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A new GIS-based biozone map of the Beaufort Group (Karoo Supergroup), South Africa

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The stratigraphic subdivision of the Karoo Supergroup of South Africa has been addressed for more than a century by various geoscience studies. A lack of good lithostratigraphic markers in the Beaufort Group and the fact that the succession preserves a rich diversity of therapsid fossils for which there is a robust taxonomic scheme, make biostratigraphy the best option for correlation. This is applicable both within the basin and when comparing the Karoo succession to other coeval depositional basins. Published biostratigraphic maps of the Beaufort Group were compiled based on rough estimates of the distribution of zone-defining tetrapod fossil genera throughout the basin. None of these simultaneously utilized all the databases of South African museum collections. The recent application of GIS technology to integrate the vertebrate fossil databases of all South African museums has resulted in a far more precise biozone map which can be continuously updated as new information is received. This digital map introduces an entirely new way of representing the geographical distribution of fossil data, and thus can potentially enhance basin development and tetrapod biogeographic studies.

Keywords: Karoo Supergroup, fossil tetrapods, biostratigraphy.

INTRODUCTION

Biostratigraphy

The rocks of the Beaufort Group (Adelaide and Tarkastad subgroups) of the Karoo Supergroup cover approximately 60% of the surface of South Africa and comprise an approximately 3000 m thick succession of predominantly sedimentary rocks that are richly fossiliferous. Absolute ages for the Beaufort Group are not well constrained, with current dates based mainly on faunal correlations. The oldest stratigraphic units are considered Middle Permian (Kazanian) (Rubidge 1995a) and the uppermost strata as Middle Triassic (Anisian) (Ochev & Shishkin 1989; Hancox *et al.* 1995; Hancox & Rubidge 1996; Hancox 1998).

The global importance of the Beaufort Group is largely due to its remarkable assemblage of tetrapod fossils representing one of the best preserved ecological assemblages of pre-mammalian (therapsid) terrestrial vertebrates in the world (Keyser & Smith 1979), and the succession is held by many to be the global biostratigraphic standard for the non-marine Permo-Triassic (e.g. Shishkin *et al.* 1995; Lucas 1998). Furthermore, the rocks of the Beaufort Group preserve one of the most complete and best-studied non-marine Permo-Triassic (PT) boundary sequences globally (Smith 1995; Ward *et al.* 2000; Smith & Botha 2005; Botha & Smith 2006). These boundary sections preserve the terrestrial record of the Permo-Triassic extinction event – the greatest mass extinction event experienced on Earth (Erwin 1993, 1994, 2006).

Tetrapod fossils (particularly therapsids) have long been used for biostratigraphic subdivision and correlation of the Group which is especially useful because of the scarcity of basin-wide lithostratigraphic marker beds (Broom 1907a, 1909; Haughton 1924, 1963, 1969; Kitching 1970, 1972, 1977, 1984; Keyser & Smith 1979; Keyser 1979; Rubidge 1995b; SACS 1980). The few major lithological boundaries that have been traced throughout the basin have been shown to be diachronous (Keyser 1979), whereas the biozones are considered to closely approximate time lines (Rubidge 2005). Dicynodonts, the dominant herbivores of the Permian and early Triassic, are the most abundant fossil tetrapod taxon in the Beaufort Group and for this reason they are used as index fossils for the majority (five of the eight) of the currently recognized vertebrate biozones (Hancox & Rubidge 1997). Moreover, due to their abundance, dicynodonts have great potential for global correlation and have therefore been used in a number of previous biogeographic studies and biochronological schemes (Cooper 1982; Cruickshank 1985, 1986; Lucas 1990, 1993, 1995, 1998; Shishkin & Ochev 1992; De Fauw 1993).

Following is a summary of the history of work on the biostratigraphy of the Beaufort Group (Table 1) since Seeley (1892) proposed the first biostratigraphic subdivision of the Karoo which included three zones. Broom (1907b, 1909) refined the biozonation of Seeley by recognizing six subdivisions. Watson (1914a) agreed with Broom's subdivision and was the first to indicate the distribution of these units (which he termed 'zones') on a map. Later he replaced the *Pareiasaurus* Zone with the *Tapinocephalus* Zone (Watson 1914b), and an updated biozone distribution map was published in 1940 by von Huene. Hotton & Kitching (1963) pointed out that *Procolophon* occurs throughout the *Lystrosaurus* Zone and suggested that a separate overlying *Procolophon* Zone was not valid. Kitching (1970, 1977) introduced the *Daptocephalus* Zone to encompass the strata between the level where *Cistecephalus* became

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Table 1. Table showing the historical progression of Beaufort Group biozonation.

