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THE ROLE OF FOSSILS IN INTERPRETING THE DEVELOPMENT OF THE KAROO BASIN

by

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ABSTRACT

The Permo-Carboniferous to Jurassic aged rocks of the main Karoo Basin of South Africa are world renowned for the wealth of synapsid reptile and early dinosaur fossils, which have allowed a ten-fold biostratigraphic subdivision of the Karoo Supergroup to be erected. The role of fossils in interpreting the development of the Karoo Basin is not, however, restricted to biostratigraphic studies. Recent integrated sedimentological and palaeontological studies have helped in more precisely defining a number of problematical formational contacts within the Karoo Supergroup, as well as enhancing palaeoenvironmental reconstructions, and basin development models.

KEYWORDS: Karoo Basin, Biostratigraphy, Palaeoenvironment, Basin Development.

INTRODUCTION

The main Karoo Basin of South Africa preserves a retro-arc foreland basin fill (Cole 1992) deposited in front of the actively rising Cape Fold Belt (CFB) in southwestern Gondwana. It is the deepest and stratigraphically most complete of several depositories of Permo-Carboniferous to Jurassic age in southern Africa and reflects changing depositional environments from glacial to deep marine, deltaic, fluvial and aeolian (Smith *et al.* 1993).

The sedimentary rocks of the Karoo Basin have yielded a diverse and important fossil biota including macro- and micro-palaeobotanical remains, vertebrate and invertebrate body fossils and traces. These fossils preserve a picture of the evolution of life during the Permo-Triassic and early Jurassic, and are also of interest for the information they supply in unravelling the geological development of the Karoo Basin.

The role of palaeobotanical megaplant fossils is reviewed by Anderson and Anderson (this volume) and will not be covered here. Research on fossil wood is becoming an important aid, both for its biostratigraphic potential, and for the elucidation of palaeoclimatic and palaeoenvironmental variables (Bamford *pers. comm.*). Palynological studies are increasingly proving important for biostratigraphic applications (MacRae 1988; Aitken 1995), age refinements and for the palaeoenvironmental information they supply.

Invertebrate fossils are rare in Karoo strata, except for the Estcourt and Molteno Formations, where insects are fairly common (van Dijk 1978; Rieck 1973, 1974, 1976 a,b,c,d; Cairncross *et al.* 1995; Anderson & Anderson, this volume). The Ecca Group and the Molteno, Elliot and Clarens Formations of the "Stormberg Group" also preserve a limited shelled invertebrate fauna (Du Toit 1936; Rilett 1951, 1963; Le Roux 1960; Teichert & Rilett 1974; Tasch 1984; Cairncross *et al.* 1995). Invertebrate remains are important as indicators of facies genesis, including water temperature and salinity, as age indicators, and for their biostratigraphic potential.

Fossil fish are relatively rare in the Karoo Supergroup, but where present are useful indicators of gross palaeoenvironments (e.g. Keyser 1966) and also have biostratigraphic potential (Jubb 1973; Bender *et al.* 1991). Current research on the fish of the Ecca Group (Evans *pers. comm.*), the Beaufort Group (Bender *pers. comm.*) and the Molteno Formation (Sytchevskaya *et al. in prep.*) of the "Stormberg Group", may show them to be valuable aids in further delineating biostratigraphic associations, palaeoenvironments and as an aid to understanding the infilling of the Karoo Basin.

Despite their relative abundance in the rocks of the Karoo Supergroup, ichnofossils have received only cursory attention in the literature, with most work being of a purely descriptive nature (e.g. Anderson 1975 a,b,c, 1981; Visser & Loock 1978; Shone 1978). Ichnofossils also have vast potential for palaeoenvironmental reconstructions in the Karoo (e.g. Hobday & Taverner-Smith 1975; Stanistreet *et al.* 1980; Smith, 1993) in that they provide for estimates of water depth, sedimentation rates and possibly even biostratigraphic studies (Ellenberger 1970; Olsen & Galton 1984; Raath *et al.* 1990). In addition their potential for aiding in the recognition of deltaic subenvironments has implications for coal exploration and exploitation.

Palaeosols (fossil soils) are also useful, in that they reflect the prevailing groundwater conditions and palaeoclimate in the basin, and also delineate times of non-deposition. Research into palaeosols has proved useful for palaeoenvironmental and basin fill interpretations of the Karoo (Smith 1990b; Smith & Kitching 1997). A recent study of the taphonomy and areal extent of the *Tritylodon* Acme Zone, a

	BEDS	ZONES				ASSEMBLAGE ZONES			
	Broom (1906)	Watson (1914a, modified 1914b)	Watson (1942)	Kitching (1970, 1977)	Cooper 1982	Keyser & Smith (1977–78)	Keyser (1979) SACS (1980)	Rubidge SACS (1996)	Kitching & Raath (1984)
CLARENS F. / ELLIOT F.									*Massospondylus*
									Euskelosaurus
MOLTENO F.									
BEAUFORT GROUP	*Cynognathus*	*Cynognathus*	B	*Cynognathus*	*Tetragonias*	*Kannemeyeria*	*Kannemeyeria–Diademodon*	*Cynognathus*	
		Cynognathus	A		*Kannemeyeria*				
	Procolophon	*Procolophon*		*Lystrosaurus*	*Lystrosaurus*	*Lystrosaurus*	*Lystrosaurus–Thrinaxodon*	*Lystrosaurus*	
	Lystrosaurus	*Lystrosaurus*							
	Kistecephalus	*Cistecephalus*	B	*Daptocephalus*	*Dicynodon*	*Dicynodon lacerticeps*	*Dicynodon lacerticeps–Whaitsia*	*Dicynodon*	
			A	*Cistecephalus*	*Cistecephalus*	*Aulacephalodon–baini*	*Aulacephalodon–Cistecephalus*	*Cistecephalus*	
	Endothiodon	*Endothiodon*	B			*Tropidostoma microtrema*	*Tropidostoma–Endothiodon*	*Tropidostoma*	
			A						
	Pareiasaurus	*Tapinocephalus*		*Tapinocephalus*	*Robertia*	*Pristerognathus/ Diictodon*	*Pristerognathus/ Diictodon*	*Pristerognathus*	
						Dinocephalian	*Dinocephalian*	*Tapinocephalus*	
								Eodicynodon	

Figure 1: Past and present biostratigraphic subdivisions of the Karoo Supergroup (modified after Rubidge, 1995).

fossiliferous palaeosol horizon, shows it to be important in understanding basinal development during upper Elliot (*Massospondylus* Assemblage Zone) times (Smith & Kitching 1997).

Although numerous different fossil types aid in our overall understanding of the Karoo Basin, this paper concentrates mainly on the role tetrapod body fossils have played in the biostratigraphic zonation, contact definitions and tectono-sedimentary development of the main Karoo Basin.

