The Geology of South Africa

The Karoo Supergroup: Modern insights from the ancient archive of Gondwana

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Abstract

The Karoo Supergroup of southern Africa offers a valuable record of Gondwana's late Palaeozoic to early Mesozoic evolution over ~120 million years of geological history. This review synthesizes advances in sedimentology, stratigraphy, palaeontology, and basin analysis in the main Karoo Basin since 2000, highlighting key lessons and ongoing challenges. Significant developments include: (1) a refined flexural foreland basin model and the recognition of extensional overprinting in the Early Jurassic; (2) palaeoclimate reconstructions revealing non-linear shifts, particularly in the upper Karoo, challenging previous ideas on gradual aridification; (3) revised biozonation and expanding fossil records demonstrating ecosystem resilience during mass extinctions (end-Permian, end-Triassic); and (4) an improved chronostratigraphic framework through volcanic ash and detrital zircon geochronology and magnetostratigraphy, facilitating pan-Gondwanan correlations. However, critical unresolved questions remain regarding the precise nature and timing of formation boundaries; the relative roles of tectonics versus climate in facies changes; within-basin heterogeneity, sediment source links, and detailed correlation with global events. Future progress requires high-resolution stratigraphy integrating new geochronological data through denser sampling across critical boundaries; AI-assisted facies analysis and remote sensing applications to address correlation challenges and basin heterogeneity; expanded palaeontological and ichnological surveys; and synthesis of tectonic models with lessons from the sedimentary record. Coupled basin evolution models linking sedimentology, geochemistry, and geochronology are essential to resolve drivers of stratigraphic architecture. Assessments of resource potential (groundwater, CO_2 storage, mineralisation) must consider the impacts of dolerite intrusion on basin-fill compartmentalisation. Revitalised institutional oversight by the South African Committee for Stratigraphy (SACS) is needed to formalise units and standardise frameworks. The Karoo's significance extends beyond Gondwana, offering insights into responses to supercontinental dynamics and fragmentation, climatic extremes, and biological crises. The Karoo remains a global deep-time laboratory for understanding tectonic-climatic-biotic interactions, but ongoing stratigraphic refinement is essential for unlocking additional Earth system insights and resource potential in southern Africa.

Introduction

The Karoo Supergroup of southern Africa (Figure 1) is one of the most iconic sedimentary archives of Gondwana's late Palaeozoic to early Mesozoic evolution, encompassing ~120 million years of Earth history, from the Late Carboniferous (Gzhelian) to the Early Jurassic (Toarcian). Its rich vertebrate and plant fossil records, glacial pavements, superbly exposed sedimentary rocks that formed in a wide array of depositional settings, and its extensive flood basalts have long drawn international geological and palaeontological interest. Historically, these features have provided foundational support for continental drift and early reconstructions of Gondwana (Du Toit, 1921, 1937) and continue to offer unique insights into both regional and global Earth system dynamics during the time period (hereafter the Karoo), covered by the rocks forming the Karoo Supergroup.

As a key archive of global events, including mass extinctions at the end-Capitanian, end-Permian, end-Triassic, and end-Pliensbachian, the Carnian Pluvial Episode (CPE), and the emplacement of the Karoo-Ferrar Large Igneous Province, the Karoo also holds immense economic value and remains a key target for applied geoscientific research in southern Africa (Figure 1). It hosts substantial reserves of groundwater, vast quantities of Permian and some Triassic coal seams, and has potential for natural gas (coalbed methane and shale gas), uranium, molybdenum, and CO_2 storage (Cole and Wipplinger, 2001; Johnson et al., 2006; Hancox and Götz, 2014). Moreover, the exceptional 3D Karoo outcrops have advanced the understanding of depositional architecture in clastic systems at various scales, from sub-microscopic to basin scale. They serve as fundamental outcrop analogues for predictive reservoir modelling, petrophysical characterisation of heterogeneity, and optimisation of hydrocarbon recovery in subsurface systems globally (Flint et al., 2011; Di Celma et al., 2011; Hodgson et al., 2016).

The Karoo Supergroup is most complete and best studied in the main Karoo Basin (MKB; Figures 1 and 2), which, at the time, was bordered to the north by the Cargonian Highlands and to the south by the towering Cape Fold Belt, placing it in a key position among the basins along the southern margin of Gondwana (Figures 1 to 3). Karoo-correlative strata extended across the rest of the supercontinent, which is now found in South Central Africa, South America, Antarctica, India, Madagascar, and Australia (Catuneanu et al., 2005). The Karoo succession developed over ~120 million years, from the Late Carboniferous (Gzhelian) to the Early Jurassic (Toarcian), ultimately accumulating several kilometres of stratigraphic thickness in the southeastern depocentre of the MKB (Johnson et al., 2006).

Its sheer volume and vast geographic extent make the Karoo succession a beacon for shedding light on the basin history of the cratonic interior of southwestern Gondwana during the late Palaeozoic to early Mesozoic. In particular, the succession enhances understanding of the tectonic evolution of this part of the Panthalassan margin of Pangea and records changing tectonic stress regimes both in its early and late phases of development (Figure 1). Currently, most authors interpret the succession – at least its lower half – as the basin fill of the Karoo Foreland Basin, which is considered part of the Pan-Gondwanan foreland basin system (Catuneanu et al., 2005). The timing of the early phases of the subsequent Gondwana breakup (i.e., the ensuing extensional tectonic setting) is debated; nonetheless, most agree that the deposition of the uppermost succession was influenced by extensional tectonic events (see also Bordy et al., 2004, 2005).

Highlighting a more complex, multiphase tectonic evolution, Tankard et al. (2009) proposed a different basin evolution model, suggesting that:

- the Permian fluvial succession was deposited in a southward-deepening ramp syncline by extensional decoupling on the intra-crustal décollement;
- the succeeding Lower Triassic units were influenced by the incipient Cape Orogeny, strike-slip faults, and thin-skinned thrusting; and
- only the sedimentation of the Late Triassic to Early Jurassic units is reconstructed in a transtensional foreland basin setting.

Although the underlying concepts of these basin dynamics models differ (also see Isbell et al., 2008), all predict diachronous lithological boundaries, major facies changes, and numerous unconformities in the succession.

In addition to clarifying the basin evolution, the most persistent stimulus for Karoo rock studies stems from research focused on its unparalleled fossil richness, which has long established the Karoo as a palaeontological wonderland (Broom, 1906; Kitching, 1977; Rubidge, 2005; Rubidge et al., 2016; Smith et al., 2020). The exceptional fossil record of the Karoo has guided much of its stratigraphic research, with early work naturally prioritising biostratigraphic correlations rooted in taxonomic and phylogenetic studies of therapsids (aka 'mammal- like reptiles'), dinosaurs, and plant remains. Over time, the biocentric foundation, focusing on fossil assemblages, was increasingly complemented with more emphasis on detailed lithostratigraphic analysis to provide an integrated understanding of basin evolution, including its inhabitants. Such lithostratigraphic practices describe units exclusively through observable changes in physical rock properties, defined by five attributes:

- lithology (e.g., sandstone, mudstone);
- mineral composition;
- texture (grain size, sorting);
- primary sedimentary structures (e.g., cross-bedding), and
- fossil content **as a lithological** component, not a biostratigraphic signal.

These properties define lithofacies: discrete units mappable via physical contrasts in outcrops or hand samples. Crucially, lithofacies reflect depositional controls – vertical changes capture temporal shifts in physical, chemical, and biological conditions, while lateral variations reveal spatial heterogeneity. Thus, lithostratigraphy hinges on recognising geometric relationships between lithofacies to reconstruct evolving basin and ultimately ecological dynamics. Lithostratigraphic unit boundaries are demarcated exclusively by lithological change – whether sharp, erosional, or gradational – and must disregard inferred age, environment, or fossil assemblages.

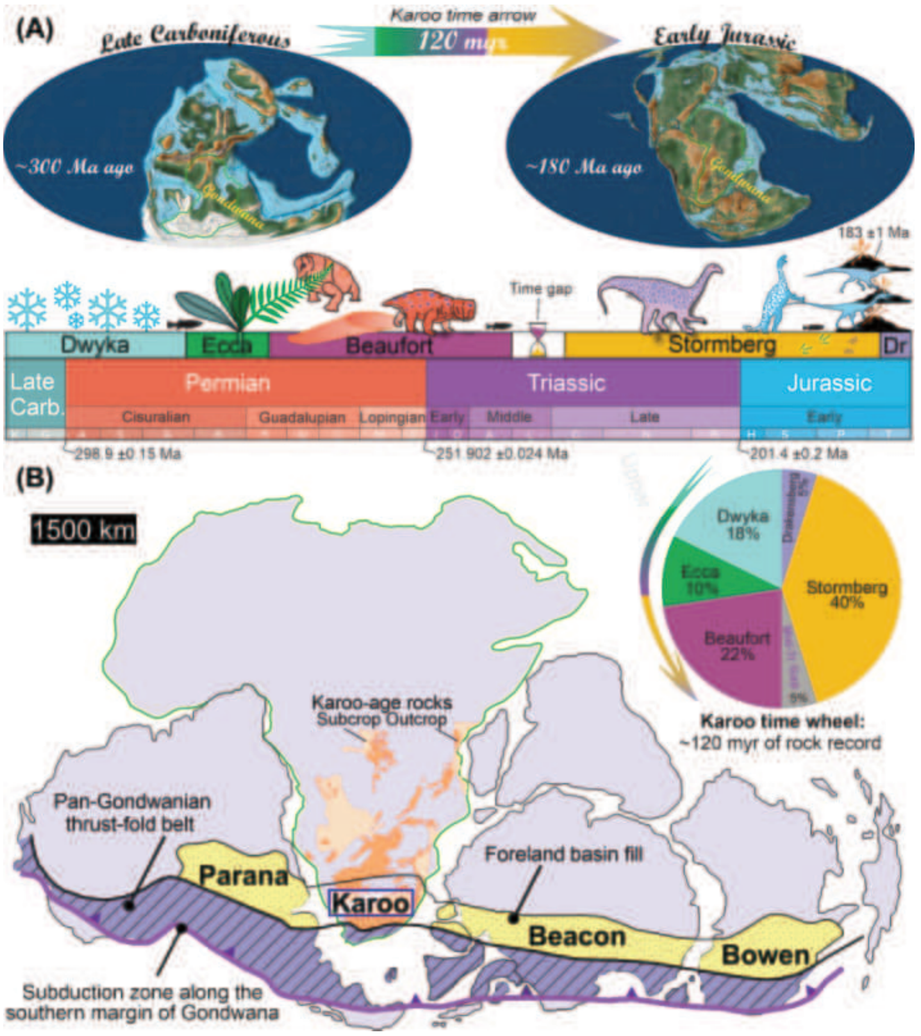

Figure 1. *Karoo times in southern Gondwana. (**A**) Gondwana's palaeogeographic evolution from Late Carboniferous to Early Jurassic during Karoo sedimentation, highlighting key features of the five stratigraphic groups. Inset: Karoo time wheel showing relative durations of each Karoo group. (**B**) Tectonic setting of Karoo-equivalent rocks in southern Gondwana; Africa map depicts the extent of Karoo-age rocks in central and southern Africa. Abbreviations: Carb=Carboniferous; Dr=Drakensberg; myr=million years. Figure compiled from Johnson et al. (2006), Scotese (2014a, b), Cohen et al. (2024).*

Reaffirming the lithofacies-first approach is essential, as boundaries emerge from observed lithofacies contrasts, ensuring that stratigraphic frameworks accurately reflect changes in depositional processes over time and space. Although some past Karoo studies have recognised boundary placement based on fossil occurrences rather than lithofacies definition – resulting in artificially 'fossil-calibrated' units – there has been a beneficial shift in the past two decades toward multidisciplinary studies. This shift has led to in refining litho-, bio-, magneto-, and chronostratigraphic relationships within the Karoo Supergroup. These studies have also produced increasingly accurate palaeoclimatic and palaeoenvironmental reconstructions, and clarified ancient ecological interactions, despite the inherent complexity of physical, chemical, and biological processes, as well as the preservational limitations of the resulting deposits.

This synthesis integrates established classical stratigraphic frameworks from foundational Karoo studies (Catuneanu et al., 2005; Johnson et al., 2006; Smith et al., 2020) with relevant recent advances in sedimentology; vertebrate palaeontology; palaeobotany; ichnology; magnetostratigraphy; radiogenic isotope dating and basin analysis. Instead of presenting – yet again – a traditional, detailed account of Karoo rock units and biozones (i.e., fossil assemblage zones), this review offers a concise synthesis that highlights key developments and gaps in understanding the Karoo rock record.

