STEPPING OUT ACROSS THE KAROO RETRO-FORELAND BASIN: IMPROVED CONSTRAINTS ON THE ECCA-BEAUFORT SHORELINE ALONG THE NORTHERN MARGIN.

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The Karoo Supergroup of South Africa, internationally renowned for its almost continuous Carboniferous to Jurassic record of deposition in a foreland basin setting, hosts an unparalleled record of fossil tetrapods that provides unique insight into terrestrial biodiversity change over this extended period. Understanding of the litho-, bio- and chronostratigraphy of the Karoo Basin has greatly improved in recent years but most work has focused on the thicker and better-exposed rocks in the basinal foredeep. A core issue that has remained ambiguous is the stratigraphic placement of the diachronous Ecca-Beaufort contact, for which different criteria have been used during mapping in different parts of the main Karoo Basin. Comparison of biostratigraphy and contrasting lithological facies changes with those in the better-studied foredeep enabled us to revise the lithostratigraphy of the Ecca and Beaufort groups in the distal part of the main Karoo Basin. The presence of proximal marine facies associations in the distal sector conform with the definition of the Waterford Formation of the Ecca Group, so far recognised only in the southern foredeep. The upper contact of the Waterford Formation represents a change from a subaqueous to a subaerial delta plain depositional environment and marks the boundary between the Ecca and Beaufort groups, as in the south. This has consequences for Beaufort Group stratigraphic subdivision in the distal sector of the Karoo foreland basin.

Keywords: Ecca Group, Beaufort Group, biostratigraphy, Permian, Ecca sea, *Tapinocephalus* Assemblage Zone, *Daptocephalus* Assemblage Zone

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1 Introduction

The main Karoo Basin of South Africa, because of its wealth of fossils, excellent outcrops, and dateable ash beds, has become an archetype for understanding deposition in foreland-type depobasins (e.g. Catuneanu, 2004; Catuneanu et al., 2005). Based on differing lithological characteristics, including facies, age, provenance, transport direction and stratal stacking patterns, the main Karoo Basin has been divided into three regions: the proximal south-western (west of 24° E), south-eastern (east of 24° E) and the distal northern or north-eastern region (SACS, 1980; Catuneanu et al., 1998; Johnson et al., 2006). Reflecting this, different lithostratigraphic names have been used to delineate the stratigraphy in these different parts of the basin (Figure 1; SACS, 1980; Johnson et al., 2006). Revision of this subdivision around the basin by the South African Committee for Stratigraphy (SACS) is ongoing e.g. the synonymisation of the now defunct Koonap Formation with the Abrahamskraal Formation of the Beaufort Group (Cole et al., 2016) and the amalgamation of the Normandien Formation with the Balfour Formation on the 2019 1:1 000 000 Geological map of South Africa (Council for Geoscience, 2019; D. Cole personal communication 2018, 2019).

Despite the well-developed litho- and biostratigraphic schemes for the Karoo Supergroup, the stratigraphic placement of the contact between the Permian Ecca and Beaufort groups remains inconsistently defined (e.g. Johnson, 1987). Previous criteria for determining the contact range from the first appearance of “reptilian fossil remains” (Schwarz, 1896; Rogers et al., 1909), the first appearance of “purplish shale or mudstone” (e.g. Mountain, 1946; Keyser and Smith, 1979), the “base of the first sandstone displaying an erosive contact” (Loock and Grobler, 1988), and the “base of the first prominent sandstone overlying the argillaceous Ecca Group” (Rogers et al., 1909; Ryan, 1967; Zawada, 1988a; Zawada and Cadle, 1988; Groenewald, 1989; Muntingh, 1989, 1997). This has resulted in mismatch of the

63 placement of the Ecca-Beaufort contact between the geographically distant proximal
64 (southern) and distal (northern) sectors of the main Karoo Basin.

65 This issue is compounded because the distal northern region has received less research
66 attention than the proximal south-western and south-eastern parts of the basin, where
67 outcrops are better exposed, and the stratigraphic sequence is most complete. Furthermore,
68 previous work on Permian Beaufort Group strata in the north of the basin (e.g. Theron, 1970;
69 Csaky and Wachsmuth, 1971; Cadle and Proedrou, 1975; Bars and Guillebert, 1976; Turner,
70 1977; Groenewald, 1984; Zawada, 1988a; Groenewald, 1989; Muntingh, 1997; Cole and
71 Wipplinger, 2001; Neveling, 2004; Rutherford, 2009; Mavuso, 2014; Rutherford et al., 2015)
72 had a strong focus on the sedimentology of the rock units, with only limited palaeontological
73 and biostratigraphic work being undertaken (e.g. Groenewald, 1989, 1990; Welman et al.,
74 2001; Hancox et al., 2002; Latimer et al., 2002; Rubidge et al., 2015; Rutherford et al., 2015;
75 Groenewald et al., 2019). Because of this, current understanding of vertebrate distribution in
76 the main Karoo Basin and mid- to late Permian Beaufort Group biostratigraphy is based
77 mostly on results from the southern parts of the basin (e.g. Kitching, 1977; Keyser and Smith,
78 1979; Rubidge, 1995, 2005; Mason, 2007; Rubidge et al., 2013; Mason et al., 2015; Smith et
79 al., 2020).

80 This paper reports on the sedimentary characteristics documented across the Ecca-Beaufort
81 contact in the distal sector of the main Karoo Basin (sensu Catuneanu et al., 1998) and
82 assesses whether the same criteria used to define the Ecca-Beaufort contact in the proximal
83 sector of the main Karoo Basin can be applied to these outcrops. Based on the stratigraphic
84 and geographic distribution of tetrapod fossils, we refine the biostratigraphy of the lowermost
85 Beaufort Group in the north of the main Karoo Basin and discuss the presence of the
86 Waterford Formation in the north of the basin and the consequent implications for the status
87 of the Normandien Formation.

2 Geological and palaeontological setting

Fieldwork was undertaken along the mapped Ecca-Beaufort contact in the distal sector of the main Karoo Basin, from Philippolis in the Free State to Estcourt in KwaZulu-Natal (Figure 1). Rock units that were focused on include the uppermost Ecca Group (Tierberg, Volksrust, and Waterford formations) and lowermost Beaufort Group (Adelaide Subgroup and Normandien Formation).

2.1 Ecca Group

The Ecca Group in the Free State and KwaZulu-Natal Province comprises the Prince Albert, Whitehill, Tierberg, Pietermaritzburg, Vryheid, Volksrust, and Waterford formations (SACS, 1980). Of these, the Tierberg, Volksrust, and Waterford formations comprise the upper part of the Ecca Group in the field study area (Linström, 1973; Zawada, 1988a; Groenewald, 1989; Muntingh, 1989, 1997; Welman et al., 2001). Except for the Vryheid Formation, rocks of the Ecca Group, are predominantly argillaceous and have been interpreted as having been deposited in marine-to-marginal marine (paralic) settings (Johnson, 1976; Van Vuuren and Cole, 1979; Cairncross and Cadle, 1988a, 1988b; Tavener-Smith et al., 1988; Cadle et al., 1993; Veevers et al., 1994; Cairncross, 2001; Viljoen, 2005; Johnson et al., 2006; Green and Smith, 2012; Hancox and Götz, 2014). While it is generally accepted that the lower part of the Ecca Group (Prince Albert Formation) was deposited under marine conditions, several studies suggest that the upper parts of the Ecca Group were deposited under brackish-to-fresh water conditions (Zawada, 1988b; Veevers et al., 1994; Muntingh, 1997), with the Waterford Formation representing the progradation of delta front and delta plain sands, and shallow marine-shelf sediments (Rust et al., 1991; Smith et al., 1993; Rubidge et al., 2000; Cole and Wipplinger, 2001).

2.2 Beaufort Group

This study focuses on rocks of the Adelaide Subgroup, which comprises a succession of mudstones and sandstones generally interpreted as having been deposited in various terrestrial fluvial to lacustrine environments (Smith et al., 1993; Johnson et al., 2006; Paiva, 2015). In the south-western part of the basin, the Adelaide Subgroup comprises sandstones and mudrocks of the Abrahamskraal and Teekloof formations (Figure 1), with the former characterised by the presence of a number of cherty beds and less red mudstone relative to the overlying Teekloof Formation (Keyser and Smith, 1979; SACS, 1980). In the south-eastern areas, it comprises the Abrahamskraal, Middleton and Balfour formations (Johnson, 1976; Day and Rubidge, 2014; Cole et al., 2016; Viglietti et al., 2017a, 2017b). In the southern and central Free State Province, individual formations within the Adelaide Subgroup have not yet been formally recognised and the Beaufort Group is mapped only at subgroup level on the most recent 1:250 000 geological map sheets. Using both lithological and biostratigraphic data, however, Groenewald *et al.* (2019) were able to distinguish between the Abrahamskraal and Balfour Formation in the southern Free State. Further north and east, in the eastern Free State and KwaZulu-Natal provinces, the only formation of the Adelaide Subgroup is the Normandien Formation, which has been equated with the now informal Estcourt Formation of Linström (1973) in KwaZulu-Natal (Johnson et al., 2006; Bordy and Prevec, 2008). Groenewald (1984, 1989) recognised four mappable units in the Normandien Formation (from bottom to top): the arenaceous Frankfort, Rooinek, and Schoondraai members, and argillaceous Harrismith Member (Figure 1). Two unnamed argillaceous intervals, rich in fossil leaf impressions, separate the Rooinek Member from the underlying Frankfort and overlying Schoondraai members, but the two are difficult to distinguish from one another in the field (Groenewald, 1984; Claassen, 2008). It has been proposed (Groenewald, 2015; Rammutla, 2016) that the majority of the Frankfort Member of the Normandien Formation,

which represents deposition under prodelta and lower delta-plain conditions, should be considered the lithostratigraphic equivalent of the Waterford Formation and should therefore be included within the Ecca Group rather than the Beaufort Group

Rocks of Abrahamskraal Formation host fossils of the *Eodicynodon* and *Tapinocephalus* assemblage zones (Day and Rubidge, 2020; Rubidge and Day, 2020). The overlying Teekloof Formation has yielded fossils of the *Endothiodon*, *Tropidostoma*, *Cistecephalus*, *Daptocephalus* assemblage zones. Fossils of the *Cistecephalus*, *Daptocephalus*, and *Lystrosaurus declivis* assemblage zones have been recovered from rocks of the Balfour Formation (Smith et al., 2020), which is correlated with the Normandien Formation based on the occurrence of *Dicynodon lacerticeps* and *Daptocephalus leoniceps* (Groenewald, 1990; Smith et al., 1993).

2.3 Ecca-Beaufort Contact

In the southern Karoo Basin, the currently accepted lithostratigraphic contact between the Ecca and Beaufort groups is taken at the Waterford- (uppermost Ecca Group) Abrahamskraal (lowermost Beaufort Group) contact (Cole *et al.* 2016; Rubidge *et al.* 2012). This reflects a change in depositional environment from subaqueous conditions to subaerial fluvial environments (Johnson, 1976; Rubidge et al., 2000, 2012; Welman et al., 2001; Mason et al., 2015). However, the Waterford Formation is not mapped north of 30° 40’ S (1:1M Geological Map 2019, Council for Geoscience, Pretoria), with the contact of the Ecca and Beaufort groups instead being shown at the contact between the shales of the Tierberg or Volksrust formations and the more arenaceous strata of the Adelaide Subgroup (Linström, 1973, 1981; Groenewald, 1984, 1987; Zawada, 1987a, 1988a; Zawada and Cadle, 1988; Muntingh, 1989; Schutte, 1993; Muntingh, 1997). Lithofacies very similar to those of the Waterford Formation, and interpreted as having been deposited in a prograding deltaic environment, have been recorded in the north of the basin (Linström, 1973; Turner, 1977;

Groenewald, 1984; Zawada, 1988a; Zawada and Cadle, 1988; Muntingh, 1997). The presence of the Waterford Formation has not, however, been formally recognised.

Welman *et al.* (2001) were the first to consider the Waterford Formation to be present in the southern Free State near Philippolis and placed the Ecca-Beaufort contact at the top of this formation. Similarly, strata mapped as lowermost Beaufort Group in the central and north-eastern Free State and KwaZulu-Natal provinces were later considered representative of the Waterford Formation, based on lithological and genetic similarities (Mavuso, 2014; Groenewald, 2015; Rammutla, 2016).

