Communs geol. Surv. Namibia, **12** (2000), 291-301

Karoo unconformities in NW-Namibia and their tectonic implications

A. Wanke[1], H. Stollhofen[1], I.G. Stanistreet[2] and V. Lorenz[1]
[1]*Institut für Geologie, Universität Wurzburg, Pleicherwall 1, 97070 Würzburg, Germany email: awanke@geologie.uni-wuerzburg.de*
[2]*Department of Earth Sciences, University of Liverpool, PO Box 147, Liverpool L69 3BX, United Kingdom*

The Karoo-Etendeka depositories in northwestern Namibia can be subdivided into (l) a Carboniferous-Permian, (2) a Triassic-Jurassic and (3) a Cretaceous megasequence, recording successive extensional periods, separated by time-stratigraphic gaps. Close to the present-day Atlantic coastline the Karoo Supergroup is only represented by the Permian succession in the Huab area. This is disconformably overlain by the Lower Cretaceous Etendeka Group. Further east, the Karoo succession becomes successively' more complete, but correlation with the main Karoo Basin in South Africa and the Brazilian Paraná Basin indicates major gaps in the sedimentary record. The gaps can be attributed to the combined effects ofthe long-lived South Atlantic rift evolution and orogenic pulses derived from the Samfrau active margin.

Introduction

The Karoo Supergroup is widespread in various Upper Carboniferous to Lower Jurassic depositories across the Gondwana supercontinent. Of these depositories, two major basin types are developed in southern Africa: (A) the main Karoo Basin in South Africa with the evolution of a foredeep in front of the northerly prograding Cape Fold Belt and (B) the elongate grabens and half-grabens in southern and particularly eastern Africa that reactivated pre-existing structural grains, mainly shear zones, imprinted on the basement (Daly *et al.*, 1989).

Both in the main Karoo Basin and in the Paraná Basin, Karoo-equivalent strata attain maximum cumulative thicknesses of 10 000 m (Visser, 1996) and 4 000 m (Zalán *et al.*, 1990) respectively. This contrasts with the Karoo in Namibia were maximum thicknesses of 700 m are reported from the Waterberg area, 520 m from the Mt. Etjo area (Holzförster *et al.*, 1999) and 250 m from the Huab area (Horsthemke, 1992). Gaps within the Karoo Supergroup were indicated by Porada *et al.* (1996) and Miller (1997) and the most obvious gap between Permian and Cretaceous strata in the Huab area has been used by Milner *et al.* (1994) as a basis for stratigraphic separation of the Carboniferous-Jurassic Karoo Supergroup from the Cretaceous Etendeka Group. Stollhofen (1999) and Stanistreet and

Stollhofen (1999) relate these contrasting stratigraphic records to the development of major unconformities expressing successive phases of extension and thermal uplift along the early southern South Atlantic rift Zone. The latter led ultimately to continental separation of South America and Africa and oceanic onset during the Early Cretaceous.

It is the aim of our contribution to analyse these time-stratigraphic gaps and to place them in a geodynamic context. Our study focuses on the Huab area in northwestern Namibia (Fig. 1) because of the advantages of good exposure with the availability of outcrops from close to the present-day continental margin and up to

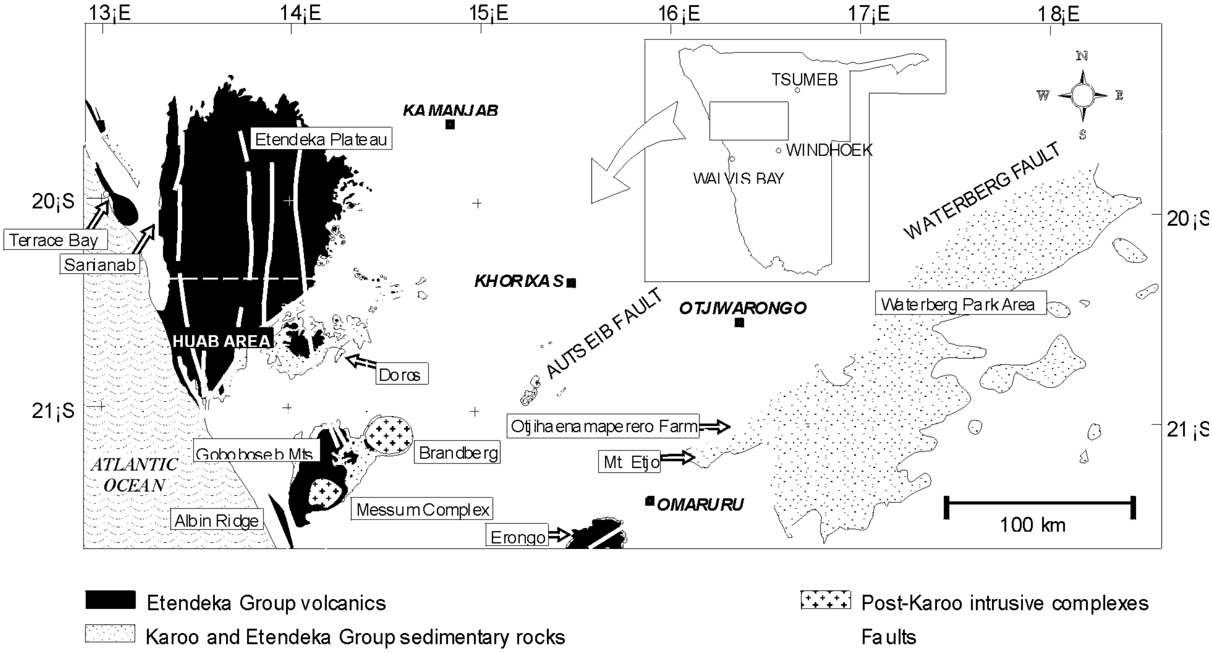

Figure 1: Overview map of the Karoo and Etendeka outcrops and the main fault systems in northwestern Namibia. Map compiled from Miller and Schalk (1980) and Milner (1997). Frame shows location of detailed map given in Fig. 2.

120 km eastward into the continental interior.

The structural fabric of the Huab area

Pan-African basement structures in northwestern Namibia show two dominant trends: (1) a NNW-SSE trend associated with the Damara coastal branch, referred to as the Kaoko Belt and (2) a SW-NE trend related to the Damara inland branch (Miller, 1983). The first direction is traced by prominent sets of NNW-SSE striking, westerly dipping normal faults with down-to-the-west sense of displacement. These major structures are referred to as the Ambrosiusberg, Uniab, Wêreldsend, Bergsig and Twyfelfontein Faults (Fig. 2) and occur in a belt that is subparallel to the present coastline and extends up to about 60 km inland. Blocks are rotated usually causing tilting of strata to the east and, if faulting occurred contemporaneous to deposition, the development of wedge-shaped sediment bodies of cover sediments (Fig. 5). Stollhofen (1999) interpreted this rotational block faulted zone to be fringed by remnants of the Triassic-Jurassic rift shoulder and the adjacent rift basin depression towards the west. The Albin Ridge (Fig. 1) therefore provides a key locality as this is one of the few exposures of the rift shoulder.

NE-SW-trending basement structures were most probably reactivated by the Huab Fault (Fig. 2), situated just northwest of the Huab River (Mountney *et al.*, 1998), the Autseib Fault (Fig. 1), southeast of the Brandberg (Milner, 1997) and the major Waterberg-Omaruru fault zone (Fig. 1). The latter has been interpreted as a Karoo-equivalent sinistral oblique-slip fault with associated pull-apart and half graben structures (Stollhofen, 1999; Holzförster *et al.*, 1999) hosting Triassic-Jurassic successions of up to 550 m and 650 m thickness in the Erongo (Hegenberger, 1988; Löffler and Porada, 1998) and central Waterberg areas respectively (Holzförster *et al.*, 1999). In these areas, however, both the Carboniferous-Permian and the Cretaceous sequences are either entirely missing or only thinly developed.