Lithostratigraphy of the Karoo Supergroup

The Karoo rocks encompass similar deposits throughout southern Africa (Figures 1 to 4), and begin with diamictites and other glaciogenic rock types, which are overlain by carbonaceous, coal-bearing strata, succeeded by varicoloured (predominantly red) fluvio-lacustrine beds capped by aeolian sandstones (Catuneanu et al., 2005; Johnson et al., 2006; Bordy, 2020). In most regions, the uppermost Karoo strata exhibit a transitional contact with the extrusive rocks formed during the Early Jurassic igneous activities

(Duncan et al., 2006; Bordy et al., 2020). The latter also resulted in an extensive sub-volcanic complex of dolerite dykes and sills that compartmentalise the Karoo sedimentary succession throughout southern Africa (Figure 3C).

The Karoo Supergroup comprises five groups: the Dwyka, Ecca, Beaufort, Stormberg, and Drakensberg (Figures 2 to 4). The latter is predominantly igneous in composition, while the former groups primarily consist of siliciclastic rocks. All Karoo contacts are diachronous, typically younging from south to north. In the northern MKB, successions are generally thinner and punctuated by more extensive stratigraphic gaps than in the south (Figures 2, 3A and 4). This pattern has been shown to coincide with the southern margin of the Kaapvaal Craton (see inset in Figure 3; Bordy et al., 2005, 2020; Hancox and Rubidge, 2023), indicating that this crustal-scale boundary had geodynamic control on the north – south variation in facies characteristics, including lithology, stratigraphic architecture, and palaeocurrent patterns, of nearly all Karoo units.

The lithostratigraphy of the Karoo Supergroup has been rigorously formalised by the South African Committee for Stratigraphy (SACS) and approved in formal lithostratigraphic descriptions, which serve as the definitive reference for stratotypes, detailed lithology, boundaries, regional variations, and correlations (De Beer, 2019). The official, SACS-ratified stratigraphic units in the Karoo Supergroup are listed in Electronic Supplement 1. (Supplementary data files are archived in the South African Journal of Geology repository (https://doi.org/10.25131/sajg.129.2748.sup-mat)). Formal Karoo stratigraphic units are described in the open-access SACS Lithostratigraphic Series and SACS Catalogues of South African Lithostratigraphic Units, as well as in the restricted-access SAJG publications and Handbook 8 (SACS, 1980). These specialist descriptions contain decades of expert consensus and function as archival 'gold standards' for reproducibility and mapping. Consequently, their reproduction in this review is both redundant and contrary to SACS guidelines. By listing the not-yet-formalised units and the established SACS descriptions rather than repeating fixed parameters (Figures 2 to 4; Electronic Supplement 1), this work prioritises synthesis over redundancy. Relying on formalised SACS descriptions aligns with global stratigraphic best practices,

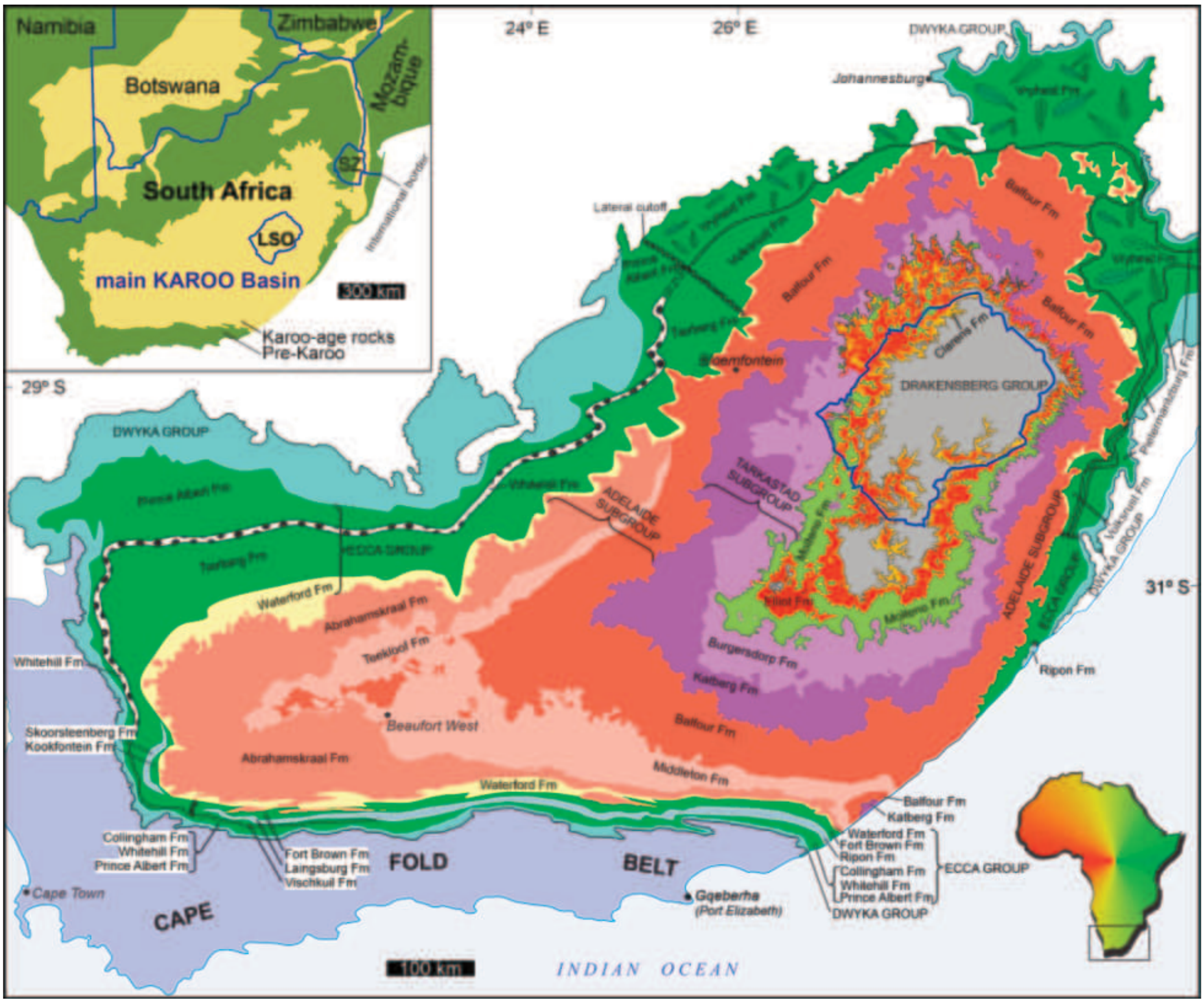

Figure 2. *Simplified geological map of the main Karoo Basin (MKB) showing the distribution of the key lithostratigraphic units in South Africa and Lesotho. Inset: Karoo-age rocks in southern Africa. Abbreviations: Gp=Group; Fm=Formation; LSO=Lesotho; SZ=Eswatini. Figure complied from Johnson et al. (2006).*

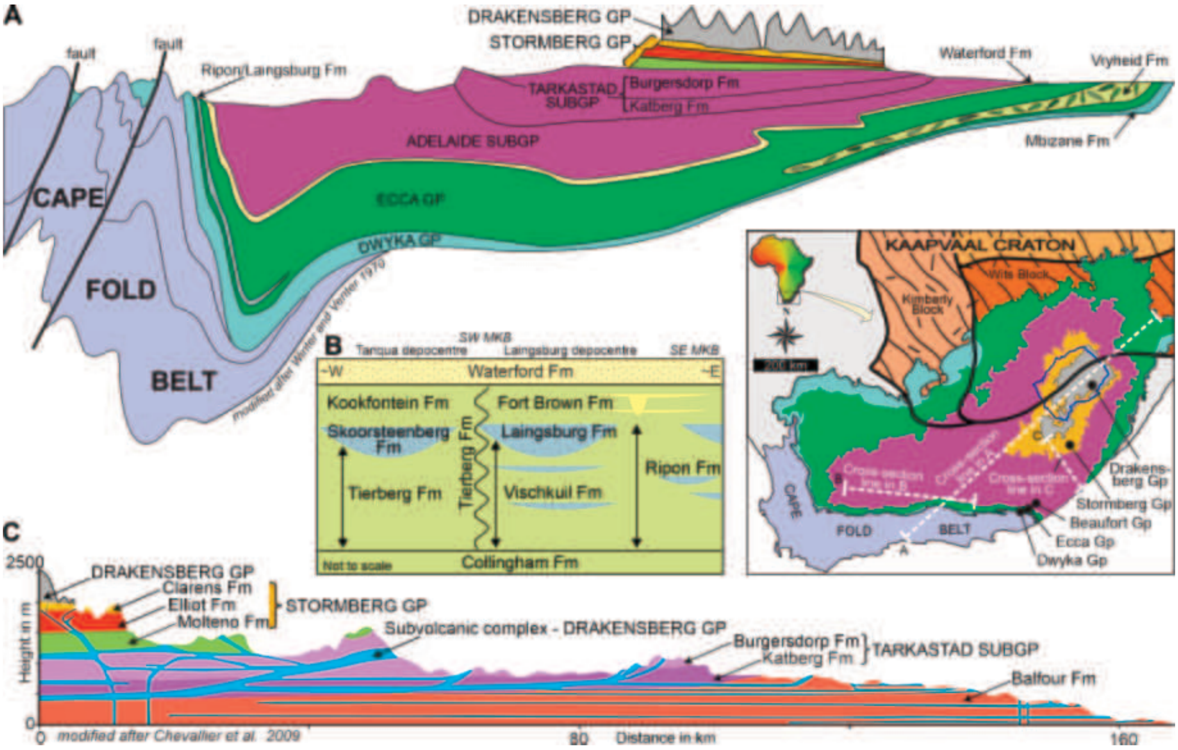

Figure 3. *Simplified cross-sections showing the Karoo stratigraphic architecture in main Karoo Basin (MKB). (**A**) southwest–northeast cross-section from the Cape Fold Belt to the northeast MKB, omitting the intrusive rocks of the Drakensberg Group. Note the extreme vertical exaggeration. (**B**) Schematic ~west–east cross-section from the southwest to the southeast MKB outlining the correlation in the upper Ecca Group. (**C**) Northwest–southeast cross-section in the southeast MKB showing the dolerite dyke-sill network within the pre-Drakensberg sedimentary rocks. Inset: location of sections (A) and (B) within the MKB and the southern limit of the Kaapvaal Craton as proposed by Skinner et al. (1992). Abbreviations: Gp=Group; Fm=Formation.*

and for the purpose of this contribution, it preserves space for novel advances and persistent gaps in our understanding of the Karoo rocks.

Dwyka Group

The Dwyka Group, representing the initial phase of Karoo sedimentation, is an indispensable stratigraphic unit that recorded intermittent melting of southern Gondwana's high-latitude ice sheets and ice caps extending over ≤70 million km² during the late Palaeozoic (Figures 1 to 4). Its deposition from the Late Carboniferous to Early Permian produced diverse glaciogenic rocks, including diamictites, mudstones (with/without dropstones), rhythmites, sandstones, conglomerates, and associated sedimentary structures (Johnson et al., 2006; Scheffler et al., 2006; Isbell et al., 2008; De Wit, 2016; Dietrich and Hofmann, 2019; Le Heron et al., 2019; Dietrich et al., 2025). In the MKB, the oldest Dwyka strata remain undated but likely formed at ~312 Ma (possibly initiating between >317 and <307.8 Ma; Isbell et al., 2008), while the youngest rocks date to <282 Ma (Griffis et al., 2025).

The Dwyka Group rests unconformably on older rocks throughout southern Africa. This unconformable contact separates it from the underlying Precambrian basement in the north and the Middle Ordovician Cape Supergroup strata in the east, west and south. Locally in the south, the Dwyka is paraconformable with the underlying Witteberg Group (~335 Ma; Isbell et al., 2008). The upper boundary is sharp, gradational, and diachronous (Figures 2 to 4).

Lithological variations across the MKB distinguish the unit into a northern and southern facies, i.e., the Mbizane and Elandsvlei formations, respectively. The Mbizane Formation contains <200 m of glaciofluvial and lacustrine deposits, characterised by striated pavements and dropstones (Figure 5). In contrast, the Elandsvlei Formation comprises ~800 m of laterally continuous glaciomarine rocks in the southern MKB (Blignault and Theron, 2012, 2015). Where the two co-occur, the Mbizane Formation conformably overlies the Elandsvlei Formation (Figures 3 to 4; Visser, 2003). Palaeocurrent data from sedimentary structures and striations indicate dominant sediment supply from the north-northeast (northern/central facies) and south (southernmost facies), matching dispersal patterns expected from multiple Gondwanan ice-spreading centres (Isbell et al., 2008; Dietrich and Hofmann, 2019; Le Heron et al., 2019). Fossil evidence, although rare, includes cold-water microfossils (sponge spicules, foraminifera, radiolaria and palynomorphs), fossils of palaeoniscoid (primitive bony) fish, gastropods, bivalves (Eurydesma), plant fragments, and trace fossils of arthropods and fish preserved in the upper bedded diamictites of the southern facies (Visser, 2003; López-Gamundí et al., 2023).

