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The Karoo basins of south-central Africa

O. Catuneanu [a,*], H. Wopfner [b], P.G. Eriksson [c], B. Cairncross [d], B.S. Rubidge [e], R.M.H. Smith [f], P.J. Hancox [e]

[a] *Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences Building, Edmonton, Alta., Canada T6G 2E3*
[b] *Geologisches Institut, Universitat zu Koln, Zulpicher Str. 49, 50674 Koln, Germany*
[c] *Department of Geology, University of Pretoria, Pretoria 0002, South Africa*
[d] *Department of Geology, University of Johannesburg, P.O. Box 524, Auckland Park, Johannesburg 2006, South Africa*
[e] *Bernard Price Institute for Palaeontological Research, University of Witwatersrand, PO Wits, Johannesburg 2050, South Africa*
[f] *Department of Karoo Palaeontology, Iziko: South African Museum, Cape Town, South Africa*

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Abstract

The Karoo basins of south-central Africa evolved during the first-order cycle of supercontinent assembly and breakup of Pangea, under the influence of two distinct tectonic regimes sourced from the southern and northern margins of Gondwana. The southern tectonic regime was related to processes of subduction and orogenesis along the Panthalassan (palaeo-Pacific) margin of Gondwana, which resulted in the formation of a retroarc foreland system known as the "main Karoo" Basin, with the primary subsidence mechanisms represented by flexural and dynamic loading. This basin preserves the reference stratigraphy of the Late Carboniferous–Middle Jurassic Karoo time, which includes the Dwyka, Ecca, Beaufort and Stormberg lithostratigraphic units. North of the main Karoo Basin, the tectonic regimes were dominated by extensional or transtensional stresses that propagated southwards into the supercontinent from the divergent Tethyan margin of Gondwana. Superimposed on the tectonic control on basin development, climatic fluctuations also left a mark on the stratigraphic record, providing a common thread that links the sedimentary fill of the Karoo basins formed under different tectonic regimes. As a general trend, the climate changed from cold and semi-arid during the Late Carboniferous–earliest Permian interval, to warmer and eventually hot with fluctuating precipitation during the rest of Karoo time.

Due to the shifts in tectonic and climatic conditions from the southern to the northern margins of Africa during the Karoo interval, the lithostratigraphic character of the Karoo Supergroup also changes significantly across the African continent. For this reason, the Karoo basins *sensu stricto*, which show clear similarities with the main Karoo Basin of South Africa, are generally restricted to south-central Africa, whereas the Karoo-age successions preserved to the north of the equator are distinctly different. This paper focuses on the Karoo basins *sensu stricto* of south-central Africa, synthesizing their sedimentological and stratigraphic features in relation to the tectonic and climatic controls on accommodation and sedimentation.

Keywords: Karoo basins; Gondwana; Flexural tectonics; Extensional tectonics; Africa

1. Introduction

The Karoo basins of south-central Africa (Fig. 1) preserve a record of a special time in Earth's history, when the Pangea supercontinent reached its maximum extent during the Late Paleozoic–Early Mesozoic interval. The term "Karoo" was extrapolated from the main Karoo Basin of South Africa, to describe the sedimentary fill of all other basins of similar age across Gondwana. The onset of sedimentation of this Karoo first-order depositional sequence is generally placed in the Late Carboniferous, around 300 Ma, following a major inversion tectonics event along the southern margin of the supercontinent that led to the assembly of Pangea. Karoo sedimentation across Gondwana continued until the breakup of the

* Corresponding author. Tel.: +1 780 492 6569; fax: +1 780 492 7598.
E-mail address: octavian@ualberta.ca (O. Catuneanu).

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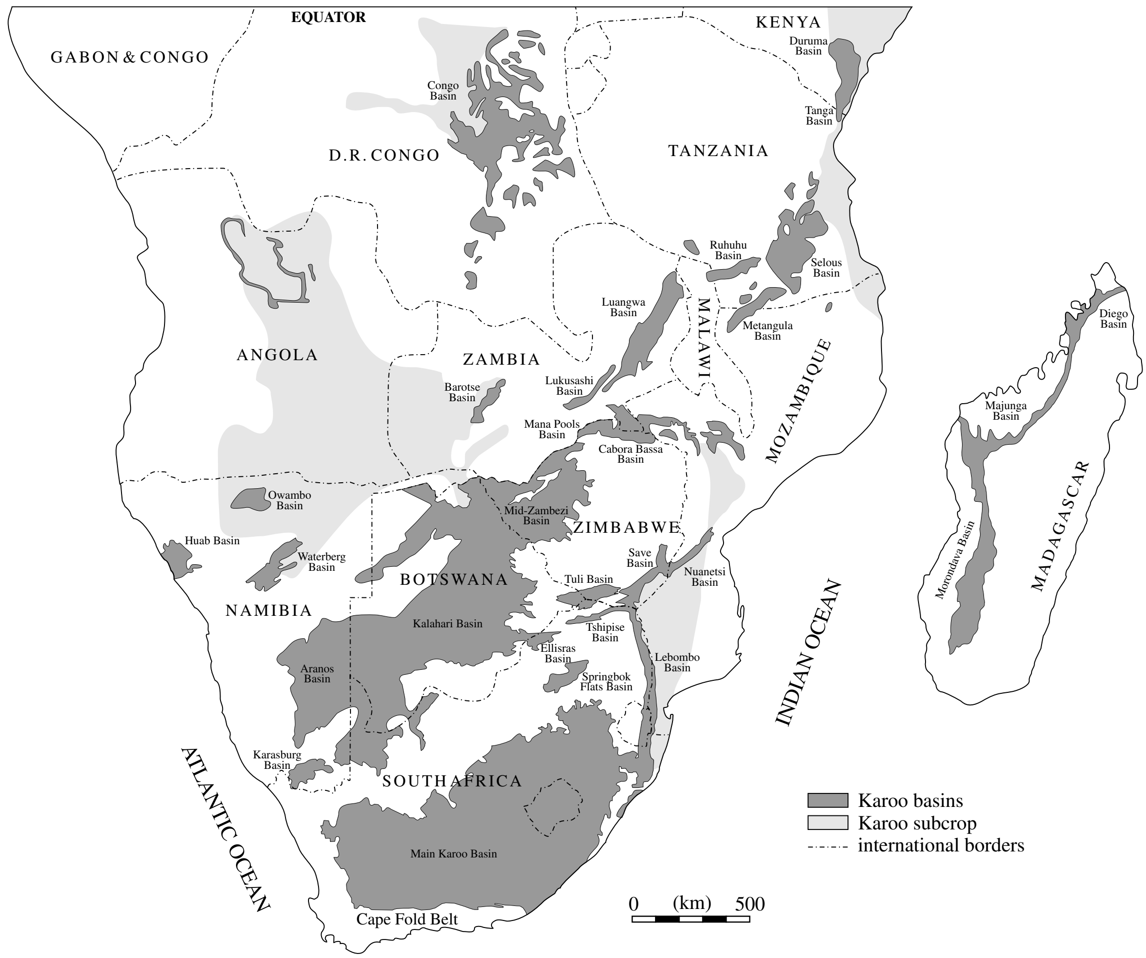

Fig. 1. The distribution of Karoo basins in south-central Africa (modified from Johnson et al., 1996; Wescott and Diggens, 1998; Nyambe, 1999; Wopfner, 2002).

supercontinent in the Middle Jurassic (c. 183 Ma; Duncan et al., 1997), when sediment accumulation was replaced by the emplacement of a large igneous province. The upper part of the Karoo sequence was subject to erosion during post-Gondwana time, and hence the age of the youngest preserved Karoo deposits varies generally from Triassic to Middle Jurassic.

The sedimentary fill of the Karoo basins accumulated under the influence of two main allogenic controls, namely tectonism and climate. Tectonic regimes during the Karoo time varied from dominantly flexural in the south, in relation to processes of subduction, accretion and mountain building along the Panthalassan (palaeo-Pacific) margin of Gondwana, to extensional to the north, in relation to spreading processes along the Tethyan margin of Gondwana. The relative importance of these tectonic regimes across the African continent is discussed in the following section of the paper. The importance of the tectonic control on Karoo basin development and sedimentation in southern Africa was first proposed by Rust (1975), and subsequently refined in a series of syntheses and research papers including Tankard et al. (1982), Turner (1986), Smith et al. (1993), Veevers et al. (1994a,b,c), Johnson et al. (1996), Visser and Praekelt (1996), Selley (1997), Catuneanu et al. (1998) and Pysklywec and Mitrovica (1999). Superimposed on the tectonic control on basin development, climatic fluctuations also left a mark on the stratigraphic record, which shows evidence of a general shift from cold and semi-arid conditions during the Late Carboniferous–earliest Permian interval, to warmer and eventually hot climates with fluctuating precipitation during the rest of Karoo time (Keyser, 1966; Johnson, 1976; Visser and Dukas, 1979; Stavrakis, 1980; Tankard et al., 1982; Visser, 1991a,b).

Within this setting, the first-order Karoo depositional sequence has the lithostratigraphic rank of Supergroup, and includes several groups defined on the basis of overall sedimentological characteristics. As established in the main Karoo Basin of South Africa, these groups are named, in stratigraphic succession, the Dwyka, Ecca, Beaufort, Stormberg and Drakensberg (Fig. 2). These groups, and their correlatives to the north of the main Karoo Basin, are described in subsequent sections of the paper. The generalized vertical profiles that define the sedimentary fill of the Karoo basins in south-central Africa, as well as the lithostratigraphic subdivisions of the Karoo Supergroup and their large-scale correlation, are illustrated in Figs. 3–6.

Due to the shifts in tectonic and climatic conditions from the southern to the northern margins of Africa during Karoo time, the lithostratigraphic character of the "Karoo sequence" also changes significantly across the African continent. For this reason, the Karoo basins *sensu stricto*, which show clear similarities with the main Karoo Basin of South Africa, are generally restricted to south-central Africa (Fig. 1). To the north of the equator, the

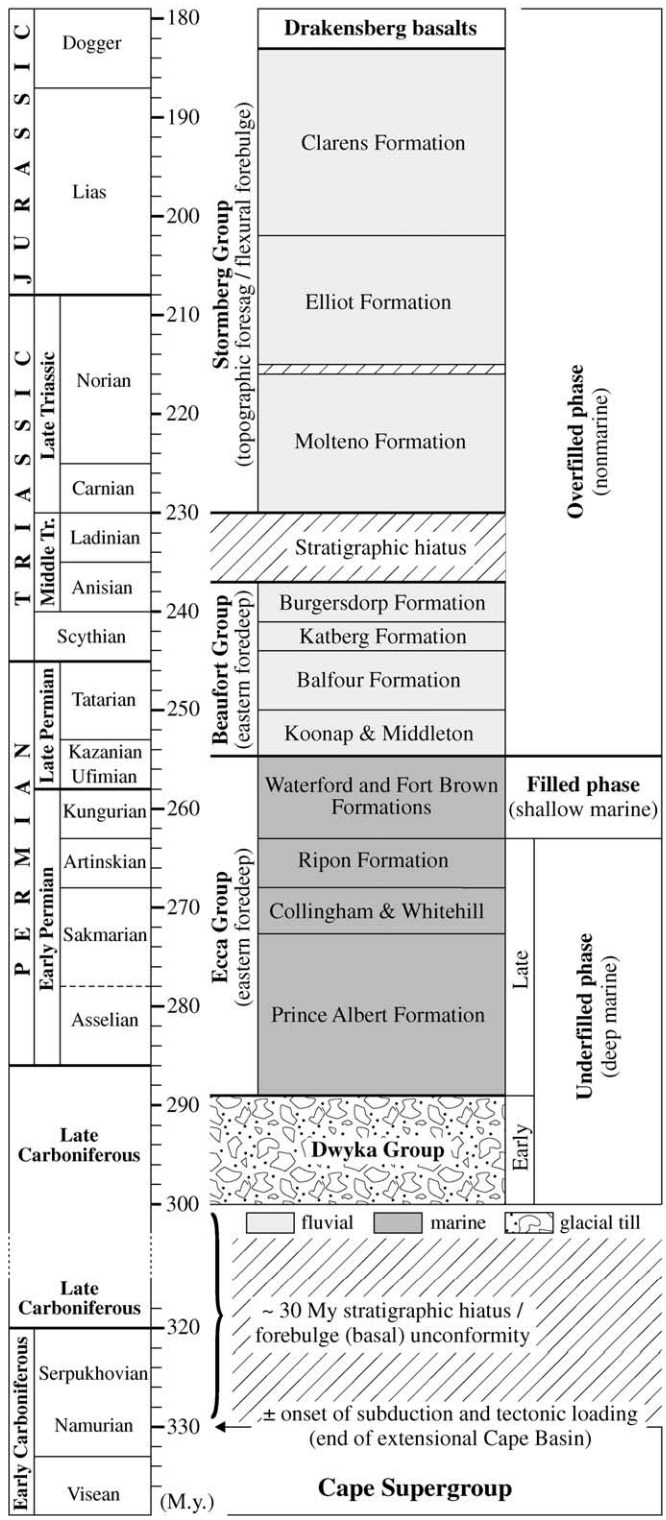

Fig. 2. Stratigraphic chart with the major lithostratigraphic subdivisions of the Karoo Supergroup in the main Karoo Basin of South Africa (based on the time scale of Palmer, 1983, and compiling information from Rubidge, 2005 and Catuneanu, 2004a).

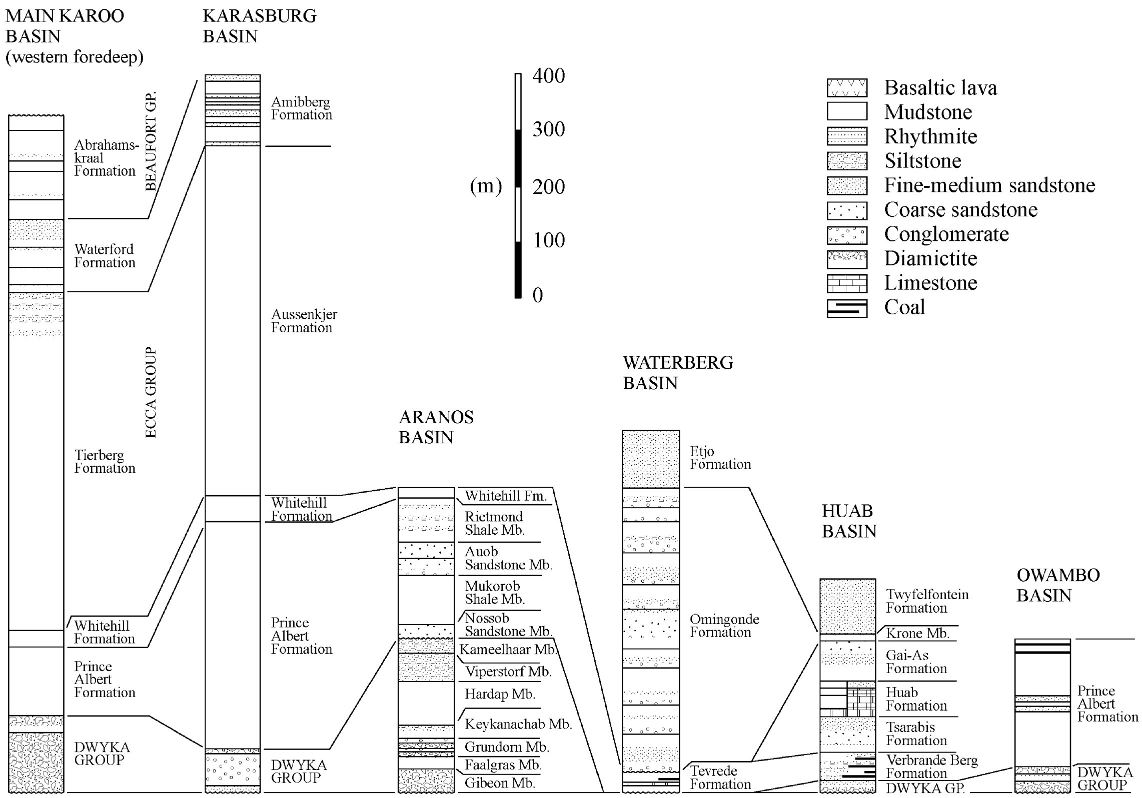

Fig. 3. South–north trending cross-section of correlation of the Karoo lithostratigraphic units along the western edge of the Karoo Supergroup outcrop area (modified from Johnson et al., 1996). See Fig. 1 for the location of the Karoo basins.

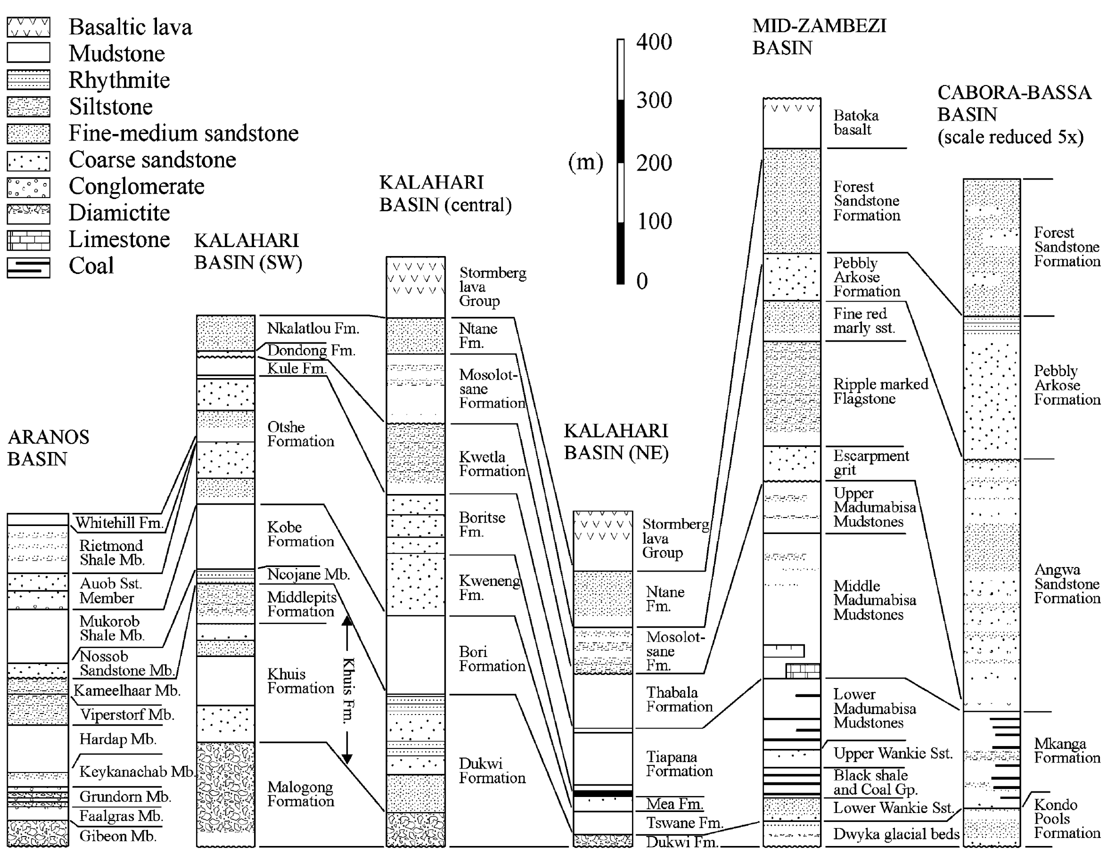

Fig. 4. Southwest–northeast trending cross-section of correlation of the Karoo lithostratigraphic units through the Aranos, Kalahari, Mid-Zambesi and Cabora Bassa basins (modified from Johnson et al., 1996). See Fig. 1 for the location of the Karoo basins.

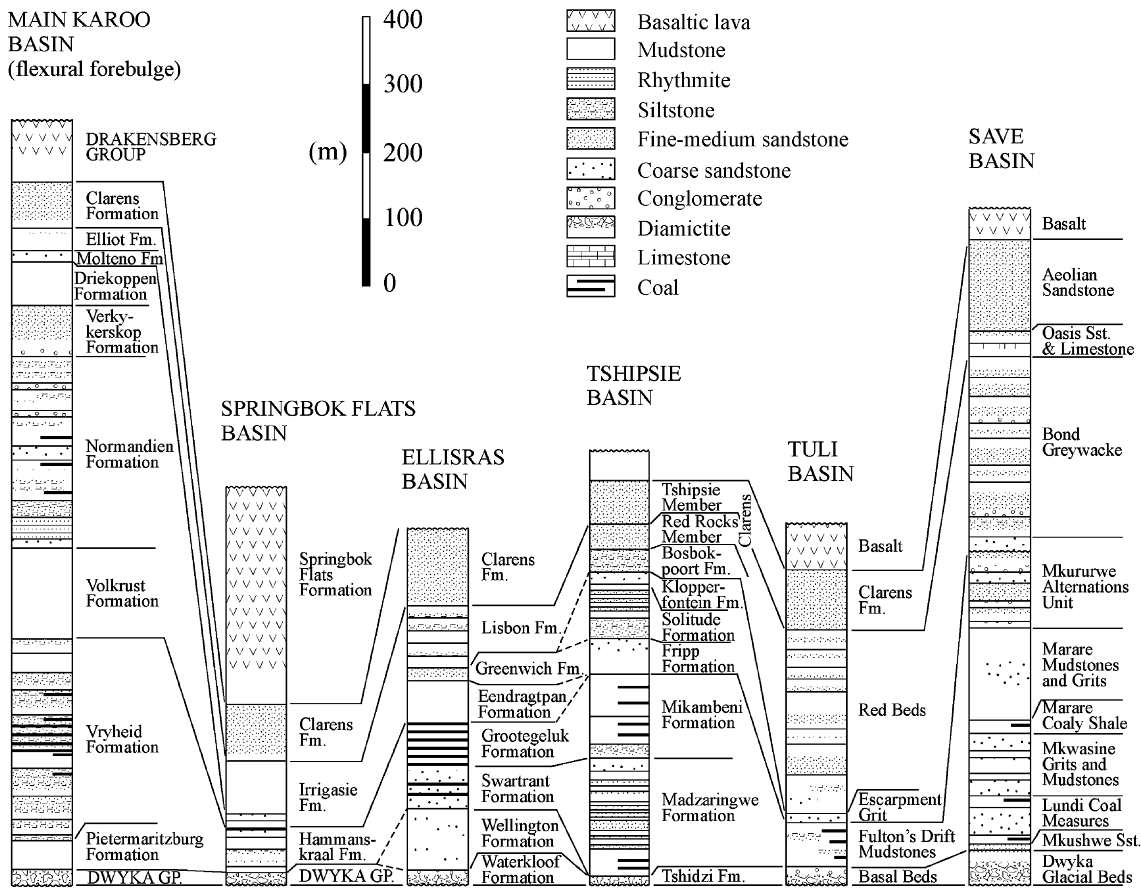

Fig. 5. South–north trending cross-section of correlation of the Karoo lithostratigraphic units along the eastern edge of the Karoo Supergroup outcrop area (modified from Johnson et al., 1996). See Fig. 1 for the location of the Karoo basins.

Karoo-age successions are distinctly different, and are dealt with in a number of other papers in this volume. The change from the Karoo-type lithofacies to their time equivalent depositional sequences in northern Africa was gradational. The northern-most traces of the Karoo Supergroup are deposits related to Dwyka-time glaciers in the coastal basin of Gabon (Jardiné, 1974) and at Wadi el Malik in Sudan (Klitzsch and Wyciks, 1987). Permo-Carboniferous glacial deposits are also well documented in Yemen (Kruck and Thiele, 1983) and southern Oman. Wopfner (1991, 1999) suggested that the northern limit of glaciation extended in a slightly north convex arch from the Gulf of Guinea to about Qatar on the eastern shore of the Arabian Peninsula (Fig. 7). The formation of Karoo coal-bearing successions, well represented in the post-Dwyka deposits, apparently did not reach quite as far, extending as far north as the Congo Basin, central Tanzania and central Madagascar. The northward change in lithofacies was accompanied by increased participation of Euramerican microfloral elements like *Lueckisporites*, *Klausipollenites* and *Tornopollenites* (Kreuser, 1983; Wopfner and Kaaya, 1991) in Middle to Late Permian deposits of the coastal basin in Gabon (Jardiné, 1974) and of the Selous Basin of Tanzania (Weiss, 2001). A European affinity of the macroflora has been noted in the Tanga Basin (Quennell et al., 1956) and Tethyan marine faunas are present in the Permian of northern Madagascar (Teichert, 1970).

This paper focuses on the Karoo basins *sensu stricto* of south-central Africa (Fig. 1), presenting an up-to-date synthesis of their evolution and stratigraphic characteristics in relation to the tectonic and climatic controls on accommodation and sedimentation. Evidence provided by intense research within the last three decades indicates tectonism as a fundamental control on the development and stratigraphic architecture of the Karoo-age basins in south-central Africa. We therefore pay particular attention to the tectonic setting that provided the framework for the formations of these basins, which is presented in detail in the next section of this paper. The following sections of the paper will then discuss the stratigraphic features of the main subdivisions of the Karoo Supergroup, namely the Dwyka, Ecca, Beaufort, and Stormberg-Drakensberg groups.

2. Tectonic setting

Accumulation of Karoo aged successions in Africa corresponds to the Pangean first-order cycle of supercontinent assembly and breakup. The tectonic regime during Karoo time was defined by compression and accretion along the southern margin of Gondwana coeval with extension

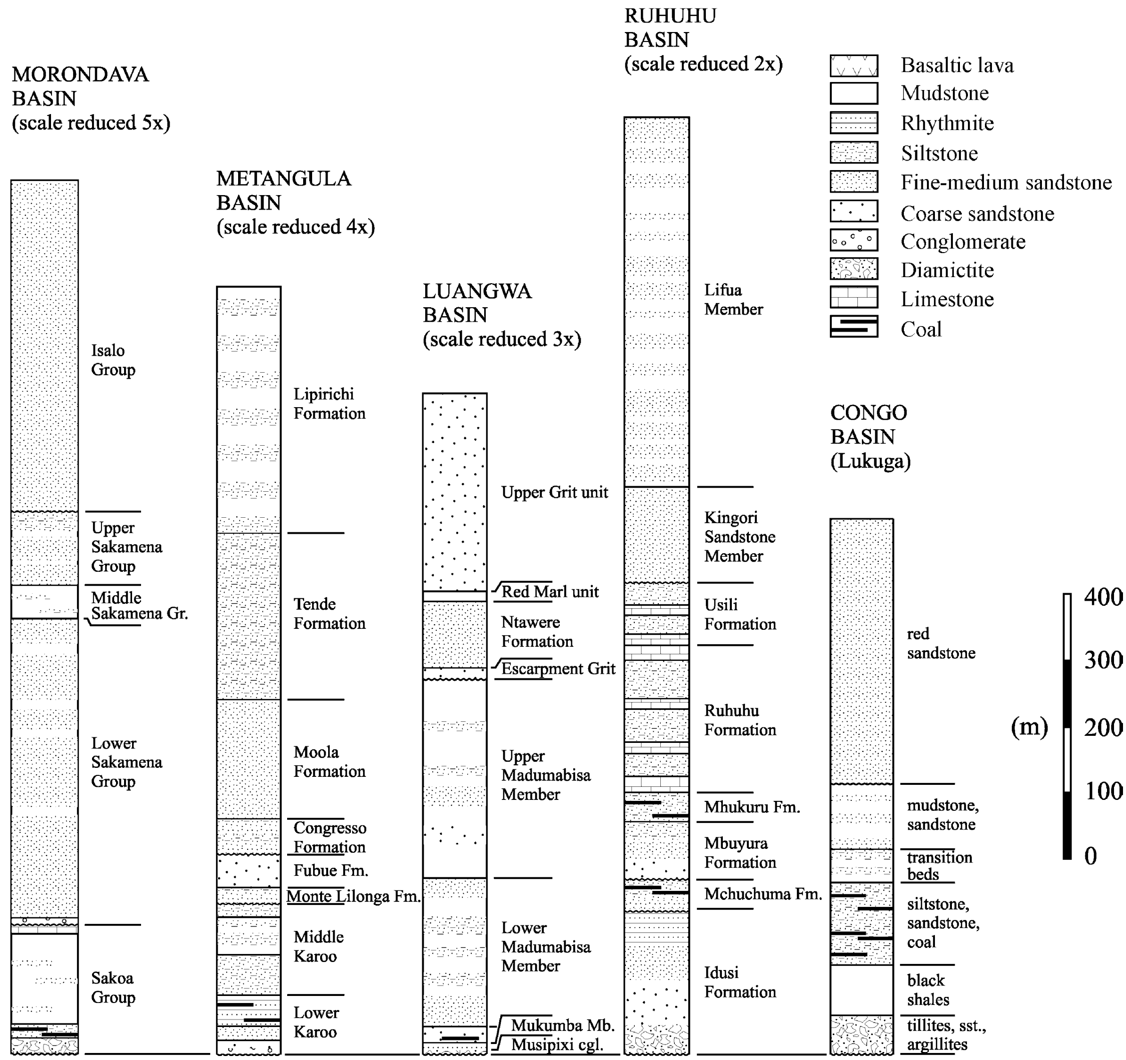

Fig. 6. Southeast–northwest trending cross-section showing the Karoo lithostratigraphic units in east-central Africa (modified from Boutakoff, 1948; Bésairie, 1972; Utting, 1978; Verniers et al., 1989). See Fig. 1 for the location of the Karoo basins.

propagating into the supercontinent from its Tethyan margin (Wopfner, 1994, 2002). This unique combination of tectonic stresses sourced from the convergent and divergent margins of Gondwana resulted in the formation of different basin types across Africa, with accommodation generated by tectonic and dynamic loads in the south, and rifting to the north. The extensional field in central and northern Africa during Karoo time is explained by the updoming caused by the self-induced Pangean heat anomaly that followed the onset of supercontinent assembly around 320 Ma (Wopfner, 1990, 1994; Veevers and Powell, 1994). Tensional regimes initiated during that time resulted in the formation of the early Tethyan spreading centre, and continued to govern the Karoo deposition until the break-up of Gondwana in the Middle Jurassic. Starting with the onset of the Late Carboniferous, tensional stresses propagated gradually to the south from the Tethyan margin, controlling the deposition of Karoo sediments in grabens and subsequent rift structures. The age of the extensional structures in southern Africa is thus inferred to be younger than in central and northern Africa (e.g., Bordy and Catuneanu, 2002c).

