processes. On a small scale, each of the stratigraphic member or formation is associated with a distinctive sedimentary facies based on their lithological characteristics and sedimentary structures. The description of the individual facies is based on the scheme proposed by refs. [28–31]. 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 palaeo-environments. In addition, 62 representative thin sections of 115 rock and core samples (67 sandstones and 48 mudrocks) were prepared and studied under optical microscope to aid for the identification and distinguish different lithofacies, particularly to determine mineral compositions, rock textures, and shape and size of grains and cements.

4 Results

The Ecca Group in the Eastern Cape Province consists of dark-grey shale, sandstones, and mudrock with subordinate chert and yellowish claystones (tuff). Tuff is an igneous rock that forms from the products of an explosive volcanic eruption. These tuff deposits are more likely to be exclusively made from fine volcanic ash particles, carried by the wind. The lithofacies in the different formations of the Ecca Group were identified based on different lithologies and sedimentary structures. Fourteen lithofacies were identified and their characteristics are described in Table 1. Seven distinct FA were recognized and interpreted based on the identified lithofacies type and internal and external geometry in the formations. The characteristics of the FA are summarized in the Table 2. The group has been subdivided into five formations, namely, the Prince Albert, Whitehill, Collingham, Ripon, and Fort Brown formations. These formations were further subdivided into informal members. The members are named after the main lithologies because the study area is situated in remote areas and the nearby locality (village) has been used when subdividing the Ecca Group into different formations by previous researchers. The marker units for subdividing the Ecca Group are the white bands in the Whitehill Formation, yellowish material that are assumed to be ash-fall tuffs in the Collingham Formation, rhythmite units in the Ripon Formation, and the varved rhythmite unit of the Fort Brown Formation. The stratigraphic member names assigned to each formation in this study are the newly established members for the Ecca Group and are proposed for the first time in the studies of the Ecca Group.

4.1 Prince Albert Formation

The Prince Albert Formation is present along regional road R67 (Ecca Pass; Grahamstown – Fort Beaufort) and is the basal formation of the Ecca Group. It consists predominantly of mudrock and has a measured thickness of about 142.7 m. The Prince Albert shale disconformably overlies the diamictites of the Dwyka Group. The shales are well-laminated to thin-bedded (Fls) and shows pencil cleavage (Figure 3). The strata generally have dip angle of about 38° and dip direction of 22°. The lower part of the formation (0 to 112.5 m) is mostly composed of weathered greenish-grey shale. The facies (Fls) is well-developed in the basal part of Prince Albert Formation and is laterally extensive throughout the study area, covering several

Table 1: Lithofacies identified in the Ecca Group [32]

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, or ripple lamination, sometimes with climbing ripple marks and low angle (<10°) 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 well-laminated, lenticular bedding, rich in organic carbon as well as 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: Facies associations identified 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

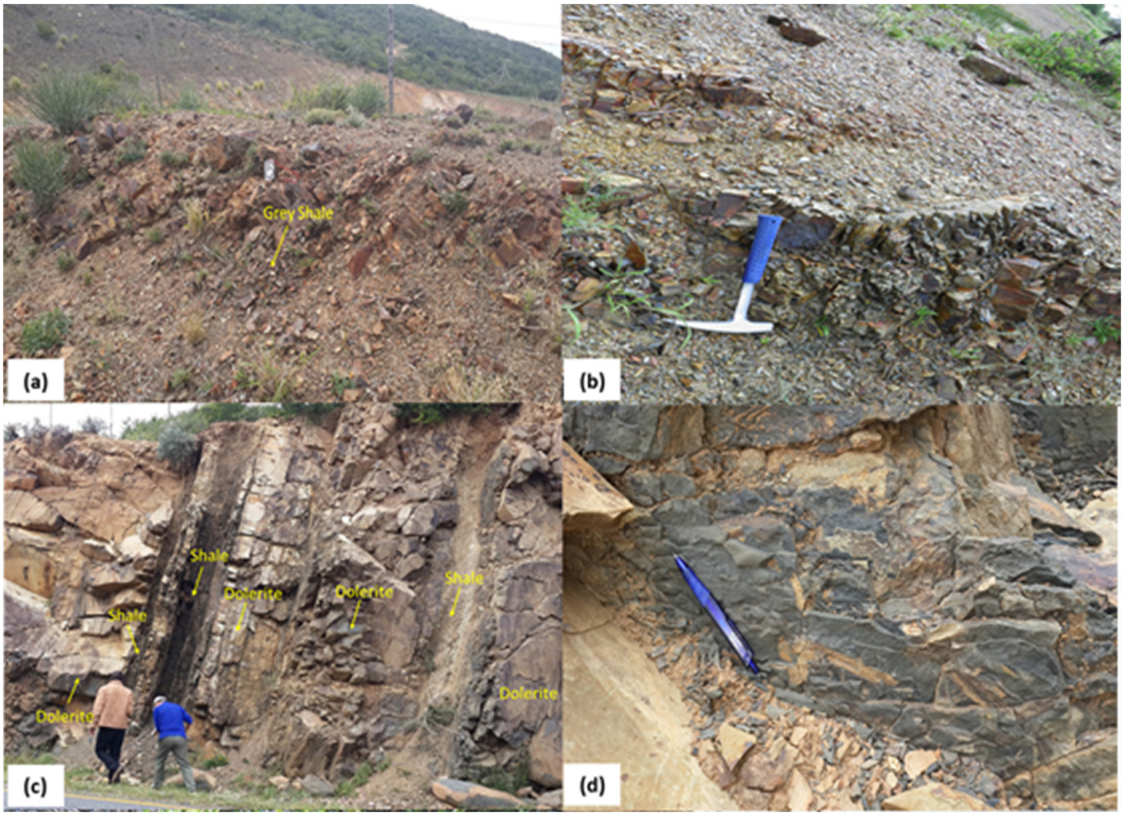

Figure 3: Photograph of the Prince Albert Formation showing: (a) weathered grey shale along the Ecca Pass (Longitude E 26°37′38.1″; Latitude S 33°12′49.5″); (b) weathered laminated khaki shale with pencil cleavage along the Ecca Pass (Longitude E 26°37′38.4″; Latitude S 33°12′59.5″); (c) intrusions of dolerite in the dark-grey shale along national road N2 between Grahamstown and Peddie (Longitude E 26°55′49.6″; Latitude S 33°15′42.9″); (d) trace fossils (a type of ichnogenera) in the shale along Peddie section (Longitude E 26°55′49.6″; Latitude S 33°15′42.9″).

kilometers, and lacks sandstone intercalation as well as current structures. The topographic relief of Fls facies is presently very low because it crumbles easily and consists mostly of clay minerals. At the exposure to the surface, the colour of the shale changes from greenish-grey to olive-grey half way up the unit and finally becomes khaki colour shale at the upper part due to weathering.

Black laminated to thin-bedded mudstone with lenticular siltstone facies (Fss) of about 30 m thick occurs just above the grey shale facies (Fls) along the Ecca Pass (Figure 4). The shale is mostly thin-bedded (at less than 8 cm for a single layer) and is rich in iron-bearing minerals like smectite, pyrite, and chlorite; thus they produce hematite after weathering. The arenaceous mudstones are steeply bedded and deformed (folded). The outcrop of the Prince Albert Formation along national road N10 (Olifantskop Pass; Paterson-Cookhouse) is made up of weathered greenish-grey shale about 64.6 m in thickness. The Prince Albert shale crumbles easily and overlies the diamictite of the Dwyka Group. Three lenticular black chert layers are present in the lower part. From the base of the formation, the first, second, and third chert layers are seen at 3.8, 9.0, and 18.7 m, respectively. Weathered phosphorous and calcareous lenses/concretions of varying shapes and sizes (between 5 and 13 cm thick) are scattered in the basal part of the formation. The upper part (48.6 to 64.6 m) is made up of khaki shale and arenaceous mudstones with some grade-bedded silty layers. Generally, at the bottom of the formation, the mudstones are mostly thin-bedded and usually less than 10 cm for a single layer in all the sections, although sometimes it is well-laminated. At the upper most part of the formation along the regional road R67 (Ecca Pass), reddish brown stains were observed in the shales which are believed to be due to leaching of iron-rich minerals resulting in the red colouration (Figure 4f). Based on the lithological and facies characteristics, the stratigraphy of the Prince Albert Formation can be subdivided into two informal members, namely, the Lower Grey Shale member and Upper Khaki Mudrock member. The Lower Grey Shale member is made

Figure 4: (a) Outcrop photograph showing laminated to thin mudstone and lenticular siltstone (Fss) in the upper part of Prince Albert Formation (Longitude E 26°37′38.1″; Latitude S 33°12′49.5″); (b) thin section photomicrograph of mudrock showing claystone (red arrows) and siltstone (yellow arrows, more than half are clays) layers; (c) thin section photomicrograph of mudrock from the Prince Albert Formation showing siltstone with pyrite (dark area, red arrows) and hematite staining (blue arrow); (d) thin section photomicrograph of mudrock showing calcite replacement of clay matrix and framework grains (brownish area, red arrows); (e) outcrop photograph showing folded well-laminated red stained shale in the upper part of Prince Albert Formation along the Ecca Pass (Longitude E 26°37′38.4″; Latitude S 33°12′ 59.5″); (f) thin section photomicrograph of mudrock from the Prince Albert Formation showing mud-siltstone with (iron-oxide) hematite staining. Note: The khaki colour shale that is mostly encountered at the upper part of the formation was the product of intense weathering that occurred as a result of tectonic uplift and exposure of the rock to the Earth's surface, leading to the alteration of the original greyish-black colour to khaki colour.

up of well-laminated to thin-bedded grey shale (Fls), while the Upper Khaki Mudrock member consists of shale and mudstones with some silty layers (Fss). The stratigraphic subdivision of the Prince Albert Formation in the five locations is depicted in Figure 5.

4.1.1 Shale and mudstones intercalated with siltstones facies association (FA 1)

FA 1 corresponds to the Prince Albert Formation and is made up of Fls and Fss facies. It is greyish in colour and shows coarsening upward sequence with the basal part

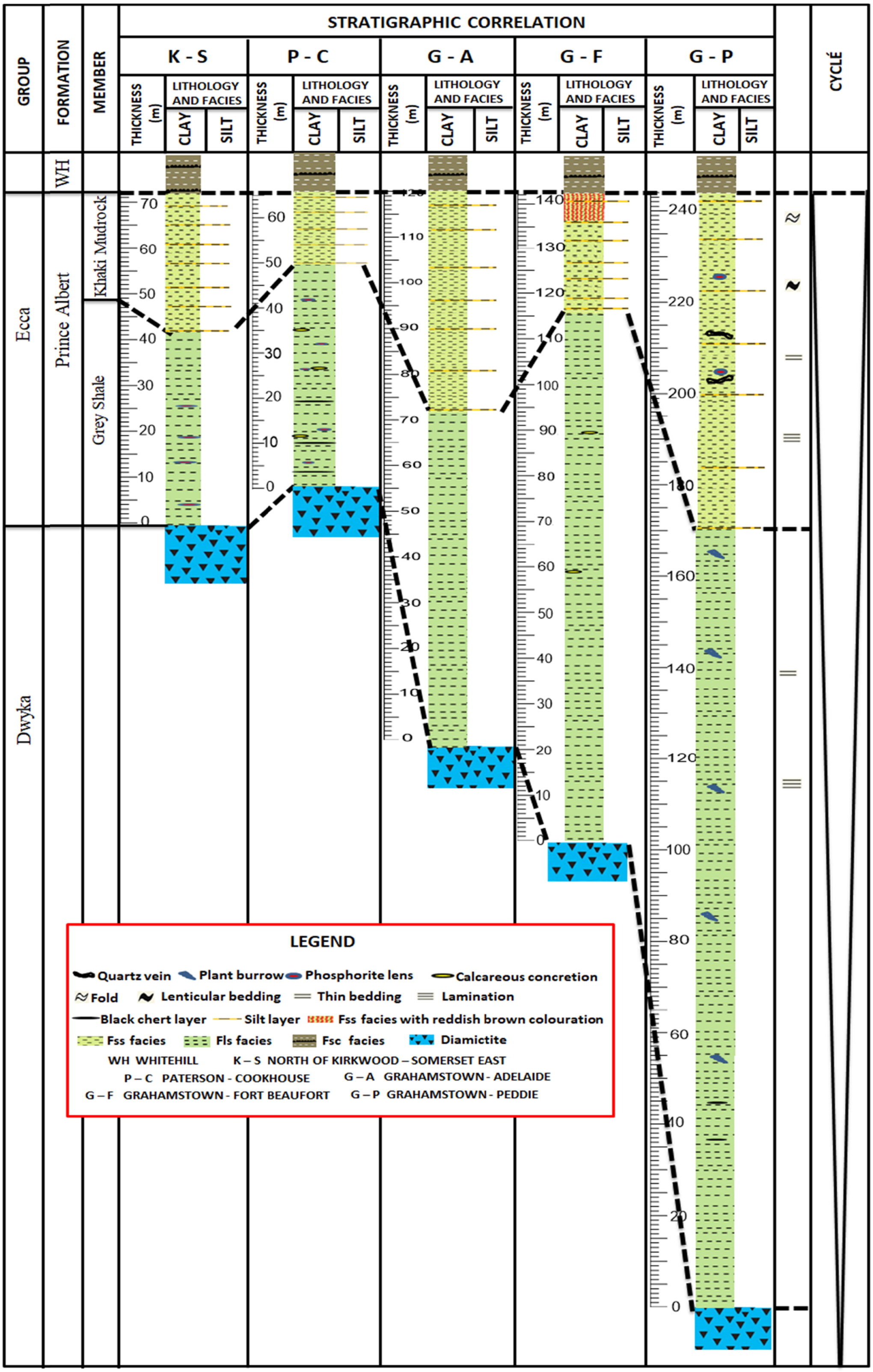

Figure 5: Stratigraphic correlation of the Prince Albert Formation in the study area.

comprising of the Fls facies, whereas the upper part is made up of the Fss facies. The contact between Fls and Fss is sharp, but in 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.