Because of their abundance in the Beaufort Group and the paucity of basin-wide lithostratigraphic marker horizons, synapsid tetrapod fossils (particularly therapsids) have long been used for the biostratigraphic subdivision and stratigraphic correlation of the Group (Broom 1906, 1907, 1909; Haughton 1924a, 1963, 1969; Kitching 1970, 1972, 1977, 1984; Keyser & Smith 1977-1978; Keyser 1979; Rubidge 1995; SACS 1980) (Figure 1). Different genera of the infra-order Dicynodontia are the most abundant fossil tetrapod taxa in the Beaufort Group and for this reason they are used as index fossils for five of the eight assemblage zones (Rubidge 1995). Although all of the eight biozones are based on therapsids, temnospondyl amphibians also form an important component of the tetrapod fauna of the Beaufort Group (Kitching 1978), and have recently been utilised in subdividing the upper Beaufort *Cynognathus* Assemblage Zone into three subzones (Hancox *et al.* 1995; Shishkin *et al.* 1995; Hancox & Rubidge 1995; Shishkin *et al.* 1996; Hancox 1998). Tetrapod fossils are relatively common in the "Stormberg Group" (Haughton 1924b) and have also been used for the biostratigraphic subdivision of the Elliot and Clarens Formations (Kitching & Raath 1984).

The biostratigraphic scheme erected for the Karoo Supergroup is used as the international standard for global correlation of Permian-Jurassic nonmarine deposits (Anderson 1973, 1977, 1980; Anderson & Anderson 1970, 1993 a,b; Anderson & Cruickshank 1978; Ochev *et al.* 1979; Ochev & Shishkin 1988; Battail 1993) and the world-wide distribution of Karoo fossils makes them ideal candidates for defining global biochrons (Cooper 1982; Lucas 1993; DeFauw 1993). In turn this allows for the relative ages of the biozones to be established, based on faunal contemporaneity with better dated European, Russian and South American sequences.

BIOSTRATIGRAPHY OF THE KAROO SUPERGROUP

Although the rocks of the Dwyka and Ecca Groups contain a variety of fossils, no formal biostratigraphic subdivision of these strata has yet been accepted. Informal biostratigraphies have, however, been proposed for the rocks of the Ecca Group, based on palynomorphs, invertebrates, fish and tetrapods.

The rocks of the Whitehill Formation (lower Ecca) are restricted to the southern Karoo Basin and contain fossils of *Mesosaurus*, the oldest tetrapod taxon known from the Karoo Supergroup. These strata also host a number of other fossils including palaeoniscid fish and the crustacean *Notocaris tapscotii* (Oelofsen 1981). Based on the presence of these forms, Oelofsen (1987) established an informal biostratigraphy for the Whitehill Formation, which he correlated with the Irati Shale Formation of Brazil. On the basis of their palynological signatures, the Whitehill Formation (southern Ecca Facies) has more recently also been correlated with the Vryheid Formation of the coal bearing northern Ecca Facies (Cairncross, 1989; Aitken & MacRae *pers. comm.*). MacRae (1988) proposed a biostratigraphic subdivision of the rocks of the Ecca Group in the Waterberg Basin based on the ranges of Permian palynomorphs and Aitken (1995) applied this scheme to the Vryheid Formation in Gauteng and Mpumalanga.

The vertebrate biostratigraphic subdivisions of the overlying Beaufort Group are better established and have become the global biostratigraphic standard for the nonmarine Permo-Triassic.The most widely followed early work was that of Broom (1906), which was accepted for some 60 years, until revised by Kitching (1970, 1972, 1977). Keyser & Smith (1977-78) proposed a new vertebrate biozonation for the Beaufort Group west of 26°E, and linked these zones to the lithostratigraphy. This work was revised by Keyser (1979) and accepted by S.A.C.S. (1980). Since this time the biostratigraphy has been further refined and expanded to include the new basal *Eodicynodon* Assemblage Zone (Rubidge 1990), in strata which were previously held to be of the Ecca Group (Barry 1970, 1974).

These new additions and revisions have culminated in the present eight-fold biostratigraphy of the Beaufort Group (Rubidge 1995) (Figure 1). At present no subdivisions of the various biozones are accepted, although recent research suggests that this may be possible for the *Tapinocephalus* Assemblage Zone (Boonstra 1969; Loock *et al.* 1995) and *Cynognathus* Assemblage Zone (Hancox *et al.* 1995).

Boonstra (1969) first suggested a threefold subdivision for the *Tapinocephalus* Assemblage Zone, based on the relative abundance of dinocephalians and dicynodonts. He proposed a lower subzone, in which dinocephalians were the most abundant form, a middle subzone in which dicynodonts were most abundant and dinocephalians were rare, and an upper subzone in which dinocephalians were absent. Boonstra's (1969) upper subzone may be equated to the *Pristerognathus* Assemblage Zone (Keyser & Smith 1978). Boonstra (1969) was, however, unable to tie the ranges and abundances to the lithostratigraphy. Loock *et al.* (1995), in a combined litho- and biostratigraphic project, were able to correlate the contact of the lower and middle subzones of Boonstra (1969) with the contact between the Wilgerbos and Koornplaats Members of the Abrahamskraal Formation. This finding has economic implications in that it allows for the stratigraphic delineation of the DR-3 Uranium anomaly near Laingsburg.

Although the *Cynognathus* Assemblage Zone is not presently biostratigraphically subdivided, previous workers (Watson 1942; Kitching 1977; Keyser & Smith 1977-78; Cooper 1982) have documented various biostratigraphic trends and Hancox *et al.* (1995) have proposed a threefold subdivision for the biozone. This subdivision is based primarily on the spatial (Figure 2) and temporal ranges (Figure 3) of three key temnospondyl amphibian genera, and their associated faunas. These workers proposed a lower subzone (A), based on the first appearance datum (FAD) of the amphibian *Kestrosaurus*, a middle subzone based on the FAD of *Parotosuchus africanus* and an upper subzone based on the FAD of new, large capitosauroid amphibians similar to *Parotosuchus megarhinus* from East Africa.