2.1. Tectonic regimes related to the Pantalassan (convergent) margin of Gondwana

The southern, convergent margin of Gondwana was characterized by shallow-angle subduction of the palaeo-Pacific plate beneath the supercontinent (Lock, 1980). This compressional regime, associated with collision and terrane accretion, led to the formation of a c. 6000 km long Pan-Gondwanian fold-thrust belt, a small portion of which is now preserved in South Africa as the Cape Fold Belt (Fig. 1) (see also, Shone and Booth, this issue). This orogen represented the supracrustal (tectonic) load that led to the formation of the Karoo retroarc foreland system, which includes the main Karoo Basin as well as other smaller Karoo basins as far north as the Tuli Basin (Fig. 1; Johnson et al., 1996; Catuneanu et al., 1999; Bordy and Catuneanu, 2001, 2002a,b,c, Catuneanu, 2004a).

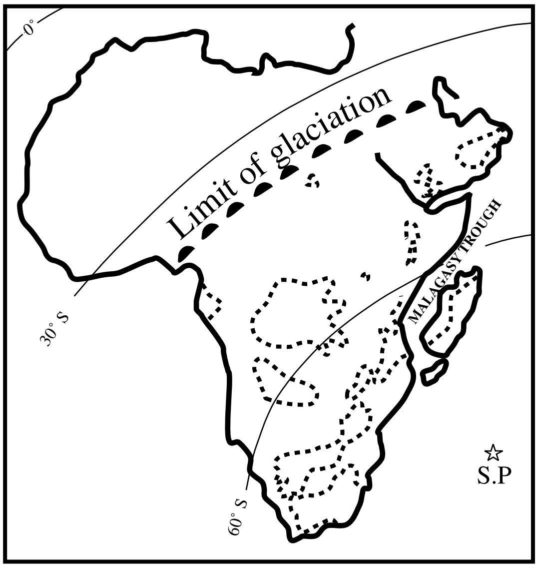

Fig. 7. Generalized distribution of Karoo basins and equivalents (Haushi Group) with manifestations of Dwyka-time glacigene deposits on the Afro-Arabian portion of Gondwana. The limit of glaciation is drawn north of the most distal glacial deposits. Star at "S.P." shows position of South Pole in the Late Carboniferous (modified from Wopfner, 1991, 1999).

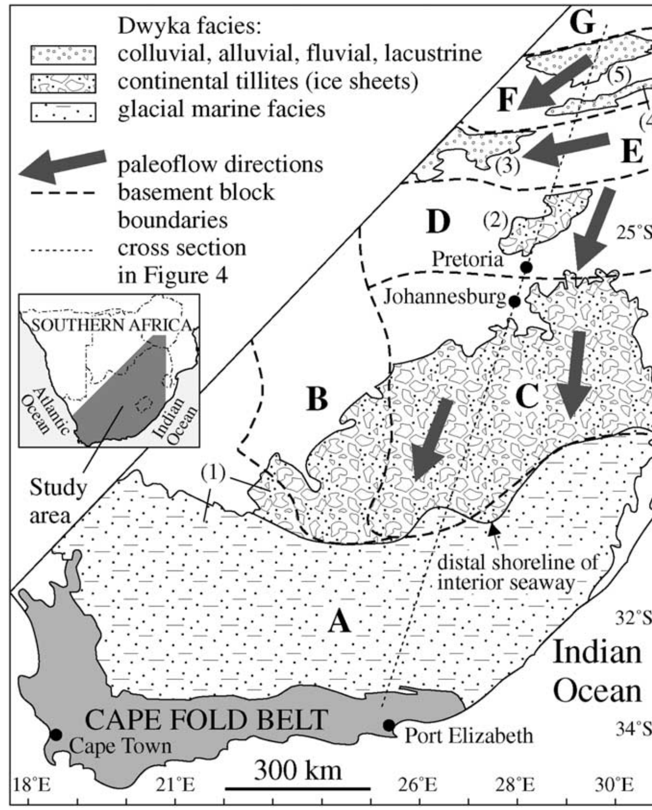

Fig. 8. Area in southern Africa that has been subject so far to foreland system analysis, with respect to the location of flexural hingelines and the distribution of flexural depozones (from Catuneanu, 2004a). The three facies zones correspond to the foredeep, forebulge and back-bulge flexural provinces of the Karoo foreland system. The foredeep overlies the Namaqua-Natal belt (A); the forebulge includes the Kimberley block (B), the Witwatersrand block (C) and the Bushveld block (D); the back-bulge overlies the Pietersburg block (E) and the Limpopo belt (F). Note that the location of flexural hingelines that separate these flexural provinces is strongly controlled by the structure of the underlying basement. This map has been constructed based on the case study of the Dwyka Group. For more details regarding the shifts through time recorded by the boundary between the foredeep and the forebulge during the entire Karoo time in the main Karoo Basin, see Catuneanu et al. (1998). Blocks B to E form the Kaapvaal craton. G marks the southern termination of the Zimbabwe craton. Karoo basins: (1) main Karoo Basin; (2) Springok Flats Basin; (3) Ellisras Basin; (4) Tshipise Basin; and (5) Tuli Basin.

Subsidence in the Tuli Basin, as well as in other basins of the Limpopo area (namely, the Tshipise and Nuanetsi basins) was initially attributed to extension that accompanied the formation of the western arm of a failed rift in a triple-junction setting. The genesis of this rift system, however, is linked to the break-up of Gondwana in the Middle Jurassic, toward the end of the evolution of the Karoo-age basins, so it is unlikely that it controlled accommodation in the Tuli and adjacent depozones during the Permo-Carboniferous stages of the basins history. Instead, it has been proposed that flexural subsidence in the back-bulge region of the Karoo foreland system was the primary control in the creation of accommodation for the deposition of Permo-Carboniferous units (at least Dwyka and Ecca equivalents) in the Limpopo area (Catuneanu et al., 1999; Bordy and Catuneanu, 2001, 2002a,b,c; Catuneanu, 2004a,b). As sedimentological evidence supports the idea of extensional tectonism during the deposition of Stormberg strata in the Tuli Basin (Bordy and Catuneanu, 2001), it can be concluded that (1) there was a gradual change in the primary mechanism responsible for the creation of accommodation in the Limpopo area, from initial flexural subsidence to subsequent extensional tectonism; (2) this change in tectonic regimes took place sometimes during Beaufort Group time; and (3) the extensional regime that originated from the Tethyan margin of Gondwana might have migrated southward through time during the Permo-Triassic, until the final break-up of Gondwana in the Middle Jurassic.

Flexural tectonics imposed by orogenic loading was the initial mechanism of subsidence of the Karoo foredeep, and resulted in the partitioning of the foreland system into foredeep, forebulge and back-bulge flexural provinces (Fig. 8; see Catuneanu, 2004b, for a review). Later in the evolution of the main Karoo Basin, flexural tectonics was supplemented by dynamic subsidence, which created additional accommodation across the entire foreland system (Pysklywec and Mitrovica, 1999). Sublithospheric "loading" of the overriding plate, referred to here as dynamic subsidence, is primarily caused by the drag force generated by viscous mantle corner flow coupled to the subducting plate, especially where subduction is rapid and/or takes place at a shallow angle beneath the retroarc foreland system (Mitrovica et al., 1989; Gurnis, 1992; Holt and Stern, 1994; Burgess et al., 1997). The onset of dynamic loading lags in time behind the initiation of subduction and tectonic loading, as it takes time for the subducting slab to reach far enough beneath the overriding plate to generate a viscous corner flow. The earliest stage in the evolution of a retroarc foreland system, including the main Karoo Basin, is thus dominated by flexural tectonics, when the foredeep is underfilled and the forebulge is elevated above the base level and is subject to erosion.

Flexural tectonics and dynamic subsidence are commonly invoked as the two most important controls on accommodation in the main Karoo Basin, whose foreland nature is now widely accepted. Earlier work assigned the onset of Karoo sedimentation (i.e., the Dwyka Group) to a transition from extensional (e.g., back-arc basin: Visser, 1993; Visser et al., 1997) to foreland setting. More recent reviews (Veevers et al., 1994c; Johnson et al., 1996; Catuneanu et al., 1998; Catuneanu, 2004b) assign the entire Karoo Supergroup, including the Dwyka Group, to a foreland system.

The onset of subduction and tectonic loading is dated as Namurian, when the development of a subduction-related volcanic arc along the Pantalassan continental rim of Gondwana marked the change from a divergent to convergent margin (Smellie, 1981; Mpodozis and Kay, 1992; Fig. 2). The Early Carboniferous (Mississippian) age for the initiation of subduction, compression and tectonic loading along the southern margin of Gondwana is also consistent with the initial deformation documented for the South American segment of the Pan-Gondwanian Mobile Belt (P.C. Soares, pers. comm., 1998). In South Africa, the end of the oldest major tectonic paroxysm identified in the Cape Fold Belt is dated as Late Carboniferous (c. 292 Ma; Hälbich et al., 1983), which indicates active tectonic loading during the sedimentation of the oldest deposits of the Karoo Supergroup. It can be concluded that the initiation of the Cape Orogeny and the associated Karoo foreland system predates the oldest preserved (Late Carboniferous) Karoo sedimentary rocks, and is approximately placed in the Namurian (Fig. 2).

The origin of the c. 30 My stratigraphic hiatus that separates the Cape Supergroup from the overlying Karoo Supergroup has received different interpretations, both independent of and within the context of the foreland system model. Before the foreland system model was applied to the main Karoo Basin, the basal Karoo unconformity was considered to correspond to a period of non-deposition due to the entire region of southern Africa being covered by a cold-based ice sheet (Visser, 1987). In support of this hypothesis, the upper Witteberg Group (Namurian; c. 330 My), which predates this hiatus, shows evidence of glacial activity (Streel and Theron, 1999). More recently, in the context of the foreland system model, the c. 30 My hiatus has been interpreted as the forebulge (basal) unconformity of the Karoo foreland system, formed during the earliest stages of tectonic loading and forebulge uplift (Fig. 2; Catuneanu, 2004a). Subsequent progradation of the orogenic front is thought to have resulted in the migration of the foredeep over the former location of the peripheral bulge, marking the onset of sedimentation in the area that presently represents the most proximal part of the preserved Karoo Basin. In this hypothesis, the earliest Karoo sedimentary rocks (330–300 My) are thought to have been overthrusted, cannibalized and included within the structures of the Cape Fold Belt (Catuneanu, 2004a). This latest interpretation of the origin of the basal Karoo unconformity is in contrast with the model proposed by Veevers et al. (1994a,b,c), which suggests that no migration of the foreland system took place during the evolution of the Karoo Basin. According to Veevers et al. (1994a,b,c), the location of the foredeep is confined to the Southern Cape Conductive Belt, which is thought to represent a zone of dense crustal material that sank during the initial stages of tectonic loading. Alternatively, Visser and Praekelt (1996) proposed thermal subsidence associated with release of Gondwana heat as the main process responsible for the formation and location of the foredeep. Newer stratigraphic evidence (Catuneanu et al., 1998) indicates, however, that the foreland system did migrate through time at least 300 km along dip in a northward direction, which validates the forebulge unconformity hypothesis of Catuneanu (2004a).

The interplay of base level changes and sediment supply controls the degree to which the available accommodation is consumed by sedimentation. This defines the underfilled, filled and overfilled stages in the evolution of the foreland system, in which depositional processes are dominated by deep marine, shallow marine, or fluvial sedimentation respectively (Sinclair and Allen, 1992; Catuneanu, 2004b). The change from underfilled to overfilled stages is best observed in the foredeep, because the forebulge may be subject to erosion in the absence of (sufficient) dynamic loading, or, at most, it may accommodate shallow marine to fluvial environments even when the foredeep is underfilled (e.g., Catuneanu et al., 2002). This predictable succession of stages also marked the evolution of the main Karoo Basin (Fig. 2; Catuneanu, 2004b).

The configuration of the earliest Karoo foreland system accounts for a forebulge elevated above the base level during Dwyka time, which allowed for the formation of continental ice sheets ("early underfilled" stage in Fig. 2). This was followed by a time of system-wide sedimentation during Ecca time ("late underfilled" stage in Fig. 2), when the forebulge subsided below the base level under the influence of dynamic subsidence. In this case, the lag time between the onset of subduction and tectonic loading in the Namurian (Smellie, 1981; Johnson, 1991; Mpodozis and Kay, 1992; Visser, 1992a,b), and the onset of dynamic loading at the beginning of the Permian was of c. 40 My (Fig. 2). During the entire underfilled time (up to c. 263 Ma; Fig. 2), the foredeep hosted a relatively deep marine environment, with glacio-marine (Dwyka) followed by pelagic and gravity flow sediments (most of Ecca; Fig. 2). The upper part of the Ecca Group reflects a filled stage of shallow marine sedimentation, followed by the overfilled style of fluvial sedimentation of the overlying Beaufort and 'Stormberg' groups.

While it is now widely accepted that contractional deformation along the southern margin of Gondwana resulted in the formation of an extensive foreland system in front of the Pan-Gondwanian mobile belt, modern foreland system analysis in terms of the location of flexural hingelines and the distribution of flexural depozones has only been applied so far to few basins in southern Africa, namely the main Karoo, Springok Flats, Ellisras, Tshipise, and Tuli basins (Fig. 8). This type of research needs to be extended in the future to all other southern African basins. Among these, the Kalahari Basin in Botswana seems particularly important to establish the northern limit of flexural deformation that can be attributed to foreland system tectonism. Research so far indicates that flexural subsidence associated with the Cape Fold Belt tectonic load only affected accommodation as far north as 1350 km away from the orogenic front of the Cape Fold Belt (Catuneanu, 2004a). Beyond this distance, farther to the north, the role of compression along the Pantalassan (convergent) margin of Gondwana on accommodation is uncertain. Daly et al. (1991) suggest that the area of influence of contractional deformation during the Permo-Triassic extended as far north as the Congo Basin of central Africa (Fig. 1), which may be possible if one considers that intraplate stresses may propagate thousands of kilometers inside the continents from the plate margins. In such cases, however, the nature of the tectonic forces that may affect each individual basin needs to be assessed on a case by case basis.

2.2. Tectonic regimes related to the Tethyan (divergent) margin of Gondwana

North of the classical main Karoo Basin structural control changed, giving way to extensional regimes along the eastern side of the African part of Gondwana and to syneclisic type sag basins on the western portion. The dividing line between the two followed roughly the present watershed of the Congo River. It is thought that this demarcation is linked to a north–northeast trending ridge created by the initial thermal upwarp in the Late Carboniferous. Dwyka time glaciers issuing into west-central and eastern Africa originated on this elevated region (Rust, 1975; Wopfner, 1991).

2.2.1. The eastern basin region

East of the demarcating highland a complex rift system developed, which extended from the Zambesi to the Ogaden and to the southern rim of the Arabian peninsula. Wopfner (1993, 1994), who termed this extensional zone the "Malagasy Trough", identified it as one of the initial fractures emanating from the Tethyan margin of Gondwana. It coincides with the northern part of the "Falkland-East African-Tethys shear system" proposed by Visser and Praekelt (1996) and the rift structure between Africa/Arabia and Madagascar/India identified by Reeves et al. (2002). The configuration of this rift complex at its junction with the precursor of the Tethys is not entirely clear. Most likely it originated in Oman, where Permian pillow lavas and marine cherts occur at the base of the sequence (Lee, 1990). Veevers et al. (1994a) suggested heat congestion beneath Pangea and right lateral translation between Gondwana and Laurasia as a possible cause for the creation of the Late Palaeozoic strain distribution.

In its entirety, the rift system extends from the Zambesi River (Cabora Bassa Basin) to the Horn of Africa and the southern margin of the Arabian Peninsula. From south to north it comprises the Lukasashi and Luangwa basins in Zambia, some remnant basins in northern Malawi, the Metangula Basin, straddling Mozambique and Tanzania, the Ruhuhu, Ilima, Galula, Selous basins (including the Mikumi and Mvua lobes of the latter) in Tanzania and the Tanga/Duruma Basin, which straddles the border between Tanzania and Kenya (Wopfner, 2002). North of the Kenyan border Karoo rifts are known from subsurface such as the Mandera-Lugh Basin in Somalia and its extension into the Ogaden Basin in Ethiopia (Dow et al., 1971; Bosellini, 1989). Some remnant Karoo rifts have been reported from Dagusi Island in northern Lake Victoria and two other localities in southern Uganda (Schlueter et al., 1993). Karoo basins of western and northern Madagascar (Bésairie and Collignon, 1956) are also part of that rift system (Fig. 1). At the time of Karoo deposition the island was positioned opposite northern Tanzania and southern Kenya (Wopfner, 1994; Reeves et al., 2002).

All these basins were typical intracratonic rifts but some of them, like the Selous and Tanga-Duruma basins in eastern Tanzania and the Morondava Basin in south-western Madagascar, evolved into pericratonic basins in the course of the opening of the Indian Ocean. Seismic reflection data demonstrate the presence of Karoo rocks below the present continental shelf (Fig. 9).

The tectonic history of these rift basins is reflected in their lithofacies successions. All these successions show a remarkable similarity, indicating that their development was controlled by similar forces. Due to the specific structural history of these basins, the older Karoo deposits were laid down and preserved within the oldest graben structures, most of which occupy the deepest parts of the basins today. As the rifts expanded, younger sedimentary sequences progressively overstepped onto domino-style tilted horsts and younger grabens. Thus, almost continuous sedimentation took place within the deep parts of the rifts whereas the successions on the rift shoulders were interrupted by hiata and erosion, evidenced by unconformities and reduced sections.

Generally the Karoo successions of the rift basins exhibits five depositional sequences, every one of them commencing with a coarse-grained or rudaceous lithotype at the base. This is exemplified by the succession of the Ruhuhu Basin in southern Tanzania (Fig. 10). A sixth sequence is present in some of the other Karoo basins (Fig. 11).

The Ruhuhu Basin is not only the northernmost basin that still comprises a fairly complete succession of typical

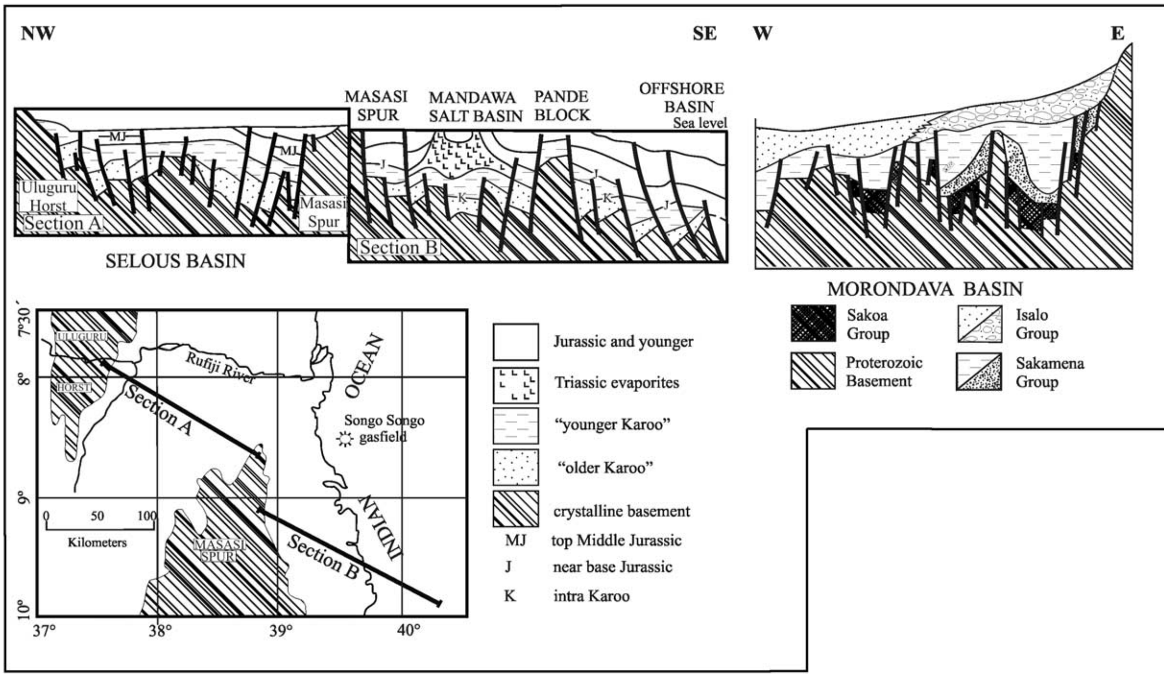

Fig. 9. Interpreted seismic section from the Uluguru Horst near Rufiji River to the Tanzanian continental shelf juxtaposed against a profile across the Morondava Basin in western Madagascar. The Selous section demonstrates the presence of ''older Karoo'' deposits in subsurface, probably equivalents of the first three depositional sequences of the Songea Group (Fig. 10). Syn-depositional faulting is indicated by increased sediment thicknesses of downfaulted portions. The ''Younger Karoo'' comprises equivalents of the Hatambulo Formation and Triassic siliciclastics. The Morondava section mirrors the Selous profile (redrawn from Wopfner, 2002).

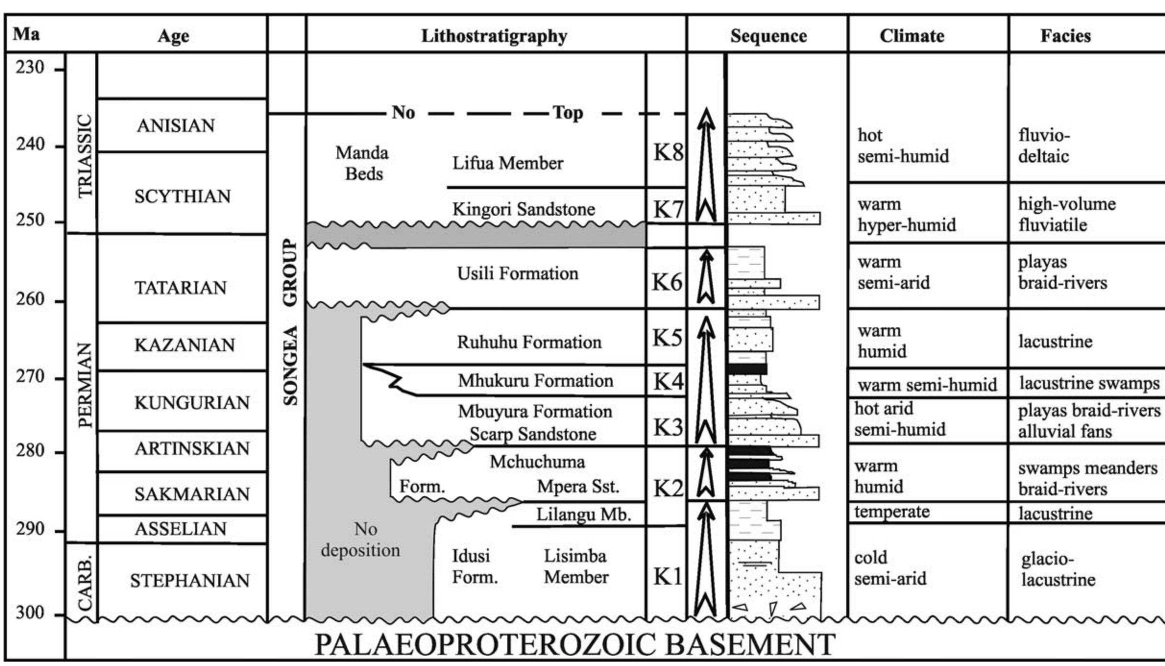

Fig. 10. Stratigraphic table of the Songea Group as established in the Ruhuhu Basin. It is representative of the depositional sequences of Karoo basins of southern Tanzania from Galula near Lake Rukwa to the Mhukuru Basin bordering Mozambique. Five sedimentary sequences are indicated by arrows. Symbols K1 to K8 identify the old, informal stratigraphic scheme (Quennell et al., 1956). Climate and facies on the right hand side of the chart are from Diekmann and Wopfner (1996), and from Wopfner and Diekmann (1996). The absolute ages for base and top of the Permian have been adopted from Wardlaw (1999). As many of the age assignments relay on ties to Australian palynological assemblage zones, the classical Permian subdivision is used in favour of the new, threefold subdivision.

Karoo lithofacies units, but due to its elevated position on the shoulder of the Neogene Nyasa Rift it provides excellent outcrops of all units, amounting to a cumulative total thickness in excess of 3000 m (Kreuser et al., 1990). The

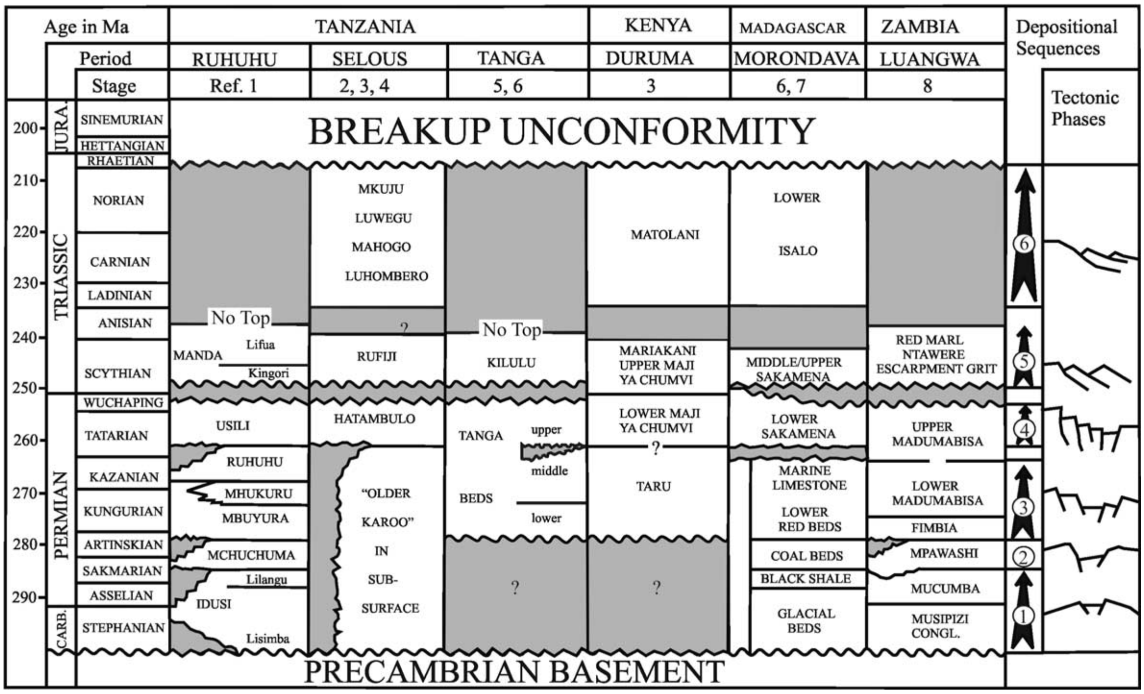

Fig. 11. Correlation chart of selected Karoo rift basins in eastern Africa and Madagascar, showing comparable onsets and duration of depositional sequences. Formation names are shown in capitals, members in caps and lower case. Tectono-sedimentary environments are indicated schematically in the right hand column. Reference numbers pertain to: (1) Wopfner (2002); (2) Hankel (1987); (3) Hankel (1994); (4) Wopfner and Kaaya (1991); (5) Quennell et al. (1956); (6) Kreuser (1990); (7) Bésairie (1972), and (8) Utting (1978).

succession of this and of adjacent Karoo basins is known under the term Songea Group (Fig. 10). As the tectonic and climatic components controlling deposition are representative for other rift basins, the Ruhuhu succession will be discussed in greater detail than others.

As in the main Karoo Basin, sedimentation in the eastern African rift basins commenced with the deposition of glacigene material. The prolonged period of denudation and erosion preceding the onset of sedimentation created a pre-Karoo landscape of extremely low relief. For the commencement of the Dwyka sedimentation the gentle landscape had to be modified to establish the uplands for the formation of the glaciers and the receptacles to accommodate the material shed by them (Janensch, 1927; Dixey, 1937; Quennell et al., 1956; Wopfner, 1994). This was achieved by thermal updoming of the "median swell" as mentioned above. Rifting was still in its incipient stage and in many instances selective erosion, scouring deep glacial valleys, still dominated over the influence of tectonic structures (Wopfner and Diekmann, 1996; Diekmann and Wopfner, 1996).