4.1.1.1 Interpretation

FA 1 is interpreted as deep-sea pelagic sediments. The homogeneity of the dark colour and appearance of the mudrock (FA 1) over a relatively large area indicate uniform environmental condition during the deposition of the pelagic sediments [17]. The slightly graded siltstones near the top of FA 1 were deposited as a result of suspension settling or tractional fall-out from low-density turbidity currents. Phosphorous and siliceous shales were developed because of biochemical precipitation under anoxic conditions in areas where cold-water upwelling occurred. The trapped organic materials in the bottom mud are the result of the rich marine life and organic carbon that was probably enhanced by the upwelling current. Early diagenetic processes could have possibly enriched the deposits resulting in the formation of the lenses and nodules that are common in the Lower Grey Mudstone member. The well-developed lamination, fine-grained sizes, pyrite-rich content, and the absence of current structures on the sediments of the Prince Albert Formation indicated deposition in an undisturbed area of relatively deep and quiet water under reducing (anoxic) condition, presumably a deep-marine environment such as a restricted deep-marine plain or deep sea basin or trench. The organic-rich mud accumulated under reducing condition in a deep-marine environment as a reducing environment is required for the pyrite to be formed [7]. Pyrite Formation as well as the well-developed lamination generally less than 3 mm also indicates a slow rate of deposition and a scarce sediments supply [34]. The non-weathered phosphatic lenses/concretions were formed as a result of biological or chemical precipitation under anoxic conditions in areas where cold-water upwelling occurred. This upwelling could have enhanced the rich marine life, which supplied the organic matter that trapped in the bottom mud. The aforementioned characteristics tend to favour an oxygen-deficient deep-sea marine environment.

4.2 Whitehill Formation

The Whitehill Formation disconformably overlies the Prince Albert Formation along regional road R67 (Ecca Pass). There is a gradational-transitional zone between the Whitehill Formation and the underlying Upper Khaki Mudrock member of the Prince Albert Formation. This zone was recognized by the slight or gradual changes in lithology and colour of the rock for approximately 1 m at the top of the underlying Prince Albert Formation. The Whitehill Formation is mainly made up of thin-bedded, laminated, greyish-black carbonaceous shale with subordinate black chert lenses, mudstones, and siltstones. The measured thickness of the formation along regional road R67 (Ecca Pass) is about 41 m thick. The outcrop is generally extensive and ultra-tabular. The strata generally have a dip angle of about 37°. The lower part of the formation (about 20.1 m from the base) consists of laminated, black carbonaceous shales intercalated with lenticular chert (Fsc) (Figure 6). The black colour shale is undergoing weathering to give grey-whitish shale (Figure 6a). The chert beds are greyish-black in colour and microcrystalline in nature, with no conspicuous organic carbon remains. The chert layers occur as lenticular beds incorporated into the shales (Figure 6a). In addition, they are more resistant to weathering and darker in colour than the carbonaceous shale. The chert layers in the basal part (0–13.6 m) are more dominant, thicker, and longer in length (averaging about 2.1 m in length), while minor, shorter, and thinner chert layers are present higher up the formation (13.6–20.1 m).

The upper part of the formation along Ecca Pass is about 20.9 m in thickness (20.1–41 m) and consists of laminated shale intercalated with mudstone and lenticular siltstone facies (Fsm). The shales are generally extensive, black-greyish in colour, well-laminated, and rich in carbon as well as iron sulphide. Fine to silty mudstones and minor lenticular sandstone layers are present in the basal part of the unit (Figure 7a). The carbonaceous materials in the shales allowed for the dark grey colour to form. Some of the black-greyish carbonaceous shale has also been weathered to grey-whitish shale with patches of red and yellow shades (Figure 7b–d). These shales are generally rich in iron sulphide (pyrite). Under the microscope, part of the black colour of the shale is weathering-off to give grey-whitish coloured shale due to subaerial oxidation of pyrite to gypsum. The beds in the upper part of the formation are thicker than those of the lower part, ranging from about 1 to 15 cm thick for individual layers and point a much quicker deposition. The thicker beds have coarser grain size, while the thinner beds are finer grained. The stratigraphy of the Whitehill Formation can be generally subdivided into two members, namely, the Lower Black Shale-Chert member and Upper Grey Mudrock member. The Lower Black Shale-Chert member has laminated black shale intercalated with thin-bedded

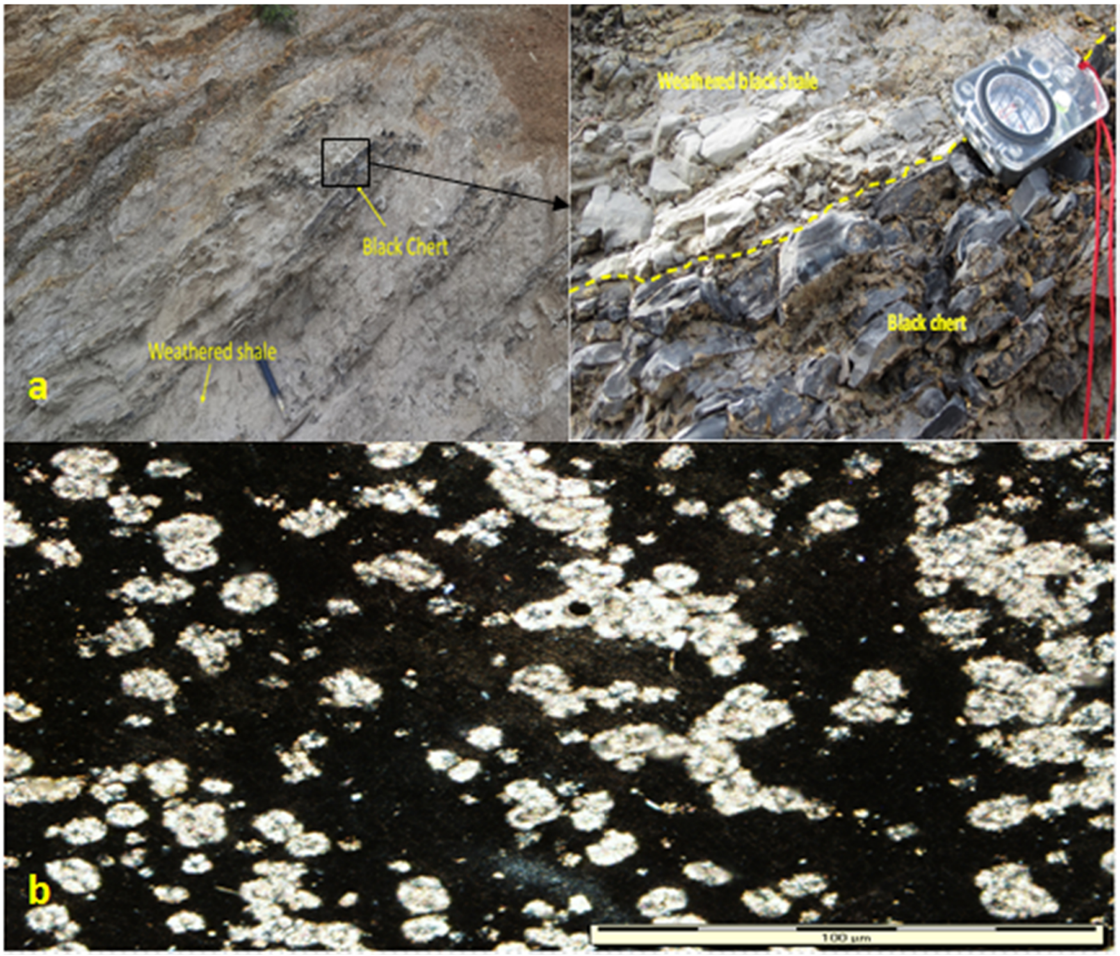

Figure 6: (a) Outcrop photograph showing laminated greyish shale with subordinate lenticular black chert (Fsc facie) (Longitude E26°37′ 34.0″; Latitude S 33°12′55.4″); (b) thin section photomicrograph of mudrock showing dark micrite and white chalcedony nodules in the Whitehill Formation.

black chert layers. The Upper Grey Mudrock member consists of darkish-grey shale with minor chert and siltstone layers. The stratigraphic subdivision of the Whitehill Formation in the five locations is shown in Figure 8.

4.2.1 Carbonaceous shale, mudstone with subordinate chert, and sandstone facies association (FA 2)

FA 2 is approximately 42 m thick in the road-cut exposure along regional road R67 (Ecca Pass), averaging 28.6 m thick in outcrop exposures in the Eastern Cape Province. It is made up of Fc, Fsc, and Fsm facies. The basal, middle, and upper parts of FA 2 are made up of Fc, Fsc, and Fsm facies, respectively. Thus, they show coarsening upward sequence. Fsc and Fsm facies dominates FA 2 and in few cases, possible water escape or deformation structure is present in the Fsm facies. The contact between Fc and Fsc is gradational, whereas the contact between Fsc and Fsm is sharp.

4.2.1.1 Interpretation

The presence of organic carbon in FA 2 suggests that the deep-sea basin was anoxic or under reducing condition. The chert layers point to a chemical or biochemical precipitation in a deep-marine environment. The FA 2 shales are generally extensive, black in colour, thin-bedded, well-laminated, rich in carbon as well as iron sulphide (pyrite), and have subordinate black chert layers. The aforementioned characteristics are almost the same with the characteristics for euxinic facies (black shale) [23,35]. The deposition of the black carbonaceous shale of the Whitehill Formation has been described as suspension settling of materials within an immature, under-filled

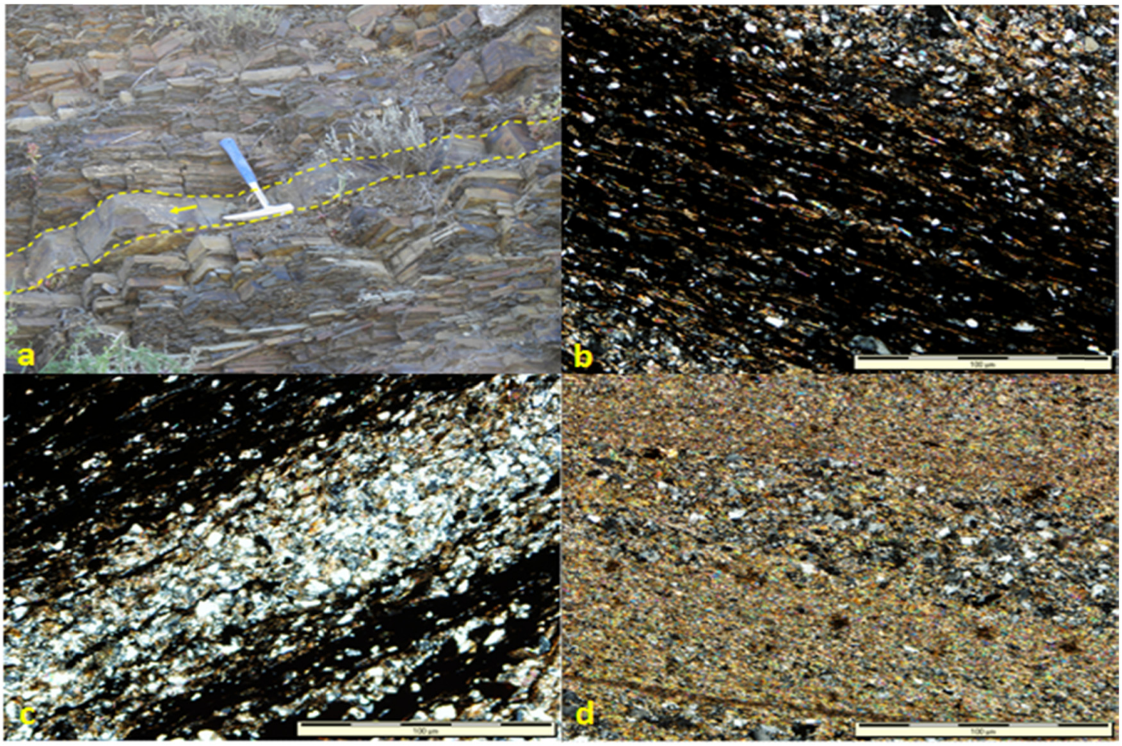

Figure 7: (a) Outcrop photograph showing Fsm facies; laminated black-greyish shale with lenticular siltstone and minor sandstone (arrow) in the upper part of Whitehill Formation along the Ecca Pass (Longitude E 26°37′38.3″; Latitude S 33°13′58.8″); (b) thin section photomicrograph of carbonaceous siltstone of the Whitehill Formation showing mineral grains lying parallel to the lamination planes (Fsc facies); (c) thin section photomicrograph showing carbonaceous shale with carbonaceous siltstone (Fsm facies); (d) thin section photomicrograph showing shale with siltstone (Fsm facies). Note: The hammer is 29.5 cm in length.

foreland basin under anoxic (reducing) conditions [17]. 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. The chert layers occur as lenticular beds incorporated into the shales. The presence of chert points to the existence of silica (SiO_2) in the deep water prior to or during the deposition of the sediments. Besides the lenticular occurrence, the microcrystalline silica occurs also as irregular nodules/concretions within the sediments; with time, these nodules/concretions may increase in size and merge with one another to form the nearly continuous chert layers observed in FA 2. The nearly continuous layers possibly indicate that the chert was chemically precipitated from the deep water. The organic materials within the clay sediments could also have served as alternative source of silica from which the chert was formed. Some of the silicon dioxide in the chert is believed to have been formed through biological/biochemical process. A large number of diatoms and radiolarians that live in deep water tend to have a glassy silica skeleton, while some sponges produce “spicules” that are also made up of silica. When these organisms die, their silica skeletons are accumulated or settled to the bottom of the deep water, then dissolve and reprecipitate as chert lenses or nodules. Hence, it is envisaged that the deposition of FA 2 would have occurred in more restricted part of the deep-marine water, thus allowing the chert layers to develop.