Karoo stratigraphy and depositional environments of the Huab area

The lowermost stratigraphic unit of the Karoo Supergroup in the Huab outcrop area is formed by thin (<15 m) and more localised glaciogenic deposits of the Carboniferous Dwyka Group which rest on metamorphosed Pan-African basement rocks (Fig. 3). During the Early Permian, the area became occupied by extensive meandering river systems adjacent to which the coal-bearing Verbrandeberg Formation was deposited under cool-temperate post-glacial climates (Horsthemke *et al.*, 1990). This setting gradually changed during deposition of the Tsarabis Formation which involves an upward transition from fluvio-deltaic to shallow marine nearshore environments. Succeeding stromatolitic carbonates and shales of the Huab Formation record a continuation of this transgressive development (Holzförster *et al.*, 2000) and the establishment of warm Mediterra-

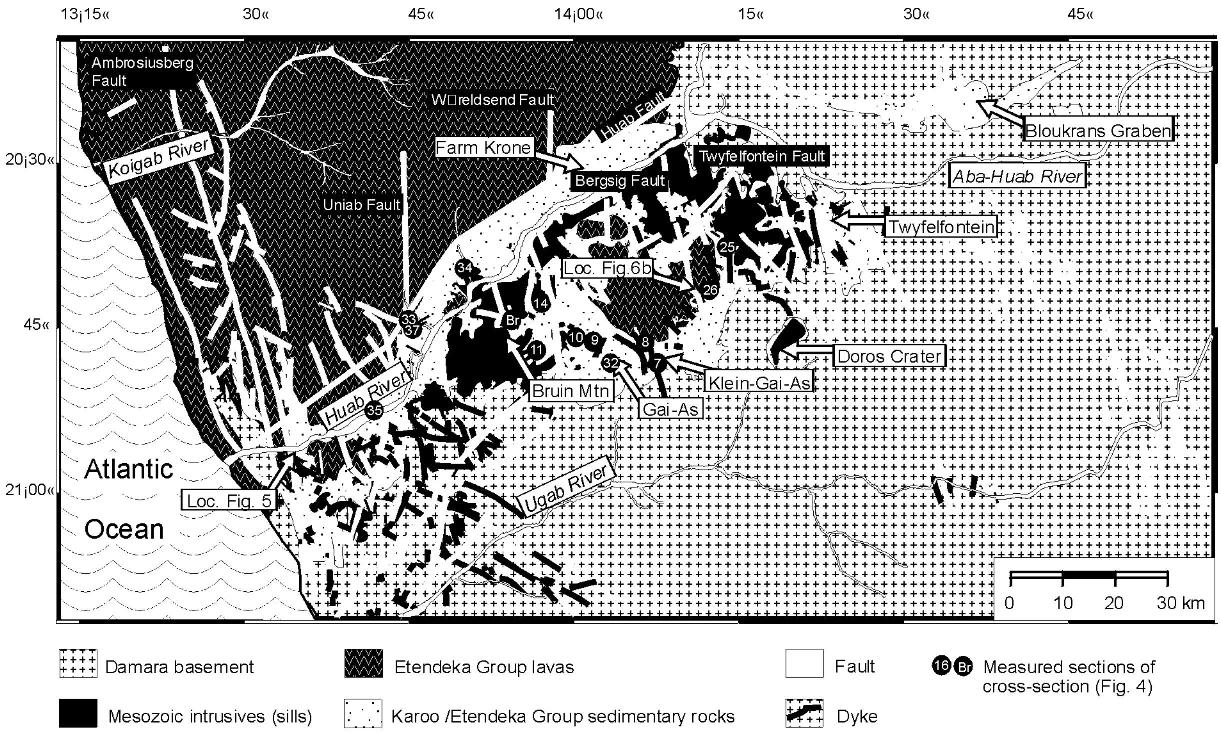

Figure 2: Map showing the structural framework of the Huab area with dominant NNW-SSE, NE-SW and subordinate NW-SE and E-W fault trends. Indicated are outcrop locations referred to in the text and the locations of measured sections (Fig. 4), of wedge-shaped sediment bodies (Fig. 5) and of sediment-filled fissure photograph (Fig. 6b). The Ambrosiusberg Fault might trace the Lower Cretaceous rift shoulder. Map based on Miller (1988).

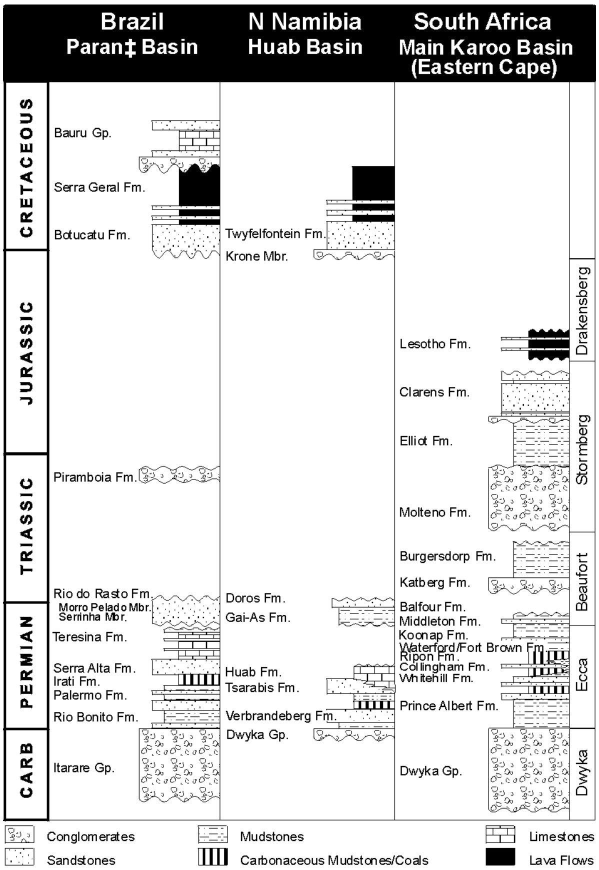

Figure 3: Stratigraphic sections comparing Karoo and Etendeka equivalents in the Huab area (Namibia), the eastern Cape region (South Africa) of the main Karoo basin (after Cairncross *et al.*, 1995) and the Paraná basin (Brazil) (compiled from Bigarella 1970; Zalán *et al.*, 1990; Milani *et al.*, 1994; Rohn, 1994; França *et al.*, 1995; Milner *et al.*, 1995).

nean climates (Ledendecker, 1992). One of the maximum marine flooding surfaces contained in the Huab Formation is marked by a widespread bonebed (Reuning and von Huene, 1925) with abundant fragments of *Mesosaurus tenuidens* which is used as a basis for correlation (Fig. 4).

Continental environments were re-established in northwestern Namibia during deposition of the Late Permian/earliest Triassic Gai-As and Doros Formations with red beds recording shallow lakes fringed by alluvial fan deltas (Stollhofen *et al.*, 2000a). In the easternmost Goboboseb Mountains, the Brandberg and Erongo regions (Fig. 1), the latter are overlain by braided fluvial deposits of the Triassic Omingonde Formation and, farther east (Waterberg area), by the fluvio-aeolian Lower Jurassic Etjo Formation and basaltic lavas of the Rundu Formation (Fig. 7). In contrast, the Huab area shows Early Cretaceous aeolianites of the Twyfelfontein Formation (Stanistreet and Stollhofen, 1999) interleaved at their top with flood basalts and quartz latite rheoignimbrites of the Etendeka Group (Milner *et al.*, 1994) sitting immediately on top of Permian Karoo strata.

Abrupt vertical facies changes and the variable completeness of the stratigraphic record of the Karoo Supergroup in northwestern Namibia indicate the existence of time-stratigraphic gaps within the volcano-sedimentary succession which need further analysis in terms of their lateral extent and duration. The importance of such major regional gaps in the stratigraphic record is that they potentially define correlative tectonostratigraphic megasequences (Hubbard, 1988) expressing successive extensional periods in the Gondwanan interior.