The first major tectonic pulse occurred prior to the onset of coal deposition at about the middle Sakmarian (Fig. 10) and marked the start of the second sedimentary sequence. In the Ruhuhu Basin, this sequence began with braided stream deposits of the Mpera Sandstone Member at the base of the Mchuchuma Formation. Equivalent deposits also occur in other Karoo rifts of eastern Africa. In the deeper parts of the basins this prominent sandstone rests either conformably or with a slight angular unconformity on the black siltstones of the Lilangu Member of the Idusi Formation (Semkiwa, 1992). The latter was the product of the deglaciation event (Wopfner, 1999). However, on upthrown blocks, as for instance the Namschweia Horst in the Ruhuhu Basin, the sandstone rests with marked unconformity on truncated remnants of the glacigene Idusi Formation (Figs. 12 and 13). On some parts of the horst, erosion has removed the entire glacigene succession and, except for some lag boulders, the Mchuchuma Formation rests directly on Palaeo-Proterozoic Ubendian

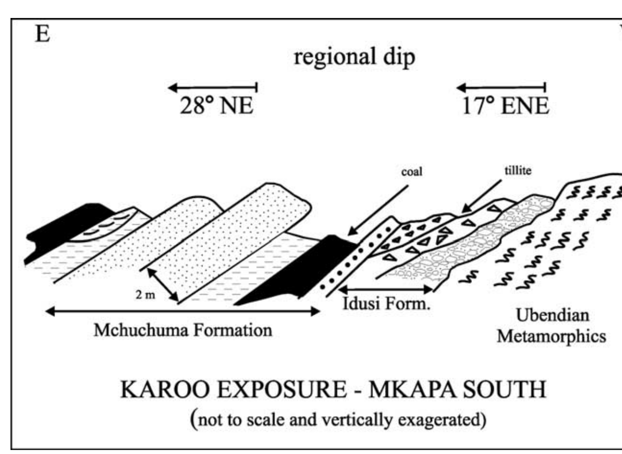

Fig. 12. Angular unconformity between the coal measures of the Mchuchuma Formation and the basal glacial deposits of the Idusi Formation at Mkapa South River, a tributary of the Mkapa River in the eastern Ruhuhu Basin (from Wopfner, 1990).

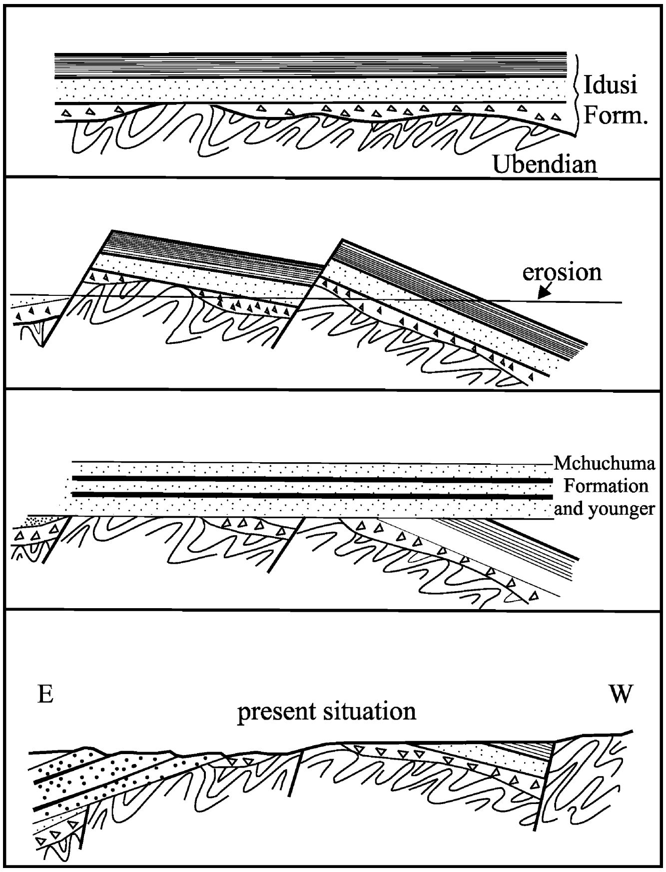

Fig. 13. Reconstruction of the stages required to derive at the present outcrop situation observed within the drainage area of the Mkapa River, demonstrating an event of brittle deformation between the Idusi and the Mchuchuma formations. The outcrop shown in Fig. 12 is at left centre of sections (modified from Wopfner, 1990).

metamorphic rocks. Repeated coarsening upward sequences of scarpfoot fans on the downthrown side of the Namschweia Fault give further evidence for syngenetic displacement along this dislocation plane during deposition of the Mchuchuma coal measures (Semkiwa, 1992; Wopfner, 2002).

Time equivalent unconformities are observed in a number of other Karoo basins of eastern Africa (e.g., Galula, Ilima, Mhukuru). In the Metangula Graben of Mozambique, Karoo sedimentation commenced at this time, the basal sandstone of the coal measure deposits resting directly on basement (Verniers et al., 1989). Similar conditions apparently also prevailed in the Cabora Bassa Basin (Dressler et al., 1990; Nyambe and Owen, 2000).

The next tectonic event took place around the last third of the Artinskian. It initiated the third depositional sequence, consisting of a thick succession of red coloured sandstones and mudstones of scarpfoot fans and braided wadi/playa systems (Mbuyura Formation), a short interval of carbonaceous siltstone and coal measure deposition (Mhukuru Formation), and a concluding succession of green lacustrine mudstones and stromatolitic carbonates (Ruhuhu Formation) (Kaaya, 1992; Wopfner, 2002). This third event caused substantial widening of the individual graben structures, evidenced by overstepping of the younger depositional units across older Karoo successions onto the basement. Indeed, in some basins, like the Mikumi Basin (Dypvik and Nilsen, 2002) or the Tanga/Duruma Basin the exposed Karoo succession commenced with deposits of this sequence, resting directly on basement. In the Ruhuhu Basin the base of the succession is formed by the Scarp Sandstone Member of the Mbuyura Formation (Fig. 10). This light coloured, coarse-grained to gritty and richly feldspatic fluviatile sandstone frequently shows a wedge shaped thickness distribution away from palaeoscarps attesting to syndepositional movements of fault blocks (Kaaya, 1992).

This tectonic pulse affected practically every Karoo basin north of the Zambezi River (Fig. 11). The Fimbia Grit in the Luangwa Basin, the coarse sandstones and conglomerates at the base of the red beds in the Metangula Graben and in Madagascar are related to this tectonic event. In some regions like the Mikumi and the Tanga/Duruma basins, Karoo deposition was initiated by that very event. However it is probable that older Karoo strata were deposited in deeper, now concealed elements of these rifts.

As is evident from the change of lithofacies, this third tectonic event was accompanied by a change from the warm humid climate that prevailed during coal deposition to the hot and arid conditions during red bed sedimentation and the more humid climate during the existence of the vast lake system in which the Ruhuhu Formation and its equivalents were laid down. Towards the end of this lacustrine phase a first marine incursion is evident in Madagascar (Bésairie and Collignon, 1956; Radelli, 1975) and slight hints for this transgression are present in the northern basins of Tanzania (Quennell et al., 1956; Kaaya, 1992).

Changes in facies distribution of this depositional sequence suggest that an easterly palaeogradient existed between south-western Tanzania and northern Mozambique. There are several indications to support such a statement, including that the average grainsize of the sandstones of the Umbuyura Formation decreases from west to east, and that the coal measures of the Mhukuru Formation increase in thickness from the Ruhuhu Basin towards the Mhukuru Basin (Semkiwa, 1992), becoming the major coal formation in the Metangula Basin (Verniers et al., 1989). Conversely, the coal facies peters out west of the Ruhuhu Basin, and is missing in the Ilima and Galula basins situated between the top of Lake Nyasa and Lake Rukwa. Equivalents of the lacustrine Ruhuhu Formation are also absent in that region.

The fourth depositional sequence is reflected by the change from the widespread lacustrine sedimentation of the Ruhuhu Formation and equivalents (Fig. 11) to the playa and flood plain succession of the Usili Formation. In the Ruhuhu Basin the latter formation commences with a pebble to cobble conglomerate with abundant reworked tetrapod fossils resting unconformably on the preceding formation. Amongst other terapod remains the skull of *Dicynodon lacerticeps* was found (Kaaya, 1992), placing the Usili Formation within the *Dicynodon* Assemblage Zone (Tatarian) of Kitching (1995a,b).

Sedimentation along the margin of the Selous Basin was also initiated at this time. The Hatambulo Formation, which is time equivalent with the Usili Formation, oversteps onto the basement. Cobble and boulder conglomerates of the basal Viransi Member, representing proximal fan and rockfall deposits, grade laterally into fluvio-lacustrine strata of the Kidahi and Pangani members and demonstrate the existence of an active fault scarp, demarcating the basin area against the rising Uluguru Horst (Wopfner and Kaaya, 1991) (Fig. 9). A break is also evident between the middle and the upper member of the Tanga Beds and probably also along the time equivalent boundary in the adjoining Duruma Basin (Fig. 11).

In Madagascar, an unconformity separates the deposits of the Sakoa Group from those of the succeeding Lower Sakamena Group, evidenced by the erosive removal of the Vohitoila Limestone and part of the Redbeds prior to the deposition of Lower Sakamena Group sediments (Hankel, 1994; Smith, 2000). Conglomerates at the base of the upper Madumabisa Mudstone of the Luangwa Basin suggest a rapid increase in gradient. Overall, this fourth depositional sequence was the result of a continuation of the process initiated by the previous tectonic phase, which involved a widening of the rift system and lowering towards a central trough between Madagascar/India and Africa.

Succeeding tectonism and erosion led to a hiatus which straddles the Permian/Triassic (P/T) boundary in almost all basins in eastern Africa (Fig. 11). In some basins it is represented by a regional unconformity between the multicoloured Late Permian strata and the generally thick, fluviatile sandstones of the Early Triassic, marking the base of the fifth depositional sequence (Wopfner, 2002).

In the Ruhuhu Basin the fifth depositional sequence is represented by the Manda Beds of Scythian to Early Anisian age. The succession commences with the supermature Kingori Sandstone Member which rests with low angle unconformity on rocks of the Late Permian Usili Formation. The base is marked by a conglomerate containing cobble and boulder sized rip-up clasts of the underlying Usili Formation. The main body of the Kingori Member consists of medium to coarse-grained, clean quartz sand, laid down in thick sets of large scale current beds with overturned friction-drag and convolute dewatering structures. Foreset azimuths are almost unidirectional to east or southeast and indicate an east-trending palaeoslope (Markwort, 1991), presumably towards the central part of the Malagasy Trough. This is interpreted as the result of crustal thinning and the beginning of detachment.

The hiatus around the P/T boundary can be observed in all Tanzanian Karoo basins and in Mozambique. In the Duruma Basin the situation still needs some clarification and so does the setting in the Morondava Basin of Madagascar. Wright and Askin (1987) thought that sedimentation had been continuous from the Lower Sakamena Group deposits to the deltaic/shallow marine strata of the Middle Sakamena Group. In their view this transition approximates the P/T boundary. On the other hand Hankel (1994) deduced from palynological studies that a depositional break existed between the Lower and the Middle Sakamena. This latter view has been adopted for the compilation of the stratigraphic chart in Fig. 11. Another doubtful case is the Luangwa Basin in Zambia. Utting (1978) interpreted the succession of that basin as a layer cake sequence, relating all fault movements to a time post-dating the Karoo deposition but preceding the intrusion of basic dykes (i.e., Middle to Late Triassic). However, the description of lithologies, especially of the base of the Escarpment Grit, allows inference of a hiatus between the Upper Madumabisa Mudstone and the Escarpment Grit as shown in Fig. 11. In the mid-Zambesi Valley of southern Zambia, Nyambe and Dixon (2000) observed an unconformity between the lacustrine Madumabisa Mudstone and the rudaceous Escarpment Grit.

The remaining part of the fifth depositional sequence was characterized by slow sag and reversion to a semi-arid climate (Wopfner, 2002). Up to 1300 m of cyclothem-like fining upward cycles of reddish feldspathic sandstones grading up to green or red micaceous siltstones of a semi-arid fluvio-deltaic environment accumulated in the Ruhuhu Basin. Markwort (1991) defined this sequence as the Lifua Member of the Manda Beds (Fig. 10). The co-occurrence of *Angonisaurus* (Hancox and Rubidge, 1996) and *Cricodon* (Abdala et al., 2005) in the rocks of the Manda and upper Burgersdorp formations, allows for a direct correlation between the Manda, and the uppermost subzone C of the *Cynognathus* Assemblage Zone of South Africa. This age is also confirmed by the occurrence of Parothosuchus and palynological data (Markwort, 1991). Chronostratigraphic equivalents of the Lifua Member are known from all rift basins of eastern Africa. In most cases they show very similar lithofacies successions. Their Anisian age precludes a correlation with the Molteno Formation of the type-Karoo Basin, which is of Late Triassic age (Anderson and Anderson, 1983).

All successions of the fifth depositional sequence are followed by a hiatus encompassing the remaining portion of the Anisian. In some of the basins (Ruhuhu, Tanga, Metangulu, Luangwa) the Karoo succession is concluded by the Manda Beds or their equivalents. Younger Triassic strata are absent and may never have been deposited.

In the remaining basins, the sixth depositional sequence commences in the early Ladinian and generally extends to the end of the Norian. As mentioned above, the sequence is separated from the preceding one by a widespread hiatus or low angle, regional unconformity, representing the last extensional pulse prior to breakup. In the whole region of eastern African Karoo basins, the Late Triassic successions are terminated by a major unconformity, reflecting the beginning of breakup and the incipient separation between Africa/Arabia and Madagascar/India. It terminated the intracratonic rift stage and marked the beginning of the pericratonic environment of a passive margin. Wopfner and Kaaya (1991) have argued therefore that the term "Karoo" or "Younger Karoo" is not applicable for post-Triassic sequences of eastern Africa. This conforms to the previously established practice in Tanzania, identifying post-Triassic sedimentary successions as "post-Karoo" (Quennell et al., 1956). There was no volcanism comparable to the flood basalts of southern Africa, the few basic dykes and kimberlite pipes being of post-Karoo age (Utting, 1978; Hankel, 1987; Kreuser, 1983; Kreuser et al., 1990).

Post-breakup Jurassic sedimentary strata rest on either Karoo or basement and are exposed along the present coastal region. They comprise shelf carbonates such as the Middle Jurassic limestone near Tanga ("Tanga Limestone") or the Callovian/Oxfordian Kidugallo Oolite on the central railway line west of Dar es Salaam. In the interior, time equivalent deposits comprise current-bedded and frequently kaolinitic, fluviatile sandstones (Quennell et al., 1956; Hankel, 1987).

2.2.2. The western basin region

The Karoo basins west of the dividing ridge are not as well known as their counterparts in the east. They appear to be sag basins that developed in depressions between the dividing ridge and a hypothetical rift shoulder or thermal swell associated with the pre-opening history of the Atlantic Ocean. Most of the Karoo deposits of this region are concealed below younger sediment covers, thus information of the deeper basin areas is restricted to a few boreholes, the description of which has been published (Hübner, 1965). The origin of these western Karoo sag basins may be related to the release of heat following the formation of the Karoo rift basins of eastern Africa (Veevers et al., 1994a,b,c).

Based on the interpretation of seismic reflection profiles, Daly et al. (1991) suggested the existence of thrust structures within the north-western Congo Basin. From this evidence these authors suggested that thrusting and contraction are the expression of a Late Palaeozoic deformation event, related to the collision along the Panthalassa margin. The existence of a synchronous tectonic pulse around the P/T boundary is not just a feature of the Congo Basin but is clearly evident in most Karoo-equivalent basins of Gondwana (see above). The present author considers a long distance stress transmission speculative and an overestimation of the physical strength of the crust. Looking at the stress distribution depicted by Daly et al. (1991) the thrust deformations may be interpreted as a transpressional effect related to strike slip movements along north-east trending compensation zones.

Similar to the situation in southern Tanzania, the Karoo sequences of the Congo Basin are best exposed along the western slope of the Neogene Tanganyika and Kivu rifts. Here, Dwyka-aged glaciers have carved a pronounced glacial morphology with deep U-shaped valleys, gouged into the Precambrian basement. Boutakoff (1948), who described these valleys in some detail, envisaged a mountainous ridge encircling the Congo and Angola basins, whence glacier tongues issued into these basins. This hypothetical mountain range roughly coincides with the dividing ridge which, as mentioned before, separated the eastern rift basins from the sag-basins to the west.

In the eastern part of the Congo Basin, Karoo deposition commenced with tillites, washout conglomerates and pebbly mudstones, succeeded by sandstones and green, laminated, fine-grained sandstone/mudstone couplets with dropstones, interpreted as varves. As in most other Pangea depositories, a black, lutitic deglaciation facies with *Gangamopteris* concludes the glacial event.

In the Lukuga area, west of the Lake Tanganyika coal measures, reddish "Transition Beds"overlie the glacigene deposits, but further north, in the Walikali/Kivu region, post (?) Sakmarian strata are missing. However, there is no evidence of rifting and contrary to the situation in Tanzania, the glaciated valleys have not been cut by syn-Karoo dislocations. The Triassic comprises a comparatively thin Anisian succession of red beds, marls and bituminous mudstones, followed by Late Triassic fluviatile sandstones and some bituminous shale, probably separated from the Early Triassic strata by a hiatus (Boutakoff, 1948).

West of the present day rift shoulder the Karoo beds are covered by younger deposits, but their presence is known from a few boreholes in the deeper part of the Congo Basin. In the Dekese borehole, situated about 670 km east–northeast of Kinshasa, 962 m of Karoo rocks were intersected between 715 m and 1677 m below surface. The section comprises 816 m of diamictites, sandstones, laminites with dropstones (interpreted as tillites), varves and other glacial and periglacial lithofacies (Hübner, 1965). The rocks are flat lying or gently dipping (up to 15°) and, especially within the laminites they are often intensely deformed by slumping or other syn-depositional deformation processes. There is no evidence for any break of deposition within the glacigene sequence. The great thickness of the sequence and the lithofacies types clearly indicate that the glaciers issued into a large lake. A north-west trending tectonic zone which transects the northern basin area has been identified by seismic reflection surveys (Daly et al., 1991).

Analogous Karoo sections have been described from northern Angola (Oesterlen, 1976, 1979). Here, the Karoo succession commences with red conglomerates and sandstones which, on the basis of the presence of *Glossopteris*, have been correlated with the tillites of the Dwyka Group. Oesterlen (1976, 1979) has pointed out that the lithofacies is that of an arid environment and has no features typical of glacigene deposits. Indeed, the rocks far more resemble the early Late Permian redbeds (e.g., Mbuyura Formation) or Beaufort Group equivalents than glacial deposits. The lutitic Fish Beds which overlie the redbeds, have been dated as Late Permian to Early Triassic. They are at the base of the "Cassange Serie" consisting of about 50 m of plant bearing siltsones (Early Triassic), succeeded by about

450–550 m of red and grey mudstones, siltstones and sandstones, of the "Phyllopod Beds". Based on an *Estheria* fauna, the strata are considered to be of Middle to Late Triassic age. The conchostracan fauna is indicative of a saline inland lake (Oesterlen, 1979). The contacts between the depositional units apparently are concordant and, as in the case of the Congo Basin, a regional sag mechanism is suggested.

In the Gabon Basin, coal measures are missing and the glacigene deposits are succeeded by evaporites, indicating a rapid warming after deglaciation. The situation was similar to other peripheral Karoo basins as for instance those of Yemen and southern Oman (Wopfner, 1999).

Tectonically, the western basins were governed by a much quieter environment than that of the rift basins, deposition being controlled by slow subsidence. Modifications of depositional patterns were caused by distal events along the basin rim, as well as by climate.

3. Dwyka group and equivalents

3.1. Introduction

The Dwyka Group and its equivalents include glacially-influenced deposits that accumulated approximately during the 300–290 Ma interval (Fig. 2; e.g., Wopfner, 2002; Catuneanu, 2004a). Visser (1997) and Bangert et al. (1999) indicate, however, that Dwyka sedimentation might have started earlier that 300 My ago, at about 305 My. The extent of this Late Carboniferous–earliest Permian glaciation may be traced from the main Karoo Basin in South Africa all the way to Gabon, western Sudan and Somalia to the north Fig. 7). The accumulation of the Dwyka glacially-influenced deposits took place in different tectonic settings across south-central Africa, ranging from the retroarc foreland system of the main Karoo Basin, to extensional basins further north.

3.2. Retroarc foreland system

The configuration of the Karoo retroarc foreland system during Dwyka times has recently been reviewed by Catuneanu (2004a), who described a foredeep transgressed by an interior seaway, a forebulge uplifted above the base level, and a shallow back-bulge depozone to the north. Lateral changes of the Dwyka facies follow closely the topographic variability of this flexural profile, showing a shift from marine facies in the foredeep, to dominantly continental facies to the north (Visser, 1987, 1989; Visser et al., 1997). Superimposed on this tectonic control, the glacial climatic conditions that dominated the Late Carboniferous interval in southern Gondwana provide a common underlying theme for the sedimentation during Dwyka times in the entire Karoo foreland system.

The foredeep accumulated up to 800 m of silt-dominated marine diamictites with dropstones derived from floating ice (Visser, 1991a,b). The distal shoreline of this interior seaway, which approximates the boundary between the subsiding foredeep and the uplifted forebulge, has been mapped by Visser (1991a,b). A general feature of the foredeep succession is the uniform character and lateral continuity of the diamictite layers, suggesting deposition from suspension in a relatively low energy environment (Tankard et al., 1982), and similar subsidence patterns at the regional scale of the basin. Processes of resedimentation of the initial fallout deposits by debris flows have also been documented in this gloacio-marine environment (Visser, 1997).

In contrast to the situation south of the shoreline, the lateral correlation of the forebulge facies is very difficult due to the irregular thicknesses and complex facies relationships of the succession. As the forebulge was uplifted above base level, the tillite accumulated largely as ground moraine associated with continental ice sheets, and is generally composed of basal lodgement and supraglacial tills (Visser, 1987). These deposits, with thicknesses in a range of metres, are generally massive, with occasional crude horizontal bedding towards the top (Tankard et al., 1982). The difficulty in correlating the forebulge Dwyka facies, even between exposures only a few kilometres apart, suggests local development of grounded ice lobes separated by ponds and outwash fans. The clasts are not imbricated, but occasionally show a weakly developed long-axis alignment parallel to the direction of ice flow as inferred from the subjacent striated pavement (Tankard et al., 1982; Visser and Loock, 1988). The general direction of ice movement within the forebulge area was from north to south, indicating a topographic profile dipping to the south (Visser, 1991a,b), but there was also movement northward into the Kalahari Basin (Visser, 1983a). Deep glacial valleys that entered both the Karoo and Kalahari basins, were incised into the forebulge and were filled with diamictite representative of lodgement till, debris rain and debris flow deposits, sandstone and conglomerate representative of outwash fans, deltas and/or proglacial traction, turbidity and debris flow deposits, and mudrock representative of suspension deposits (Visser, 1983b; Visser and Kingsley, 1982; Cole, 1991).

The back-bulge basin of the Karoo foreland system includes sedimentary strata preserved in the Ellisras, Tshipise and Tuli basins (Bordy and Catuneanu, 2002c; Catuneanu, 2004a). The back-bulge deposits, with thicknesses in a range of metres to tens of metres, are markedly different from their foredeep or forebulge correlatives, and include a mixture of colluvial and glacial outwash alluvial facies sourced from the more elevated forebulge to the south, as well as fluvial deposits derived from the craton (Faure et al., 1996a,b; Bordy and Catuneanu, 2002c). Deposition in these environments took place under high water table conditions, marked by the presence of glacial or periglacial lakes. The lacustrine facies contain angular clasts "floating" in a muddy matrix, similar to the dropstones in the foredeep, supporting the presence of floating ice (Bordy and Catuneanu, 2002c).

3.3. Extensional basins

The influence of the Gondwana glaciation is manifested well to the north of the main Karoo Basin of South Africa and its adjacent basins in southern Africa. Tillites combined with periglacial and deglaciation sequences are observed in many parts of subequatorial Africa and Madagascar and are evidence of that global climatic event. As mentioned in the introduction and shown on Fig. 7, Late Paleozoic glacial deposits extend north beyond the present equator into Gabon, the Sudan, Ethiopia, the Ogaden and southern parts of the Arabian Peninsula (Wopfner, 1991, 1999; Bosellini, 1989; Schandelmeier et al., 1997, p. 6).

Some of the best known equivalents of the Dwyka Group are the glacigene sequences of southern Tanzania and Madagascar. Not only are they well exposed along the shoulders of the Neogene graben structures of Lake Nyasa and Lake Rukwa but due to numerous bore holes drilled in the course of extensive investigations of the coal deposits of the overlying Mchuchuma Formation (Ecca equivalent), their subsurface configuration is well known (see Wopfner and Diekmann, 1996 for references). The glacigene sequence is referred to as the Idusi Formation. It is subdivided into the lower, glacial to periglacial Lisimba Member and the upper, deglaciation sequence of the Lilangu Member (Fig. 14). This stratigraphic scheme has been applied in all basins of southern Tanzania (see Wopfner, 2002, for references).

The type section of the Idusi Formation is situated in the Idusi River Gorge, at the north-western boundary of the Ruhuhu Basin. There, a thin, massive tillite (6–8 m) rests unconformably on high grade metamorphics of the Palaeoproterozoic Ubendian Metamorphic Complex (Fig. 15). The contact surface is planar and smooth and suggestive of a glaciated surface. The tillite is a typically matrix-supported diamictite with pebble to boulder sized clasts, consisting entirely of basement rocks. The prevalent shape of the clasts is pentagonal—subrounded with abrupt changes of the radii of the rounded surfaces. The clasts exhibit typical features of glacial transport like soled and facetted surfaces, striations and pressure flaking (Wopfner and Kreuser, 1986). At the top the massive tillite gives way to slurried, flow banded tillites and sandy, faintly bedded diamictites with lenses of washout conglomerates and occasional cobble- to boulder-sized lonestones. This part, which is interpreted as subaquaous meltout tillite, is succeeded by generally massive, greenish grey diamictic sandstone and slumped masses with contorted bedding. The upper third of the glacial sequence (Lisimba Member) comprises green laminites, consisting of alternating silt and lutite laminae, comprising up to 15 laminae per

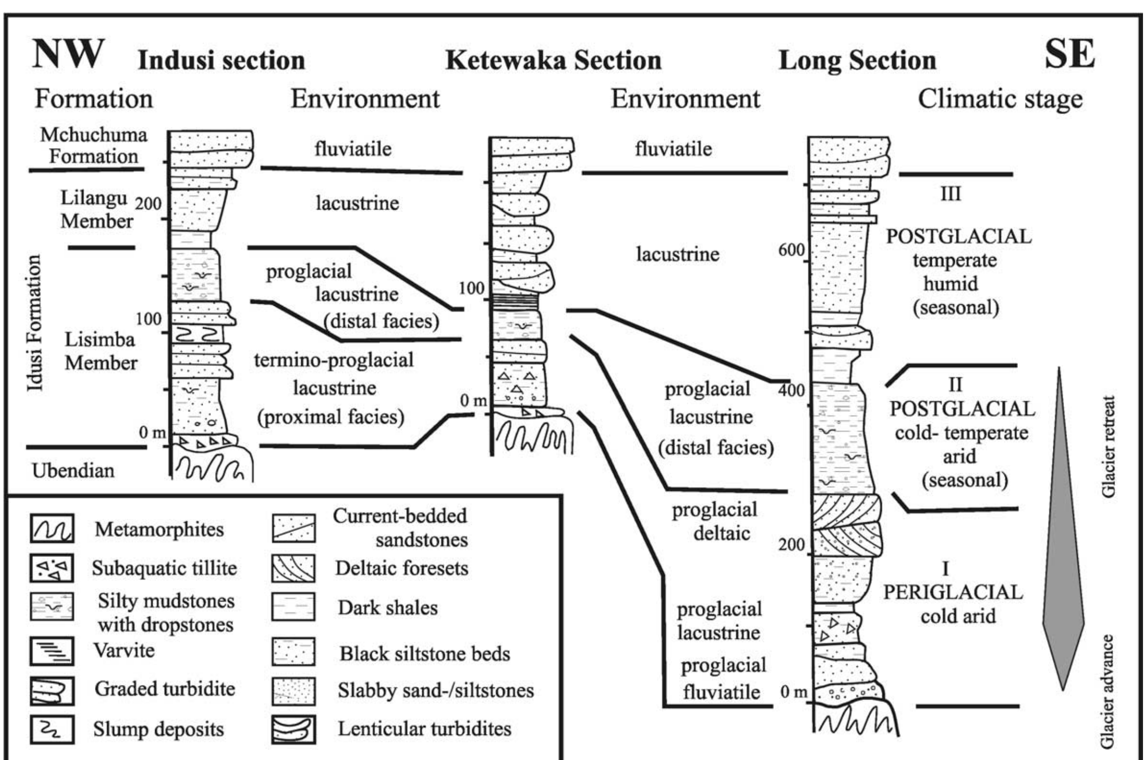

Fig. 14. Lithofacies distribution, depositional environment and interpretation of palaeoclimate of the Idusi Formation in the Ruhuhu Basin of southern Tanzania. Note the marked increase in thickness, especially of the proximal proglacial facies towards the glacial valley of the "Long Section". In the same direction the deglaciation facies of the Lilangu Member changes from the lutite/siltstone succession at Idusi Gorge to a turbidite dominated sequence with interbedded lutites at Ketewaka River. At the "Long Section" the black lutite/siltstone facies prevails with intercalations of sandy, kaolinitic turbidites (after Diekmann and Wopfner, 1996).

Fig. 15. In Idusi River Gorge basal diamictite of the Idusi Formation rests unconformably on dark blue amphibolites and migmatites of the Palaeoproterozoic Ubendian System. Person in right centre of picture is standing on unconformity surface. Note large, matrix supported clasts near base of diamictites just to the right of shaded cleft.

centimetre. Small dropstones are common and occasionally dropstones up to cobble size occur. The laminae, including the lutites, are composed of finely ground up quartz, feldspar and chlorite (Diekmann, 1993; Diekmann and Wopfner, 1996). The laminites are interpreted as seasonal deposits of a periglacial lake.