4.3 Collingham Formation

The Collingham Formation conformably overlies the Upper Grey Mudrock member of the Whitehill Formation along the Ecca Pass and has a transition zone of about 52 cm from the top of the Whitehill member. The measured thickness of the Collingham Formation along the Ecca Pass is about 62.8 m thick. Greyish mudstone and claystone turbidite facies (Ftb) form the basal part of the formation (about 38.2 m thick). It mainly consists of thin to medium-bedded olive-black or light grey mudstone layers (about 2.3–11.8 cm thick) with a random distribution of yellowish claystones (thin ash layers) and some thin silty classic turbidites (Figure 9a). The claystones are

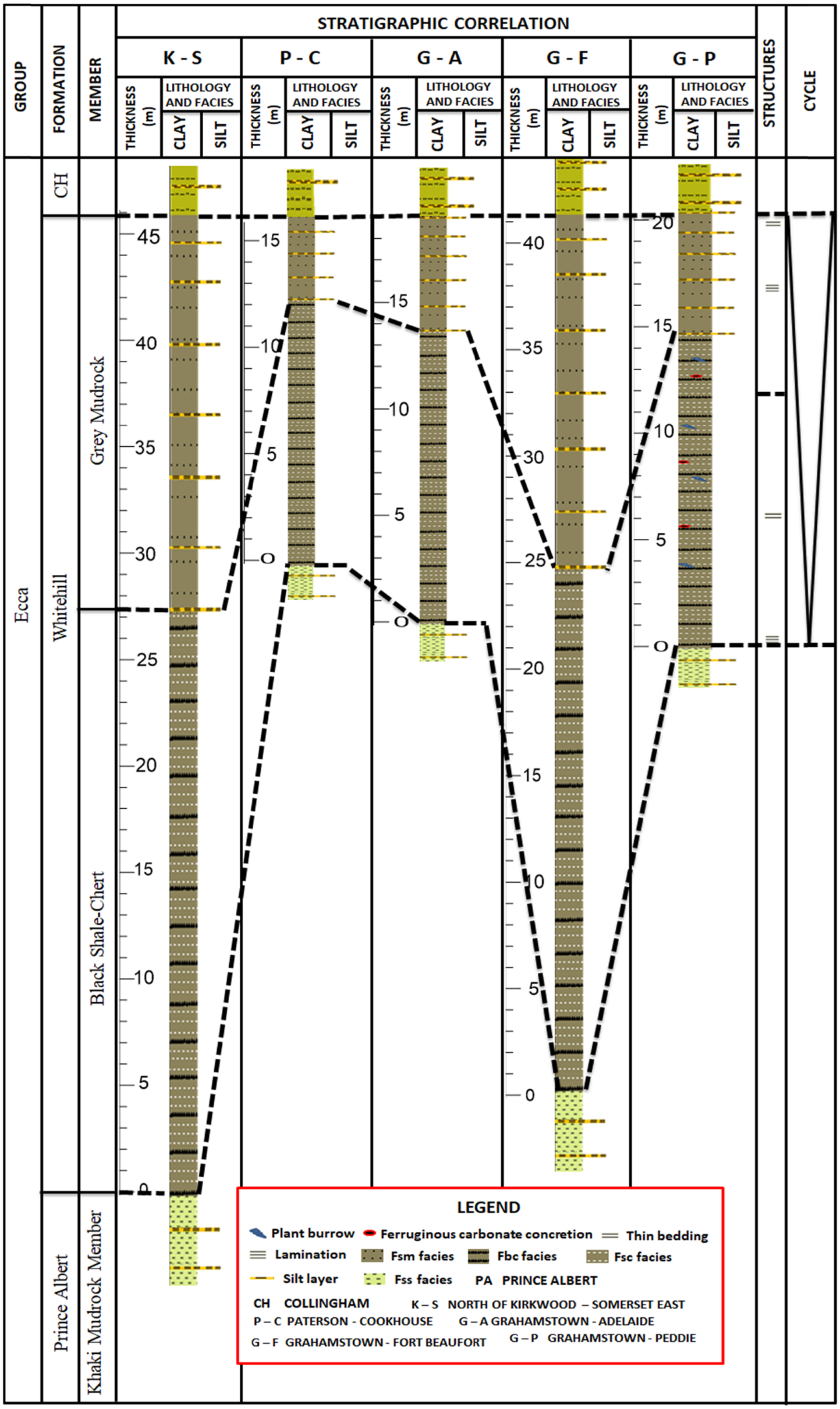

Figure 8: Stratigraphic correlation of the Whitehill Formation in the study area.

soft, well-laminated, crumbles easily, pale yellowish in colour, and are relatively pure in clay mineral composition, which resulted in their flakiness as well as crumble characteristics. The mudstone layers are hard, well-laminated, greyish black in colour, and finer grain sized. Originally, the colour of the shale and claystones is believed to be dark-grey, but due to weathering, the greyish colour of the claystones changed to the present pale-yellowish colour, as well as resulted in the purer clay content. Average thickness of the soft claystone and hard mudstone layers are 2.8 and 4.2 cm thick, respectively. Underneath the microscope, the mudstone has manganese-iron-rich nodules (Figure 9b). Generally, the mudstone beds exhibit horizontal lamination. In addition, micro-ripple laminations, climbing ripple lamination, convolute bedding (Figure 9c), and erosional wave mark structures have been found in the dark hard mudstone, but are absent in the soft claystone layers. In some places, the claystones alternated with minor silty layers that are weakly graded.

The upper part of the Collingham Formation has a thickness of about 24.6 m and it is made up of thin, well-laminated dark-grey shale which can be split along bedding planes and alternated with yellow claystone and silty layers that are weakly graded in some places. The thickness of the mudstone beds ranges from about 1.7 cm up to 11.9 cm thick. Fine grain size is usually associated with the thinner beds, while the thicker beds are mostly made up of the coarser grain size. The mudstones are the hard and dark coloured layers with relatively coarser grain size, while the soft and light coloured layers with fine-grained size are the claystones (Figure 9c). The soft beds are well-laminated with relatively pure clay mineral composition which resulted in their flakiness and friable characteristics. Trace fossils assumed to be a type of ichnogenera are relatively common from about 40.2 m above the base of the formation, up to 56.4 m. Also, there is presence of micro-ripple laminations in the mudstone layers, which are absent or not seen in the claystone layers. No distinctive feature is seen in the outcrop of the Collingham Formation along regional roads R344 (Grahamstown-Adelaide) and R350 (North of Kirkwood-Somerset East), and along national road N2 (Grahamstown-Peddie) and N10 (Cookhouse-Paterson) which differs from the exposure along regional road R67 (Ecca Pass) and national road N2 (Grahamstown-Peddie). Based on the lithological and facies characteristics, the stratigraphy of the Collingham Formation can be subdivided into two members, namely, the Lower Black Shale-Tuff member and Upper Grey Mudrock member. The Lower Black Shale-Tuff member is made up of shale with a random distribution of yellowish claystones and some thin silty classic turbidites, while the Upper Grey Mudrock

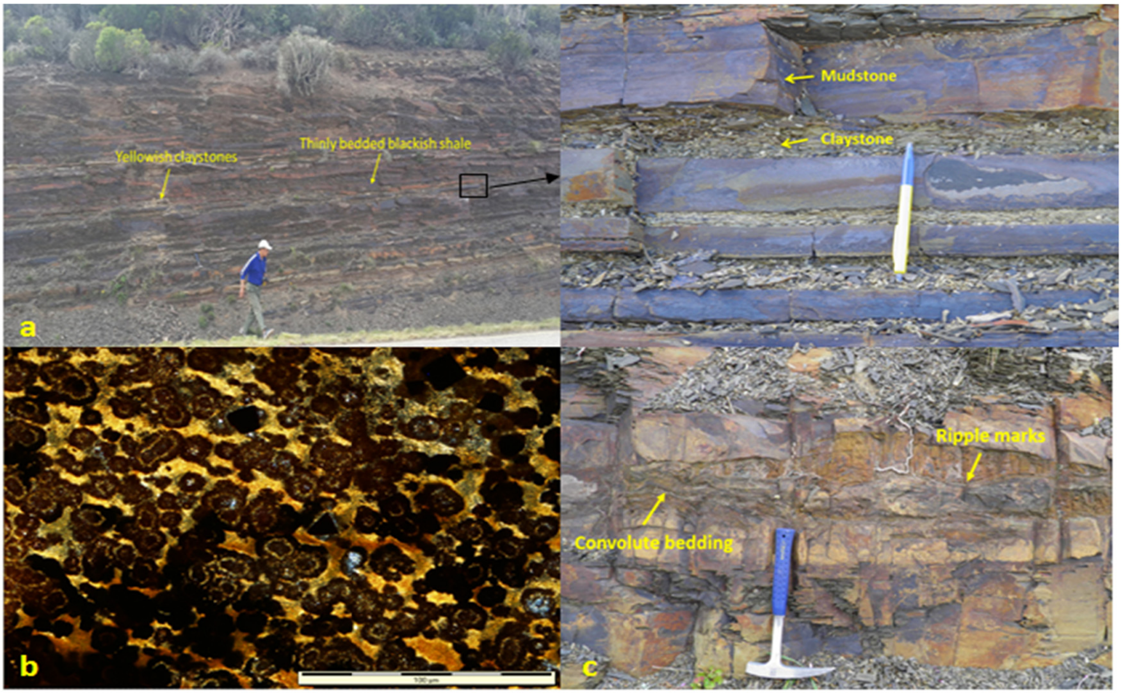

Figure 9: (a) Outcrop photograph of the greyish mudstone and claystone turbidite (Ftb) along Ecca Pass (Longitude E 26°37′35.7″; Latitude S 33°12′56.0″) showing laminated or thin-bedded greyish black mudstone layers and softer yellowish bentonite claystone layers which were thought to be ash-fall tuffs; (b) thin section photomicrograph of mudrock showing manganese-iron-rich nodules in mudrock of the Collingham Formation; (c) convolute bedding and ripple marks in the mudstone of the Collingham Formation along the Ecca Pass (Longitude E 26°37′20.3″; Latitude S 33°12′41.0″; Photo by Nonhlanhla Nyathi). Note: The hammer is 29.5 cm in length.

member consists of well-laminated shale, claystone, and minor siltstone. The stratigraphic subdivision of the Collingham Formation in the five locations is presented in Figure 10.

4.3.1 Mudstones rhythmite with thin-bedded mudstone and lenticular siltstone facies association (FA 3)

FA 3 corresponds to the Collingham Formation and comprises Ftb and Fss facies. The contact between Ftb and Fss facies is gradational. FA 3 shows finning upward sequence with Ftb facies making up the basal part, while the upper part comprises of the Fss facies. FA 1 reaches a maximum thickness of about 60 m in road-cut exposure along the Ecca Pass, with an average thickness of 64 m in the Eastern Cape Province.

4.3.1.1 Interpretation

The laterally extensive individual beds, fine-grained characteristics as well as the absence of current structures in the FA 3 point to deposition in relatively deep water, probably a deep-sea basin. The lateral persistence of the fine-grained beds coupled with the presence of trace fossils indicates suspension settling in deep water. The regular alternation of thin-bedded mudstones and claystones (Ftb) depicts a classic rhythmite facies, which possibly signifies that the deposits were probably turbidite sediments in origin. The laminated mud points to pelagic sedimentation or fine-grained low-density turbidity deposition. The combination of climbing ripple cross-lamination, parallel lamination, and ripple cross-lamination within the hard mudstone beds (Fss) also support the assumption that low-density distal turbidity currents existed during the time deposition of the pelagic sediments. The presence of the wave mark structures points to the fact that the water energy was not always quiet during the deposition of the thin-bedded sediments. The hard mudstones layers with horizontal lamination and graded bedding and ripple lamination are considered to have been deposited in a relatively disturbed water period, showing that the energy of the turbidity current varied when the sediments were deposited. The presence of small-scale convolute lamination in the Lower Black Shale-Tuff member shows that the structure was formed as a result of current movement over mud laminae in which deformation has taken place during or just after its deposition and before the deposition of the overlying parts of the same bed [17,36]. FA 3 is interpreted as suspension settling of mudstones intermixed with distal turbidites in a deep-marine environment.

4.4 Ripon Formation

The Ripon Formation conformably overlies the Upper Grey Mudrock member of the Collingham Formation. It has a measured thickness of approximately 900 m along the Ecca Pass. The formation consists of sandstones alternating with mudstones. Silicification is well-developed in the Ripon Formation than those of the Prince Albert, Whitehill, and Collingham Formations. The Ripon Formation along the Ecca Pass can be subdivided into three members, namely, the Lower, Middle, and Upper member. Greyish lenticular and thin-bedded sandstones facies (Slt) (Figure 11a) occupies the basal part of the Lower member (Unit 1) in the Ripon Formation and overlies facies Ftb. It is mainly composed of very fine- to fine-grained lenticular-bedded sandstones and sometimes horizontally laminated with low angle cross bedding. Furthermore, the original dark-grey colour of the sandstone has changed to light grey colour as a result of weathering. These sandstones are light-grey in colour, thin to thick-bedded, poorly sorted, and immature with sub-angular to sub-rounded grains. Generally, the sandstones have irregular jointing pattern with the sub-horizontal joints being the most common. The thickness of the sandstone beds usually increases from the bottom to the top of the unit, with thickness ranging between 1.8 and 13 m. Low angle cross-bedding, joints, and calcareous nodules are present in the light-grey coloured, medium to thick-bedded sandstones. Under the microscope, the grains consist of quartz, potash feldspar and plagioclase and metamorphic, and volcanic and igneous lithic fragments. The matrix is composed of kaolinite, sericite, illite, and smectite (Figure 11b–d).