Gaps in the sedimentary record

Early/Late Permian

A significant hiatus is apparently located between the Huab and Gai-As Formations in northwestern Namibia (Fig. 4). Field evidence for this hiatus is given by the abrupt environmental change from the marine-dominated Huab Formation (Holzförster *et al.*, 2000) to the continental red beds of the entirely continental, predominantly lacustrine Gai-As Formation (Horsthemke, 1992). Although an angular unconformity is not clearly developed, phases of non-deposition and erosion are indicated by abundant pedogenic features (auto brecciation, carbonate nodules, root tubes) and erosion of stromatolitic carbonates at the top of the Huab Formation. The boundary between the Huab and Gai-As Formations, however, has much more the character of a para-conformity than of a typical disconformity.

The extent of this gap can only be estimated by the large-scale correlation of Permian strata in the Huab area of Namibia with more complete successions in the main Karoo Basin of South Africa and in the Paraná Basin of Brazil (Stollhofen *et al.*, 2000a). The *Mesosaurus*-bearing Lower Permian Huab Formation serves as a marker unit as it is widespread and correlates with the Whitehill Formation of the main Karoo Basin in South Africa and southern Namibia and the Irati Formation in the Brazilian Paraná province (Oelofsen and Araujo, 1987; Ledendecker, 1992). In the Paraná area the Irati Formation is followed by up to 750 m of the Teresina Formation and the Upper Permian Serrinha Member of the Rio do Rasto Formation (Fig. 3). These Formations contain contrasting bivalve assemblages: The *Pinzonella illusa* and *Pinzonella neotropica* assemblages characterise the Teresina Formation, whereas the overlying Serrinha Member contains the *Leinzia similis* assemblage (Rohn *et al.*, 1995). The Huab Formation in Namibia is directly overlain by the Gai-As Formation, the latter containing the same *Leinzia similis* assemblage as the Serrinha Member in Brazil. Such a correlation implies, that equivalents of the Teresina Formation, characterized by the *Pinzonella illusa* and *Pinzonella neotropica* assemblages are missing in Namibia.

This gap is confirmed by additional biostratigraphically and tephrostratigraphically-based correlations with the main Karoo Basin. Remains of the dicynodont *Endothiodon* occur at the base of the Morro Pelado

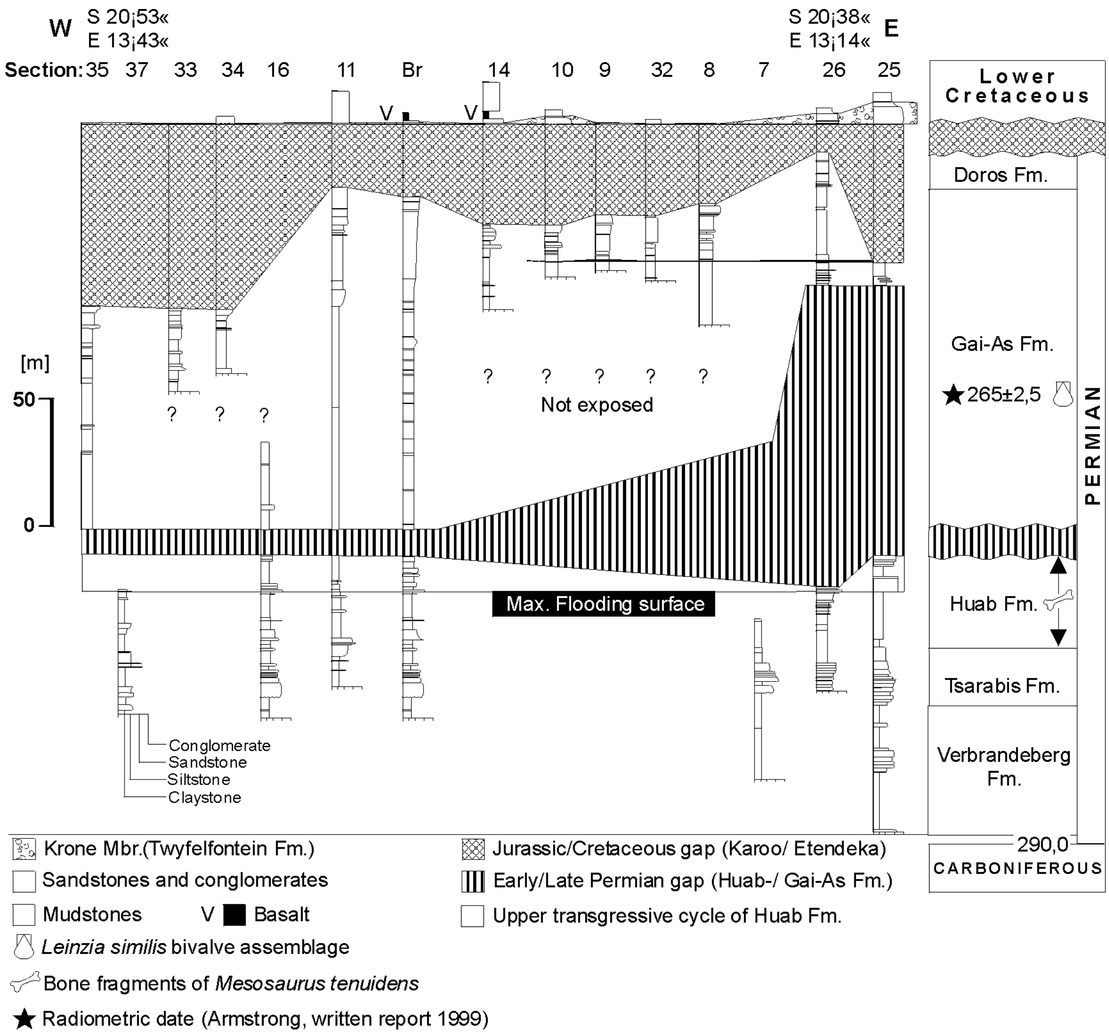

Figure 4: W-E cross-section through the Huab area illustrating the stratigraphic position of the Permian and Jurassic/Cretaceous gaps in the Karoo-Etendeka succession. Note the variable vertical extent of the gaps. Correlation is based on a maximum flooding surface within the Huab Formation that is characterized by fragments of *Mesosaurus tenuidens*. Locations of measured sections are given in Fig. 2. Horizontal distances not to scale.

Member, immediately above the Serrinha Member in Brazil and suggest a faunistic affinity to the *Pristerognathus*, *Tropidostoma* and *Cistecephatus* assemblage zones (*sensu* Rubidge *et al.*, 1995) of the Upper Permian Teekloof Formation in South Africa (Barberena *et al.*, 1991). The latter provided U/Pb zircon ages of 261 Ma (Rubidge, pers. comm., 1998) derived from tuffs of the *Cistecephatus* zone which fit quiet well with new U/Pb zircon ages of 265±2.5 (Armstrong, written report, 1999) for the top of the middle part of the Gai-As Formation in Namibia. Based on this correlation, the gap extends to more than 2000 m of missing strata represented in the eastern Cape province of the main Karoo Basin in South Africa by the Collingham, Ripon, Fort Brown and Waterford Formations (Fig. 3). On a broader scale we suggest that this stratal gap correlates with a pre-Beaufort Group unconformity identified by Turner (1999) in the main Karoo Basin of South Africa that might be related to an orogenic pulse in the Cape Fold Belt, dated at 258±2 Ma (Hälbich *et al.*, 1983).

Late Triassic

A second hiatus is located between the Middle to Late Triassic middle Omingonde Formation and the Early Jurassic middle Etjo Formation. Evidence for this gap is well constrained by outcrop geology at Mt. Etjo, on the farm Otjihaenamaperero and in the Waterberg National Park (Fig. 1). There, Holzförster *et al.* (1999) described a threefold subdivision of the Etjo Formation comprising (1) a fluvial-dominated lower unit, (2) a fluvio-aeolian middle unit and (3) an aeolian-dominated upper unit. A comparable architecture of the Etjo equivalents in South Africa (Eriksson, 1979; Kitching and Raath, 1984) implies that this organisation of Etjo subunits is not a local, but a regional development.