The stratigraphic architecture reflects complex sedimentation driven by glacial waxing and waning events in multiple ice

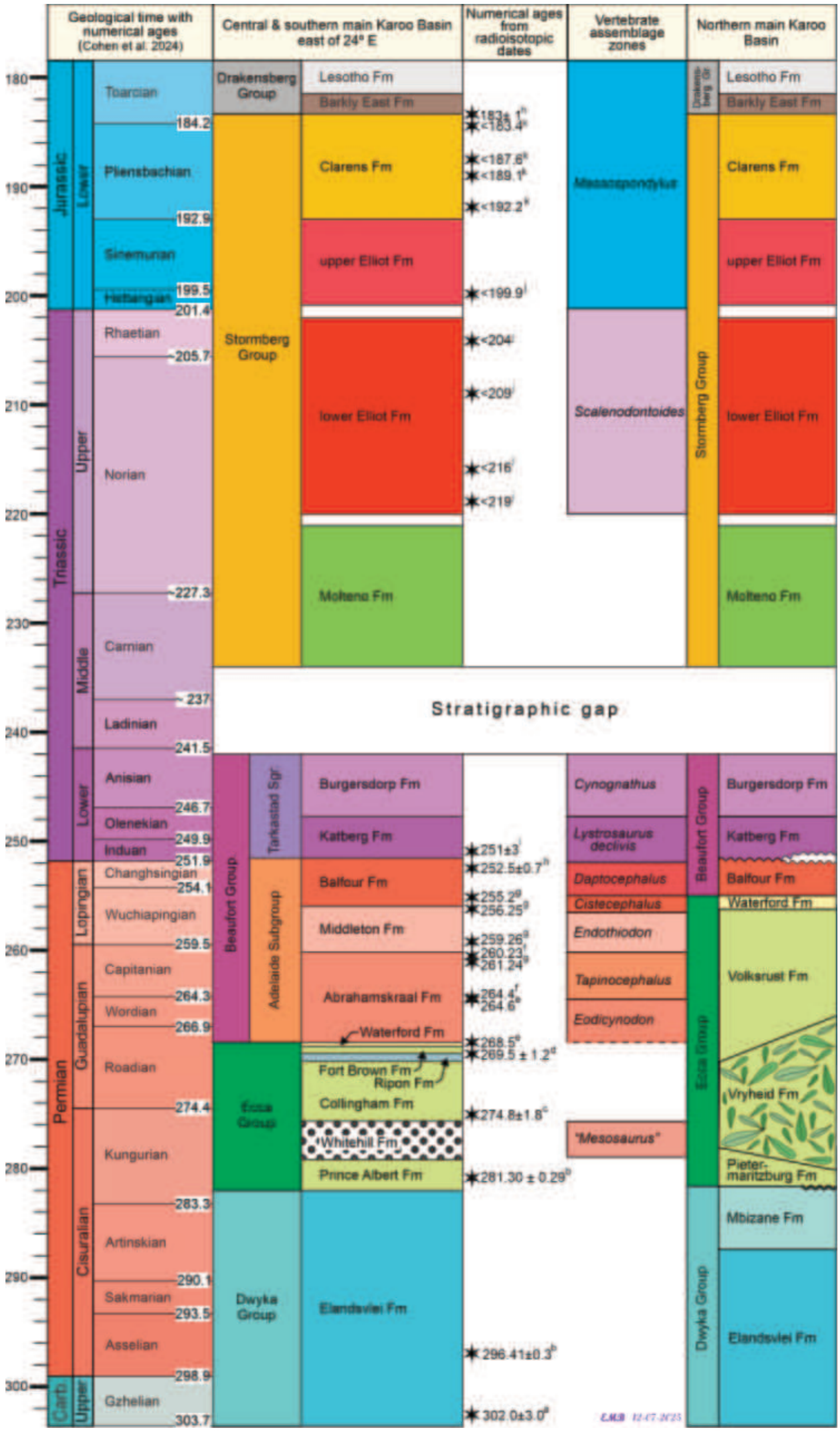

Figure 4. *Stratigraphy of the Karoo Supergroup in the main Karoo Basin (MKB). Figure compiled from Hancox et al. (2002), Rubidge et al. (2013), Barbolini et al. (2018), Bordy et al. (2019, 2020). Radioisotopic dates are from: a: Bangert et al. (1999), b: Griffis et al. (2025), c: Fildani et al. (2007), d: Belica et al. (2017), e: Lanci et al. (2013), f: Day et al. (2022), g: Rubidge et al. (2013), h: Coney et al. (2007), i: Rochín-Bañaga et al. (2023), j: Bordy et al. (2020), k: Head and Bordy (2024), l: Moulin et al. (2017). Note that most lithostratigraphic boundaries are diachronous. Abbreviations: Gp=Group; Fm=Formation.*

centres, intricate meltwater and re-sedimentation processes, as well as relative sea/base-level changes resulting from the interplay of ice dynamics (isostatic rebound/subsidence) and local/regional tectonics (Isbell et al., 2008; Craddock et al., 2019; Dietrich and Hofmann, 2019; Le Heron et al., 2019; Dietrich et al., 2025). Stratigraphic relationships suggest that continental glaciation persisted longest in the elevated north, particularly in the northeast and east (Catuneanu, 2004; Isbell et al., 2008; Bordy et al., 2017; Dietrich and Hofmann, 2019). The environmental dichotomy, featuring marine-terminating ice margins with floating shelves in the south and continental ice caps over northern basement highs (i.e., alpine glaciers), remains well-supported. However, correlation of ice advance-retreat events in the basin and Gondwana-wide is challenging mostly due to limited modern radiogenic isotope dating (Dietrich and Hofmann, 2019; Griffis et al., 2025).

Despite extensive research on the Dwyka Group, key uncertainties persist regarding:

- the depositional environment of pre-Dwyka (uppermost Witteberg) strata in the MKB;
- genetic drivers of the basal unconformity;
- age of lowermost Dwyka strata;
- ice-sheet dynamics (location, spatial extent, volume fluctuations, drivers of growth-decay cycles);
- southern African-Gondwanan correlations (Bordy and Catuneanu, 2002; Bordy, 2018, 2020; Craddock et al., 2019); and
- nuanced regional palaeoenvironmental reconstructions of the Permo-Carboniferous ice age.

Resolving these requires improved chronostratigraphy, high-resolution facies mapping, and basin-scale dynamic modelling to constrain local-to-regional interplay of ice dynamics, tectonics, and climate during the late Palaeozoic glaciation (Catuneanu, 2004; Isbell et al., 2008; Dietrich and Hofmann, 2019; Dietrich et al., 2025; Griffis et al., 2025).

Ecca Group

The overlying Ecca Group encompasses rocks that formed during Gondwanan post-glacial warming, and records the progressive infilling of the MKB via deep-, shallow-water and ultimately fluvio-deltaic deposition during the Middle Permian (~282 to 255 Ma; Figures 2 to 4; Catuneanu et al., 2005; Johnson et al., 2006; Scheffler et al., 2006). It remains the most economically critical unit in the MKB, hosting its coal and unconventional gas resources, and serving as outcrop analogues for subsurface exploration (Di Celma et al., 2011; Hancox and Götz, 2014; Pohl et al., 2023).

Comprising multiple formations that reflect considerable lateral facies variability across the basin (Figures 2 to 4), the Ecca Group consists of regionally and vertically contrasting abundances of siltstones, sandstones, including greywackes, carbonaceous mudstones, and coal-bearing strata. Both the lower and upper, as well as the within-formation boundaries of the Ecca Group, are conformable and strongly diachronous throughout the basin (Rubidge et al., 2000, 2012; Mason et al., 2015; Bordy et al., 2017; Mosavel and Cole, 2019; De Kock and Abubakre, 2022). Overall, the Ecca Group was initially deposited in a deepwater setting under fluctuating oxic to dysoxic and anoxic to euxinic as well as marine and freshwater conditions (Scheffler et al., 2006; Geel and Bordy, 2021). Later, the gradual shallowing of the basin resulted in sedimentation on or near an open shelf, where shoreface and deltaic environments advanced from the soth, north, and northeast (Rubidge et al., 2000, 2012; Groenewald et al., 2022, 2023).

In the southeast depocentre (Figures 2 to 4), with a maximum thickness of 3 000 m, the succession begins with deep-water, grey to black argillaceous rocks with variable organic-carbon content and authigenic nodules (phosphate, carbonate, manganese, etc. in the Prince Albert and Whitehill formations; Johnson et al., 2006; Bordy, 2018; Mosavel and Cole, 2019; Geel and Bordy, 2021). Associated fossil remains include rare sharks and palaeoniscoid fish, petrified wood, sponge spicules, foraminifera, radiolaria, acritarchs, and miospores (Johnson et al., 2006). The Whitehill Formation contains various fossilised marine fauna, such as *Mesosaurus tenuidens* (reptile), *Palaeoniscus capensis* (fish), and *Notocaris tapscotti* (crustacean), as well as washed-in terrestrial organisms, such as insects, palynomorphs, and plant fragments (Chukwuma and Bordy, 2016). Deposition in deepwater fan complexes, influenced by turbidity currents and airborne detritus from extrabasinal volcanic sources (Collingham Formation), was succeeded by increasingly coarser, shallower-water sedimentation (Ripon Formation). This shallowing-up process culminated in extensive fluvio-deltaic progradation, as observed in the Fort Brown and Waterford formations (Rubidge et al., 2000, 2012; Catuneanu et al., 2005).

The overarching shallowing-upward trend observed in the southern MKB is similarly present in the southwestern MKB (Figures 2 to 4). The remarkable exposures in this region have not only produced a plethora of formations but have also enabled detailed stratigraphic and sedimentological investigations. These efforts have culminated in the production of over 80 publications since 2001 by a single UK-based research team, the Stratigraphy Group (Electronic Supplement 3). Their integrated approach analyses grain-to-basin fluid dynamics, mass-transport processes, and allocyclic/autocyclic controls to decode facies architecture and depositional controls from the Lower Karoo stratigraphy. Summarising the standardised SACS descriptions of the Ecca formations in the southwestern MKB and the interpretations concerning bed-scale process sedimentology or sequence stratigraphy is beyond the scope of this review; however, nearly 100 relevant publications on these topics are collated in the Electronic Supplements 1 and 3 available online.

In the southwestern MKB, the Ecca Group preserves a ~2 km-thick, shallowing-upward succession deposited in laterally adjacent environments, ranging from basin plain to deep-water fan, shelf, shoreface, delta, and shoreline settings. Clastic sediment, sourced from the S, accumulated under deep, open water conditions, from distal to proximal regions, and well below storm-wave base, on the basin floor and deep-water basin-floor fan complexes (with well-developed lobes), extending through channelised slopes to wave- and storm-dominated shelf-edge deltas (Flint et al., 2011). These settings are archived in the Tanqua and Laingsburg depocentres of the southwestern MKB (Figure 3B) as a conformable vertical succession, where the oldest Tierberg and Vischkuil formations (distal basin plain) transition to the Skoorsteenberg and Laingsburg formations (sand-prone basin-floor fans), followed by the Kookfontein (slope and shelf-edge delta) and Fort Brown (leveed slope channels and entrenched valleys) formations, ultimately capped by the youngest, the Waterford Formation (mixed river- and wave-influenced shelf deltas).

The Ecca Group in the northern MKB (Figures 2 to 4) exhibits two distinct upward-coarsening successions: the argillaceous Pietermaritzburg Formation is succeeded by the coal-bearing, sandstone-rich Vryheid Formation, which is in turn overlain by the argillaceous Volksrust Formation and all units are capped by the sandstone-dominated Waterford Formation, the youngest Ecca unit. The Ecca Group rocks along the eastern flank of the MKB remain understudied, and their stratigraphic subdivision has not yet been formalised (Johnson et al., 2006).

In the northeastern depocentre, the basal Ecca unit is the Pietermaritzburg Formation (Figures 2 and 4), comprising 150 to 500 m of carbonaceous siltstones that grade upward into bioturbated sandstones, deposited during the transgressive marine phase, post-Dwyka deglaciation, in the Kungurian. It thins northward from >400 m in the southeast to a pinch-out against Dwyka Group/basement north of 26°30'S, with a sharp, often conformable lower contact on Dwyka strata and a gradational but strongly diachronous upper boundary to the Vryheid Formation (Bordy et al., 2017). As a stratigraphic equivalent of the Prince Albert Formation, the Pietermaritzburg Formation records low-energy, northerly shallowing marine shelf deposition below storm-wave base, transitioning to storm-influenced prodelta environments, evidenced by soft-sediment deformation, trace fossils (e.g., *Helminthopsis*) and rare, fragmented *Glossopteris* remains (Bordy et al., 2017).