Further collecting and research has allowed for the refinement of this subdivision and of the biostratigraphic ranges of the component faunas. *Kestrosaurus*, the index genus for subzone A is restricted in its range to the subzone, and the subzone may be further delineated by: the presence of the trematosuchid amphibian *Trematosuchus* (Shishkin & Welman 1995); primitive brachyopid amphibians (Shishkin *pers. comm.*); primitive archosaurs, similar to the Russian genus *Gaijania* (Welman *pers. comm.*); and the cynodont *Trirachodon kannemeyeri* (Welman *pers. comm.*). To date no dicynodonts are known from subzone A. The base of the overlying subzone B is further characterised by: the FAD of the dicynodont *Kannemeyeria*; the presence of the brachyopid amphibian *Batrachosuchus*; the archosauriforms *Erythrosuchus* and *Euparkeria*; the rhynchosaurs *Howesia* and *Mesosuchus*; and the cynodont *Trirachodon berryi* (Welman *pers. comm.*). The uppermost subzone (C) is further defined by the presence of stahleckeriid and shansiodontid dicynodonts (Hancox & Rubidge 1994, 1996; Hancox 1998) (Figure 3).

The biostratigraphy of the overlying "Stormberg Group" is not as well constrained and although the Molteno Formation preserves one of the richest assemblages of Triassic megaplant and insect fossils, it is presently not biostratigraphically subdivided. Ellenberger (1970) proposed a biostratigraphic subdivision for the Molteno, Elliot and Clarens Formations based on vertebrate trackways. This division has however failed to find general scientific acceptance. Recent discoveries by Raath *et al.* (1990) of dinosaur trackways in the upper Molteno Formation may shed new light on the biostratigraphic potential of trackways in the upper part of the Molteno Formation. Anderson & Anderson (*pers. comm.*) propose a five-fold subdivision for the Molteno Formation based on the association of various plant and insect genera.

Kitching & Raath (1984) proposed a two-fold subdivision of the Elliot and Clarens Formations, based on the ranges of the prosauropod dinosaurs, *Euskelosaurus* and *Massospondylus*. Within the *Massospondylus* Assemblage Zone is

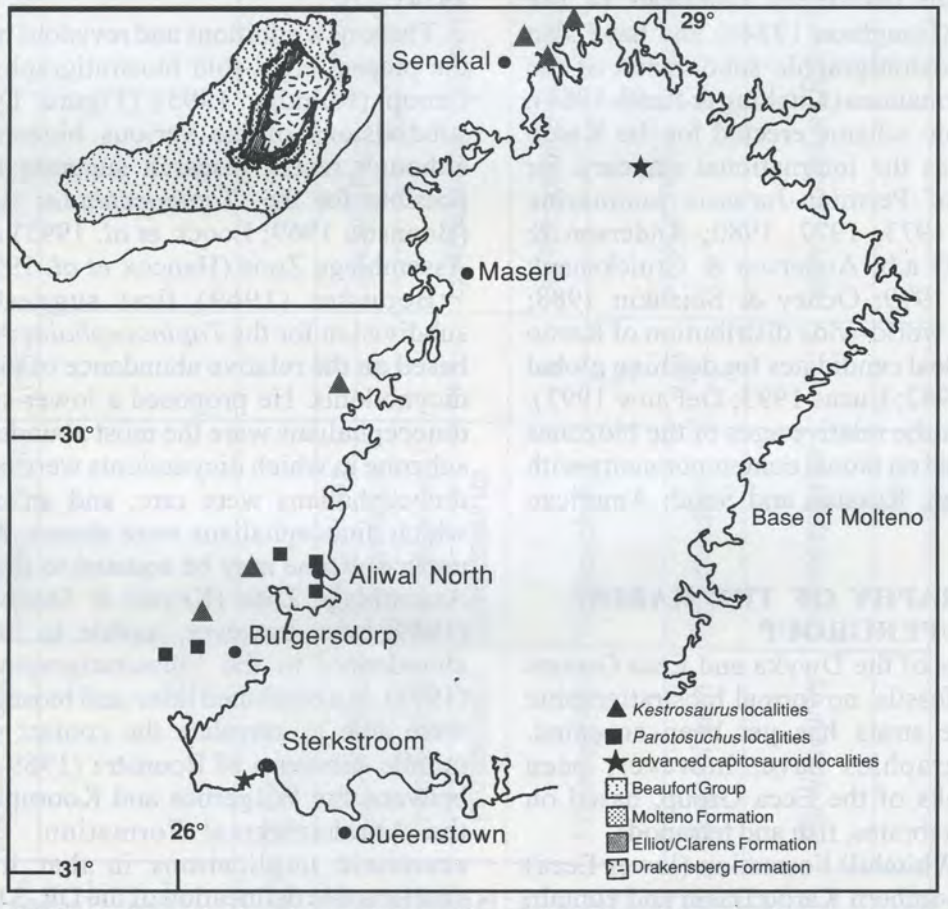

Figure 2 : Spatial distribution of the three key capitosauroid amphibian genera from the *Cynognathus* Assemblage Zone.