At Otjihaenamaperero the above gap is associated with a well defined angular unconformity. Intensively folded coarse fluvial clastics of the middle to basal upper Omingonde Formation (Holzförster *et al.*, 1999) are overlain by slightly deformed to undeformed fluvio-aeolian deposits of the middle Etjo Formation with the majority of the upper Omingonde Formation and the entire lower Etjo Formation missing. When compared to the Waterberg Park sections (Holzförster *et al.*, 1999), this equates to at least 120 m of missing strata but could exceed as much as 500 m if a gap comprising equivalents of the entire South African Elliot Formation (Smith *et al.*, 1993) could be proved. Confirmation of such an extent depends upon an improved resolution of the biostratigraphic framework of the upper Omingonde Formation. So far, only biostratigraphic correlatives of the Beaufort Group and the Molteno Formation (Stormberg Group) have been identified in Namibia but not elements biostratigraphically correlating with the Late Triassic/Early Jurassic Elliot Formation.

The Triassic and Jurassic sediments at Mt. Etjo, Waterberg and Erongo (Fig. 1) were deposited in the tectonically active environment of the Waterberg-Omaruru transfer fault zone (Stollhofen, 1999). The synsedimentary tectonic control on Omingonde deposition is recorded by both thickening of strata towards the fault and by the pronounced shift of the adjacent depocentre, the latter suggesting left-lateral oblique slip movements (Holzförster *et al.*, 1999). Evidence for a temporarily transpressive regime in the vicinity of the fault is given by dominantly SW-NE striking and south-easterly inclined fold axes in the middle and upper Omingonde Formation at Otjihaenamaperero. From this perspective it appears that the unconformity at the Triassic/Jurassic boundary could be locally exaggerated due to the structural setting of the Waterberg region; elsewhere it is less well defined. We suggest, however, that the gap has regional importance and probably correlates with a major second-order sequence boundary between the Molteno and Elliot Formations in the main Karoo Basin (Turner, 1999). It may also coincide with the major pre-Piramboia Group unconformity in the Paraná Basin if a latest Triassic/earliest Jurassic age for the latter (Porada *et al.*, 1996) is correct.

Jurassic/Cretaceous

Age constraints

A major stratal gap is developed between the Karoo Supergroup and the overlying Etendeka Group in the Huab area and along the Namibian Skeleton Coast. The Etendeka Group is dominated by basaltic to andesitic lava flows and quartz latitic rheoignimbrites (Milner *et al.*, 1994). Fluvial and aeolian sediments, up to 150 m thick, are restricted to the base of the succession (Jerram *et al*., 1999). In NW-Namibia, the Etendeka Group volcanics cover at least 0.08 x 10^6 km^2 (Erlank *et al.*, 1984; Milner *et al.*, 1995a). Considering their prebreakup position, however, they form part of the extensive Paraná-Etendeka flood basalt province that ranks as one of the worlds largest igneous provinces, covering more than 1,28 x 10^6 km^2 with a volcanic pile up to 1 723 m thick (Wilson, 1989; Milner *et al.*, 1995a). Fluvial and aeolian deposits below the Etendeka Group volcanics have traditionally been ascribed to the Etjo Formation (e.g. Miller and Schalk, 1980), including the basal Krone Member. It was only when Early Cretaceous K/Ar ages were derived from lavas above the "Etjo correlates" in the Etendeka sequence (Siedner and Mitchell, 1976; Renne *et al.*, 1992; Milner *et al.*, 1995b) that Martin (1982), Porada *et al.* (1996) and Löffler and Porada (1998) speculated that aeolianites in the Huab area could be younger than the Etjo Formation in its Mount Etjo-Waterberg type area farther east. This conforms with recent $^{40}Ar/^{39}Ar$ dates of 132±1 Ma for basalts interfingering with the top part of the underlying fluvio-aeolian succession (Renne, written comm. 1997) and $^{40}Ar/^{39}Ar$ dates of 132.3±0.7 to 131.7±0.7 Ma (Renne *et al.*, 1996) for overlying Etendeka volcanics. Recent discoveries of tetrapod vertebrae in a bone bed of the basal Krone Member suggest a Jurassic maximum age for the overlying aeolianites (Löffler and Porada, 1998).

As the Huab aeolianites are conformable with, and in some cases interbedded with, lavas at the base of the Etendeka succession Milner *et al.* (1994) argued for a much closer temporal relationship with the Etendeka volcanic rocks than with the underlying Karoo Sequence. Following sedimentological and stratigraphical investigations, Stanistreet and Stollhofen (1999) consequently introduced the term Twyfelfontein Formation for the aeolianites of the Huab area: The Twyfelfontein aeolianites classify as subarkosic medium- to coarse-grained sandstones deposited dominantly by straight crested transverse dunes in a dry desert environment with traces of life only rarely preserved (Mountney *et al.*, 1998). In contrast, the Early Jurassic Etjo Formation in its central Namibian type area is structurally and compositionally more mature and has been deposited by sinuous-crested dunes in a relatively wet semi-desert environment (Holzförster *et al.*, 1999). Such a setting is indicated by the abundant preservation of bioturbation traces and various tetrapod tracks (Pickford, 1995) associated with deflation surfaces (Stanistreet and Stollhofen, 1999). Considering the relatively low structural and compositional maturity of the Twyfelfontein Formation aeolianites, lack of well developed palaeosols and other hiatal gap indicators, as well as consistent southwesterly wind directions deduced from dune foresets, we find a permanent sand desert lasting more than 60 Ma unlikely. This conforms with the negligible age variations of lavas interfingering with the upper Twyfelfontein Formation (Renne *et al.*, 1996), the latter indicating relatively rapid deposition of the aeolianites. We therefore conclude an Early Creta-ceous age for the entire Twyfelfontein Formation which suggests a considerably pre-Cretaceous stratal gap.

The anatomy of the pre-Cretaceous unconformity

The anatomy of the pre-Cretaceous unconformity varies considerably in the Huab area. Most commonly channelized, conglomeratic, braided stream deposits of the Krone Member are incised into the underlying Karoo succession. This type of boundary developed particularly in the central Huab area, between Doros and the outcrops immediately north of the Huab River as well as within the Bloukrans Graben (Fig. 2). Only north of the Huab River and at the Albin Ridge (Fig. 1) are matrix-supported debris flow deposits intercalated with the braided stream deposits or completely replace them (Swart, 1992/93; Mountney *et al.*, 1998).

Pedogenic features associated with the pre-Cretaceous boundary surface have only rarely been observed north of the Huab river (e.g. at Sanianab locality, Fig. 1). There, fine-grained sandstones of the underlying Karoo sequence developed reddish-yellowish marble textures, autobreccisation, alveolar-structure and abundant carbonate concretions in zones up to 30 cm thick. From field relationships it is suggested that the presence of such well-drained palaeosols mainly depends on their preservation potential which is essentially controlled by the structural position of the outcrop area during and after soil development as well as the degree of incision of the overlying Krone Member.

Elsewhere, but particularly west of Gai-As (Fig. 2), a plane palaeo-deflation surface defined by a single layer of polished, wind-grooved and partly wind-faceted quartz pebbles defines the unconformity which is then directly overlain by aeolian dune deposits of the Twyfelfontein Formation. These dune deposits, however, are usually considerably thinner (<15 m) when compared to equivalent lithologies farther north or east and typically consist of only small barchans (Horsthemke, 1992). We ascribe both the development of a pronounced deflation surface and the occurrence of small barchans instead of the thick transverse dune deposits which occur farther north and east to a lack of available accommodation space suppressing deposition and preservation of aeolianites in the westernmost Huab outcrop area.

