Revised lithostratigraphy of the Upper Permian Balfour and Teekloof formations of the main Karoo Basin, South Africa

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Abstract

A new lithostratigraphic framework is introduced for the Permian Balfour and upper Teekloof formations (lower Beaufort Group) in the main Karoo Basin of South Africa. The Balfour Formation's Barberskrans Member (BM) is identified as the Oudeberg Member at its current type location. Thus the BM requires renaming, and is here defined as the Ripplemead member (RM) after Ripplemead farm 20 km north of Nieu Bethesda. The upper Teekloof Formation is subdivided into the sandstone-poor Steenkampsvlakte Member and sandstone-rich Javanerskop member which occurs in the highest points of the western escarpment between Beaufort West and Fraserburg. The thickness of the Balfour Formation does not significantly change from east to west, but thins rapidly northwards to a point where the Oudeberg Member is not present, and other subdivisions are much attenuated. Recent biostratigraphic revisions of Lopingian tetrapod fauna show the Ripplemead and Javanerskop members are not contemporaneous. Therefore, no lithostratigraphic members in the Upper Permian Beaufort Group have basin wide distribution, and it is recommended that they be used as local markers only in conjunction with other proxies (e.g. biostratigraphic and chronostratigraphic markers). Patterns of biostratigraphic disappearance of tetrapods in the Balfour Formation at the same stratigraphic interval throughout the basin despite the thinning of strata northward, supports a temporally phased terrestrial Permo-Triassic mass extinction (PTME). The lack of basin wide lithostratigraphic markers highlights the variable aggradation rates during the deposition of the Beaufort Group caused by foreland tectonics and localised subsidence. A need for a full consideration of these complexities and their effects on the fossil records is therefore required in determining whether the terrestrial PTME is synchronous with the marine extinction.

Introduction

The Balfour and Teekloof formations are continental sandstone and mudstone successions, and are part of the Adelaide Subgroup (Johnson, 1976; SACS, 1980) (Figure 1, Table 1) of the Beaufort Group. First described by Johnson (1966), the Balfour Formation is documented east of 24°E in the Eastern Cape and the southern Free State Province (Cole and Wipplinger, 2001). Biostratigraphically it correlates mainly with the Lopingian *Daptocephalus* Assemblage Zone (DaAZ) but also contains strata assigned to the uppermost *Cistecephalus* and lowermost *Lystrosaurus* assemblage zones (Figure 1) (Viglietti et al. 2016). Previous workers such as Johnson (1966, 1976), Tordiffe (1978), Visser and Dukas (1979), and Smith (1995) subdivided the

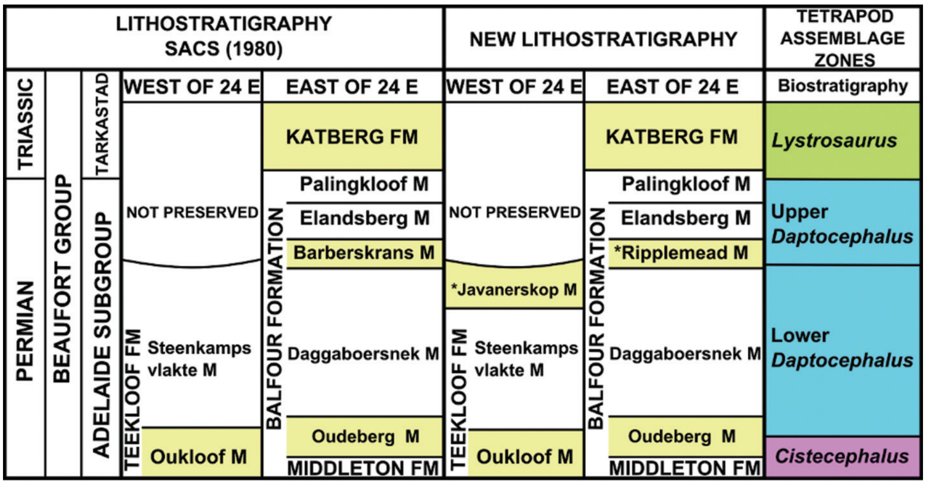

Figure 1. *Proposed stratigraphic framework for the Balfour and upper Teekloof formations. Note that the Barberskrans Member is renamed as the Ripplemead member. Also note proposed names for the new arenaceous units identified within the Balfour and uppermost Teekloof Formation in this study, by Le Roux (1985) (Javanerskop member). Note that they are not at the same stratigraphic position.*

Balfour Formation into the Oudeberg, Daggaboersnek, Barberskrans (previously Zone 3 of Johnson, 1966), Elandsberg, and Palingkloof members. These stratigraphic units are particularly well-exposed in the Winterberg and Sneeuberg mountain ranges near Cradock, Graaff-Reinet, and Nieu Bethesda (Figure 2). Work conducted by Smith and Botha (2005), Botha and Smith (2006), and Smith and Botha-Brink (2014) on the Permo-Triassic mass extinction (PTME) in the southern Free State Province has identified only some of these lithological units in the Bethulie area. The maximum thickness of the Balfour Formation is estimated to be 2150 m in the Fort Beaufort area (Table 2) (Johnson, 1976; Catuneanu and Elango, 2001).

The Teekloof Formation, is historically believed to reach a maximum thickness of ~1400 m (Johnson and Keyser, 1979; Johnson, 1994), although more accurate measurements give the Teekloof Formation a maximum thickness of ~ 400 m (Smith, 1993b; Rubidge et al., 1995; Day, 2013). The Teekloof Formation lies to the west of longitude 24°E (Cole and Wipplinger, 2001), and best outcrops are visible along the escarpment between Sutherland and Beaufort West in the Nuweveld mountain range, Roggeveld, and the Koup. The formation was deposited during the Lopingian period (Day et al., 2015; Rubidge et al., 2013) and is represented by the Poortjie, Hoedemaker, Oukloof, and Steenkampsvlakte members (Figure 1, Table 1) (Turner, 1979; Stear, 1980, Johnson, 1994). Currently, the base of the Steenkampsvlakte Member is considered to coincide with the Lower DaAZ and although predominantly argillaceous, it does contain some sandstone-rich zones in the uppermost layers, which form amalgamated bodies of limited lateral extent (Keyser and Smith, 1979; Smith, 1987). One of these sandstone-rich intervals, noted in the Steenkampsberg area, was named the Javanerskop member after a hill on Oukloof Pass (Le Roux, 1985). This unit has also been identified by Smith (pers. comm. 2013) north of Beaufort West in the highest points of the escarpment (Figure 2, GPS coordinates -32,20245; 22,644383).

Separate lithostratigraphic units were defined because outcrops of the Karoo Basin's Beaufort Group are widely separated by poor exposure. Lack of dateable beds has also made correlation difficult but progress has been made in this regard (Rubidge et al., 2013). Locally mudstone and sandstone-rich units have been given member status by their apparent utility as local marker horizons (Figure 1, Table 1) however, the regional extent and distribution of most of these units has not been well-documented. Tordiffe's (1978) Barberskrans Member (BM) consists of 20 to 25 m paired tabular sandstones within the predominantly argillaceous Balfour Formation and has been highlighted as a potential marker unit for the latest Permian in the main Karoo Basin (Johnson, 1976; Tordiffe, 1978). Currently, Tordiffe's (1978) BM is named after the Barberskrans Cliffs type section where a steep sandstone outcrop overlooks the N10 highway south of Cradock (Tordiffe, 1978; SACS, 1980). From there, Tordiffe (1978) traced the BM in the mountains south of Cradock and Mortimer (Gannashoekberg). Near Nieu Bethesda previous sedimentological and stratigraphic work by Visser and Dukas (1979) identified a sandstone rich interval as Tordiffe's (1978) BM. Subsequently, Cole et al. (2004) also mapped this unit in the area, and in turn Smith and Botha-Brink (2014) identified this unit on their vertical sections.

During this study, fieldwork in the Cradock area documented stratigraphic relationships and lithological properties of the subdivisions of the Balfour Formation and confirmed that the sandstone at the Barberskrans Cliffs is in fact the upper part of the Oudeberg Member which has nomenclatural priority (Johnson, 1976). Thus, to deal with the absence of Tordiffe's (1978) BM unit at the Barberskrans Cliffs locality in accordance with South African and international lithostratigraphic terminology and nomenclature (Johnson, 1987, 1996; Murphy and Salvador, 1999; Owen, 2009), this unit now requires renaming as well as a new type locality. This study investigates and introduces a revised lithostratigraphy of the Lopingian Balfour and Upper Teekloof formations (Figure 1). Secondly it identifies the relative stratigraphic positions of the lithostratigraphic subdivisions using revised biostratigraphic data. Finally, new distribution and thicknesses for the

Table 1. Lithostratigraphic units of the Balfour, Teekloof, and Katberg formations. Formation (F), member (M), and bed (B) status, proposer, type location, stratigraphic position, and lithological properties are summarized. An asterisk (*) next to the rank means the unit is not yet formally accepted by the South African Committee for Stratigraphy.