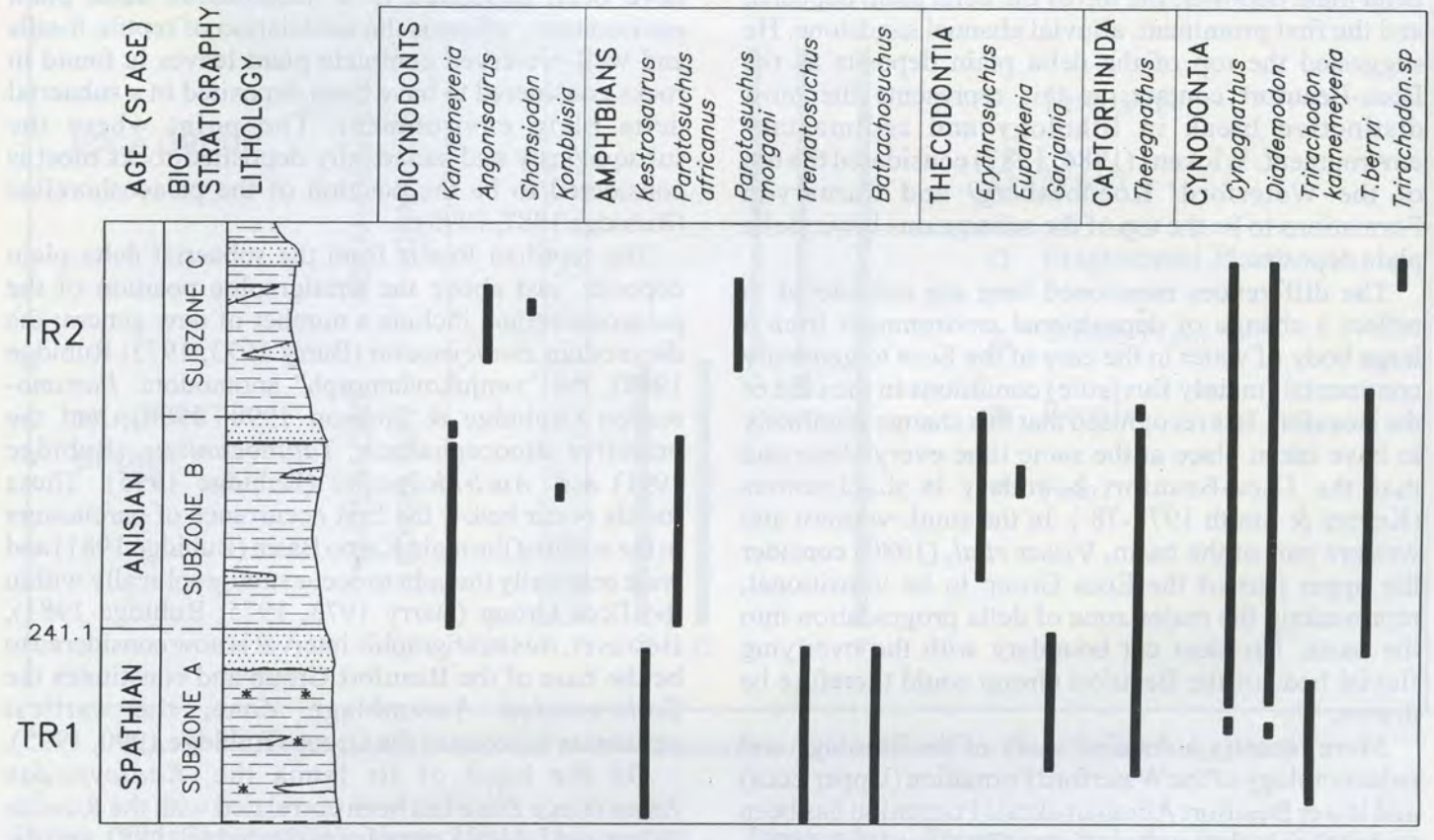

Figure 3: Temporal ranges of the key amphibian genera and associated tetrapod faunas of the *Cynognathus* Assemblage Zone (from Hancox, 1998).

a thin reworked palaeosol unit (Smith & Kitching, 1997), designated the *Tritylodon* Acme Zone based on the abundance of the cynodont *Tritylodon longaevus* (Kitching & Raath 1984).

THE USE OF FOSSILS IN AIDING IN THE DEFINITION OF FORMATIONAL CONTACTS.

Apart from their biological and biostratigraphic significance, fossils have also been utilised in defining formational contacts in the Karoo Supergroup (e.g. Rubidge 1987, 1988; Turner 1975; Christie 1981; Hancox 1998). The following section documents two case studies, the first for the basal Beaufort-Ecca Group contact, and the second for the upper Beaufort "Stormberg Group" contact.

The Ecca-Beaufort Contact

The exact stratigraphic position of the Ecca-Beaufort boundary in the southern Karoo Basin has long been a contentious issue and various parameters have in the past been used to define the boundary. This has resulted in confusion amongst workers, as the criteria previously used to define the boundary represent variations of lithostratigraphic, biostratigraphic, and palaeo-environmental characteristics.

Initially the boundary between the Ecca and Beaufort Groups was defined biostratigraphically as the FAD of pareiasaurian remains (Hatch & Corstophine 1909; Rogers 1905; Rogers & du Toit 1909; Schwarz 1912). Researchers later defined the contact lithologically, on the occurrence of the first purple mudstones (Haughton *et al.* 1953; Mountain 1946; Rossouw 1961; Rossouw & De Villiers 1952). This boundary is no longer regarded as satisfactory because the first appearance of purple mudstones varies stratigraphically on a regional scale (Johnson 1976, 1979). Chert beds have also been considered as a useful lithostratigraphic criterion in defining the boundary as lenses of cherty rock occur at various horizons in typically Beaufort beds, but are absent below the purple shale except for one well-defined chert horizon not far below the first purple shale (Haughton 1969; Haughton *et al.* 1953; Rossouw *et al.* 1964). Another lithostratigraphic character previously used is the base of the first massive sandstone above the argillaceous Fort Brown Formation (Venter 1969; Woodward 1964).

More recently a lithostratigraphic boundary based on the change in lithology from thick accumulations of dark fines, to interbedded lenticular sandstones and fines has been used. This contact is further thought to reflect a change from deposition in a deep-water marine and deltaic environment in the case of the Ecca, to continental fluviatile conditions in the Beaufort Group (Johnson 1976, 1979; Loock *et al.* 1979; S.A.C.S. 1980; Visser & Loock 1974). Jordaan (1981) identified four sedimentary associations in the Ecca-Beaufort transition in the Western Karoo which reflect deposition in the prodelta, delta front, delta plain, and flood plain environments. He considered four options for the Ecca-Beaufort contact in this area: the base of the Upper Ecca (Waterford Formation); the base of the

delta plain deposits; the top of the delta plain deposits; and the first prominent, alluvial channel sandstone. He suggested the top of the delta plain deposits as the Ecca-Beaufort contact, as this represents the most distinctive break in lithology and sedimentary environment. Wickens (1984, 1987) considered the top of the Waterford/ Koedoesberg/ and Carnarvon Formations to be the top of the subaqueous lower delta plain deposits.

The differences mentioned here are considered to reflect a change of depositional environment from a large body of water in the case of the Ecca to generally continental (mainly fluviatile) conditions in the case of the Beaufort. It is recognised that this change is unlikely to have taken place at the same time everywhere and that the Ecca-Beaufort boundary is diachronous (Keyser & Smith 1977-78). In the south-western and western part of the basin, Visser *et al.* (1980) consider the upper part of the Ecca Group to be transitional, representing the major zone of delta progradation into the basin. No clear cut boundary with the overlying fluvial beds of the Beaufort Group could therefore be drawn.

More recently a detailed study of the lithology and palaeontology of the Waterford Formation (Upper Ecca) and lower Beaufort Abrahamskraal Formation has been undertaken in the southern Karoo (Rubidge 1987, 1988). At all localities studied, therapsid fossils were found only in the upper part of the stratigraphic sequence, together with the remains of complete well-preserved leaves and stems of the plants *Glossopteris* and *Schizoneura*. Some of the latter were found in their position of growth (Rubidge 1987; 1988). Raindrop impressions, wrinkle marks, and rare sand-filled mudcracks have been found on the upper surface of mudrocks and suggest subaerial exposure. Furthermore, calcareous nodular horizons, of possible palaeosol origin (Smith 1990), are frequently present in the argillaceous sediments. The association of fossil reptiles and well-preserved fossil plants, some even in their growth position, in the upper part of the stratigraphic interval, supports the concept of a subaerial depositional environment for these rocks, which are considered to have been deposited in a subaerial delta plain environment (Loock *et al.* 1979; Stear 1980 a,b; Rubidge 1988).