Beds	Zones		Assemblage Zones		
Broom (1906)	Watson (1914 a, modified 1914b)	Kitching (1970, 1977)	Keyser & Smith (1979)	Keyser (1979) SACS (1980)	Current Biozonation Rubidge (1995b)
Cynognathus	*Cynognathus*	*Cynognathus*	*Kannemeyeria*	*Kannemeyeria Diademodon*	*Cynognathus*
Procolophon	*Procolophon*	*Lystrosaurus*	*Lystrosaurus*	*Lystrosaurus Thrinaxodon*	*Lystrosaurus*
Lystrosaurus	*Lystrosaurus*				
Kistecephalus	*Cistecephalus*	*Daptocephalus*	*Dicynodon lacerticeps*	*Dicynodon lacerticeps Whaitsia*	*Dicynodon*
		Cistecephalus	*Aulacephalodon baini*	*Aulacephalodon Cistecephalus*	*Cistecephalus*
Endothiodon	*Endothiodon*		*Tropidostoma microtrema*	*Tropidostoma Endothiodon*	*Tropidostoma*
Pareiasaurus	*Tapinocephalus*	*Tapinocephalus*	*Pristerognathus/Diictodon*	*Pristerognathus/Diictodon*	*Pristerognathus*
			Dinocephalian	*Dinocephalian*	*Tapinocephalus*
					Eodicynodon

extinct and the first appearance of *Lystrosaurus*, and discarded Broom's *Endothiodon* and *Procolophon* Zones. Kitching (1977) also produced a map showing zone-defining fossil localities. Keyser & Smith (1979) proposed a more refined vertebrate biozonation (and accompanying biozone map) for the Beaufort Group in the western part of the basin and linked their assemblage zones to the litho-stratigraphic scheme proposed by SACS (1980). The discovery of a tetrapod fauna from below the *Tapinocephalus* Assemblage Zone (Rubidge 1984; Rubidge *et al.* 1983; Rubidge *et al.* 1994) led to the erection of the *Eodicynodon* Assemblage Zone, which is currently the oldest vertebrate biozone of the Beaufort Group (Rubidge 1990, 1995a).

Following the recommendations of the International Stratigraphic Guide (ISSC 1976), the names of the assemblage zones that were accepted by SACS (1980) incorporated two genera. The most recent biostratigraphic scheme of the Beaufort Group which recognized eight biozones (Rubidge 1995b) follows the most recent nomenclatorial practice of the ISSC (1994) and uses only one taxon name in defining a biozone. This biozonation was represented in map form (Rubidge 1995b) and has since been the standard reference for the biozones of the Beaufort Group. The method used to create this map was manual drawing by enhancing the biozone maps of Kitching (1977) and Keyser & Smith (1979). This was essentially an exercise in outlining diagnostic fossil localities on an A3-sized map with a consequent low-level resolution. Over the past 15 years many more fossils from the Beaufort Group with quantifiable provenance data have been accessioned into museum collections and provide the impetus for a reassessment of biozone boundaries. In addition, since 2007 a GIS database has been built up incorporating data relating to all fossil specimens from the Beaufort Group which are curated in South African palaeontological collections (Nicolas 2007; Nicolas & Rubidge 2009) and is an excellent tool to produce an updated biozone map.

MATERIALS AND METHODS

To produce the refined biozonation map from the GIS locality data, each biozone had to be defined in terms of key or 'marker' genera. Filtering for key genera allowed for biozone boundaries from the database to be defined. Ideally the lowermost boundary of a biozone is marked by the first appearance datum (FAD) of a key taxon, but in practise this is not always practical in the Beaufort biozonation scheme, which is based on assemblage zones, as the stratigraphic range of some biozone defining fossils are not necessarily restricted to the Assemblage Zone named after them. The diagnostic taxa utilized to define the individual biozones were taken from data presented in Rubidge (1995b), but in order to circumscribe the lower boundary of each biozone on the map the criteria set out in Table 2 were used.