Unit	Rank	Source of name	Stratotype(S) Type locality(L) Type area(A)	Stratigraphic position	Thickness and boundaries	Lithological features
Balfour (Johnson, 1966)	F	Village	Fort Beaufort-Balfour road (S)	Late Permian (Lopingian) in age (255 to 252 Ma), *Daptocephalus* AZ Overlies the Middleton F and underlies the Lower Triassic Katberg F (Tarkastad Subgroup). Correllates to the upper Teekloof F in the west and Normandien F in the northeast.	Maximum thickness 2150 m. Average thickness 450 to 500 m. Lower and upper boundaries sharp.	Sandstone (20 to 25%): Mean thickness 5 m. Maximum thickness 40 m. Fine to medium grained, moderatley sorted, crossbedded, horizontally laminated, massive, ripple cross to lamiated, pale olive (10Y 6/2) or greenish grey (5G 6/1) tabular or lenticular sublitharenites. Average palaeocurrent direction ~291˚. Mudstone (75 to 80%): Mean thickness 20 m. Structureless or finely laminated red (4YR 10/1) or green (5GY 5/2, 5G 4/1) mudstone. Pedogenic and diagenetic carbonate nodules, plant, vertebrate, and ichno fossils common. Comprises alternating mudstone and subordinate lense to tabular shaped laterally discontinuous sandstones. Subdivided into the Oudeberg, Daggaboersnek, Barberskrans, Elandsberg, and Palingkloof members. Well to exposed in the Winterberg and Sneeuberg ranges near Cradock, Graaff to Reinet, and Nieu Bethesda.
Katberg (Johnson, 1966)	F	Katberg Pass	Pass along the Fort Beaufort-Queenstown road (S)	Lower Triassic in age (*Lystrosaurus* AZ). Overlies the Balfour F and underlies the Burgersdorp F.	Maximum thickness 1000 m. Average thickness ~200 m. Lower boundary is sharp and the upper boundary is gradational.	Sandstone (90 to 95%): Fine to medium grained, moderatley sorted, crossbedded, horizontally laminated, massive, ripple cross to lamiated, pale olive or greenish grey tabular subarkose sandstones. Average palaeocurrent direction ~342°. Mudstone (10 to 25%): Structureless or horizontally laminated, medium to thick bedded red and minor green mudstone. Pedogenic and diagenetic carbonate nodules, plant, vertebrate, and ichnofossils common. Thin mudstone beds are present, with red mudstone beds increasing in abundance towards the upper boundary of the formation as it grades into the Burgersdorp F (Johnson, 1976; Johnson et al., 2006).

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Teekloof (Keyser and Smith, 1979)	F	Pass south of Fraserburg	Road cuttings pass (S)	Middle Permian (Guadalupian) to Lopingian in age. Overlies the Abrahamskraal F and its upper bounding surface is a regional unconformable surface.	Maximum thickness ~1400 m (Johnson and Keyser, 1979; Johnson, 1994). Maximum thickness ~500 m. but more recent work by Smith (1993b), Rubidge et al., (1995); and Day (2013) suggest this maximum thickness is closer to ~400 m. The lower boundary is sharp and conformable. The upper boundary is an erosional hiatus.	Sandstone (20 to 25%): Mean thickness 5 m. Maximum thickness 30 m. Fine to medium grained, moderatley sorted, crossbedded, horizontally laminated, massive, ripple cross to lamiated, pale olive or greenish grey tabular or lenticular litharenites. Average palaeocurrent direction ~58° .Mudstone (75 to 80%): Mean thickness 20 m. Generally structureless or horizontally laminated, medium to thick bedded red or minor green mudstone. Pedogenic and diagenetic carbonate nodules, plant, vertebrate, and ichnofossils common. Four subdivisions correlate to four biostratigraphic zones: Poortjie (*Pristerognathus* AZ), Hoedemaker (*Tropidostoma* AZ), Oukloof (*Cistecephalus* AZ), and Steenkampsvlakte (*Daptocephalus* AZ) members. Uranium mineralisation locally abundant (Turner, 1978; Le Roux, 1985). Outcrops in the Nuweveld escarpment near Beaufort West and Fraserburg but grades into the Balfour F to the east (Turner, 1981).
Oudeberg (Keyser, 1973)	M	Pass northwest of Graaff-Reinet	The pass (L)	Lopingian in age (*Cistecephalus* AZ). Overlies the Middleton F and is the lowermost member of the Balfour F. Underlies the Daggaboersnek M.	Maximum thickness is 40 to 180 m (Johnson, 1994). 50 m. Average thickness 40 m. Lower contact is sharp and upper contact is gradational.	Sandstone (70 to 75%): Maximum thickness 50 m. Average 40 m. Several fine to medium grained tabular to lenticular, massive or trough crossbedded, ripple cross to laminated pale olive sublitharenites. Mudstone (30 to 25%): Subordinate green mudstone is structureless and other features (eg. fossils, rootlets nodules) rare. Individual sandstones can be traced over tens of kilometres. Pedogenic nodule conglomerates common at bases. Fossils of *Cistecephalus microrhinus* are found above the unit (Keyser, 1973; Kitching, 1977). Good outcrops of the unit can be found on Oudeberg Pass and north of Cookhouse, although it can be traced east to East London and northwest to Richmond (Johnson, 1976; Tordiffe, 1978; Visser and Dukas, 1979).

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Unit	Rank	Source of name	Stratotype(S) Type locality(L) Type area(A)	Stratigraphic position	Thickness and boundaries	Lithological features
Daggaboersnek Johnson (1976)	M	Saddle north of Cookhouse	Road cutting and slopes (L)	Lopingian in age (*Daptocephalus* AZ). It overlies the Oudeberg M and underlies the Ripplemead M, both arenaceous units in comparison to the Daggaboersnek M.	A Maximum thickness is 1200 m per Tordiffe (1978). Maximum of 440 m documented by Visser and Dukas. Average thickness ~300 m in this study. Lower boundary is gradational and upper boundary is transitional although, sandstone content rapidly increases.	Sandstone (20 to 25%): Maximum thickness 3 m. Average thickness 1.5 m. Dark greenish grey (5GY 4/1) or pale olive lithofeldspathic sandstone ripple crosslaminated lenses are encountered but in general crossbedded units are uncommon. Mudstone (75 to 80%): Average thickness 20 m. Regularly bedded, varve to like tabular green and minor red mudstone beds. Interbedded with thin wave to rippled shales and sandstones. In the Cradock area pedogenic nodules are rare in comparison to where it outcrops near Nieu Bethesda. Vertebrate fossils are encountered but this unit is most well known for its plant fossils, in particular leaf impressions of *Glossopteris*. (Johnson 1976; Tordiffe, 1978; Johnson et al., 2006) Good outcrops of this unit can bee seen in the Daggaboer area between Cradock and Cookhouse, and also in the Graaff to Reinet area along the Murraysburg road. This unit thin rapidly northwards and is not present north of the Orange River.
Ripplemead (Viglietti, 2016)	*M	Farm north of Nieu Bethesda.	Farm area (A)	Lopingian in age (*Daptocephalus* AZ). It overlies the Daggaboersnek M and underlies the Elandsberg M.	Maximum thickness 96 m. Average thickness of 70 m. The lower boundary is transitional and the upper boundary is sharp.	Sandstone (70 to 80%): Maximum thickness 40 m. Average thickness 20 to 25 m. Fine to medium to grained tabular pale olive, crossbedded, and ripple cross to laminated sublitharenites. Mudstone (20 to 30%): Maximum thickness 20 m thick. Green, structureless mudstone. Sometimes pedogenic nodules and rootlets encountered. Vertebrate fossils are also found in mudstones. A conspicuous sandstone rich unit that lies between the argillaceous Daggaboersnek and Elandsberg members. Sandstones are often paired and continue laterally for a few kilometres (Tordiffe, 1978). Mud pellet/feldspathic conglomerates, plant and fish fossils are common at sandstone bases, particularly in Nieu Bethesda (Bender, 2000). Cradock, Cookhouse and northwest of Nieu Bethesda have good exposure of this unit.

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Unit	Rank	Source of name	Stratotype(S) Type locality(L) Type area(A)	Stratigraphic position	Thickness and boundaries	Lithological features
Elandsberg (Tordiffe, 1978)	M	Mountain 10 km east of Cradock.	The mountain (A)	Lopingian in age (*Daptocephalus* AZ). It overlies the Ripplemead M and underlies the Palingkloof M.	Maximum thickness 320 m (Tordiffe, 1978; Johnson, 1994). Hill (1993) has also reported 200 m for this unit. Maximum thickness in this study is 42 m. Average thickness 37 m. These thicknesses by previous workers are likely excessive. Lower bounding surface is sharp, whereas its upper boundary is gradational.	Sandstone (20 to 25%): Maximum thickness 3 m. Average thickness 1.5 m. Fine to medium to grained, crossbedded to ripple cross to laminated, greenish grey or pale olive sublitharenites. Average palaeocurrent direction ~291˚ . Mudstone (75 to 80%): Average thickness 20 m. Massivley bedded or horizontally laminated green or greenish greay mudstone Red mudstone is sometimes locally common. (Johnson, 1976). Mudstones rich in pedogenic and diagenetic carbonate nodules. In particular large brown weathering (10R 2/2) nodules with green mudstone pellets are a conspicuous feature (Smith and Botha to Brink, 2014). Tetrapod fossils are common as are plant impressions at the bases of the thin sandstone beds. Good outcrops can be seen on Elandsberg near Cradock, and also in the Nieu Bethesda area west of Compassberg.
Palingkloof (Johnson, 1976)	M	Farm south of Tarkastad	Farm area (A)	Transitional between Lopingian and Lower Triassic in age. The Permo-Triassic extinction event (PTME) and faunal transition between the Upper *Daptocephalus* and *Lystrosaurus* assemblage zones is documented.	Maximum thickness 100 m (Johnson, 1976, 1994). However, maximum thickness documented by Smith and Botha-Brink (2014) 60 m. Average thickness in this study is 46 m. Its lower and upper boundaries are transitional.	Sandstone (40 to 45%): Maximum thickness 3 m. Average thickness 1.5 m. Fine to medium to grained, crossbedded to ripple cross to laminated, greenish grey or pale olive sublitharenites with ubiquitous nodule conglomerates at their bases. Average palaeocurrent direction ~291°. Mudstone (55 to 60%): Average thickness 20 m. Massivley bedded or horizontally laminated red and minor green mudstone. (Johnson, 1976). Locally green mudstone can be dominant as observed in this study. Pedogenic nodule layers become very frequent as do large black or brown weathering diagenetic nodules. Fossil content is abundant and does not change throughout the unit even though the terrestrial PTME is documented (Smith and Botha to Brink, 2014).
Oukloof (Turner, 1979)	M	Pass northwest of Beaufort West	The pass (L)	Lopingian in age (*Cistecephalus* AZ). Has been correlated to the Oudeberg M.	Maximum thickness is 125 m. Lower boundary with is sharp while its upper boundary is gradational.	Sandstone (70 to 75%): Maximum thickness 28 m. Average thickness 18 m. Fine to medium to grained, crossbedded, horizontally laminated, ripple cross to laminated, greenish gray to pale olive sublitharenites with mudstone pellet conglomerates (Turner, 1981). Average palaeocurrent direction ~58˚ . The sandstones form prominent cliffs and ledges. Mudstone (25 to 30%): Average thickness 7 m. Red and green structureless or horizontally laminated mudstone. Vertebrate burrows, fossils, and carbonate nodules (pedogenic and diagenetic) common (Turner, 1981). Good outcrops on Oukloof and Teekloof Pass near Beaufort West.