3 Materials and Methods

Lithostratigraphic investigations involved measuring 16 vertical sections of natural outcrops with Jacob's staff and Abney level, supplemented with data from the literature, and by logging two borehole cores stored at the Council for Geoscience National Core Library at Donkerhoek, Pretoria (see Supplementary Table 1 for the GPS coordinates and Groenewald 2021 for the individual sections). Because this study focussed on the Ecca-Beaufort contact, sections were started in the upper parts of the Volksrust or Tierberg formations where possible and measured upwards as high up into the Beaufort Group as the exposures permitted in the southern and central Free State and KwaZulu-Natal, and to within the arenaceous Schoondraai Member of Groenewald (1984) in the north-eastern Free State. Features such as lithology, colour, sedimentary structures, palaeocurrent directions, nodules, fossils, and burrows were all noted. These 18 stratigraphic logs were used to compile six composite sections (Figure 2) that are representative of the interval through the Ecca-Beaufort contact in the study area. This study uses the lithofacies, facies association, and architectural element classification schemes modified from Miall (1996, 2016), Colombera *et al.* (2013), and Gani and Bhattacharya (2007). Lithofacies types (hereafter also referred to as facies) from the study area (presented in Results: Table 1) are given facies codes which

include an upper-case letter denoting lithology (gravel (G), sandstones (S), siltstone and mudstone fines (F) and carbonates (Ca)) followed by a lower-case letter for characteristic features such as sedimentary structures (e.g. r = ripple cross-lamination, t = trough cross-stratification). Where outcrops permitted, architectural element analysis was conducted to aid with palaeoenvironmental interpretation. Based on the geometry of three-dimensional bodies, and arrangement of facies within, 14 principal architectural elements as defined for fluvial systems by Miall (1985, 1996, 2006, 2016), Platt and Keller (1992), and Colombera et al. (2012, 2013), and for deltaic systems by Gani and Bhattacharya (2007) and Ahmed *et al.* (2014) were recognised (presented in Results: Table 2). Considering that invertebrate trace fossils are decidedly more useful as indicators of sedimentary environments than for biostratigraphic purposes (Ekdale et al., 1984; Seilacher, 2007; Buatois and Mángano, 2011; Knaust and Bromley, 2012), ichnofossils have been included in the facies association descriptions where applicable. The co-occurrence of different lithofacies types, architectural elements, and ichnofossils allowed for five facies associations to be recognised (presented in Results: Table 3).

Palaeontological investigation resulted in the discovery of 65 vertebrate fossils that are curated at the Evolutionary Studies Institute (ESI). Their stratigraphic positions were recorded on sections and location documented using a handheld GPS device. Vertebrate fossils were mechanically prepared using air scribes and were identified by the authors and visiting palaeontologists (F. Abdala, K. Angielczyk & C. Kammerer personal communication). The sample was augmented by an additional 342 records of specimens from the Beaufort Fossil Vertebrate database (Nicolas, 2007; Nicolas and Rubidge, 2009; van der Walt et al., 2010). This database is maintained by the ESI and includes fossils stored at the National Museum, Bloemfontein; the Evolutionary Studies Institute, Johannesburg; the Council for Geoscience, Pretoria; Iziko Museum, Cape Town; KwaZulu-Natal Museum,

Pietermaritzburg; and Ditsong Museum, Pretoria. Although more fossils have been recovered from the study area, many of these were collected historically, have poor provenance data attached to them, and/or are too fragmentary or unprepared to be identified. Fossil tetrapod taxa recovered from the study area were compared with those reported from the better sampled southern parts of the basin to determine which vertebrate biozones are present in the north of the main Karoo Basin.

4 Results

4.1 Facies analysis

The six composite sections shown in Figure 2 highlight the lateral differences in thickness of geological formations in the north of the main Karoo Basin. Characteristics of the 15 different lithofacies types, the 14 recognised architectural elements, and the five facies associations are summarised in Tables 1, 2, and 3, respectively, and illustrated on figures 3-6.

Facies associations 1, 2, and 3 form a (generally gradational) coarsening- and thickening-upward succession (Figure 4A). Facies associations 1, 2 and 3 are always overlain by facies associations 4 and 5, which together form discrete fining-upward successions.

4.1.1 Facies Association 1 (Prodelta)

Description: Facies Association 1 (FA1) comprises a monotonous succession of moderate grey to dark grey (Munsell colour: N3 to N5) mudrocks and includes lithofacies types Fl and Fm. Facies Association 1 shows an upwards change from predominantly horizontally laminated and massive mudstones lower down to ripple-laminated and lenticular-to-wavy bedded facies higher up, along with an increase in the abundance and thickness of sandstone beds. This facies association, which is found throughout the study area, always occurs at the base of the stratigraphic section (Figure 2 and 4) and corresponds to the Tierberg and Volksrust formations of the Ecca Group. The Volksrust and Tierberg formations are between

100 and 300 metres thick within the study area (Linström, 1981; Muntingh, 1989; Schutte, 1993).

This mudrock dominated succession corresponds broadly to the "Prodelta Fines" (PF) architectural element described by Gani and Bhattacharya (2007) and Ahmed *et al.* (2014), based on the fine grain size, thickness, and lateral extent. Occasional thin (< 5 cm thick) lenticular- and wavy-bedded lighter-coloured (N6 to N8) silts and very fine sands corresponding to Frontal Splay (FS) architectural elements (Gani and Bhattacharya, 2007; Ahmed et al., 2014) are present. These become thicker and more abundant higher up, at the transition from Facies Association 1 (FA1) to Facies Association 2 (FA2) or Facies Association 3 (FA3).

Facies Association 1 is characterised by a low diversity and abundance of ichnofossils, mostly *Thalassinoides* and *Planolites isp.* (Figure 5). Putative limulid trackways have also been reported from the upper Tierberg Formation in the southern portion of the study area (Anderson, 1975). Stratabound sideritic concretions (< 30 cm) and calcareous nodules (up to 3 m in diameter) were commonly observed. Unidentifiable fossilized fish scales and bones are sometimes present, either within the mudrock or in sideritic nodules. The calcareous nodules typically weather to brown, or sometimes white, and may preserve sedimentary structures such as ripple cross-lamination. The round sideritic concretions are similar to those described from the Mississippian shales at Wardie, Scotland by Bojanowski and Clarkson (2012), and were likely formed during early diagenesis of the fine-grained, organic-rich sediments as a result of precipitation of Fe-bearing authigenic minerals (including siderite and pyrite) prior to significant compaction. Facies Association 1 displays almost no lateral variation throughout the study area and grades vertically into the proximal prodelta (FA2) or lower shoreface (FA3) facies associations, both of which have a much higher proportion of sandstones.

Interpretation: FA1 is interpreted to represent the deposition of silts and clays, predominantly from suspension, in the prodelta environment. This is based on the fine-grained nature, continuous lateral extent, thickness of the facies association, and its basal position in a generally upwards coarsening succession. This interpretation follows studies based on similar muddy facies associations (e.g. Olariu and Bhattacharya, 2006; Fielding, 2010; Ahmed et al., 2014; Jorissen et al., 2018), and is in agreement with previous interpretations from the study area (e.g. Zawada, 1988a; Muntingh, 1990; Cairncross et al., 2005). Deposition is considered to have occurred predominantly from suspension settling in deeper water (beneath wave base), forming finely laminated to massive beds of mudstone. Some of the massive mudstones (Facies Fm) may have been deposited more rapidly, by hypo- and hyperpycnal flow processes (Bhattacharya and MacEachern, 2009). Ripple and wavy laminations, and the deposition of coarser-grained sediments, resulted from occasional influxes of higher energy conditions such as during storms or from floods. The upwards change from predominantly horizontally laminated and massive mudstones lower down to ripple-laminated and lenticular-to-wavy bedded facies towards the top of FA1 records the progradation of the delta front, associated with decreasing water depth, increasing energy conditions, and more proximal deposition.

FA1 is considered to have been deposited under brackish to marine conditions. This interpretation is supported by the presence of the ichnogenera *Thalassinoides* and *Planolites*, the limulid trackways [reported by Anderson (1975)], and the bivalve *Megadesmus* (Cairncross et al., 2005). Marine to brackish conditions during deposition are further supported by trace element analyses undertaken for the uppermost Tierberg and Volksrust formations in the study area (Zawada, 1988b; Muntingh, 1997).

A depauperate ichnofauna may result from a stressed, including brackish, environment (MacEachern et al., 2005; James and Dalrymple, 2010). It has also been noted that

bioturbation density and trace diversity tends to decrease in an offshore direction, e.g. the sharp decrease in diversity and density of trace fossils below ~35 m water depth in the Gulf of Mexico (Dashtgard et al., 2015). The general low abundance and diversity of ichnofossils observed in FA1 suggest that the muds were deposited under dysaerobic conditions, or at least in water with lower dissolved oxygen levels (MacEachern et al., 2005; Dashtgard et al., 2015). Such conditions may be linked to poor circulation or turnover of the water column in distal settings below wave-base (MacEachern et al., 2005).

4.1.2 Facies Association 2 (Delta front)

Facies Association 2 (FA2) includes the lithofacies types Fl, Fm, R, and Sd, with defined sandstone sheets comprising Shx, Sa, Sr, Sh, and Sm. Architectural elements in this facies association include Frontal Splays (FS) and Storm Sheets (SS; Figure 4; Table 2). Architectural elements of FA4, including Sediment-Gravity-Flow Deposits (SG), Bar Accretion (BA), and Channel Fill (CH) elements, are sometimes bounded by FA2 deposits.

Mudstones of FA2 are commonly dark to medium grey (N3 - N5) and sometimes yellow to pale olive (5Y6/4 to 10Y 6/2) in colour. Siltstones and sandstones are typically lighter in colour, generally varying between medium light grey to light grey (N6 – N8), and occasionally light brown (5YR 6/4). Between the towns Kroonstad and Newcastle, rocks of this facies association, and lithofacies type R in particular, are mica rich.

Plant remains comprising fossil wood pieces and fragmentary, and occasionally more complete, *Glossopteris* leaf and horsetail stem impressions are common (see Groenewald, 2021 for examples). Occasional fish scales and bones are present in the mudstones or in sideritic nodules. The density of bioturbation structures and number of identifiable ichnogenera is similar to that observed in FA3 and is much greater than in the other facies associations. The bioturbation index (BI; MacEachern et al., 2010) is normally between 1 and

309 3 but may be as high as 4 locally. Ichnogenera observed in FA2 include *Arenicolites*,
310 *Cochlichnus*, *Diplocraterion*, *Lockeia, Gyrochorte*, *Gordia*, *Ophiomorpha, Palaeophycus*,
311 *Planolites*, *Rosselia, Rusophycus*, *Skolithos*, *Teichichnus*, and *Thalassinoides* (Figure 5).

312 Ground up plant material, similar to the "coffee grounds" reported from the Mississippi delta
313 (Tye and Kosters, 1986) and the Waterford Formation in the southern portion of the basin
314 (Rubidge, 1988; Rubidge et al., 2000), is relatively common in siltstone or sandstone beds of
315 Facies R. Sandstone beds generally become thicker towards the top of FA2. In the study area,
316 FA2 overlies FA1 with a gradational contact. Facies association 2 may grade upwards into
317 FA3, or have a sharp, sometimes truncated contact with FA3 or FA4 (Figure 4). Laterally,
318 FA2 may interfinger with either FA1 or FA3.

319 *Interpretation:* FA2 is interpreted as being deposited on the delta front and in
320 interdistributary areas and bays. This interpretation is supported by its stratigraphic position,
321 the predominance of shallow-marine indicating horizontal traces (Buatois and Mángano,
322 2011), the presence of asymmetrical and symmetrical ripples, indicating both fluvial and
323 wave influence, and hummocky cross-stratification suggesting periodic storm influence
324 (Dumas and Arnott, 2006). Under normal conditions, the CH and BA elements of FA4, which
325 are present at the top of the overall upward coarsening succession, are interpreted to have
326 accumulated in the more proximal areas of the delta front with finer material being deposited
327 more distally. Periods of higher discharge, e.g. during flooding, and by migration and
328 reworking of sediment from distributary mouth bars and splay elements by longshore
329 currents, waves, and periodic storms (Elliott, 1974; Coleman and Prior, 1982; Walker and
330 James, 1992; Bhattacharya, 2010), could have resulted in coarser material being introduced to
331 the prodelta. Reworking of this coarser material by waves and during storms produced the SS
332 elements. Lithofacies type R indicates alternations between higher energy periods, during
333 which the coarser grained beds were deposited as FS elements, and periods of low-to-very

low energy, including during the waning period of a storm, during which the finer-grained interbeds were deposited by suspension settling. Splay deposits were reworked by waves and during storms, as evidenced by the abundance of wave and local hummocky cross-stratification. Higher up in the section, thicker beds of lithofacies types Fm and Fl that interfinger with lithofacies type R, and locally display extensive bioturbation, represent deposition under quiet water conditions of the interdistributary bay. Here the coarser beds of lithofacies type R were likely deposited as sheets following crevassing or overbank flooding of the channels into the interdistributary bays, with levées being formed immediately adjacent to the distributary channel (Elliott, 1974; Zawada, 1988a; Groenewald, 1989; Muntingh, 1997). Closer to the distributary channels, this resulted in the formation of levée deposits. In the eastern portion of the study area, FS elements that display an alternation of sedimentary structures within the same bed e.g. horizontally-laminated to massive to ripple-laminated, have previously been interpreted as turbidite deposits with incomplete Bouma sequences (Muntingh, 1997; Selover and Gastaldo, 2005). However, hyperpycnal flow deposits on the delta front have been noted to resemble turbidite deposits from deep-water settings, and often display a similar alternation of sedimentary structures linked to the pulsatory nature of the flow (Mulder et al., 2003; Olariu et al., 2005, 2010). Such flows are common in fluvial-dominated deltaic environments, and are triggered by flood events of the feeder river, with thicker (0.5 m to 1 m thick) beds of horizontally laminated sandstones (within element FS) being attributed to sustained hyperpycnal flows (Plink-Björklund and Steel, 2004; Petter and Steel, 2006; Olariu et al., 2010). Higher discharge rates of the feeder river, and a correspondingly high rate of sedimentation on the delta front, resulted in subaqueous density flows (element SG of FA4) and abundant soft sediment deformation features (lithofacies type Sd; (Coleman and Prior, 1978; Shanmugam, 2006; Bhattacharya, 2010).