Carbonate cement is the dominant cement in the rock. The nodules are thought to have been formed due to precipitation of calcium carbonate as well as the alteration or mineral replacement of feldspars by calcium carbonate. The presence of calcite cement also supports the earlier statement that calcium carbonates precipitated to form the nodules. Calcite concretions are mostly seen in the thick-bedded and structureless sandstones and occasionally present in the thin-bedded sandstones. The nodules are mostly spherical in shape, although a few of them are elongated. Originally, the sandstones are dark-grey in colour, but have been weathered to greyish-white due to the alteration of feldspars to

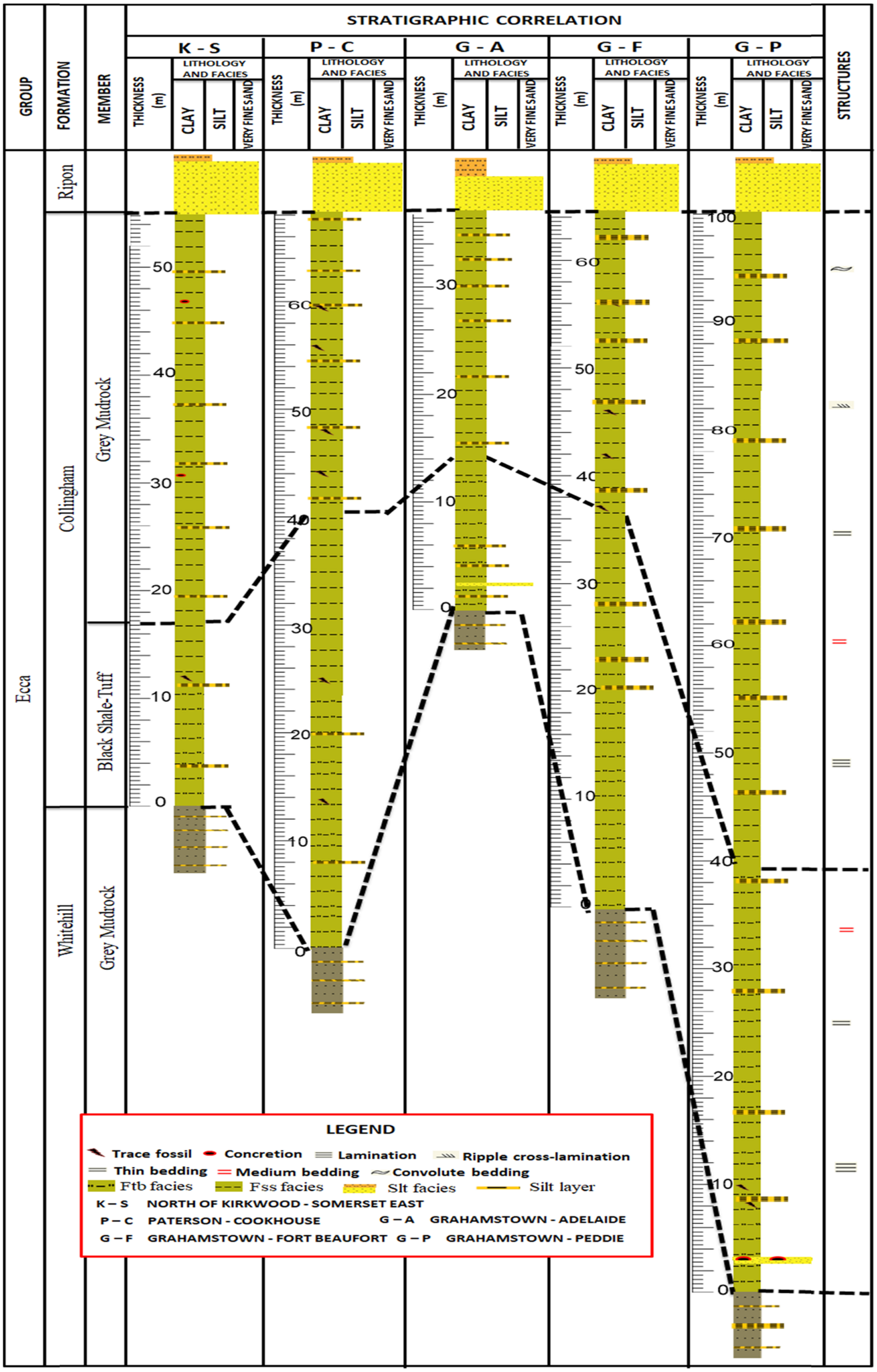

Figure 10: Stratigraphic correlation of the Collingham Formation in the study area.

kaolinite. Apart from the calcitization of feldspar, diagenetic changes that are observed in the rocks are sericitization of feldspars, alteration of feldspar to illite as well as the recrystallization of matrix materials.

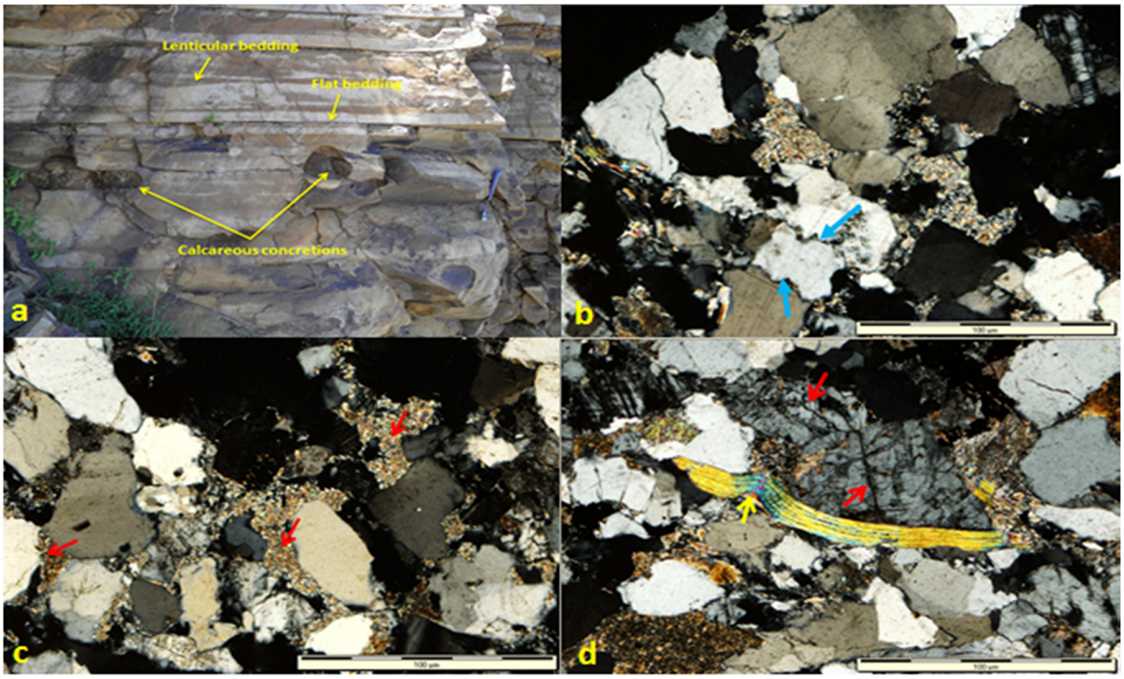

Figure 11: (a) Outcrop photograph showing greyish lenticular and thin-bedded sandstones (Slt) with diagenetic nodules; (b) thin section photomicrograph of sandstone showing K-feldspar twin crystals and sutured quartz grain (blue arrows); (c) thin section photomicrograph of sandstone showing clay (illitized smectite) matrix around feldspar and quartz grains (red arrows); (d) thin section photomicrograph of sandstone showing fractured feldspar grains (red arrows) and deformed mica (yellow arrow).

Thin- to-medium-bedded sandstone interbedded with laminated shale facies (SFt) (Figure 12) occupies the upper part of the Lower member (Unit 2) and overlies the Slt facies. It consists of greyish thin to medium-bedded sandstone alternating with laminated shale beds (Figure 12a). The thickness of the sandstone beds varies between approximately 0.4 and 35 m. The sandstone beds usually grade from fine-grained sandstone at the base to well-laminated siltstone and silty shale at the top. Generally, the contact between the sandstones and mudstones is sharp. In some places, the lower contact in the mudstones beds gradually grades from laminated siltstone to shale. Furthermore, some of the sandstone beds lack sedimentary structures with the shales only displaying lamination. Small-scale syn-depositional structures such as horizontal and cross-lamination, trough cross bedding, climbing lamination, convolute bedding, plane parallel lamination (Figure 12b–f), wavy bedding, and calcareous concretions are present in the medium-bedded sandstones as well as in the coarse siltstones. Some of the sandstones in the upper part of the unit are mottled and are more vulnerable to weathering than the non-mottled sandstones. Mostly, the mottled sandstones tend to alternate with the non-mottled sandstones. Small trace fossils (worm trails) and calcareous concretions are occasionally present in the mottled sandstones.

The Middle member of the Ripon Formation largely consists of medium to thick-bedded dark-grey shale (Fts) (Figure 13). The shale splits perfectly along well-defined bedding planes. The thickness of the homogenous shale generally increases from east to west side of the study area (Figure 1). Occasionally, the shale is massive with very faint lamination. Well-laminated, medium-bedded shales are interbedded with four small-scale sandy beds at the upper part of unit.

The basal part of the Upper member of the Ripon Formation along the Ecca Pass (thickness of about 12 m from the top of Fts facies) is made up of tabular laminated, organic-rich black shale with greyish mudstone (Fc) (Figure 14a). The basal shale layer is dark-grey in colour, homogenous, and faintly laminated. The dark-grey colour of the shale becomes greyish-black (5–7 m) and eventually changes to black in the upper part of the basal shale layer (9–12 m). The change in the colour of the shale signifies that the organic carbon content increases from bottom to the top of the basal shale layer. It is thought that the persistence of the reducing conditions/environment resulted in the increase of organic carbon content. Very small micro-cross-lamination of about 2 mm thick occurs in some of the thin-bedded mudstones. Mostly, the black shales are well-laminated and crumble easily as compared to the dark-grey and greyish-

Figure 12: (a) Outcrop photograph showing sandstone intercalated with shale of SFt; (b) horizontal and faint cross-lamination in the sandstone of SFt; (c) trough cross-bedded sandstone of SFt; (d) climbing laminated sandstone of SFt; (e) convolute bedding in the mudstone-siltstone of SFt; (f) plane parallel lamination in the sandstone of SFt.

black shale. The crumble or flaky nature of the black shale can be attributed to their high organic carbon content, as well as the alignment of clay particles and presence of laminae (Figure 14b–d).

Dark thin-bedded bioturbated mudstone (Fbm) facies overlies the Fc facies (Figure 15). The original dark or black colour of the mudstone changed to the present light grey colour due to weathering. Greyish laminated to thin-bedded mudstone and lenticular siltstone facies (Fms) is seen in the Upper member of the Ripon Formation (Figure 16a). The laminations on the siltstone are thin perhaps indicating that the supply of silt materials into the depositional basin was deficient. The siltstones show low angle cross-bedding and unidirectional scouring surfaces. In some places, especially near the top of the unit, these structures have been truncated and their amplitude considerably decreased. It is believed that the siltstone surfaces were probably reworked by erosional processes. Recumbent deformation structures are also present in the greyish mudstone (Figure 16b).

Thin to medium-bedded sandstone alternated with thin-bedded mudstone facies (SFm) (Figure 17) overlies the Fms facies and covers the largest extent of the Upper member in the Ripon Formation. The SFm facies consists of thin to medium-bedded sandstones alternating with thin-bedded mudstones. The basal part of the unit is made up of greyish-black organic-rich shale with light-grey mudstone and sandstone (Figure 17a). In the middle to upper part of the unit, the sandstones are dark grey in colour and very fine to fine-grained. Micro-cross-lamination and current ripple cross-lamination are present in the sandstone beds. In some places, micro-cross-lamination is associated with wavy lamination (Figure 17b), ball and pillow load cast structures. The sandstone beds in the upper part of the unit often show continuous trend of A (graded bedding), B (horizontal lamination), and C

Figure 13: Dark-grey medium to thick-bedded mudstone (Fts) in the Wonderfontein Shale Member of the Ripon Formation.

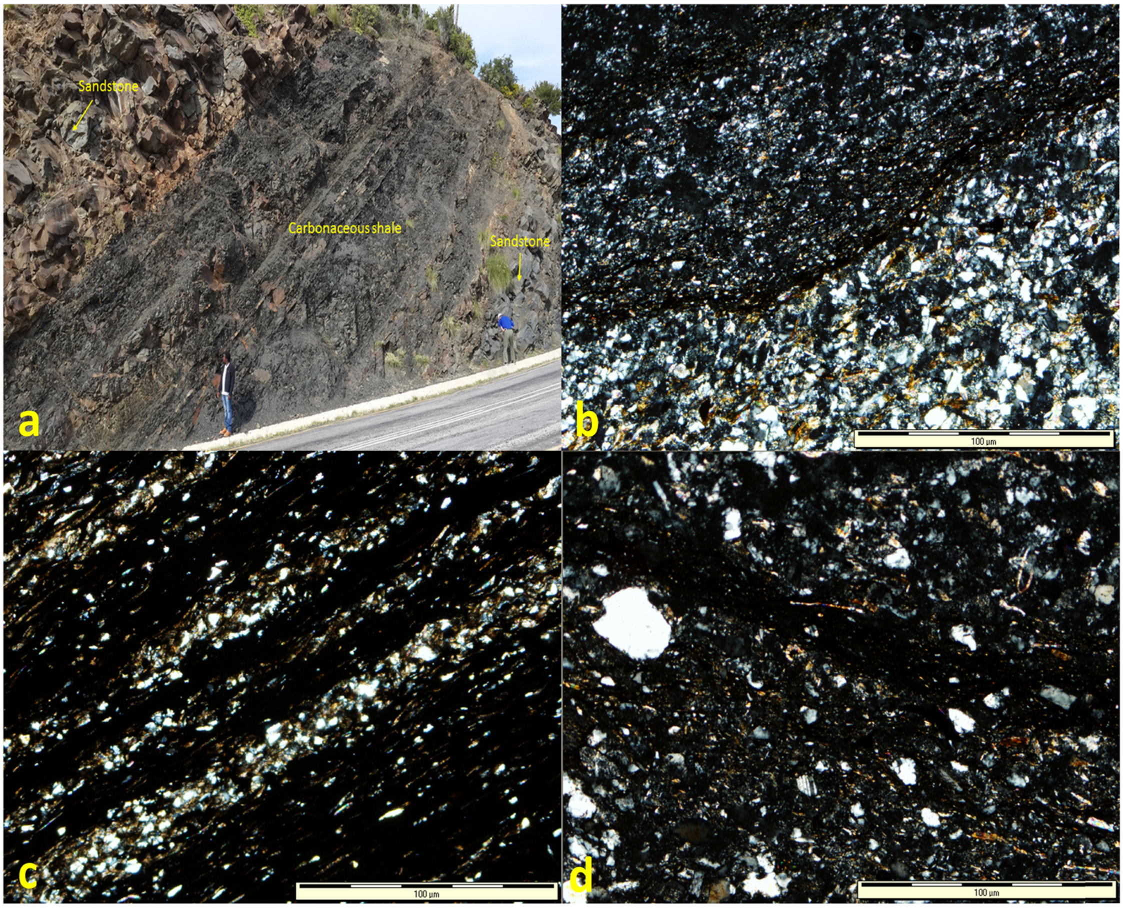

Figure 14: (a) Outcrop photograph showing dark laminated organic carbon-rich shale with sandstone; (b) thin section photomicrograph of carbonaceous shale and siltstone; (c) thin section photomicrograph showing carbonaceous shale with mineral grains lying parallel to the lamination planes; (d) thin section photomicrograph showing carbonaceous shale and carbonaceous siltstone.