Pre- and syn- Twyfelfontein faulting

The age of the strata underlying the pre-Cretaceous unconformity is highly variable. Northeast of the farm Krone (Fig. 2) the Twyfelfontein Formation rests with a pronounced unconformity on top of metamorphosed Damaran basement rocks. Directly north and south of the Huab River it overlies the Lower Permian Verbrandeberg and Tsarabis Formations whereas elsewhere in the Huab outcrop area the Upper Permian to lowermost Triassic Gai-As and Doros Formations occur below the unconformity. This indicates a pronounced pre-Twyfelfontein relief which is deduced to be essentially fault-generated with a cumulative vertical displacement approaching 300 m.

The influence of pre- and syn- Twyfelfontein rotational block faulting is particularly well documented in several outcrops close to the present-day coastline such as at Sanianab (Fig. 1), Ambrosiusberg (Fig. 2) and in an area extending for about 15-30 km north of Terrace Bay (Fig. 1). There, the Twyfelfontein Formation is preserved as wedge-shaped sedimentary bodies which developed on top of easterly dipping Gai-As Formation sediments (Ambrosiusberg, Fig. 5) or metamorphosed Damaran basement (north of Terrace Bay). Associated westerly dipping normal faults can be clearly traced upward as far as the base of the aeolian units but die out at higher levels. Another key locality is Krone farm (Fig. 2), near the southern end of the SW-NE trending Huab Fault. This outcrop shows eastward thrusted

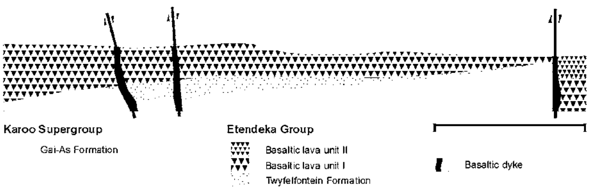

Figure 5: Line drawing of Huab river cut wall illustrating the development of wedge-shaped geometries by the Twyfelfontein aeolianites at Ambrosiusberg locality (Fig. 2). The eastern faults were active immediately prior or during deposition of the Twyfelfontein Formation. The westernmost fault was reactivated after deposition of Etendeka Group lava units I and II.

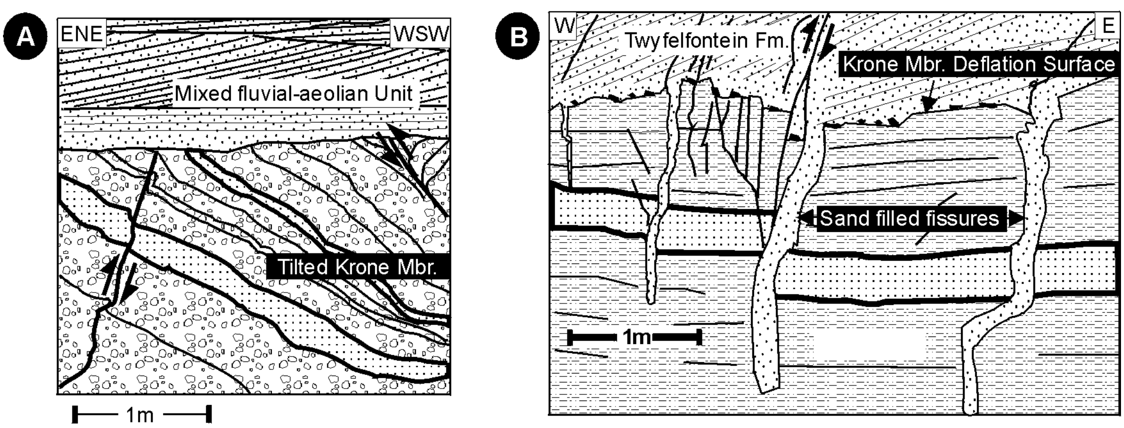

Figure 6: Outcrop photographs showing (A) the deformed fluvial Krone Member overlain by undeformed Twyfelfontein aeolianites at Krone farm outcrop, (B) sand-filled fissures within the Gai-As Formation adjacent to the Bergsig Fault system. See Fig. 2 for localities.

slices of the Krone Member (Fig. 6a), dipping up to 20° SW (240°) and containing abundant water escape structures. Within the inclined part sheared bands and microthrusts are abundant on a metre scale. Associated faults are almost vertical normal faults with preferred N-S and E-W trends and 35 cm maximum displacement. The shear and thrust sense coincides with an inferred sinistral oblique-slip movement of the Huab Fault. All deformation structures are of hydroplastic nature indicating that faulting, shearing and thrusting occurred shortly after deposition.

Brittle deformation is documented by sand-filled fissures which are particularly well developed in the Gai-As Formation (Fig. 6b) and in the Krone Member. Such fissures penetrate up to 25 m down into strata underlying the pre-Twyfelfontein unconformity and vary in width from less than 1 cm to more than 20 cm. The fissures are commonly subvertical with planar walls and their preferred orientation coincides with the general N-S, NE-SW and NW-SE fault trends. Maximum density and size of the fissures has been observed in the central Huab area in the vicinity of Gai-As and Klein Gai-As (Fig. 2). The fissures are filled with aeolian sand and sometimes also contain pebbles of the Krone Member. At places (e.g. north of Doros), the fissures end not directly at the top of the Karoo succession, but can be traced through the Krone Member up to a few tens of centimetres into the overlying aeolianites of the Twyfelfontein Formation.

The tectonostratigraphic importance of the pre-Cretaceous unconformity

This unconformity most probably correlates with another pronounced unconformity at the base of the aeolian dominated Botucatu Formation in the Brazilian Paraná Basin, if a Cretaceous age for the latter is valid (cf. Bigarella, 1970; Holz, pers.comm 1997; Milani and Zalán, 1999). The anatomy of the pre-Cretaceous unconformity suggests a peak of extensional tectonic activity and thermal uplift just prior to the effusion of huge volumes of flood basalts and quartz latitic rheoignimbrites that form the Paraná-Etendeka volcanic province. This was followed ultimately by South Atlantic oceanic onset in the rift segment west of the Huab area as documented by magnetic anomaly M4 which has been assigned to a Barremian age (Rabinowitz, 1976; Harland *et al.*, 1990).

The contrasting structural setting of the NW Namibian continental margin and the continental interior

Previous studies have proposed the existence of an early southern South Atlantic rift-valley depression (Erlank *et al.*, 1984) which became repeatedly flooded by Early Permian marine incursions (Stollhofen, 1999; Bangert *et al.*, 2000; Holzförster *et al.*, 2000) and then hosted the large intracontinental Gai-As lake system during the Late Permian/earliest Triassic (Stollhofen *et al.*, 2000a). Holzförster *et al.*, (2000) and Stollhofen *et al.* (2000) describe to what extent the thickness and facies of Permian deposits in the Huab area were controlled by contemporaneously active NNW-SSE to N-S trending faults paralleling the rift zone. Greater subsidence within the rift depression is indicated by enhanced stratal thicknesses and facies indicative of deposition under greater water depth when compared to facies development in areas farther east. In contrast, extensive pedogenic overprinting of both the Permian Huab and Gai-As Formations occurs in the eastern Huab area, as documented by rootlet horizons, calcareous nodules and autobrecciation (Holzförster *et al.*, 2000). During deposition of the Triassic middle Omingonde Forma-