4.1.3 Facies Association 3 (Lower shoreface)

The sandstone-dominated Facies Association 3 (FA3) is characterised by a predominance of non-amalgamated to amalgamated cosets of lithofacies type Shx, with subordinate bedsets of lithofacies type R, and minor, often bioturbated, interbedded mudstones of lithofacies type Fm and Fl (Figure 4). Architectural element SS, comprising single or stacked beds of Shx, is the main element present within this facies association. FA3 is poorly expressed in the field study area and is best exposed at the Barend Wessel Dam at the town of Kroonstad (Figure 4). Here FA3 gradationally overlies FA1 and is sharply overlain by sandstones of FA4. Abundant fragmentary plant material, similar to the "coffee grounds" reported from the Mississippi delta (Tye and Kosters, 1986), are present in some of the sandstone beds. The bioturbation index of FA3 ranges from 1- 3. FA3 hosts a similar diversity of ichnogenera to that of FA2, with *Arenicolites*, *Cruziana*, *Gyrochorte*, *Ophiomorpha, Palaeophycus*, *Planolites*, *Rosselia, Skolithos*, and *Thalassinoides* being identified during this study (Figure 5).

Interpretation: FA3 is interpreted as being deposited on the lower shoreface in a wave- and storm-dominated shallow marine environment. Such environments are typically situated at or above storm-wave base and are subject to periodic stormweather conditions, during which time storm sheet deposits are formed under storm-related oscillatory and unidirectional current hydrodynamic conditions, as well as suspension sedimentation conditions during fair weather conditions (Bhattacharya and Giosan, 2003; Bhattacharya, 2010; Plint, 2010; Penn-Clarke et al., 2019). Ichnofossils from FA3 are typical of the *Cruziana* ichnofacies, which is generally interpreted to occur in shallow marine environments on the lower shoreface to lower offshore zone (Seilacher, 2007; Buatois and Mángano, 2011).

4.1.4 Facies Association 4 (Confined Channelised deposits)

Facies Association 4 (FA4) comprises upward-fining, single- to multi-storey sandstones up to 30 m thick. Lithofacies types present in FA4 include Ss, St, Sh, Sp, Sr, Sm, Sa, and Sd, with occasional occurrences of Gmm. Architectural elements identified from this facies association include Channel Fill (CH), Bar Accretion (BA), Sediment-Gravity-Flow Deposits (SG), Sandy Bedforms (SB), Lateral Accretion (LA) macroforms, Downstream Accretion (DA) macroforms, and Downstream and Lateral Accretion (DLA) macroforms (Table 2; Figure 4 and 6). When present, elements BA and CH are usually found in close association and are best developed towards the top of the overall upwards-coarsening succession from FA1 to FA2 or FA3 (i.e. the Waterford Formation). Elements CH, DA, and LA are typically found in close association and are generally bounded by, or associated with, elements of FA5. Bioturbation is uncommon and, where present, is generally restricted to the upper surfaces of rippled sandstone beds.

Sandstone colours vary from light to very light grey (N7 – N8), light olive grey (5Y 6/1), yellowish grey (5Y 7/2), greenish grey (5GY 6/1) yellow to pale olive (5Y 6/4 to 10Y 6/2), and pale greenish yellow (10Y 8/2), often weathering to a more yellowish orange colour (10YR 8/6 or 10YR 6/6). Carbonate concretions 0.3 m to > 2 m in diameter are present in sandstone bodies of FA4 throughout the study area but are more abundant in sandstones from the interval straddling the Ecca-Beaufort contact. A diagenetic origin for these concretions is likely, based on their round shape and the fact that they often preserve sedimentary structures not seen in the surrounding rock (Marshall and Pirrie, 2013). FA4 is relatively conspicuous in the study area because of the cliff-forming nature of the sandstone deposits.

Interpretation: FA4 is interpreted to represent deposition by predominantly fluvial processes on the proximal delta front to alluvial plain. Where CH and BA elements are found in intimate association, typically overlying or interbedded with FA2 deposits, these elements are

406 interpreted to represent distributary channels (CH) and proximal mouth bars (BA) deposits on
407 the proximal delta front to lower delta plain environment. Some of the channelised elements
408 contain abundant floating clasts (Facies Sa) and may show stratification. These are similar to
409 channel deposits described from the Wall Creek Member of the Cretaceous Raptor Delta
410 (Gani and Bhattacharya, 2007) and from the Jackfork Group (Shanmugam, 2006) and are
411 interpreted to be sediment density flow deposits (element SG) that likely formed during
412 periods of higher discharge. Bar elements, formed through the migration of dunes within the
413 distributary channels, and mouth-bar deposits, which form at the mouths of channels due to
414 the change in flow conditions from confined to unconfined flow, and the associated sharp
415 decrease in velocity (Wright, 1977; Olariu and Bhattacharya, 2006), coalesce to form bar
416 assemblages that are intimately associated with the distributary channels. The generally low
417 intensity of bioturbation present in these deposits (BI 0 – 1) suggests proximity to the river
418 mouth (MacEachern et al., 2005; Gani and Bhattacharya, 2007). Delta lobe switching and
419 abandonment or a decrease in sediment supply from the feeder river, followed by wave
420 reworking and winnowing of the finer-grained sediments, may have resulted in the
421 development of cheniers along the coastline (Augustinus, 1989; Muntingh, 1997; Gani and
422 Bhattacharya, 2007; Bhattacharya, 2010; Plint, 2010).

423 In most localities in the study area, the distributary channels and bar complexes are, in turn,
424 overlain by fluvial channel deposits (often with erosive bases and pebble lags concentrated at
425 the base) and their associated overbank deposits (FA5). These deposits, characterised by
426 architectural elements CH, SB, DA, LA, and DLA, often occur in intimate association with
427 elements of FA5 and are interpreted to be deposited on the subaerial upper delta and alluvial
428 plain. However, at some localities e.g. Kalkwal and Brandfort hill (locality 3: Figure 2),
429 erosive based channels with pebble lags at the base directly overly FA2 deposits and the
430 distributary channels, bar complexes, and upper part of the genetically related prodelta

deposits are considered to have been eroded away (Loock and Grobler, 1988). The characteristics of this suggests either a shallow platform (Galloway, 1975) or potentially a period of forced regression (Bhattacharya, 2010; Plint, 2010).

4.1.5 Facies Association 5 (Floodplain fines and overbank deposits)

Facies Association 5 (FA5) always occurs in intimate association with FA4 and is the most common facies association in the Abrahamskraal and Balfour formations in the study area. This mudrock dominated facies association comprises lithofacies types Fl, Fm, C, Ca, Ss, Sr, Sd, Sh, and Sm, and four principal architectural elements have been recognised, including Overbank (floodplain) Fines (FF), Abandoned Channel (AC), Crevasse Splay (CS), and Levées (LV; Table 2; Figure 6). Abundant slickensides, desiccation cracks, silicified gypsum roses, blocky and fissile weathering features, articulated and disarticulated vertebrate fossils, large and small fragments of silicified wood, plant rootlets, and extensive nodular horizons (Figure 6) are all features that commonly occur within FA5 deposits and provide evidence for subaerial exposure and palaeosol development (Smith, 1990; Retallack, 2001; Miall, 2006; Smith and Botha-Brink, 2014). Because the finer grained facies tend to weather rapidly and are often covered with scree and/or vegetation, outcrops of FA5 within the study area are largely restricted to erosional dongas, steep unvegetated slopes, or man-made cuttings. This makes the description of vertically and laterally continuous sequences difficult.

Mudstone colours of FA5 vary depending on the stratigraphic and geographic position. In the southern Free State Province, the mudrocks of the Abrahamskraal Formation are predominantly greenish grey (5G 6/1), moderate yellow green (5G 5/2), and greenish grey (5GY 6/1). This is quite different to what is observed in the overlying Balfour Formation, where mudrock colours include blackish red (5R 2/2), brownish grey (5YR 4/1), greyish red (5R 4/2), greenish grey (5G 6/1 and 5GY 6/1), yellowish grey (5Y 7/2), pale olive (10Y 6/2), and dusky yellow green (5GY 5/2). In the central Free State Province, mudrocks are

predominantly dusky yellow green (5GY 5/2), greenish grey (5GY 6/1) and pale olive (10Y 6/2), with brownish grey (5YR 4/1) and greyish red (5R 4/2) mudrocks only observed at the locality Esbachskop near the town of Brandfort. In the north-eastern Free State and KwaZulu-Natal provinces, mudrocks of FA5 are greyish olive (10Y 4/2), light olive grey (5Y 5/2), pale olive (10Y 6/2), dusky yellow (5Y 6/4), dark greenish grey (5G 4/1), olive grey (5Y 3/2), dark greenish yellow (10Y 6/6), moderate yellow (5Y 7/6), light olive brown (5Y 5/6), medium grey (N5), and light blueish grey (5B 7/1).

Interpretation: FA5 is interpreted as terrestrial floodplain deposits, predominantly from suspension settling (FF), with intermittent higher energy splay (CS) and levée (LV) deposits. Floodplains typically act as sinks for finer material in alluvial systems, and are predominantly formed by vertical accretion during floods, with lateral accretion deposits being of minor importance (Nanson and Croke, 1992; Wright and Marriott, 1993). Deposition occurred in temporary bodies and pools of standing water following flood events, or in semi-permanent to permanent shallow lakes on the flood plain that allowed for the development of palustrine carbonates (Ca). The presence of thin coal beds (C) and highly carbonaceous shales interbedded within the FA5 deposits provides evidence for the existence of marshes in the interdistributary areas and in low-lying areas of the alluvial floodplain (Miall, 2006, 2016). Where floodplain accumulation was slow enough, and occurred over long periods, soil formation processes began. This is evidenced by the abundant presence of palaeosol horizons rich in carbonate nodules, colour mottling, plant rootlets and slickensides (Retallack, 1990; Smith, 1990). The presence of mud crack features indicate that the alluvial floodplain was subject to periodic drying.

4.2 Palaeontology

A total of 407 identifiable tetrapod fossils have been recovered from the study area. These include a variety of dicynodont anomodonts, cynodonts, gorgonopsians, therocephalians, a

biarmosuchian, rhinesuchid amphibians, and the reptile *Eunotosaurus africanus* (Table 4). Stratigraphic ranges of vertebrate fossils collected during this study are indicated on the composite stratigraphic logs (Figure 2). For the full list of tetrapod fossils used for this study, please see Supplementary Table 2 and Groenewald (2021) for photographs and identifications.

Two distinctive and stratigraphically disparate faunal assemblages were recovered in the Beaufort Group of the southern Free State (Figure 2; Groenewald et al., 2019; Groenewald, 2021). The lower of these is characterised by an abundance of *Eosimops* specimens in association with *Robertia*, *Pristerodon*, *Eunotosaurus*, and the scylacosaurid therocephalian *Glanosuchus* and is assigned to the middle Permian (Capitanian) *Glanosuchus-Eosimops subzone* of the *Tapinocephalus* AZ (Groenewald et al., 2019; Day and Rubidge, 2020). The upper assemblage, characterised by an abundance of *Oudenodon* specimens in association with *Rhachiocephalus*, *Aulacephalodon, Diictodon; Basilodon; Dinanomodon*, and gorgonopsians, is assigned to the late Permian (Lopingian) uppermost *Cistecephalus* AZ or the *Dicynodon-Theriognathus* subzone of the *Daptocephalus* AZ (Groenewald et al., 2019; Smith, 2020; Viglietti, 2020; Groenewald, 2021).

Northwards, around Bloemfontein, the stratigraphically lowest tetrapod fossils recorded in the Beaufort Fossil Vertebrate database were collected from the locality Kranskraal. This locality is situated approximately 22 km northeast of Bloemfontein along exposures adjacent to the Modder River and has yielded the holotypes of *Rhachiocephalus angusticeps* (Broom, 1937) and *Compsodon helmoedi* (van Hoepen, 1934) along with specimens of *Oudenodon bainii* and the gorgonopsid *Arctognathus curvimola*, all of which have stratigraphic ranges extending from the *Cistecephalus* to lower *Daptocephalus* AZs. The specimen number and whereabouts of the holotype of *Rhachiocephalus angusticeps* is not known but the species is considered synonymous with *Rhachiocephalus magnus,* as listed in Kitching (1977).