Figure 15: Outcrop photograph showing mudstones of the Fbm facies in the Ripon Formation.

(micro-cross-lamination) of the Bouma sequences [33]. The upper mudstone units are faintly laminated and thin-bedded. The thickness of mudstone beds increases from about 0.4 m in the basal part to roughly 4.3 m in the upper part of the unit. The mudstones have higher amount of carbonaceous materials compared to the sandstones and this is evident in the greyish-black colour of the mudstones. In some places, the laminated sandstone grades upward into a poorly defined wavy laminated silty shale. Some of the slightly silty shale bed shows indistinct graded bedding. In most cases, the upper and lower boundaries between the shale and sandstone are sharp. However, some of the upper contacts are irregular and this irregularity can be attributed to load casting of the overlying sandstone bed. Erosional surface, worm burrows (Figure 17c), few calcareous concretions, small-scale ball and pillow structures, disc structures, and load casts are present in some of the sandstone bed. The sandstones are originally greyish in colour, but have been weathered to reddish-brown in the exposures along Grahamstown-Adelaide road (Figure 17d).

Based on the lithological and facies characteristics, the stratigraphy of the Ripon Formation can be subdivided into three members, namely, Lower Greywacke-

Figure 16: (a) Outcrop photograph showing laminated to thin-bedded mudstone (dark colour) intercalated with lenticular siltstone (light colour) (Fms facies); (b) Recumbent deformation structures in the greyish mudstone of the Ripon Formation.

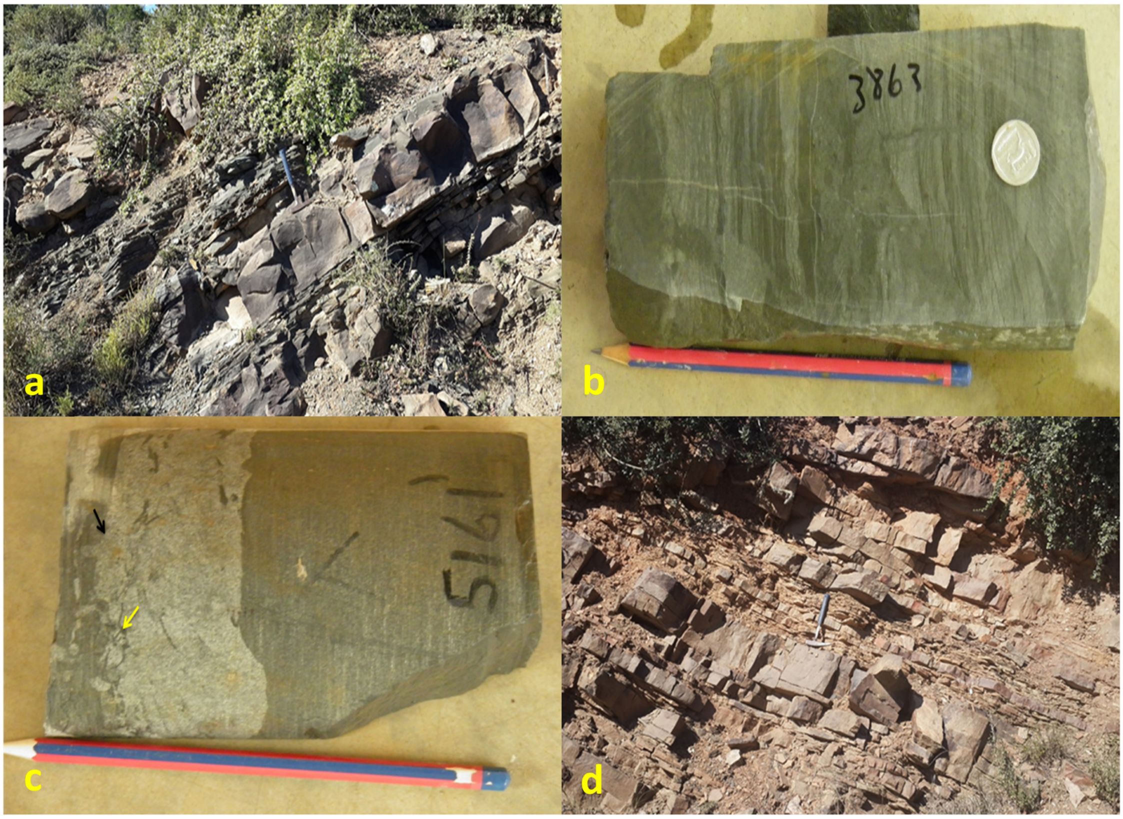

Figure 17: (a) Outcrop photograph showing thin to medium-bedded sandstone alternated with thin-bedded mudstone; (b) Wavy laminated sandstones of SFm; (c) Erosional surface (arrow) in the bottom of sandstone (white) and burrows on the mudstone (dark); (d) Greyish thin to medium-bedded sandstone intercalated with thin-bedded shale.

Mudrock member, Middle Black Mudrock member, and Upper Black Mudrock-Sandstone member. The Lower Greywacke-Mudrock member consists mainly of thick-massive-bedded greywackes with subordinate mudstones. The Middle Black Mudrock member is mainly made up of greyish-black shale with minor sandstone layers, while the Upper Grey Mudrock-Sandstone member is made up of alternating dark-grey greywacke and greyish-black shale that depicts a classic rhythmite rock. The stratigraphic subdivisions of the Ripon Formation in the five locations are depicted in Figure 18.

4.4.1 Greyish medium-bedded sandstone intercalated with laminated mudstone facies association (FA 4)

FA 4 is made up of Slt and SFt facies. It is greyish in colour and covers the Lower member of the Ripon Formation. The basal part of FA 4 comprises of the greyish lenticular and thin-bedded sandstones facies (Slt), whereas the upper part is made up of thin to medium-bedded sandstone interbedded with laminated mudstone facies (SFt). The contact between Slt and SFt facies is sharp.

4.4.1.1 Interpretation

The coexistence of depositional and deformational structures such as current ripple lamination, groove cast, convolute bedding, graded bedding, and slumping in the FA 4 shows that the sandstone beds are of turbidity current deposits. The presence of thick convolute bedding in the basal sandstone bed signifies fast rate of deposition, just above the bed where convolute bedding occurred; the thickness of the overlying sandstone beds increases which also supports a fast rate of sediments supply from the source area (prograding). The multiple cyclicity of alternating sandstone and mudstone layers points to the fact that the turbidites are essentially related to autocyclic processes like fan progradation or recession and lobe-switching among others [37]. The transportation of the turbidites down the slope in the turbidite fan complexes is possibly associated with the major regression that occurred during the Ecca time. The general thickening upward sequence of FA 4 also points to the fact that the depositional lobe prograded since marginal facies in depositional lobes are expected or thought to be thinner-bedded than those near the apex of the lobe.

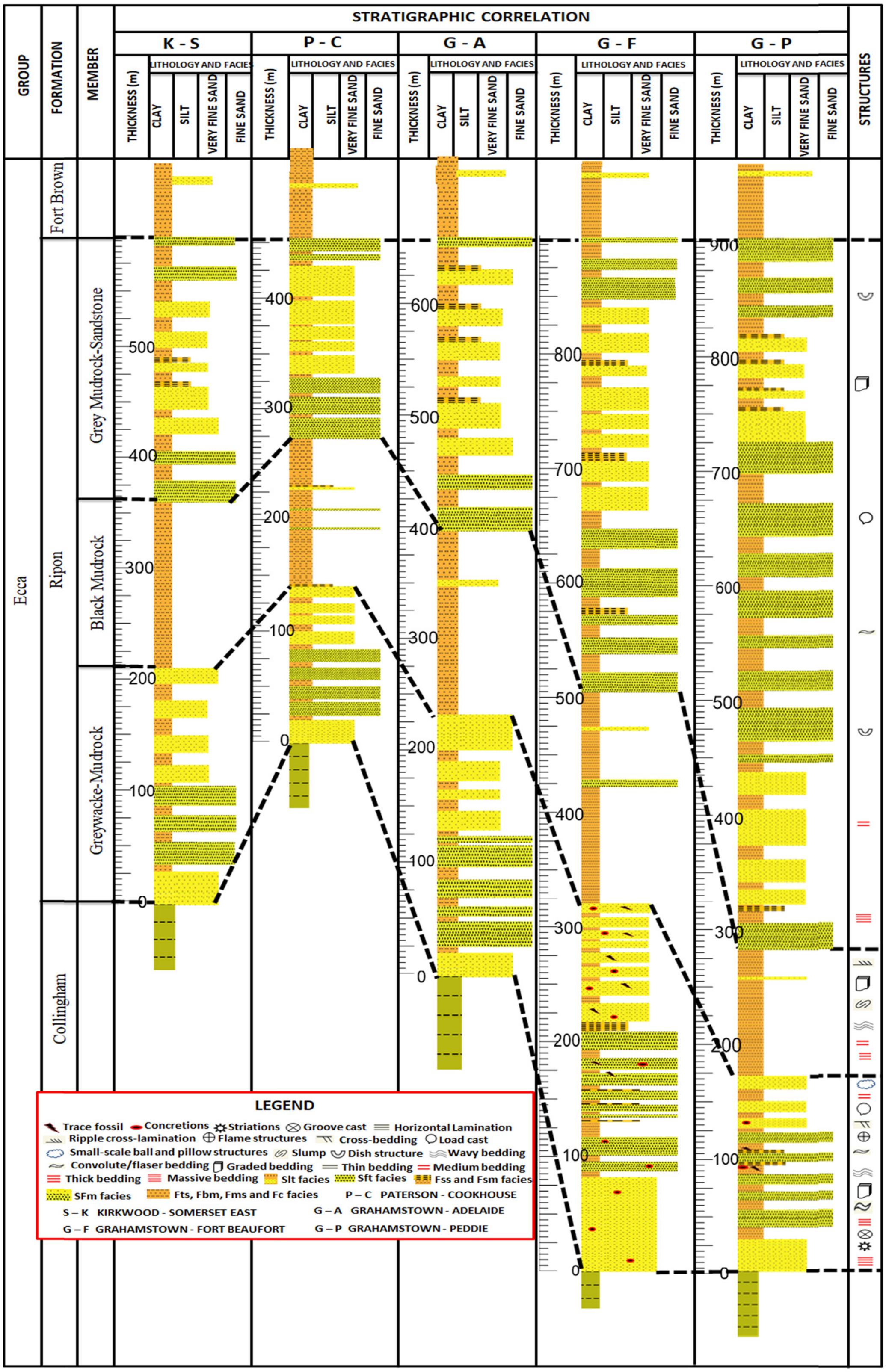

Figure 18: Stratigraphic correlation of the Ripon Formation in the study area.

FA 4 is interpreted as distal outer fan turbidites in the lower continental slope environment (lobe region). The massive shale beds in the middle member probably developed in a river channel where sediments were deposited from a fast flowing current carrying a large volume of suspended sediments. These currents then experienced a rapid decrease in velocity and the suspended sediments were suddenly deposited resulting in the massive beds. The rate at which the current flows gives no time for internal layering to develop, thus most of the shales show massive bedding and faintly graded in some places.

4.4.2 Dark-grey medium to thick-bedded mudstone and siltstone facies association (FA 5)

The Middle member of the Ripon Formation largely consists of dark-grey medium to thick-bedded shale, mudstone, and minor 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 splits perfectly along well-defined bedding planes.

4.4.2.1 Interpretation

The occurrence of massive homogenous shale in the FA 5 points to suspension deposition [17]. FA 5 represents pelagic sedimentation or low energy periodic sedimentation and low-density turbidity current deposition (moderate depth setting), perhaps in the continental slope environment. FA 5 marks a recession in the supply of sediments possibly during a period of small transgression of the southern basin edge [17]. The parallel horizontal laminated shale suggests turbulent suspension in a relatively deep-water environment with frequent variation of hydrodynamic energy. Decreased organic-carbon content in FA 5 points to increased clastic dilution, as well as increased rate of consumption by benthic organisms.

4.4.3 Thin to medium-bedded sandstone alternated with thin-bedded carbonaceous mudstone facies association (FA 6)

The Upper member of the Ripon Formation is made up of FA 6 which consists of Fc, Fbm, Fms, and SFm facies. FA 6 is generally greyish-black in colour with the basal, middle, and upper parts consisting of Fc and Fbm, Fms, and SFm facies, respectively. Most of the mudstones are thin-bedded and have traces of plant fossils. The thickness of the mudstone beds increases from about 0.4 m in the basal part to roughly 4.3 m in the upper part of FA 6. In most cases, the upper and lower boundaries between the mudstone and sandstone are sharp and occasionally irregular.