The fossils that characterise the lower part of the stratigraphic interval are fragments of silicified wood and fossil tree stumps, as well as numerous small plant fragments similar to those often referred to as 'coffee grounds' in the Mississippi delta. The fragmentary nature of the plant material probably reflects the fact that they had been transported, and not preserved close to their growth positions. The wood probably drifted in (Visser & Loock 1978), became waterlogged and sank, and, as driftwood is hard and resistant, the fragments could have been transported a long way (Rubidge 1987). It is considered that the rocks of this interval were deposited in a subaqueous delta plain environment.

Two biological associations are thus evident (Figure 4): waterlogged wood and finely ground-up plant remains tend to be confined to the rocks considered to have been deposited in a subaqueous delta plain environment, whereas the association of reptile fossils and well-preserved complete plant leaves is found in rocks considered to have been deposited in a subaerial delta plain environment. The point where the subaqueously and subaerially deposited rocks meet is considered to be the position of the palaeoshoreline (Rubidge 1987, 1995).

The reptilian fossils from the subaerial delta plain deposits, just above the stratigraphic position of the palaeoshoreline, include a number of new genera; the dicynodont *Eodicynodon* (Barry 1973, 1975; Rubidge 1988), the "venjukoviamorph" anomodont *Patranomodon* (Rubidge & Hopson 1990, 1996), and the primitive dinocephalians *Tapinocaninus* (Rubidge 1991) and *Australosyodon* (Rubidge 1995). These fossils occur below the first occurrence of pareiasaurs in the south of the main Karoo Basin (Rubidge 1981) and were originally thought to occur stratigraphically within the Ecca Group (Barry 1973, 1975; Rubidge 1981). However, this stratigraphic interval is now considered to be the base of the Beaufort Group and constitutes the *Eodicynodon* Assemblage Zone, the earliest vertebrate biozone of the Group (Rubidge 1990, 1995).

On the basis of its fauna the *Eodicynodon* Assemblage Zone has been correlated with the Russian Ocher and Isheevo complexes (Rubidge 1995), and the Xidagou Formation at Yumen in the Gansu Province of China (Li & Cheng 1995; Li *et al.* 1996). Correlation of the primitive anomodont and dinocephalian fauna of this zone with a similar fauna from the Russian complexes suggests a Kazanian age (Rubidge 1987, 1995).

The recognition of a new fauna at the base of the Beaufort has important implications for the placement of the Ecca-Beaufort contact on the palaeoshoreline and the recognition of the palaeoenvironment of the Upper Ecca and Lower Beaufort (Figure 5). Lowering the stratigraphic position of the Ecca-Beaufort contact has increased the thickness of the Lower Beaufort by some 300-650m, dependant on the locality (Rubidge 1990) and has given new insight for interpretation on the basinal development of the earliest terrestrial deposits of the Karoo. Because the oldest biozone of the Beaufort is found only in the southwestern part of the basin, it is evident that the oldest terrestrial deposits of the Karoo are limited to that part of the basin. This feature has important implications for defining the diachronous nature of the Ecca-Beaufort contact, as progressively younger fossils are found along this contact farther north in the Karoo Basin (Ryan & Whitfield 1979). Because reptilian fossils have now been found immediately above the stratigraphic position of the palaeoshoreline, it is unlikely that remains of older terrestrial reptiles will be found in the Karoo Supergroup of South Africa, unless their remains were washed into the Ecca "sea" (Rubidge 1995a).

The Beaufort-Molteno Contact

The nature and stratigraphic position of the contact between the Beaufort and "Stormberg" Groups has also been the subject of much debate (e.g. Du Toit 1954;

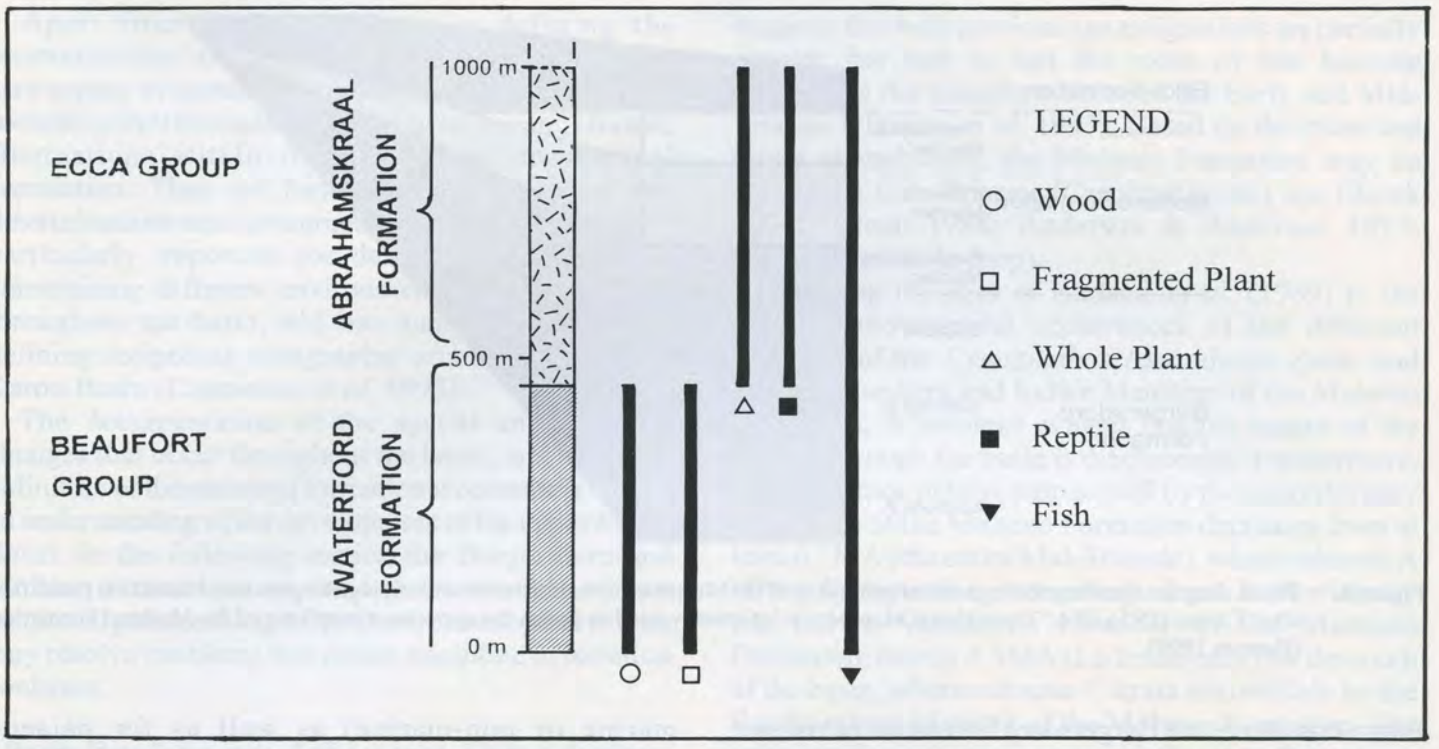

Figure 4 : Biostratigraphy of the rocks of the Ecca-Beaufort transition in the southern Karoo (From Rubidge, 1988).