The Beaufort Fossil Vertebrate database records numerous fossils that have been recovered from up to 100 m (based on elevation) stratigraphically higher than the fossils from Kranskraal. The recovered taxa include *Oudenodon bainii, Daptocephalus*/*Dicynodon*, and *Theriognathus microps*. East of this, in the Thaba 'Nchu district, *Lystrosaurus* is the most abundant genus collected, with over 90 specimens representing the species *L.maccaigi. L. murayi. L. curvatus, L declivus*. Other genera from this area include *Daptocephalus leoniceps, Dicynodon lacerticeps, Oudenodon bainii, Moschorhinus kitchingi, Scaloposaurus constrictus, Vetusodon elikhulu* and *Procolophon trigoniceps.*

Farther north, between Brandfort and Kroonstad, exposures of the lowermost Beaufort Group become sparser and the tetrapod species recovered closest to the Ecca-Beaufort contact in this part of the basin are limited to an undescribed burnetiid specimen (BP/1/8262), the only specimen of the therocephalian *Zorillodontops gracilis* (SAM-PK-K1392), and some rhinesuchid temnospondyl material, including an axial skeleton from the Farm Malana (BP/1/8195) that is tentatively identified as *Uranocentrodon senekalensis* (Groenewald, 2021). East of this, in the area between the towns Excelsior and Verkeerdevlei, *Theriognathus microps* co-occurs with *Oudenodon bainii* and *Aulacephalodon bainii.*

Rocks of the Balfour Formation (Normandien Formation) in the eastern Free State have yielded a diverse faunal assemblage [Figure 2; (Groenewald, 2021)] that includes *Daptocephalus leoniceps*, *Dicynodon lacerticeps, Dinanomodon gilli, Oudenodon bainii, Kitchinganomodon crassus*, *Rhachiocephalus magnus, Lystrosaurus spp.,* rhinesuchids (e.g. *Laccosaurus*), gorgonopsians, and an unidentified cynodont. Here some stratigraphic separation of taxa is evident, with the large dicynodonts *Rhachiocephalus magnus* and *Kitchinganomodon crassus* both restricted to the stratigraphic interval from immediately below to just above the arenaceous Rooinek Member, and the stratigraphically lowest large

Lystrosaurus specimens (based on catalogue information) recovered from the argillaceous interval immediately underlying the Schoondraai Member (Figure 2).

Fossils recovered from the Estcourt district of KwaZulu-Natal include *Daptocephalus leoniceps, Dicynodon lacerticeps,* and *Oudenodon bainii*, and a rhinesuchid amphibian (c.f. *Laccosaurus*). Further south, at Oatesdale Quarry near Mooi River, three specimens identified as *Lystrosaurus maccaigi* were found in close association with a *Dicynodontoides* mandible, the partial axial skeleton of an unidentified cynodont, and an isolated gorgonopsian canine. The quarry is situated roughly 50 m below the sandstones of the Katberg Formation and these specimens are therefore from the upper Balfour Formation (Viglietti et al., 2017b, 2021).

5 Discussion

5.1 Lithostratigraphy

The overall coarsening- and thickening-upward succession formed by Facies associations 1, 2 and/or 3, and 4 in the study area is typical of a prograding delta front or shoreface (Moore, 1966; Collinson and Thompson, 1989; Walker and James, 1992; James and Dalrymple, 2010), whereas the overlying FA5 (and in places FA4 when found in association with FA5), which form discrete upward fining successions, are more typical of alluvial (fluvial and floodplain) deposits (Walker and James, 1992; Miall, 2006, 2016; James and Dalrymple, 2010). We therefore interpret the studied stratigraphic interval as recording an upwards change from deposition on the prodelta, through the delta front or lower shoreface, on the lower delta plain, and finally on the upper delta plain. This is in broad agreement with interpretations of previous workers (Linström, 1973; Botha and Linström, 1977; Turner, 1977; van Dijk et al., 1978; Zawada, 1988a; Groenewald, 1989; Muntingh, 1997; Welman et al., 2001).

In this study, we consider rocks of FA1 to belong to the Tierberg or Volksrust formations of the Ecca Group. Where FA4 and FA5 are found in association, we consider the rocks to belong to the Beaufort Group. The intermediate stratigraphic interval, which separates the mudrocks of the Tierberg/Volksrust formations (Ecca Group; FA1) from those of the overlying fluvially dominated Beaufort Group (FA4 and FA5), contains a unique association of lithofacies types and facies associations (FA2, FA3, and FA4) that can be recognised both in the field and in borehole core. In the north-eastern part of the basin, this interval, which broadly corresponds with Groenewald's (1984, 1989) Frankfort Member of the Normandien Formation, has previously been included within the Beaufort Group. Elsewhere in the study area, this interval includes rocks previously assigned to both the uppermost Ecca and lowermost Beaufort groups. The interval is 30-45 m thick in the southern and north-eastern Free State and thickens south-eastwards to more than 144 m near the town of Estcourt in KwaZulu-Natal.

The rocks in this interval are here interpreted as having been deposited in a shallow marine environment typified by both shoreface and deltaic environments. Deposition in a shallow marine environment is supported by the ichnofaunal assemblages e.g. *Cruziana* ichnofacies, while rhythmically interbedded sandstones/siltstones and mudstones (lithofacies type R) indicate periodic (possibly seasonal) fluctuations in river discharge, with hyperpycnal flows generating during flood events resulting in the deposition of frontal splay elements (element FS). Evidence for high sedimentation rates include the abundance of soft-sediment deformation structures (lithofacies type Sd) along with relatively abundant sediment gravity and hyperpycnal flow deposits (elements FS and SG). Wave ripples and hummocky cross-stratification (element SS) bear testament to periodic storm and wave influence on the system. This interpretation is also in line with that of previous workers in the study area, who all document several facies that are generally restricted to the interval between the Ecca and

579 Beaufort groups and interpret them as having been deposited in an essentially deltaic
580 environment (Linström, 1973, 1987; Turner, 1977; Botha and Linström, 1978; van Dijk et al.,
581 1978; Behounek, 1980; Zawada, 1987b, 1987a; Loock and Grobler, 1988; Groenewald, 1989,
582 2015; Muntingh, 1990, 1997; Green, 1997; Mavuso, 2014; Rammutla, 2016); although
583 Selover and Gastaldo (2005) suggested the presence of a deeper water turbidite system near
584 Estcourt.

585 Furthermore, some of the lithofacies that dominate this interval, and the interpreted
586 depositional environments, are very similar to those described from the Waterford Formation
587 of the Ecca Group by Rubidge et al. (2000) and Mason et al. (2015) from the south-western
588 and south-eastern main Karoo Basin, respectively. In particular, Rubidge's (1988) Facies A
589 and E, which are considered to be most diagnostic of the Waterford Formation further south
590 in the basin (Rubidge et al., 2000, 2012; Mason, 2007; Mason et al., 2015), correspond
591 directly with Lithofacies types R and Sd, respectively. Based on lithologic and genetic
592 similarities, we consider the stratigraphic interval where FA2, FA3, and FA4 occur to be
593 lithologically equivalent to the Waterford Formation, which forms the uppermost
594 stratigraphic unit of the Ecca Group in the south of the main Karoo Basin, and these rocks
595 should thus be included within the Ecca rather than the Beaufort Group. While younger in the
596 north than in the south (based on the biostratigraphy), we consider the Waterford Formation
597 to be present in the northern part of the main Karoo Basin. Here, it overlies the Tierberg or
598 Volksrust formations, forming the uppermost stratigraphic unit of the Ecca Group and
599 corroborating recent work (Welman et al., 2001; Mavuso, 2014; Groenewald, 2015;
600 Rammutla, 2016). The Waterford Formation is overlain by the Abrahamskraal Formation in
601 the southern Free State (Groenewald et al., 2019) and by the Balfour Formation in the central
602 and eastern Free State and KwaZulu-Natal.

For the purpose of mapping, the base of the first prominent sandstone was traditionally used for the placement of the Ecca-Beaufort contact (Botha and Linström, 1978; Linström, 1981, 1987; Groenewald, 1984, 1987; Zawada, 1988a; Zawada and Cadle, 1988; Muntingh, 1989, 1997; Schutte, 1993). However, the current study has shown that this contact, as it outcrops in the study area, corresponds to different stratigraphic horizons, e.g. it could represent either the base of the Waterford Formation or a sandstone unit within it. As currently mapped, the Waterford Formation in the study area encompasses strata assigned to the uppermost Volksrust/Tierberg formations of the Ecca Group and/or the lowermost Adelaide Subgroup/Normadien Formation of the Beaufort Group. Application of lithofacies analysis can be used to map the different Facies Associations as discrete lithodemes, which can be used to refine the lithostratigraphic placement of the contact between the Tierberg/Volksrust and the Waterford formations, and between the Ecca and Beaufort groups. We suggest that the top of both the Tierberg and Volksrust formations should be placed at the contact between FA1 and FA2 or FA3. This is a similar contact to one that has previously been considered for the Ecca-Beaufort contact in the southern Free State (Siebrits, 1987; Zawada and Cadle, 1988), and is the same as that proposed by Terblanche (1979) for the contact between the Tierberg and Carnarvon [= Waterford (Cole and Wipplinger, 2001)] formations. To be consistent with lithostratigraphic application in the rest of the basin, the Ecca-Beaufort contact should be placed at the top of the Waterford Formation, at the point where FA4 and FA5 predominate. This corresponds to the change from the lower to upper delta plain environment and, at most localities, the contact can be placed at the base of a prominent sandstone horizon with a basal pebble lag.

Groenewald *et al.* (2019) demonstrated that rocks of the lowermost Beaufort Group in the southern Free State can be subdivided on both lithological and biostratigraphic grounds into a lower and an upper interval, assignable to the Abrahamskraal and Balfour formations,

628 respectively. The most distinctive and easily observable lithological difference between the
629 two formations is the change in mudrock colours, with reddish mudstones [blackish red (5R
630 2/2), brownish grey (5YR 4/1) and greyish red (5R 4/2)] being almost entirely absent from
631 the Abrahamskraal Formation but predominant in the Balfour Formation.

632 While the data from this work is insufficient to positively attribute a fluvial style to the
633 Abrahamskraal Formation in the study area because of the paucity of good outcrop, a low
634 sinuosity fluvial style with ephemeral flow conditions as proposed by Zawada (1988a) is
635 supported by the abundance of SB and DA elements, coupled with high-consistency
636 palaeocurrent measurements (Groenewald, 2021), and the lack of features such as cut-banks
637 and major lateral accretion surfaces. Low sinuosity fluvial styles have also been identified
638 within the Abrahamskraal Formation in the south-western portion of the basin (Wilson et al.,
639 2014; Gulliford et al., 2014; Paiva, 2015). Finer material is interpreted as having been
640 deposited on the floodplain flanking the network of low-sinuosity streams. The presence of
641 lithofacies types Fl and Ca provide evidence for the development of floodplain lakes, while
642 the predominantly drab blueish colours of the mudrocks suggest a higher water table with
643 deposition under reducing conditions (Wilson et al., 2014; Bordy and Paiva, 2021).
644 Palaeocalcrete sheets similar to those described from the Teekloof Formation by Smith
645 (1990) are well exposed at Uitspankop (near locality 1: Figure 2) and possibly formed in the
646 zone of capillary rise just above the groundwater table. At several localities, including
647 Uitspankop, fossils were found as isolated skulls. This, coupled with the palaeocalcrete
648 sheets, is considered indicative of a proximal floodplain environment (Smith, 1990, 1993).

649 In the southern and central Free State, the Balfour Formation records a complex interaction
650 between a northern and southern fluvial system (Kingsley and Theron, 1964; Cole and
651 Wipplinger, 2001; Rutherford et al., 2015; Groenewald, 2021). Although the data from this
652 study do not allow a fluvial style to be positively attributed to the Balfour Formation in the

653 southern Free State, a high sinuosity fluvial style has been proposed based on the presence of
654 extensive lateral accretion surfaces (element LA) at Boomplaas Hill (Viglietti, 2016), with
655 overbank deposits (FA5), resulting from floodplain aggradation through suspension settling
656 of finer grained material and by deposition of crevasse splay deposits (Miall, 2006; Viglietti,
657 2016; Viglietti et al., 2018). Similarly, a high sinuosity fluvial style for the Balfour Formation
658 in the north-eastern Free State and KwaZulu-Natal, with river channels flanked by broad
659 floodplains, has previously been proposed (Turner, 1977; Groenewald, 1984, 1990; Green,
660 1997) and is supported by the abundance of LA elements (Figure 6). The predominance of
661 lithofacies type Fl (sometime associated with abundant leaf impressions), carbonaceous
662 mudstones, and even thin coal beds (lithofacies type C), provide evidence for the presence of
663 ponds/lakes and swampy conditions on the floodplain (Miall, 2006; Viglietti et al., 2018).

664 As noted earlier, the Balfour Formation in the southern Free State can be easily distinguished
665 from the underlying Abrahamskraal Formation based on the predominance of reddish
666 mudrocks. Reddish mudrocks are also present in the lower parts of the Beaufort Group in the
667 central Free State (Brandfort and Theunissen districts) but become less common towards the
668 north and east. In the vicinities of Virginia and Kroonstad, reddish mudrocks are absent from
669 the Balfour Formation and green grey and yellow grey mudrocks are predominant. A similar
670 situation is present in the north-eastern Free State and KwaZulu-Natal, with reddish
671 mudrocks entirely absent from the interval investigated during this study.

672 Reddish mudrocks have traditionally been cited as an indicator of increased aridity in
673 continental settings (Sheldon, 2005) and the increased abundance of reddish mudrocks in the
674 upper interval suggests a change in climatic conditions between the Abrahamskraal and
675 Balfour formations. This simplistic view is not always the case as mudrock colours are
676 influenced by oxidation and can be affected by several factors, including the level of the
677 water table at the time of deposition, hydrological drainage, and through diagenetic processes

(Miall, 1977; Sheldon, 2005; Wilson et al., 2014; Paiva, 2015; Li et al., 2017). Following the conceptual model presented by Wilson *et al.* (2014), variations in the height of the water table (shortly after deposition) drive the oxidation of iron, and thereby the colour of the mudrocks. More drab colours indicate reducing conditions during higher water table conditions, whereas redder colours indicate lower water tables that resulted in subaerial exposure (Wilson et al., 2014).