4.4.3.1 Interpretation

The alternation of sandstone and mudstone beds in FA 6 points to deposition under fluctuating energy conditions and represents the proximal fan sediments. The laminations and flat beds in the mudstones are indicative of quiet waters and slow settling of the sediments, whereas the thin to medium beds of the sandstone layers are indicative of rapid deposition and high water energy during the deposition. In the first rhythm, the black shale becomes darker in colour towards the top of the formation as a result of increase in organic carbon content in the marine environment. This increase in the organic carbon content is possibly due to the persistence of the anoxic conditions, suggesting that there was an abundance of organic material in the depositional area that used up the available oxygen, thus creating conditions under which organic-rich sediments were accumulated. The deposition of fines from suspension is represented by the alternated mudrock units. The coarsening upward sequence near the top of the FA 6 resulted from the progradation that formed when a distributary within a turbidite fan complex advances [17]. Due to the absence of shallow water indicators, the sandstones of the FA 6 are believed to have been deposited by gravity flows along the foot of a prograding delta-slope in an environment of a turbidite fan complex [17]. There is no coarse sand in the FA 6 and it is due to the absence of coarse grained sand in the source areas of the turbidity current [18]. FA 6 is interpreted as proximal turbidites in a deep-marine environment.

4.5 Fort Brown Formation

The Fort Brown Formation conformably overlies the Upper Grey Mudrock-Sandstone member of the Ripon Formation along the Ecca Pass. The measured thickness of this formation along road cutting is about 910 m. The basal part of the formation (445 m from the base) is entirely made up of Frh facies (Figure 19), which consists of grey mudstones rhythmite intercalated with subordinate sandstones. The rhythmites are represented by the regular alternation of claystone and siltstones (Figure 19). The light coloured varve layers are siltstones, whereas the dark coloured varve layers mainly consist of clay minerals.

Figure 19: Photograph showing Frh facies of the Fort Brown Formation along regional road R67 between Grahamstown and Fort Beaufort (Longitude E 26°36′43.26″; Latitude S 33°10′57.31″). The alternated light and dark coloured mudstones depict seasonal changes.

The thicknesses of the regularly alternated light and dark coloured layers are approximately the same, ranging from about 0.4 up to 1.8 mm. The alternation is perhaps as a result of compositional changes as well as changes in grain sizes of the sediments. The light coloured (coarser) sediments were transported into the basin when the flow of water energy was high, whereas the dark coloured (finer) sediments were deposited from suspension settling when the flow of the water was slow. The rhythmites are fresh water lacustrine facies. The alternated light and dark coloured mudstones reflect deposition of summer and winter seasonal changes.

Ripple cross-laminated sandstone (Srl) facies occur in the upper part of Fort Brown Formation (Figure 20). The sandstones are very fine- to fine-grained, thin-bedded, and often shows ripple-cross-lamination. The thickness of the sandstone layers increases upwards. Several finely laminated siltstones, shale, and a few medium-bedded sandstones are present in the upper part of the unit. The contact between the shale and sandstone is mostly sharp, but some of the sandstone beds grade into shale. In addition, the shale is occasionally silty with faint to well-developed lamination. Generally, where the shale is very silty, it tends to be olive-grey in colour, well-laminated, graded, and displays a blocky type of weathering. But where the silty content is low or small, the shale usually has a dark-grey to black colour and exhibits pencil cleavage. A few of the current rippled sandstone beds are very calcareous with laminae that are characterized by brownish weathered surfaces. Wave ripples with average length of about 25 cm are well-defined in the upper part of unit. Trace fossils (trails, horizontal, and vertical worm burrows) are fairly abundant in the sandstone beds.

Based on the lithological and facies characteristics, the stratigraphy of the Fort Brown Formation can generally be subdivided into two members, namely, the Lower Grey Varved Rhythmite member and the Upper Grey Mudrock-Sandstone member. The Lower Grey Varved Rhythmite member is made up of well-laminated to thin-bedded rhythmites of grey mudstone with minor lenticular siltstone and fine sandstone intercalation. The Upper Grey Mudrock-Sandstone member consists of silty, well-laminated greyish shale alternating with siltstone and sandstones. There are more sandstone beds in the Upper Grey Mudrock-Sandstone member than the underlying Lower Grey Varved Rhythmite member. The stratigraphic subdivision of the Fort Brown Formation in the five locations is depicted in Figure 21.

4.5.1 Varved mudstone rhythmite intercalated with minor siltstone and sandstone facies association (FA 7)

The Fort Brown Formation is entirely made up of FA 7. It consists of varved, well-laminated to thin-bedded greenish-grey mudstone rhythmite (Frh) with minor sandstones

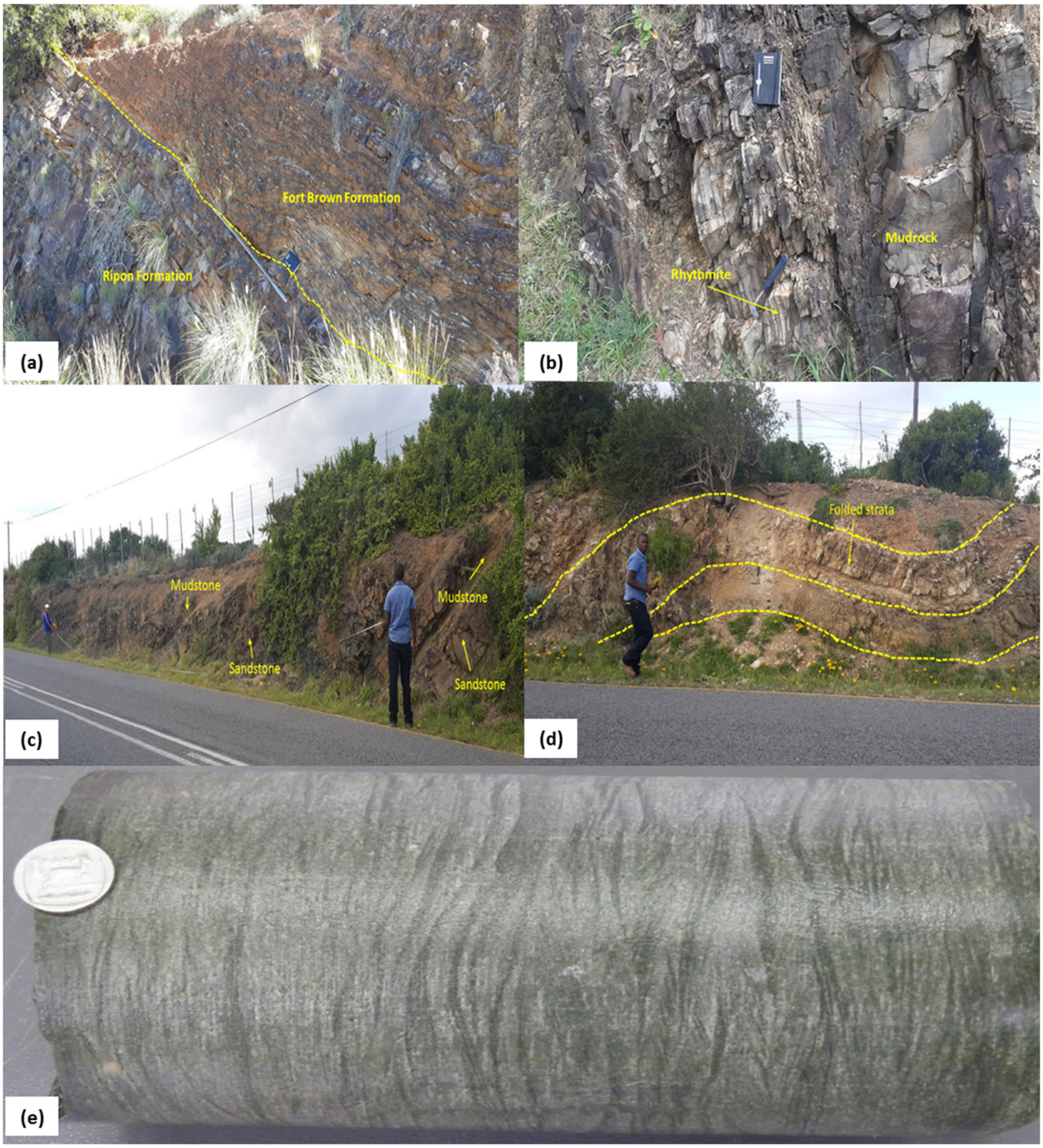

Figure 20: Photograph of the Fort Brown Formation showing: (a) sharp contact between the Fort Brown Formation and the underlying Upper Mudrock-Sandstone Member of the Ripon Formation along national road N10 between Paterson and Cookhouse (Olifantskop Pass); (b) Greyish mudstones rhythmite intercalated with mudrock layers along the Ecca Pass; (c) Grey mudstones alternating with minor sandstones along national road N2 between Grahamstown and Peddie (Longitude E 26°56′29.93″; Latitude S 33°15′27.76″); (d) folded strata of the Fort Brown Formation along national road N2 between Grahamstown and Peddie (Longitude E 26°57′1.44″; Latitude S 33°15′ 14.01″); (e) Wavy ripple lamination in the sandstone.

intercalation (Srl). The basal part of FA 7 is made up of the Frh facies, whereas mudstones are intercalated with Srl facies in the upper part of FA 7. Thus, they show coarsening upward sequence. In addition, thickness of the sandstone layers increases upward. Several finely laminated siltstones and a few medium-bedded sandstones are present in the upper part of FA 7.

4.5.1.1 Interpretation

The regular alternation of layers of light (coarser) and dark (finer) sediments (varved rhythmite) possibly signifies a fluctuating sedimentary supply. Alternating sandstone and mudrock beds within this facies represent deposition under fluctuating energy conditions. The mudrock beds

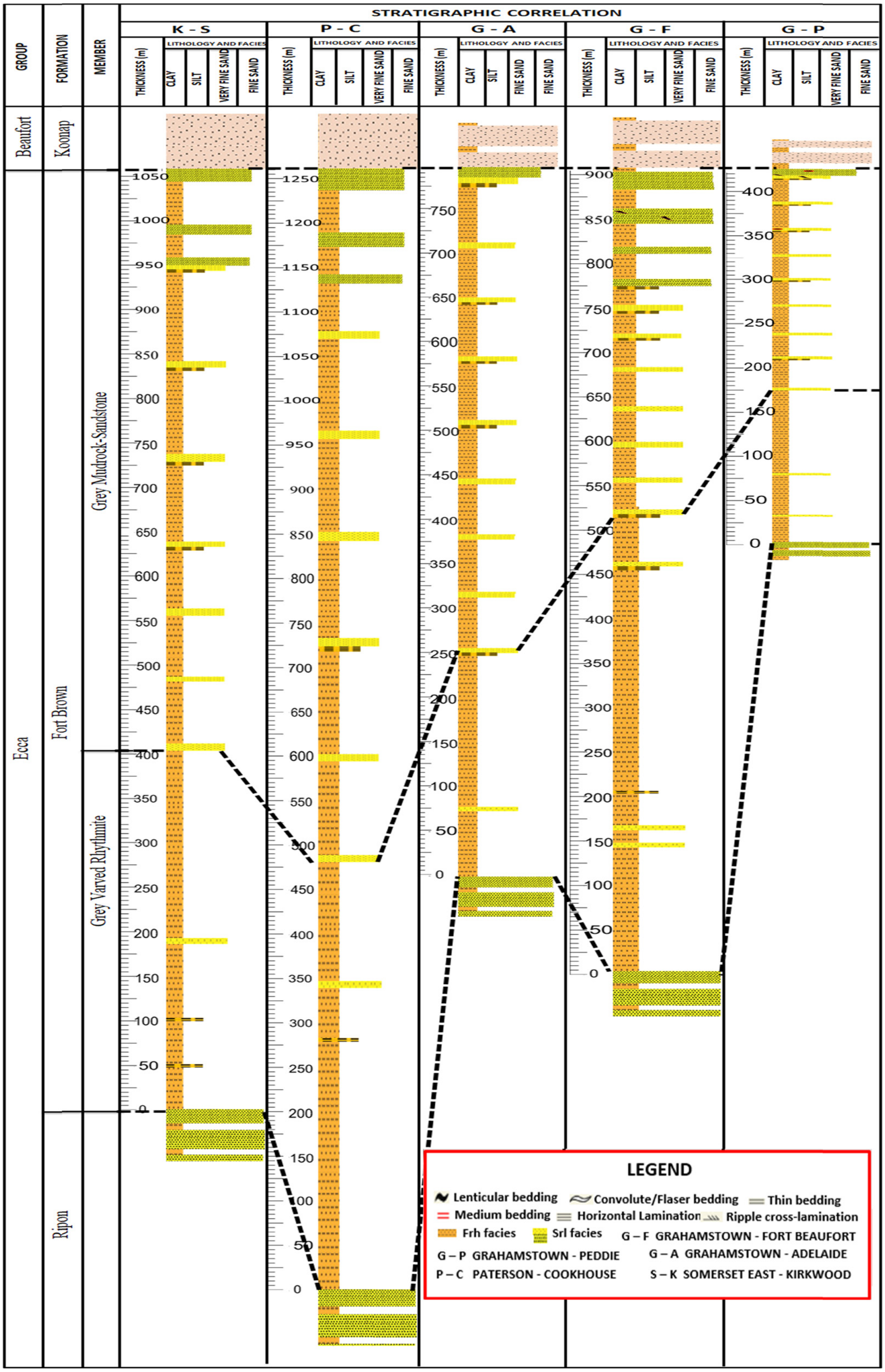

Figure 21: Stratigraphic correlation of the Fort Brown Formation in the study area.

consist of horizontal bedding indicative of low energy deposition by suspension settling, whereas ripple laminations are present in the sandstone beds, indicating deposition under lower flow regime conditions [38,39]. Ripple lamination formed as a result of reworking by dilute turbulent flows with moderate aggradation rates. The repetitive nature of the mudrock and sandstone beds points to a pulsatory depositional system. The FA 7 is believed to have been deposited in a deep-water depositional environment, which is thought to represent deposition at a shallower water depth to that of the underlying sequences (prodelta environment). Hence, the Fort Brown rhythmites are deep-marine shelf shales and prodelta deposits. The presence of finely laminated siltstone in the upper part of FA 7 points to continuous sedimentation from suspension in a more shallowing up environment. The increase in number of the sandstone beds in the Upper member supports deposition in deep-water prodelta environment. The occurrence of wave ripples, the overall coarsening upward sequence, and an increase in the number of sandstone beds in the upper part of FA 7 possibly indicate a slightly more proximal setting in the prodelta environment [17]. The sandstone beds were perhaps washed into the basin during periods of high-energy floods, leading to the development of ripples in areas with sufficient sand (rippled sandstones). The presence of large-scale wave ripples also points to shallowing up of the basin. The occurrence of few thin micrite laminae in the upper part of FA 7 also support the shallowing of the environment [20]. The stratigraphic correlations of the Ecca Group within the study, from both borehole logs and outcrop sections, are presented in Figures 22 and 23.