Turner 1975; Christie 1981; Visser 1991). This contact has in the past been defined as the base of the first coarse glittering sandstone of the Molteno Formation (Du Toit 1954); on the change in the predominant type and colour of the strata (Rust 1959, 1962; Kitching 1977); by the occurrence of well rounded pebbles in the sandstones (Kitching 1977); by its dominantly arenaceous nature (Turner 1975; Christie 1981); by the presence of coal (Du Toit 1954); and as a ± 100m thick, conformable transitional zone (Johnson & Hiller 1990). Presently the lower contact of the Molteno Formation in the south of the basin is placed at the boundary between the Burgersdorp Formation and the Bamboesberg Member of the Molteno Formation, whereas in the northern part of the basin the boundary is between the Burgersdorp Formation and the Indwe Sandstone Member of the Molteno Formation (Figure 6).

The lower boundary of the Molteno Formation has therefore been the subject of several attempts at definition, with much debate centred around the definition and placement of the basal contact. Most of the criteria previously used are untenable and of the previous lithological criteria, only the inclusion of quartz pebbles and the presence of coal are valid at present (Hancox 1998).

Rust (1959, 1962) proposed that a better contact might be established palaeontologically and Turner (1975) noted that the lower boundary of the Molteno Formation recorded an important palaeontological break, in that the vertebrate fossils so prolific in the Elliot

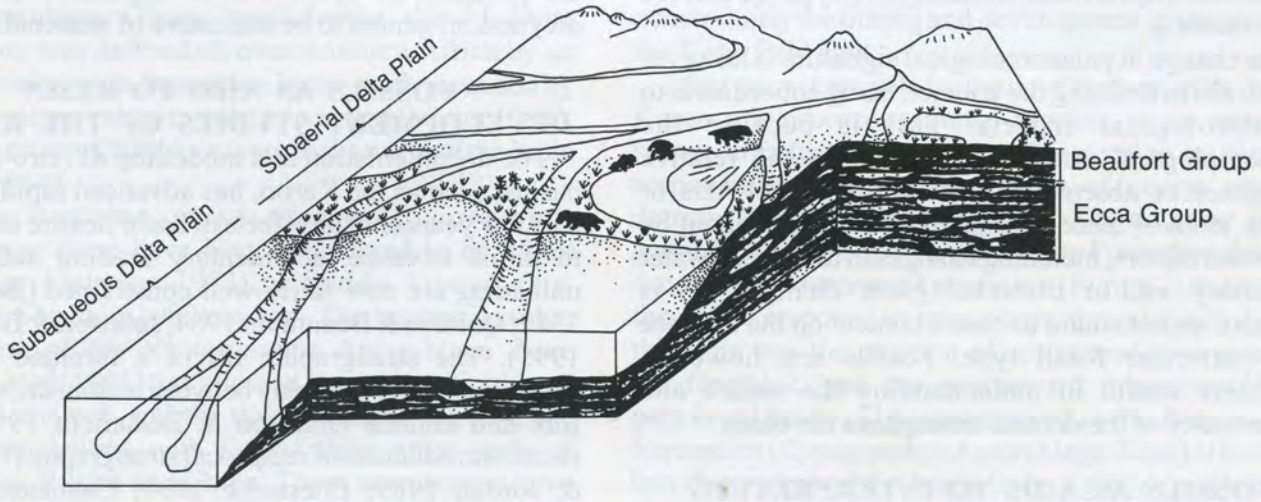

Figure 5: Palaeoenvironmental interpretation of the rocks of the Ecca-Beaufort contact in the southern Karoo. Note the relationship between the palaeoenvironment and the lithofacies associations (from Rubidge 1988, 1995).

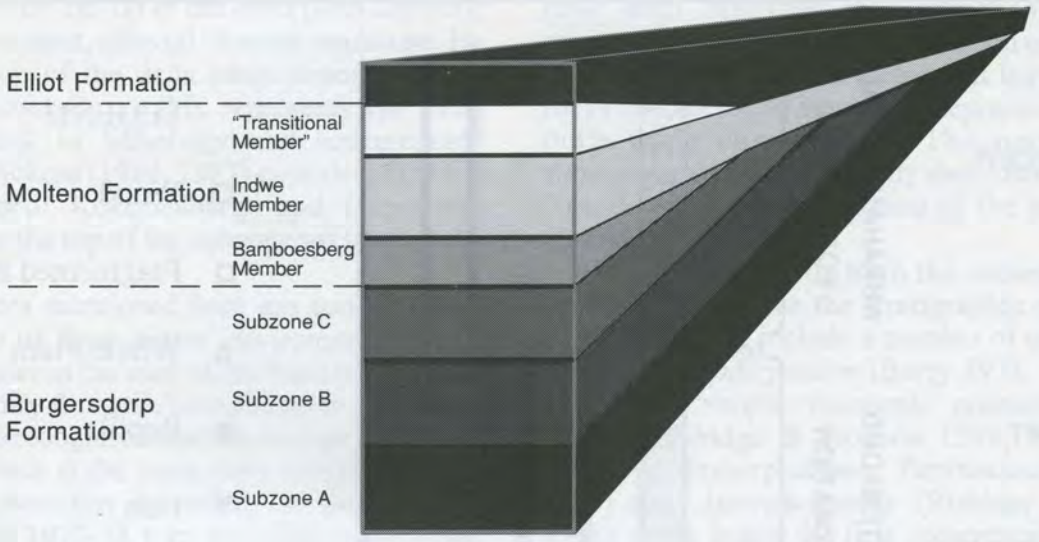

Figure 6: Block diagram showing the regional relationship of the Molteno Formation to the underlying Burgersdorp Formation (modified after Turner 1975). The 'Transitional Member' is informally used to group the uppermost members of the Molteno Formation (Hancox 1998).

Formation above and Burgersdorp Formation below, are absent in the Molteno Formation (Turner, 1972). The abrupt palaeontological break as noted by Turner (1975) has been verified by numerous authors including Anderson & Anderson (1993), Cairncross *et al.* (1995) and Hancox (1998).