Poorly diversified but well preserved palynological assemblages from the lower part of the Lisimba Member indicate an age range from Late Stephanian to Early Asselian. Time equivalent deposits are the Musipizi Conglomerate Member and the lower part of the Mukumba Siltstone Member of north-eastern Zambia and the lower part of the Siankondodo Sandstone of southern Zambia (Weiss and Wopfner, 1997).

The laminites are succeeded by black shale and siltstone of the Lilangu Member. In contrast to the arkosic, chlorite-dominated lutites of the proceeding sequence, the shale and siltstones of the Lilango Member are composed of kaolinite. They are pyritic and more or less bituminous. Near the base they typically contain ellipsoidal to loaf shaped carbonate concretions up to 60 cm in diameter, cone-in-cone limestones and occasional sulfates. *Glossopteris*, *Gangamopteris* and other plant fossils are abundant higher up in the more silty succession. Palynological assemblages indicate an early to middle Sakmarian age (Wopfner and Kreuser, 1986; Weiss and Wopfner, 1997). In the type section the thickness of the Lilangu Member is about 70 m but in the deeper parts of the basin the thickness increases considerably due to intercalations of metres to decametres of sandy, kaolinitic turbidites (Fig. 14). Diekmann and Wopfner (1996) showed that this sequence originated in a euxinic environment with high organic intake. It was deposited during the time of the final climatic amelioration and the ensuing deglaciation.

In many instances the existence of a glacially-shaped geomorphology like troughs, U-shaped valleys and rounded hummocks is evident (Wopfner and Kreuser, 1986; Wopfner and Diekmann, 1996), but the most striking feature is the so called Long Section where a deep trough, incised into the Ubendian basement of the Namschweia Ridge, accumulated more than 650 m of glacial and post-glacial sediments (Fig. 14). The irregular geomorphology was an additional cause for marked lithofacies changes within the Idusi Formation, not only in the Ruhuhu Basin but also in other Karoo basins of southern Tanzania (see Wopfner and Diekmann, 1996 for additional examples and references). The Idusi Formation is still recognized in the Mhukuru Basin in the Ruvuma district of south-eastern Tanzania. This northernmost extension of the Metangula rift basin displays a complete contingent of lithofacies, from basal tillites to the kaolinitic deglaciation deposits in a marked onlap/overlap arrangement (Kreuser et al., 1990; Kaaya, 1992; Semkiwa, 1992). By analogy with other rift basins, this indicates that glacial deposits should also be present in the deeper parts of the Metangula Basin in Mozambique.

The threefold subdivision of lithofacies types generally observed within the Idusi Formation, i.e., in ascending order, rudaceous/arenitic "rock flour" facies, chloritic laminite facies and kaolinitic, black lutitic and turbiditic deglaciation facies, can be recognized in all eastern African rift basins and in Madagascar. In the northern Lilangu Basin, Utting (1978) describes the deposits at the base of the Karoo succession (Musipizi Conglomerate Member) as mixtites, containing boulder sized clasts up to 1 m. Judging from his illustration the main part of this unit consists of subangular clasts, ranging in size between 1 and 20 cm, supported in a silty matrix. Striated pebbles and cobbles are rare. It is suggestive of some morainal type of deposit. An interesting feature is the presence of weathered basement at the contact with the overlying diamictite of the Musibizi Conglomerate Member at some localities, including in certain bore holes. The succeeding Mucumba Siltstone Member comprises washout conglomerates near the base, grading up to greenish grey banded to laminated siltstones with some dropstones in the lower part of this periglacial sequence, and carbonaceous shale at the top. The latter strata apparently represent the deglaciation event (Fig. 11).

In the Morondava Basin the tillites are overlain by proglacial and periglacial deposits, varying considerably in both thickness and facies distribution. Lacustrine laminites of periglacial origin are succeeded by the deglaciation facies of the *schistes noirs* of Sakmarian age. The latter are lithologically identical with the Lilangu Member. In fact, Wopfner (1999) demonstrated that this deglaciation facies can be recognized all along the Tethyan margin of Gondwana from eastern Africa via Oman, India and south-west China to Australia. Within the limit of palaeobiological dating methods it represents a synchronous event which was associated with a pronounced eustatic rise of sea level and a marine transgression along the Tethyan margin (Archbold, 2001).

3.4. Western sag basins

The U-shaped, glacial valleys of the eastern margin of the Congo Basin as described by Boutakoff (1948) have been mentioned in the general description. The succession contained within these valleys, termed Kiralo ya Mungu Beds, commences generally with conglomerates and matrix-supported sandy diamictites which appear to be mainly washout tillites. Boutakoff (1948) interpreted some of them as marginal moraines and some apparently as placement tills. The basal rudites are overlain by current-bedded sandstones which in turn are succeeded by greenish grey laminites with dropstones, interpreted as seasonal deposits of periglacial lakes (varves). The final member of the glacigene sequence consists of dark blue to black, plant-bearing lutites with pyrite and ovoid, calcareous concretions. This topmost unit bears all characteristics of the Lilangu Member of southern Tanzania and is considered here as an equivalent of the deglaciation facies. The total thickness of the Kiralo ya Mungu Beds is between 140 and 160 m.

Within the deeper part of the Congo Basin the thickness of the glacigene sequence increases to more than five times that observed at the eastern margin of the basin. According to Hübner (1965) the total thickness of the glacial sequence in the borehole "Dekese" amounts to 816 m, of which almost 680 m comprise laminites with dropstones (varvites) and turbidites. Some of them are classical varvites with beautifully impacted dropstones, an example of which is depicted in Fig. 16.

Although Hübner (1965) describes some massive diamictites with soled and striated pebbles from the base of the bore hole, their depositional environment cannot be identified with certainty. Some of them could be subglacial placement tills, but faint bedding and sorting in some of them is suggestive of meltout, debris flow or rainout tills. Regardless of the actual depositional environment of the very basal diamictites, there can be little doubt that the major part of the succession was laid down in an aqueous, presumably lacustrine environment. Interleaved with the regular laminites are intervals of contorted strata, apparently formed by slumping. Based on the study of drill cores, Hübner (1965) indicated the existence of two unconformities within the laminite succession, possibly caused by syngenetic movements but more probably caused by slump overthrusting. The fold pattern as observed in drill cores is not symptomatic for tectonic deformation as suggested by Daly et al. (1991). No typical deglaciation facies, comparable to the black, kaolinitic and pyritic facies of the Lilangu Member could be identified in this part of the basin.

As mentioned above, the glacial nature of the Karoo deposits in Angola is uncertain and requires clarification (Oesterlen, 1976, 1979).

Fig. 16. Portion of drill core 82/56 from the depth interval 931–947 m in the Dekese borehole in the central portion of the Congo Basin. The cut face of the core shows a laminate consisting of couplets of dark mudstone and light coloured, very fine sandstone with several dropstones recognizable by the impact structures below and the draped sediment above. Especially the clast at the top left of the picture is a very fine example. The core is from the topmost unit of the glacigene succession. Hübner (1965) interpreted this sequence as varve deposits. Reproduced from Hübner (1965), but in corrected orientation.

The Late Carboniferous/Early Permian strata along the northern limit of the Karoo glaciation still exhibit clear signatures of glacial action, like the tillites, periglacial and termino-glacial deposits of Gabon. These were brought into the basin from some highlands to the east-southeast, which is in accordance with the general palaeogeographic picture (e.g. Rust, 1975). However, as mentioned before, instead of the Ecca-equivalent coal measures, the glacigene sequence is overlain here by strata of a mildly evaporitic environment (Jardiné, 1974). An identical situation is known from the southern Arabian Peninsula, demonstrating the very rapid climatic change and the associated global shift of climatic belts in Early Sakmarian times (Wopfner, 1999).

4. Ecca Group and equivalents

4.1. Introduction

Rubidge (1858) coined the term "Ecca" for argillaceous sedimentary strata exposed in the Ecca Pass, near Grahamstown in the Eastern Cape Province, South Africa.

The rocks of the Ecca Group, essentially a clastic sequence of mudstone, siltstone, sandstone, minor conglomerate and coal (in places) outcrop extensively in the main Karoo Basin in South Africa, and in all the other southern African Karoo Supergroup localities (SACS, 1980; Cairncross, 1987; Johnson et al., 1996; Johnson et al., 1997). In the type-Karoo Basin of South Africa, the Ecca Group occurs between the Late Carboniferous Dwyka Group and the Late Permian-Middle Triassic Beaufort Group, occupying most of the Permian time slot for Karoo Supergroup lithologies (Fig. 2). Elsewhere, the Ecca occupies the same time interval, but the lithostratigraphic names of the South African Dwyka and Beaufort Groups are different in neighbouring countries (Cairncross, 2001). The Ecca Group attains its maximum thickness of 3000 m in the southern part of the main Karoo Basin, i.e. the foredeep. Elsewhere in southern Africa it is considerably thinner.

The absolute age of the Ecca Group is not perfectly constrained, and most age determinations and correlations rely on fossil wood biostratigraphy (Bamford, 2000) and palynology. Radiometric ages have been determined from tuff beds in the Dwyka Group in Namibia and similar tuff beds in the basal section of the Prince Albert Formation in the southern Karoo Basin. These ages are 302 ± 3.0 Ma and 299 ± 3.2 Ma for the Namibian Dwyka, and 288 ± 3.0 Ma and 289 ± 3.8 Ma for the Prince Albert Formation (Bangert et al., 1999). These absolute ages are generally in agreement with the 290 Ma age inferred from palynomorphs (Loock and Visser, 1985; MacRae, 1988; Visser, 1990; Fig. 2).

Ash beds in the Collingham Formation in the southern Karoo Basin have been dated at 270 ± 1 Ma (Catuneanu et al., 2002, quoting De Wit and Bowring pers. comm.; Fig. 2) and the overlying Ripon Formation is correlated with the northern Vryheid Formation (Catuneanu et al., 2002). This correlates well with the generally accepted age for the Permian coal deposits contained in the Ecca Group as Artinskian–Kungurian and Ufimian-Kazanian (Cairncross, 2001).

4.2. Retroarc foreland system

The lithostratigraphical subdivisions of the Ecca Group in southern Africa are presented in Fig. 17. Usage of the term "Ecca Group" outside of the main Karoo Basin is questionable because the criteria used to define the Ecca may not be applicable in the other regions (M.R. Johnson, pers. comm., 2004). If correlation at group level is questionable, then formational correlation is even more doubtful. Notwithstanding these problems, most of the Permian ("Ecca") rocks in southern Africa have some form of lithostratigraphic subdivision, either at a formational or sometimes at a member level (Fig. 17). For simplicity's sake, the term Ecca is retained here.

With few exceptions, the Ecca Group is composed of mixed clastic sediments, but minor carbonates are found in the Huab Basin in Namibia (Fig. 1). In most southern African deposits, the Ecca Group consists of two or more formations. The most complex subdivision is in the southern part of the main Karoo Basin in South Africa where up to seven formations are defined (Wickens, 1994; Johnson et al., 1997; Grecula et al., 2003a). The lateral correlation of these, even between the western and eastern extremities in this part of the basin, is somewhat difficult and problematical with lateral facies variations causing the merging of one formation with another (Johnson et al., 1997). Subbasins are recognized in the southern Karoo Basin, namely the western Tanqua, Laingsburg and southern subbasins (Wickens, 1994; Catuneanu et al., 2002). Although these share some correlatable formations, for example the Prince Albert, Collingham (Viljoen, 1992a) and Whitehill (Fig. 18), others such as the Vischkuil (Viljoen and Wickens, 1992), Laingsburg (Viljoen, 1992b) and Skoorsteenberg are not as laterally extensive (Fig. 17). The complexity of the main Karoo Basin stratigraphy is related to its mode of origin, deep-water and shallow-water marine turbidites and submarine fan deposits from specific source areas, which are rare or absent in other southern African Karoo basins. The northern Karoo Basin Ecca formations, namely the Pietermaritzburg, Vryheid and Volksrust Shale, do not have southern facies equivalents, although the coal-bearing Vryheid Formation is considered the time equivalent of the upper Prince Albert and Whitehill Formations (Van Vuuren and Cole, 1979; Visser, 1993; Langford, 1992; Fig. 17) and the Volksrust Formation grades laterally into the Tierberg Formation. The Vryheid Formation is a clastic wedge, thickest in the northeast and east and pinching out towards the south and southwest (Hobday, 1978; Van Vuuren and Cole, 1979; Veevers et al., 1994a,b,c).

The first comprehensive sedimentological interpretation based on modern facies analysis of portions of the Ecca was by Hobday (1973). He interpreted the Vryheid Formation (then called the Middle Ecca) in terms of a deltaic facies model. Prior to this, various other authors had implied certain depositional environments elsewhere in southern Africa, but these mostly predated modern facies analysis techniques.

The most convenient way to describe the palaeogeographic setting and accompanying depositional environments of the Ecca in the African Karoo basins is to view these in time slices (Langford, 1992). Following the Dwyka glaciation, the Karoo basins typically contain a variety of facies ranging from meltwater rain-out debris, glaciofluvial and glaciolacustrine deposits, as found in the northern Karoo Basin (Le Blanc Smith and Eriksson, 1979), contemporaneous with deep water marine sedimentation in the foredeep (Smith et al., 1993; Visser, 1997; Catuneanu et al., 2002). Similar glacigenic deposits are found in the other southern African basins.

In the main Karoo Basin, during the **Asselian-Sakmarian**, the argillites of the Prince Albert Formation and lateral equivalents in Namibia and Botswana were deposited under deep to shallow marine conditions (Visser, 1994; Catuneanu et al., 2002). The Whitehill Formation

	ECCA GROUP					
	Early Permian				Late Permian	
BASIN	**Asselian**	**Sakmarian**	**Artinskian**	**Kungurian**	**Ufimian / Kazanian**	**Selected References**
SOUTH AFRICA						Johnson *et al.* (1996 & 1997)
Main Karoo (southwest)	Prince Albert (mds)	Whitehill (mdsc) & Collingham (tuf; mds)	Skoorsteenberg (sst; mds), Tierberg (mds)	Kookfontein (mds) & Waterford (sst)		" "
(south)	Prince Albert	Whitehill &Collingham	Laingsburg (sst; mds), Vischkuil (mds; sst)	Fort Brown, Waterford (mds; sst)		Grecula *et al.* (2003)
(southeast)	Prince Albert	Whitehill & Collingham	Ripon (sst)	Fort Brown & Waterford		
(north & northeast)	Pietermaritzburg (mds; slt)		Vryheid (mds; slt; sst; cgl; c)		Volksrust Shale (mds; slt)	Cairncross (2001)
Lebombo	Pietermaritzburg		Vryheid		Volksrust Shale	
Springbok Flats	Hammanskraal (sst; mds; c)					Johnson *et al.* (1996)
Ellisras	Wellington (mds)	Swartrant (sst; mds; c)			Grootegeluk (mds; c)	Dreyer (1994); De Korte (1995); Faure *et al.* (1996); Johnson *et al.* (1996)
Tshipise	Madzaringwe (sst; mds; c)			Mikambeni (slt; mds; c)		McCourt and Brandl (1980); Sullivan *et al.* (1994)
SWAZILAND	Pietermaritzburg		Vryheid		Volksrust Shale	(Cairncross, 2001)
BOTSWANA						Clark *et al.* (1986)
Kalahari:						Smith (1984)
(southwest)	Kobe (mds)		Otshe (sstp; sst; mdsc)			"
(southeast)	Makoro (mds)		Kamotaka (sstp)	Morupule (mdsc; c)	Serowe (mdsc; c)	"
(central)	Bori (mds)		Kweneng (sst)	Boritse (sst; c)		"
(east)	Bori		Mosomame (sstp; c)	Mmamabula (mdsc; sstp)	Korotla (slt)	"
(northeast)	Tswane (mds)		Mea Arkose (sstp)	Tlapana (mds)		"
(northwest)	Tale (mds; mdsp)			Marakwena (sstp)		"
Tuli	Mofdiahogolo (mds)		Seswe (mds; mdsc; c; sst)			Bordy and Catuneanu (2002); Smith (1984)

Fig. 17. The lithostratigraphic subdivision of the "Ecca" Group for Karoo basins in Africa. Note that some lithologies have Formational status while others have informal status and that dolerite sills and dykes cross-cut the Ecca Group lithologies in many regions. A few of the East and Central African subdivisions are unnamed. The rigid placing of the lithostratigraphic units into the specific Permian stages is problematical because absolute ages are not available, only relative or palynologic dates. Dashed lines between table cells indicate areas of overlap. Main lithofacies: Cgl = conglomerate; sstp = pebbly sandstone; sst = sandstone; slt = siltstone; mds = mudstone; mdsp = pebbly mudstone; mdsc = carbonaceous mudstone; c = coal; lms = limestone; tuf = tuf.

carbonaceous shale in the main Karoo Basin and in Namibia contains marine fauna including the reptile *Mesosaurus*, the fish *Palaeonsicus* (Fig. 19) and the crustacean *Notocaris tapscotti* (Smith et al., 1993; Johnson et al., 1997). These

BASIN	Asselian	Sakmarian	Artinskian	Kungurian	Ufimian / Kazanian	References
NAMIBIA						Hegenberger, (1992)
Karasburg	Prince Albert (mds)	Whitehill (mds)	Aussenkjer (sst; mds)			Schreuder & Genis, (1975)
Aranos	Prince Albert (sst; mds, c)	Whitehill	Vreda (sst)			Kingsley, (1985)
Waterberg	Tevrede (cgl; sst; mds; c)					Horsthemke et al. (1990) Holzförster et al. (1999)
Ovambo	Prince Albert (sst; slt, mds; c)					Momper (1982)
Huab	Verbrande Berg (sst; mds; mdsc; c) & Tsarabis (sst; slt; mds) Huab (=Whitehill) (slt; mds; lms)					Hegenberger (1992)
ZIMBABWE						
Tuli (Save)	(unnamed sandstone)	Fultons Drift Mudstones				Barber (1986a)
Save	Lower Mkushwe Sandtone	Lower Mkushwe Shale (c)	Songwe Grits (sstp; sst)	Malilongwe Shale (c) & Mkwasine (sstp; sst; mds)	Marare Mudstone (c)	Barber (1987)
Mid-Zambezi (Wankie)	Lower Wankie Sandstone	Black Shale (mds; c)	Upper Wankie Sandstone		Lower Madumabisa Mudstone	Bartholomew (1992)
MOZAMBIQUE						
Tete	Productive Series (sstp; sst; mdsc; c)				Matinde Series (sst; mds)	Neto (1976)
MALAWI						
Southern Basins (Sumb / Chiromo)	(No Karoo stratigraphy)				Unnamed cgl / Unnamed mds; c	Kreuser, (1994)
Northern Basins (Ngana)	(No Karoo stratigraphy)	Basal cgl	Lower Coal Series (sst; mds; c)	Upper Shale Series (mds)		Ortlepp (1977)
Northern Basins (Livingstonia)	(No Karoo stratigraphy)	Basal cgl	Unnamed sst & c		Unnamed sst; slt; mds	Cooper and Habgood (1959)
ZAMBIA						Money (1972);
Mana Pools (Gwembe)	Siankandobo sst & Maamba sst		Gwembe Coal (sst; mds; c)			Money and Drysdale (1975); Nyambe and Utting (1997)
Lukusashi (Luano)	Unnamed sst & Red mds		Gwembe Coal (sst; mds; c)			Gair (1960)
Luangwa	Luwumbu Coal Formation (sst; slt; mds; c)				Lower Madumabisa (sst; mds)	Nyambe and Dixon (2000)
Barotse (central Zambia)	Kado Sandstone (sst)		Luampa Coal (sst; mds; c)		Lower Madumabisa	Money (1972 & 1981)

Fig. 17 *(continued)*

organic, carbon-rich muds were deposited under anoxic bottom conditions (Visser, 1992a,b; Johnson et al., 1997). Minor sand-rich interbeds originated under shallower conditions as distal turbidites and storm deposits (Cole and McLachlan, 1991, 1994). The Collingham Formation (Fig. 18) has been interpreted as passive suspension settling of mud intermixed with distal turbidites, periodically interrupted by volcanic ash fallout (Viljoen, 1994). The latter

BASIN	Asselian	Sakmarian	Artinskian	Kungurian	Ufimian / Kazanian	References
ANGOLA						
?	Unnamed sstp	Lower Cassanje (sst; mds)	Middle Cassanje (sst)	Upper Cassanje (sst; mds)		Rocha-Campos and de Oliveira (1972)
TANZANIA						Semkiwa *et al.* (1998); Kalkreuth *et al.* (1999); Wopfner (2002)
Ruhuhu		Mchuchuma (sst; mds; c)	Mbuyura (sst; mds)	Mhukuru (sst; mds; c)		Semkiwa (1992)
Metangula (Mhukuru)		Mchuchuma (sst; mds; c)	Mbuyura (sst; mds)	Mhukuru (sst; mds; c)		Wopfner (2002)
D.R. CONGO						
Congo	Unnamed sst & c	Coal Measures, Lukuga Formation mst.&sst. Unnamed mds				Cahen (1954); Cahen and Lepersonne (1978)
KENYA						
Duruma				Lower Taru grits (cgl; sstp; sst) Upper Taru grits (sstp; sst)		Mbede (1987)

Fig. 17 *(continued)*

Fig. 18. The Whitehill Formation (arrowed) overlain by the Collingham Formation, outcropping in the Laingsburg district, southern part of main Karoo Basin, South Africa.

Fig. 19. *Palaeoniscus capensis* fish from the Whitehill Formation.

have undergone secondary alteration to K-bentonites (Fig. 20) and have been traced northeastward across the main Karoo Basin as far as Kimberley and Bergville (Viljoen, 1992a).

During the **Ufimian-Kazanian**, terrestrial depositional systems predominated in most southern African Karoo basins. Exceptions are the Volksrust Formation in the northern part of the main Karoo Basin, The Tierberg Formation in the central part of the basin and the Fort Brown and Waterford formations in the south. The Volksrust argillaceous succession represents a final transgressive phase with initial deltaic progradation in proximal northern areas giving rise to the upper part of the Vryheid Formation (Van Vuuren and Cole, 1979). Shallow marine settings were present in the north (Tavener-Smith and Cooper, 1988; Cairncross et al., 1998) with deepening of the basin in the south, prior to massive Beaufort Group clastic influx principally from the south during the Tatarian (Langford, 1992; Veevers et al., 1994c). The uppermost Ecca

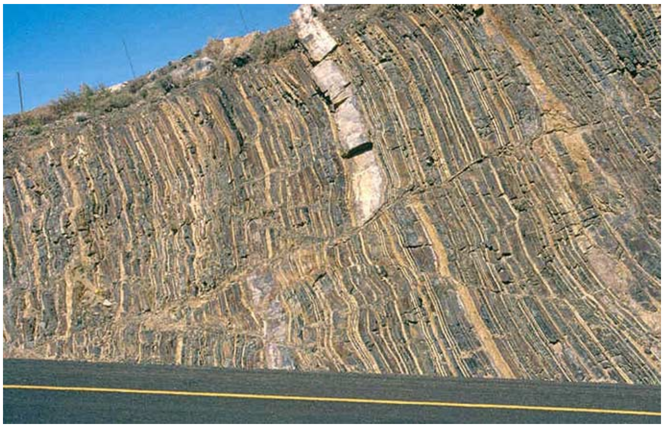

Fig. 20. Steeply dipping beds of the Collingham Formation exposed in a road cutting west of Laingsburg, southern part of main Karoo Basin. The yellow beds are altered volcanic tuf interlayered with mudrock. The thick white bed is chert.

formations in the main Karoo Basin, the Waterford and Fort Brown in the south, were deposited under shallow marine/paralic conditions. The Fort Brown rhythmites are marine shelf shales and pro-delta deposits. These were most likely the distal delta deposits to the overlying Waterford Formation which displays delta front facies assemblages (Johnson et al., 1997). Sandstone and mudstone dominate this final portion of the Ecca in the other basins, the sandstone being primarily fluvially-derived and the mudstones, lacustrine.

4.3. Eastern rift basins

According to lithofacies and chronostratigraphic comparisons, the base of the equivalent unit of the basal Ecca Group would be the black, kaolinitic deposits of the Lilangu Member of the Idusi Formation and its equivalents in other extensional basins of eastern Africa and southern Arabia. However, the unconformity at the base of the coal-bearing Mchuchuma Formation, representing a time of deformation and erosion, clearly separates the deglaciation facies from the succeeding coal bearing succession. Therefore, the terms "Ecca, etc." equivalents cannot be used in a strictly correlative sense.

Typical lithological equivalents of the Ecca Group are the mainly fluviatile, coal bearing deposits of the Mchuchuma Formation of the Ruhuhu, Ilima/Kiwira and Galula basins (Semkiwa, 1992; Semkiwa et al., 1998) in Tanzania and their time equivalents in Madagascar and Zambia of Artiskian age and the late Kungurian to early Kazanian, generally paludal coal deposits of the Mhukuru Formation and its equivalents in Mozambique. These two coal-bearing sequences contrast with the intervening Mbuyura Formation, the red bed character of which is reminiscent of a Beaufort lithofacies (see Fig. 11).

The salient lithostratigraphic features of the eastern rift basins and the western sag basins (Congo and Angola) are summarized in Fig. 17. The common features of the Ecca Group in the foreland Karoo basin are that all the sequences are characterized by mixed clastic sequences. The sequence is poorly described in the Congo Basin which has the Permian Lukuga Series and associated unnamed mudstones and sandstones (Fig. 17).

The Ecca stratigraphy is well documented in Namibia, Botswana, Zimbabwe and Tanzania (Fig. 17). It is less well described in Zambia, Malawi and Kenya. For example Some African Karoo basins were sites of non-deposition or have sections of stratigraphy eroded away. For example the early Permian in Malawi (Fig. 17) has missing stratigraphy, as do the Waterberg and Ovambo basins in Namibia. The complete southern African Karoo "Ecca" lithostratigraphic subdivisions, together with their dominant lithologies, are presented in Fig. 17.

In the Aranos and Karasberg basins, the lithostratigraphy and depositional environments mirror those in the Main Karoo basin with exception of the Vreda Formation sandstone that overlies the Whitehill Formation (Kingsley, 1985) and the Aussenkjer Formation (Schreuder and Genis, 1975) in the Karaberg basin. The Waterberg, Huab and Ovambo rift basins contain clastics—sandstones, mudstones, conglomerates, and some coal and limestone (Fig. 17). Most of the post-Sakmarian Formations are missing in these latter three basins.

The lithostratigraphic terminology together with the constituent lithofacies that comprise the individual formations for the remaining eastern rift basins is summarized in Fig. 17. The common element in all these basin fills is alternating sandstone, mudstone and conglomerate, and some coal. In some basins, for example the southern basins of Malawi, there were periods of non-deposition, and some lithologies are not classified into formations but remain unnamed. Relatively recent work in Tanzania (Kreuser, 1994; Semkiwa et al., 1998; Kalkreuth et al., 1999; Wopfner, 2002) provides good lithological descriptions of this country's rift basins. The Mid-Zambezi basin (Fig. 1) has also been well documented by Barber (1986, 1987) because of the economic coal deposits that are exploited in at the Wankie Colliery (Fig. 17).

The southern African rift basins to in Zambia, Zimbabwe, Malawi, Tanzania, Mozambique and Kenya are all characterized by terrestrial depositional systems (Cairncross, 1987, 2001). These constitute lacustrine and fluvial overbank settings for many of the mudstones and shales in the rift basins, and fluvial and fluvio-lacustrine origins for the bulk of the sandstone and siltstone. "Grits" are documented in basins such as Save in Zimbabwe, and in Kenya in the Duruma Basin which constitute coarse-grained bedload alluvial or distal fan sandstones. Some regions were high ground and sites of non-deposition such as the northern basins of Malawi (Ortlepp, 1977; Langford, 1992).

The Mpawashi, Fimbia and the lower part of the Lower Madumabisa formations of the Luangwa Basin correlate with the Ecca Group of the main Karoo Basin. In the Morondava Basin of Madagascar, the Coal Beds and the

Lower Redbeds may also be regarded as time equivalents of the Ecca Group.

The apparently different timing of the tectonic events compared to those in the main Karoo Basin is evident in the Tanga and Duruma basins of northern Tanzania and southern Kenya, where the basal parts of the overstepping Tanga Beds and Taru Formation chronostratigraphically correlate with the Ecca, but their depositional cycle extends well into Beaufort time.

4.4. Western sag basins

In the Congo Basin, Ecca equivalents are represented by the coal measures and the succeeding "Transition Beds" of the Lukuga area (Boutakoff, 1948). Brownish claystones and sandstones, resting with a basal conglomerate on the glacigene deposits encountered in the Dekese drillhole are labelled "periglacial sediments" by Hübner (1965), but unfortunately their exact age is not known. The lithology is similar to the siliciclastics associated with the coal measures, hence a correlation with the Ecca would be feasible. Daly et al. (1991) depict the extend of the "Lower Karoo" almost up to the base of the Triassic, but unfortunately they lump the total succession within the term Lukuga Formation, making a differentiation impossible.

The lack of reliable age determinations of the early/middle Permian sedimentary succession of the Angola Basin precludes an exact correlation. The deposits predate the Late Permian to Early Triassic Fish Beds (Oesterlen, 1976, 1979), and are therefore older than Beaufort.

Ecca equivalents of the Gabon Basin comprise grey to reddish, gypsiferous siltstones, sandstones and marls (Jardiné, 1974) which, like the post-glacial deposits of southern Arabia (e.g., Khuff Formation) are indicative for an evaporative environment (Wopfner, 1999).