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Unit	Rank	Source of name	Stratotype(S) Type locality(L) Type area(A)	Stratigraphic position	Thickness and boundaries	Lithological features
Steenkampsvlakte (Stear, 1980)	M	Farm northwest of Beaufort West	Farm area (A)	Lopingian in age (*Daptocephalus* AZ). Overlies the Oukloof M and underlies the Javanerskop M.	Maximum thickness 200 m. Lower is gradational while its upper boundary is sharp.	Sandstone (~20%): Fine to medium-grained crossbedded, horizontally laminated, ripple cross-laminated pale olive or greenish grey sublitharenite lenses. Average palaeocurrent direction ~41°. Mudstone (~80%): Average thickness ~20m. Red horizontally laminated mudstone very common. Rich in vertebrate fossils, pedogenic nodules, palaeosols, and rooted horizons. Good outcrop of this unit can be seen on Steenkampsberg on Oukloof Pass and north of Beaufort West in the highest parts of the escarpment.
Javanerskop (Le Roux, 1985)	M*	Hill northwest of Beaufort West	The hill (A)	Correlates to the *Daptocephalus* Assemblage Zone. It overlies the Steenkampsvlakte M and is overlain by a regional hiatus.	Total thickness ~125 m. Lower bounding surface sharp.	Has been described by Le Roux (1985) as a series of ribbon-shaped sandstones in the Upper Steenkampsvlakte M. Is identified in outcrop by an increase in sandstone content relative to the underlying Steenkampsvlakte M and lower red mudstone content identified in this study.
Musgrave Grit (Loock pers. comm.)	M*	City of Bloemfontein location	Bloemfontein location (A)	Lopingian in age (*Daptocephalus AZ*). Is underlain by argillaceous Balfour F (informally named the Dubbeldam mudrocks) and overlian by the Lower Triassic Sepenareshoek sandstones.	Maximum thickness 35 m. Lower boundary sharp but upper boundary gradational.	Sandstone (~90%). Maximum thickness 5 m. Average thickness 2 m. Coarse-grained, trough/planar crossbedded sublitharenites rich in large quartz and feldspar clasts. Average palaeocurrent direction ~223°. Mudstone (~10%): Structureless greenish grey mudstone with brown weatherin nodules. Identified by significant increase in coare-grained sandstone and anomalous southwesterly palaeocurrent directions which are different to underlying and overlying units (Rutherford, 2009; Rutherford et al., 2015).
Boomplaas sandstone (Viglietti, 2016)	M*	Hill east of Jagersfontein	The hill (A)	Lopingian in age. Could correlate to *Cistecephalus or Daptocephalus* assemblage zone stata.	Maximum thickness 20 m. Lower boundary sharp and upper boundary gradational.	Sandstone (80 to 90%): Maximum thickness 20 m. Coarse-grained, trough/planar crossbedded sublitharenite with gravel lags containing quartz and feldspar. Fossil plant stems, wood, and leaf fragments common. Average palaeocurrent direction ~255° . Mudstone (20 to 10%): Structureless greenish grey mudstone. Good outcrop on Boomplaas Hill on Buffelsboutfontein, Trifaldi Major, and Excelsior farms.

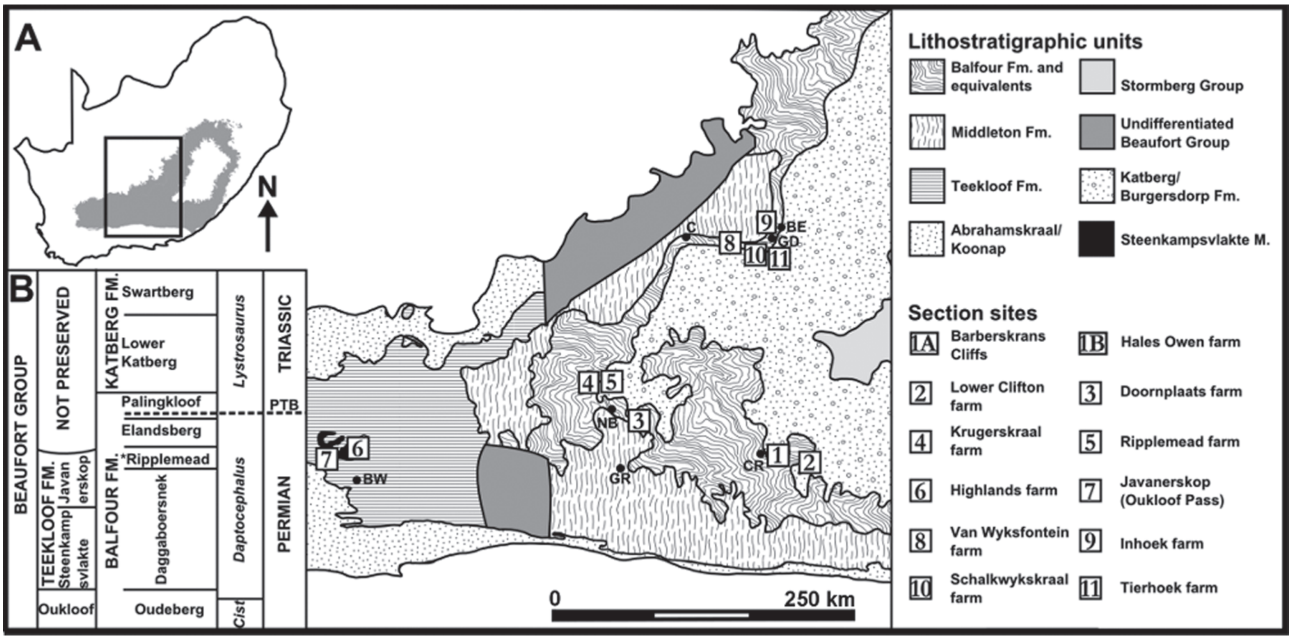

Figure 2. *(**A**) map of South Africa showing the position of the field sites in the main Karoo Basin, local geology, and numbered field sites. The field sites are near ten major town and abbreviations for town names are: Bethulie (BE), Gariep Dam (GD), Colesburg (C), Cradock (CR), Nieu Bethesda (NB), Graaff-Reinet (GR), and Beaufort West (BW). (**B**) Proposed lithostratigraphic subdivisions of strata correlated to the Daptocephalus and Lystrosaurus Assemblage Zones.*

lithostratigraphic units of the Balfour and Upper Teekloof formations are discussed and the implications for documentation of the terrestrial Permo-Triassic extinction event (PTME) are outlined.

Materials and methods

Study locations

The study area encompasses much of the south-central Karoo Basin and field sites were selected for outcrops that covered most of the stratigraphic range of the Balfour and upper Teekloof formations. Detailed work was undertaken at eleven sites near Cradock, Nieu Bethesda, Beaufort West, and Gariep Dam (Figures 2 and 3). At these localities, stratigraphic sections were measured, and lithostratigraphic units and formations were traced out laterally in the field, or by using Google Earth and data from previous investigations (van der Walt et al., 2011; Day et al., 2015). Additional vertical stratigraphic information for the Bethulie and Lootsberg Pass areas was retrieved from Botha and Smith, (2006), Botha-Brink et al. (2014), and Smith and Botha-Brink, (2014).

Stratigraphy

Eleven vertical sections measured during this study were combined into four composite sections to represent the four main field sites in this study (Figure 4), and were made using a Jacob staff and Abney level. Wherever possible, vertically logged lithological units were followed out laterally for at least 50 m. Vertical sections were measured through as much of the Balfour and upper Teekloof formations as possible and up to the first Katberg Formation sandstone, or from the upper contact of a recognized underlying unit (Oukloof or Oudeberg members). Features such as lithology, textures, colours, sedimentary structures, bounding surfaces, nodules, and fossils were noted. Locally occurring sandstone-rich units were identified by their stratigraphic position and their lithological properties (see Table 1). Table 1 summarizes the lithostratigraphic units investigated in this study using their lithological properties in the field. The lithostratigraphy at each field site was described, identified, and updated where necessary using the protocol of Johnson (1987), SACS (1980, 1996), Murphy and Salvador (1999), and Owen (2009). Vertical sections were digitized using Inkscape, Gimp, and Adobe Illustrator and show information concerning lithology, grain size, colour, fossils, and carbonate nodules.

The biostratigraphic review of the *Dicynodon* Assemblage Zone (Rubidge et al. 1995) by Viglietti et al. (2016) revised and renamed the assemblage zone the *Daptocephalus* Assemblage Zone. This study updated the stratigraphic ranges of all Lopingian-aged Karoo tetrapods by using locality data of fossils from the Karoo Basin present in local and international collections. These results helped to refine the stratigraphic relationships of lithostratigraphic units for this investigation. Therefore, the updated distribution of DaAZ fauna from Viglietti et al. (2016) is used as a tool to discern whether locally prominent lithostratigraphic units can be correlated temporally across the main Karoo Basin. Finally, the combined litho- and biostratigraphic information allowed for lateral correlation of composite sections between the four field sites (Figure 4).

Table 2. Total thicknesses of the lithostratigraphic units from previous workers, and from this study. Note that the total thicknesses are often significantly less than previously documented. Therefore many of the thicknesses documented by previous workers are likely excessive.