The Vryheid Formation (Figures 2 to 5), renowned for its economically significant coal seams, comprises dark grey carbonaceous mudstones and white, medium- to coarse-grained, poorly sorted, micaceous, feldspathic sandstones, characterised by slump structures, cross-bedding, and scouring. Upward-fining successions dominate in the upper part of the formation, in contrast to the rest of the unit, which is characterised by multiple upward-coarsening successions (Viljoen et al., 2010). In the east, its lower contact is gradational with the Pietermaritzburg Formation; it unconformably overlies the Dwyka Group or basement rocks in the northwest and near Virginia. The formation thins southward from ~500 m near Vryheid to eventually pinching out in the central MKB, where borehole data show that these coal-bearing strata grade laterally into the Prince Albert and Whitehill formations (Cole, 2005; Hancox and Götz, 2014; Bordy et al., 2017). The formation preserves a rich *Glossopteris*-dominated macrofloral assemblage (lycopods, rare ferns and horsetails, abundant glossopterids, cordaitaleans, conifers, ginkgoaleans), diverse palynomorphs, rare insects, bivalves, fish scales, and trace fossil assemblages of marine affinity (Figure 5; Prevec et al., 2008; Hancox and Götz, 2014).

Palaeocurrent data in the northeastern MKB indicate dominant sediment transport from the northwest, northeast, north and east (Hastie et al., 2019). Deposition occurred in a cool-temperate, humid, and seasonally stormy climate within fluvial and river-dominated deltaic systems prograding from the north across a wave-dominated, storm-influenced shoreface to sand ridges on the shelf in the southeastern MKB (Green and Smith, 2012). Characteristic palynomorph assemblages biostratigraphically constrain the Vryheid Formation to the Kungurian-Wordian (Barbolini et al., 2016, 2018).

The Volksrust Formation (Figures 2 and 4) consists of dark grey to black, micaceous, well-laminated mudstones with rare interbeds of very fine-grained, horizontally and cross-laminated sandstones, mostly in its upper part. Occasional ferruginous bands, impure limestone layers, and calcium phosphate concretions are present, but it is devoid of coal seams. It has conformable yet highly diachronous contacts with the underlying Vryheid Formation and the overlying Waterford Formation in the northern MKB, as well as the carbonaceous Emakwezini Formation in the southern Lebombo Basin (Bordy and Prevec, 2008). Typically, it has a thickness of 150 to 250 m, with some areas in the northeast Free State reaching up to ~300 m (Johnson et al., 2006). This transgressive open-shelf succession formed in storm-influenced prodelta to nearshore marine environments, as evidenced by hummocky cross-stratification in tempestites and a large pelecypod bivalve (*Megadesmus* sp.; Cairncross et al., 2005). Additional fossils include a low diversity ichnofauna, fish remains, insects and plant fossils – particularly well-preserved *Glossopteris* leaves and silicified wood (Cairncross et al., 2005; Hancox and Götz, 2014; Groenewald et al., 2022). A Late Wuchiapingian to Early Changhsingian beetle assemblage has also been reported (Ponomarenko and Mostovski, 2005, p. 260). The upper Volksrust Formation is palynologically most similar to the Abrahamskraal Formation, and this biostratigraphic data constrain the formation to Roadian – Changhsingian (Rubidge et al., 2016; Barbolini et al., 2018).

The Waterford Formation (Figures 2, 4 and 6), the uppermost Ecca unit in the MKB, comprises rhythmically bedded, ripple-marked sandstones and mudstones with pervasive soft-sediment deformation structures, deposited in fluvial-dominated deltaic and shallow water environments, including shelf-edge and shelf deltas (Rubidge et al., 2012; Jones et al., 2015; Groenewald et al., 2022). The formation thins from 770 m in the southern MKB to 70 m in the northeastern MKB, with isolated remnants (<50 m) in the southeastern MKB (Cole and Wipplinger, 2001; Rubidge et al., 2012; Groenewald et al., 2022). Originally thought to pinch out in the central MKB, it is now recognised basinwide (Rubidge et al., 2012; Mason et al., 2015; Groenewald et al., 2022, 2023). It conformably overlies the Fort Brown Formation in the southeast and southwest, and the Tierberg/Volksrust formations in the central/northeastern MKB (Welman et al., 2001; Groenewald et al., 2022). Sandstones in the northeast MKB, formerly interpreted as turbidites (Selover and Gastaldo, 2005), are now reconsidered as hyperpycnal flows from flood-driven river pulses (Groenewald et al., 2022). Fossils from the Waterford Formation include diverse ichnofossils, fish remains, bivalves, silicified wood, and plant material, including fragmentary *Glossopteris* leaves and horsetail ferns (Rubidge et al., 2000; Groenewald et al., 2022, 2023). The Waterford Formation youngs

Figure 5. *Reconstruction of the palaeoenvironment in the north main Karoo Basin (MKB) during the late Early Permian (~282 Ma). Regional warming triggered alpine glacier retreating in the Cargonian Highlands (background), reshaping the landscape and increasing water and sediment supply to rivers and prograding deltaic systems. Dense vegetation in Glossopteris forests and extensive wetlands led to peat accumulation, culminating in economically significant coal deposits that underpin South Africa's modern coal industry and consistently rank it among the top ten global coal producers. See Electronic Supplement 2 for detailed explanation, including the other life forms shown in this geo-palaeo artwork by Maggie Lambert-Newman.*

north- and eastwards, and is the oldest in the southwestern MKB, where the age of the base of the overlying Abrahamskraal Formation is considered to be ~268.5 Ma (Figures 4 and 6). Based on the vertebrate fossils present in the overlying Abrahamskraal/Balfour formations, the top of the Waterford Formation is biostratigraphically constrained to >262 Ma old in the central MKB, and <255 Ma old in the northeastern MKB (Groenewald et al., 2022, 2023).

Palaeoenvironmental reconstructions of the Ecca Group have benefited from significant refinement in recent decades (Figure 5). Improved palaeogeographic models emphasise complex shoreline migration, basin asymmetry, and shifting deltaic entry points, reflecting evolving subsidence patterns tied to continued foreland loading, isostatic adjustments due to ice volume changes, and palaeoclimatic influences (Catuneanu et al., 2005; Jones et al., 2015; Geel and Bordy, 2021). Provenance studies, sedimentary petrography, and detrital zircon geochronology have also advanced understanding of sediment routing systems across the foreland basin (Veevers and Saeed, 2007; Andersen et al., 2016; Walters and Tucker, 2020; Geel and Bordy, 2021; Vorster et al., 2024). Exceptional outcrop-scale studies in the southwestern MKB, mostly by the UK-based Stratigraphy Group (Electronic Supplement 3), have offered globally influential insights into the architecture and depositional processes of deepwater clastics in the upper Ecca Group, transforming these outcrops into textbook deep-water reservoir analogues and high-resolution, process-based models.

Despite the pivotal role the Ecca Group plays in recording Early to Middle Permian palaeoenvironmental and tectonic transitions across Gondwana (Figures 1 to 5), age constraints for key units remain poor. While advances in bio- and chronostratigraphy (especially of the overlying Beaufort Group; see next section) and lithostratigraphic correlations have provided a broad temporal framework, reliable radiogenic isotope dates are sparse and often outdated. Certain attempts to revise Ecca Group chronology have, in several instances (Fildani et al., 2007; McKay et al., 2015), overlooked the importance of well-established regional stratigraphic knowledge accumulated over 150 years. This had led to a persistent disconnect between isotopic datasets and field-based litho- and biostratigraphy in the Ecca Group across the MKB. A forward path requires renewed, locally grounded geochronological efforts that integrate basin-wide stratigraphy and prioritise regional geological continuity. Moreover, combining innovative outcrop investigations (drone photogrammetry) and emerging techniques (e.g., AI-assisted pattern recognition) may offer solutions to lingering gaps in stratigraphic predictions and process quantification at multiple scales. Anchoring the Ecca Group in time will be critical for achieving precise correlations across Gondwana (e.g., Whitehill Formation to Brazil's Irati Formation) not only to enhance basin evolution models, but also to improve its economic relevance for local communities (e.g., management of Karoo aquifers, carbon sequestration). Other notable ambiguities and research gaps requiring resolution include the precise mechanism governing:

- the abrupt Dwyka-Ecca transition (the sudden glacial to post-glacial changeover), and
- absolute (rather than relative) fluctuations in water depth, oxygenation, and salinity levels within each unit of the Ecca Group across the MKB.

Beaufort Group

The Beaufort Group (Figures 1, 4 and 6) represents the longest and most continuous continental sedimentary succession in the Karoo Supergroup, spanning the Middle Permian (~268 Ma) to the early Middle Triassic (~240 Ma). It consists primarily of mudstone units containing pedogenic and diagenetic carbonate nodules, interbedded with thinner (5 to 25 m), multistoried sandstone intervals typically arranged in upward-fining successions. This lithological contrast is prominently expressed in the terraced hillslopes of the Karoo koppies. With a cumulative thickness of ~5 000 m in the southern MKB, this stratigraphic unit is subdivided into two major subunits: the Permian Adelaide Subgroup and the Triassic Tarkastad Subgroup (Johnson et al., 2006). These are separated by a regionally mappable contact marked by an increased abundance of sandstone and red-coloured mudstones in the latter unit (Hancox, 2000; Neveling, 2004).

The Beaufort Group overlies the Ecca Group conformably throughout the basin, with the contact exhibiting strong diachroneity, progressively younging toward the north and east (Rubidge, 2005; Mason et al., 2015; Groenewald et al., 2022; De Kock and Abubakre, 2022). Its upper boundary with the Stormberg Group (Figure 1) is marked by a major unconformity that represents the largest stratigraphic gap within the Karoo, with an estimated duration of 8 to 12 Ma; the precise causes of the hiatus remain under investigation (Hancox and Rubidge, 2023).

In the central and northern MKB (Figures 2, 4 and 6), the Beaufort strata are notably thinner and exhibit more stratigraphic gaps, suggesting geodynamic control influenced by the southern margin of the Kaapvaal Craton. In this region, the Beaufort strata are mapped at lower stratigraphic resolution, with individual formations left undifferentiated. However, biostratigraphic and radiometric data confirm the presence of coeval sedimentary rocks correlating with those found in the southern MKB. Sandstone-rich packages (Figure 6) are effective for subdividing the Beaufort formations and have been informally designated as members. However, the limited lateral continuity of these members restricts their utility, making them more suitable for local rather than basin-scale correlations (Neveling, 2004; Neveling et al., 2005; Cole et al., 2016; Viglietti et al., 2017a, b, 2018; Groenewald et al., 2019, 2022; Hancox and Rubidge, 2023).

Renowned for its exceptional fossil content, the Beaufort Group preserves one of the most complete Permo-Triassic continental vertebrate fossil records globally and serves as the biostratigraphic standard for this interval (Hancox, 2000; Rubidge, 2005; Rubidge et al., 2016; Smith et al., 2020). Its abundant tetrapod fossils underpin a robust biostratigraphic framework defined by seven vertebrate assemblage zones, four of which have been further subdivided into subzones (Figures 4 and 6). Associated Glossopteris-dominated plant assemblages, fossil wood, and palynomorphs provide additional stratigraphic resolution (Prevec et al., 2009, 2010; Bamford, 2016; Barbolini et al., 2018).