4.5. Economic aspects of the Ecca Group

Coal is by far the major economic deposit contained in the Ecca Group. Some coal deposits occur in Early-Late Permian strata, most notably the thick (±80 m) coal-shale sequence of the Grootegeluk Formation in the Ellisras Basin, South Africa (Fig. 1; Dreyer, 1994) (Fig. 17). The coal seams are not basin-specific, but time-constrained to the **Artinskian-Kungurian** Stage. Therefore coal deposits occur in all three basin types and are described here collectively. The coal-forming period was characterized by an extensive peat-forming period during which time the subcontinent's coal deposits originated, although coal does not occur in all these deposits (Cairncross, 2001). For example, the southern Karoo foredeep was receiving deep-water clastic sediment that now constitutes the Ripon Formation. The Ripon Formation, and its correlatives, the Tierberg and Skoorsteenberg Formations in the Tanqua subbasin and the Vischkuil and Laingsburg Formations in the Laingsburg subbasin (Figs. 21 and 22) have been well documented as submarine fan complexes (Johnson et al., 2001; Catuneanu et al., 2002; Grecula et al., 2003a,b; Van der Werff and Johnson, 2003). The overlying Fort Brown and Kookfontein Formations are shallow marine successions (Cole et al., 1990, 1998).

With the exception of the Late Triassic Molteno coalfield in South Africa, most of the region's coal is contained in Artinskian-Kungurian strata of the Permian Ecca Group. The host rock to the coal varies from basin to basin. In some cases, such as the main Karoo Basin, eastern Botswana, and southern Namibia, the coal seams occur interbedded in sandstone (Fig. 23). In contrast, at Wankie in Zimbabwe, and in Mozambique, the coal is interleaved in mudstone/shale sequences (Fig. 17). There are two general periods of coal formation, one in the late part of the Early Permian, the other in the early part of the Late Permian. In the northern main Karoo Basin, these swamps were associated with paralic and fluvio-deltaic depositional systems with coal seams capping upward-coarsening

Fig. 21. A submarine channel (way-up to the right) incised into turbidites of the Laingsburg Formation, Laingsburg district, southern part of main Karoo Basin, South Africa.

Fig. 22. Well-developed load casts on the base of a turbidite in the Skoorsteenberg Formation on the farm Blouheuwel, southern part of main Karoo Basin, South Africa.

Fig. 23. Two bituminous coal seams, each approximately 2 m thick, contained in bedload fluvial sandstones in the Vryheid Formation, Vryheid district, northeastern part of main Karoo Basin, South Africa.

deltaic and upward-fining fluvial successions (Cairncross, 1987, 1989, 2001). Some torbanites occur in back-barrier, lagoonal settings (Winter, 1985; Christie, 1988). The other southern African basins to the north and west contain similar terrestrial deposits. During this period, the Kalahari Basin was characterized by the deposition of fluvio-deltaic sands, muds and peat (Smith, 1984). Different facies assemblages exist in other basins, e.g., the Gwembe Formation in Zambia (Money and Drysdall, 1975).

The Permian Karoo coal ranges in rank from high-volatile bituminous to anthracite. Regional variations in rank are attributed to differences in geothermal gradients and local effects of dolerite intrusions (Falcon and Ham, 1988; Cairncross, 1989; Snyman and Barclay, 1989). As with many other Permian Gondwana coals, the southern African deposits are generally relatively high in ash and inertinite (Falcon, 1986a,b). Most coal mined is used for local power consumption although some is exported to overseas markets.

Extensive coal exploration has been carried out in the Karoo basins of southern Tanzania and northern Mozambique. Coal of the Mchuchuma Formation is being mined in the Ilima/Kiwira Basin in south-west Tanzania. The coal seams form the end-member of fining-upward sequences, mainly of point bar cycles (Semkiwa, 1992; Semkiwa et al., 1998). Subcommercial quantities of natural gas have been encountered in the north-central part of the Karoo Basin.

5. Beaufort Group and equivalents

5.1. Introduction

The term Beaufort "Beds" was first introduced by Jones (1867, quoted in North, 1878) for sedimentary rocks of the lower part of the Karoo "Series" at Beaufort West in South Africa but has subsequently been expanded to include a wider range of fluvially deposited Permo-Triassic rocks in the main Karoo Basin (Fig. 24). The absolute age of the Beaufort Group is not perfectly constrained but the wealth of fossil tetrapods and the extensive exposures in the Karoo Basin of South Africa has allowed biostratigraphic subdivision (Fig. 25; Keyser and Smith, 1978; Kitching, 1977; Rubidge et al., 1995) into eight biozones which are listed in stratigraphic order: *Eodicynodon*, *Tapinocephalus*, *Pristerognathus*, *Tropidostoma*, *Cistecephalus*, *Dicynodon*, *Lystrosaurus* and *Cynognathus* assemblage zones which have allowed for correlation with other better dated fossil-bearing successions elsewhere in the world. Several refinements have recently been suggested. Work on the Permo-Triassic boundary in the south of the basin (Smith, 1995; MacLeod et al., 1999) has shown that there is an overlap in the ranges of *Dicynodon* and *Lystrosaurus*, as first proposed by Hotton (1967). The base of the *Lystrosaurus* Assemblage Zone (i.e., the first appearance datum of *Lystrosaurus*) is now considered to be in the Permian, and the Permo-Triassic boundary (251 Ma) is considered to be within a non-fossiliferous "event bed" situated above the last appearance datum of *Dicynodon* (Smith and Ward, 2001). Based on the stratigraphic distribution of the capitosaurids (mastodonsaurids) *Kestrosaurus dreyeri*, *Xenotosuchus* (*Parotosuchus*) *africanus* and *Paracyclotosaurus morganorum*, the *Cynognathus* Assemblage Zone is considered to comprise three subzones known informally as subzones A, B, and C which have been correlated with Early to Middle Triassic aged successions in Europe and Asia (Hancox et al., 1995; Shishkin et al., 1995; Hancox, 2000).

5.2. Retroarc foreland system

The term Beaufort Group is restricted to fluvially deposited Permo-Triassic rocks deposited within the Main Karoo Basin of South Africa. These rocks cover a surface area of some 200 000 km^2, making up about 20% of the total surface area of South Africa, and attains a maximum cumulative thickness of about 7000 m in the foredeep, thinning rapidly northwards (Johnson et al., 1997). Beaufort Group strata consist predominantly of mudstones and siltstones with subordinate lenticular and tabular sandstones deposited by a variety of fluvial systems. The boundary with the underlying Ecca Group is transitional and diachronous, recording a gradual change from deltaic to fluvial depositional systems (Rubidge et al., 2000). As a result the boundary is not always easy to place, although thick, laterally persistent delta-front sheet sandstones at the top of the Ecca Group make a useful local lithostratigraphic marker.

By Beaufort Group times, the climate had warmed sufficiently to become semi-arid with seasonal rainfall capable of supporting the growth of *Glossopteris* dominated riparian-type vegetation concentrated along watercourses (Smith, 1990). Lower Beaufort sediments were derived from different margins of the Karoo Basin, giving rise to pebbly sandstones in the north and fine-grained sandstones elsewhere (Cole, 1998; Cole and Wipplinger, 1991, 2001;

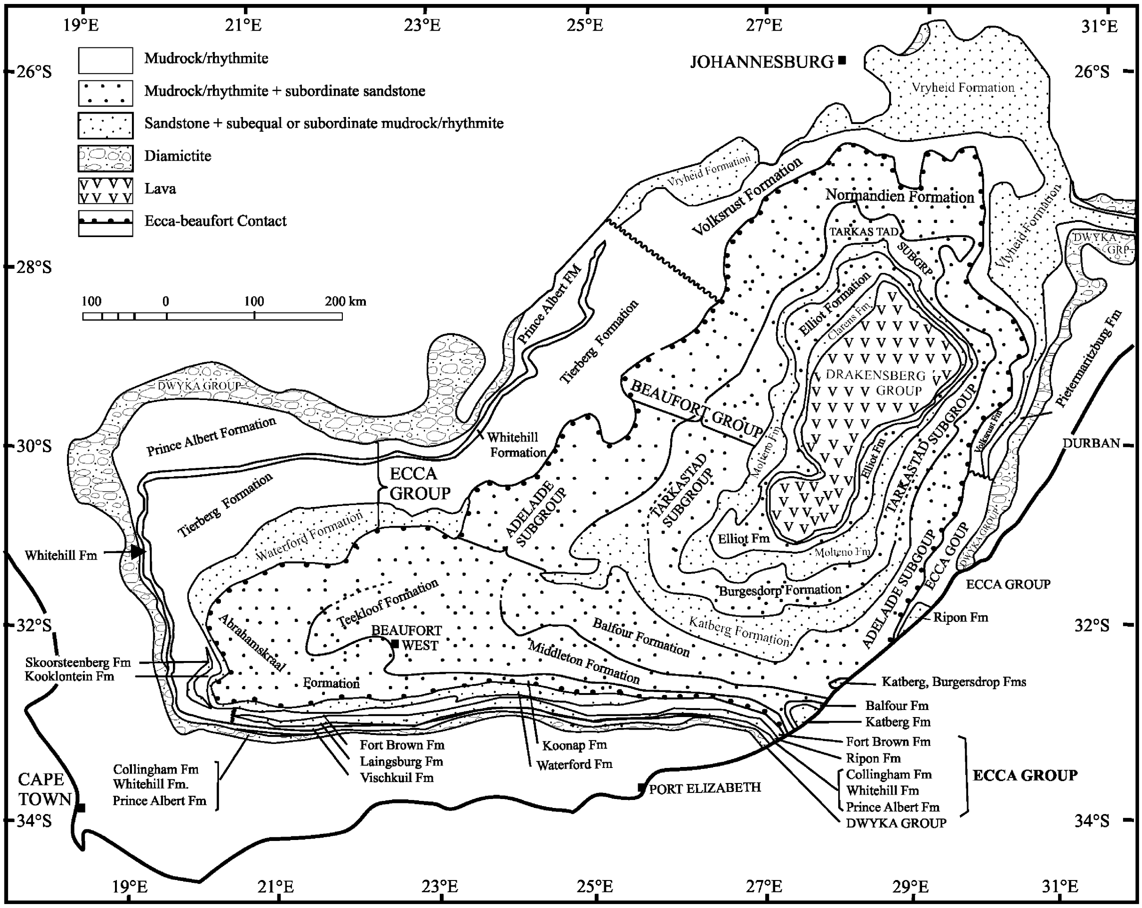

Fig. 24. Schematic plan of the main Karoo Basin showing the geographic and stratigraphic relationship of the formations of the Beaufort Group and the position of the Willowmore arch (modified from Johnson et al., 1997).

Groenewald, 1989). The lithostratigraphic subdivisions of the Beaufort Group are presented in Fig. 25, but as they do not all have basin-wide distribution, biostratigraphic correlation is a more effective means of establishing time equivalence, both within the basin and with other Beaufort-aged deposits in south-central Africa.

In the south-western Karoo Basin sedimentation of the Beaufort Group was initiated in the middle Permian by uplift in the Gondwanide mountainlands (Hälbich, 1983; Cole, 1992; Veevers et al., 1994c; Rubidge, 2005). This resulted in deposition, in the foredeep, of a 3500 m thick (Cole et al., 1998) fining-upward succession of sandstones and purple mudstones containing numerous thin chert bands and rich tetrapod faunas (Abrahamskraal and Teekloof formations of the Adelaide Subgroup). The succession was deposited mainly by overbank flooding of large meandering rivers of variable sinuosity, draining an extensive alluvial plain sloping gently towards the northeast in the direction of the receding Ecca shoreline (Turner, 1978). Deposition occurred under semi-arid climatic conditions as evidenced by the presence of desiccation cracks, palustrine carbonate beds, pedogenic carbonate horizons and gypsum desert-rose evaporites (Keyser, 1966). The irregular accretion topography (Smith, 1987) and preferential preservation of upper flow regime plane beds and lower flow regime ripple cross-lamination within channel sandstones, reflect the seasonally fluctuating discharge regime of the main rivers. Sandstone-rich intervals from 50 to 350 m thick (Cole and Wipplinger, 2001), represent the basal coarse member of at least five major fining-upward megacycles (Visser and Dukas, 1979; Stear, 1980) within the lower Beaufort succession. These sandstone "packages" relate to northeasterly, north-northwesterly and east-southeasterly directed fluvial transport systems (Cole, 1992), interpreted as subsidence-controlled shifts in the locii of channelisation on the alluvial plain (Smith, 1990), and in the case of one "package", the Poortjie Member, climatic control (Cole and Wipplinger, 2001). The overall fining-upward trend of the lower Beaufort succession is interpreted in terms of decreasing foredeep slope, channel gradients and sediment supply (Catuneanu and Elango, 2001; Catuneanu and Bowker, 2001). The presence of calc-alkaline volcaniclastic detritus and "cherts" of tuffaceous origin (Ho-Tun, 1979) suggests that the provenance rocks in the southwest may have included an active andesitic volcanic chain located on the eastern side of the Andean Cordillera in South America and West Antarctica (Veevers et al., 1994c).

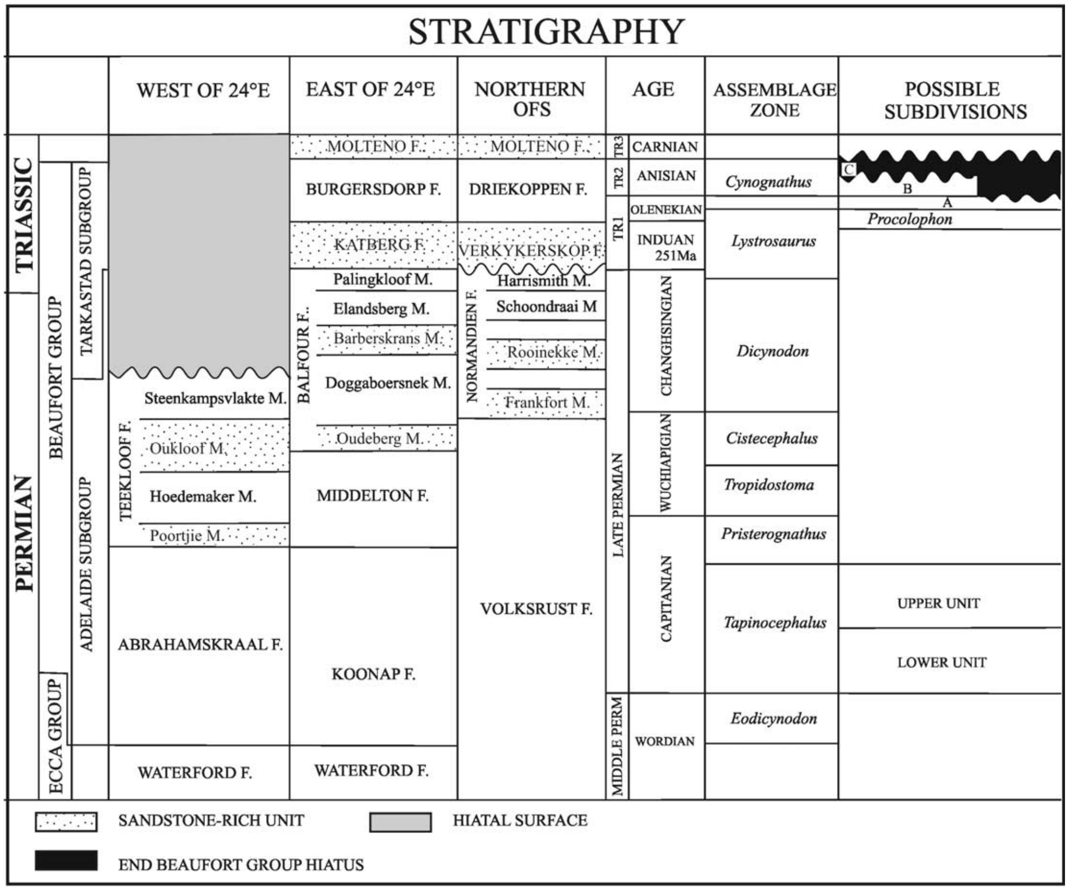

Fig. 25. Relationship between the biostratigraphy and lithostratigraphy of the Beaufort Group in the main Karoo Basin of South Africa.

The Abrahamskraal and Teekloof formations grade, eastwards of longitude 24°, into the Koonap, Middleton and Balfour formations of the eastern Karoo Basin (Fig. 25), over a palaeohigh known as the "Willowmore Arch" (Van Eeeden, 1972). Cole (1998) suggested that this palaeohigh was actually a north-trending trough based on the fact that east- and west-directed palaeocurrents meet over this site and gradually converge northward into the northeasterly and north-northwesterly directed fluvial transport systems. The Koonap and Middleton formations east of 24° comprise a 2800 m thick mudrock-dominated succession consisting of a shallow lacustrine facies at the base, overlain by vertically stacked fining-upward sequences on a variety of scales (200–600 m thick) (Johnson, 1976). The sequences comprise erosively-based sandstone, siltstone and mudstones deposited by delta distributary and meandering river channels, flanked by crevasse splays and extensive areas of mud-dominated floodplain (Figs. 26 and 27). These are overlain by the 120 m thick Oudeberg Member that defines the base of the 2000 m thick Balfour Formation (Johnson, 1976). This member comprises fining-upward sandstone-dominated sequences deposited by a network of low sinuosity streams (Turner, 1978). In the south-central parts of the Karoo Basin around Middleburg/Graaff Reinet the succession above the Oudeberg Member is again dominantly argillaceous. Within this succession are subordinate laterally-accreted sandstone bodies that form a sandstone-rich interval or "package",

Fig. 26. Outcrop of typical Beaufort shales of the Hoedemaker Member (Teekloof Formation) with pedogenic carbonate horizon in foreground. The high sinuosity Reiersvlei Sandstone featured in Fig. 27 caps the cliff section.

Fig. 27. Aerial photo of the Reiersvlei meanderbelt near Fraserburg showing four consecutive point-bar surfaces with "accretion ridges", abandoned channel-fill and crevasse splay.

up to 190 m thick, named the Barberskrans Member (Fig. 25; Tordiffe, 1978). Towards the top of the Balfour Formation the mudrock sequences of the Palingkloof Member change in texture to more siltstone-rich with numerous clay chip-breccia lenses and the first appearance of dark reddish brown mudrock colours is noted. The sandstones too change in geometry from laterally-accreted ribbon bodies to vertically accreted sheet-like bodies with distinctively gullied basal surfaces. The Permian/Triassic boundary has been identified within this Palingkloof Member some 15–30 m below the base of the overlying Katberg Formation (Fig. 25; Smith and Ward, 2001). In the eastern part of the basin, the succession above the Oudeberg Member of the Balfour Formation consists of a sequence of lacustrine mudstones, shales, rhythmites and sandstones with wave ripples, which becomes more sandy and redder in colour towards the top.

In the northern part of the main Karoo Basin the presence of the therapsid *Dicynodon lacerticeps* in the Normandien Formation suggests a time equivalence with the fluvio-lacustrine Balfour Formation in the southeast (Fig. 25). Sediment was deposited in floodbasins and shallow lakes via overbank floods and crevassing from sinuous distributary channels, which gradually deposited coarser sands as energy levels increased (Groenewald, 1989, 1996). Locally, the Beaufort Group sedimentary strata in the northern part of the basin are much coarser-grained. The lowermost strata (30–50 m thick) of the Normandien Formation, informally named the Frankfort Member, have a "coal measures" character not unlike the older Vryheid Formation, and consist of two coarsening-upward deltaic cycles (Groenewald, 1989). The coarse-grained sandstones in the remainder of the Normandien Formation are concentrated in the 20 m thick Rooinek Member and the 15 m thick Schoondraai Member (Fig. 25), which display fining-upward profiles and represent proximal meandering river palaeoenvironments (Groenewald, 1989). These sandstones contain conglomerates with quartz and granite clasts that were derived from granitic highlands to the east (Eastern Highlands) and the Witwatersrand Arch to the north (Groenewald, 1989; Cole and Wipplinger, 2001).

A sudden change in depositional conditions is thought to have occurred at the Paleozoic-Mesozoic boundary in the main Karoo Basin due to episodic, but pronounced tectonic uplift of the southeasterly source area as well as rapid climatic warming initiated by the end-Permian extinction event (Smith and Ward, 2001). The injection of greenhouse gases into the atmosphere, possibly from massive basaltic eruptions in Laurasia and/or methane release from the Panthalassian ocean bed, or even an extraterrestrial impact (Bekker et al., 2001), resulted in aridification on a Pangean scale. However, active tectonism along the southern margin of the main Karoo Basin resulted in a steepening of the foredeep slope and basinward progradation of the Katberg Formation clastic wedge at this time. The Permo-Triassic "event bed" has been defined both sedimentologically and biostratigraphically some 15–30 m below the base of the Katberg Formation (Smith, 1995). Internally the sandstones of the Katberg Formation are dominated by upper flow regime plane beds associated with heavy mineral laminae, with lesser but significant amounts of cross-stratification of dune and transverse bar origin (Fig. 28; Stavrakis, 1980). Intraformational mud pebble and glaebule conglomerate lenses are common. Large brown-weathering

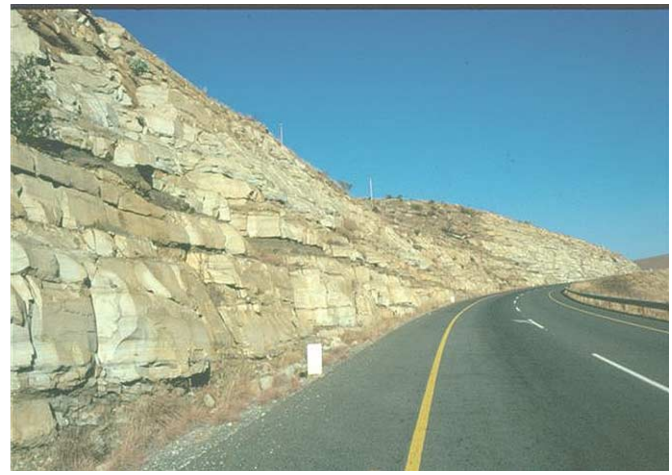

Fig. 28. Outcrop of the Katberg Formation at Katberg Pass showing numerous vertically stacked and amalgamated sheet sandstones typical of the proximal braidplain facies of this formation.

spherical calcareous concretions of early diagenetic origin are characteristic of the Katberg sandstones throughout the basin (Johnson, 1976). The Katberg Formation attains a maximum thickness of about 1000 m near East London (Hiller and Stavrakis, 1984), and can be divided into two main progradational wedges separated by floodplain aggradational fines. It was deposited under arid climatic conditions within the more distal parts of a sandy, bed-load-dominated, ephemeral braided stream complex draining a source area composed predominantly of granitic, metamorphic and alkaline volcanic rocks (Hiller and Stavrakis, 1984; Smith, 1995). The overlying Burgersdorp Formation, which hosts a rich reptilian and amphibian fauna, consists mainly of dark reddish brown mudstone with subordinate siltstones and sandstones deposited on a semi-arid, slowly aggrading floodplain drained by sluggish meandering stream channels, which supplied water and sediment to the pedogenically-influenced overbank environments via crevasse splays (Hancox, 1998). Lakes and ponds developed on the floodplain, but these were mostly temporary features of the dry alluvial landscape, which suffered a period of regional downwasting (the so called "Ladinian vacuity"; Cole, 1992; Veevers et al., 1994c) prior to deposition of the Molteno Formation (Hancox, 1998; Neveling, 2002).

5.3. Eastern rift basins

Beaufort Group equivalents, unrelated to compressional flexural tectonics, occur in various other basins of south-central Africa (Fig. 29). These, eastern rift basins are here taken to include extensional basins in Namibia (Pickford, 1995), Botswana (Smith, 1984), Zimbabwe (Boonstra, 1946; Bond, 1973), Mozambique (Haughton, 1963; Latimer et al., 1995), Tanzania (Haughton, 1932; Cruickshank, 1965, 1967; Kaaya, 1992; Markwort, 1991; Wopfner, 2002), Madagascar (Mazin and King, 1991; Smith, 2000) Zambia (Cox, 1969; Crozier, 1970; Utting, 1978) and Malawi (Haughton, 1926; Jacobs, pers. comm., 2003). None of these sequences are as complete, or as well studied as those of the main Karoo Basin (Fig. 11). Fortuitiously the presence of tetrapod fossils has enabled biostratigraphic correlation of these deposits with the more complete succession in the main basin (Fig. 29).

The Waterberg Basin of Namibia is the only Karoo basin in this country that has Beaufort-equivalent strata (Pickford, 1995). No Permian fluvially deposited rocks are present in Namibia, but the Anisian Omingonde Formation has fossils that correlate with the *Cynognathus* Assemblage Zone of South Africa (Smith and Swart, 2002). The predominantly argillaceous lower Omingonde Formation was deposited in a paludal floodplain setting with marginal allucial fans, this is overlain by the much more arenaceous Middle Omingonde Formation which was deposited by Gravel-Bed Braided Rivers and Marginal alluvial fans. The sedimentologically more heterogeneous Upper Omingonde Formation comprises sandstones and mudstones deposited in a fluvial environment of loessic plains and saline lakes (Smith and Swart, 2002).

The Kalahari Basin of southern Africa, situated mainly in Botswana, comprises a number of subbasins (Smith, 1984) which contain Beaufort aged strata but are largely unstudied because they are covered by Cenozoic Kalahari Group beds (Key et al., 1998). Based on palynological evidence from borehole core Key et al. (1998) correlate a thin mudrock succession (Kule Formation; Smith, 1984) which overlies the Otshe Formation in the south west of Botswana with the Beaufort Group of South Africa, while Smith (1984) tentatively correlated the Tlhabala, Kwetla Formations of the Central Kalahari Basin with the South African Beaufort Group.

Although Karoo-aged strata outcrop in the Tuli, Mid-Zambezi and Caborra Bassa basins (Fig. 1) of Zimbabwe, Beaufort Group equivalents are present only in the Mid-Zambezi Basin where coal measures (K2 and K3) are overlain by the Upper Wankie Sandstone (K4) and a thick largely homogenous Madumabisa mudstone interval (K5) and Pebbly Arkose (K6). The undifferentiated Madumabisa mudstones (K5) correlate with the Middel–Late Permian *Tapinocephalus*, *Tropidostoma* and *Cistecephalus* Assemblage Zones of the Beaufort Group (Bond, 1973; Lepper et al., 2000).

Karoo-aged sequences are widespread in Zambia, occurring in the Luangwa, Luano and Zambezi Valleys (Fig. 1). Tetrapod fossils are however known only from the Luangwa Basin, where Wichiapingian and Chansingian tetrapod fossils from the Madumabisa Mudstone Formation correlate with the *Pristerognathus—Dicynodon* Assemblage Zones of South Africa (Kemp, 1976; Lee et al., 1997; King and Jenkins, 1997). This Formation is unconformably overlain by the Anisian Ntawere Formation, which correlates with the Anisian B and C subzones of the *Cynognathus* Assemblage Zone of South Africa (Hancox, 1998). Karoo-aged rocks of the mid-Zambezi Valley Basin of southern Zambia consist of an Upper Permian Madumabisa Formation which is unconformably overlain by the mid-Triassic N'tawere Formation.

In Mozambique, Karoo-aged strata are exposured only in the Upper Zambezi depression, the southern Mozambique Basin and the Metongula Basin. Because of extensive Quaternary cover and resultant lack of outcrop the palaeontological signatures of the latter basin are poorly documented, but in the mudrocks of Member number 10 of the Lugno Series in the Metongula Basin (Haughton, 1963) fossils of the *Pristerognathus* and *Tropidostoma* Assemblage Zones have been reported (Latimer et al., 1995).

The Sakamena Rift Basin, today situated in Madagascar accumulated fluvio-lacustrine mudrocks and sandstones of the Lower Sakamena Formation during the Late Permian (Mazin and King, 1991; Smith, 2000). A period of tectonic quiescence during the Early Triassic allowed significant flooding of the Basin and deposition of the marine rocks of the Early Triassic Middle Sakamena Formation (Smith, 2000).

BEAUFORT GROUP									
	Permian				**Triassic**				**References**
Basin	**Wordian**	**Capitanian**	**Wuchiapingian**	**Changhsingian**	**Induan**	**Olenekian**	**Early Anisian**	**Late Anisian**	
Retroarc Foreland System									
SOUTH AFRICA Main Karoo	*Eodicynodon*	*Tapinocephalus*	*Pristerognathus* *Tropidostoma* *Cistecephalus*	*Dicynodon*	*Lystrosaurus*	"*Procolophon*" *Cynognathus* A	*Cynognathus* B	*Cynognathus* C	Hancox et al. 1995 Rubidge et al. 1995 Hancox 1998 Neveling 2002
Eastern Rift Basins									
BOTSWANA		Tlabala/Kwetla/Kule formations							Smith 1984 Key et al 1998
NAMIBIA Waterberg							Omingonde Fm	Omingonde Fm	Pickford 1995 Smith & Swart 2002
ZIMBABWE Zambezi		Madumabisa Mudstone	Madumabisa Mudstone						Bond 1973 Gaffney & McKenna 1979 Leppeer al 2000
MOCAMBIQUE Metagula Graben			Lugno series						Haughton 1963 Latimer et al. 1995
MALAWI			Chiweta Beds						Dixey 1926 Haughton 1926 Jacobs pers com 2004
ZAMBIA Luangwa Valley			Madumabisa Mudstones	Madumabisa Mudstones			N'tawere Fm	N'tawere Fm	Kemp 1976 Lee et al. 1997 King & Jenkins 1997 Hancox 1998 Damiani et al. 2000
TANZANIA Ruhuhu Basin			Ruhuhu Fm (K5), Songea Group	Usili Fm (K6), Songea Group			Kingori SS (K7)	Manda Fm (K7)	King 1988 Hancox 1998 Gay & Cruickshank 1999 Abdala et al. 2005
MADAGASCAR				Lower Sakamena Fm	Lower Sakamena Fm				Mazin & King 1991 Hewison 1996 Schoch & Milner 2000* Smith 2000
Western Sag Basins									
ANGOLA			Fisch-Schichten						Oesterlen 1979
DR CONGO			Lukunga Series						Haughton 1963 Yemane & Kelts 1990

Fig. 29. Table showing the correlation of Permian and Triassic continental rocks of southern Africa based on tetrapod biostratigraphy.