Location/Field/Site	Formation	Member/Unit	Thickness (m)	Source
King William's Town	Balfour	Total thickness	2350 m (± 500 m)	Johnson (1976)
Fort Beaufort	Balfour	Total thickness	2150 m (± 150 m)	Johnson (1976)
Cradock	Balfour	Total thickness	1220 m (± 150 m)	Johnson (1976)
Cradock	Balfour	Total thickness	1770 m	Tordiffe (1978)
Nieu Bethesda	Balfour	Total thickness	450 m	Johnson (1976)
Nieu Bethesda	Balfour	Total thickness	650 m	Visser and Dukas (1979)
Nieu Bethesda	Balfour	Total thickness	500 m	Rubidge et al. (1995)
Nieu Bethesda	Balfour	Upper Balfour	135 m	Jordaan (1990)
Nieu Bethesda	Balfour	Upper Balfour	150 m	Cole et al. (2004)
Thaba Nchu	Balfour	Total thickness	57 m	Rutherford et al. (2015)
Cradock	Balfour	Oudeberg	180 m	Tordiffe (1978)
Nieu Bethesda	Balfour	Oudeberg	50 m	Visser and Dukas (1979)
Cradock	Balfour	Daggaboersnek	1200 m	Tordiffe (1978)
Nieu Bethesda	Balfour	Daggaboersnek	440 m	Visser and Dukas (1979)
Nieu Bethesda	Balfour	Daggaboersnek	300 m	Cole and Wipplinger (2001)
Cradock	Balfour	Barberskrans	190 m	Tordiffe (1978)
Nieu Bethesda	Balfour	Barberskrans	60 m	Visser and Dukas (1979)
Cradock	Balfour	Elandsberg/Palingkloof	200 m	Tordiffe (1978)
Nieu Bethesda	Balfour	Elandsberg/Palingkloof	100 m	Visser and Dukas (1979)
Nieu Bethesda	Balfour	Elandsberg/Palingkloof	100 to 150 m	Cole and Wipplinger (2001)
Nieu Bethesda	Balfour	Elandsberg	37 to 42 m	Smith and Botha-Brink (2014)
Bethulie	Balfour	Elandsberg	41 m	Smith and Botha-Brink (2014)
Nieu Bethesda	Balfour	Palingkloof	60 m	Smith and Botha-Brink (2014)
Bethulie	Balfour	Palingkloof	46 m	Smith and Botha-Brink (2014)
Thaba Nchu	Balfour	Musgrave Grit	2 m	Rutherford et al. (2015)
Beaufort West	Teekloof	Total thickness	~1400 m	Johnson and Keyser (1979); Johnson (1994)
Beaufort West	Teekloof	Total thickness	~400 m	Smith (1993)
Beaufort West	Teekloof	Upper Teekloof	500 m	Cole and Wipplinger (2001)
Beaufort West	Teekloof	Oukloof	~125 m	Turner (1981)
Beaufort West	Teekloof	Steenkampsvlakte	~200 m	Stear (1980)
Beaufort West	Teekloof	Javanerskop	unknown	Le Roux (1985)
Cradock	Balfour	Total thickness	513 m	Viglietti (2016)
Nieu Bethesda	Balfour	Total thickness	506 m	Viglietti (2016)
Cradock	Balfour	Upper Balfour	94 m	Viglietti (2016)
Nieu Bethesda	Balfour	Upper Balfour	100 m	Viglietti (2016)
Gariep Dam	Balfour	Total thickness	90 m	Viglietti (2016)
Gariep Dam	Balfour	Oudeberg	not present	Viglietti (2016)
Cradock	Balfour	Daggaboersnek	300 m	Viglietti (2016)
Nieu Bethesda	Balfour	Daggaboersnek	330 m	Viglietti (2016)
Gariep Dam	Balfour	Daggaboersnek	20 m	Viglietti (2016)
Cradock	Balfour	Ripplemead	78 m	Viglietti (2016)
Nieu Bethesda	Balfour	Ripplemead	96 m	Viglietti (2016)
Gariep Dam	Balfour	Ripplemead	30 m	Viglietti (2016)
Cradock	Balfour	Elandsberg	63 m	Viglietti (2016)
Nieu Bethesda	Balfour	Elandsberg	37 m	Viglietti (2016)
Gariep Dam	Balfour	Elandsberg	26 m	Viglietti (2016)
Cradock	Balfour	Palingkloof	32 m	Viglietti (2016)
Nieu Bethesda	Balfour	Palingkloof	43 m	Viglietti (2016)
Gariep Dam	Balfour	Palingkloof	17 m	Viglietti (2016)
Beaufort West	Teekloof	Upper Teekloof	235 m	Viglietti (2016)
Beaufort West	Teekloof	Steenkampsvlakte	100 m	Viglietti (2016)
Beaufort West	Teekloof	Javanerskop	125 m	Viglietti (2016)

Results

The revised lithostratigraphy at each of the main field sites is briefly outlined below. Firstly, the stratigraphic positions of known lithostratigraphic units are compared to units under investigation such as Tordiffe's (1978) Barberskrans and Le Roux's (1985) Javanerskop members. Distribution of *Daptocephalus* Assemblage Zone tetrapod fauna documented by Viglietti et al. (2016) is then used to estimate relative age of these lithostratigraphic units. Finally changes in thicknesses of the lithostratigraphic subdivisions of the Balfour Formation are also outlined between the different field sites.

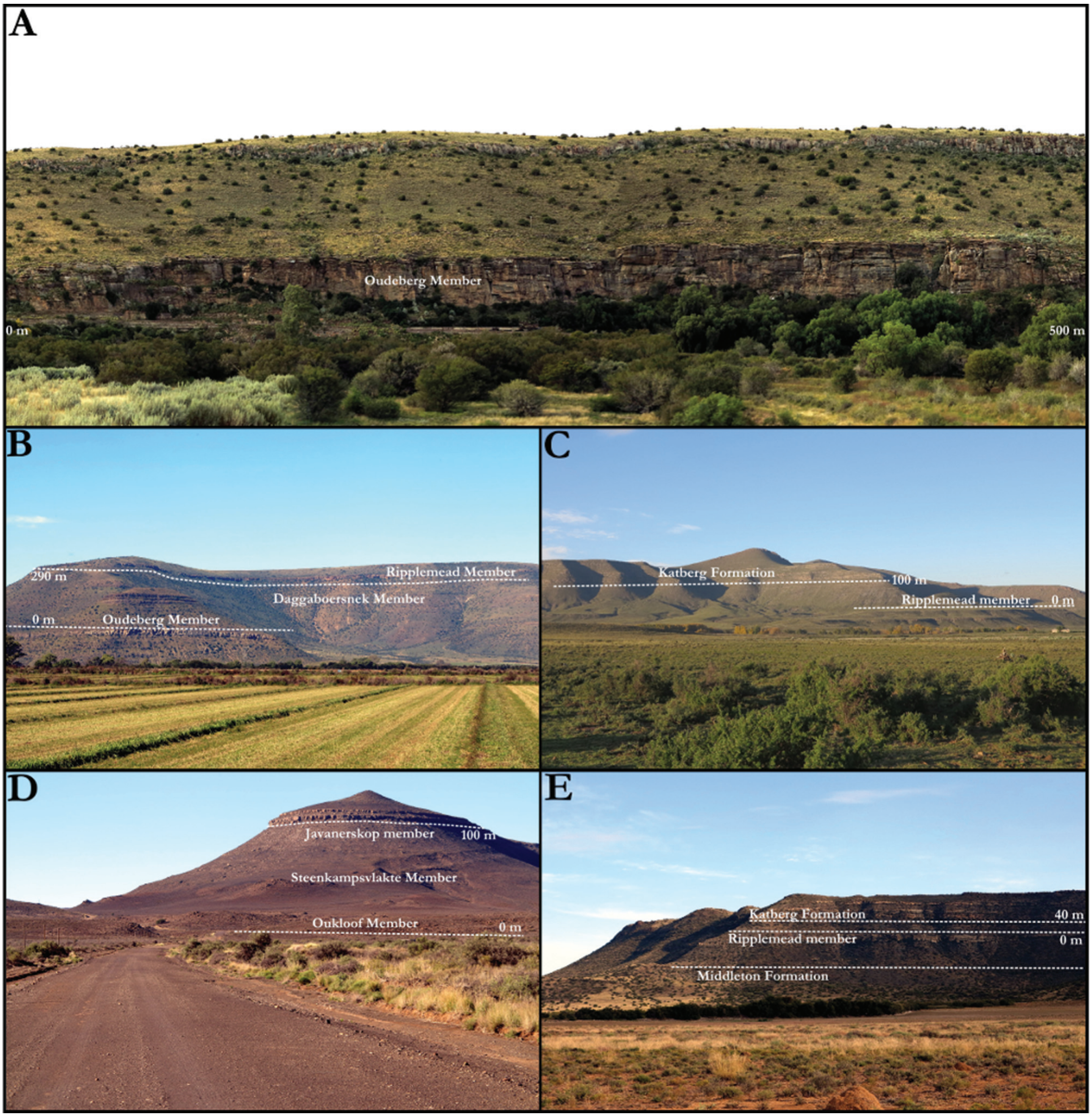

Figure 3. *(**A**) The current type locality of Tordiffe's (1978) Barberskrans Member (looking north). GPS coordinates are -32.214506°; 25.700256° (**B**) Photograph taken from the Mortimer road (R309) looking east towards Koppie Aleen and Rayner's kop. It shows the position of the Oudeberg Member and Ripplemead member which Tordiffe (1978) identified in the field area as belonging to the same unit and named the Barberskrans Member. They are in fact stratigraphically separated by 300 m of strata assigned to the Daggaboersnek Member. The RM does not occur at the Barberskrans Cliffs and thus Tordiffe's (1978) BM cannot retain its name. GPS coordinates are -32.374496°; 25.747157°. (**C**) Ripplemead farm, the new type location for the Ripplemead member. The distance to the base of the Katberg Formation is shown. GPS coordinates are -31.830114°; 24.412238°. (**D**) The Javanerskop member outcropping at its type location on Javanerskop, Oukloof Pass near Beaufort West. GPS coordinates are -32.153262°; 21.732731°. (**E**) Inhoek farm near Gariep Dam. Here the Ripplemead member is identified although in a condensed stratigraphy. The Katberg Formation is also identified for the first time at this site using lithological properties outlined in Table 1. The distance from the Ripplemead member to the base of the Katberg Formation is shown, and demonstrates significant attenuation. GPS coordinates are -30.524225°, 25.466010°.*