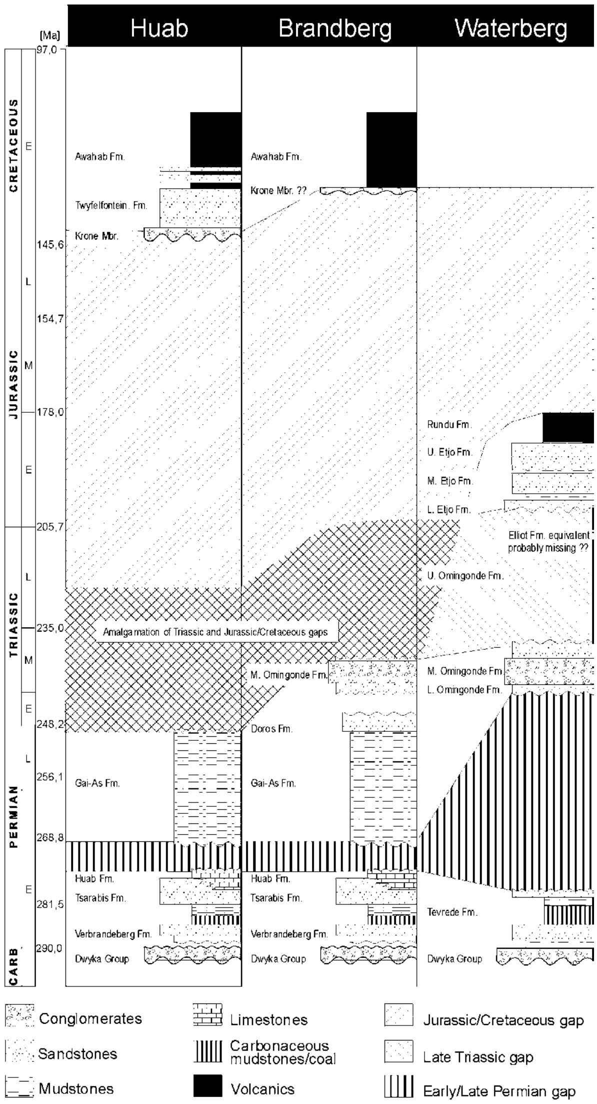

Figure 7: Comparison of the completeness of Karoo and Etendeka sections and correlatives along an E-W traverse covering (A) the Huab, (B) the Brandberg and (C) the Waterberg areas in northwestern and central Namibia. Indicated is an increasing stratigraphic incompleteness towards the rift shoulder, situated along the western margin of the Huab area. Numerical time scale is from Harland *et al.* (1990).

tion and the Early Jurassic Etjo Formation, easterly directed drainage systems were set up (Wanke *et al.*, 1998; Holzförster *et al.*, 1999) which most probably reflects the "Skeleton Coast Uplift", suggested by Porada *et al.* (1996). This uplift is also recorded by a westerly decreasing stratigraphic completeness of the Triassic/ Jurassic sequence, with equivalents of the Omingonde, Etjo and Rundu Formations entirely missing in the coastal area (Fig. 7). Such a scenario was repeated just prior to the effusion of the voluminous Parami-Etendeka volcanics when the thick Twyfelfontein erg accumulated in the tectonically subsiding Huab area but only minor barchans developed in the coastal area.

It is suggested that these differences between Karoo sections measured close to the present-day coastline and those measured farther inland reflect a long-lived tectonic zonation comprising from west to east (a) the relatively rapidly subsiding rift valley depression with a relatively complete stratigraphic record preserved, (b) an adjacent rift shoulder with well developed stratigraphic gaps, (c) a rotational block-faulted zone with contrasting hanging wall and footwall developments and (d) the relatively stable continental interior with gradually decreasing thicknesses and palaeosol development during the Permian (Stollhofen, 1999) (Fig. 1). It is important to point out that this zonation was not spatially fixed throughout its development but changed slightly in orientation and width during successive phases of rifting and basin development.

Significance of the gaps in a geodynamic context

Stollhofen *et al.* (2000b) suggest that marine incursions during the Late Carboniferous/Early Permian history of the southern South Atlantic rift valley depression were favoured through the combined effects of glacio-eustatic sea level fluctuations and extensional faulting. During Dwyka Group deposition, contemporaneous tectonism is expressed by the activity of NW-SE trending normal faults followed by the activity of NNW-SSE trending fault sets during deposition of the Ecca Group (Holzförster *et al.*, 2000). Both the timing and the considerable amount of Carboniferous-Permian tectonic subsidence, followed by thermal cooling, are clearly displayed by the backstripped subsidence curve from a representative well in the Paraná basin area (Zalán *et al.*, 1990: Fig. 33-13). During the Early Permian, the rift valley depression extended a long way into the Gondwanan interior, reaching as far as central Brazil to accommodate the Irati-Whitehill sea (Oelofsen, 1987; Williams, 1995). Following this marine incursion the sedimentary environment within the rift valley depression changed gradually into a freshwater lake. This cutoff from the marine realm towards the south was probably caused by large-scale uplift of the Argentinian Puna Highlands during the Cape-Ventana and San Rafael orogenies (Veevers *et al.*, 1994; Porada *et al.*, 1996). The depositional sequence recording the marine-non-marine transition (Teresina Formation and equivalents) is only fully preserved in the Karoo foreland basin and the Paraná basin, the latter including the more central parts of the rift depression. In NW Namibia, however, a para-conformity, probably caused by early uplift of the rift shoulder, separates the marine Whitehill equivalents (Huab Formation) from the overlying continental Gai-As red beds (Fig. 4).

Another period of uplift, but on a continental scale and much more pronounced, occurred during the Triassic and was succeeded by Early Jurassic rifting and volcanism. This is particularly well documented in southern Namibia where the Kalkrand Formation preserves a record of Early Jurassic flood basalt volcanism and contemporaneous extensional tectonism (Stollhofen *et al.*, 1998). The activity of NNW-SSE and NE-SW trending faults continued with the NE-SW trending fault sets showing considerable involvement of sinistral oblique slip movements. The latter caused localized transpression associated with the development of angular unconformities, as described previously from the vicinity of the Waterberg-Omaruru fault zone in Central Namibia. A maximum of regional uplift then preceded Early Cretaceous rifting and emplacement of the Paraná-Etendeka volcanics in NW Namibia. This period of uplift is responsible for the development of the pronounced pre-Cretaceous unconformity, defining the Karoo/Etendeka stratigraphic boundary (Figs. 4 and 7).

The observation that some of the time-stratigraphic gaps in Namibia and South Africa coincide with compressional deformation events in the Cape Fold Belt south of the main Karoo Basin suggests a genetic coupling. It is assumed that, particularly during the Carboniferous-Permian, continental-scale stresses were transmitted by impact tectonics along the southern convergent margin of Gondwana (de Wit and Ransome, 1992; Cobbold *et al.*, 1992) causing collision-induced rifting that was followed by rift shoulder uplift in the foreland of the developing orogen. In contrast, regional doming occurred prior to Jurassic and Cretaceous flood basalt emplacements which is the predictive sequence of an active rift model (Keen, 1985).

Conclusions

Based on the identification of unconformities and their lateral correlatives, the fill of the Namibian Karoo-Etendeka depositories can be subdivided into (1) a Carboniferous-Permian, (2) a Triassic-Jurassic and (3) a Cretaceous megasequence, each recording extensional periods, separated by time-stratigraphic gaps. We speculate that the latter are coupled with compressional phases related to the Samfrau subduction margin. Zalán *et al.* (1990: Fig. 33-14) made a similar observation as they viewed the Paraná area not as a single basin in the strict sense, but as a combination of tectonically different types of basins with varying outlines stacked on top of one another. All together these developed a cumulative geometry, commonly referred to as the Paraná "basin". Some of the evolutionary steps of the Paraná (Klein, 1995) compare well with the development of African Karoo rifts involving sequential stages of extensional faulting, heating and mechanical, fault-controlled subsidence succeeded by subsidence related to periodic thermal cooling and contraction. A comparative example is the North Sea basin, recognized by Schiter and Christie (1980) from backstripped subsidence curves to involve two phases of rifting and thermal cooling superimposed on top of one another. The present North Sea "basin" geometry is superficially that of the last phase of thermal cooling and subsidence.

Acknowledgements

We owe particular thanks to the Geological Survey of Namibia for cooperation and the Deutsche Forschungsgemeinschaft for funding our work. The staff of the Skeleton and Waterberg National Parks supported our fieldwork as did Rosemarie and Hugo Zahrt at Farm Otjihaenamaperero which is gratefully acknowledged. We also benefited from many discussions with Prof. B. Rubidge and Drs. W. Hegenberger, R. Rohn, B. Turner, D. Jerram and N. Mountney. Many thanks to R. Miller, B. Cairncross and A. B. França for their helpful comments to the manuscript.