The regional water table is considered a landward extension of the relative sea level in fluvial sequence stratigraphy (Gulliford et al., 2014). As such, a change in base level would affect the water table and the change in colouration may reflect the proximity to the coastline i.e. the Balfour Formation in the southern part of the study area was deposited further from the shoreline where the water table was subject to more rapid (seasonal?) fluctuations, resulting in an increased abundance of reddish mudrocks. If, however, the colouration is the result of climatic conditions, the abundance of reddish mudrocks in the upper interval may indicate increased aridity with a lower water table and prolonged subaerial conditions (Wilson et al., 2014). The presence of desiccation cracks and gypsum crystals are further indicators of prolonged and repeated wetting and drying events that occur in subaerial and semi-arid conditions (Smith, 1990, 1993).

The absence of reddish mudrocks from the studied interval of the Balfour Formation in the north-eastern Free State and KwaZulu-Natal, suggests that the water table in this part of the basin was relatively high and subject to little variation. A high water table is corroborated by abundant soft-sediment deformation structures in the interval between the Waterford Formation of the Ecca Group and Rooinek Member of the Balfour Formation. The higher water table, at least in the lower parts of the Balfour Formation, may be associated with the proximity to the shoreline. However, it is also plausible that the Balfour Formation in the north-eastern part of the basin was deposited in a generally moist environment as a result of

703 the topographic effect of the Eastern Highlands. A similar mechanism was proposed by
704 Bordy and Prevec (2008) for the (likely) contemporaneous Emakwezini Formation.

705 5.2 Biostratigraphy

706 5.2.1 Biostratigraphy of the southern Free State

707 The lowest biozone present immediately above the Ecca-Beaufort contact in the southern
708 Free State is the *Eosimops–Glanosuchus* subzone of the *Tapinocephalus* AZ, and the rocks
709 are assigned to the Abrahamskraal Formation (Groenewald et al., 2019; Day and Rubidge,
710 2020; Groenewald, 2021). The northward thinning strata of the *Eosimops–Glanosuchus*
711 subzone can be followed northwards from the Orange River to the Fauresmith and
712 Jagersfontein districts, where this stratigraphic interval pinches out somewhere to the north of
713 the locality Vaalkop 695 near Jagersfontein (Groenewald et al., 2019; Day and Rubidge,
714 2020; Groenewald, 2021). While the immediately overlying strata are assigned to the Balfour
715 Formation (Viglietti, 2016; Groenewald, 2021), it is difficult to positively assign the faunal
716 assemblage to the upper *Cistecephalus* or lower *Daptocephalus* AZs. This is because faunas
717 of the uppermost *Cistecephalus* AZ and lower *Daptocephalus* AZ have many species in
718 common, including the dicynodonts *Aulacephalodon*, *Basilodon*, *Dinanomodon*, *Oudenodon,*
719 and *Diictodon* (Nicolas, 2007; Smith et al., 2012; Viglietti, 2016, 2020; Viglietti et al., 2016;
720 Smith, 2020), and none of the index fossils (*Cistecephalus microrhinus*, *Daptocephalus*
721 *leoniceps,* and *Theriognathus microps*) have been recovered from this area to date. However,
722 because *Cistecephalus* has not been recovered from within the study area, but has been
723 recovered from several localities immediately south of the study area (Kitching, 1967, 1977),
724 most localities yielding *Oudenodon* north of the Orange River are assigned to the *Dicynodon-*
725 *Theriognathus* subzone (Viglietti, 2016, 2020; Groenewald et al., 2019; Groenewald, 2021).
726 The potential exception to this is strata at the base of Boomplaas Hill (locality 2: Figure 2)
727 and along the ridges in the vicinity, which may include uppermost *Cistecephalus* AZ based

728 on the presence of the *Endothiodon* specimen BP/1/7962 (Groenewald et al., 2019;
729 Groenewald, 2021).

730 5.2.2 Biostratigraphy of the central and north-eastern Free State and KwaZulu-Natal

731 Kitching (1977) considered the locality Kranskraal to fall within either the upper
732 *Cistecephalus* AZ or *Daptocephalus* AZ, whereas Angielczyk and Kammerer (2017) assign it
733 to the lower *Daptocephalus* AZ (*Dicynodon-Theriognathus* subzone; Viglietti 2020). Based
734 on the presence of *Rhachiocephalus* and *Compsodon*, the absence of *Cistecephalus*, and in
735 contrast to Viglietti (2016, 2020), we consider the *Dicynodon-Theriognathus* subzone of the
736 *Daptocephalus* AZ to be present immediately above the Ecca-Beaufort contact near
737 Bloemfontein in the central Free State.

738 Viglietti (2016) considered the sandstones exposed on Tafelkop, Bloemfontein, the
739 equivalent to the "Musgrave Grit" exposed near Thaba 'Nchu (Rutherford, 2009; Rutherford
740 et al., 2015) and assigned them to the *Lystrosaurus maccaigi-Moschorhinus* subzone of the
741 *Daptocephalus* AZ. Rutherford *et al.* (2015) point out that the Palingkloof Member, or its
742 equivalents, are not preserved near Thaba 'Nchu, and the *Daptocephalus* AZ is therefore
743 disconformably overlain by the *Lystrosaurus declivis* AZ. This is similar to the situation
744 observed by Hancox *et al.* (2002) near Senekal.

745 Of the few tetrapod fossils recovered near to the Ecca-Beaufort contact between Brandfort
746 and Kroonstad in the central portion of the study area, the *Uranocentrodon* specimen
747 BP/1/8195 is stratigraphically most useful. This is because the stratigraphic range of
748 *Uranocentrodon* is restricted to the *Daptocephalus* AZ (Latimer et al., 2002; Damiani, 2004;
749 Tarailo, 2018). However, most of the known *Uranocentrodon* specimens were collected from
750 a single locality near the town Senekal in the Free State Province where the Permo-Triassic
751 boundary is considered to be absent and a hiatus of unknown duration exists between the

Daptocephalus AZ and overlying *Lystrosaurus declivis* AZ (Hancox et al., 2002; Latimer et al., 2002). As such, the range of *Uranocentrodon* within the *Daptocephalus* AZ is uncertain at this stage. The presence of the *Daptocephalus* AZ in the central part of the study area is further supported by the co-occurrence of *Theriognathus microps, Oudenodon bainii,* and *Aulacephalodon bainii* in an area between the towns of Excelsior and Verkeerdevlei. However, since these taxa all have stratigraphic ranges that extend upwards through the *Dicynodon-Theriognathus* subzone AZ into the lower *Lystrosaurus maccaigi-Moschorhinus* subzone (Viglietti et al., 2016; Viglietti, 2020), it is uncertain which of the subzones of the *Daptocephalus* AZ is present in this part of the basin immediately above the Ecca-Beaufort contact.

In the eastern Free State and KwaZulu-Natal, rocks of the Balfour Formation (Normandien Formation) can be confidently assigned to the late Permian (Lopingian) *Daptocephalus* AZ, which is in agreement with previous work (Groenewald, 1989, 1990; van der Walt et al., 2010; Rubidge et al., 2016; Viglietti, 2020). Since both *Rhachiocephalus* and *Kitchinganomodon* have their upper ranges in the *Dicynodon-Theriognathus* subzone (Viglietti et al., 2016; Viglietti, 2020), this subzone is considered to be present at the base of the Beaufort Group in the north eastern Free State.

The first appearance datum of *Lystrosaurus maccaigi* is used to define the lower boundary of the *Lystrosaurus maccaigi-Moschorhinus* subzone of the *Daptocephalus* AZ (Viglietti et al., 2016; Viglietti, 2020) and the association of *Lystrosaurus* with *Daptocephalus* at the locality Venus suggests that the *Lystrosaurus maccaigi-Moschorhinus* subzone is present from approximately 7 m below the Schoondraai Member in the north-eastern Free State. This is further supported by a very large gorgonopsian maxilla (BP/1/8205) from a clay-pebble lag at the base of the second sandstone of the Schoondraai Member at the locality Cliffdale, which may be the same species as the large gorgonopsians (e.g. NMQR 3707) reported from the

uppermost *Daptocephalus* AZ at Nooitgedacht 68 (Botha-Brink et al., 2014; Butler et al., 2017), and the presence of a *Lystrosaurus declivis* AZ fauna in the overlying Harrismith Member (Groenewald, 1990, 1996; Botha et al., 2020; Botha and Smith, 2020).

In KwaZulu-Natal, the presence of *Daptocephalus* and *Dicynodon* supports the presence of the *Daptocephalus* AZ. Based on the current data, however, it is uncertain at this stage whether the *Dicynodon-Theriognathus* subzone is present near Estcourt. This is because most of the vertebrate fossil yielding localities in the Estcourt District are in the upper portion of the Balfour Formation. Although it is difficult to get an accurate thickness for the Balfour Formation in this part of the basin (Botha and Linström, 1978), it is estimated that some of these localities e.g. Oatesdale, are up to 150 m above the Ecca-Beaufort contact as defined by this study. As such, it is possible that the lower *Daptocephalus* AZ is present in the Estcourt district, but further collecting is required to confirm this. Oatesdale Quarry near Mooi River, which is slightly higher in the stratigraphic succession, has yielded *Dicynodontoides* and a gorgonopsian in association with *Lystrosaurus maccaigi*. Strata at this locality are therefore confidently assigned to the latest Permian (Changhsingian) *Lystrosaurus maccaigi-Moschorhinus* subzone (Viglietti et al., 2016; Viglietti, 2020).

5.3 Status of the Normandien Formation

On the 2019 1:1 M geological map (Council for Geoscience, 2019), the Normandien Formation is included in the Balfour Formation of the Beaufort Group. As the Frankfort Member, the lowermost stratigraphic unit of the Normandien Formation, (Groenewald, 1984, 1989), is here considered equivalent to the Waterford Formation, it should therefore be included in the Ecca Group rather than the Beaufort Group. We propose that the Normandien Formation in the northern Karoo Basin be replaced by the Balfour Formation. The arenaceous Rooinek and Schoondraai members and argillaceous Harrismith Member (Groenewald, 1984, 1989) which are useful regional stratigraphic markers in the northern part of the Karoo Basin

(Muntingh, 1989; Claassen, 2008) should be retained and given formal status as members within the Balfour Formation.

6 Conclusions

This study has demonstrated that the Waterford Formation of the Ecca Group, not previously recognised in the distal sector of the Karoo Basin, is present throughout the study area and includes strata currently mapped as both the uppermost Volksrust/Tierberg formations of the Ecca Group and lowermost Adelaide Subgroup of the Beaufort Group. This has implications for the mapped position of the Ecca-Beaufort contact which, we have demonstrated, should coincide with the top of the Waterford Formation rather than the base of the first prominent sandstone.

In the southern Free State Province, rocks of the lowermost Beaufort Group correlate with the Abrahamskraal Formation based on biostratigraphy. Here the middle Permian Abrahamskraal Formation is directly and unconformably overlain by rocks of the late Permian Balfour Formation, which can be easily recognised by the predominance of reddish brown mudrock.

In the central and north-eastern Free State and KwaZulu-Natal, most of the mapped Frankfort Member of the Normandien Formation (Groenewald, 1984, 1989, 1990) has been shown to be lithologically the same as the Waterford Formation of the Ecca Group and thus it is recommended that the term Normandien Formation no-longer be used. Rather, the remainder of the Normandien Formation including the prominent arenaceous Rooinek and Schoondraai members and argillaceous Harrismith Member, should be incorporated into the Balfour Formation and these units should be given formal member status.

Extensive fossil collecting for this project, coupled with recent Karoo biostratigraphic advancements (Smith et al., 2020), has enabled refined biostratigraphic determination of lower Beaufort Group deposits in the distal parts of the main Karoo Basin. Based on the co-

826 occurrence of *Eosimops* and *Glanosuchus* in the southern Free State, it is apparent that,
827 contrary to previous understanding (Rubidge, 1995; van der Walt et al., 2010), the oldest
828 tetrapod biozone present in this part of the basin is the *Eosimops*-*Glanosuchus* subzone of the
829 *Tapinocephalus* AZ (Groenewald et al., 2019; Smith et al., 2020). Rocks immediately
830 overlying the *Tapinocephalus* AZ strata in the southern Free State host a tetrapod fossil fauna
831 characteristic of either the upper *Cistecephalus* AZ or lower *Daptocephalus* AZ (*Dicynodon*-
832 *Theriognathus* subzone; Groenewald *et al.* 2019).

833 In the central and north-eastern Free State and in KwaZulu-Natal, the *Dicynodon*-
834 *Theriognathus* subzone of the *Daptocephalus* AZ directly overlies the Waterford Formation
835 based on the presence of *Rhachiocephalus* and *Kitchinganomodon*. In turn it is overlain by
836 the *Lystrosaurus maccaigi*-*Moschorhinus* subzone of the *Daptocephalus* AZ. The first
837 appearance datum of *Lystrosaurus maccaigi*, which demarcates the lower boundary of the
838 *Lystrosaurus maccaigi*-*Moschorhin*us subzone (Viglietti, 2020), coincides roughly with the
839 Musgrave Grit and Schoondraai Member in the central and north-eastern Free State,
840 respectively.