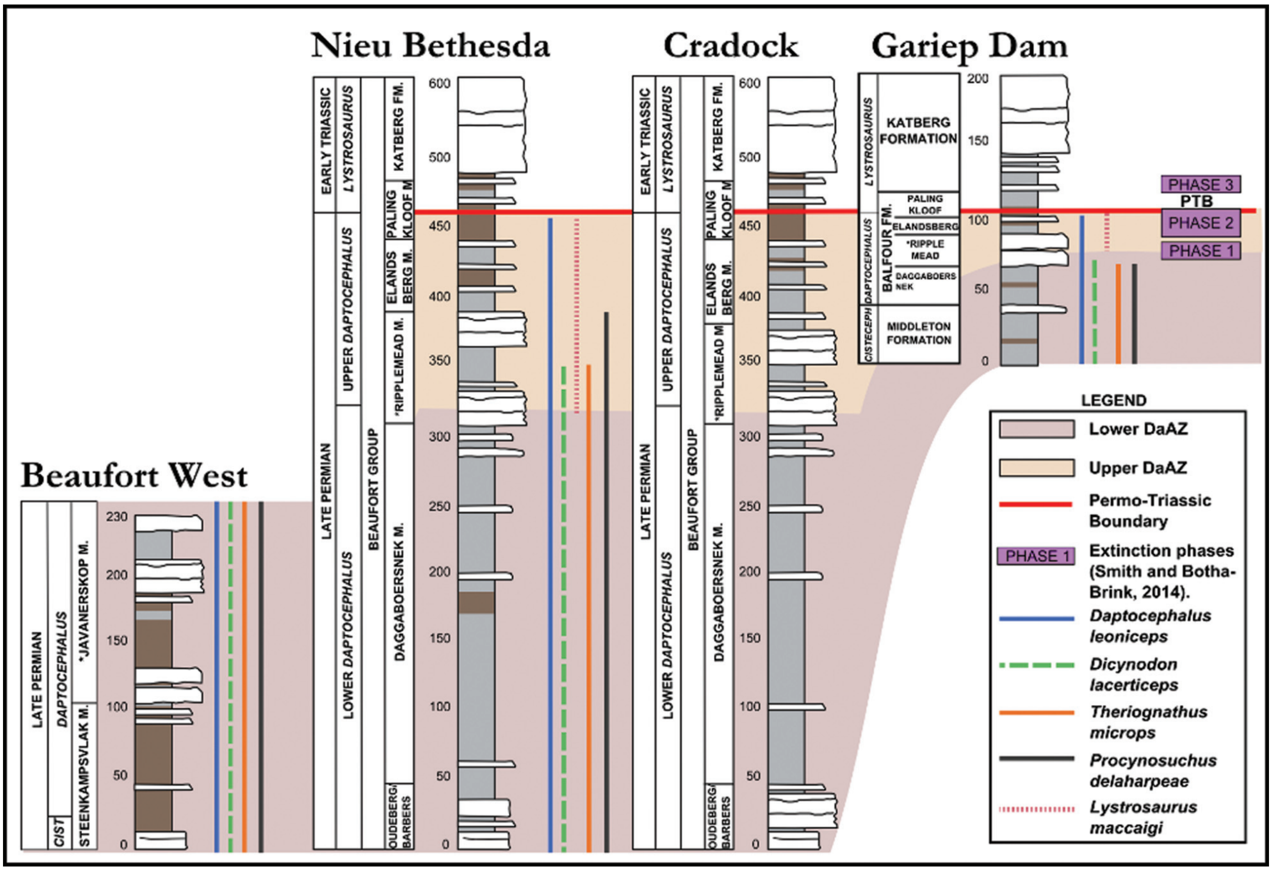

Figure 4. *Composite sections created at the field sites of this study. The distribution of strata assigned to Lower DaAZ and Upper DaAZ is also shown by use of the first appearance datum of Lystrosaurus maccaigi. The distribution of fauna in the Balfour and upper Teekloof formations shows that strata in the Beaufort West area (upper Teekloof Formation) are considered the oldest due to the current absence of L. maccaigi in this part of the basin. In the Nieu Bethesda area the appearance of L. maccaigi's is close to the base of the Ripplemead member. Although palaeontological evidence is lacking in the Cradock area, the similar thicknesses for lithostratigraphic units and similar fossil fauna found in the Elandsberg and Palingkloof members suggest the same lithostratigrphic scheme as at Nieu Bethesda. At Gariep Dam, L. maccaigi appears at a similar stratigraphic position in the sandstone defined as the RM, but this unit is much thinner than in Nieu Bethesda. This implies that there is a northward younging of DaAZ strata and importantly that the Javanerskop and Ripplemead members are not isochronous.*

New Upper Permian lithostratigraphic subdivisions

Cradock

The 40 m thick multi-storey sandstone at the Barberskrans Cliffs south of Cradock represents the type location for Tordiffe's (1978) Barberskrans Member. However, when this unit is traced laterally for about 2000 m it does not correlate to the 20 to 25 m thick sandstone couplets mapped by Visser and Dukas (1979), and Cole and Wipplinger (2001) as the Barberskrans Member. It is instead separated from the Barberskrans Member by a ~300 m thick argillaceous unit comprising varved laminated mudstone and sandstone couplets with many east-west trending ripple surfaces. By these characteristics, this argillaceous unit is identified as Johnson's (1976) Daggaboersnek Member and is mapped as such in the study area by Johnson (1976) and Tordiffe (1978). This means the unit at the Barberskrans Cliffs lies stratigraphically below the Daggaboersnek Member and at the level of Johnson's (1976) Oudeberg Member. The unit at the Barberskrans Cliffs lies at an altitude of between 865 m and 900 m above sea level which is similar in altitude to a sandstone north of the town Cookhouse identified as the Oudeberg Member by Johnson (1976) and Tordiffe (1978).

The biostratigraphy for this unit is the Lower *Daptocephalus* Assemblage Zone (DaAZ) which agrees with the revised biostratigraphy for this biozone, that incorporates the upper Oudeberg Member (Viglietti et al., 2016). A *Cistecephalus* Assemblage Zone fauna is identified by Kitching (1977) in the Bedford area, where the upper Oudeberg Member can be traced laterally from the Barberskrans Cliffs in the north, where it overlies this fauna. Also, an Upper DaAZ fauna is identified in the Baviaansrivier valley to the east of the Barberskrans Cliffs during this study where this unit can also be laterally traced. In addition, the 40 m thick multi-storey unit is lens-shaped and interbedded with subordinate green mudstone which is lithologically identical to the Oudeberg Member as documented in the literature (Johnson, 1976; Tordiffe, 1978; SACS, 1980) and in this study (Table 1). This stratigraphic relationship is demonstrated in Figure 3 (A and B). Therefore, the sandstone at the Barberskrans Cliffs is now identified as the Oudeberg Member.

Nieu Bethesda

Because the sandstone at the Barberskrans Cliffs south of Cradock, named the Barberskrans Member (Tordiffe 1978), was later incorrectly correlated with a prominent arenaceous unit in the Nieu Bethesda area, the name Barberskrans Member was also applied in this part of the basin (Visser and Dukas 1979; Cole et al., 2004, Smith and Botha-Brink 2014). As this unit is particularly well-exposed and accessible near Nieu Bethesda on the farm Ripplemead to the north of the village, Tordiffe's (1978) BM is now renamed the Ripplemead member (RM) in this study (Figure 3). On Ripplemead farm the RM represents paired 20 to 25 m multi-storey tabular lenses within a 71 m thick interval which share lithological characters of the RM at the Cradock field site (See Table 1). In addition many fossil fish were documented in this unit in this study and also by Bender (2001) in the Nieu Bethesda area.

Although not exposed on Ripplemead farm, the Oudeberg Member is present at its type location, Oudeberg Pass near Graaff-Reinet (Johnson, 1976; SACS, 1980) which is only 45 km away from the RM type location. At its type location the Oudeberg Member outcrops usually as three but in some places four laterally continuous sandstone lenses over a 50 m interval (Visser and Dukas, 1979; Turner, 1981; Johnson et al. 2006). Fossils are uncommon within the Oudeberg Member and subordinate green mudstone interbeds are also present unlike the RM (see Table 1 for more detailed lithological descriptions on these units). Tracing the Oudeberg Member to Doornplaats farm north-west of Graaff-Reinet, a vertical section could be measured from this unit to the RM, which overlies 300 m of argillaceous rocks characteristic of the Daggaboersnek Member (Table 1).

Beaufort West

Only the Teekloof Formation and its lithostratigraphic subdivisions are present in this part of the basin (Cole and Wipplinger, 2001) however, biostratigraphic correlation has enabled the 240 m stratigraphic package comprising the Oukloof and Steenkampsvlakte members to be correlated to the Balfour Formation in the eastern parts of the Basin (Smith, 1993b; Rubidge et al., 1995; Smith et al., 2012). Near Beaufort West, uppermost Permian strata are present as erosive remnants and only outcrop on the highest points of the escarpment. Vertical sections measured in this study near Beaufort West and Oukloof Pass document Le Roux's (1985) Javanerskop member in the highest points of the escarpment.