The most complete Permian-Triassic sequences in the Eastern Rift Basin setting are preserved in the Ruhuhu Basin of Tanzania , with less extensive sections in the Mhukuru, Njuga, Songwe-Kiwara and Mbamba Bay basins, as well as in the coastal region, the latter including the Tanga, Mikumi/Nyakatitu, Ruvu and Selous basins (Kreuser et al., 1990; Wopfner and Kaaya, 1991; Wopfner, 2002). These sequences occur in several NNE-NE striking, intracratonic grabens and half-grabens, and are dominantly terrestrial, except in the Mikumi/Nyakiitu basins, which document a short marine incursion during the Late Permian (Cox, 1935). The Usili Formation of the Songea Group of the Ruhuhu Basin (Fig. 10) preserves faunal elements of the Permian *Tropidostoma*, *Cistecephalus* and *Dicynodon* Assemblage Zones (Gay and Cruickshank, 1999; King, 1988). The Lifua Member of the Manda Beds (Fig. 10) contains *Parothosuchus* and Anisian palynomorphs (Markwort, 1991). It correlates with the Anisian subzones B and C of the *Cynognathus* Assemblage Zone of South Africa (Abdala et al., 2005; Hancox, 1998). Synsedimentary faulting preceeding the onset of deposition of the Manda Beds was important as a control on sedimentation in the upper part of the sequence (Kreuser et al., 1990).

The Karoo sedimentary succession of Malawi comprises basal coal-bearing strata which have been correlated with the Ecca of South Africa (Cairncross, 2001) which are overlain by the fluvially deposited Chiweta Beds which comprise sandstones and mudstones (Dixey, 1926) and has yielded a tetrapod fauna, which correlates with the *Tropidostoma* and *Cistecephalus* Assemblage Zones of the Beaufort Group (Haughton, 1926; L. Jacobs, pers comm., 2004).

5.4. Western sag basins

The Permian-Triassic successions of the western sag basins have not received much research attention and are poorly understood as a result. The Fisch-Schichten rocks in the Malanje area of Northeast Angola is an approximately 10 m thick succession of light grey mudstones, siltstones and sandstones deposited in a closed lake (Oesterlen, 1976, 1979). These deposits have yielded a fossil fish fauna which has been correlated with the Upper Permian and Lower Triassic of Madagascar and is considered to represent the transition between the lower and middle Beaufort Group (Haughton, 1963; Yemane and Kelts, 1990). The Karoo infill of the Congo Basin covers a very large area but is pooly known. The lowermost stratigraphic unit in the basin the Lukuga Series is considered to correlate with the Dwyka and Ecca of South Africa, with the upper "Transitional Beds" consisting mainly of red, green and mottled mudstones with a basal conglomerate at many places which in the eastern part of the basin may be Triassic (Haughton, 1963) and can thus be correlated with the Beaufort Group of South Africa (Sherlock, 1947).

6. Stormberg and Drakensberg groups, and equivalents

6.1. Introduction

Although use of the term "Stormberg Series" for the combined Molteno, Elliot and Clarens Formations, and the Drakensberg Group of the main Karoo Basin (e.g., SACS, 1980) has fallen into disfavour in recent years, the same four-part general lithostratigraphic succession can be identified readily in almost all the central-south African Karoo basins. The base-Molteno angular unconformity, well developed in many basins, indicates a significant tectonic event across the region to usher in "Stormberg" sedimentation. We here group the three sedimentary formations into the Stormberg Group, and the uppermost volcanic rocks into the succeeding Drakensberg Group (cf. Johnson, 1994). Of the many Karoo basins (Fig. 1), the main Karoo, Mid-Zambezi and the Cabora Bassa basins contain the greatest thicknesses of these units, respectively c. 1200 m, 3000 m and 8000 m (Johnson et al., 1996). The same broad tectonic subdivision of the Karoo basins is adopted here as in the rest of this paper: into (1) retroarc flexural foreland-related basins (Main Karoo basin and north to the Ellisras-Tuli-Save basins and most likely all or at least the south-southeastern parts of the Kalahari basin; Fig. 1); (2) eastern rift or extensional basins (Mid-Zambezi and NE to the Tanga and Duruma basins along the Tanzania-Kenya border, plus the Waterberg basin of Namibia; Fig. 1); and (3) western sag basins (Huab Basin, Namibia; others in Angola and the D.R.C.; Fig. 1). However, as published information on the latter group of basins is poor, with few reliable data for the Stormberg-equivalent units, we here concentrate on the first two groups of basins, (1) and (2).

Of the four units, identification of the Molteno-equivalents presents the greatest difficulty, and this Stormberg unit is easily confused with analogous upper Beaufort Group (Permo-Triassic) fluvial deposits. However, commonly the base-Molteno unconformity oversteps older, underlying Karoo units onto basement rocks, thus making it distinguishable, on a regional scale, from the localised-type unconformity beneath the Katberg Formation (Beaufort Group) and correlated fluvial sandstone wedges. Although Molteno-like successions of varying thickness (Fig. 30) occur in many of the African Karoo basins (e.g., Ntabene Formation, Lebombo Basin; "Middle Unit", Tuli Basin; "unit 3" of the Omingonde Formation, Waterberg-Namibia Basin; Kingori Member (K7), Ruhuhu Basin; Rufiji Formation, Selous Basin; Kilulu Sandstone, Tanga Basin), their ages and correlation are uncertain; an upper Beaufort (commonly Katberg) equivalence is generally preferred by most authors to a Molteno correlation, based largely on palaeontological evidence (e.g., SACS, 1980; Holzförster et al., 1999; Bordy and Catuneanu, 2001; Wopfner, 2002). Molteno-type units appear to be absent in the Ellisras (however, the Greenwich Formation here may be a Molteno-equivalent, or, alternatively be part of the Elliot successions; see Johnson et al., 1996) and Huab basins, and only thin (c. 10–25 m), erosively-based, fluvial sandstones are known from Springbok Flats, Tshipise, Save and the Kalahari basins (SACS, 1980; Johnson et al., 1996; Mountney et al., 1998). The Late Triassic Isalo Group in Madagascar may also be an equivalent, with the medial Isalo II fluvial conglomerates and sandstones in the Morondavo Basin having a marked basal unconformity overstepping onto the basement, and being succeeded by transgressive marine Liassic deposits (Piqué et al., 1999). Within the correlated Majunga Basin to the north, Isalo I appears to be the equivalent unit rather than Isalo II (Razafindrazaka et al., 1999).

Units analogous to the Elliot Formation of the main Karoo Basin occur in almost all the African Karoo depositories, with the exception of the Tanga Basin, those on

BASIN	Molteno equivalent unit	Elliot equivalent unit	Clarens equivalent unit	Drakensberg equivalent unit	References
Main Karoo	Molteno (460m) *Carnian-Norian*	Elliot (480m) *Norian-Liassic*	Clarens (c. 300m) *Liassic-Dogger*	Drakensberg (1370m) *Dogger*	Visser (1984); Smith et al. (1993); Johnson et al. (1996); Catuneanu and Bowker (2001)
Lebombo	Ntabene (" 100m)	Nyoka (250m)	Clarens (45m)	Lebombo (>10km)	SACS (1980)
Springbok Flats	Codrington member (c.10m)	Upper Irrigasie (Worthing member; c.80m)	Clarens (c.80m)	Letaba	Roberts (1992); Johnson et al. (1996)
Tshipise	Klopperfontein (20m)	Bosbokpoort and Red Rocks (<280m)	Clarens (150m)	Letaba	Johnson (1994); Johnson et al. (1996)
Tuli	Middle Unit (c.70m)	Upper Unit (200-280m) *Norian-Liassic*	Clarens (140m)	Letaba	Bordy and Catuneanu (2001, 2002a and b)
Save	Upper Mkururwe (c.25m)	Bond, Sandota and Oasis (c.300m)	Aeolian Sandstone (c.130m)	lavas	Johnson et al. (1996)
Ellisras	Greenwich (c. 30m)	Lisbon (c.100m)	Clarens (>120m)	X	Johnson (1994); Johnson et al. (1996)
Kalahari-SW	Lowermost Dondong (very thin)	Upper Dondong (thin)	Nkalatlou (c.60m)	X	Johnson et al. (1996)
Kalahari-central	Lowermost Mosolotsane (<10m)	Upper Mosolotsane (c. 110m)	Ntane (c.60m)	Stormberg	Smith (1984); Johnson et al. (1996)
Kalahari-NE	Lowermost Mosolotsane (<10m)	Upper Mosolotsane (c.70m)	Ntane (c.90m)	Stormberg	Smith (1984); Johnson et al. (1996)
Waterberg	Lower Omingonde (c.220m)	Upper Omingonde (100m)	Etjo (c.140m)	X	Holzförster et al. (1999)
Huab	X	X(?)	Twyfelfontein (150-300m) *Early Cretaceous*	Etendeka	Mountney et al. (1998); Marsh et al. (2003)
Mid-Zambezi	Escarpment Grit (c.55m) *Upper Scythian*	Ripple Marked Flagstone, Fine Red Marly Sandstone, Pebbly Arkose (c. 340m) *Scythian-Anisian*	Forest (c. 160m) *Norian*	Batoka	Nyambe and Utting (1997); Nyambe (1999)

Fig. 30. Karoo stratigraphic units, approximate thickness (brackets) and ages (italics) for the Karoo basins of Africa in which "Stormberg" and "Drakensberg" equivalent units are identified (references used noted in the table).

Cabora Bassa	Lower Angwa (c. 1700-2500m)	Upper Angwa, Pebbly Arkose (950-3500m) *Scythian-Norian*	Forest (500-2000m) *Norian*	Batoka	Oesterlen and Millstead (1994); d'Engelbronner (1996)
Zambia	Escarpment Grit (500m) *Scythian (?)*	Interbedded Sandstone-Mudstone (2000m) *Late Scythian or Anisian*	Red Sandstone (500m) *Carnian-Norian (?)*	Batoka (400m) *Liassic*	Nyambe and Uttig (1997); Nyambe (1999)
Tanga	Kilulu (?)	X	X	X	Wopfner (2002)
Madagascar basins	Isalo II (?) *Norian*	X	X	X	Piqué et al. (1999); Razafindrazaka et al. (1999)

Fig. 30 *(continued)*

Madagascar (where marine deposits occur at the relevant stratigraphic level; Piqué et al., 1999; Razafindrazaka et al., 1999) and, possibly, the Huab Basin, Namibia. In the latter, the basal, c. 10 m thick Krone Member of the predominantly aeolian Etjo Formation, passes gradationally up into these wind deposits, overlies lower Karoo strata unconformably, and is ascribed to an arid wadi flash-flood genesis (Mountney et al., 1998). This would appear to be an Elliot rather than a Molteno analogue in terms of depositional style; however, they are probably about 45 million years younger than Elliot-type deposits across the rest of Africa, and should thus be excluded. General characteristics of the Elliot-like units found across the African Karoo basins are a pervasive, diagenetic red colouration, upward-fining cycles of sandstones and mudrocks, interpreted as either braided or meandering river deposits (or, commonly both, as a result of variable discharge rates) within a semi-arid palaeoclimatic setting subject to increasing aridity with stratigraphic height (e.g., Nyambe and Utting, 1997; Holzförster et al., 1999; Nyambe, 1999; Bordy and Catuneanu, 2001). In most of the basins, the lower Elliot contact is gradational, and the upper conformable and sharp. Thickness of the "Elliot" interval varies between c. 70 and c. 340 m within most of the depositories, is up to 480 m in the main Karoo Basin, with the greatest development being recorded in the Cabora Bassa (up to 3500 m), Lukusashi-Luangwa (up to 2000 m) and Tanzanian (1300–2000 m) rift basins (Fig. 30).

Of the three sedimentary Stormberg formations, the Clarens and equivalents have the most uniform characteristics. A sheet (mostly c. 45–150 m thick) of fine-grained, mature, aeolian sandstones is preserved within all the African Karoo basins except for those in Tanzania and Madagascar (Fig. 30), and is mostly associated with wet desert (fan and wadi, playa lakes) subenvironments, which tend to occur in the basal portions of the unit, attesting to the gradational change from Elliot semi-arid settings (e.g., Visser, 1984; Smith et al., 1993; Oesterlen and Millsteed, 1994; Nyambe and Utting, 1997; Holzförster et al., 1999; Bordy and Catuneanu, 2002b; references therein). As with the underlying Stormberg units, the greatest thickness is in the Cabora Bassa Basin (Forest Sandstone; up to 2000 m), with about 500 m preserved in the Lukusashi-Luangwa Basin (Red Sandstone Formation), and up to c. 300 m in the Huab and main Karoo depositories (Fig. 30). The upper contact with the lavas suggests synchronous desert sedimentation and early volcanism, particularly in the Huab and main Karoo basins (e.g., Visser, 1984; Eriksson, 1983, 1986; Mountney et al., 1998).

The Drakensberg flood basalts originally covered much of southern Africa (Du Toit, 1954), but today are generally preserved in association with the various basins discussed in this paper. Their extrusion, which began in the Late Triassic and continued until the early Cretaceous was related to the breakup of Gondwana (e.g., Eales et al., 1984). Duncan et al. (1984) recognize four major southern African provinces: tholeiitic lavas (main Karoo, Springbok Flats, Aranos basins), olivine-poor basalts and acid lavas (Lebombo Group, Lebombo Basin), olivine-rich basalts (northern part of Lebombo Basin; Batoka basalts of the Zimbabwean basins), and silica-rich basalts and latites (Etendeka basalts, Huab Basin). By far the greatest thickness of lavas occurs in the Lebombo Basin, which is essentially a late Karoo depository formed by rifting due to the breakup of Gondwana; here the basaltic, 1600 m thick Letaba Formation is succeeded by c. 4800 m of acidic lavas, and an uppermost c. 200 m of largely basaltic lavas (SACS, 1980; Visser, 1984; Smith et al., 1993). The lavas were previously thought to have younged towards the north and west of the 190 Ma Lebombo Group: Drakensberg (187 Ma), Batoka lavas (166–105 Ma) and Etendeka (136–114 Ma) (Fitch and Miller, 1971), but recent dating indicates two short-lived events at 180 Ma and 132 Ma (Marsh, 2002).

Within the Mid-Zambezi and Cabora Bassa basins as well as in the Tanzanian rift basins, an uniformitarian stratigraphic code is in widespread usage (Figs. 10 and 11), with, for example, the Manda Beds being Scythian-Anisian (see also, Bond, 1967). Generally, across all these African Karoo basins, there is a trend that the north-western rift-type (and sag-type) basins (Huab sag basin—but excluding Twyfelfontein aeolian sandstones which are Early Cretaceous—Stanistreet and Stollhofen, 1999; Mid-Zambezi basin; Cabora Bassa; and, to a lesser extent, Tanzanian rift depositories) accumulated Stormberg-type sediments earlier, from Scythian to Norian times; deposition within the main Karoo Basin was from Carnian to Dogger, and that in Madagascar began in the middle of the Norian (Fig. 30).

6.2. Retroarc flexural foreland-related basins

Within the main Karoo Basin, the Molteno Formation is seen as a northerly-thinning (maximum thickness 460–600 m), intracratonic, bedload-dominated fluvial wedge deposit, sourced from tectonically active provenance areas (Cape Fold Belt) to the south and southeast (Turner, 1975, 1980, 1983, 1986; Smith et al., 1993; Cairncross et al., 1995). A major unconformity separates the Molteno and Burgersdorp formations. This contact is highly diachronous representing the entire Middle and early Late Triassic in the north of the basin and only the Ladinian—early Carnian in the south (Hancox, 1998). Overlying this contact, sandstones in the field have a sparkling appearance from pervasive quartz overgrowths (Smith et al., 1993). Within its type area in the south of the main Karoo Basin, the Molteno is characterized by six stacked, large scale upward-fining successions (Turner, 1983), with dominant pebbly, poorly sorted basal sandstone sheets (up to 40 m thick), passing up into finer-grained and better sorted sandstones (Smith et al., 1993) and uppermost thin mudrocks and rare coals (e.g., Cairncross et al., 1995). Of these six cycles, the lowermost Bamboesberg Member is restricted to the south of the preserved basin, but the erosively-based Indwe Member extends to the northernmost reaches thereof; the third to sixth cycles (the Transitional Member) becoming increasingly restricted to the southeast of the known depository (Turner, 1983, 1999; Cairncross et al., 1995). Turner (e.g., 1986) modelled these deposits as proximal braided river systems in which high stage pebbly sands were laid down by longitudinal bars, with the finer sands being draped over them and reworked as sand flats at lower flow stages (Eriksson, 1984). Cairncross et al. (1995) detailed channel-fill and floodplain subenvironments within coarse bedload systems which were replaced by mixed-load meandering channels as gradients decreased towards the end of each cycle. The floodplains supported a rich floral and insect population, with crevasse splays, sheetfloods, small lakes, marshes and rare peat swamps supporting *Dicroidium* forests and woodlands (Cairncross et al., 1995). A cool-temperate and humid palaeoclimate is inferred for the Molteno Formation in the main Karoo Basin (Anderson, 1976), and source area uplift due to early rifting and opening of the South Atlantic may have promoted intense orographic rainfall, leading to high erosion and sedimentation rates (Turner, 1983, 1986). Turner (1999) has challenged application of the retro-arc foreland basin model commonly inferred for the main Karoo Basin (e.g., Catuneanu et al., 1998) to the Stormberg portion of the basin-fill. Instead, he relates age data, stratigraphic and stacking patterns, as well as supposed volcanic detritus within the upper Karoo formations to mantle plume-linked thermal uplift and the onset of early rifting, to the southeast of the preserved basin, close to the later Agulhas Falkland fracture zone.

Within the main Karoo Basin, where Elliot studies have been the most detailed (e.g., Bordy et al., 2004a,b,c,d), this unit forms a northward-thinning and -fining, wedge-shaped deposit, dominated by upward-fining cycles of various sandstone grades and mudrocks (e.g., Visser, 1984). Within the main Karoo Basin, there is disagreement on the nature of the lower contact, with almost all earlier workers supporting a gradational relationship with the Molteno (e.g., Smith et al., 1993 and references therein) while Bordy et al. (in press) find it to be a disconformity. The latter researchers discuss differences in sandstone architecture, palaeocurrent patterns, pedogenic indicators, detrital composition and fossil content in support of their view (E.M. Bordy, pers. comm., 2004). In the south of the main Karoo Basin, lenticular sandstone geometries within predominant floodplain fine-grained rocks reflect a semi-arid meandering river style (Visser and Botha, 1980), in contrast to the northern areas, where less common tabular sheet-sandstones ascribed to ephemeral flooding are interbedded within predominant, commonly loessic floodplain fines (Eriksson, 1983, 1985). Bordy et al. (in press) define Lower and Upper Elliot Members which correlate broadly (and respectively) with the above two settings, and have been able to define both units across the preserved depository, the lower one being more subject to the northward-thinning than the upper. In the south, Visser and Botha (1980) interpreted an uppermost flood-fan, playa and aeolian dune interval; in the north, the contact with the wind-deposited Clarens Formation is conformable and sharp, with the lower Clarens deposits in many areas being wet desert deposits analogous to those of the upper Elliot in the south (Eriksson, 1985; Smith et al., 1993). Where most previous workers see the Elliot as a distal facies equivalent of the Molteno sandstone wedge in the main Karoo Basin (e.g., Turner, 1975, 1999; Visser, 1984; Smith et al., 1993), Bordy et al. (in press) argue for a separate tectonic control from a discrete paroxysm within the Cape Fold Belt in post-Molteno (cf. at c. 215 ± 3 Ma; Hälbich et al., 1983).

The Clarens sandstones within the main Karoo Basin are typically pale yellow (locally red) quartz-rich feldspathic wackes; the relative immaturity of the aeolian sediments reflects their desert-fan and wadi channel derivation (Eriksson et al., 1994). Wet desert and loessic deposits are more common in the south of the main Karoo Basin (Visser, 1984), and fan-wadi systems draining southeasterly source areas analogous to those for the Molteno and Elliot Formations predominate in the SE-Drakensberg area

(Eriksson, 1986). Palaeowinds were essentially from the W–NW in the main Karoo Basin, with NW winds being recorded from the Tuli Basin (Visser, 1984; Eriksson, 1986; Bordy and Catuneanu, 2002b).

Within the main Karoo Basin, the 1370 m thick Drakensberg Group reflects initial phreatomagmatic volcanism in the S and SE, followed by fissure-type eruptions building up thick sequences of evenly superposed flows (mostly 10–20 m thick), and associated with numerous dolerite dykes and sills, as well as diatremes and vents (Du Toit, 1954; Bristow and Saggerson, 1983; Van Rooy, 1991).

6.3. Eastern rift or extensional basins

Time equivalents of the Stormberg Group were laid down during the sixth and final depositional sequence (see Fig. 11) of the Karoo succession. They are separated from the preceeding sequences by the mid-Triassic hiatus and they are terminated in Raethian times by the breakup unconformity. They are best known from the Selous Basin, where they have been studied, amongst others by Hankel (1987, 1994), Kreuser (1983) and Wopfner and Kaaya (1991). Hankel (1987) included this succession originally within the Luwegu Basin, whereas Kreuser (1983) and others before him used the term Rufiji Basin. The nomenclature was revised by Wopfner and Kaaya (1991) who placed the Karoo megasequence within the Selous Basin, thus separating it from the post-Triassic succession of the Luwegu Basin. The deposits are mainly the product of low sinuosity or meandering stream systems, some grey, some of red bed nature (Hankel, 1987). They comprise, in ascending order, the Luhombero, Mahogo, Luwegu and Mkuju Formations. They represent the transition period from the intracratonic rift stage to the pericratonic basin configuration.

The same transition period is also reflected by the Matolani Formation of the Duruma Basin in southern Kenya and the Lower Isalo of the Morondava Basin, whereby the latter already experienced some marginal marine influences.

North of the Tanga/Duruma Basin information on younger Karoo deposits is scarce. The Adigrat Sandstone of Somalia, which was laid down prior to the breakup, contains a rich, Late Triassic microflora near its base (Bosellini, 1989), but its main body is of Early Jurassic age. Whether this and similar units may still be classified as Karoo is not clear at this stage.

The greatest thickness of Molteno-like sediments occurs within the Cabora Bassa rift basin, which is characterized by a half-graben geometry along its northern edge and strike-slip fault systems along the south. The Middle to Late Triassic (D'Engelbronner, 1996) Angwa Sandstone here has a basal angular unconformity and comprises two very thick members separated by a diachronous boundary: lower Massive Sandstone (500–2500 m thick) and overlying Alternations Member (100–1500 m thick) (Oesterlen and Millsteed, 1994; D'Engelbronner, 1996). The lower member has a basal conglomerate followed by predominant medium- to very coarse-grained and relatively poorly sorted pebbly quartz sandstone with uppermost finer arenites (Oesterlen and Millsteed, 1994 and references therein). An upward-fining, cyclical arrangement of lesser coarse sandstones and predominant fine sandstones and mudstones characterize the Alternations Member; thin ironstones, micritic limestones and a 2–3 m coal seam occur (Oesterlen and Millsteed, 1994). Low sinuosity braided rivers are inferred to have deposited the lower member, with smaller, meandering channels on a predominant floodplain (with lateritic palaeosols, lacustrine limestones and extensive coal swamps) postulated for the upper member. Palaeoclimate was warm and humid, with longitudinal river systems prograding largely towards the west, parallel with the basin axis (Oesterlen and Millsteed, 1994). The correlated Escarpment Grit Formation (c. 55 m thick) within the Mid-Zambezi half-graben basin has a similar basal unconformity, which oversteps lower Karoo strata onto basement rocks; it comprises coarse to conglomeratic sandstones fining up into fine sandstones and mudstones, deposited on a broad floodplain by braided river systems under a seasonal rainfall regime (Nyambe and Utting, 1997; Nyambe, 1999). Analogous Escarpment Grits also occur in the Lukusashi-Luangwa Basin, where they reach up to 500 m in thickness (Nyambe and Utting, 1997; Nyambe, 1999).

Within the Cabora Bassa Basin, the Pebbly Arkose Formation (950–3500 m thick; Table Stormberg) is regionally conformable (but locally unconformable) upon the thick Molteno-type deposits and shares much of their lithological and interpreted palaeoenvironmental character, except for an interpreted semi-arid palaeoclimate. The Pebbly Arkose comprises three-dimensionally interfingering of a massive, coarse, pebbly arkosic sandstone facies and a predominant finer, graded, subarkosic sandstone-mudstone facies (Oesterlen and Millsteed, 1994). Braided channel systems and finer interchannel flood basins subject to crevasse-splays and ephemeral lakes are inferred.

The Etjo Formation, the Clarens-equivalent desert deposits in the Waterberg Basin, Namibia, is characterized by wet desert—style facies within its lower and upper portions, with ephemeral lake and sand sheets surrounded by aeolian dune systems; this palaeoenvironmental interpretation has much in common with the modern Kalahari desert (Holzförster et al., 1999). Clean, very fine-grained aeolian sandstones typify the Forest Sandstone in the Cabora Bassa Basin, with minor (i.e. episodic) fluvially-deposited sandstones and conglomerates; fans were present in the SE and NE of the preserved rift basin, with fluvial deposits being more towards the N and SW margins (Oesterlen and Millsteed, 1994). The deposits in this basin thin from 2 km to 0.5 km, from NE to SW (Table Stormberg). A similar association of predominant aeolian and subordinate alluvial sedimentation marks the Mid-Zambezi Basin, with the former deposits being replaced upwards with windlain sediments (Nyambe and Utting, 1997), as aridity intensified.

6.4. Western sag basins

In the Congo Basin, Stormberg equivalents are represented by fluviatile sandstones of Late Triassic age, exposed along the eastern basin margin (Boutakoff, 1948). These correlate at least in parts with the Haute Lueki Formation, described by Daly et al. (1991) from the subsurface of the central and north-western basin area.

The Middle to Late Triassic Phyllopod Beds conclude the Karoo sequence in the Angola Basin.

Some of the most interesting aeolian deposits (possible Clarens equivalents) are those from the Etjo Formation of the Huab Basin; the aeolian-ephemeral fluvial succession typical of the lower "Clarens" succession is followed here by transverse draa bedsets of the Main Aeolian Unit, with barchanoid palaeodunes preserved in the Upper Aeolian Unit as eruption of the c. 132 Ma Etendeka flood basaltic lavas reduced aeolian sediment supply (Mountney et al., 1998). SW–NW palaeo-wind directions are recorded (Mountney et al., 1998). The latter authors argue for a Cretaceous age for these Etjo deposits based on the interfingering of sedimentary and volcanic lithologies. However, this only makes the uppermost Huab Aeolian units of unequivocal Cretaceous age, and the lower wind-deposited units may be older, and possibly partially equivalent to the widespread Clarens sandstones of southern and eastern Africa.

6.5. Regional synthesis of Stormberg Group sedimentation and Drakensberg Group volcanism

The character of the "Molteno" sandstones of the African Karoo basins encompasses a basal unconformity, locally overstepping lower Karoo rocks onto the basement, followed by basal conglomerates; upward-fining fluvial sandstones and lesser mudrocks are pervasive, with inferred palaeoenvironments comprising bedload-dominated braided systems commonly passing into high sinuosity, mixed-load channels and floodplain settings. Palaeocurrent patterns, geometry, thicknesses and palaeoclimate appear to reflect local tectonic conditions controlling individual basin evolution, with the onset of Molteno sedimentation suggesting a possible relationship with early rifting of Gondwana. Veevers (1989) suggested that subsidence leading to the development of sedimentary depositories was caused by the release of Pangean heat during the Carnian.

In general, the African Karoo basins accumulated fluvial red beds during Elliot times. Thicknesses reflect the tectonic setting, with the rift basins such as Mid-Zambezi, Cabora Bassa and the Tanzanian grabens accumulating several kilometres of sediment. Changes from braided coarse-load fluvial systems to mixed-load and fine-grained meandering systems can be ascribed to sediment supply rates, reflecting in turn, the interaction of tectonic setting and palaeoclimate. The latter was pervasively semi-arid, and deteriorated upwards as aeolian conditions set in across southern and eastern Africa.

The most consistent Stormberg Group sediments are those of the Clarens and correlated formations, which formed sheet-like deposits across much of southern and eastern Africa as Karoo sedimentation came to an end, to be replaced by the equally pervasive Drakensberg Group volcanics (and equivalents). Being largely aeolian in nature, the Clarens deposits were less susceptible to tectonic controls than their underlying fluvial deposits, thus developing a different architecture.

Recent ages (see Marsh et al., 1997; Duncan et al., 1997; discussion in Marsh, 2002) indicate that the entire Drakensberg Group was formed in a very short time interval at 193 Ma, being coeval with mafic volcanism in central Namibia and Lebombo; in the latter basin, mafic volcanism continued for longer, being superseded by the 179 Ma acid lavas. The end-Karoo volcanism across southern Africa is essentially restricted chronologicaly to two short-lived events: a 180 Ma (main Karoo and Lebombo being the best developed) and a 132 Ma Etendeka event in Namibia (Marsh, 2002).