841 This enhanced understanding of the bio- and lithostratigraphy of the northern (distal) sector
842 of the main Karoo Basin has important consequences for Karoo Basin development
843 modelling during the Permian. Of particular importance is an apparent ~6 Ma hiatus in the
844 southern Free State Province (Groenewald et al., 2019; Groenewald, 2021) and the out of
845 phase deposition of sandstone rich intervals in the Balfour Formation in the north versus the
846 south e.g. the Schoondraai and Ripplemead members (Viglietti et al., 2017a; Groenewald,
847 2021). The implications of these observations will be discussed in a future paper.

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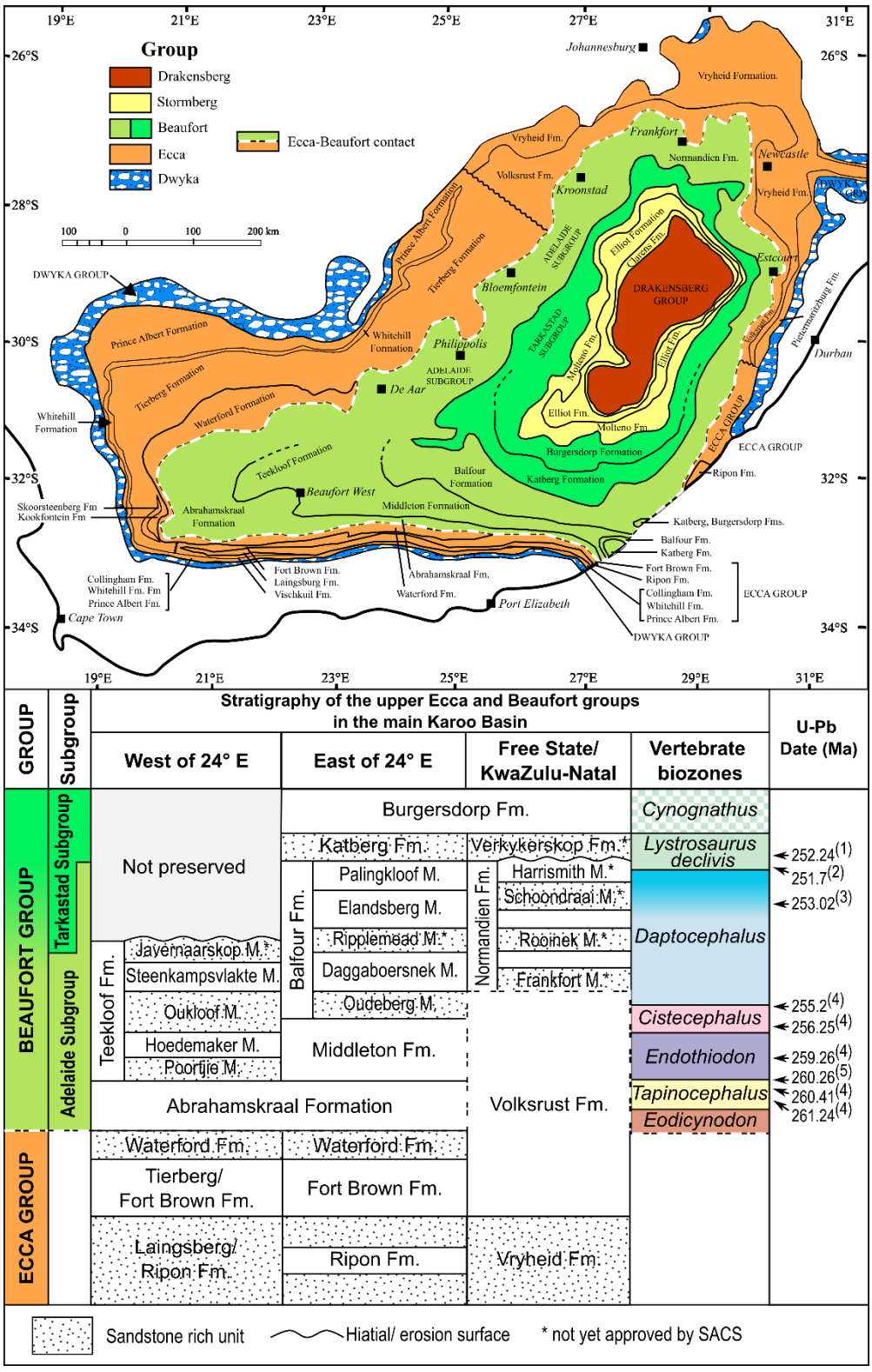

Figure 1 Simplified geological map of the main Karoo Basin and table reflecting the present understanding of the stratigraphy of the upper Ecca and Beaufort groups in the different portions of the basin. Map modified from Catuneanu et al. (2005). Members of the Abrahamskraal Formation are not shown, and thicknesses of stratigraphic units are not to scale. Subdivisions of biozones are also not shown. Biozone colours correspond to those in Figure 2. Fm. = Formation; M. = Member. Table modified from Barbolini et al. (2016) with additional data from Viglietti (2016), Cole et al. (2016), and Smith et al. (2020). Sources for radiometric ages: (1) Gastaldo et al. (2020); (2) Botha et al. (2020); (3) Gastaldo et al. (2015); (4) Rubidge et al. (2013); (5) Day et al. (2015).

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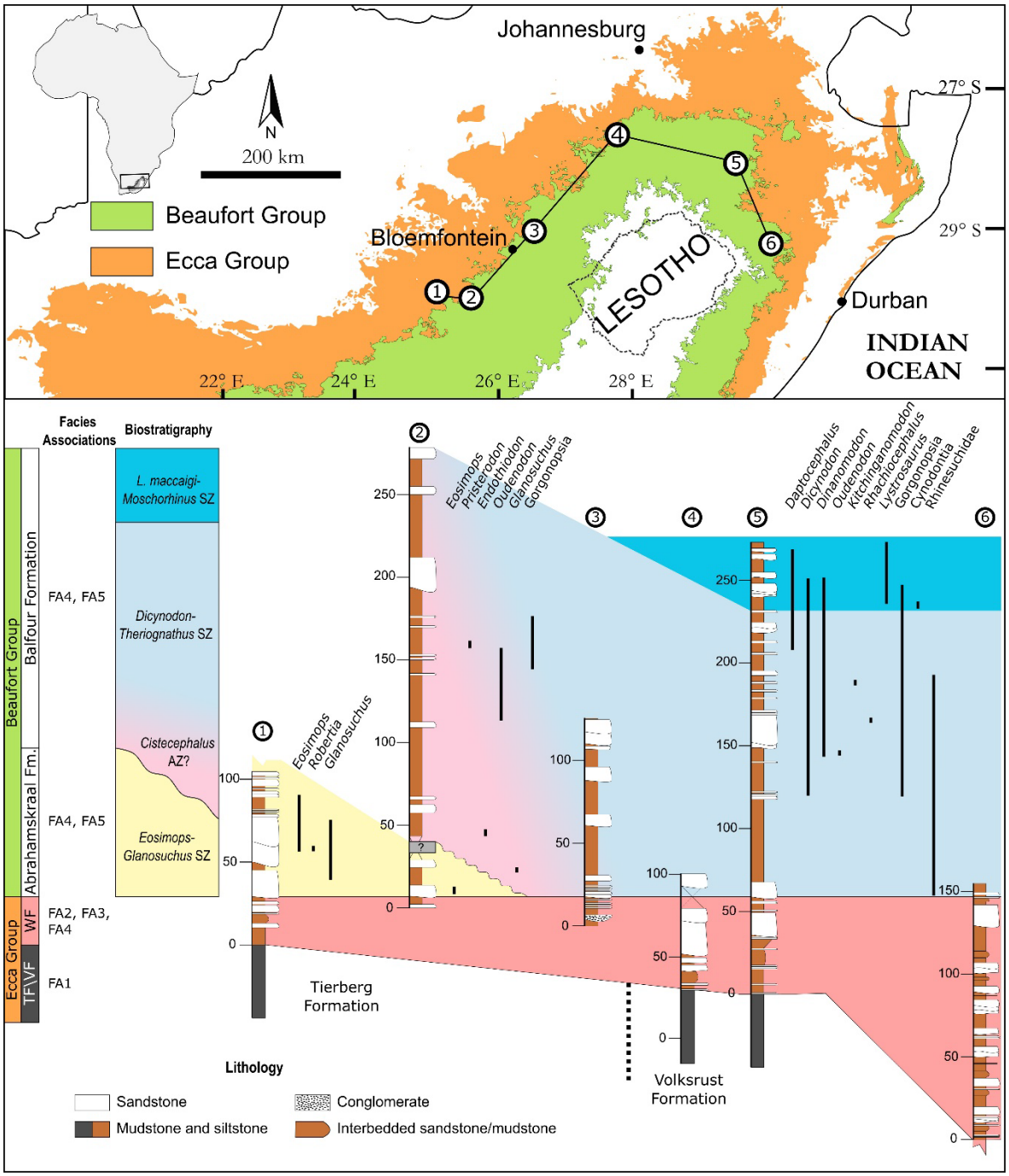

Figure 2 Fence diagram of six composite stratigraphic sections across the study area, highlighting the difference in thicknesses of stratigraphic units throughout the northern part of the main Karoo Basin, and showing the stratigraphic ranges of collected vertebrate fossils. Positions of stratigraphic sections numbered 1-6 are shown in the overview map. Localities: (1) Sandymount Park; (2) Jagersfontein; (3) Brandfort; (4) Borehole J.82/6; (5) North-eastern Free State; (6) Van der Merwe's Kraal, Estcourt. AZ = Assemblage Zone; SZ = subzone; TF = Tierberg Formation; VF = Volksrust Formation; WF = Waterford Formation. The shading between the *Cistecephalus* AZ? and the *Dicynodon-Theriognathus SZ* (*Daptocephalus* AZ) reflects the uncertainty surrounding the presence and placement of the contact between the two zones in this part of the basin.

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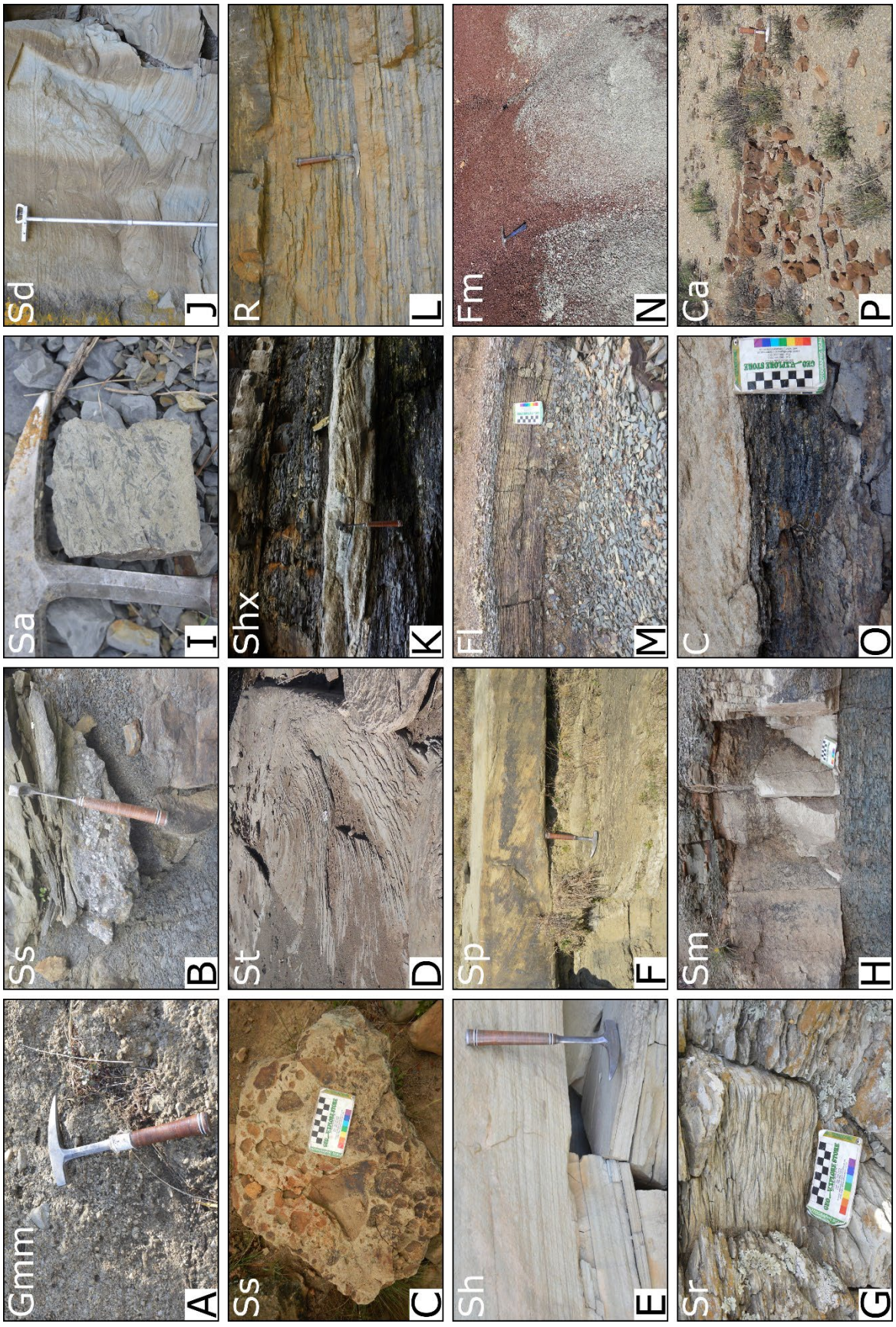

Figure 3 Field photographs showing examples of lithofacies types Gmm, Ss, St, Sh, Sp, Sr, Sm, Sa, Sd, Shx, R, Fl, Fm, C, and Ca in the study area. See Table 1 for more details of each lithofacies type.