Although ArcGIS allows for complex spatial analyses, numerous obstacles relating to data quality were encountered that presented barriers to the generation of biozone boundaries. These were:

1) *Quality of the locality data*. For older collections this often constitutes a farm name only. These are represented on the GIS map as farm centroids (Nicolas 2007). A farm covering two or more biozones may thus group genera from different biozones at a single point. Problematic localities were checked and topography examined to deduce the cause and nature of such apparent overlaps.
2) *The relationship between geology and topography.* At localities of high relief, the surface area of each biozone represented on the map is much smaller than when

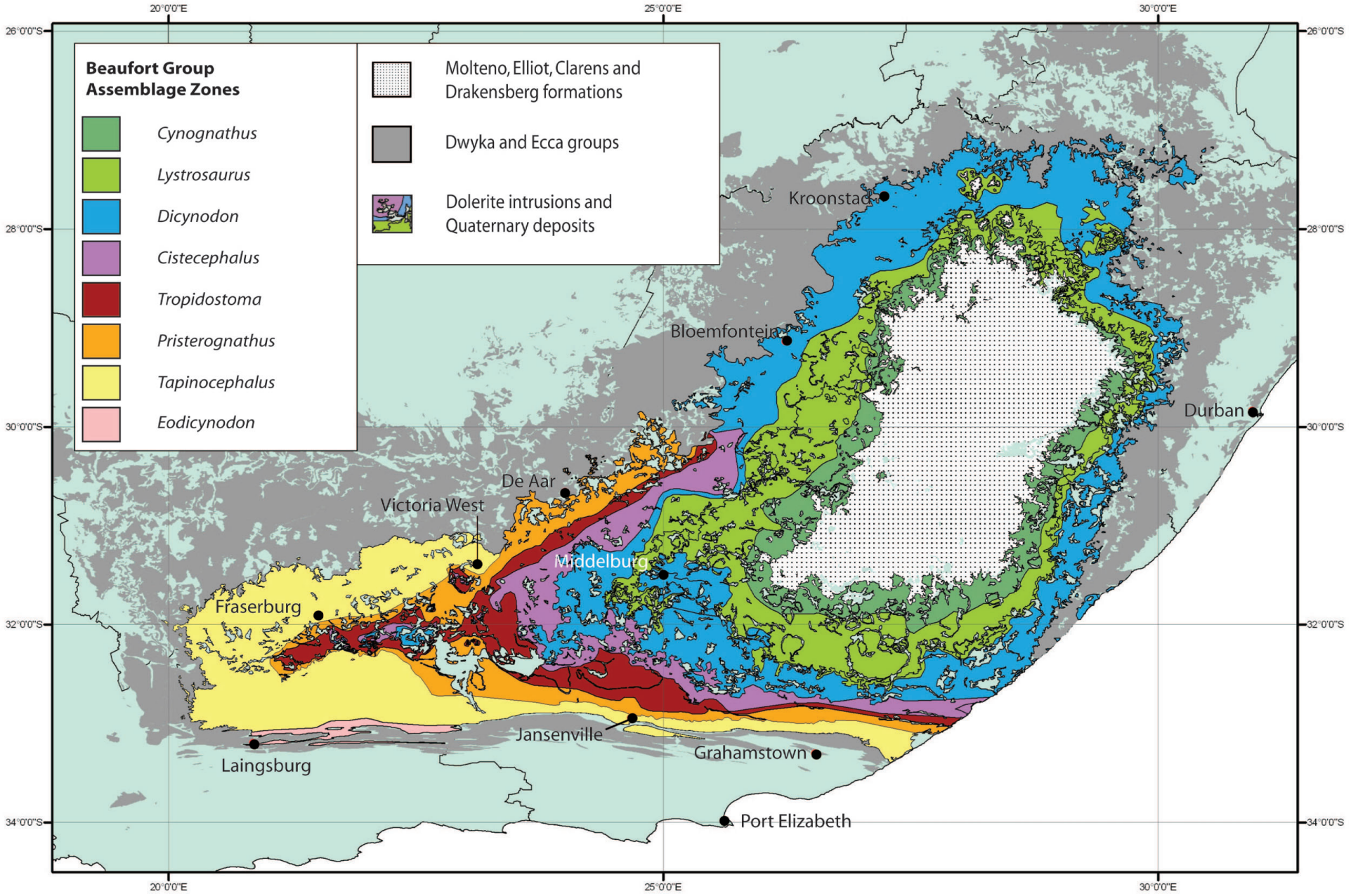

Figure 1. Geographic distribution of the vertebrate biozones of the Beaufort Group based on a GIS database.

Table 2. Criteria used to circumscribe lower boundaries of biozones shown on the map.