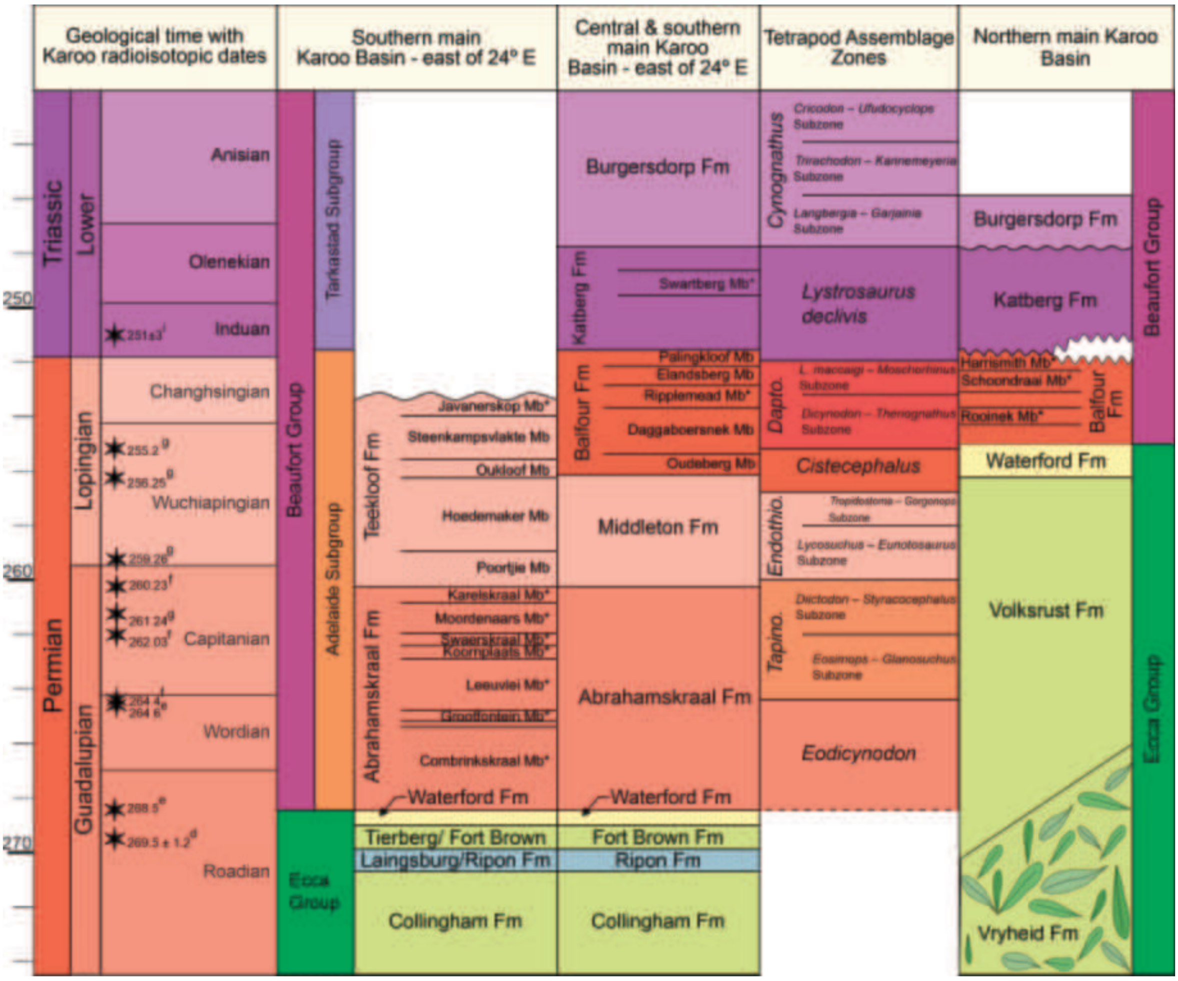

*Figure 6. Litho- and biostratigraphic correlation of the formations in the Beaufort Group in the main Karoo Basin (MKB). The arenaceous units are marked with dots. Figure compiled from Rubidge et al. (2013), Smith et al. (2020), Day et al. (2022) and Groenewald et al. (2022). Radioisotopic dates are shown in Figure 4. Note that most lithostratigraphic boundaries are diachronous. *-informal unit, yet to be approved by SACS. Abbreviations: Gp=Group; Fm=Formation.*

Over the past two decades, extensive interdisciplinary research has focused on multiple branches of stratigraphy, including litho-, magneto-, cyclo-, chemo-, and chronostratigraphy (Lindeque et al., 2011; Lanci et al., 2013, 2022; Rubidge et al., 2013; Smith and Botha-Brink, 2014; Tohver et al., 2015; Scheiber-Enslin et al., 2016; Rey et al., 2016, 2018; Belica et al., 2017; Krummeck and Bordy, 2018; Viglietti et al., 2017a,b, 2018, 2021; Bordy et al., 2011, 2019; Gastaldo et al., 2019, 2020a, b, 2021; Marchetti et al., 2019; Botha et al., 2020; Day and Rubidge, 2021; Retallack, 2021; Day et al., 2022; Smith et al., 2022, 2025; Prevec et al., 2022; Shen et al., 2023; Ronchi et al., 2023). These studies have significantly advanced our understanding of pre-extinction ecosystems, survival strategies during biocrises, and patterns of biological recovery following at least two catastrophic events that drove floral and faunal turnovers at the end-Capitanian (~260 Ma; Figure 7) and end-Permian (~252 Ma; and Figure 8). The latter mass extinction is widely regarded as the greatest extinction event of all time, with estimated losses of up to 81% of marine genera and 89% of tetrapod genera (Botha et al., 2020; Viglietti et al., 2021).

Research on Beaufort Group strata has been driven by their unique fossil record; however, their exceptional outcrop continuity has also enabled high-resolution analysis of spatial and temporal changes in stacking patterns and depositional styles. Detailed sedimentological, ichnological, and taphonomic studies indicate that Beaufort Group deposition occurred in a fluvio-lacustrine setting with extensive vegetated floodplains within an endorheic basin under a semi-arid climate marked by extreme seasonal precipitation fluctuations. Fluvial styles varied between high- and low-sinuosity channel patterns, a topic of ongoing refinement in current investigations, which reveal a complex hierarchy of channel-belt complexes, reflecting mixed lateral and downstream accretion influenced by flashy discharge regimes and high-frequency climate cycles. Stratigraphic evidence suggests a long-lived distributive fluvial system that originated from the Cape Fold Belt (Figures 1 to 3), punctuated by sequence-boundary events that triggered shifts in channel incision and progradation rates (Wilson et al., 2014; Gulliford et al., 2014, 2017; Bordy and Paiva, 2021; Lanci et al., 2022; Gibling et al., 2023).

Adelaide Subgroup

In the southern MKB, the Middle to Upper Permian (~268 to 252 Ma) Adelaide Subgroup (Figures 2 to 5) consists of blue-grey to green-grey mudstones interbedded with moderately to well-sorted, very fine- to medium-grained litho-feldspathic sandstones. These strata are formally classified as the Abrahamskraal, Teekloof, and Balfour formations, with only the latter mappable in the northeastern MKB (Day and Rubidge, 2014; Jirah and Rubidge, 2014; Cole et al., 2016; Viglietti et al., 2017a; Groenewald et al., 2022).

The Abrahamskraal Formation, which includes the now-defunct Koonap Formation, is the basal unit of the Beaufort Group. It is primarily composed of mudstones, with subordinate sandstones and thin lenticular to sheet-like chert beds (Rubidge et al., 2000, 2012; Cole et al., 2016). The formation reaches a maximum thickness of 2 200 to 2 565 m in the southeastern MKB, thinning to the northeast in line with the younging of its lower contact with the underlying Ecca Group and the overlap by the overlying units. Lithostratigraphic subdivision of the formation relies on the distribution of mappable sandstone-rich packages, although this subdivision becomes uncertain east of 24° longitude due to increasing mudstone content and consequent scarcity of outcrops (Day and Rubidge, 2014; Cole et al., 2016). The sandstone packages of the upper Abrahamskraal Formation are dominated by downstream accretion elements and are interpreted as deposits of high-energy, low-sinuosity fluvial systems operating within a semi-arid environment (Bordy and Paiva, 2021). This formation hosts the *Eodicynodon* and most of the *Tapinocephalus* assemblage zones (Figures 4, 6 and 7; Rubidge and Day, 2020; Day and Rubidge, 2020). The end-Capitanian event, characterised in the Karoo by the extinction of dinocephalian therapsids and bradysaurian pareiasaurs, is recorded at the transition of the Abrahamskraal-Teekloof formations and was linked to a short-lived period of greater aridity (Rey et al., 2018; Day and Rubidge, 2021).

The Teekloof Formation predominantly outcrops along the Great Escarpment in the western MKB. It features a single upward-fining megacycle characterised by an upward-increase in variegated red and maroon mudstone content. Within the mudstones, subordinate fine- to very fine-grained sandstones are tabular to lenticular in shape. They are pale olive to greenish- grey in colour and have a mean thickness of ~5 m (maximum 30 m). Locally, the sandstones host uranium mineralisation. Along strike, the formation merges with the Middleton and Balfour formations east of 24°. The total thickness is <500 m. The fluvial style transitions upward from short-lived, low-sinuosity to more permanent, high-sinuosity channels. The Teekloof Formation hosts fossils of the (uppermost) *Tapinocephalus*, *Endothiodon*, *Cistecephalus*, and lower *Daptocephalus* assemblage zones (Figures 4 and 6; Viglietti et al., 2017a, 2018; Viglietti, 2020; Day and Smith, 2020; Day and Rubidge, 2020; Smith, 2020).

The Middleton Formation is a mudstone-dominated unit, 1 650 to 2 000 m-thick, characterised by sparse outcrops. A distinctive feature is the presence of <1 m thick, greyish-red to greyish-red-purple mudstone interbeds occurring in discrete zones within the predominantly grey mudstones. These maroon interbeds serve to differentiate it from the conformably underlying and overlying formations, which consist mainly of grey mudstones. Sandstones, comprising 20 to 25% of the formation, are primarily grey, fine- to very fine-grained, lenticular, and average ~1 m in thickness. Weakly developed major upward-fining successions, each 400 to 500 m-thick and containing roughly 10% sandstone, show a subtle grain size decrease upward. These successions are interpreted to represent a fluvial style change from short-lived, low-sinuosity to more permanent, high-sinuosity channels, while the overall upward-fining trend is attributed to a progressive decrease in regional palaeoslope gradient (Bordy et al., 2011a). This formation hosts fossils of the (uppermost) *Tapinocephalus*, *Endothiodon*, and lower *Cistecephalus* assemblage zones (Figures 4 and 6; Day and Smith, 2020; Day and Rubidge, 2020; Smith, 2020).

The Balfour Formation is the youngest unit of the Adelaide Subgroup east of 24° longitude. It shows an upward increase in lenticular sandstone bodies and red mudstones, indicating subtle aridification potentially linked to climatic drying across the Permian-Triassic boundary (Johnson et al., 2006). While the maximum thickness is estimated to be ~2150 m in the southeastern MKB, the Balfour Formation has an average thickness of ~450 to 500 m, thinning to ~60 m in the northern MKB (Rutherford et al., 2015; Viglietti et al., 2017a). Its lateral equivalent in the Lebombo Basin is the Emakwezini Formation (Bordy and Prevec, 2008). The Balfour Formation comprises two major upward-fining depositional successions (Viglietti et al., 2017a,b; 2018). In the central MKB, it rests unconformably on the Abrahamskraal Formation, reflecting a stratigraphic hiatus of up to ~6 million years in duration. In the northern MKB, the Balfour Formation conformably overlies the Waterford Formation (Groenewald et al., 2019, 2022, 2023). The formation hosts abundant vertebrate fossils characteristic of the *Cistecephalus*, *Daptocephalus*, and *Lystrosaurus declivis* assemblage zones (Figures 4 and 6; Smith, 2020; Viglietti, 2020; Botha and Smith, 2020).

Fluvial style changes within the Balfour Formation are interpreted as tectonically controlled, linked to the proximity of the Cape Fold Belt and shifting palaeoslope gradients (Figures 1 to 3). A complex interaction between a northern and southern fluvial system of the MKB is recorded in the southern and central Free State (Cole and Wipplinger, 2001; Rutherford et al., 2015). In the southern MKB, there is a transition from low- to high-sinuosity channel systems, whereas in the northern MKB a shift from sand-bed to fine-grained, high-sinuosity channels is documented, alongside evidence for early climatic drying preceding the end-Permian mass extinction (Viglietti et al., 2018). The uppermost part of the formation, consisting of red and brightly coloured mudstones, is attributed to a low-sinuosity system and preserves the most complete continental record of the vertebrate-defined Permian-Triassic boundary within the MKB, coinciding with the transition between the *Daptocephalus* and *Lystrosaurus declivis* assemblage zones (Viglietti, 2020; Botha and Smith, 2020). In the northwestern MKB, this upper part of the Balfour Formation is missing and is unconformably overlain by the Katberg Formation of the Tarkastad Subgroup (Figures 4 and 6; Rutherford et al., 2015).