The Javanerskop member (Figure 3D) is lithologically distinct from the underlying argillaceous Steenkampsvlakte member due to its higher sandstone and lower red mudstone content (see Table 1). The member comprises the youngest strata preserved in this part of the Basin and consists of two or three sandstones within an interval reaching a maximum thickness of 125 m. The individual sandstones are a maximum of 10 m in thickness and single-storied, and appear as discontinuous couplets in outcrop. The sandstones contain many erosional surfaces which are lined with siltstone or mudstone pellet conglomerates. This study proposes that the Steenkampsvlakte Member now comprises lower sandstone poor portion of the upper Teekloof Formation (~110 m in total thickness) and the Javanerskop member represents the overlying 125 m thick sandstone-rich portion. This outlines a maximum thickness for the Upper Teekloof Formation of ~235 m which fits with reliable thicknesses for the upper Teekloof Formation in Rubidge et al., (1995) and total thicknesses for the entire Teekloof Formation (Smith, 1993; Day, 2013).

Gariep Dam

A single prominent sandstone unit within an attenuated Balfour Formation is laterally traceable in the area and because all lithological subdivisions of the Balfour Formation with exception to the Oudeberg Member, can be identified. Figure 3E shows a unit identified in this study as being an attenuated RM overlain by attenuated Elandsberg and Palingkloof members, and the Katberg Formation. The multi-storey 20 to 25 m tabular sandstones which lack nodules in their basal conglomerates and instead contain plant remains, as well as extra-, and intraformational clasts are identified as the RM based on these outlined features (Table 1). The underlying Daggaboersnek Member comprises repeated argillaceous beds as identified in Cradock and Nieu Bethesda but is difficult to distinguish from the underlying Middleton Formation because of the absence of the Oudeberg Member in this part of the basin. In the Gariep Dam area, the Elandsberg and Palingkloof members are recognised above the RM by their argillaceous nature and a colour change from dominantly green mudstone (Elandsberg Member) to dominantly red mudstone (Palingkloof Member). Southerly palaeocurrents and facies changes documented north of Gariep Dam near Jagersfontein and Fauresmith mean that the Balfour Formation probably is not present farther north in the main Karoo Basin. Published work (Welman et al., 2001; Rubidge et al., 2015; Viglietti., 2016) has identified *Daptocephalus* Assemblage Zone strata overlying *Pristerognathus* Assemblage Zone in this portion of the basin.

Thicknesses of the Balfour Formation

The composite sections in Figure 4 and Table 2 demonstrate little change in thickness of the lithostratigraphic units between Cradock and Nieu Bethesda, with both sites recording ~500 m total thickness for the Balfour Formation (Figure 4, Table 2) but are different to those recorded in previous studies (Table 2). Thicknesses of more than 2000 m (Johnson 1976; Tordiffe 1978; Catuneanu and Elango 2001), are much greater than those resulting from this study, but it is possible that thicknesses do increase to the east as suggested by Johnson (1976). However, the stratigraphic thickness of the Balfour Formation recorded by these authors is unlikely, given the relatively short distance over which the stratigraphic package would increase from ~500 m to over 2000 m. The position of this site, which would have formed part of the Lopingian Karoo foreland system, is the reason this is unlikely. Accommodation would have changed in a south to north direction rather than a west to east direction due to the trough shape of the foreland accommodation, which was caused by down-warping of weaker Namaqua-Natal Metamorphic belt crustal material (Catuneanu et al., 1998).

Near Cradock and Nieu Bethesda, the stratigraphic interval between the top of the RM and the base of the Katberg Formation is ~100 m. This thickness is also less than previously measured by Jordaan (1990) and Cole et al. (2004) who measured 135 and 150 m for this interval respectively however, it is within reasonable estimates of lateral and local variation in thickness documented by other workers in different parts of the basin (e.g. Day, 2013; Smith and Botha-Brink, 2014). This is to be expected in continental fluvial system where accommodation is controlled by foreland tectonics and other local variations in subsidence.

Near Beaufort West, thicknesses obtained for the Teekloof Formation (~1400m) (Johnson and Keyser, 1979; Johnson, 1994), and upper Teekloof Formation (~500 m) (Cole and Wipplinger) by previous workers are also significantly thicker than documented in in this study for the upper Teekloof (~235 m) and by other workers for the entire Teekloof Formation (~400 m) (Smith, 1993b; Rubidge et al., 1995; Day, 2013). The total thickness for the Teekloof documented by Johnson and Keyser (1979), Johnson (1994), and Cole and Wipplinger (2001) is also potentially exaggerated because these thicknesses were not obtained using a Jacob staff or Abney level (see Table 1 and 2).

Stratigraphic sections measured near Gariep Dam area for this study confirm significant thinning of the Balfour Formation strata in this part of the basin. Here the maximum thickness for the Balfour Formation is ~91 m and the stratigraphic distance to the Katberg from the top of the RM is 40 m, which is significantly thinner than the southern Balfour Formation near Cradock and Nieu Bethesda. Near Bethulie, 70 km east of Gariep Dam, Smith and Botha-Brink (2014) record thicknesses for the Elandsberg and Palingkloof members that are similar to those documented in Nieu Bethesda. This does not match the thicknesses documented for these units in the Gariep Dam area during this study and degree of attenuation was likely underestimated for all lithostratigraphic units.

Notable is the fact that the Oudeberg Member cannot be traced further north than Richmond (Cole and Wipplinger, 2001) and is not present in the Gariep Dam area (Figures 3E and 4). By contrast the RM extends northwards from Nieu Bethesda and Cradock to Springfontein in the Free State Province, but the unit is significantly attenuated as are the other lithostratigraphic units at this northerly juncture.

The Katberg Formation is also identified for the first time west of the N1 at Donkerpoort, highlighting this significant attenuation (Figure 3C). This formation, which is the basal formation of the Tarkastad Subgroup, is characterised by a significant increase in the sandstone:mudstone ratio from 1:3 or 1:6 in the Adelaide Subgroup to 1:2 or 1:0.8 in the Tarkastad Subgroup. In percentages, this is a jump from ~32% sandstone in the Balfour Formation to ~90 to 95% in the Katberg Formation (Johnson, 1976; Johnson and Keyser, 1976; Groenewald, 1996). The sandstones of the Katberg Formation are also tabular to sheet like in geometry and are mainly single-storey units with conglomerates comprising pedogenic nodules at their bases (although this lithofacies can be found in the upper Elandsberg Member). Sandstones are interbedded with thin floodplain deposits that are not always red but almost always contain immature palaeosols, except in the informally named Swartberg member in which sandstones are significantly amalgamated (Neveling, 2002). In addition, average palaeocurrents change from northwesterly in the Balfour Formation to northeasterly in the Katberg Formation (Johnson, 1976), a trend which was also identified in this study and used in part to help distinguish the Katberg from the Balfour Formation.

Ranges of Daptocephalus Assemblage Zone tetrapod fauna

Figure 4 demonstrates that the distribution of DaAZ defining fauna through the Balfour and Upper Teekloof formations is the same but the lithostratigraphy is different. Lithostratigraphic units correlate with either the Lower DaAZ or Upper DaAZ by the stratigraphic distribution of *Lystrosaurus maccaigi* in the composite sections.

Throughout the study area an arenaceous package is present toward the top of the sequences studied (Javanerskop and Ripplemead members) and one might initially be tempted to correlate these laterally separated units across the basin. Figure 4 demonstrates that the stratigraphic ranges of *Daptocephalus, Dicynodon lacerticeps*, *Theriognathus* and *Procynosuchus* are similar for the upper Teekloof and Balfour formations for the lower *Daptocephalus* Assemblage Zone. *Lystrosaurus maccaigi,* which is present only in the Upper *Daptocephalus* Assemblage Zone, is not present in the upper Teekloof Formation.

Biostratigraphic correlation thus indicates that the arenaceous Javanerskop member, which is present as a lithostratigraphic unit of the upper Teekloof Formation in the western part of the basin, cannot be correlated with the Ripplemead member of the Balfour Formation in the east. This suggests that the Javanerskop member correlates with the Lower DaAZ because *L. maccaigi* has not yet been found the western part of the basin. Since there has been regional post-Karoo erosion down to the mid-Lower DaAZ strata in this part of the basin, it is difficult to estimate how much more of the succession was once present. Karoo sills cap this erosional surface at many places and since there are hyperbyssal intrusions that had been emplaced in the shallow crust (Duncan et al. 1997), it could be estimated that between 2 and 3 km of strata once lay above this erosional boundary (Hanson et al. 2009). Therefore, both Upper DaAZ and *Lystrosaurus* AZ (Katberg Formation) may have been present in this part of the basin, but it appears they have since been eroded.

In the Nieu Bethesda area the appearance of *L. maccaigi* is close to the base of the RM (~130 m below the Permo-Triassic Boundary) which indicates that strata assigned to both Lower and Upper DaAZ are present here. Although palaeontological evidence is lacking in the Cradock area, the similar lithostratigraphic successions and thicknesses of units, coupled with a similar fossil fauna above the RM in the Elandsberg and Palingkloof members in the Cradock and Nieu Bethesda areas (Viglietti, 2016) suggest that the lithostratigraphic successions of both areas can be temporally correlated. At Gariep Dam, *L. maccaigi* also appears near the base of sandstones defined as the RM and thus the RM here can be temporally and lithostratigraphically correlated with the RM in the Cradock and Nieu Bethesda areas. However, this unit is much thinner (e.g. is 20 to 25 m thick and appears ~ 30 m below the PTB) because the rock record is condensed in this part of the basin. This indicates that either the entire *Daptocephalus* biozone is represented in the Gariep Dam area as a condensed section, or the lower part of the *Daptocephalus* Assemblage Zone is not present and was not deposited. The latter proposal alludes to the northward younging of Lopingian strata as theorized by Catuneanu et al. (1998).