References

Bangert, B., Stollhofen, H., Geiger, M. and Lorenz, V. 2000. High resolution tephrostratigraphy, fossil record and age of Carboniferous-Permian glaciomarine mudstones within the Dwyka Group of southern Namibia. *Communs geol. Surv. Namibia*, **12**, (this volume).

Barberena, M.C., Araujo, D.C., Lavina, E.L. and Faccini, V.F. 1991. The evidence for close paleofaunistic affinity between South America and Africa, as indicated by late Permian and Triassic tetrapods. *Proc. Pap. 7th Int. IUGS Gondwana Symp., São Paulo*, 455-467.

Bigarella, J.J., 1970. Continental drift and paleocurrent analysis. *Proc. Pap. 2nd IUGS Int. Gondwana Symp., Pretoria*, 73-97

Cairncross, B., Groenewald, G.H., Rubidge, B.S. and von Brunn, V. 1995. Karoo sedimentology and palaeontology. *Excursion Guidebook, Geocongress '95, geol. Soc. S. Afr*., 48 pp.

Cobbold, P.R., Gapais, D., Rossello, E.R., Milani, E.J. and Szatmari, P. 1992. Permo-Triassic intracontinental deformation in SW Gondwana. *In*: De Wit, M.J. and Ransome, LG.D. (eds) *Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa*, Balkema, Rotterdam, 23-26.

Daly, M.C., Chorowicz, J. and Fairhead, J.D. 1989. Rift basin evolution in Africa: the influence of reactivated steep basement sheer zones. *In*: Cooper, M.A. and Williams, G.D. (eds) *Inversion tectonics*. Spec. Publ. geol. Soc. London, **44**, 309-334.

De Wit, M.J. and Ransome, I.G.D. 1992. Regional inversion tectonics along the southern margin of Gondwana. *In*: De Wit, M.J. and Ransome, I.G.D. (eds) *Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous Basins of Southern Africa*, Balkema, Rotterdam, 15-21.

Eriksson, P.G. 1979. Mesozoic sheetflow and playa sediments of the Clarens Formation in the Kamberg area of the Natal Drakensberg. *Trans. geol. Soc. S. Afr.*, **82**, 251¬258.

Erlank, A.J., Marsh, J.S., Duncan, A.R., Miller, R.McG., Hawkesworth, S.C., Betton, B.J. and Rex, D.C. 1984. Geochemistry and petrogenesis of the Etendeka volcanic rocks from South West Africa/Namibia, 195-245. *In*: Erlank, A.J. (ed.) *Petrogenesis of the volcanic rocks of the Karoo Province*, Spec. Publ. geol. Soc. S. Afr., **13**, 395 pp.

Francça, A.B., Milani, E.J., Schneider, R.L., Lopez-Paulsen, M., Suarez-Soruco, R., Santa-Ana, A., Wiens, F., Ferreiro, O., Rossello, E.A., Bianucci, H.H., Flores, R.E.A., Vistalli, M.C., Fernandez-Seveso, F., Fuenzalida, R.P. and Munoz, N. 1995. Phanerozoic correlation in southern South America. *In*: Tankard, A.J., Suarez-Soruco, R. and Welsink, H.J. (eds) *Petroleum basins of South America*. Mem. Am. Assoc. Petrol. Geol., **62**, 129-161.

Hälbich, I.W., Fitch, F.J. and Miller, J.A. 1983. Dating the Cape orogeny, 149-164. *In*: Söhnge, A.P.G. and Hälbich, I.W. (eds) *Geodynamics of the Cape Fold Belt*, Spec. Publ. geol. Soc. S. Afr., **12**, 184.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig. L.E., Smith, A.G. and Smith D.G. 1990. *A geological time scale*. Cambridge University Press, Cambridge, 263 pp.

Hegenberger, W.F. 1988. Karoo sediments of the Erongo Mountains, their environmental setting and correlation. *Communs geol. Surv. Namibia*, **4**, 51-57.

Holzförster F., Stollhofen, H. and 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**, 105-123.

Holzförster, F., Stollhofen, H. and Stanistreet, I.G. 2000. Early Permian deposits of the Huab area, NW-Namibia: A continental to marine transition. *Communs geol. Surv. Namibia*, **12**, (this volume).

Horsthemke, E. 1992. *Fazies der Karoosedimente in der Huab-Region, Damaraland, NW-Namibia*. Göttinger Arb. Geol. Paläont., 5.5, 102 pp.

Horsthemke, E., Ledendecker, S. and Porada, H. 1990. Depositional environments and stratigraphic correlation of the Karoo Sequence in Northwestern Damaraland. *Communs geol. Surv. Namibia*, **6**, 63-73.

Hubbard, R.J. 1988. Age and Significance of Sequence Boundaries on Jurassic and Early Cretaceous Rifted

Continental Margins. *Bull. Am. Assoc. Petrol. Geol.*, **72**, 42-72.

Jerram, D.A., Mountney, N. and Stollhofen, H. 1999. Facies architecture of the Etjo Sandstone Formation and its interaction with the basal Etendeka Flood basalts of NW Namibia: Implications for offshore analogues. *In*: Cameron, N., Bate, R. and Clure, V. (eds) *The Oil and Gas Habitats of the South Atlantic*. Spec. Publ. geol. Soc. London, **153**, 345-365.

Keen, C.E. 1985. The dynamics of rifting: deformation of the lithosphere by active and passive driving forces. *Geophys. J. R. astr. Soc.*, **80**, 95-120.

Klein, G.D. 1995. Intracratonic basins. *In*: Busby, CJ. and Ingersoll, R.V. (eds) *Tectonics of sedimentary basins*. Blackwell, Cambridge, 459-478.

Kitching, J.W. and Raath, M.A. 1984. Fossils from the Elliot and Clarens Formations (Karoo Sequence) of the northeastern Cape, Orange Free State and Lesotho, and a suggesteted biozonation based on tetrapods. *Palaeont. Afr.*, **25**, 111-125.

Ledendecker, S. 1992. Stratigraphie der Karoosedimente der Huabregion (NW-Namibia) und deren Korrelation mit zeitäquivalenten Sedimenten des Paranábeckens (Südamerika) und des großen Karoobeckens (Südafrika) unter besonderer Berücksichtigung der überregionalen geodynamischen und klimatischen Entwicklung Westgondwanas. *Göttinger Arb. Geol. Paläiont.*, **54**, 87 pp.

Löffler, T. and Porada, H. 1998. Tonttiten (“Mud curls”) aus der Etjo Formation am Gr. Waterberg (Namibia) und dem Germanischen Buntsandstein - Über die Erhaltungsbedingungen von aufgerollten Trockenriß-Segmenten. *Freiberger Forschungsheft*, **C475**, 201-221.

Martin, H. 1982. Die Trias im südlichen Afrika. *Geol. Rundsch.*, **71**, 937-947.

Milani, E.J. and Zahin, P.V. 1999. An outline of the geology and petroleum systems of the Paleozoic interior basins of South America. *Episodes*, **22**, 199-205.

Milani, E.J., França, A.B. and Schneider, R.L. 1994. Bacia do Paraná. Bol. Geociêne. *Petrobás*, **8**, 69-82.

Miller, R.McG. 1983. The Pan-African Damara Orogen of South West Africa/Namibia, 431-515. *In*: Miller, R. McG. (ed.) *Evolution of the Damara Orogen of South West Africa/Namibia*. Spec. Publ. geol. Soc. S. Afr., **11**, 515 pp.

Miller, R.McG. 1988. Geological map, sheet 2013, Cape Cross, 1:250 000. *Geol. Surv., S.W Afr./Namibia*, Windhoek.

Miller, R.McG. 1997. The Owambo basin of Northern Namibia, 237-268. *In*: Selley, R.C. (ed.) *Sedimentary Basins of the world, 3. African Basins*, Elsevier, Amsterdam, 394 pp.