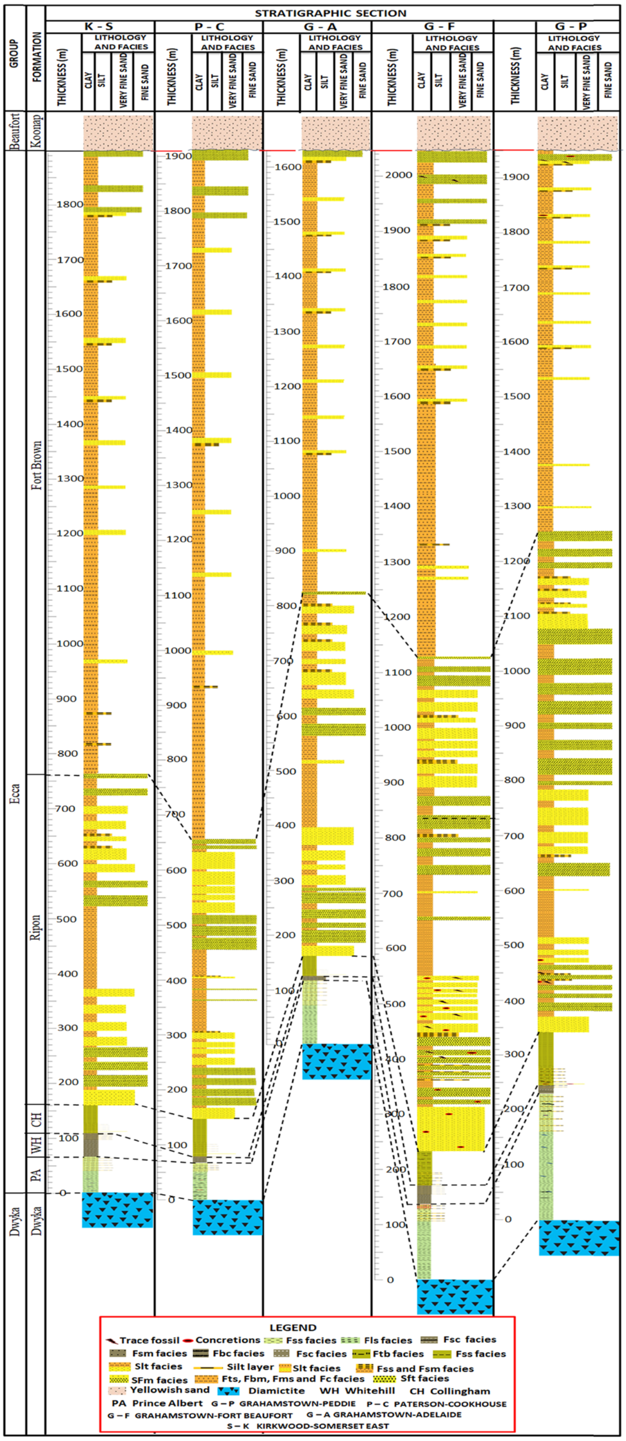

Figure 22: Stratigraphic correlation of the Ecca Group within the study area.

5 Facies model

Internal sedimentary structures (i.e. ripple lamination, climbing ripple marks and cross-lamination, etc.), lithofacies (Fls, Fss, Fsc, Fbc, Fsm, Ftb, Slt, SFt, Fts, Fc, Fbm, Fms, SFm, Frh, and Srl facies), their interrelationship, sequence, and FA (FA 1–7)) are taken into consideration for the interpretation of depositional environments. On a small scale, each of the stratigraphic member or formation is associated with a distinctive sedimentary facies based on their lithological characteristics and sedimentary structures. The facies model for the depositional environment of the Ecca sediments is expressed as a paleo-geographical and depositional process restoration, which shows deep-marine basin and turbidity dynamics as well as their deposits, by using a simplified depositional model for the Ecca Group in the south-eastern 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), mid-fan, and proximal fan to slope consisting of hemipelagic sediments that enclose large sandstone bodies resulting from the filling of fan feeder systems. This was done in accordance to published models [37] which attempted to combine the model of [40–42] on a research of facies, facies models, and modern stratigraphic concepts. The proposed depositional model for the Ecca sediments in the southeastern Karoo Basin in South Africa is depicted in Table 3 and Figure 24.

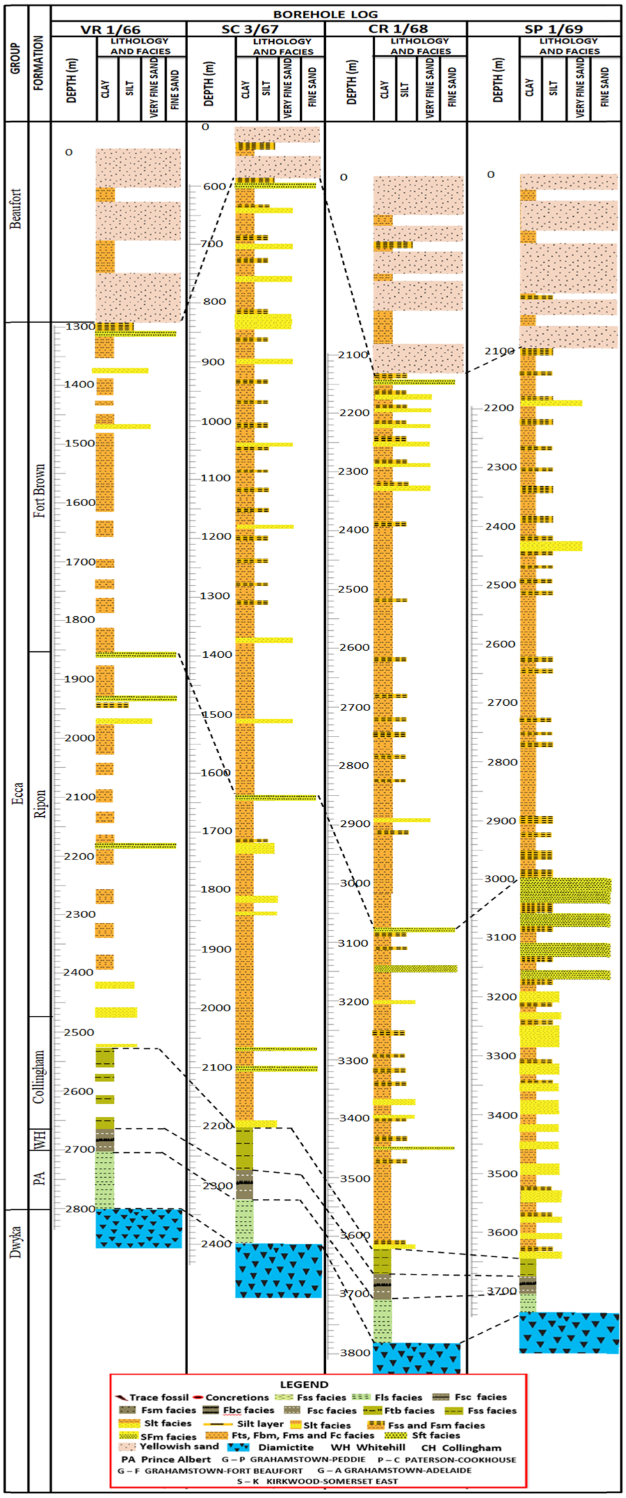

Figure 23: Stratigraphic correlation of the borehole logs within the study area.

Table 3: Interpretation and depositional environment of the Ecca Group in the study area

Group	Formation	Member	Lithology	Interpretation	Depositional Environment	Climate change
Ecca	Fort Brown (FA 7)	Upper Grey Mudstone–Sandstone	Shale–Sandstone	Prodelta sediments	Relatively deep marine	Warm temperature
		Lower Grey Varved Rhythmite	Mudstone–Siltstone	Prodelta sediment	Relatively deep marine	
	Ripon (FA 4–6)	Upper Black Mudstone–Sandstone	Sandstone–Shale	Proximal turbidites	Relatively deep marine	Mild/relatively warm temperature
		Middle Black Shale–Sandstone	Shale–Sandstone	Pelagic sediments	Deep marine (Relatively deep water)	
		Lower Grey Greywacke–Mudstone	Sandstone–Mudstone	Distal outer fan turbidites	Deep marine	
	Collingham (FA 3)	Upper Grey Mudrock	Shale–Claystone	Distal turbidites	Continental slope turbidite	Cool temperature
		Lower Black Shale–Tuff	Shale–Tuff–Siltstone	Distal turbidites mixed with falling tuff	Continental slope turbidite	
	Whitehill (FA 2)	Upper Grey Mudrock	Shale–Mudstone–Chert	Distal deep sea rift sediments	Deep marine	Cold temperature
		Lower Black Shale–Chert	Shale–Chert	Deep sea rift sediments (Deep sea floor)	Deep marine (restricted deep-basin)	
	Prince Albert (FA 1)	Upper Khaki Mudrock	Shale–Mudstone–Siltstone lenses	Deep sea basin	Deep marine	
		Lower Grey Mudstone	Shale	Deep sea plain	Deep marine	

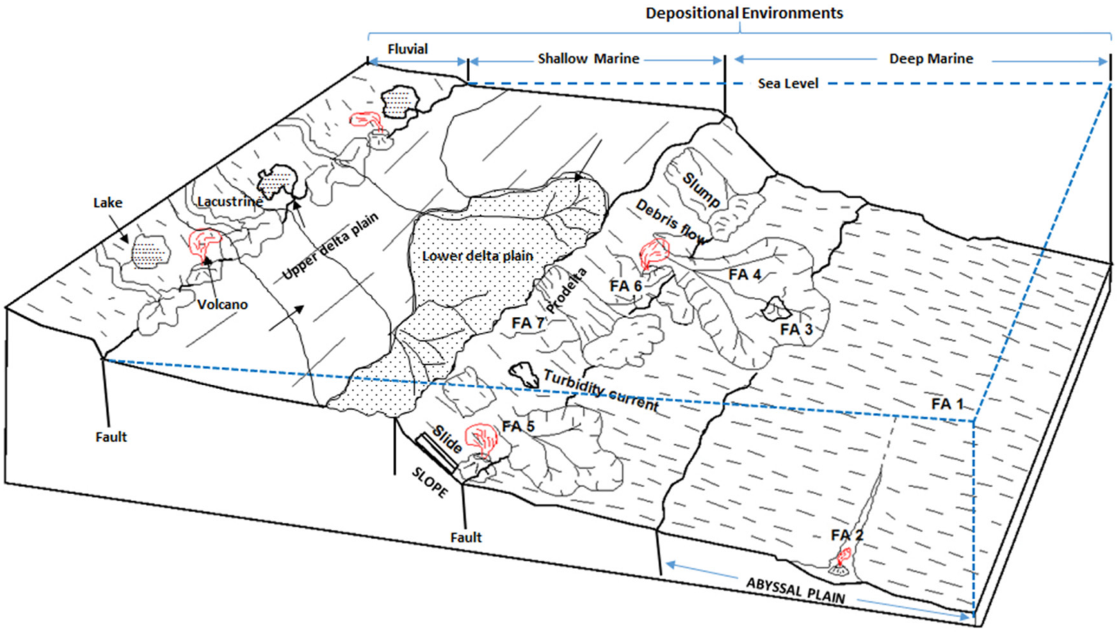

Figure 24: Proposed depositional model for the Ecca sediments in the Eastern Cape Province of South Africa (Modified from [21]). Note: The proposed model is restricted to the study area and thus cannot be used to directly represent other part of the basin since stratigraphy of the group in the northern (distal) region differs from the stratigraphy in the southern (proximal) region.

6 Discussion

The Prince Albert, Whitehill, Collingham, and Fort Brown Formations in this study have been further subdivided into two members each, while the Ripon Formation is subdivided into three members. The new names for the members were coined from lithological features (mainly colour and rock types). From west to east, the measured thickness of the whole Ecca Group along the roads R350 (North of Kirkwood-Somerset East), N10 (Cookhouse-Paterson), R344 (Grahamstown-Adelaide), R67 (Ecca Pass; Grahamstown-Fort Beaufort), and N2 (Grahamstown-Peddie) are 1,893, 1909.6, 1625.3, 2,057, and 1738.2 m, respectively (Figure 22), while the borehole logs (CR 1/68, SP 1/69, VR 1/66, and SC 3/67) are 1508.8, 1798.3, 1645.3, and 1673.4 m, respectively (Figure 23). The stratigraphic succession of the Ecca Group was interpreted as a regression sequence, showing that the marine water slowly retreated and the sea-level steadily falls [43–50]. The stratigraphic correlation of the measured sections and borehole core logs shows that the Ecca Group generally undulates in thickness in the study area. The undulations in the thickness of the Ecca Group across the study area are inferred to be due to synsedimentary deformation. The main deformation that took place in the Cape Fold Belt at about 250 Ma affected the Proterozoic meta-sediments, as well as the overlying Paleozoic cover [51]. The Karoo Basin was first referred to as a passive margin [44]. Subsequently, it was generally referred to as a retro-arc foreland basin, with fills in front of the Cape Fold Belt situated in southwestern Gondwana [52]. The rocks of the Cape Supergroup are more resistant to erosion when compared to the softer rocks of the Karoo Supergroup. The sedimentary fill of the Karoo Basin is the result of crustal uplift, fault-controlled subsidence, and long periods of regional subsidence during which faulting was subordinate [8,9]. The lower units of the Karoo Basin, as well as the Cape Supergroup rocks, were deformed at about 250 Ma, with the formation of north-vergent asymmetric or overturned folds and thrust faults [53]. The development of the Cape Fold Belt during the deposition of sediments within the Karoo Basin greatly influenced the depositional environments within the basin and is in turn considered as the major source of detritus to the Karoo Supergroup. The intense deformation of the Cape Supergroup strata and some lower units of the Karoo Supergroup along the southern margin of the basin are considered to be a direct consequence of the orogeny [13].