Figure 7. *Reconstruction of the palaeoenvironment in the southwest main Karoo Basin (MKB) during the Middle Permian (~262 Ma). The floodplain ecosystem features Tapinocephalus, Glanosuchus, and Glossopteris-dominated flora. See Electronic Supplement 2 for detailed explanation, including the other life forms shown in this geo-palaeo artwork by Maggie Lambert-Newman.*

Tarkastad Subgroup

In the central and northern MKB, the Triassic (Induan-Anisian) Tarkastad Subgroup (Figure 2, 4 and 6) consists of alternating red and greenish-grey mudstones and fine- to medium-grained sandstones. From a maximum thickness of ~1 900 m in the southeastern MKB (in outliers along the coast near East London), it thins progressively northward to ~1 750 m near Komani (Queenstown), and to <100 m in the northern MKB. These strata are classified into the relatively arenaceous Lower Triassic Katberg and the relatively argillaceous Lower to Middle Triassic Burgersdorp formations (Hancox, 2000; Neveling, 2004; Johnson et al., 2006).

The primarily arenaceous Katberg Formation (Figure 2 to 5) features stacked, multistoried tabular sandstone bodies interbedded with subordinate mudstones. The formation exhibits substantial lateral variability in sandstone-mudstone ratios, with sandstone content reaching up to 90% in the southeastern MKB, progressively decreasing northward where it becomes harder to distinguish it from the paraconformably overlying, finer-grained Burgersdorp Formation. Thickness also varies significantly, exceeding 1 200 m in the south and thinning drastically to ~70 m in the north. The Katberg-Burgersdorp contact is conformable in the south and occurs within a ~100 m-thick transitional zone, with lithostratigraphic and biostratigraphic data confirming lateral facies equivalence (Neveling, 2004; Neveling et al., 2005; Pace et al., 2009; Bordy et al., 2011b; Krummeck and Bordy, 2018). Supported primarily by palaeontological data, the upper part of the Katberg Formation is absent in the northern MKB, where the Katberg-Burgersdorp contact is postulated to coincide with a regional unconformity (Neveling, 2004; Neveling et al., 2005; Rutherford et al., 2015).

The sandstones, typically light olive grey to light brownish-grey and fine- to medium-grained, form sheet-like beds 5 to 10 m-thick, with individual beds generally <1.5 m-thick and separated by laterally extensive, sharp erosional surfaces. These sandstone bodies mainly exhibit vertical and downstream accretion, with lateral accretion being rare. Notable sedimentary structures include trough and planar cross-bedding, horizontal lamination, and ripple cross-lamination. Intraformational mudstone clasts and reworked pedogenic nodule conglomerates are common, especially at the base of sandstone units. Brown-weathering, diagenetic calcareous concretions with diametres of 3 to 10 cm are frequently preserved *in situ* within the sandstones (Neveling, 2004; Pace et al., 2009; Bordy et al., 2011b; Bordy and Krummeck, 2016; Krummeck and Bordy, 2018; Gibling et al., 2023). Interbedded fine-grained deposits consist mainly of siltstones and mudstones, 2 to 10 m-thick, with red, olive-yellow, and greenish hues. These finer units contain pedogenic calcareous nodules, fossil rootlets, vertebrate and invertebrate burrows, desiccation cracks, and rare thin (<1 m) sandstone interbeds.

Depositional environments show spatial variation: southern exposures feature coarser, pebbly sandstones, massive bedding, and multistoried architecture, indicative of high-energy, low-sinuosity fluvial systems. In contrast, northern exposures display increased mudstone abundance and distinct fining-upward successions, reflecting lower-energy, low-sinuosity fluvial conditions. The widespread presence of pedogenic calcareous nodules suggests alkaline soil development under semi-arid conditions. Despite an overall background of warm and dry conditions, evidence indicates several short periods of increased precipitation during the earliest Triassic. The occurrence of desiccation cracks, pedogenic nodules, and thick sandstones with reworked local clasts points to episodic flash flooding after extended dry periods (Figure 8). Collectively, the sedimentary facies indicate that Early Triassic rivers were predominantly non-perennial, influenced by highly variable and seasonal precipitation regimes (Neveling, 2004; Johnson et al., 2006; Bordy et al., 2011b; Smith and Botha-Brink, 2014; Rey et al., 2016; MacLeod et al., 2017; Retallack, 2021; Smith et al., 2022; Gibling et al., 2023). The Katberg Formation hosts fossils of the *Lystrosaurus declivis* Assemblage Zone, which represents fauna from the early stages of recovery from the end-Permian mass extinction in the MKB (Figures 4, 6 and 8; Botha and Smith, 2020).

The Burgersdorp Formation (Figure 2, 7 and 6) is the youngest stratigraphic unit of the Beaufort Group, spanning the Early to Middle Triassic (Olenekian–Anisian) boundary. It conformably overlies the Katberg Formation in the south and is unconformably overlain by the Stormberg Group. The formation's thickness varies significantly, reaching up to ~1 000 m in the southeastern MKB, thinning to ~600 m near Komani, and further reducing to ~20 m in the northern MKB, where only the lower part of the formation is preserved (Neveling, 2004; Johnson et al., 2006; Rutherford et al., 2015; Bordy and Krummeck, 2016; Bordy et al., 2019; Hancox and Rubidge, 2023; Wolvaardt et al., 2023).

Dominated by red to maroon siltstone and mudstone packages, the Burgersdorp Formation alternates with subordinate fine- to medium-grained sandstones that are olive grey, greenish, or light brownish-grey. At coastal localities in the southeastern MKB, sandstones may comprise up to 50% of the succession but decrease to less than 20% northwards. Sandstone bodies typically exhibit upward-fining successions a few to tens of metres thick and are laterally restricted compared to those in the Katberg Formation. Common features within mudstone intervals include intraformational mud clast conglomerates, reworked pedogenic nodule conglomerates, and silt- and sandstone-filled desiccation cracks (Neveling, 2004; Johnson et al., 2006; Bordy and Krummeck, 2016; Bordy et al., 2019; Wolvaardt et al., 2023). Mudstones are generally structureless (massive), range in colour from red-maroon to red-purple-grey, and often display pedogenic features such as calcretes, fossil rootlets, desiccation cracks, white calcareous mottles, and invertebrate trace fossils. Laminated mudstones increase in frequency in the northern MKB, suggesting variations in depositional energy and water saturation (Neveling, 2004; Neveling et al., 2005; Rubidge, 2005; Yates et al., 2012; Bordy and Krummeck, 2016; Rubidge et al., 2016; Hancox and Rubidge, 2023; Wolvaardt et al., 2023).

Sedimentological and palaeontological evidence indicate deposition in northeast-flowing, low-energy, high-sinuosity fluvial system characterised by extensive floodplains and large, shallow lakes, drained by ephemeral channels. Several sandstone units are interpreted as crevasse splay deposits, reflecting periodic fluvial flooding events within a predominantly lacustrine-floodplain system. Notable palaeosol features include

Figure 8. *Reconstruction of the palaeoenvironment in the south central main Karoo Basin (MKB) during the earliest Triassic (~251 Ma), capturing the aftermath of the "mother-of-all-mass extinctions" in southern Gondwana and depicting some of the survivors of the ecosystem collapse in a drought-stricken floodplain setting. See Electronic Supplement 2 for detailed explanation, including the other life forms shown in this geo-palaeo artwork by Maggie Lambert-Newman.*

'desert roses' (nodular gypsum or calcite crystals) reported from the central MKB (Thaba Nchu) and indicative of seasonal aridity and episodic drying. These pedogenic indicators, along with widespread calcretes and desiccation cracks, serve as important proxies for interpreting semi-arid, seasonally variable palaeoenvironmental conditions during deposition (Bordy et al., 2019). The Burgersdorp Formation contains fossil faunas from the *Cynognathus* Assemblage Zone (Figures 4 and 6) that indicate a rich Early to Middle Triassic ecosystem, capturing the later stages of biotic recovery from the end-Permian mass extinction in the MKB. It is particularly notable for its diverse lacustrine fossil fauna (Neveling et al., 2005; Yates et al., 2012; Bordy et al., 2019; Hancox et al., 2020; Lucas and Hancox, 2022).

Recent decades have significantly advanced our understanding of the geological history of the Beaufort Group, driven by improvements in geological mapping, high-resolution sedimentological analyses, refined vertebrate and palynomorph biostratigraphy, and enhanced radiometric dating (Figures 1 to 4 and 6 to 8). These advancements have strengthened intra-basin stratigraphic correlations, which are particularly complicated by the pronounced vertical and lateral facies variability of sedimentary rocks formed in dynamic fluvial systems. Despite the heterogeneous nature of fluvial facies, these integrated studies have facilitated robust comparisons with other Gondwanan basins (Catuneanu et al., 2005; Rubidge, 2005; Bordy and Prevec, 2008; Prevec et al., 2009, 2010; Barbolini et al., 2016; Rubidge et al., 2016; Lucas and Hancox, 2022; Wolvaardt et al., 2023; Smith et al., 2025).

Palaeoenvironmental interpretations, both classic and recent, indicate that the Beaufort Group was deposited within a predominantly fluvio-lacustrine system, free of marine influence, from the Middle Permian to the Middle Triassic. Located near the latitude of modern temperate climate zones, the region experienced a warm, dry continental climate with pronounced seasonal rainfall. The Cape Fold Belt (Figures 1 to 3) likely acted as an orographic barrier to the south, shielding the MKB from moist air masses and enhancing its continentality throughout the ~25 million years of Beaufort deposition. This persistent barrier influenced a dominant northward sediment supply that fed a long-lived fluvial megafan system within the Karoo foreland basin.

The sedimentary facies of the Beaufort Group primarily record deposits from high-sinuosity rivers and lacustrine environments, while low-sinuosity fluvial settings are limited to the Katberg Formation and minor portions of the Adelaide Subgroup. Fluvial styles changed in response to climatic fluctuations and tectonics, resulting in progradational and retrogradational phases of this megafan system. A clear northward decrease in strata thickness, grain size, and channel scale reflects diminishing discharge characteristics of fluvial systems in semi-arid to arid, closed-basin settings distal from sediment sources. Particularly in the Triassic, assemblages of desiccation cracks, pedogenic nodules, fossil desert roses, and vertebrate burrows indicate floodplain and lacustrine environments that experienced periodic desiccation, consistent with ephemeral streamflow and seasonal wetness under an overall semi-arid to arid climate regime (Johnson et al., 2006; Bordy et al., 2011b, 2019; Smith and Botha-Brink, 2014; Bordy and Krummeck, 2016; Smith et al., 2022, 2025; Gibling et al., 2023).

Despite the apparent conformability of Beaufort Group strata, significant stratigraphic discontinuities exist, but their spatial extent, precise timing, and palaeoenvironmental and tectonic drivers remain poorly constrained. Additionally, the major unconformity at the upper boundary of the Beaufort Group – estimated at 10 to 12 million years in duration and representing the largest stratigraphic gap within the Karoo Supergroup – lacks clarity regarding its timing, duration, and formative processes. These challenges are compounded by the difficulty of correlating regional stratigraphic and facies changes in the MKB with contemporaneous global climatic events and regional tectonics, especially those of the Cape Fold Belt. A central unresolved issue is disentangling the intricate roles of climate and tectonics in driving the cyclic progradational and retrogradational evolution of the Beaufort fluvial megafan system. Understanding these controls is essential for accurately reconstructing basin evolution and comprehending the complex interactions among tectonic deformation during and after sedimentation, climate variability, biological evolution, and sedimentary processes that governed sediment accumulation, erosion, and landscape changes in Gondwana during the critical Permian-Triassic transition.

Addressing these uncertainties requires a continued multidisciplinary approach integrating detailed outcrop-scale sedimentological analysis, high-resolution chronostratigraphic frameworks, and basin-wide stratigraphic correlation. The targeted application of remote sensing (e.g., drones, satellite imagery) for mapping sedimentary facies architecture, together with machine learning-assisted facies classification and stacking-pattern recognition, are key for resolving outstanding questions regarding the geological evolution of the Beaufort Group.

Stormberg Group

The Stormberg Group (Figures 1 to 4 and 9) records the final and longest phase of Karoo sedimentation during the Late Triassic to Early Jurassic (~235 to 183 Ma), preceding the onset of continental flood basalt volcanism and the associated magmatism of the Karoo Large Igneous Province across a significant portion of southern Gondwana. The upper Karoo succession captures important transitions in continental sedimentation patterns, climate regimes, faunal-floral assemblages, and basin evolution, as Gondwana approached its initial phase of disintegration (Hancox, 2000; Catuneanu et al., 2005; Johnson et al., 2006; Bordy et al., 2020).

The Stormberg Group has been mapped across southern Africa and is most extensively studied in the MKB, where it exhibits a tripartite lithostratigraphic subdivision: the Molteno, Elliot, and Clarens Formations, which collectively archive >52 million years of continental deposition within ~1200 m of stratigraphic thickness (see Karoo time wheel in Figure 1). This condensed yet significant succession is marked by a major unconformity at its base and reflects a dramatic landscape transition from lushly vegetated Carnian floodplains (Molteno

Formation) to increasingly ephemeral rivers and lakes, culminating in a regional sand sea with shifting dune fields among temporarily extensive lakes (Elliot and Clarens formations) during the latest Triassic and Early Jurassic. This stratigraphic package illustrates the interplay of climatic changes and tectonism, including flexural processes and early rifting that heralded the breakup of Gondwana. It contains evidence of one mass extinction event at the end of the Triassic and sets the stage for another at the end of the Pliensbachian (Bordy et al., 2020).