7. Discussion and conclusions

The formation of the Karoo-age basins of Africa took place during the Late Paleozoic–Early Mesozoic interval, when the Pangea supercontinent reached its maximum extent. Tectonism was the primary control on accommodation in the Karoo basins, with subsidence mechanisms ranging from flexural in the south, in relation to processes of subduction and orogenesis along the palaeo-Pacific margin, to extensional in the north, propagating southwards from the divergent Tethyan margin. The interplay of these tectonic mechanisms, combined with the influence exerted by the inherent structures of the underlying Precambrian basement, resulted in the formation of discrete depozones that follow regional tectonic trends. Sedimentation patterns in these Karoo basins were further influenced by a shift in climatic regimes, from early cold conditions during the Late Carboniferous–earliest Permian interval, to warmer and eventually hot climates with fluctuating precipitation during the rest of Karoo time. The climatic background provided a common thread for the sedimentary fill of all Karoo basins, which resulted in the development of similar depositional trends across much of south-central Africa in spite of the change in tectonic regimes.

The lacuna which followed the coalescence of Pangea led to extensive denudation and peneplanation of central and eastern African cratonic regions. The first release of heat from the self-induced Pangean heat anomaly (Veevers et al., 1994a,b) caused updoming, followed by rifting in the eastern African and Malagasy region. Rust (1975) and subsequently Tewari and Veevers (1993) suggested that the shape of Pangean basins (like the Karoo basins) was largely determined by the structure of the basement. Syneclisic type Karoo basins formed by flexure and thermal sagging over isotropic, mainly Archean basement (e.g., Congo Craton), whereas linear, east African type basins developed by fracturing over anisotropic, mainly Proterozoic fold belts (Wopfner, 1993, 1994). Similarly, Radelli (1975) thought that syn-depositional faulting within the Morondava Basin followed old zones of weaknesses within the underlying Mozambique Fold Belt. More recently, Visser and Praekelt (1996) suggested a similar model for the breakup between East Africa and Madagascar/India.

Whilst the concept of rift directions being inherited from tectonic trends within the underlying basement holds true in a general way, there are a number of cases where Karoo rifts cut right across older fold structures. One of the best examples is the Ruhuhu Basin, the rift structures of which cut the fold fabric of the Palaeoproterozoic Ubendian Metamorphic Complex almost at a right angle (Wopfner and Diekmann, 1996).

Although the dominant trend of the eastern African and Malagasy graben structures is northeast, there are a number of shorter structures with northerly or even northwesterly trends. Some of them may be simple accommodation faults, but the great thickness of sediments accumulated against some of them suggests a pull-apart mechanism. It may be concluded therefore that the East African/ Malagasy rifts were not just simple tensional systems but that they were governed by a transtensional stress field with a clear left-lateral component (Wopfner et al., 1993).

North of Kenya, at the point where later in the Jurassic the northwest trending, failed rift of the Anza Trough developed (Reeves et al., 1986), the Karoo rift system deviated from the trend of the Mozambique Belt altogether and presumably continued northeastward to southern Oman. Such a continuation is indicated not only by various palaeobiological assemblages (see Wopfner et al., 1993; Wopfner, 1994, 1999, 2002 for references) but also by the relationship of the glacigene deposits of southern Oman to the Huqh-Haushi uplift (Lee, 1990). Permian pillow lavas overlain by radiolarian cherts in the Oman Mountains show that here the intracratonic rift of the Malagasy Trough merged with the Neotethyan Ocean.

In summary it can be stated that the formation of the Karoo rift basins of eastern Africa resulted from left lateral transtension between India/Madagascar and Africa. Although the onset of rifting was triggered by an anomalous heat accumulation under the insulating blanket of the vast continental crust, transtension was the controlling mechanism for the establishment of rift directions. The forces were created by the opening of Neotethys combined with the right-lateral rotation between Gondwana and Laurasia (Veevers et al., 1994a). The release of heat from the self-induced heat anomaly is considered the cause for the sagging and the formation of the syneclise-type basins on the western side of African Gondwana.

At the same time with the manifestation of dominantly extensional or transtensional tectonic regimes across much of Gondwana, the evolution of the southern part of the supercontinent was primarily linked to the formation of the Pan-Gondwanian fold-thrust belt, which provided the supracrustal load for the flexural subsidence recorded in the main Karoo Basin. Flexural loading, coupled with dynamic subsidence related to the process of subduction beneath Gondwana, conferred the main Karoo Basin of southern Africa unique characteristics that set it apart from all other Karoo-age basins of Africa. This retroarc foreland basin preserves the reference stratigraphy for the Late Carboniferous–Middle Jurassic interval of Gondwana, which includes the regionally correlatable Dwyka, Ecca, Beaufort and Stormberg lithostratigraphic units.

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References

Abdala, F., Hancox, P.J., Neveling, J., 2005. Cynodonts from the uppermost Burgersdorp Formation, South Africa, and their bearing on the biostratigraphic subdivision and correlation of the Triassic *Cynognathus* Assemblage Zone. J. Vertebr. Paleontol.

Anderson, H.M., 1976. A revision of the genus *Dicroidium* from the Molteno Formation. Ph.D. thesis (unpubl.), Univ. Witwatersrand, 146p.

Anderson, J.M., Anderson, H.M., 1983Palaeoflora of Southern Africa Molteno Formation (Triassic), vol. II. A.A. Balkema, Rotterdam.

Archbold, N.W., 2001. Pan-Gondwana, Early Permian (Asselian–Sakmarian–Aktastinian) correlations. In: Weiss, R.H. (Ed.), Contributions to Geology and Palaeontology of Gondwana in Honour of Helmut Wopfner. Geological Institute, University of Cologne, pp. 29–40.

Bamford, M.K., 2000. Fossil wood of Karoo age deposits in South Africa and Namibia as an aid in biostratigraphical correlation. J. Afr. Earth Sci. 31, 119–132.

Bangert, B., Stollhofen, H., Lorenz, V., Armstrong, R., 1999. The geochronology and significance of ash-fall tuffs in the glaciogenic Carboniferous-Permian Dwyka Group of Namibia and South Africa. J. Afr. Earth Sci. 29, 33–49.

Barber, B., 1986. The Tuli coal district. Records of Zimbabwe Coalfields, vol. XIV. Zimbabwe Geological Survey, Harare, 16p.

Barber, B., 1987. The Save-Runde coal area, Save-Limpopo basin. Records of Zimbabwe Coalfields, vol. XVI. Zimbabwe Geological Survey, Harare, 31p.

Bekker, L., Poreda, R.J., Hunt, A.G., Bunch, T.E., Rampino, M., 2001. Impact event at the Permian-triassic boundary: evidence from extraterrestrial noble gases in fullerines. Science 291, 1530–1533.

Bésairie, H., 1972. Gèologie de Madagascar, I: Les terrains sèdimentaires. Annales Géologie Madagascar, Tananarive, vol. 35, 82pp.

Bésairie, H., Collignon, M., 1956. Lexique Stratigraphique International, vol. 4, Fascicule 11, Madagascar. Centre National de la recherche scientific, Paris.

Bond, G., 1967. A review of Karroo sedimentation and lithology in southern Rhodesia. In: Reviews prepared for the First Symposium on Gondwana Stratigraphy, IUGS. Mar del Plata, Argentina, pp. 173–195.

Bond, G., 1973. The palaeontology of Rhodesia. Bull. Rhodesia Geol. Surv. 70, 121.

Boonstra, L.D., 1946. Report on some reptilian fossils from Gunyanka's Kraal, Busi Valley. Trans. Rhodesian Sci. Assoc. 41, 46–49.

Bordy, E.M., Catuneanu, O., 2001. Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. J. Afr. Earth Sci. 33 (3–4), 605–629.

Bordy, E.M., Catuneanu, O., 2002a. Sedimentology of the Beaufort-Molteno Karoo fluvial strata in the Tuli Basin, South Africa. S. Afr. J. Geol. 105, 51–66.

Bordy, E.M., Catuneanu, O., 2002b. Sedimentology and palaeontology of upper Karoo aeolian strata (Early Jurassic) in the Tuli Basin, South Africa. J. Afr. Earth Sci. 35, 301–314.

Bordy, E.M., Catuneanu, O., 2002c. Sedimentology of the lower Karoo Supergroup fluvial strata in the Tuli Basin, South Africa. J. Afr. Earth Sci. 35, 503–521.

Bordy, E.M., Hancox, P.J., Rubidge, B.S., 2004a. Fluvial style variations in the Late Triassic-Early Jurassic Elliot Formation, main Karoo Basin, South Africa. J. Afr. Earth Sci. 38, 383–400.

Bordy, E.M., Hancox, P.J., Rubidge, B.S., 2004b. Basin development during the deposition of the Elliot Formation (Late Triassic-Early Jurassic), Karoo Supergroup, South Africa. S. Afr. J. Geol. 107, 395–410.

Bordy, E.M., Hancox, P.J., Rubidge, B.S., 2004c. Provenance study of the Late Triassic–Early Jurassic Elliot Formation, main Karoo basin, South Africa. S. Afr. J. Geol. 107, 587–602.

Bordy, E.M., Hancox, P.J., Rubidge, B.S., 2004d. A description of the sedimentology and palaeontology of the Late Triassic–Early Jurassic Elliot Formation in Lesotho. Palaeontologia Africana 40, 37–57.

Bosellini, A., 1989. The continental margins of Somalia: their structural evolution and sequence stratigraphy. Memorie di Science Geologiche, Universita di Padova 41, 373–458.

Boutakoff, N., 1948. Les formationes glaciaires et post glaciaires fossilifères d'age permo-carbonifère (Karroo inferieur) de la Région Walikale (Kivu, Congo belge). Memoire Institute Geologie Universitè Louvain, vol. 9, 124pp.

Bristow, J.W., Saggerson, E.P., 1983. A review of Karoo vulcanicity in South Africa. Afr. Bull. Volcanol. 46, 135–159.

Burgess, P.M., Gurnis, M., Moresi, L., 1997. Formation of sequences in the cratonic interior of North America by interaction between mantle, eustatic, and stratigraphic processes. GSA Bull. 108 (12), 1515–1535.

Cairncross, B., 1987. Permian coal deposits of Southern Africa (Incorporating Botswana, Malawi, Mozambique, Namibia, Republic of South Africa, Swaziland, Tanzania, Zambia and Zimbabwe). BHP-Utah International Co. Report, Herndon, Virginia, USA, 187p.

Cairncross, B., 1989. Paleodepositional environments and tectono-sedimentary controls of the postglacial Permian coals, Karoo basin, South Africa. Int. J. Coal Geol. 12, 365–380.

Cairncross, B., 2001. An overview of the Permian (Karoo) coal deposits of southern Africa. J. Afr. Earth Sci. 33, 529–562.

Cairncross, B., Anderson, J.M., Anderson, H.M., 1995. Palaeoecology of the Triassic Molteno Formation, Karoo Basin, South Africa—sedimentological and palaeontological evidence. S. Afr. J. Geol. 98, 452–478.

Cairncross, B., Beukes, N.J., Muntingh, D.J., Rehfeld, U., 1998. Late Permian deltaic successions from the Karoo Supergroup, South Africa: freshwater or marine? Abstract. 15th International Sedimentological Congress, Alicante, Spain, Abstract volume, p. 224.

Catuneanu, O., 2004a. Basement control on flexural profiles and the distribution of foreland facies: the Dwyka Group of the Karoo Basin, South Africa. Geology 32 (6), 517–520.

Catuneanu, O., 2004b. Retroarc foreland systems—evolution through time. J. Afr. Earth Sci. 38, 225–242.

Catuneanu, O., Bowker, D., 2001. Sequence stratigraphy of the Koonap and Middleton fluvial formations in the Karoo foredeep, South Africa. J. Afr. Earth Sci. 33, 579–595.

Catuneanu, O., Elango, H.N., 2001. Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa. Sediment. Geol. 140, 291–313.

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

Catuneanu, O., Kun-Jager, E.M., Rubidge, B.S., Hancox, P.J., 1999. Lateral changes of the Dwyka facies: implications for the initiation of the Cape Orogeny and the associated Karoo foreland system. In: Abstracts of proceedings, American Association of Petroleum Geologists Annual Meeting, 11–14 April, San Antonio, TX, p. A22.

Catuneanu, O., Hancox, P.J., Cairncross, B., Rubidge, B.S., 2002. Foredeep submarine fans and forebulge deltas: orogenic off-loading in the underfilled Karoo Basin. J. Afr. Earth Sci. 35, 489–502.

Christie, A.D.M., 1988. Sedimentology of a torbanite seam in the vicinity of Wakkerstroom, southeastern Transvaal. S. Afr. J. Geol. 91, 226–238.

Cole, D.I., 1991. Depositional environment of the Dwyka Group in the Boshof-Hertzogville area, Orange Free State. S. Afr. J. Geol. 94, 272–287.

Cole, D.I., 1992. Evolution and development of the Karoo Basin. In: De Wit, M.J., Ransome, I.G.D. (Eds.), Inversion Tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa. A.A. Balkema, Rotterdam, pp. 87–99.

Cole, D.I., 1998. Palaeogeography and palaeocurrent distribution of the Beaufort Group in the Karoo Basin, South Africa during the Late Permian. J. Afr. Earth Sci., Special Abstract Issue, Gondwana 10: Event Stratigraphy of Gondwana 27 (1A), 46–47.

Cole, D.I., McLachlan, I.R., 1991. Oil potential of the Permian Whitehill Shale Formation in the main Karoo basin, South Africa. In: Ulbrich, H., Rocha Campos, A.C. (Eds.), Proceedings, Gondwana Seven: Sao Paulo, Instituto de Geociencias, Universidade de Sao Paulo, pp. 379–390.

Cole, D.I., McLachlan, I.R., 1994. Oil shale potential and depositional environment of the Whitehill Formation in the main Karoo basin. Report, Geological Survey of South Africa, 1994-0213.

Cole, D.I., Wipplinger, P.E., 1991. Uranium and molybdenum occurrences in the Beaufort Group of the main Karoo basin, South Africa. In: Ulbrich, H., Rocha Campos A.C. (Eds.), Proceedings, Gondwana Seven: Sao Paulo, Instituto de Geociencias, Universidade de Sao Paulo, pp. 391–406.

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

Cole, D., Smith, R.M.H., Wickens, H.deV., 1990. Basin plain to fluvio-lacustrine deposits in the Permian Ecca and Lower Beaufort groups of the Karoo Sequence. Karoo Excursion Guidebook (PO2). Geological Society of South Africa Geocongress, vol. 90, University of Cape Town, South Africa, 83p.

Cole, D., Wickens, H.deV., Viljoen, J., 1998. Lower Karoo Supergroup: glacial, basinal and terrestrial environments in the southwestern part of the Main Karoo basin. Guidebook 10th Gondwana Conference. University of Cape Town, South Africa, 77p.

Cox, L.R., 1935. Karoo lamellibranches from Tanganyika and Madagascar. Quart. J. Geol. Soc. London 92 (1), 32–57.

Cox, C.B., 1969. Two new dicynodonts from the Triassic N'tawere Formation, Zambia. Bull. Br. Mseum Natural History (Geology) 17, 255–294.

Crozier, E.A., 1970. Preliminary report on two Triassic dicynodonts from Zambia. Palaeontol. Africana 13, 39–45.

Cruickshank, A.R.I., 1965. On a specimen of the Anomodont reptile *Kannemeyeria latifrons* (Broom) from the Manda Formation of Tanganyika, Tanzania. Proc. Linnean Soc. London 176, 149–157.

Cruickshank, A.R.I., 1967. A new dicynodont genus from the Manda Formation of Tanzania (Tanganyika). J. Zool., London 153, 163–208.

Daly, M.C., Lawrence, S.R., Kimun'a, D., Binga, M., 1991. Late Palaeozoic deformation in Central Africa: a result of distant collision? Nature 350, 605–607.

D'Engelbronner, E.R., 1996. New palynological data from Karoo sediments, Mana Pools basin, northern Zimbabwe. J. Afr. Earth Sci. 23, 17–30.

Diekmann, B., 1993. Paläoklima und glazigene Karoo-Sedimente des späten Paläozoikums in SW-Tansania. Geologisches Institut Universität Köln, Sonderveröffentlichungen, Cologne, Germany, vol. 90, 193 pp.

Diekmann, B., Wopfner, H., 1996. Petrographic and diagenetic signatures of climatic change in peri- and postglacial Karoo sediments of SW Tanzania. Palaeogeogr. Palaeoclimatol. Palaeoecol. 125, 5–25.

Dixey, F., 1926. Notes on the Karroo sequence north-west of Lake Nyasa. Trans. Geol. Soc. S. Afr. 29, 59–68.

Dixey, F., 1937. The Pre-Karoo landscape of the Lake Nyasa region and a comparison of the Karoo structural directions with those of the Rift Valley. Quart. J. Geol. Soc. London 93, 77–93.

Dow, D.B., Beyth, M., Hailu, T., 1971. Palaeozoic glacial rocks recently discovered in northern Ethiopia. Geol. Mag. 108, 53–60.

Dressler, E., Manhiça, A., Sippel, V., 1990. Contribution to the geology of the hard coal deposits of Moatize in the district Tete of the P.R. Mozambique. Z. Geol. Wissensch. Berlin (east) 18, 467–476.

Dreyer, J.C., 1994. Total utilization of the coal resource: the Grootegeluk experience. In: Anhaeusser, C.R. (Ed.), Proceedings XVth CMMI Congress, Symposium Series, S14. South African Institute of Mining and Metallurgy, Johannesburg, pp. 153–164.

Du Toit, A.L., 1954. The Geology of South Africa, third ed. Oliver and Boyd, Edinburgh, 611p.

Duncan, A.R., Erlank, A.J., Marsh, J.S., 1984. Regional geochemistry of the Karoo igneous province. In: Erlank, A.J. (Ed.), Petrogenesis of the volcanic rocks of the Karoo Province. Geological Society of South Africa, Johannesburg, Special Publication 13, pp. 355–388.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., Duncan, A.R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. J. Geophys. Res. 102, 18127–18138.

Dypvik, H., Nilsen, O., 2002. The Kilombero Rift Valley, Tanzania. In: Weiss, R.H. (Ed.), Contributions to Geology and Palaeontology of Gondwana in honour of Helmut Wopfner. Geological Institute, University of Cologne, pp. 159–174.

Eales, H.V., Marsh, J.S., Cox, K.G., 1984. The Karoo igneous province: an introduction. In: Erlank, A.J. (Ed.), Petrogenesis of the Volcanic Rocks of the Karoo Province. Special Publication 13, Geological Society of South Africa, Johannesburg, pp. 1–26.

Eriksson, P.G., 1983. A palaeoenvironmental study of the Molteno, Elliot and Clarens Formations in the Natal Drakensberg and northeastern Orange Free State. Ph.D. thesis (unpubl.), Univ. Natal, 209p.

Eriksson, P.G., 1984. A palaeoenvironmental analysis of the Molteno Formation in the Natal Drakensberg. Trans. Geol. Soc. S. Afr. 87, 237–244.

Eriksson, P.G., 1985. The depositional palaeoenvironment of the Elliot Formation in the Natal Drakensberg and north-eastern Orange Free State. Trans. Geol. Soc. S. Afr. 88, 19–26.

Eriksson, P.G., 1986. Aeolian dune and alluvial fan deposits in the Clarens Formation of the Natal Drakensberg. Trans. Geol. Soc. S. Afr. 89, 389–394.

Eriksson, P.G., McCourt, S., Snyman, C.P., 1994. A note on the petrography of upper Karoo sandstones in the Natal Drakensberg: implications for the Clarens Formation palaeoenvironment. S. Afr. J. Geol. 97 (1), 101–103.

Falcon, R.M.S., 1986a. A brief review of the origin, formation and distribution of coal in Southern Africa. In: Anhaeusser, C.R., Maske, S. (Eds.), Mineral Deposits of Southern Africa, vols. I and II. Geological Society of South Africa, Johannesburg, pp. 1879–1898.

Falcon, R.M.S., 1986b. Classification of coals in Southern Africa. In: Anhaeusser, C.R., Maske, S. (Eds.), Mineral Deposits of Southern Africa, vols. I and II. Geological Society of South Africa, Johannesburg, pp. 1899–1921.

Falcon, R.M.S., Ham, A., 1988. The characteristics of southern African coals. J. S. Afr. Inst. Mining Metall. 88, 145–161.

Faure, K., Willis, J.P., Dreyer, J.C., 1996a. The Grootegeluk Formation in the Waterberg coalfield, South Africa: facies, palaeoenvironment and thermal history—evidence from organic and clastic matter. Int. J. Coal Geol. 29, 147–186.

Faure, K., Armstrong, R.A., Harris, C., Willis, J.P., 1996b. Provenance of mudstones in the Karoo Supergroup of the Ellisras Basin, South Africa: geochemical evidences. J. Afr. Earth Sci. 23 (2), 189–204.

Fitch, F.J., Miller, J.A., 1971. Potassium-argon radio-ages of Karroo volcanic rocks from Lesotho. Bull. Volcanol. 35, 64–84.

Gay, S.A., Cruickshank, A.R.I., 1999. Biostratigraphy of the Permian tetrapod faunas from the Ruhuhu Valley, Tanzania. J. Afr. Earth Sci. 29, 195–210.

Grecula, M., Flint, S., Potts, G., Wickens, H.deV., Johnson, S., 2003a. Partial ponding of turbidite systems in a basin with subtle growth-fold topography: Laingsburg-Karoo, South Africa. J. Sediment. Res. 73, 603–620.

Grecula, M., Flint, S.S., Wickens, H.deV., Johnson, S.D., 2003b. Upward-thickening patterns and lateral continuity of Permian sand-rich turbidite channel fills, Laingsburg Karoo, South Africa. Sedimentology 50, 831–853.

Groenewald, G.H., 1989. Stratigrafie en sedimentologie van die Groep Beaufort in die Noordoos-Vrystaat. Bulletin, Geological Survey of South Africa 96, 62p.

Groenewald, G.H., 1996. Stratigraphy and sedimentology of the Tarkastad Subgroup, Karoo Basin, South Africa. Ph.D. thesis (unpublished) University Port Elizabeth.

Gurnis, M., 1992. Rapid continental subsidence following the initiation and evolution of subduction. Science 255, 1556–1558.

Hälbich, I.W., 1983. A tectogenesis of the Cape Fold Belt (CFB). Söhnge, A.P.G., Hälbich, I.W. (Eds.), Geodynamics of the Cape Fold Belt, Special Publication of the Geological Society South Africa, vol. 12, pp. 165–175.

Hälbich, I.W., Fitch, F.J., Miller, J.A., 1983. Dating the Cape Orogeny. In: Söhnge, A.P.G., Hälbich, I.W. (Eds.), Geodynamics of the Cape Fold Belt, Special Publications of the Geological Society South Africa, vol. 12, pp. 149–164.

Hancox, P.J. 1998. A stratigraphic, sedimentological and palaeonvironmental synthesis of the Beaufort-Molteno contact in the Karoo Basin. Ph.D. thesis, University of the Witwatersrand, Johannesburg, South Africa.

Hancox, P.J., 2000. The continental Triassic of South Africa. Zbl. Geol. Paläontol. Teil 1, 1998, 1285–1324.

Hancox, P.J., Rubidge, B.S., 1996. The first specimen of the Mid-Triassic dicynodont *Angonisaurus* from the Karoo of South Africa, implications for the dating and biostratigraphy of the *Cynognathus* Assemblage Zone, Upper Beaufort Group. S. Afr. J. Sci. 92, 391–392.

Hancox, P.J., Shishkin, M.A., Rubidge, B.S., Kitching, J.W., 1995. A threefold subdivision of the *Cynognathus* Assemblage Zone (Beaufort Group, South Africa) and its palaeogeographical implications. S. Afr. J. Sci. 91, 143–144.

Hankel, O., 1987. Lithostratigraphic subdivision of the Karoo rocks of the Luwegu Basin, Tanzania and their biostratigraphic classification based on microflora, fossil wood and vertebrates. Geol. Rundsch. 76, 539–566.

Hankel, O., 1994. Early Permian to Jurassic rifting and sedimentation in East Africa and Madagascar. Geol. Rundsch. 83, 703–710.

Haughton, S.H., 1926. On Karoo vertebrates from Nyasaland. Trans. Geol. Soc. S. Afr. 29, 69–83.

Haughton, S.H., 1932. On a collection of Karroo vertebrates from Tanganyika Territory. Quart. J. Geol. Soc. London 88, 634–671.

Haughton, S.H., 1963. The Stratigraphic History of Africa South of the Sahara. Oliver and Boyd, London, 365 pp.

Hiller, N., Stavrakis, N., 1984. Permo-Triassic fluvial systems in the southeastern Karoo Basin, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 45, 1–21.

Hobday, D.K., 1973. Middle Ecca deltaic deposits in the Muden-Tugela Ferry area of Natal. Trans. Geol. Soc. S. Afr. 76, 309–318.

Hobday, D.K., 1978. Fluvial deposits of the Ecca and Beaufort Groups in the eastern Karoo basin, southern Africa. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Canadian Society Petroleum Geologists, Memoir 5, 413–429.

Holt, W.E., Stern, T.A., 1994. Subduction, platform subsidence and foreland thrust loading: the late tertiary development of Taranaki basin, New Zealand. Tectonics 13, 1068–1092.

Holzförster, F., Stollhofen, H., Stanistreet, I.G., 1999. Lithostratigraphy and depositional environments in the Waterberg-Erongo area, central Namibia, and correlation with the main Karoo Basin, South Africa. J. Afr. Earth Sci. 29 (1), 105–123.

Ho-Tun, E., 1979. Volcaniclastic material in the Lower Beaufort Group, Karoo rocks. Geological Society of South Africa Geokongress'79, vol. 1, pp. 197–199.

Hotton, N., 1967. Stratigraphy and sedimentation in the Beaufort Series (Permian-Triassic), South Africa. In: Teichert C., Yochelson, E.I. (Eds.), Essays In Palaeontology and Stratigraphy. Special Publication of the University of Kansas, pp. 390–427.

Hübner, H., 1965. Permokarbonische glazigene und periglaziale Ablagerungen aus dem zentralen Teil des Kongobeckens. Stockholm Contributions in Geology, 13, 41-61, 14 plates.

Janensch, W., 1927. Beiträge zur Kenntnis der Karru-Schichten im östlichen Deutsch-Ostafrika. Palaeontographica (Suppl. VII), 107–142.

Jardiné, S., 1974. Microflores des formations du Gabon attribuées au Karroo. Rev. Palaeobot. Palynol. 17, 75–112.

Johnson, M.R., 1976. Stratigraphy and Sedimentology of the Cape and Karoo sequences in Eastern Cape Province. Unpublished Ph.D. thesis, Rhodes University, Grahamstowm, 366pp.

Johnson, M.R., 1991. Sandstone petrography, provenance and plate tectonic setting in Gondwana context of the south-eastern Cape Karoo Basin. S. Afr. J. Geol. 94 (2/3), 137–154.

Johnson, M.R., 1994. Lexicon of South African Stratigraphy. Part 1: Phanerozoic Units. Publication, South African Committee for Stratigraphy. Council for Geoscience Pretoria, 56p.

Johnson, M.R., Van Vuuren, C.J., Hegenberger, W.F., Key, R., Shoko, U., 1996. Stratigraphy of the Karoo Supergroup in southern Africa: an overview. J. Afr. Earth Sci. 23 (1), 3–15.

Johnson, M.R., van Vuuren, C.J., Visser, J.N.J., Cole, D.J., Wickens, H.deV., Christie, A.D.M., Roberts, D.L., 1997. The foreland Karoo Basin, South Africa. In: Selley, R.C. (Ed.), African Basins—Sedimentary Basins of the World. Elsevier, Amsterdam, pp. 269–317.

Johnson, S.D., Flint, S., Hinds, D., Wickens, H.deV., 2001. Anatomy, geometry and sequence stratigraphy of basin floor to slope turbidite systems, Tanqua Karoo, South Africa. Sedimentology 48, 987–1023.

Kaaya, C.Z., 1992. Depositional environment of Late Permian Karoo beds in the Ruhuhu Basin and Mikumi area of Tanzania. Geologisches Institut Universität Köln, Sonderveröffentlichungen, vol. 83, 26pp.

Kalkreuth, W., Holz, M., Cazzulo-Klepzig, M., Marques, M., Utting, J., Semkiwa, P., 1999. A comparative study of the geology, petrology and palynology of Permian coals in Tanzania and southern Brazil. J. Afr. Earth Sci. 29, 91–104.

Kemp, T.S., 1976. Vertebrate localities in the Karoo system of the Luangwa Valley, Zambia. Nature 254, 415–416.

Key, R.M., Tidi, J., Mc George, I., Aitken, G., Cadman, A., Anscombe, J., 1998. The lower Karoo supergroup geology of the southwestern part of the Gemsbok sub-basin of the Kalahari Basin, Botswana. S. Afr. J. Geol. 101, 225–236.

Keyser, A.W., 1966. Some indications of an arid climate during deposition of the Beaufort Series. Ann. Geol. Survey S. Africa 5, 77–80.

Keyser, A.W., Smith, R.M.H., 1978. Vertebrate biozonation of the Beaufort Group with special reference to the Western Karoo Basin. Ann. Geol. Survey S. Afr. 12, 1–36.

King, G.M., 1988. Anomodontia. In: Wellnhofer, P. (Ed.), Encyclopedia of Paleoherpetology 17C. Gustav Fischer, Stuttgart, pp. 1–174.

King, G.M., Jenkins, I., 1997. Thedicynodont *Lystrosaurus* from the Upper Permian of Zambia: evolutionary and stratigraphic implications. Palaeontology 40 (1), 149–156.

Kingsley, C.S., 1985. Sedimentological aspects of the Ecca Sequence in the Kalahari basin, South West Africa/Namibia. CDM Mineral Surveys, Open File Report, 13/175/510/85/277. Geological Survey, Windhoek, Namibia, 35p.

Kitching, J.W., 1977. The distribution of the Karroo vertebrate fauna. Memoir Bernard Price Institute Palaeontological Research, University Witswatersrand, vol. 1, pp. 1–131.