The glacio-marine sediments of the Dwkya Group are overlain successively by the Prince Albert, Whitehill, Collingham, Ripon, and Fort Brown Formations. Based on sedimentological evidences, deep-marine environment (mainly deep-sea basin sediments) is inferred for the

Prince Albert Formation. Using a ternary plot of phytoclasts-amorphous organic matter (AOM)-palynomorphs, a marginal dysoxic-anoxic depositional environment was reported for the Prince Albert Formation [46]. The organic matters in the Prince Albert Formation accumulated under reducing or anoxic condition in a deep-marine environment probably were the main source for shale gas hosted in the Ecca Group. The Whitehill Formation which corresponds to FA 2 is suggested to have been deposited in a more restricted part of the deep marine (probably, deep sea floor), thus allowing the chert layers to develop and is also supported by palynofacies [46]. They suggested a stratified deep basin setting for the southeastern part of the main Karoo basin based on the low marine phytoplankton percentages (prasinophytes), good amorphous organic matter (AOM) preservation, high terrestrial input, and a moderate spores-bisaccates ratio.

The Collingham Formation is interpreted as suspension settling of mudstones intermixed with distal turbidites. Turbidites in ancient and modern basins are mostly reported from deep-sea marine sedimentary systems near continental slope, thus synsedimentary deformation could have occurred as a result of slope instability. However, turbidity currents could have existed also in shallow and non-marine environments [45]. The turbidity current that transported the sediments into the deep basin is thought to be non-channelized or have spread across a wide front from a depositionally active prograding slope as envisaged by [17] rather than turbidity current that moved along the channels. The analysis of the palynofacies assemblages of the Collingham shales along the Ecca Pass revealed a high content of both AOM and prasinophytes, which are usually associated with a deep, stratified marine basin [46]. In addition, the palynofacies of the studied Collingham shales data are plotted in the field representing shelf to basin transition with suboxic-anoxic conditions. The turbidity current that transported the sediments into the deep basin is thought to be non-channelized or have spread across a wide front from a depositionally active prograding slope rather than turbidity current that moved along the channels [17].

The combination of FA 4, FA 5, and FA 6 makes up the Ripon Formation and it is envisaged that the formation was deposited in a relatively deep-water environment, perhaps representing mid-fan or inter-channel deposits. The erosive contacts as well as the fine- to medium-grained sizes of the sandstones point to a position in the “middle-fan region between proximal and distal close enough to the sediment source to account for the medium grained sand and high-energy deposition, but far enough away to account for the massive-bedded style” [47]. A position that is very close (proximal) to the source would remove the possibility of large inter-channel areas, whereas a position that is far away (distal) from the source would eliminate the erosive power of the turbidity current [47]. The turbidity current that transported the Ripon sediments down the slope must have spread across a wide front from a depositionally active prograding slope instead of turbidity current that moved along the channels [17]. The Fort Brown Formation, which corresponds to FA 7, is inferred to represent deep-water deposits, which are thought to represent deposition at a shallower water depth to that of the underlying sequences deep-marine deposits. The formation is more argillaceous and [17] proposed that it represents deposition in a prodelta setting. The absence of turbidite features in the Fort Brown Formation is interpreted as a prograding sequence in a delta-slope environment [48]. The increase in the sandstone interbeds upwards as well as the occurrence of wave ripples in the upper part of FA 7 and the general coarsening upward sequence of FA 7 points to slightly more proximal turbidites in the prodelta setting and shallowing up of the basin as a result of continued accumulation or deposition of sediments. The inferred depositional environments are in agreement with the works of several researchers [4,42–44] that previously documented depositional environments of the Ecca sediments in southern Africa.

Field and petrographic observations from the studied formations document facies change, water depth variation, sea-level, and climate alteration which are reflected in Table 3 in agreement with the generally accepted model of Karoo Supergroup. The Prince Albert, Whitehill, and Collingham Formations were suggested to have formed due to the accumulation of starved sediments in a stratified, reducing (anoxic) water column [2]. On the contrary, [47] suggested that the depositional setting of the Prince Albert Formation is not completely anoxic due to the lack of abundant black shales, gypsum, and sulphides. There is a possibility that the depositional environment could have been sub-oxic, reason being that the sediment seems to contain significant amount of organic matter. The Ripon Formation is overlain by the delta-lacustrine deposits of the Fort Brown Formation. The changes in the depositional environments of the Ecca Group from deep-water marine environment to prodelta environment are evident and recorded by the lithological, sedimentary structural, and environmental changes in the rock record. This is in agreement with the work of ref. [46] using new palynological and sedimentological data to unravel the depositional environment of the Ecca Group. As documented by ref. [46], deep marine to prodelta depositional setting is inferred for the Ecca Group. Ref. [46] reported that the present palynofacies data obtained from different part of the main Karoo Basin in South Africa indicate a "much more complex basin architecture with partly – regionally and temporally – restricted and stratified areas".

In Africa, the most widespread and thick Phanerozoic deposits are those of the Karoo Supergroup, which are well-preserved throughout southern Africa. The deposition and accumulation of Karoo successions in southern Africa were in response to the Pangean first-order cycle of supercontinent assembly and subsequent break-up [4]. Therefore, the Karoo Basin represents episodes of subsidence and sedimentation within the interior of Gondwana [8,9], with depocentres changing from a passive continental margin in the Early Paleozoic to a landlocked foreland basin during the Permo-Triassic [10]. During the Early Paleozoic, most of the continents gathered around the equator, with Gondwana (representing majority of the old Rodinia) slowly drifting south across the South Poles. This resulted in two episodes of glaciation; the latest which occurred during the Carboniferous led to the deposition of tillite (Dwyka glaciation) [54]. The glaciation was related to the formation of ice-caps on elevated coastal ranges and in high lying interior regions. These regions were thought to be "ice spreading centres" for Gondwana ice sheets in the Late Carboniferous, signifying the onset of sedimentation in the Karoo Basin [10,13]. By the Mid Carboniferous, the ice-caps were located on the uplifted Pampean-North Patagonian-Deseado massif from where glacial sediment was shed towards the south. During this time, the interior of the supercontinent uplift axes was located in the Damara and Mozambiquan Mobile Belts, perhaps pointing to the existence of a major stress regime. The accreting Panthalassan terrane joined with the mainland and formed a transtensional foreland basin that may have led to a reversal in sediment supply [55].

At about 310 Ma, a subduction zone developed along the southern margin of Gondwana due to closure of the rift valley that started at about 330 Ma, and the internal part of the supercontinent began to experience compression [49]. This caused the sedimentary rocks of the Cape Supergroup to begin to fold or buckle and the crust thickened, forming a mountain range in the place where the Agulhas Sea formerly existed. Thus, the earlier known Agulhas Sea became the Cape Mountains. According to [49], at the time of formation of the Cape Mountain, South Africa was believed to be located over the South Pole due to the steady northward drifting of Gondwana. The ice sheet that covered the southern Gondwana (i.e. Africa) was probably of several kilometers thick. The glacial deposits from the ice sheet were the first of the sediments to be deposited in the developing Karoo depression, thus making the Dwyka Group as the earliest and lowermost of the sedimentary deposits of the Karoo Supergroup. The basin in which the sediments were deposited was deepest in the south along the Cape Mountain front, thus the ice sheet floated on an inland lake, also known as the Karoo inland sea [49]. Subsequently, the glaciers that emerged from the mountains floated out of the sea as icebergs; they seasonally melted and retreated leaving some enormous quantities of unsorted mud and large fragments of rock that characterized the Dwyka Group. The earliest Karoo sedimentary rocks (about 330–300 Ma) must have been over-thrusted, "cannibalized," and included within the structures of the Cape Fold Belt [56]. According to ref. [8], the Cape orogeny is predated by the dynamic phase of subsidence experienced by the early Karoo basin during the Permian. They suggested rapid rate of collapse of the Carboniferous high plateau due to the lack of marked transition to the Dwyka basement high and platform FA. Vertical displacement of rigid basement blocks decoupled along crustal-scale boundary was the main subsidence that occurred, which is revealed in the distribution of the Dwyka FA [8]. The rate of subsidence of the Namaqua and Natal blocks exceeded the rate in which sediments were supplied, and thus led to the under-filled basin of the platform facies association. The different types of glacial deposits in the Dwyka Group are attributed to the several episodes of advance and retreat of the ice sheets [49].

Continued northward drifting of the Gondwana away from the polar region caused all the ice to melt; after all the ice had melted, a vast inland water body (inland sea) remained, which extended across South Africa and the neighboring regions of Gondwana. According to [49], this inland sea might have had an opening to the ocean, but with a lesser or small tidal effects (probably, it is similar to the Black Sea). The Cargonian Highlands formed the high ground, north of the sea, and the rivers draining the mountains that are north of the Karoo Sea deposited their sediments along the northern shoreline, forming large swampy deltas. However, some of the sediments deposited into the Karoo Sea were derived from the Cape Mountain to the south of the basin. These latter deposits make up the Ecca Group of the Karoo Supergroup, consisting of mudrocks and sandstones. The style of subsidence in the Dwyka Group continued into the Ecca Group which is an under-filled basin, dominated by argillaceous sedimentation [9].

During the Ecca time, the Falklands Plateau collided and was later joined with the southern Africa, resulting in the range of mountains that is seen south of the Cape

Fold Belt. The Karoo Basin subsidence resulted from mantle flow, but becomes complex due to variable degrees of foundering of the basement blocks [9]. These basement blocks are coincident with the Hex River area oroclinal bend in the present day Cape Fold Belt and possibly behaved as a buried basin boundary during the Ecca Group time, probably influencing the position of the shelf edge in a way that is similar to a passive margin [9]. With the continued accumulation or deposition of sediments into the Karoo Sea as well as formation of the Falkland Plateau and Cape Fold Mountain ranges, the Karoo Sea gradually got filled with sediments that were mostly derived from the Cape Mountains in the south. By this time, the highlands that were formed, north of the Karoo Sea, had been probably levelled by erosion and subsequently buried beneath the newer sediments, and the Mississippi-like rivers flowed over the filled-up Karoo Basin from the south, providing new habitats for a variety of flora and fauna. These newer sediments form the overlying Beaufort Group. The deduced depositional environments (Table 3 and Figure 24) are indicative of a gradual shallowing of the depositional environment. This also agrees with the findings of [49,50] that the deeper marine facies of the lower Ecca Group was accumulated during the under-filled phase of the foreland system, whereas the shallow marine facies of the upper Ecca Group corresponds to the filled phase of the basin, which was followed by an overfilled phase dominated by fluvial sedimentation of the Beaufort Group. It is recommended that in the future study of a depositional environment of the Ecca Group across the Karoo, it would be more appropriate to integrate sedimentological, palynological, and geochemical data to unravel the complexity about the post-glacial basin with regard to their depositional history.

7 Conclusion

The study on the sedimentary facies, stratigraphy, and depositional environments of the Ecca Group in the Eastern Cape Province of South Africa was performed to give new insight to enhance the understanding of the depositional environment of the Ecca Group. The formations of the Ecca Group have now been further subdivided into informal stratigraphic members. The stratigraphy of the Prince Albert, Whitehill, Collingham, and Fort Brown Formations is subdivided into two informal members each, while the Ripon Formation is subdivided into three informal members. The new names for the members were coined from lithological features (mainly colour and rock types). From west to east, the measured thickness of the whole Ecca Group along the roads R350 (North of Kirkwood-Somerset East), N10 (Cookhouse-Paterson), R344 (Grahamstown-Adelaide), R67 (Ecca Pass; Grahamstown-Fort Beaufort), and N2 (Grahamstown-Peddie) are 1,893, 1909.6, 1625.3, 2,057, and 1738.2 m, respectively, while the borehole logs (CR 1/68, SP 1/69, VR 1/66 and SC 3/67) are 1508.8, 1798.3, 1645.3, and 1673.4 m, respectively. The stratigraphic correlation of the measured sections and borehole core logs shows that the Ecca Group generally undulates in thickness in the study area. The undulations in the thickness of the Ecca Group across the study area are inferred to be due to deformation, which are considered to be a direct consequence of the orogeny. This structural phenomenon is most likely related to tectonism which took place during the compressional phases associated with the Cape Fold Belt, during the Permian/Triassic Periods. A total of twelve lithofacies were identified in the Ecca Group, which were further grouped into seven distinct FAs. Based on the stratigraphic and facies analyses, it can be inferred that the Prince Albert and Whitehill Formations are deep-marine deposits. The Collingham Formation is a typical turbidite deposit. The Ripon Formation represents mid-fan deposits. The Fort Brown Formation represents prodelta deposits. This shows that the incoming sediments were gradually filling up the Karoo basin, thus resulting in the gradual decrease of the water depth or shallowing up of the basin, which also concur with the general believe that the overlying Beaufort Group was deposited in a fluvial environment as a result of the continuous retreating or dropping of water depth or sea-level in the Karoo Basin. With time, the once prevailing reducing environment finally changed to an oxidic continental inland environment.

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