Assemblage Zone	Criteria used to circumscribe lower boundary
Eodicynodon	Ecca-Beaufort boundary
Tapinocephalus	Last appearance of *Eodicynodon, Australosyodon* and *Tapinocaninus*
Pristerognathus	Last appearance of dinocephalians, presence of *Pristerognathus*
Tropidostoma	First appearance of *Tropidostoma* with presence of *Endothiodon*
Cistecephalus	First appearance of *Aulacephalodon* with presence of *Cistecephalus*
Dicynodon	Presence of *Dicynodon, Daptocephalus* absence of *Cistecephalus*
Lystrosaurus	Last appearance of *Dicynodon, Daptocephalus*
Cynognathus	First appearance of *Trirachodon* and *Cynognathus*

exposed on flat ground. The orientation of topographic features, such as escarpments, relative to dip is also important as this defines whether the zone remains at a constant level or alters in height laterally. This meant that without sophisticated three-dimensional modelling the accurate mapping of biozone boundaries was not possible, even if all locality input data was exact. As a result, biozone boundaries were drawn digitally utilising overlays of fossil genus localities, as well topographic and geological maps. In areas of great fossil abundance accuracy is highest, but for many areas, particularly in the Free State and eastern portion of the Eastern Cape provinces, this could not be achieved as there is a dearth of collecting localities. In these places, where fortuitously the strata are relatively horizontal, biozone boundaries were established through extrapolation by following mapped contour lines from one locality to the next. In a few instances where fossil localities are separated by tens of kilometres and the topography is complex as a result of folding of the strata or dolerite intrusions, biozone boundaries were traced by assessing lithostratigraphic boundaries. It should be noted that neither topography nor geology are always reliable features to follow because of the dip of beds and the diachroneity of lithostratigraphic boundaries. However, in the absence of fossil data, this method provides the best approximation.

There are some spurious specimen localities in the database that are aberrant compared to surrounding data points and cannot be explained by the farm centroid effect. Possible causes include the presence of an outlier of another biozone, specimen misidentification, the specimen not being *in situ* or incorrect cataloguing. In areas without physical deformation and flat topography, the former could be ruled out with confidence. Specimens with apparently anomalous localities that could not be explained by relief or physical deformation had their provenance and description data checked. If they were incorrectly situated then they were either moved to the correct locality or, if their true provenance could not be determined, ignored. Any specimens that were correctly situated but the authors remained unconvinced of their identity, were ignored and listed to be reidentified at a later date.

DISCUSSION

The new, GIS-based biozone map (Fig. 1) shows relatively few large-scale changes compared to its published precursors (Rubidge 1995b). The termination of the *Tapinocephalus* AZ close to the town of De Aar is an educated estimation because of the absence of dinocephalian fossils further north. The exact position of the boundary here is unknown due to a lack of collecting and the Ecca-Beaufort boundary at the nearest site to the north at Somersfontein near Philippolis is known to be *Pristerognathus* AZ (Welman *et al.* 2001). Also, small biozone outliers which usually coincide with high hills, have been acknowledged where fossil evidence illuminates their position. Previously these occurrences were too small-scale to be mapped, but the far higher resolution of the new digital map now makes this possible.

Despite the caveats discussed above, it is clear that the use of GIS greatly increases the achievable accuracy and ultimately the utility of the resulting digital map. It can be viewed at both small-scale, for the observation of broad overall patterns, and at large-scale for the assessment of smaller areas. It will be useful to identify areas where collecting has been sparse and the need for further research is greatest, as well as those locations where the boundary is best visible. One of the foremost applications, at least in the early stages, will be to draw attention to misidentified specimens, or specimens identified long ago using outdated characters.

This is an ongoing project. The GIS database, which is housed and curated at the BPI Palaeontology (University of the Witwatersrand, Johannesburg), will be updated continuously to include nomenclatorial modifications of existing specimens as well as the inclusion of new acquisitions to collections. The map is available at http://web.wits.ac.za/Academic/Science/GeoSciences/BPI/ . Updating metadata will increase the accuracy of the map and provide an accessible record in 2D and ultimately in 3D. Use of this kind of spatial modelling will revolutionize the way biozones are mapped and will ensure that all new data are recorded in a systematic and centralized manner. The final product will serve as an up-to-date representation of the surface expression of vertebrate fossil assemblage zones of the main Karoo Basin in South Africa.

Setting up the Karoo fossil GIS database has been a long-term project which would not have been possible without the cooperation and enthusiasm of the curators of all the Karoo fossil collections in South Africa. We record our gratitude to Sheena Kaal and Roger Smith (Iziko South African Museum), Billy de Klerk (Albany Museum), Richard, Robert and Marion Rubidge (Rubidge Collection), Elize Butler and Jennifer Botha-Brink (National Museum), Bernhard Zipfel (BPI Palaeontology), Heidi Fourie (Transvaal Museum) and Johann Neveling and Ellen de Kock (Council for Geoscience). We are greatly indebted to Cynthia Kemp for the many hours she spent painstakingly editing and updating records. We also record our gratitude to the Palaeontological Scientific Trust (PAST), the Department of Science and Technology (DST), and the (National Research Foundation) NRF for providing funding. We are grateful to Jennifer Botha-Brink and an anonymous reviewer for improving the manuscript.

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