The Molteno Formation (Figures 1 to 4 and 9) is characterised by thin, erosively based basal conglomerates followed by thick, feldspathic, quartz-rich upward-fining, multistoried channel sandstones with subordinate, sometimes carbonaceous, mudstone and historically important, but minor, coal horizons (Hancox and Götz, 2014; Hancox and Rubidge, 2023). The upward-fining successions are <10 to 15 m in thickness but laterally extensive (>150 m), giving a sheet-like appearance to the units. The unit is bound by regional disconformities and locally overlies basement rocks. The mostly northward-directed palaeocurrent indicators, maximum thickness of ~450 to 600 m, and a strongly northward thinning geometry are linked to regional tectonic controls. The latter was still flexural tectonics in the final MKB chapter, but further north it is tentatively linked to early Gondwana rifting and ensuing Carnian thermal subsidence (Bordy et al., 2005; Hancox and Rubidge, 2023). Only the middle part of the formation is present in the northern MKB. Sedimentological and palaeontological evidence reflect deposition on a fluvial megafan in bedload-dominated low-sinuosity, shallow channels, and associated floodplains with small lakes and large swamps subdivided into various peat-forming habitats: riparian forests, woodlands, thickets, marshes, and fern meadows, formed under persistently humid conditions.

Rich plant fossil assemblages, including diverse *Dicroidium*-dominated gymnospermous floras, are well-preserved on bedding planes or dispersed within the siltstones and mudstones, although fossil wood is generally poorly preserved (Anderson and Anderson, 2003, 2008, 2018, 2023; Anderson et al., 2007; Bamford, 2004, 2016; Hancox and Rubidge, 2023). The Molteno Formation contains the oldest reported fossil amber in Africa, freshwater invertebrates, rare fish, and an abundant and diverse insect fauna with an associated plethora of insect-plant interactions (e.g., leaf-mining activities; Scott et al., 2004; Labandeira et al., 2018; Hancox and Rubidge, 2023). The tetrapod footprints preserved in the formation are among the oldest records of putative dinosaur tracks in the world and mark a major shift in vertebrate life by a faunal turnover from therapsid- to dinosaur-dominated fossil biota in the MKB (Johnson et al., 2006; Bordy et al., 2023a; Hancox and Rubidge, 2023).

The major climatic shift from the dominant semi-arid conditions of pre-Stormberg to the humid continental climate during the Molteno depositional phase is a long-noted anomaly of the Triassic in the MKB. Recent ichnological, sedimentological, and radioisotopic dating have led to significant reinterpretations of this period. Aligning with biostratigraphic evidence, new unpublished data constrains Molteno deposition to the Carnian Pluvial Episode (~234 to 232 Ma), a brief yet intense global humid phase that dramatically impacted ecosystems worldwide (Bordy et al., 2023a). Recognising the Molteno as southern Africa's representative of the Carnian Pluvial Episode enhances its global palaeoenvironmental significance and connects it to a crucial climatic interval marked by ecological perturbations and major palaeobiological changes in the Late Triassic.

The Elliot Formation (Figures 1 to 4 and 9), the middle unit of the Stormberg Group in the MKB, exemplifies a classic redbed succession and represents a prolonged fluvio-lacustrine depositional phase during the Late Triassic (Norian-Rhaetian) and Early Jurassic (Hettangian-Sinemurian). The formation comprises mainly mudstones and sandstones in stacked, upward-fining successions, and forms a wedge-shaped unit that thins northward. Its maximum thickness reaches ~500 m in the southern outcrop area but often decreases to <30 m in the north. The lower contact is marked by a regional disconformity, while the upper contact is transitional as the unit grades into the

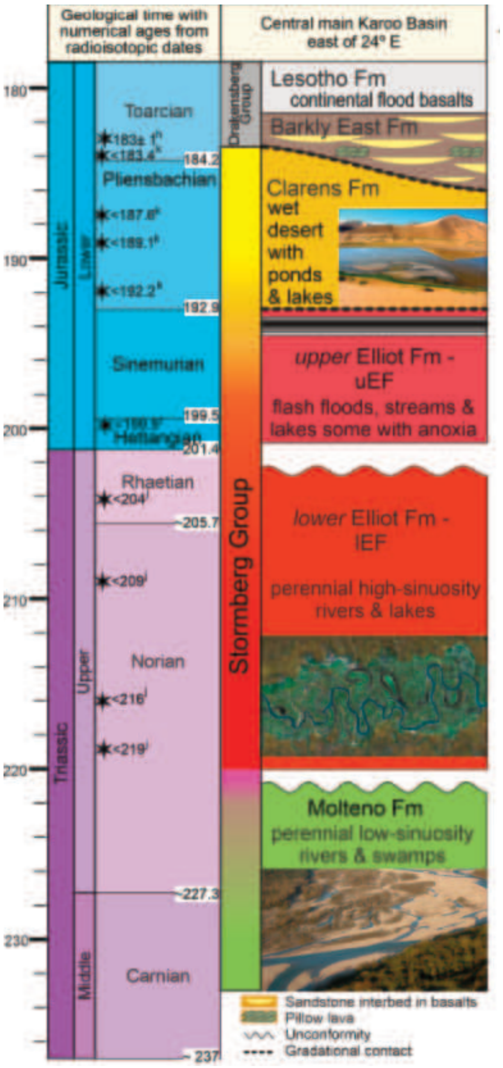

Figure 9. *Lithostratigraphy of the Stormberg and Drakensberg groups in the main Karoo Basin (MKB), showing the nature of the formation boundaries and main depositional settings. Radioisotopic dates are shown in Figure 4. All boundaries are diachronous. Inset image source: WikiMedia. Abbreviation: Fm=Formation.*

Clarens Formation. Variations in sedimentary architecture, palaeocurrent patterns, palaeosol abundance, provenance, and fossil assemblages signify a notable stratigraphic and palaeoenvironmental shift, dividing the formation into two informal members: the lower Elliot Formation (lEF) and upper Elliot Formation (uEF) (Figures 4 and 9; Bordy et al., 2004, 2020).

The lEF consists of multistoried, asymmetric channel-fill sandstones with lateral accretion surfaces, point-bar architecture, and interbedded red mudstones. These deposits indicate perennial, moderately high-sinuosity channels with stable flow regimes, reflecting fluvial conditions under semi-arid to sub-humid climates. In contrast, the uEF is characterised by sheet-like, tabular, multistoried sandstones with low-angle cross-bedding and erosional bases, interbedded with loessic strata and mudstones exhibiting desiccation cracks, calcareous concretions, and pedogenic carbonate nodules. The uEF captures episodic flash floods during prolonged dry periods, demonstrating increased climatic seasonality, strong precipitation, and water-table fluctuations. The uEF also exhibits alternations of red and black mudstones, with black organic-rich mudstones suggesting stratified lakes during humid phases, indicating significant climatic oscillations and challenging prior interpretations of a unidirectional climate shift toward aridity during Elliot deposition.

The facies changes from the lEF to the uEF also reflect the last deformation events in the Cape Fold Belt (Figures 1 to 3) and the onset of extensional tectonics during the Early Jurassic. The shift from compressional to extensional basin dynamics is further evidenced by changes in sediment provenance, and presence of syn-sedimentary normal faults and large-scale convolute bedding in the uppermost uEF.

The facies shift in the Elliot Formation coincides with faunal turnover. The lEF hosts fossil assemblages dominated by basal sauropodomorph dinosaurs, traversodontid cynodonts, and other vertebrates typical in the Late Triassic of Gondwana (assigned to the *Scalenodontoides* Assemblage Zone Viglietti et al., 2020a; Figure 9). In contrast, the uEF reveals increased faunal diversity, including early ornithischian dinosaurs, theropods, crocodylomorphs, mammaliaforms, and semionotid fishes (assigned to the *Massospondylus* Assemblage Zone; Figure 9; Viglietti et al., 2020b). Vertebrate trackways and trace fossils, including vertebrate burrows, invertebrate, and plant remains, are present in both members, indicating active continental ecosystems. Notably, the uEF fossil record includes evidence of some of the earliest large-bodied basal sauropodomorph dinosaurs, with individuals exceeding 12 tonnes (Figure 10; McPhee et al., 2018). Additionally, very large predatory theropod trackways in the uEF suggest that large vertebrate taxa persisted despite climatic fluctuations, challenging earlier views that aridification led to size reduction in vertebrate faunas. Straddling the Triassic-Jurassic boundary, these redbeds are critical for understanding the end-Triassic extinction event and subsequent ecosystem recovery in Gondwana and beyond (Bordy et al., 2020; Abrahams et al., 2020, 2022; Abrahams and Bordy, 2023; Sciscio et al., 2023).

Recent integrated chronostratigraphic studies, including magnetostratigraphy and U-Pb detrital zircon geochronology, refine age constraints, placing the lEF predominantly in the Norian to Rhaetian and extending the uEF from the Hettangian to Sinemurian. Radiometric dating indicates that <500 m of Elliot sediment accumulated over ~35 million years, implying multiple unconformities within the succession. The sedimentary facies and faunal changes across the lEF–uEF boundary are recognised as a significant stratigraphic marker and regional unconformity; however, recent dating has left the duration and relative position of this unconformity to the Triassic-Jurassic boundary unclear (Bordy et al., 2020).

In summary, the Elliot Formation captures a complex interplay of tectonics, climate, and sedimentary processes during a critical period of Gondwana's geological history. It highlights a climatic transition from cooler, humid conditions in the Carnian Molteno to a more arid, seasonally variable Pliensbachian Clarens palaeoclimate, evidenced by sedimentological and palaeontological proxies. The stratigraphic architecture of these classical redbeds transitions from perennial high-sinuosity channels in the lEF to ephemeral, sheet sandstone-dominated fluvial systems in the uEF, reflecting progressive climatic drying and tectonic reorganization. High-resolution studies are increasingly providing a more nuanced understanding of climatic, tectonic and ecological changes, which was not linear as previously thought. The rich vertebrate fossil record of the Elliot Formation makes it a cornerstone for interpreting terrestrial ecosystem evolution across the Triassic-Jurassic boundary globally.

The Clarens Formation (Figures 1 to 4 and 9) the youngest fully sedimentary unit within the MKB, represents some of the most extensive and well-preserved late Sinemurian to early Toarcian aeolian deposits in southern Pangea (Head and Bordy, 2023, 2025; Head et al., 2024). It consists mainly of fine- to very fine-grained, well-sorted, pale yellow to pink quartz-rich sandstones and coarse siltstones with remarkable lithological uniformity, reflecting widespread aeolian transport and mixing. Typically, it has a thickness of 90 to 150 m, and a maximum thickness of 300 m. Unlike all the other Karoo units, it does not show systematic thinning from south to north. The formation conformably overlies the redbeds of the Elliot Formation and underlies the Karoo continental flood basalts of the Drakensberg Group, indicating continuous deposition across the sedimentary-volcanic boundary. Recent U-Pb detrital zircon geochronology dates the Clarens Formation to ~192 to 181 Ma, a depositional phase spanning ~10 million years in the Early Jurassic (Head et al., 2024).

Traditionally viewed as an aeolian dune system propelled by an east- to southeast-directed wind system during the Karoo's desertification (Johnson et al., 2006), recent analyses reveal, in detail, episodic wet intervals within the dominant aeolian deposits, including extensive loessites (Head and Bordy, 2023). Facies analysis identifies a stratigraphic megacycle driven by climate fluctuations: an initial semi-arid phase with ephemeral interdune lakes and minor fluvial input, characterised by ripple-marked silty sandstones, desiccation cracks, and calcareous nodules; a middle peak-aridity phase dominated by large cross-bedded dunes with scarce wet facies; and a terminal wetter phase marked by renewed interdune silty sandstones featuring raindrop imprints and microbial textures. These reflect episodic water availability in an overall arid desert landscape, with large, persistent lakes depositing laminated mudstones during wet

Figure 10. *Reconstruction of the palaeoenvironment in the central main Karoo Basin (MKB) during the late Early Jurassic (~195 Ma), featuring dinosaurs (Massospondylus, Heterodontosaurus, and Dracovenator) amid ferns forests with ginkgoes as well as early mammals (Megazostrodon) and an armoured crocodile (Protosuchus). See Electronic Supplement 2 for detailed explanation, including the other life forms shown in this geo-palaeo artwork by Maggie Lambert-Newman.*

intervals (Head and Bordy, 2022). Sedimentation occurred during the final chapter of the Karoo foreland basin evolution that was increasingly influenced by syn-depositional extensional tectonics.

