Geological Society of America
Memoir 184
1994

Southern Africa: Karoo Basin and Cape Fold Belt

J. J. Veevers
Australian Plate Research Group, School of Earth Sciences, Macquarie University, North Ryde, N.S.W. 2109, Australia
D. I. Cole
Geological Survey of South Africa P.O. Box 572, Bellville 7535, South Africa
E. J. Cowan*
Australian Plate Research Group, School of Earth Sciences, Macquarie University, North Ryde, N.S.W. 2109, Australia

ABSTRACT

Three basement trends, defined by the 1.0–0.5 Ga foldbelts of weak crust that wrap around the 1 Ga Namaqua-Natal Belt and >2.5 Ga Kaapvaal Province, provide a tub-shaped template that was impressed on succeeding structures up to the Cretaceous breakup of Pangea along the present divergent margins. The pattern is reprinted during the Ordovician-Devonian deposition of the Cape Supergroup in grabens on the northwest and northeast linked by an east-west depositional axis and during the Permian and Triassic development of the Cape Fold Belt along the east-west trend linked with intermittent uplifts to the northwest (Atlantic upland) at a syntaxis around Cape Town and to the northeast (Eastern upland) at a syntaxis in the (restored) Falkland Islands.

The inception of the Karoo (Gondwanan) Sequence in the latest Carboniferous (290 Ma) reflected the Gondwanaland-wide relaxation of the Pangean platform in sags (Karoo terrain) and rifts (Zambezian terrain). The first appearance of tuffs from a convergent arc in the Sakmarian (ca. 277 Ma) marked the onset of a foreland basin. Material derived from the south included a small component of mainly rhyodacitic tuff which persisted to the end of Beaufort deposition, when the presumed southern magmatic arc became extinct. Karoo deposition expanded northward over the interior beyond that of the confined pre-Gondwanan Cape Sequence. The axis of maximum thickness of the Permian-Triassic foredeep remained near the South Crop of the Karoo Basin; the parallel drainage axis migrated northward from an initial distance of 80 km during Dwyka deposition through 400 km during Ecca deposition and 550 km during Beaufort to a final 1,000 km during Stormberg deposition. The increasing separation of foredeep and drainage axis reflects the widening during the growth of the Cape Fold Belt of the southern depositional flank of the Karoo Basin at the expense of the starved northern cratonic side. Only during Stormberg deposition did the northern craton match the Cape Fold Belt as a source of voluminous sediment.

*Present address: Department of Geology, University of Toronto, Toronto, Ontario M5S 3B1, Canada.

Veevers, J. J., Cole, D. I., and Cowan, E. J., 1994, Southern Africa: Karoo Basin and Cape Fold Belt, *in* Veevers, J. J., and Powell, C. McA., eds., Permian-Triassic Pangean Basins and Foldbelts Along the Panthalassan Margin of Gondwanaland: Boulder, Colorado, Geological Society of America Memoir 184.

Renewed and more extensive deposition in the Late Triassic corresponds to a singularity in Pangean history: terminal compression of foldbelts (Cape Fold Belt, Bowen-Sydney Basin, Canning Basin) and widespread subsidence, mainly in rifts that prefigured the divergent margins of the Atlantic and Indian Ocean regions. The subsequent Karoo volcanism reflects the increased activity of Pangean hotspots.

INTRODUCTION

This synopsis of the geologic history of southern Africa, south of 26°S, focuses on the Permian-Triassic Karoo Sequence of the Karoo Basin in its Gondwanan setting. The Karoo Sequence (Figs. 1–3) is a component of the Pangean Supersequence of the Gondwanaland cratonic province of Pangea (Veevers, 1990). In the latest Carboniferous (290 Ma), the Karoo Sequence started to accumulate in the oval-shaped Karoo Basin and narrow, fault-affected, Zambezian basins. From 277 Ma, the Karoo Basin became a foreland basin that subsided along a zone of inherited (pre-Gondwanan) structure behind the Panthalassan margin. Information was compiled from the regional accounts of Kent (1980), Tankard et al. (1982), Dingle et al. (1983), Söhnge and Hälbich (1983), and from the primary literature. Original contributions are Cole's field studies and Cowan's petrographic studies of the Karoo Basin (Appendix 1). Particular attention is given to an appraisal of the contribution to the Karoo Basin fill by the source region to the south, comprising the Cape Fold Belt and an inferred magmatic arc generated by the convergence of Panthalassa and Pangea. The data are presented in the figures and documented in the captions and tables; the text is reserved for critical evaluation of the pre-Gondwanan inheritance of the Karoo Basin and Cape Fold Belt and the influence of the inferred magmatic arc.