Miller, R.McG. and Schalk, K.E.L. 1980. Geological map of South West Africa/Namibia, 1: 1 000 000. *Geol. Surv. Namibia, Windhoek*.

Milner, S.C. 1997. Geological map of sheet 2114, Omaruru, 1 :250 000. *Geol. Surv. Namibia, Windhoek*.

Milner, S.C., Duncan, A.R., Ewart, A. and Marsh, J.S. 1994. Promotion of the Etendeka Formation to Group status: A new integrated stratigraphy. *Communs geol. Surv. Namiba*, **9**, 5-11.

Milner, S.C., Whittingham, A.M. and Ewart, A. 1995a. Trans-Atlantic correlation of eruptive sequences and individual silicic volcanic units within the Paraná-Etendeka igneous province. *J. Volcanol. geotherm. Res.*, **69**, 137-157.

Milner, S.C., le Roex, A.P. and O’Connor, J.M. 1995b. Age of Mesozoic igneous rocks in northwestern Namibia, and their relationship to continental breakup. *J. geol. Soc. London*, **152**, 97-104.

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

Oelofsen, B.W. 1987. The Biostratigraphy and Fossils of the Whitehill and Irati Shale Formations of the Karoo and Paraná basins. *Proc. Pap. 6th IUGS Gondwana Symp., USA*, 131-138.

Oelofsen, B.W. and Araujo, D.L. 1987. *Mesosaurus tenuidens* and Stereosternum tumidum from the Permian Gondwana of both Southern Africa and South America. *S. Afr. J. Sci.*, **83**, 370-372.

Pickford, M. 1995. Karoo Supergroup palaeontology of Namibia and brief description of a thecodont from Omingonde. *Palaeont. Afr.*, **32**, 51-66.

Porada, H., Löffler, T., Horsthemke, E., Ledendecker, S. and Martin, H. 1996. Facies and paleo-environmental trends of northern Namibian Karoo sediments in relation to West Gondwanaland paleogeography. *Gondwana nine*, **2**, Geol. Surv. India, New Dehli, 1101-1114.

Rabinowitz, P.D. 1976. Geophysical study of the continental margin of southern Africa. *Bull. geol. Soc. Am.*, **87**, 1643-1653.

Renne, P.R., Ernesto, M., Pacca, I.G., Coe, R.S., Jonathon, M.G., Prevot, M. and Perrin, M. 1992. The age of Paraná flood volcanism, rifting of Gondwanaland and the Jurassic-Cretaceous boundary. *Science*, **258**, 975-979.

Renne, P.R., Glen, J.M., Milner, S.C. and Duncan, A.R. 1996. Age of Etendeka flood volcanism and associated intrusions in southwestern Africa. *Geology*, **24**, 659-662.

Reuning, E. and von Huene, D. 1925. Fossilführende Karooschichten im nördlichen S.W.A. *Neues Jb. Paläont. Geol., Beil.*, **52, Abt B**, 94-122.

Rohn, R. 1994. *Evolução ambiental de Bacia do Paraná durante o Neopermiano no leste de Santa Catarina e do Paraná*. Unpubl. PhD thesis, Univ. São Paulo, 386 pp.

Rohn, R. Perinotto, J.A.J., Fulfaro, V.J., Saad, A.R. and Simoes, M.G. 1995. On the significance of the *Pinzonella neotropica* assemblage (Upper Permian) for the Paraná Basin - Brazil and Paraguay: VI Simpósio Sul-Brasileiro de Geologia, I Econtro de Geologia do Cone Sul, Porto Alegre, Brasil, Sociedade Brasileira de Geologia. *Boletim de Resumos Expandidos*, 260-261.

Rubidge, B.S., Johnson, M.R., Kitching, J.W., Smith, R.M. H., Keyser, A.W. and Groenewa1d, G.H. 1995. An introduction to the biozonation of the Beaufort Group. *In*: Rubidge, B.S. (ed.) *Biostratigraphy of the Beaufort Group (Karoo Supergroup)*, S. Afr. Committee for Stratig. Biostratigraphic Ser., **1**, 1-45.

Sclater, J.G. and Christie, P.A.F. 1980. Continental stretching: an explanation of the post-mid Cretaceous subsidence of the Central North Sea. *J. geophys. Res*., **85**, 3711-3739.

Siedner, G. and Mitchell, J.A. 1976. Episodic Mesozoic volcanism in Namibia and Brazil: K-Ar isochron study bearing on the opening of the South Atlantic. *Earth Planet. Sci. Lett*., **30**, 292-302.

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

Stanistreet, I.G. and Stollhofen, H. 1999. Onshore equivalents of the main Kudu gas reservoir in Namibia. *In*: Cameron, N., Bate, R. and Clure, V. (eds) *The Oil and Gas Habitats of the South Atlantic*. Spec. Publ. geol. Soc. London, **153**, 345-365.

Stollhofen, H. 1999. Karoo Synrift-Sedimentation und ihre tektonische Kontrolle am entstehenden Kontinentalrand Namibias. *Z. dt. geol. Ges*., **149**, 519-632.

Stollhofen, H., Gerschtitz, S., Stanistreet, I.G. and Lorenz, V. 1998. Tectonic and volcanic controls on early Jurassic rift-valley lake deposition during emplacement of Karoo flood basalts, southern Namibia. *Palaeogeogr., Palaeo-climatol., Palaeoecol*., **140**, 185-215.

Stollho fen, H. Stanistreet, I.G., Rohn, R., Holzförster, F. and Wanke, A. 2000a. The Gai-As lake system, northern Namibia and Brazil, 87-108. *In*: Kelts, K.R. and Gierlowski-Kordesch, E. (eds) *Lake Basins through space and time*. Studies in Geol., Am. Assoc. Petrol. Geol., **46**.

Stollhofen, H., Stanistreet, I.G., Bangert, B. and Grill, H. (2000b). Tuffs, tectonism and glacially related sea-level changes, Carboniferous-Permian, Southern Namibia. *Palaeogeogr., Palaeoclimat., Palaeoecol*, **161**, 127-150.

Swart, R. 1992/1993. Note: Cretaceous synvolcanic conglomerates on the coastal margin in Namibia related to the break-up of West Gondwana. *Communs geol. Surv. Namiba*, **8**, 137-141.

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

Veevers, U., Powell, C.McA., Collinson, J.W. and López-Gamundi, O.R. 1994. Synthesis. *In*: Veevers, U. and Powell, C.McA. (eds) *Permian- Triassic basins and fold-belts along the Panthalassan margin of Gondwanaland*. Mem. geol. Soc. Am., **184**, 331-353.

Visser, J.N.J. 1996. Controls on Early Permian shelf deglaciation in the Karoo Basin South Africa. *Palaeogeogr., Palaeoclimatol. Palaeoecol.*, **125**, 129-139.

Wanke, A, Stollhofen, H., Lorenz, V. and Stanistreet, I.G. 1998. The pre-breakup evolution of a continental margin: Synsedimentary Karoo tectonics of the Huab basin in NW-Namibia. *J. Afr. Earth Sci.*, **27**, 206.

Williams, K.E. 1995. Tectonic subsidence analysis and Paleozoic paleogeography of Gondwana. *In*: Tankard, A.J., Smirez-Soruco, R. and Welsink, H.J. (eds) *Petroleum basins of South America*. Mem. Am. Assoc. Petrol. Geol., **62**, 79-100.

Wilson, M. 1989. *Igneous Petrogenesis*. Unwin Hyman, London, 466 pp.

Zalán, P.V., Wolff, S., Astolfi, M.A.M., Vieira, LS., Conceição, J.C.J., Appi, V.T., Neto, E.V.S., Cerqueira, J.R. and Marques, A. 1990. The Paraná basin, Brazil. *In*: Leighton, M.W., Kolata, D.R., Oltz, D.F. and Eidel, J.J. (eds) *Interior cratonic basins*. Mem. Am. Assoc. Petrol. Geol., **51**, 681-708.