Discussion

Implications for lithostratigraphic correlation

The new stratigraphic framework for the Upper Permian Karoo strata highlights that the Ripplemead and Javanerskop members were not deposited synchronously. Accommodation in the main Karoo Basin varied greatly in the west and central portions of the proximal Karoo Basin (i.e. foredeep). Thus, correlation of lithostratigraphic units westward and northward is problematic due to varied periods of non-deposition or out-of-phase deposition. The marked changes in thickness of the JM and RM are testament to the fact that the different lithostratigraphic units not only reflect changes in depositional rates in different parts of the basin, but also the diachronous nature of deposition in the Karoo Basin.

In the past attempts have been made to locate marker horizons in the lithostratigraphic succession of the Beaufort Group for use in correlation but this has not always been possible (Broom, 1907, 1909; Haughton and Brink, 1954; Haughton, 1963; Keyser, 1979; Keyser and Smith, 1979; Rubidge et al., 1995). Miall (1996) stresses sandstone-rich units should not be used as regional marker horizons because their deposition is defined and controlled by multiple events of incision and erosion and as a result can represent significant missing time. Locally lithostratigraphic members could serve as marker horizons (Smith, 1990; Botha-Brink et al., 2014; Day et al., 2015), but at regional scale across the Karoo Basin, correlation is dubious.

Therefore, the biozonation of the Karoo Supergroup has been a useful tool for correlating the lithostratigraphic subdivisions as they represent more fixed time lines than the lithostratigraphic boundaries (Rubidge et al., 1995; van der Walt et al., 2011). The diachronous nature of the Ecca-Beaufort contact (which is a lithostratigraphic boundary) is well-demonstrated around the Karoo Basin (Rubidge, 1988; Rubidge et al., 2000; Catuneanu, 2002; Rubidge, 2005) as well as several other major lithological boundaries that have been traced throughout the basin such as the Teekloof Formation (Keyser, 1979) Balfour and Normandien formations (Catuneanu et al., 1998), the Beaufort-Molteno contact (Hancox, 1998), and Katberg and Burgersdorp contact (Neveling, 2002).

Recognition of a northward thinning of the Upper Permian stratigraphic succession in the Karoo Basin demonstrates that there was generally more accommodation available in the south with less frequent and shorter periods of non-deposition compared to the north. Progradation of sediment northwards was also not synchronous nor continuous, leading to several periods of non-deposition in the distal foredeep of the basin.

The Permo-Triassic mass extinction

Figure 4 demonstrates that the same patterns of disappearance of Lopingian tetrapod fauna related to the terrestrial Permo-Triassic mass extinction (PTME) and the phased nature of the extinctions documented by Smith and Botha-Brink (2014) are observed at the same stratigraphic interval throughout the basin, despite the thinning of strata northward. This suggests that the preserved extinction event in the north is a condensed record in comparison to the south. Recently, high precision dates from a silicified ash layer 60 m below the current Permo-Triassic boundary (PTB), and assumptions about sedimentation rates, have been used to argue that the real PTB is higher in the section than previously recognized, and that faunal turnover in the Karoo was not coeval with the marine event (Gastaldo et al., 2015).

Sedimentation rates varied greatly in the Karoo Basin making the use of stratigraphic thicknesses as indicators of timing of sedimentation problematic. New thickness and stratigraphic data indicate significant faunal and climatic changes were already occurring below the dated horizon and support a phased terrestrial PTME in the Karoo Basin. Determining whether the Karoo PTME was synchronous with the marine event will require accurate radiometric dates for strata closer to the inferred PTB and a full consideration of the complexities of the geological and fossil records in the basin.

Conclusions

This study provides a revised lithostratigraphy for the Lopingian Balfour and upper Teekloof formations. The Balfour Formation's Barberskrans Member was previously named after its type location (Barberskrans Cliffs) south of Cradock but the unit is now confirmed to be absent at this location. Since the “Barberskrans Member” is not present at the Barberskrans Cliffs it is renamed as the Ripplemead member after its new type location, on Ripplemead Farm near Nieu Bethesda. The upper Teekloof Formation is subdivided in this study into the sandstone-poor Steenkampsvlakte Member and sandstone-rich Javanerskop member. This unit is named after Javanerskop on Oukloof Pass near Beaufort West, and is mappable within the highest points of the western escarpment near Beaufort West and Fraserburg.

Thickness of the Balfour Formation does not change between Cradock and Nieu Bethesda (e.g. ~500 m) but is less than that recorded in previous studies (e.g. >2000 m) (Johnson, 1976; Tordiffe, 1978; Catuneanu and Elango, 2001). The Balfour Formation thins rapidly northwards towards Gariep Dam and facies changes north of this field site suggest the Balfour Formation does not occur much further north in the main Karoo Basin. The lowermost Oudeberg Member is missing from this part of the basin, highlighting the significant attenuation in the Balfour Formation at its most northerly juncture.

Recent biostratigraphic revisions of the Lopingian tetrapod fauna demonstrate that the Ripplemead and Javanerskop members are useful local correlation tools but do not represent synchronous deposition. Thus, correlation of lithostratigraphic units west and north in the Karoo Basin is problematic due to variable and out of phase deposition. Therefore, refined stratigraphic ranges of tetrapod taxa are useful correlating tools in the Beaufort Group as they represent more fixed time lines than the lithostratigraphic boundaries.

The same patterns of disappearance of Lopingian tetrapod fauna are observed at the same stratigraphic interval throughout the basin despite the thinning of strata northward, which supports a phased terrestrial Permo-Triassic mass extinction (PTME). This is testament to the highly variable sediment accumulation rates during the deposition of the Beaufort Group strata. Determining whether the terrestrial PTME is synchronous with the marine extinction will require full consideration of the complexities of the geological and fossil records in the Karoo Basin.

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References

Bender, P.A., 2001. A New Actinopterygian Fish Species From the Late Permian Beaufort Goup, South Africa. Palaeontologia Africana, 37, 25-40.

Botha-Brink, J., Huttenlocker, A.K. and Modesto, S.P., 2014. Vertebrate paleontology of Nooitgedacht 68: A *Lystrosaurus maccaigi*-rich Permo-Triassic Boundary locality in South Africa. In: C.F. Kammerer, K.D. Angielczyk, J. Fröbisch, (Editors). Early Evolutionary History of the Synapsida, 289-304 Springer Netherlands.

Botha, J. and Smith, R.M.H., 2006. Rapid vertebrate recuperation in the Karoo Basin of South Africa following the End-Permian extinction. Journal of African Earth Sciences, 45, 502-514.

Broom, R., 1907. On the geological horizons of the vertebrate genera of the Karoo formation. Records of the Albany Museum, 2, 156-163.

Broom, R., 1909. An attempt to determine the horizons of the fossil vertebrates of the Karoo. Annals of the South African Museum, 7, 285-289.

Catuneanu, O., Hancox, J.P. and Rubidge, B.S., 1998. Reciprocal flexural behaviour and contrasting stratigraphies: A new basin development model for the Karoo retroarc foreland system, South Africa. Basin Research, 10, 417-439.

Catuneanu, O. and Elango, H.N., 2001. Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa. Sedimentary Geology, 140, 291-313.

Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits, and pitfalls. Journal of African Earth Sciences, 35, 1-43.

Cole, D.I., Neveling, J., Hattingh, J., Chevallier, L.P., Reddering, J.S.V. and Bender, P.A., 2004. The Geology of the Middelburg Area. Explanation sheet 3124 (scale: 1:250 000). Council for Geoscience, Pretoria, 43pp.

Cole, D.I. and Wipplinger, P.E., 2001. Sedimentology and molybdenum potential of the Beaufort Group in the main Karoo basin, South Africa. Memoir, Council for Geoscience, Pretoria, 80, 225pp.

Day, M.O., 2013. Middle Permian continental biodiversity changes as reflected in the Beaufort Group of South Africa: A bio- and lithostratigraphic review of the Eodicynodon, Tapinocephalus, and Pristerognathus assemblage zones. , PhD thesis, University of the Witwatersrand, 394pp.

Day, M.O., Ramezani, J., Bowring, S.A., Sadler, P.M., Erwin, D.H., Abdala, F. and Rubidge, B.S., 2015. When and how did the terrestrial mid-Permian mass extinction occur? Evidence from the tetrepod record of the Karoo Basin, South Africa. Proceedings of the Royal Society, 282, 1-8.

Duncan, R.A., Hooper, P.R., Rehacek, J. and Marsh, J.S., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. Journal of Geophysical Research, 138, 127-138.

Gastaldo, R.A., Kamo, S.L., Neveling, J., Geissman, J.W., Bamford, M. and Looy, C.V., 2015. Is the vertebrate-defined Permian-Triassic boundary in the Karoo Basin, South Africa, the terrestrial expression of the end-Permian marine event? Geology, 43, 1-5.

Groenewald, G.H., 1996. Stratigraphy and sedimentology of the Tarkastad Subgroup, Karoo Supergroup, South Africa. PhD thesis, University of Port Elizabeth, 341pp.

Hancox, P.J., 1998. A Stratigraphic, sedimentological and palaeoenvironmental synthesis of the Beaufort-Molteno contact, in the Karoo Basin. PhD thesis, University of the Witwatersrand, 381pp.

Hanson, E.K., Moore, J.M., Bordy, E.M., Marsh, J.S., Howarth, G. and Robey, J.V.A., 2009. Cretaceous erosion in central South Africa: Evidence from upper-crustal xenoliths in Kimberlite diatremes. South African Journal of Geology, 112, 125-140.

Haughton, S.H. and Brink, A.S., 1954. A bibliographical list of Reptilia from the Karroo beds of Africa. Die Afrikaanse Pers.

Haughton, S.H., 1963. Note on the distribution of fossil reptiles of Karroo age. Palaeontologia Africana, 7, 1-11.

Hill, R.S., 1993. Geological Sheet 3224 (Graaff-Reinet), scale 1:250 000 (R.S. Hill, compiler). Geological Survey, Government Printer, Pretoria.

Hill, R.S., 1993. The Geology of the Graaff-Reinet Area. Explanation Sheet 3224 (scale: 1:250 000). Geological Survey, Pretoria, 31pp.