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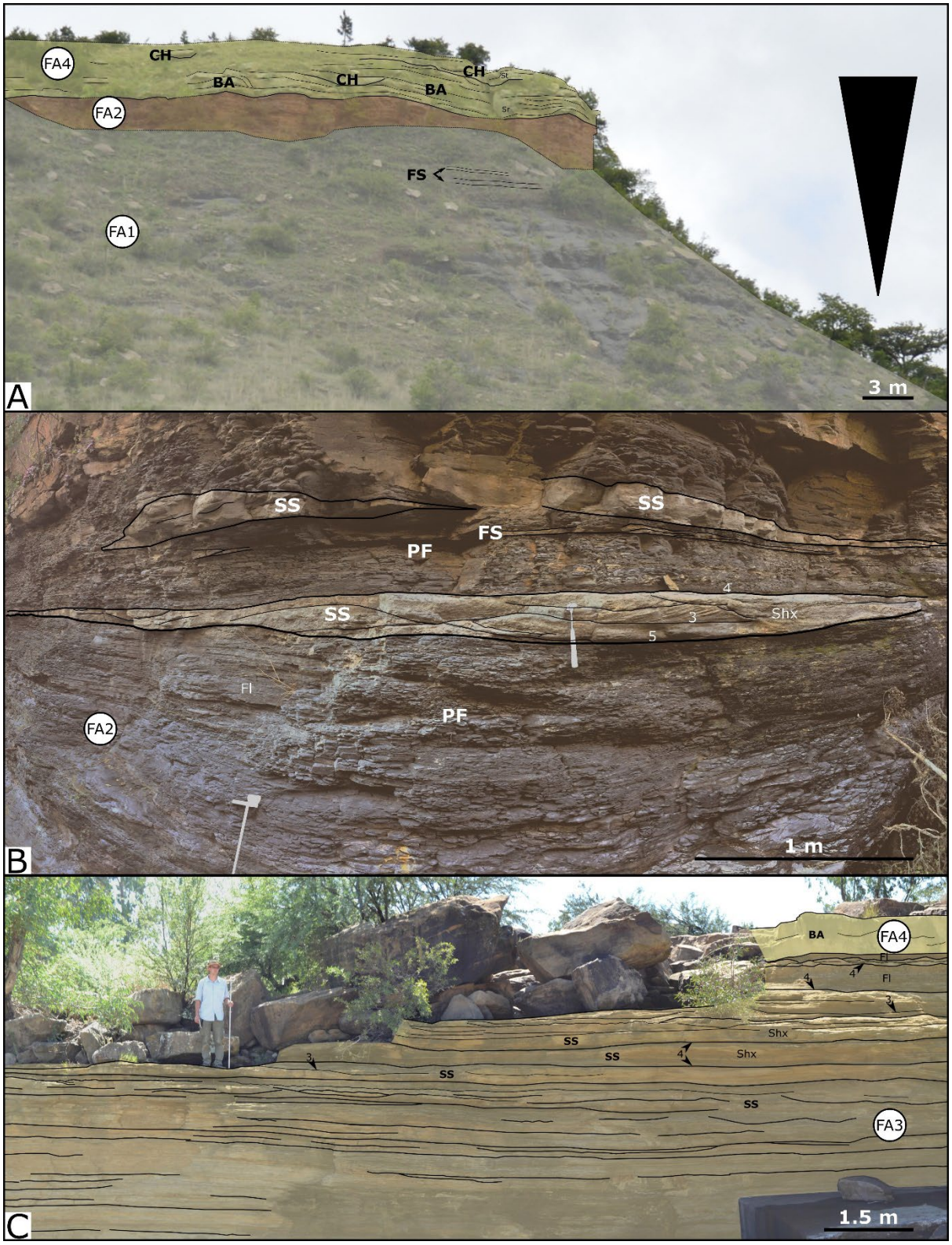

Figure 4 A) Field photograph and interpretive sketch overlay showing the overall upward coarsening trend of FA1, FA2, and FA4, and examples of Prodelta Fines (PF) and Frontal Splay (FS) architectural elements observed in FA1, and Bar Accretion (BA) and Channel Fill (CH) architectural elements from FA4, at the locality Goewermentskop near Newcastle. B) Field photographs with interpretive sketch overlays showing examples of architectural elements Prodelta Fines (PF), Frontal Splay (FS), and Storm Sheets (SS) within FA2 on the farm Van der Merwe's Kraal. C) Panel section with interpretive sketch overlay showing FA3 and FA4, characterised by lithofacies type Shx and Storm Sheet (SS) elements, sharply overlain by Bar Accretion (BA) elements from FA4 at the outflow of the Barend Wessel Dam, Kroonstad. Numbered arrows indicate order of bounding surfaces.

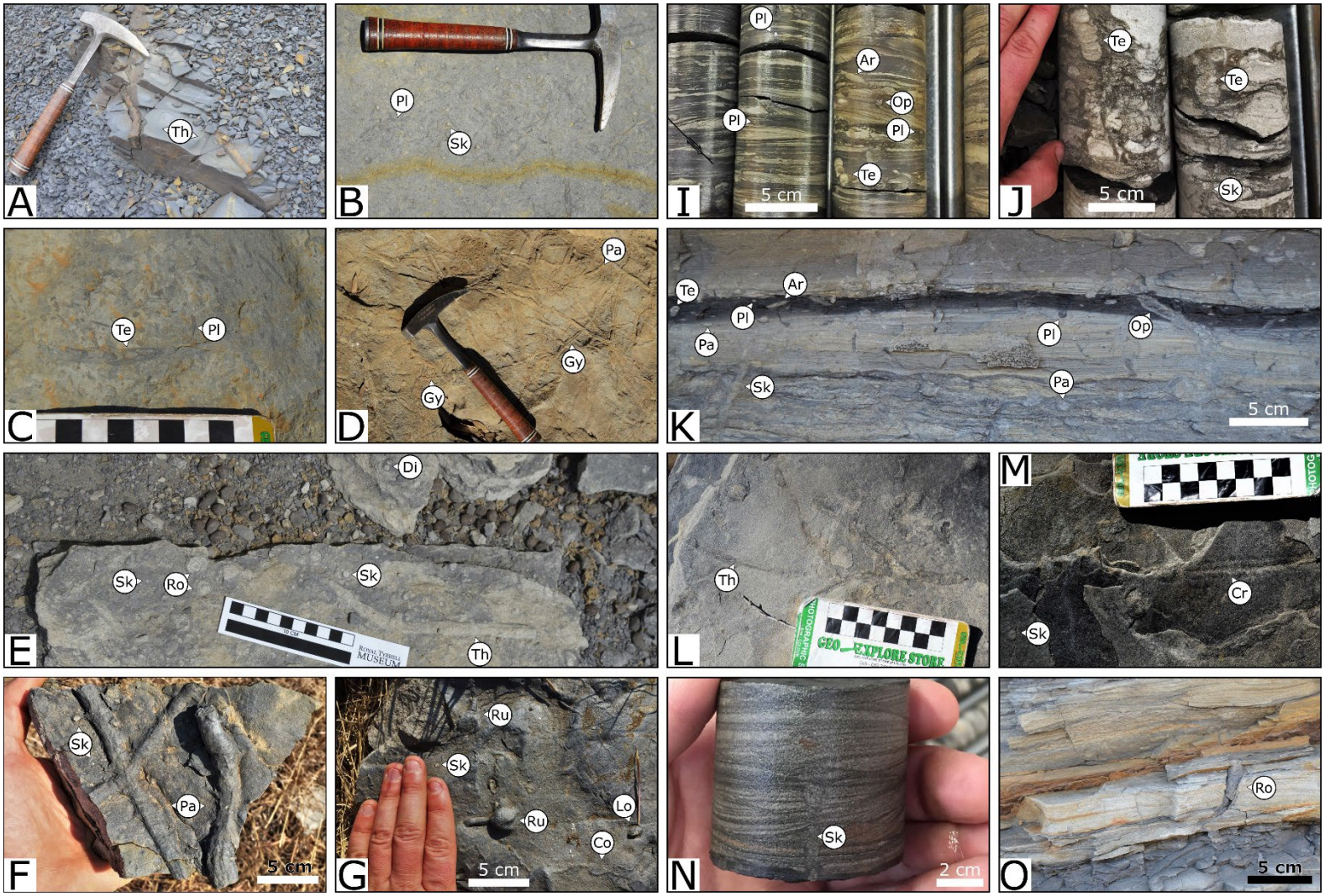

Figure 5 Examples of ichnofossils from Facies Association 1, Facies Association 2, and Facies Association 3 in the study area. Borehole cores: I and J = GR1/76; N = J82/6. Abbreviations for ichnogenera: Ar = *Arenicolites*; Co = *Cochlichnus*; Cr = *Cruziana*; Di = *Diplocraterion*; Gy = *Gyrochorte*; Lo = *Lockeia*; Op = *Ophiomorpha*; Pa = *Palaeophycus*, Pl = *Planolites*; Ro = *Rosselia*; Ru = *Rusophycus*; Sk = *Skolithos*; Te = *Teichichnus*; Th = *Thalassinoides*.

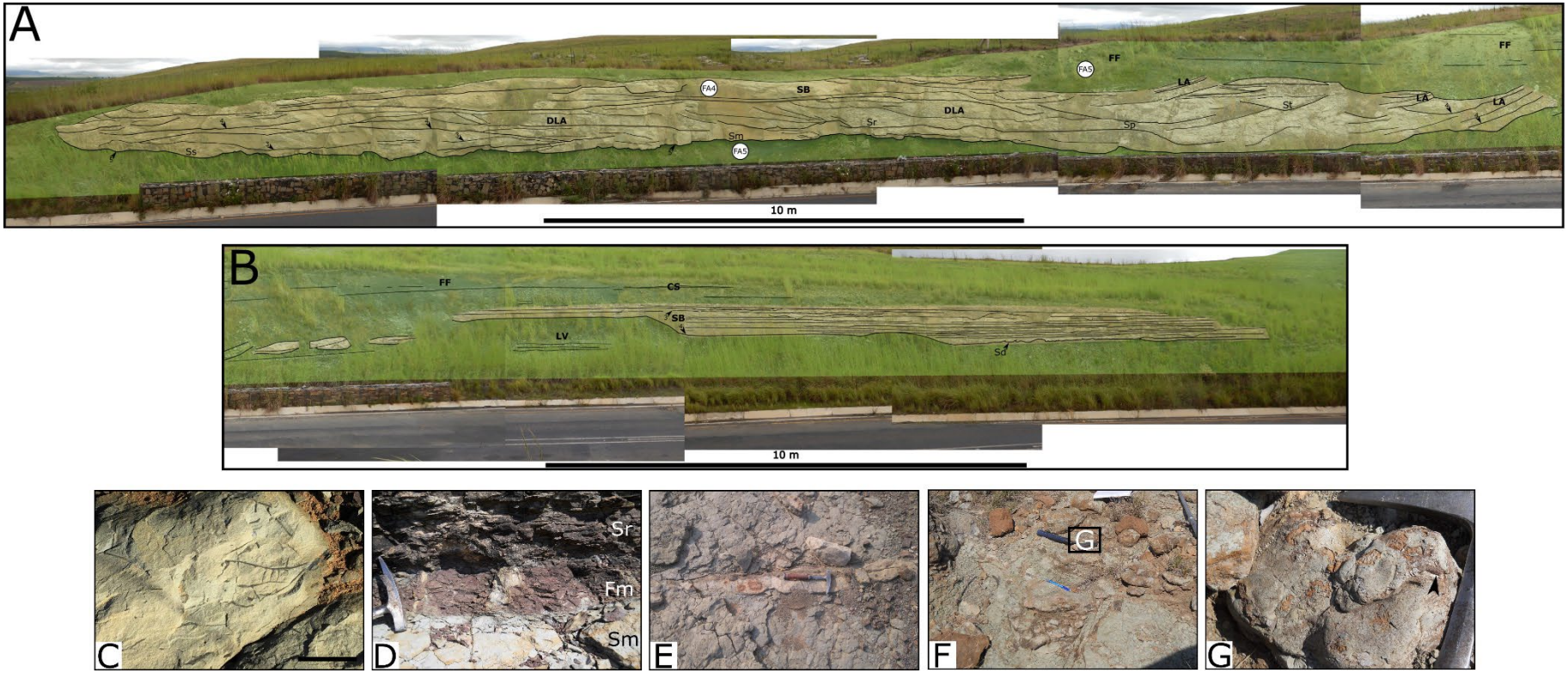

Figure 6 A and B) Panel section with interpretive sketch showing architectural elements (**bold**) and lithofacies (normal) characteristic of FA4 and FA5 at Rooinek Pass in the north-eastern Free State Province. Numbers indicate bounding surface order. C- G) Examples of sedimentological features observed in Facies Association 5, including C) Root traces in a siltstone of Facies Fm; D) sand-filled mudcracks, E) Large, ~15 cm wide sandstone dyke; F and G) extensive nodular horizon with skull of the dicynodont *Diictodon* (tusk is arrowed).