Despite its overall aridity, the Clarens Formation supported diverse palaeoecosystems, particularly in interdune and lacustrine settings within lower and upper stratigraphic intervals. Fossil evidence includes microbial mats, freshwater invertebrates, basal sauropodomorphs, ornithischian dinosaurs, cynodonts, crocodylomorphs, and semionotid fishes. Petrified forests, charcoal layers, plant impressions, vertebrate trackways (notably tridactyl dinosaur footprints), and termite nests indicate an episodically habitable dune system where moisture sustained life (Bamford, 2004; Bordy et al., 2020, 2021; Mukaddam et al., 2020; Dollman et al., 2021).

The Clarens Formation is globally significant as one of the most extensive and exceptionally preserved Early Jurassic wet-erg systems, dominated by migrating aeolian dunes and sand sheets, with loess plains developing downwind, intermittently interrupted by lacustrine and ephemeral fluvial deposits under variable palaeoclimate. This stratigraphic unit captures climate extremes in an ancient inland desert, reflecting transitions between peak aridity and wetter phases. It provides critical insights into desert system responses to long-term climatic cycles and abrupt changes. Its sedimentary architecture, palaeocurrent consistency, and rich fossil record, including plants, invertebrates, and early dinosaurs, points to the persistence of a terrestrial ecosystem and the adaptation of the biota within harsh desert environments, offering a high-fidelity archive crucial for reconstructing palaeoecological responses in other arid/dryland systems. The Clarens Formation documents the intricate interplay of climate, declining regional compressional tectonics, and the onset of extensional rifting and Karoo- Ferrar volcanism. Future research integrating high-resolution geochronology, multi-proxy palaeoclimatic reconstructions, and palaeowind modelling will be essential to further unravel the complexities of this iconic wet dune system in southern Pangea.

Drakensberg Group

The Drakensberg Group (Figures 1 to 4 and 9) is the youngest unit of the Karoo Supergroup, and marks the Pliensbachian–Toarcian eruption of extensive continental flood basalts concurrent with the incipient phase of Gondwana's breakup. These basalts are part of the Karoo-Ferrar Large Igneous Province, a significant geological event that reshaped the landscape of southern Gondwana and has been linked to the end-Pliensbachian mass extinction (Bordy et al., 2023b).

This group is dominated by basaltic lava flows that have a cumulative preserved thickness of >1 600 m. The basalts form sheets of varying lava flow types and produced the prominent bedded cliffs and terraced hillsides of the Drakensberg and Maluti mountains in South Africa and Lesotho, respectively. Minor sedimentary interbeds, mainly sandstone and less commonly mudstone, are interspersed throughout the volcanic pile, and are particularly abundant in the lower Drakensberg Group. This and the conformable contact with the Clarens Formation indicate continuous sedimentation during early volcanic activity. Additionally, subvolcanic dolerite sills and dykes intruded the Karoo succession, and caused contact metamorphism that affects coal rank, hydrocarbon maturation, and compartmentalised aquifers, thus altering host rocks and contributing to the structural complexity of the MKB (Figure 3C).

The flood basalts of the Drakensberg Group were emplaced rapidly across multiple eruptive phases, with geochronological data suggesting that the main lava pile erupted within as little as 250 000 years (Moulin et al., 2017). This voluminous outpouring blanketed southern Africa ~183 ± 1 Ma, reshaping and fragmenting the landscape, and sharply reducing clastic sediment input. In the lower part of the Drakensberg succession, pillow lavas, indicative of lava extrusions into lakes up to ten metres deep, formed lava-fed deltas, a rare volcano-sedimentary environment (Bordy et al., 2021).

Sedimentological features in the interbeds include ripple cross-lamination, horizontal bedding, desiccation cracks, and raindrop impressions, providing crucial evidence of continental deposition concurrent with flood basalt eruptions during a seasonally wet, warm-temperate palaeoclimate. This palaeoclimate supported fluvio-lacustrine settings with ephemeral streams, ponds, and shallow lakes, sustaining a moderately diverse biota. Fossil assemblages include vascular plants (conifers, cycads, petrified gymnosperm wood), invertebrates (arthropods, conchostracans, gastropods), trace fossils, and vertebrate footprints, including small mammaliamorphs, crocodylomorphs, and dinosaurs. These findings reveal a dynamic landscape with complex food webs thriving in freshwater habitats that initially adapted to significant volcanic activity but later fragmented and dwindled as the MKB transformed into a land of fire (Bordy et al., 2020; 2021; 2023b).

In summary, although subordinate in volume to the basalts, the Drakensberg Group's sedimentary rocks are essential archives preserving the last terrestrial ecosystems of the MKB before complete inundation by flood basalts. This integrated sedimentary-volcanic record provides unparalleled insights into continent-scale volcanic impacts on ecosystems, marking the transition of the MKB from a continental sedimentary basin to a continental flood basalt province. It highlights the interplay of tectonics, magmatism, sedimentation, and biotic resilience during the Early Jurassic, capturing the environmental and biological perturbations linked to the massive volcanic outpouring of the Karoo-Ferrar Large Igneous Province and global climatic and biotic changes, including the end-Pliensbachian extinction event (Ruhl et al., 2022).

Synthesis and future directions

The tectonic evolution of the MKB, the mega-depression containing rocks of the Karoo Supergroup, is a subject of some debate within the broader context of Gondwana's dynamic tectonic history. The most enduring model of MKB development characterises it as a retro-arc foreland basin shaped by crustal loading from subduction along Gondwana’s southern margin and the orogenic uplift of the Cape Fold Belt (Figures 1 to 3; Catuneanu et al., 2005). Over the past 25 years, this model has effectively explained the basin's distinctive southward-thickening geometry, the distribution of glaciogenic and deepwater deposits in the Dwyka and lower Ecca groups, and the facies changes in the long-lived fluvial distributary system sourced from the Cape Fold Belt during the Beaufort and Stormberg groups. Research conducted since 2000 has confirmed the model's utility in elucidating changes in accommodation space, sediment supply, and facies distribution (i.e., architecture) of all Karoo stratigraphic units. While the broad flexural architecture is generally accepted for earlier Karoo deposition, it is increasingly clear that superimposed strike-slip faulting, pre-Karoo topography, differential subsidence due to a heterogeneous basin floor, basin segmentation, and localised accommodation zones, significantly influenced this evolution until the onset of extensional tectonics as evidenced by the uppermost units of the Karoo succession. Current discussions increasingly focus on the precise timing, spatial extent, and interplay of these tectonic controls on sedimentation throughout the complex history of the MKB.

The Karoo Supergroup preserves one of the most detailed records of Gondwana's climatic evolution from the Late Carboniferous to the Early Jurassic, over 120 million years of depositional history. Multi-proxy studies since 2000 have revealed the complexity of Karoo palaeoclimatic dynamics, challenging earlier assumptions of linear climate deterioration (i.e., simple progressive aridification) and emphasising episodic and non-linear climatic oscillations in the MKB. For instance, highlights for the Stormberg Group include the recognition of fluctuating climate within the Elliot Formation, contrasting with previous interpretations of steady aridification, and widespread lacustrine phases in the Clarens Formation, once deemed a Jurassic sand sea. Temporal assessment palaeoclimate proxies have also revealed how Permo-Triassic aridification and subsequent climate oscillations in the Jurassic continuously influenced Karoo sedimentation. Multiple chemical and isotopic datasets now indicate shifting palaeoenvironments in tandem with tectonic pulses and volcanic events. These climatic and tectonic drivers modulated sediment supply, facies changes, and preservation potential across the basin, making them essential components for interpreting the Karoo stratigraphic record accurately.

The Karoo Supergroup remains a palaeontological treasure trove, with ongoing discoveries significantly advancing our understanding of the evolution of life on Earth. Indeed, much of the recent research on the Beaufort and Stormberg groups has been carried out with the aim of better contextualising contained fossil assemblages. Advances in palaeontological techniques – such as X-Ray micro-Computed Tomography, photogrammetry, refined phylogenies from genomic and morphometric studies – have led to landmark discoveries since 2000, including several new therapsid, diapsid, and dinosaur taxa, and numerous trackways across the Karoo. New fossil finds have also contributed to refining the vertebrate-based biozonation scheme, improving correlations both basin-wide and intercontinentally. Notably, fossil discoveries in post-Ecca rocks have clarified ecosystem transitions during the end-Capitanian, end-Permian, end-Triassic, and end-Pliensbachian. Karoo rocks, recording physical, chemical and biological changes that occurred during several mass extinction events, remain integral to global extinction driver models and recovery processes and offer valuable insights into biological turnover and environmental change.

Recent biostratigraphic advances complement lithostratigraphic frameworks, allowing for more accurate basin evolutionary models and overall stratigraphic frameworks. Significant progress since 2000 includes the integration of fossil vertebrate biozones, plant biostratigraphy, palynomorph assemblages, and ichnological data, enhancing the temporal and spatial resolution of Pan-Gondwanan correlations and strengthening global integration of Karoo records. Intra- and inter-basin correlations across Gondwana have also greatly benefited from magnetostratigraphic investigations and geochronological work. Although not yet systematically applied across the entire MKB, these methods are increasingly refining stratigraphic frameworks, particularly in the Beaufort and Stormberg Groups. Moreover, radiometric dating and provenance studies provide higher precision geochronological control points than biostratigraphic proxies, enabling more accurate placement of major biotic, tectonic, and climatic events. Detrital zircon U-Pb geochronology has revolutionised our understanding of sediment provenance changes across the Karoo succession, with shifts in zircon age spectra reflecting progressive unroofing of source areas and evolving orogenic activity and basin dynamics. Provenance studies have documented changes in sediment-routing systems, basin compartmentalisation, and sediment dispersal pathways from early Ecca deep-water settings to later Beaufort and Stormberg fluvial and aeolian systems.

Despite significant advancements, several key questions remain unresolved, including quantitative links between tectonics, climate, and sedimentation patterns; detailed facies correlations; and understanding the nature, timing, and controls of facies changes, formation boundaries, and unconformities. Further research is needed to clarify basin evolution and landscape development within the MKB and in the sediment source areas, as well as to establish precise correlations with global events, including the end-Capitanian, end-Permian, end-Triassic, and end-Pliensbachian events.

The Karoo Supergroup offers rich opportunities for multidisciplinary research. Future breakthroughs are expected from:

- Integrated sedimentological, geochemical, palaeontological, and geochronological datasets derived from coordinated, high-density sampling to constrain basin evolution, palaeogeography, climate, and biotic change at high temporal resolution;
- Improved quantification of links between Karoo stratigraphy, global climatic events, and major biotic crises;
- Coupled high-resolution sedimentology and inorganic–organic geochemistry to refine palaeoenvironmental reconstructions;
- Expanded use of advanced imaging in palaeontological and ichnological studies to strengthen palaeoecological interpretations;
- Targeted application of detrital geochronology, remote sensing, and machine learning-assisted facies analysis to resolve key regional stratigraphic uncertainties, including unconformity detection;
- Systematic evaluation of Karoo resource potential (including groundwater, CO_2 storage, mineralisation) within the context of basin architecture and igneous overprinting;

- Karoo explorers who can authoritatively answer the common question: “Where exactly are we in the stratigraphy?” – This requires the formalisation and systematic revision of Karoo lithostratigraphy that integrates modern sedimentological and chronostratigraphic insights under coordinated oversight by the SACS, in line with its national mandate. A robust lithostratigraphic framework further depends on the continued protection, promotion, maintenance, and enhancement of its existing foundations, as well-defined rock units remain fundamental to all geological investigations, particularly to high-resolution studies such as geochronology, geochemistry, and evolutionary research.

In closing, over the past 25 years, significant advances in tectonic models, sedimentology, palaeontology, and geochronology, have revised long-standing paradigms regarding the formation of Karoo rocks and revealed new insights encoded within them. The Karoo hosts several informal global type sections documenting continental-scale biocrisis responses – particularly in the Beaufort, Stormberg, and lower Drakensberg groups – where landscape, sedimentation, climate, and life coevolved under profound environmental changes. Notably, this record illustrates that biotic resilience often exceeded theoretical limits, with groups such as therapsids surviving episodes of extreme warming and drought, and life persisting through voluminous volcanic upheaval during the Drakensberg flood basalt emplacement. But beyond its ever-expanding palaeontological legacy, the Karoo remains an invaluable archive for understanding the complex interactions between tectonics and climate over vast geological intervals, ensuring it remains a wondrous destination for all students of the Earth.

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