Johnson, M.R., 1966. Stratigraphy and sedimentology of the Cape and Karoo sequences in the Eastern Cape Province. Geology. MSc thesis, Rhodes University, 336pp.

Johnson, M.R., 1976. Stratigraphy and sedimentology of the Cape and Karoo sequences in the Eastern Cape Province., PhD thesis, Rhodes University, 351pp.

Johnson, M.R. and Keyser, A.W., 1976. Explanatory notes. 1: 250 000 Geological Series 3226 King Williams Town. Government Printer, Pretoria.

Johnson, M.R. and Keyser, A.W., 1979. The Geology of the Beaufort West Area. Explanation Sheet 3222 (scale: 1:250 000). Geological Survey, Pretoria, 14pp.

Johnson, M.R., 1987. Guidelines for standardised lithostratigraphic descriptions. Govt. Printer, 1, 1-18.

Johnson, M.R., 1994. Lexicon of South African Stratigraphy. Part 1: Phanerozoic Units. South African Committee for Stratigraphy, 56pp.

Johnson, M.R., 1996. South African code of stratigraphic terminology and nomenclature. South African Committee for Stratigraphy.

Johnson, M.R., Van Vuuren, C.J., Visser, J.N.J., Cole, D.I., Wickens, H.D.V., Christie, A.D.M., Roberts, D.L. and Brandl, G., 2006. Sedimentary rocks of the Karoo Supergroup., Geological Society of South Africa, Council for Geoscience, 691pp.

Jordaan, M.J., 1990. Basin analysis of the Beaufort Group in the western part of the Karoo basin. PhD thesis, University of the Orange Free State, Bloemfontein, 272pp.

Keyser, A.W., 1973. A preliminary study of the type area of the *Cisticephalus* zone of the Beaufort series and a revision of the anomodont family Cisticephalidae. Memoirs of the Geological Survey of South Africa, 62, 1-71.

Keyser, A.W., 1979. A review of the biostratigraphy of the Beaufort Group in the Karoo Basin of South Africa Geocongress Abstracts II, Johannesburg. Geological Society of South Africa, 13-29.

Keyser, A.W. and Smith, R.M.H., 1979. Vertebrate biozonation of the Beaufort Group with special reference to the western Karoo Basin. Annual Geological Survey of South Africa, 12, 1-36.

Kitching, J.W., 1977. The distribution of the Karroo vertebrate fauna. Bernard

Price Institute for Palaeontological Research Memoir 1., 1-131pp.

Le Roux, J.P., 1985. Palaeochannels and Uranium mineralisation in the main Karoo Basin of South Africa. PhD thesis, University of Port Elizabeth, 250pp.

Le Roux, F.G. and Keyser, A.W., 1988. The Geology of the Victoria West Area. Explanation Sheet 3122 (scale: 1:250 000). Geological Survey, Pretoria, 31pp.

Miall, A.D., 1996. The geology of fluvial deposits., Springer, 582pp.

Murphy, M.A. and Salvador, A., 1999. International subcommission on stratigraphic classification of IUGS international commission on stratigraphy-international stratigraphic guide-an abridged version. Episodes 22, 255-271.

Neveling, J., 2002. Biostratigraphic and sedimentological investigation of the contact between the *Lystrosaurus* and *Cynognathus* Assembalge Zones (Beaufort Group; Karoo Supergroup). PhD thesis, University of the Witwatersrand, 232pp.

Owen, D.E., 2009. How to use stratigraphic terminology in papers, illustrations, and talks. Stratigraphy, 6, 106.

Rubidge, B.S., 1988. A palaeontological and palaeoenvironmental synthesis of the Permian Ecca-Beaufort contact in the southern Karoo between Prince Albert and Rietbron, Cape Province, South Africa. PhD thesis, University of Port Elizabeth, 290pp.

Rubidge, B.S., Johnson, M.R., Kitching, J.W., Smith, R.M.H., Keyser, A.W. and Groenewald, G.H., 1995. Biostratigraphy of the Beaufort Group (Karoo Supergroup). Biostratigraphic series 1, South African Committee for Stratigraphy, 46pp.

Rubidge, B.S., Hancox, J.P. and Catuneanu, O., 2000. Sequence analysis of the Ecca-Beaufort contact in the southern Karoo of South Africa. South African Journal of Geology, 103, 81-96.

Rubidge, B.S., 2005. 27th Du Toit Memorial Lecture: Re-uniting lost continents - fossil reptiles from the ancient Karoo and their wanderlust. South African Journal of Geology, 108, 135-172.

Rubidge, B.S., Erwin, D.H., Ramezani, J., Bowring, S.A. and de Klerk, W. J., 2013. High-precision temporal calibration of Late Permian vertebrate biostratigraphy: U-Pb zircon constraints from the Karoo Supergroup, South Africa. Geology, 10, 1-4.

Rubidge, B.S., Day, M.O., Viglietti, P.A. and Abdala, A., 2015. Recognising stratigraphic gaps in the Beaufort Group - consequences for basin modelling. In: B. Linol, W. Miller, M.J. De Wit, (Editors). Proceedings of the Proceedings of the Cape-Karoo Imbizo conference. Nelson Mandela Metropolitan University, Port Elizabeth.

Rutherford, A.B., Rubidge, B.S. and Hancox, J.P., 2015. Sedimentology and palaeontology of the Beaufort Group in the Free State Province supports a reciprocal foreland basin model for the Karoo Supergroup, South Africa. South African Journal of Geology, 118, 355-372.

SACS. 1980. Stratigraphy of South Africa, Part 1 (Compiler LE Kent), Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Boputhatswana, Transkei and Venda Geological Survey of South Africa Handbook, 8, 1-690.

Smith, R.M.H., 1987. Helical burrow casts of therapsid origin from the Beaufort Group (Permian) of South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 60, 155-169.

Smith, R.M.H., 1990. Alluvial paleosols and pedofacies sequences in the Permian Lower Beaufort of the southwestern Karoo Basin, South Africa. Journal of Sedimentary Research, 60, 258-276.

Smith, R.M.H., 1993a. Sedimentology and ichnology of floodplain paleosurfaces in the Beaufort Group (Late Permian), Karoo sequence, South Africa. Palaios, 8, 339-357.

Smith, R.M.H., 1993b. Vertebrate taphonomy of Late Permian floodplain deposits in the southwestern Karoo Basin of South Africa. Palaios, 8, 45-67.

Smith, R.M.H., 1995. Changing fluvial environments across the Permian-Triassic boundary in the Karoo Basin, South Africa and possible causes of tetrapod extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology, 117, 81-104.

Smith, R.M.H. and Botha, J., 2005. The recovery of terrestrial vertebrate diversity in the South African Karoo Basin after the end-Permian extinction. Comptes Rendus Palevol, 4, 623-636.

Smith, R.M.H., Rubidge, B.S. and Van der Walt, M., 2012. Therapsid Biodiversity Patterns and Paleoenvironments of the Karoo Basin, South Africa. In: A. Chinsamy-Turan, (Editor). Forerunners of Mammals, Indiana University Press, Bloomington, 31-62.

Smith, R.M.H. and Botha-Brink, J., 2014. Anatomy of a mass extinction: sedimentological and taphonomic evidence for drought-induced die-offs at the Permo-Triassic boundary in the main Karoo Basin, South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 396, 99-118.

Stear, W.M., 1980. The sedimentary environment of the Beaufort Group uranium province in the vicinity of Beaufort West, South Africa. PhD thesis, University of Port Elizabeth, 250pp.

Tabor, N.J., Montañez, I. P., Steiner, M. B. and Schwindt, D., 2007. δ 13°C values of carbonate nodules across the Permian-Triassic boundary in the Karoo Supergroup (South Africa) reflect a stinking sulfurous swamp, not atmospheric CO_2. Palaeogeography, Palaeoclimatology, Palaeoecology, 252, 370-381.

Tordiffe, E.A.W., 1978. Aspects of the hydrogeochemistry of the Karoo Sequence in the Great Fish River Basin, Eastern Cape Province, with special reference to groundwater quality. PhD thesis, University of the Orange Free State, 307pp.

Turner, B.R., 1978. Sedimentary Patterns of Uranium Mineralization in the Southern Karoo (Gondwana) Basin, South Africa. In: A.D. Miall, (Editor). Fluvial Sedimentology, vol, 5, Canadian Society for Petroleum Geologists. 831-848.

Turner, B.R., 1979: Excursions Guidebook, Geocongress '79. In, Geological Society of South Africa, Port Elizabeth.

Turner, B.R., 1981. Revised stratigraphy of the Beaufort Group in the southern Karoo Basin. Palaeontologia Africana, 24, 87-98.

van der Walt, M., Day, M.O., Rubidge, B.S., Cooper, A.K. and Netterberg, I., 2011. A new GIS-based biozone map of the Beaufort Group (Karoo Supergroup), South Africa. Palaeontologia Africana, 45, 1-5.

Viglietti, P.A., 2016. Stratigraphy and sedimentary environments of the late Permian Dicynodon Assemblage Zone (Karoo Supergroup, South Africa) and implications for basin development. PhD thesis, University of the Witwatersrand, 273pp.

Viglietti, P.A., Smith, R.M.H., Angielczyk, K.D., Kammerer, C.F., Fröbisch, J. and Rubidge, B.S., 2016. The *Daptocephalus* Assemblage Zone (Lopingian), South Africa: A proposed biostratigraphy based on a new compilation of stratigraphic ranges. Journal of African Earth Sciences, 113, 153-164.

Visser, J.N.J. and Dukas, B.A., 1979. Upward-fining mega-cycles in the Beaufort Group, north of Graaff-Reinet, Cape Province. Transactions of the Geological Society of South Africa., 82, 149-154.

Welman, J., Loock, J.C. and Rubidge, B.S., 2001. New evidence for diachroneity of the Ecca-Beaufort contact (Karoo Supergroup, South Africa). South African Journal of Science, 97, 320-322.

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