Kitching, J.W., 1995a. Biostratigraphy of the *Dicynodon* Assemblage Zone. In: Rubidge, B.S. (Ed.), Biostratigraphy of the Beaufort Group (Karoo Supergroup). Biostratigraphic Series, Geological Survey of South Africa, vol. 1, pp. 29–34.

Kitching, J.W., 1995b. Biostratigraphy of the *Cynognathus* Assemblage Zone. In: Rubidge, B.S. (Ed.), Biostratigraphy of the Beaufort Group (Karoo Supergroup). Geological Survey of South Africa, Biostratigraphic Series, vol. 1, pp. 40–45.

Klitzsch, E., Wyciks, P., 1987. Geology of the sedimentary basins of northern Sudan and bordering areas. Berliner Geowissensch. Abhandlungen (A) 75, 97–136.

Kreuser, T., 1983. Stratigraphie der Karoo-Becken in Ost-Tansania. Geologisches Institut Universität Köln, Sonderveröffentlichungen, vol. 45, 217pp.

Kreuser, T., 1990. Permo-Trias im Ruhuhu Becken (Tansania) und anderen Karoo Becken von SE-Afrika. Geologisches Institut Universität Köln, Sonderveröffentlichungen, vol. 75, 131pp.

Kreuser, T., 1994. Karoo and transition to post-Karoo rifts in East Africa—evolution and fossil energy potential. Afr. Geosci. Rev. 1 (4), 425–447.

Kreuser, T., Wopfner, H., Kaaya, C.Z., Markwort, S., Semkiwa, P.M., Aslanidis, P., 1990. Depositional evolution of Permo-Triassic Karoo basins in Tanzania with reference to their economic potential. J. Afr. Earth Sci. 10, 151–167.

Kruck, W., Thiele, J., 1983. Late Palaeozoic glacial deposits in the Yemen. Geologisches Jahrbuch (B), 46, Hannover.

Langford, R.P., 1992. Permian coal and palaeogeography of Gondwana (with contributions by B. Cairncross, M. Friedrich, J.M. Totterdell and G. Liu). Bureau of Mineral Resources/Australian Petroleum Industries Research Association. Palaeogeographic Maps Project, BMR Record 1991/95 Palaeogeography 29, Canberra, ACT, Australia, 136p.

Latimer, E.M., Gow, C.E., Rubidge, B.S., 1995. Dentition and feeding niche of *Endothiodon* (Synapsida; Anomodontia). Palaeontol. Africana 32, 75–82.

Le Blanc Smith, G., Eriksson, K.A., 1979. A fluvioglacial and glaciolacustrine deltaic depositional model for Permo-Carboniferous coals of the northeastern Karoo basin, South Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 27, 67–84.

Lee, C.W., 1990. Review of platform sedimentation in the Early and Late Permian of Oman, with particular reference to the Oman Mountains. In: Robertson, A.H.F. et al. (Eds.), The Geology and Tectonics of the Oman region. Geological Society London, Special Publication 49, 39–47.

Lee, M.S.Y., Gow, C.E., Kitching, J.W., 1997. Anatomy and relationships of the pareiasaur *Pareiasuchus nasicornis* from the Upper Permian of Zambia. Palaeontology 40, 307–335.

Lepper, J., Raath, M.A., Rubidge, B.S., 2000. A diverse dinocephalian fauna from Zimbabwe. S. Afr. J. Sci. 96, 403–405.

Lock, B.E., 1980. Flat-plate subduction and the Cape Fold Belt of South Africa. Geology 8, 35–39.

Loock, J.C., Visser, J.N.J., 1985. South Africa In: Diaz, C.M. (Ed.), The Carboniferous of the World II. Australia, Indian Subcontinent, South Africa, South America and North Africa. IUGS Publication of the Institute of Geology, Minero Spain, vol. 20, pp. 167–174.

MacLeod, K.G., Smith, R.M.H., Koch, P.L., Ward, P.L., 1999. Timing of mammal-like reptile extinctions across the Permian-Triassic boundary in South Africa. Geology 28, 227–230.

MacRae, C.S., 1988. Palynostratigraphic correlation between the lower Karoo sequence of the Waterberg and Pafuri coal-bearing basins and the Hammanskraal plant macrofossil locality, Republic of South Africa. Memoir of the Geological Survey of South Africa, vol. 75, 217p.

Markwort, S., 1991. Sedimentation and diagenese der untertriadischen Karoo Schichten des Ruhuhu Beckens, SW Tansania. Geologisches Institut, Univbersität Köln, Sonderveröffentliochungen, vol. 80, 118pp.

Marsh, J.S., 2002. The geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana: discussion. J. Afr. Earth Sci. 35, 525–527.

Marsh, J.S., Hooper, P.R., Rehacek, J., Duncan, A.R., 1997. Stratigraphy and age of Karoo basalts of Lesotho and implications for correlations within the Karoo Igneous Province. In: Mahoney, J.J., Coffin, M.F. (Eds.), Large Igenous Provinces: Continental, Oceanic and Planetary Flood Volcanism, Geophysical Monograph, vol. 100. American Geophysical Union, Washington, DC, pp. 247–272.

Mazin, J.M., King, G.M., 1991. The first dicynodont from the Late Permian of Malagasy. Palaeontology 34, 837–842.

Mitrovica, J.X., Beaumont, C., Jarvis, G.T., 1989. Tilting of Continental Interiors by the Dynamical Effects of Subduction. Tectonics 8 (5), 1079–1094.

Money, N.J., Drysdall, A.R., 1975. The geology, classification, palaeogeography and origin of the mid-Zambezi coal deposits of Zambia. In: Campbell, K.S.W. (Ed.), Gondwana Geology. Third Gondwana Symposium. Australian National University Press, Canberra, pp. 249–270.

Mountney, N., Howell, J., Flint, S., Jerram, D., 1998. Aeolian and alluvial deposition within the Mesozoic Etjo Sandstone Formation, northwest Namibia. J. Afr. Earth Sci. 27 (2), 175–192.

Mpodozis, C., Kay, S.M., 1992. Late Paleozoic to Triassic evolution of the Gondwana margin: evidence from Chilean frontal cordilleran batholiths (28°S to 31°S). Geol. Soc. Am. Bull. 104, 999–1014.

Neveling, J., 2002. The biostratigraphy and sedimentology of the contact area between the *Lystrosaurus* and *Cynognathus* Assemblage Zones (Beaufort Group, Karoo Supergroup). Ph.D. dissertation, University of the Witwatersrand, Johannesburg.

North, F.W., 1878. Colonial Mining Engineers Report on the Coalfield of the Stormbergen. Parliamentary Report of the Cape of Good Hope, G47.

Nyambe, I.A., 1999. Tectonic and climatic controls on sedimentation during deposition of the Sinakumbe Group and Karoo Supergroup, in the mid-Zambezi Valley Basin, southern Zambia. J. Afr. Earth Sci. 28 (2), 443–463.

Nyambe, I.A., Dixon, O., 2000. Sedimentology of the Madumabisa Mudstone Formation (Late Permian), Lower Karoo Group, mid-Zambezi valley basin, southern Zambia. J. Afr. Earth Sci. 30, 535–553.

Nyambe, I.A., Owen, D., 2000. Sedimentology of the Madumabisa mudstone formation (Late Permian), Lower Karoo Group, mid-Zambesi Valley basin, southern Zambia. J. Afr. Earth Sci. 30, 535–553.

Nyambe, I.A., Utting, J., 1997. Stratigraphy and palynostratigraphy, Karoo Supergroup (Permian and Triassic), mid-Zambezi Valley, southern Zambia. J. Afr. Earth Sci. 24, 563–583.

Oesterlen, M., 1976. Karoo-System und präkambrische Unterlage im nördlichen Angola—I. Stratigraphie, Tektonik und Petrographie. Geologisches Jahrbuch, Reihe B, 20, 3-55, Hannover.

Oesterlen, M., 1979. Karoo-System und präkambrische Unterlage im nördlichen Angola—II. Diagenese und Sedimentologie des Karoo Systems. Geologisches Jahrbuch, Reihe B, 36, 3-41, Hannover.

Oesterlen, P.M., Millsteed, B.D., 1994. Lithostratigraphy, palaeontology and sedimentary environments of the western Cabora Bassa Basin, Lower Zambesi Valley, Zimbabwe. S. Afr. J. Geol. 97, 205–224.

Ortlepp, G.J., 1977. The reserves of the Ngana coalfield. Chamber of Mines South Africa Report. Malawi Mineral Development Section, Johannesburg, 11p.

Pickford, M., 1995. Karoo Supergroup Palaeontology of Namibia and brief description of a thecodont from Omingonde. Palaeontol. Africana 32, 51–66.

Piqué, A., Laville, E., Bignot, G., Rabarimanana, M., Thouin, C., 1999. L'ouverture et le développement du bassin de Morondava (Madagascar) du Carbonifère supérieur au Jurassique moyen. Données stratigraphiques, sédimentaires, paléontologiques et structurales. J. Afr. Earth Sci. 28 (4), 931–948.

Pysklywec, R.N., Mitrovica, J.X., 1999. The role of subduction-induced subsidence in the evolution of the Karoo Basin. J. Geol. 107, 155–164.

Quennell, A.M., McKinlay, A.C.M., Aitken, W.G., 1956. Summary of the geology of Tanganyika, Part I: Introduction and Stratigraphy. Geological Survey of Tanganyika, Memoir 1, 264pp.

Radelli, L., 1975. Geology and oil of Sakamena Basin, Malagasy Republic (Madagascar). Am. Assoc. Petrol. Geol. Bull. 59, 97–114.

Razafindrazaka, Y., Randriamananjara, T., Piqué, A., Thouin, C., Laville, E., Malod, J., Réhault, J.-P., 1999. Extension et sédimentation au Paléozoïque terminal et au Mésozoïque dans le bassin de Majunga (Nord-Ouest de Madagascar). J. Afr. Earth Sci. 28 (4), 949–959.

Reeves, C.V., Karanja, F.M., MacLeod, I.N., 1986. Geophysical evidence for a failed Jurassic rift and triple junction in Kenya. Earth Planetary Sci. Lett. 81, 299–311.

Reeves, C.V., Sahu, B.K., de Wit, M., 2002. A re-examination of the paleo-position of Africa's neighbours in Gondwana. J. Afr. Earth Sci. 34, 101–108.

Rubidge, R.N., 1858. Notes on the geology of some parts of South Africa. Quart. J. Geol. Soc. London 12, 237–238.

Rubidge, B.S., 2005. Reuniting lost continents—fossil reptiles from the ancient Karoo and their wanderlust. S. Afr. J. Geol. 108, 135–172.

Rubidge, B.S., Johnson, M.R., Kitching, J.W., Smith, R.M.H., Keyser, A.W., Groenewald, G.H., 1995. An introduction to the biozonation of the Beaufort Group. In: Rubidge, B.S. (Ed.), Biostratigraphy of the Beaufort Group (Karoo Supergroup). SACS Biostratigraphic Series 1, 1–2.

Rubidge, B.S., Hancox, P.J., Catuneanu, O., 2000. Sequence analysis of the Ecca-Beaufort contact in the southern Karoo of South Africa. S. Afr. J. Geol. 103 (1), 81–96.

Rust, I.C., 1975. Tectonic and sedimentary framework of Gondwana basins in southern Africa. In: Campbell, K.S.W. (Ed.), Gondwana Geology (3rd Gondwana Symposium). Australian National University Press, Canberra, pp. 537–564.

SACS (South African Committee for Stratigraphy), 1980. Stratigraphy of South Africa, Part 1. L.E. Kent, compiler. Handbook Geol. Surv. S. Afr., Pretoria, vol. 8, 690p.

Schandelmeier, H., Reynolds, P.O., Semtner, A.K., 1997. Palaeogeographic-Palaeotectonic Atlas of North-Eastern Africa, Arabia, and Adjacent Areas. Balkema, Rotterdam, 160pp., 17 Pl.

Schlueter, Th., Picho-Olarker, G., Kreuser, T., 1993. A review of some neglected Karoo grabens of Uganda. J. Afr. Earth Sci. 17, 415–428.

Schreuder, C.P., Genis, G., 1975. Die geologie van die Karasburg Karookom. Ann. Geol. Survey S. Afr. 9, 7–22.

Selley, R.C. (Ed.), 1997. Sedimentary Basins of the World. African Basins, vol. 3. Elsevier, Amsterdam, p. 394.

Semkiwa, P.Z., 1992. Depositional environment and coal petrography of Permian coal deposits in Karoo basins of SW Tanzania. Geologisches Institut, Universität Köln Sonderveröffentlichungen, vol. 84, 184pp.

Semkiwa, P.Z., Kalkreuth, W., Utting, J., Mayagilo, F., Mpanju, F., Hagemann, H., 1998. The geology, palynology and geochemistry of Permian coal basins in Tanzania.1. Namwele-Mkomolo, Muze and Galula coalfields. Int. J. Coal Geol. 36, 63–110.

Sherlock, R.L., 1947. The Permo-Triasic Formations, A World Review. Hutchinson's Scientific and Technical Publications, London, 367pp.

Shishkin, M.A., Rubidge, B.S., Hancox, P.J., 1995. Vertebrate biozonation of the Upper Beaufort Series of South Africa—a new look on correlation of the Triassic biotic events in Euramerica and southern

Gondwana. In: Sixth Symposium on Mesozoic Terrestrial Ecosystems. China Press, Beijing, pp. 39–41.

Sinclair, H.D., Allen, P.A., 1992. Vertical versus horizontal motions in the Alpine orogenic wedge: stratigraphic response in the foreland basin. Basin Res. 4, 215–232.

Smellie, J.L., 1981. A complete arc-trench system recognised in Gondwana sequences of the Antarctic Peninsula region. Geol. Mag. 118, 139–159.

Smith, R.A., 1984. The lithostratigraphy of the Karoo Supergroup in Botswana. Bulletin of the Geological Survey Botswana, vol. 26, 239pp.

Smith, R.M.H., 1987. Morphology and depositional history of exhumed Permian point bars in the southwestern Karoo, South Africa. J. Sedimen. Petrol. 57, 19–29.

Smith, R.M.H., 1990. A review of the stratigraphy and sedimentary environments of the Karoo basin of South Africa. J. Afr. Earth Sci. 10, 117–137.

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. Palaeogeogr. Palaeoclimatol. Palaeoecol. 117, 81–104.

Smith, R.M.H., 2000. Sedimentology and taphonomy of Late Permian vertebrate fossil localities in southwestern Madagascar. Palaeontol. Africana 36, 25–41.

Smith, R.M.H., Swart, R., 2002. Changing fluvial environments and vertebrate taphonomy in response to climatic drying in a Mid-Triassic rift valley fill: the Omingonde Formation (Karoo Supergroup) of central Namibia. Palaios 17, 249–267.

Smith, R.M.H., Ward, P.D., 2001. Pattern of vertebrate extinctions across an event bed at the Permian-Triassic boundary in the Karoo Basin of South Africa. Geology 29 (12), 1147–1150.

Smith, R.M.H., Eriksson, P.G., Botha, W.J., 1993. A review of the stratigraphy and sedimentary environments of the Karoo-aged basins of Southern Africa. J. Afr. Earth Sci. 16, 143–169.

Snyman, C.P., Barclay, J., 1989. The coalification of South African coal. Int. J. Coal Geol. 13, 375–390.

Stanistreet, I.G., Stollhofen, H., 1999. Onshore equivalents of the main Kudu gas reservoir in Namibia. In: Cameron, N.R., Bate, R.H., Clure, V.S. (Eds.), The Oil and Gas Habitats of the South Atlantic. Geological Society of London, Special Publication, vol. 153, pp. 345–365.

Stavrakis, N., 1980. Sedimentation of the Katberg sandstone and adjacent formations in the south-eastern Karoo Basin. Trans. Geol. Soc. S. Afr. 83, 361–374.

Stear, W.M., (1980). The sedimentary record of the Beaufort group uranium province in the vicinity of Beaufort West, South Africa. Ph.D. thesis, University of Port Elizabeth, 188pp.

Streel, M., Theron, J.N., 1999. The Devonian-Carboniferous boundary in South Africa and age of the earliest episode of the Dwyka glaciation: new palynological result. Episodes 22, 41–44.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R., Minter, W.E.L., 1982. Crustal Evolution of Southern Africa: 3.8 Billion Years of Earth History. Springer-Verlag, Berlin, 523p.

Tavener-Smith, R., Cooper, J.A.G., 1988. Depositional environments in the Volksrust Formation (Permian) in the Mhlatuze River, Zululand. S. Afr. J. Geol. 91, 198–206.

Teichert, C., 1970. Marine fossil invertebrate faunas of the Gondwana region. In: Proceedings and Papers of Second Gondwana Symposium, South Afrika,pp. 125–138.

Tewari, R.C., Veevers, J.J., 1993. Gondwana basins of India occupy the middle of a 7500km sector of radial valleys and lobes in central-eastern Gondwanaland. In: Findlay et al. (Eds.), Gondwana Eight: Proceedings of the Eighth Gondwana Symposium, Hobart. Balkema, pp. 507–512.

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 the groundwater quality. Ph.D. thesis (unpublished), University of the Orange Free State, Bloemfontein, 307p.

Turner, B.R., 1975. The stratigraphy and sedimentary history of the Molteno Formation in the main Karoo Basin of South Africa and Lesotho. Ph.D. thesis (unpubl.), Univ. Witwatersrand, 314p.

Turner, B.R., 1978. Sedimentary patterns of uranium mineralization in the Beaufort Group of the southern Karoo (Gondwana) Basin, South Africa. In: Miall, A.D. (Ed.), Fluvial Sedimentology, Canadian Association of Petroleum Geologists, Memoir 5, 831–848.

Turner, B.R., 1980. Palaeohydraulics of an Upper Triassic braided river system in the main Karoo Basin, South Africa. Trans. Geol. Soc. S. Afr. 83, 425–431.

Turner, B.R., 1983. Braidplain deposition of the Upper Triassic Molteno Formation in the main Karoo (Gondwana) Basin, South Africa. Sedimentology 30, 77–89.

Turner, B.R., 1986. Tectonic and climatic controls on continental depositional facies in the Karoo Basin of northern Natal, South Africa. Sediment. Geol. 46, 231–257.

Turner, B.R., 1999. Tectonostratigraphical development of the Upper Karoo foreland basin: orogenic unloading versus thermally-induced Gondwana rifting. J. Afr. Earth Sci. 28, 215–238.

Utting, J., 1978. Karoo stratigraphy of the northern part of the Luangwa valley, Zambia. Memoir Geological Survey Zambia, vol. 4, 64pp, Lusaka.

Van der Werff, W., Johnson, S., 2003. High resolution stratigraphic analysis of a turbidite system, Tanqua Karoo Basin, South Africa. Marine Petrol. Geol. 20, 45–69.

Van Eeeden, O.R., 1972. The geology of the Republic of South Africa: An explanation of the 1:000 000 map, 1970 edition. Special Publication, Geological Survey of South Africa, vol. 18, 85p.

Van Rooy, J.L., 1991. The durability characteristics and testing of Drakensberg basalts. Ph.D. thesis (unpubl.), Univ. Pretoria, 182p.

Van Vuuren, C.J., Cole, D.I., 1979. The stratigraphy and depositional environments of the Ecca Group in the northern part of the Karoo Basin. In: Anderson, A.M., Van Biljon, W.J. (Eds.), Some Sedimentary Basins and Associated Ore Deposits of South Africa. Special Publication Geological Society South Africa, vol. 6, pp. 103–111.

Veevers, J.J., 1989. Middle/Late Triassic (230 +/− 5 Ma) singularity in the stratigraphic and magmatic history of the Pangean heat anomaly. Geology 17, 784–787.

Veevers, J.J., Powell, C.McA., 1994. Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland. Geological Society of America, Memoir 184.

Veevers, J.J., Clare, A., Wopfner, H., 1994a. Neocratonic magmatic-sedimentary basins of post-Variscan Europe and post-Kanimblan eastern Australia generated by right-lateral transtension of Permo-Carboniferous Pangea. Basin Res. 6, 141–157.

Veevers, J.J., Powell, C.McA., Collinson, J.W., Lopez-Gamundi, O.R., 1994b. Synthesis. In: Veevers, J.J., Powell, C.McA. (Eds.), Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland. Geol. Soc. America, Boulder, Colorado, Memoir 184, pp. 331–353.

Veevers, J.J., Cole, D.I., Cowan, E.J., 1994c. Southern Africa: Karoo basin and Cape Fold Belt. In: Veevers, J.J., Powell, C.McA. (Eds.), Permian-Triassic Pangean Basins and Foldbelts along the Panthalassan Margin of Gondwanaland. Geol. Soc. America, Boulder, Colorado, Memoir 184, pp. 223–279.

Verniers, J., Jourdan, P.P., Paulis, R.V., Frasca-Spada, L., DeBock, F.R., 1989. The Karoo graben of Metangula, northern Mozambique. J. Afr. Earth Sci. 9, 137–158.

Viljoen, J.H.A., 1992a. Lithostratigraphy of the Collingham Formation (Ecca Group) including the Zoute Kloof, Buffels River and Wilgehout River members and the Matjiesfontein chert bed. Lithostratigraphic Series no. 22. Geological Survey, Pretoria, South Africa, 9p.

Viljoen, J.H.A., 1992b. Lithostratigraphy of the Laingsburg Formation (Ecca Group). Lithostratigraphic Series no. 20. Geological Survey, Pretoria, South Africa, 7p.

Viljoen, J.H.A., 1994. Sedimentology of the Collingham Formation, Karoo Supergroup. S. Afr. J. Geol. 97, 167–183.

Viljoen. J.H.A., Wickens, H.deV., 1992. Lithostratigraphy of the Vischkuil Formation (Ecca Group). Lithostratigraphic Series no. 19. Geological Survey, Pretoria, South Africa, 7p.

Visser, J.N.J., 1983a. An analysis of the Permo-Carboniferous glaciation in the marine Kalahari Basin, Southern Africa. Palaeogeogr. Palaeoclimatol. Palaeoecol. 44, 295–315.

Visser, J.N.J., 1983b. Submarine debris flow deposits from the Upper Carboniferous Dwyka Tillite Formation in the Kalahari Basin, South Africa. Sedimentology 30, 511–523.

Visser, J.N.J., 1984. A review of the Stormberg Group and Drakensberg volcanics in Southern Africa. Palaeont. Afr. 25, 5–27.

Visser, J.N.J., 1987. The palaeogeography of part of southwestern Gondwana during the Permo-Carboniferous glaciation. Palaeogeogr. Palaeoclimatol. Palaeoecol. 61, 205–219.

Visser, J.N.J., 1989. The Permo-Carboniferous Dwyka Formation of Southern Africa: deposition by a predominantly subpolar marine ice sheet. Palaeogeogr. Palaeoclimatol. Palaeoecol. 70, 377–391.

Visser, J.N.J., 1990. The age of the late Palaeozoic glacigene deposits in southern Africa. S. Afr. J. Geol. 93, 366–375.

Visser, J.N.J., 1991a. Geography and climatology of the Late Carboniferous to Jurassic Karoo Basin in south-western Gondwana. Ann. S. Afr. Museum 99, 415–431.

Visser, J.N.J., 1991b. The paleoclimatic setting of the Late Paleozoic marine ice sheet in the Karoo Basin of Southern Africa. In: Anderson, J.B., Ashley, G.M. (Eds.), Glacial Marine Sedimentation: Paleoclimatic Significance. Geological Society of America Special Paper 261, pp. 181–189.

Visser, J.N.J., 1992a. Basin tectonics in southwestern Gondwana during the Carboniferous and Permian. In: de Wit, M.J., Ransome, I.G.D. (Eds.), Inversion Tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa. Balkema, Rotterdam, pp. 109–115.

Visser, J.N.J., 1992b. Deposition of the early to Late Permian Whitehill Formation during a sea-level highstand in a juvenile foreland basin. S. Afr. J. Geol. 95, 181–193.

Visser, J.N.J., 1993. Sea-level changes in a back-arc—foreland transition: the Late Carboniferous-Permian Karoo Basin of South Africa. Sediment. Geol. 83, 115–131.

Visser, J.N.J., 1994. A Permian argillaceous syn- to post-glacial foreland sequence in the Karoo Basin, South Africa. In: Deynoux, M., Miller, J.M.G., Domack, E.W., Eyles, N., Fairchild, I.J., Young, G.M. (Eds.), Earth's Glacial Record: International Geological Correlation Project 260. Cambridge University Press, Cambridge, pp. 193–203.

Visser, J.N.J., 1997. Deglaciation sequences in the Permo-Carboniferous Karoo and Kalahari basins of southern Africa: a tool in the analysis of cyclic glaciomarine basin fills. Sedimentology 44, 507–521.

Visser, J.N.J., Botha, B.J.V., 1980. Meander channel, point bar, crevasse splay and aeolian deposits from the Elliot Formation in Barkly Pass, north-eastern Cape. Trans. Geol. Soc. S. Afr. 83, 55–62.

Visser, J.N.J., Dukas, B.A., 1979. Upward fining fluviatile megacycles in the Beaufort Group north of Graaff Reinet, Cape Province. Trans. Geol. Soc. S. Afr. 82, 149–154.

Visser, J.N.J., Kingsley, C.S., 1982. Upper Carboniferous glacial valley sedimentation in the Karoo Basin, Orange Free State. Trans. Geol. Soc. S. Afr. 85, 71–79.

Visser, J.N.J., Loock, J.C., 1988. Sedimentary facies of the Dwyka Formation associated with the Nooitgedacht glacial pavements, Barkly West District. S. Afr. J. Geol. 91, 38–48.

Visser, J.N.J., Praekelt, H.E., 1996. Subduction, mega-shear systems and Late Paleozoic basin development of Gondwana. Geol. Rundsch. 86, 632–646.

Visser, J.N.J., van Niekerk, B.N., van der Merwe, S.W., 1997. Sediment transport of the Late Paleozoic glacial Dwyka Group in the southwestern Karoo Basin. S. Afr. J. Geol. 100 (3), 223–236.

Wardlaw, B.R., 1999. Notes from the SOS Chair. Permophiles 35, 1–2.

Weiss, R.H., 2001. Middle to Late Permian microfloral assemblages from the Ruhuhu and Selous basins, Tanzania. In: Weiss, R.H., (Ed.), Contributions to Geology and Palaeontology of Gondwana in honour of Helmur Wopfner, Geological Institute, University of Cologne, pp. 497–592.

Weiss, R.H., Wopfner, H., 1997. Palynology and palaeoecology of Late Palaeozoic glacigene Idusi Formation of southern Tanzania. Geologisches Institut, Universität Köln, Sonderveröffentlichungen Nr. 114 (Festschrift E. Kempf), pp. 535–559.

Wescott, W.A., Diggens, J.N., 1998. Depositional history and stratigraphic evolution of the Sakamena Group (Middle Karoo Supergroup) in the southern Morondava Basin, Madagascar. J. Afr. Earth Sci. 27 (3/4), 461–479.

Wickens, H.deV., 1994. Basin floor fan building turbidites of the southwestern Karoo Basin, Permian Ecca Group, South Africa. Ph.D. thesis, University of Port Elizabeth, South Africa, 223p.

Winter, M.F.W., 1985. Lower Permian palaeoenvironments of the northern Highveld Coalfield and their relationship to the characteristics of coal seams. Ph.D. thesis, University of Witwatersrand, Johannesburg, 254p.

Wopfner, H., 1990. Rifting in Tanzanian Karoo basins and its economic implications. In: Rocci, G., Deschamps, M. (Eds.), Etudes recentes sur la Geologie de l'Afrique. Centre International pour la Formation et les Echanges Geologiques (CIFEG), Orleans, Publication Occasionelle 1990/22, pp. 217–220.

Wopfner, H., 1991. Extent and timing of the late Palaeozoic glaciation in Africa. Geologisches Institut, Universität Köln, Sonderveröffentlichungen 82 (Brunnacker Festschrift), pp. 447–453.

Wopfner, H., 1994. The Malagasy Rift, a chasm in the Tethyan margin of Gondwana. J. Southeast Asian Earth Sci. 9, 451–461.

Wopfner, H., 1999. The Early Permian deglaciation event between East Africa and northwestern Australia. J. Afr. Earth Sci. 29, 77–90.

Wopfner, H., 2002. Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. J. Afr. Earth Sci. 34, 167–177.

Wopfner, H., Diekmann, B., 1996. The Late Palaeozoic Idusi Formation of southwestern Tanzania: a record of change from glacial to postglacial conditions. J. Afr. Earth Sci. 22, 575–595.

Wopfner, H., Kaaya, C.Z., 1991. Stratigraphy and morphotectonics of Karoo deposits of the northern Selous Basin, Tanzania. Geol. Mag. 128, 319–334.

Wopfner, H., Kreuser, T., 1986. Evidence for Late Palaeozoic glaciation in southern Tanzania. Palaeogeogr. Palaeoclimatol. Palaeoecol. 56, 259–275.

Wopfner, H., 1993. Structural development of Tanzanian Karoo basins and the break-up of Gondwana. In: Findlay, A. et al. (Eds.), Gondwana Eight: Proceedings of the Eighth Gondwana Symposium Hobart. Balkema, pp. 531–539.

Wright, R.P., Askin, R.A., 1987. The Permian-Triassic boundary in the southern Morondava Basin of Madagascar as defined by plant microfossils, Proceedings of Gondwana VI. American Geophysical Union, pp. 157–164.

Yemane, K., Kelts, K., 1990. A short review of palaeoenvironments for Lower Beaufort (Upper Permian) Karoo sequences from southern to central Africa: A major Gondwana Lacustrine episode. J. Afr. Earth Sci. 10, 169–185.