Recent application of integrated stratigraphic, sedimentological and palaeontological studies has allowed for a more detailed description of the nature of this contact and the contact has now been defined sedimentologically (Hancox 1998) in terms of the differences in the gross sandstone geometries, architectural elements and facies associations between the Burgersdorp and Molteno Formations. These changes occur concomitantly with a sharp palaeontological break as documented by Turner (1975). Palaeontological criteria used to aid in defining the contact are: that tetrapod fossils are absent in the Molteno Formation; the presence of an abundant flora and insect fauna (Cairncross *et al.* 1995); and the change in wood from podocarp type to *Auricarioxylon* and *Rhexoxylon* type (Bamford *pers. comm.*).

The change in palaeontological signature is however used to aid in defining the contact, being subordinate to the lithological criteria. This is because the palaeontological criteria are based on the relative abundance or absence of taxa and not on FADs or ranges. Both of these criteria may be brought about by numerous factors, including changes in the groundwater chemistry and/or climatological changes. It is furthermore not sound to base a contact on the absence of a particular fossil type. Fossils are, however, extremely useful in understanding the nature and diachroneity of the contact throughout the basin.

FOSSILS AS AIDS TO INTERPRETING PALAEOENVIRONMENTS OF THE KAROO

Fossils have been used in interpreting the broad-scale palaeoenvironmental setting of depositional facies (i.e. marine or non-marine) as well as for palaeoenvironmental reconstructions within the Karoo Supergroup (e.g. Hotton 1967; Boonstra 1969), including palaeoclimatic models (Visser 1991; Rayner 1995). More recently, detailed studies of the fossil assemblages have been employed to enhance earlier palaeoenvironmental interpretations (Kitching 1977; Kitching & Raath 1984) and high resolution taphonomic studies of vertebrate fossil assemblages have played an important role in recognising and delineating the spatial aspects of floodplain sub-environments within the Lower Beaufort (Smith 1978, 1980, 1981, 1989), and regional base level changes in the Elliot Formation (Smith & Kitching 1997). Rubidge (1988) used palaeontological criteria for documenting terrestrial versus subaqueous facies, as well as for delineating the palaeoshoreline of the Beaufort Group.

The presence of growth rings in fossil wood has been used to infer seasonality (Anderson 1976) and more recently Chinsamy & Rubidge (1993) have suggested the presence of cyclical bone deposition in certain dicynodont genera to be indicative of seasonality.

FOSSILS AS AIDS TO BASIN DEVELOPMENT STUDIES OF THE KAROO

The documentation and modelling of retro-foreland basins, such as the Karoo, has advanced rapidly in the past few years and the effects of basin flexure in relation to thrust advance, sedimentary loading and source unloading are now fairly well constrained (Beaumont 1981; Quinlan & Beaumont 1984; Johnson & Beaumont 1995). The stratigraphic fill of a foreland basin is controlled by the interplay between tectonism, sediment flux and climate (Johnson & Beaumont 1995). The recent introduction of reciprocal stratigraphy (Flemings & Jordan 1989; Ettensohn 1994; Cataneanu 1997; Cataneanu *et al.* 1998) has meant that there is a strong need to recognise synchronous shallow and deep water settings.

Apart from their usefulness in defining the biostratigraphy and formational contacts, fossils may also supply evidence for a number of these parameters including: the timing and duration of tectonism; climatic fluctuations within the basin; and intrabasinal correlation. They are further of use in relative age determinations and for intrabasinal correlation. This is particularly important for defining time lines and constraining different environments of the same age throughout the basin, and has major applications in defining reciprocal stratigraphic architectures for the Karoo Basin (Cataneanu *et al.* 1998).

The documentation of the spatial and temporal changes that occur throughout the basin, and a concise definition of the nature of formational contacts is vital to an understanding of the development of the upper Karoo Basin. In the following section the Burgersdorp and Molteno Formations are used as an example of how combined palaeontological and sedimentological studies may resolve problems that either discipline in isolation could not.

Basin development of the upper Karoo during the Triassic

Prior to the combined use of palaeontological and sedimentological data, the controls on facies genesis for the Burgersdorp and Molteno Formations were not well understood. The proposed palaeoclimate for the Molteno Formation deviated dramatically from the global standard (Frakes 1979) and the ages of the two formations were poorly interpreted. This meant that the time represented by the contact between the Beaufort and "Stormberg" groups was not constrained and the timing of events that controlled their sedimentary fill was not well understood.

Because of the lack of direct palaeontological correlatives between the Burgersdorp and Molteno Formations, Turner (1975) found the time represented by the unconformity at the base of the Formation difficult to evaluate, but thought that the disconformity suggested a considerably greater timespan than the physical evidence indicated. Visser (1984) felt that the base of the "Stormberg Group" and hence the Molteno Formation, was defined all over southern Africa by an unconformity, with deposition in the south preceded by an erosional period up to 10MA in extent (Visser 1991), but in the order of 50MA or more in the north of the basin (Visser 1984).

In the past the rocks of the *Cynognathus* Assemblage Zone have been considered to be either Early (e.g. Anderson 1973) or Middle Triassic (e.g. Ochev & Shishkin 1989) in age. The biostratigraphic subdivision of the *Cynognathus* Assemblage Zone (Hancox *et al.* 1995) has allowed for the partitioning of its faunal content, and the direct comparison of these faunal associations with faunas from other parts of Gondwana, Russia and China. These correlations have shown that subzone A is late Early Triassic (Scythian) in age, whereas subzones B and C encompass most of the early Middle Triassic (Anisian). This partitioning suggests that both previous age assignations are partially correct, but that in fact the rocks of this biozone encompass the boundary between the Early and Mid-Triassic (Hancox *et al.* 1995). Based on the plant and insect assemblages, the Molteno Formation may be assigned a Late Triassic (Carnian/Norian) age (Rieck 1974; Falcon 1986; Anderson & Anderson 1993; Anderson *et al.* in prep).

Applying the ages of Harland *et al.* (1989) to the spatial and temporal occurrences of the different subzones of the *Cynognathus* Assemblage Zone, and the Bamboesberg and Indwe Members of the Molteno Formation, it becomes evident that the nature of the contact through the basin is diachronous. Furthermore, the magnitude of time represented by the unconformity at the base of the Molteno Formation decreases from at least 6.1MA (the entire Mid-Triassic), where subzone A of the *Cynognathus* Assemblage Zone is overlain by the Indwe Sandstone Member of the Molteno Formation, to only 4.5MA (Ladinian only) for the south of the basin, where subzone C strata are overlain by the Bamboesberg Member of the Molteno Formation. The palaeontological signatures of the two formations therefore show that the time break between the two is of far less magnitude than suggested by previous authors (e.g. Visser 1991) and that the Mid-Triassic Lacuna proposed by Cole (1992) probably only spans the upper Anisian and parts of the Ladinian in the south of the basin.