1421 **Table 1** Descriptions and interpretations of lithofacies types (modified after Miall (2006); * denotes newly
1422 erected lithofacies types) from the studied stratigraphic interval in the northern part of the main Karoo Basin.

Lithofacies Code	Lithofacies	Description	Interpretation
Gmm	Matrix supported gravel	Matrix supported conglomerate with quartzite extraclasts up to 15 cm across. Poorly sorted, ungraded and may display crude bedding	Debris flow
Ss	Scour-fill sand	Medium to very coarse-grained sandstone with granule- to pebble-sized intraclasts and extraclasts. Common at base of channels	Lag deposit formed as scour-structures fill up during the waning phase of a flood
St	Trough cross-stratified sandstone	Medium- to coarse-grained sandstones with cross-stratification in which the lower bounding surfaces are curved and truncate other facies or cosets	Migration of three-dimensional dunes
Sh	Horizontally stratified sandstone	Well sorted, horizontally laminated and bedded. Occurs in fine- to medium-grained sandstones	Plane-bed flow (upper flow regime)
Sp	Planar cross-bedded sandstone	Fine- to coarse-grained sandstones in which the foresets dip between 15° and 35°	Migration of two-dimensional dunes
Sr	Ripple cross-laminated sandstones	Very fine- to medium-grained sandstones with ripple cross-laminations	Lower flow regime, wave and wind induced ripples
Sm	Massive or weakly graded sandstone	Very fine- to coarse-grained sandstones in which no internal sedimentary structures are observed	Rapid deposition e.g. sediment gravity flows. Alternatively, loss of sedimentary structures could be due to bioturbation and/ or weathering
Sa*	Sandstone with floating mudstone clasts	Fine- to medium-grained sandstones containing thin argillaceous acicular structures throughout. Ripple cross-lamination and horizontal bedding may be present	Rapid subaqueous deposition by turbidity currents
Sd*	Sandstone/siltstone beds with deformation structures	Fine-grained sandstone and siltstone beds that display soft-sediment deformation structures including load casts, ball and pillows, and water escape and flame structures	Rapid sedimentation, liquefaction, reverse density gradation, shear stress, or collapse of channel banks
Shx*	Hummocky cross-stratified sandstone	Medium-grained sandy units displaying large wave-form internal laminae, comprising almost flat-to-low angle negative relief convex-down swales and positive relief convex-up hummocks	Deposition on the shoreface and shelf environments under the influence of both oscillatory and unidirectional currents related to storm activity
R*	Rhythmically interbedded mudstones, siltstones, and sandstones	Alternating heterolithic beds of fine- to medium-, and occasionally coarse-grained sandstones, siltstones, and mudstones. Lower bounding surface of coarser beds is sharp, whereas the upper bounding surface commonly has symmetrical ripple marks	Deposition in parts of the interdistributary bay proximal to subaqueous distributary channels. Finer-grained argillaceous beds were deposited through suspension settling during periods of lower energy while the interbedded coarser-grained beds were deposited under higher energy conditions

Fl	Laminated siltstones and mudstones	Relatively thick (> 0.5 m) successions of horizontally and ripple-cross laminated mudstones	Suspension settling, or deposition under lower flow regime conditions. Depositional settings include distal interdistributary bays, lagoons, and on tidal flats; away from channels and where wave activity is minimal. Fluvial settings include ephemeral floodplain pools and ponds
Fm	Massive siltstones and mudstones	Massive beds of siltstone and mudstone displaying no apparent bedding planes. Co-occurs with Facies Fl and thin sandstone lenses may be present	Either through suspension settling, with bioturbation, diagenesis, or weathering resulting in the lack of sedimentary structures, or through rapid deposition e.g. hyperpycnal/hypopycnal flows
C	Carbonaceous black shales and coal	Finely to very finely laminated, highly carbonaceous shales containing thin beds and lenses of coal up to 0.5 m thick	Suspension settling of fines in low-lying interchannel plains, abandoned channels and backswamp environments on the upper delta plain and flood plain. Peat deposits or other accumulations of organic matter gave rise to thin coal seams
Ca	Carbonate horizon	Laterally extensive (10 – 30 m) carbonate horizons, commonly 30 – 50 cm thick. Upper and lower bounding surfaces are either straight or irregular, with sharp contacts	Deposition under waterlogged or palustrine conditions on the floodplain

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1424 **Table 2** Description and interpretation of the architectural elements from the studied stratigraphic interval in the
1425 northern part of the main Karoo Basin. Modified after Miall (1985), Miall (2006), Colombera et al. (2013), Platt
1426 and Keller (1992), Gani and Bhattacharya (2007), and Ahmed et al. (2014). See Table 1 for descriptions of
1427 lithofacies types.

Architectural element Code	Architectural element	Description	Interpretation
PF	Prodelta Fines	Aerially extensive fine-grained body with sheetlike geometry and bounded by third-order surfaces. Comprised of laminated to massive mudstones, siltstones (lithofacies types Fl and Fm), and subordinate very fine- to-fine-grained lenticular sandstones	Deposition in very low-to-low energy conditions, mainly through suspension settling (Fl) or by hypo- and hyperpycnal flow processes (Fm)
FS	Frontal Splay	5 to 50-cm-thick sandstones bound by third- to fourth-order surfaces. Consists of sandstone beds, with sharp, sometimes erosional bases, and that are often continuous across the outcrop. Internally, sandstone beds may be structureless, horizontally-, and/or ripple cross-laminated	Non-channelized sediment gravity flows, potentially originating from high sediment discharge during river floods, slump failures at a river mouth, and/or storm resuspension of bottom sediments
SS	Storm Sheet	Hummocky-cross stratified sandstones bounded by third- or fourth-order surfaces. Can comprise either single or stacked beds of lithofacies type Shx	Deposition and reworking of sediment on the lower to middle delta front or shoreface by storms and waves
CH	Channel Fill	Sandstones bound by third- to fifth-order surfaces. CH elements have a concave-up, often erosive base, whereas the upper bounding surface can be sharp or gradational. Multi-storey fills are common, with each storey bounded by an erosional surface and smaller channels that overlap and crosscut one another	Aggradational channel fill in active channels
BA	Bar Accretion	Flat to sloping, lens shaped sandstones bounded by third- or fourth-order surfaces. Internal sedimentary structures include Sd, Sm, Sr, St, Sh, and occasionally Shx	Produced mainly by river-fed currents and sediments. Deposition via migration of dunes. Increase or decrease in the flow velocity is recorded by lithofacies types Sh and Sr, respectively. Occasional Shx indicates periodic storm reworking of the bars, while the lithofacies types Sm and Sd suggest rapid deposition and dewatering of sediments

SG	Sediment-Gravity-Flow Deposits	Narrow, elongate lobes or multistorey sheets that may be intimately interbedded with element SB. Can have a channelised form. Boundaries are irregular, often nonerosive, and beds may have an irregular shape. Internally a wide variety of textures and fabrics may be present, although a chaotic fabric is common. Lithofacies types include Gmm, Sa, Sd, and Sm	Debris flows with high sediment concentration. The flows often occupy existing erosion channels, or the irregular topography formed by a previous flow or sheet flood event, thereby taking on a channelised form
SB	Sandy Bedforms	Tabular sheets or lenticular sandbodies that have flat, sometimes slightly erosive, bases and sharp upper surfaces. Element SB occurs as isolated or stacked tabular sand bodies and is commonly infilled with lithofacies types Sh, Sp, St, and Sr. Internal bounding surfaces are of the first- to third-order	This element forms under conditions where trains or fields of individual bedforms accumulate predominantly through vertical aggradation as opposed to lateral or downstream accretion (LA or DA elements). SB elements can form within channels, as channel floor dune fields or shallow channel fill and bar top assemblages, or as a result of unconfined flows during flood events. Changes in flow regime, either long- or short-term, results in the vertical stacking of different bedform types
LA	Lateral Accretion	Slightly concave upward sandstone bodies, often with erosional bases, and containing dipping third-order internal bounding surfaces	Lateral accretion of sediment (oblique to the palaeo-flow) within a channel, as opposed to the vertical aggradation of sandy bedform (SB) and channel elements (CH), or downstream accretion (DA)
DA	Downstream Accretion	Sandstone bodies with internal bounding surfaces that dip gently (<10°) in a downstream direction and enclose cosets of downstream orientated flow-regime bed-forms with second- and third-order internal erosion surfaces, and 4th order bounding surfaces. DA elements typically have a flat or channelled base and convex-up profile. Where palaeocurrent direction cannot be determined, LA/DA is used	Accretion of sediment in the downstream direction
DLA	Downstream and Lateral Accretion	Sandstone bodies that typically have a wedge or lens geometry. Intermediate bar forms between DA and LA elements. Bedding geometries demonstrate dominantly oblique accretion due to downstream accretion on the downstream end and cross-bar accretion along the flank	Formed when downstream and lateral accretion occurs in comparable proportions
FF	Overbank (floodplain) Fines	Tabular to prismatic bodies of fine-grained deposits (lithofacies types Fm and Fl) bounded by planar surfaces. Laterally persistent depositional increments tend to be vertically stacked and pedogenic alteration is common	Aggradational deposits from suspension setting on the floodplain

AC	Abandoned Channel	Heterolothic bodies with a similar geometry to Channel Fill (CH) elements. Dominated by vertically stacked facies. Lithofacies types Fl and Fm are predominant	Deposition in lower energy conditions e.g. in ponded waters of an abandoned reach, where suspension settling is predominant and stream flow processes are intermittent
CS	Crevasse Splay	Tongue- or lobe-shaped sandstone bodies bordering the channel margins and bounded by fourth-order surfaces. CS elements have flat, sharp, and sometimes erosive bases, and often thin away from the channel margins, interfingering or grading laterally into other elements, mainly FF	Periodic unconfined flow emerging from a channel onto the floodplain
LV	Levées	Rhythmically bedded mudstone/siltstone and ripple-laminated sandstone. Has the form of tapering wedges that thin and fine away from channel-belt margins. Fine-scale loading, water escape and slump structures (lithofacies type Sd) may be present. Base is often poorly defined and internal accretion surfaces offlap and/or downlap at low angles (2° – 10°). Palaeo-flow direction is usually oriented at high angles to the channel border	The most proximal overbank deposits. Deposited in areas separating the channel from the floodplain. Loading and water escape structures indicate high sedimentation rates

1428

1429 **Table 3** Characteristics of the five facies associations encountered in the studied stratigraphic interval in the
1430 northern part of the main Karoo Basin.

Facies Association	Lithofacies present	Architectural elements	Ichnogenera
Facies Association 1: Prodelta	Fl; Fm	PF; FS	*Thalassinoides*, *Planolites*, limulid trackways
Facies Association 2: Delta front	Sh; Sr; Sm; Sd; Shx; R; Fl; Fm	FS; SS	*Arenicolites, Cochlichnus, Diplocraterion, Lockeia, Gyrochorte, Gordia, Ophiomorpha, Palaeophycus, Planolites, Rosselia, Rusophycus, Skolithos, Teichichnus,* and *Thalassinoides*
Facies Association 3: Lower shoreface	Shx; R; Fl; Fm	SS	*Arenicolites, Cruziana, Gyrochorte, Ophiomorpha, Palaeophycus, Planolites, Rosselia, Skolithos*, and *Thalassinoides*
Facies Association 4: Confined channelised system	Gmm; Ss; Sm; Sh; St; Sr; Sp; Sa; Sd	CH; BA; SG; SB; LA; DA; DLA	
Facies Association 5: Floodplain fines and overbank deposits	Ss; Sh; Sr; Sm; Sd; Fl; Fm; C; Ca	FF; AC; CS; LV	

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1432 **Table 4** Representative taxonomic list of tetrapod fossils that have been recovered from the study area.

Formation	Biozone	Clade	Species
Balfour Formation	*Cistecephalus*-to-*Daptocephalus* Assemblage Zone	Anomodontia	*Diictodon feliceps*
			Pristerodon mackayi
			Endothiodon bathystoma
			Compsodon Helmoedi
			Dicynodontoides recurvidens
			Cistecephalus microrhinus
			Oudenodon bainii
			Aulacephalodon baini
			Kitchinganomodon crassus
			Rhachiocephalus magnus
			Dicynodon lacerticeps
			Daptocephalus leoniceps
			Dinanomodon gilli
			Basilodon woodwardi
			Lystrosaurus maccaigi
			Lystrosaurus curvatus
		Therocephalia	*Zorillodontops gracilis*
			Moschorhinus kitchingi
			Theriognathus microps
		Biarmosuchia	Burnetiidae indet.
		Cynodontia	Cynodontia indet.
		Gorgonopsia	Gorgonopsia indet.
		Amphibia	*Uranocentrodon senekalensis*
			Laccosaurus watsoni
Abrahamskraal Fm.	*Tapinocephalus* Assemblage Zone	Anomodontia	*Robertia broomiana*
			Eosimops newtoni
			Pristerodon mackayi
		Therocephalia	*Glanosuchus macrops*
			Pristerognathus polyodon
		Pantestudines	*Eunotosaurus africanus*
		Amphibia	Rhinesuchidae indet.

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