The spatial and temporal distribution of the *Cynognathus* Assemblage Zone faunas also shows that the aerial extent of the Burgersdorp Formation decreased and shifted sourceward through time (Hancox 1998) (Figure 7). In foreland basins, such sourceward facies migrations are controlled by the flexural response to source area loading. Tectonism in the thrust belt brings about downward flexure of the lithospheric plate and the creation of accommodation space proximal to the thrust belt (Beaumont 1981; Quinlan & Beaumont 1984). This flexure also brings about the sourceward migration of the peripheral bulge and its uplift. This has important implications for constraining the timing and development of thrusting in the Cape Fold Belt.

Most current models for the development of the upper Karoo are process-response models, in as much as source area tectonism (process) is seen to be directly responsible for the progradation of coarse grained detritus into the basin (response). The decrease in the aerial distribution of the Burgersdorp Formation through time and its sourceward migration (Figure 7) shows that the actual response to source area thrusting (P) during this time was the creation of accommodation space in the forethick, and the sourceward migration of the peripheral bulge. The ages applied to the Burgersdorp Formation (*Cynognathus* Assemblage Zone) allows for this deepening of the basin to be tightly correlated to source area activity at ±239 Ma (Gresse *et al.* 1992).

These findings, especially the timing of events based on biostratigraphic data, have allowed for previous

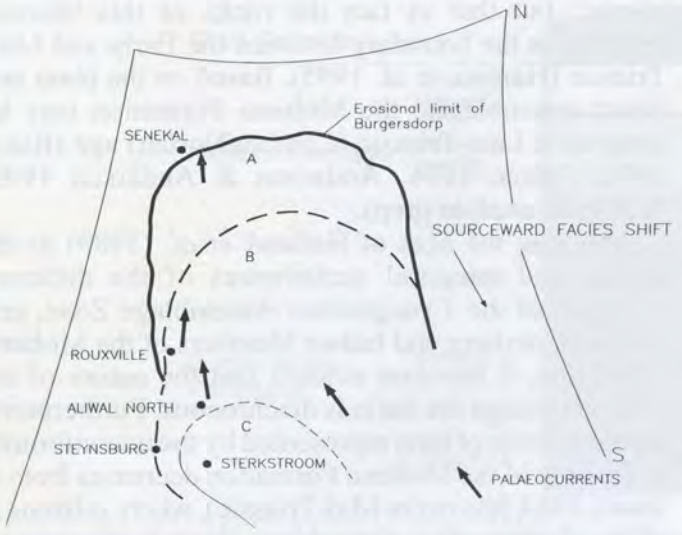

Figure 7: Spatial distribution of the Burgersdorp Formation through time, showing a retrogradational sourceward facies shift.

models for the development of the fill of the upper Karoo (Rust 1959, 1962; Cole 1991; Smith *et al.* 1993; Hancox & Rubidge 1995; Groenewald 1996) to be revised. Based on these ideas, the progradation of coarse grained detritus into the basin (such as the basal part of the Molteno Formation) represent a period of quiescence (Q) following source area thrusting, where sediment supply exceeds thrust induced subsidence. Such pulse-quiescence cycles may be more accurately modelled using the current literature on foreland basin development (Beaumont 1981; Quinlan & Beaumont 1984; Flemings & Jordan 1989; Beaumont *et al*, 1993; Ettensohn 1994; Cataneanu 1997).

In the upper Karoo Supergroup, fossils have therefore played an important role in re-evaluating the fill of the basin (Hancox *et al.* 1995; Hancox 1998; Cataneanu *et al.* 1998) by allowing for the recognition of synchronous, spatially separate depositional settings and by the delineation of chronostratigraphically significant surfaces.

DISCUSSION AND CONCLUSIONS

Fossils from the Karoo Supergroup have provided not only important data about the evolutionary history of life through the Permo-Triassic and early Jurassic, but also provide the basis for the biostratigraphic subdivision of the sequence, aid in defining formational contacts and considerably enhance palaeoenvironmental reconstructions. New finds over the past two decades have allowed for the refinement of the biostratigraphy of the Karoo Supergroup and improved correlation with faunas from other parts of southern Gondwana, Russia and China. This in turn has allowed for the refinement of the relative ages of various parts of the Karoo. The application of these relative ages to the stratigraphy has allowed for the definition of diachronous contacts within the basin (Rubidge 1988; Hancox *et al.* 1995) and the generation of chronostratigraphically significant timelines. This represents a significant step forward in the definition of sequence based stratigraphy. Relative dating based on faunal contemporaneity is also critical for the information it supplies regarding the timing of events within the basin, and the correlation of these events to dated periods of tectonic activity in the source area (Hälbich 1983, 1992; Gresse *et al.* 1992).

It is becoming clear that biostratigraphy and lithostratigraphy have a complex inter-relationship in the Karoo Basin and although biostratigraphic subdivisions may cross lithological contacts, they are often fairly similarly constrained (Keyser & Smith 1977-8; Groenewald 1990; Loock *et al.* 1995). The combined use of biostratigraphy and lithostratigraphy has allowed for the delineation of economically important ore bodies, including the DR3 Uranium anomaly (Loock *et al.* 1995) and palaeontological parameters are also useful in defining the spatial aspects of coal deposits (Stanistreet *et al.* 1980).

Fossils have recently proved useful in the development and refinement of basin models for the deposition of the rocks of the Karoo Supergroup Group (Rubidge 1988; Hancox *et al.* 1995; Cataneanu *et al.* 1998) and have solved problems that lithological studies alone could not.

Fossil data, including vertebrate and invertebrate body fossils, micro and macrofloral remains, palaeosols and traces have helped to define the stratigraphy, facies genesis and palaeoclimate prevailing during the deposition of the Burgersdorp and Molteno Formations. Fossils have also played a pivotal role in defining the timespan represented by the hiatal surface between the Burgersdorp and Molteno Formations. Megafloral remains, in particular silicified wood, have also been useful in dispelling the myth of the anomalous cold, wet Molteno.

Numerous authors have previously correlated tectonic events in the Cape Fold Belt (Hälbich *et al.* 1983) with their sedimentary responses. Recent holistic studies based on combined sedimentological and palaeontological evidence have, however, added more refined time constraints to the sedimentary responses.

Combined sedimentological, stratigraphic and palaeontological studies have therefore allowed for greater stratigraphic resolution than could isolated studies on their own. Such holistic studies have allowed for the Karoo basin's long and complex developmental history to be better understood and constrained, largely due to the wealth of information provided by the fossil record.

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This review paper is based on the work of numerous earth scientists whose work during the past century and a half has brought our knowledge of the Karoo Basin to its present level. The few highlighted workers are but a small number of the many upon whose work the current state of knowledge was dependant, the authors' own contributions being but a very small part of the accumulated knowledge.

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