Reconstruction of the Falkland Islands off southeast Africa

A prerequisite to the analysis is a palinspastic reconstruction of the Falkland Islands off southeast Africa before this part of Gondwanaland started to break up in the Middle-Late Jurassic and Early Cretaceous (Ben-Avraham et al., 1993).

On structural and stratigraphical grounds, Adie (1952a) fitted an inverted Falkland Islands off the Transkei coast, between 33° and 34°S, to complete the truncated Karoo Basin and Cape Fold Belt. Adie's (1952a) reconstruction was confirmed by Mitchell et al. (1986, p. 131)

> with preliminary palaeomagnetic evidence from [Early Jurassic] dolerite dykes on West Falkland which suggests that the Falkland Islands were rotated through ~120° during the early stages of the break-up and dispersal of the southern part of Gondwanaland. . . .The first stage of continental drift probably took place during the Jurassic, as Antarctica separated from southern Africa, the islands moving as a microplate to a position approximately 500 km south-east of present-day Cape Town. Subsequently, during the opening of the South Atlantic, the islands and the Falklands Plateau have drifted to their present position and undergone a further rotation of ~60°.

The pre-Middle Jurassic reconstruction, shown in Fig. 1, entails the following connections.

(1) >0.5 Ga: Rex and Tanner (1982) dated gneiss of the Cape Meredith amphibolite-grade Complex of the Falkland Islands (Fig. 4) by the K-Ar method on biotite and hornblende as 963 ± 30 and 987 ± 40 Ma (converted with the new constants). Rex and Tanner (1982) compared these dates with K-Ar ages of 950–1150 Ma on gneisses from the Natal coast of the Namaqua-Natal Belt affected by the Kibaran orogenic event. The Cape Meredith dates straddle the boundary between the Namaqua-Natal Belt (2.1–1.0 Ga) and the Saldanian Province (1.0–0.5 Ga) so that the possible connections of the Cape Meredith Complex are (1) with the Natal Belt, either a southern salient, e.g., the Transkei amphibolite-grade terrane at 31.3°S on the coast, or an allochthonous block of the Natal Belt within the Southern Cape Conductive Zone–Saldanian Belt, or (2) with an extension of the Saldanian Belt. The strongest connection is through the common amphibolite grade of the Transkei terrane and the Cape Meredith Complex (Thomas, 1989; Thomas and Mawson, 1989).

(2) <0.5 Ga: (a) Port Stephens–Fox Bay–Monte Maria (Port Stanley plus Port Philomel) Formations (Adie, 1952a, 1952b; Frakes and Crowell, 1967; Barrett and Isaacson, 1988). The Port Stephens Formation, 1,500 m of cross-bedded quartzose sandstone with minor conglomerate and red shale, nonconformably overlies the Cape Meredith Complex and passes conformably upwards into the Fox Bay Formation, 800 m of interbedded shale and sandstone with Emsian brachiopods and trilobites of the Malvinokaffric Realm. The conformably overlying 800 m of Monte Maria Formation comprises the Port Philomel Beds in West Falkland, sandstone and shale with Lepidodendroid plants, and the Port Stanley Beds in East Falkland, white quartzite with relatively few intercalated shales.

Adie (1952a, 1952b) correlated the Port Stanley Beds with the Witteberg Group, the Port Philomel Beds and Fox Bay Beds with the Bokkeveld Group, and the Port Stephens Beds with the Table Mountain Group. The only secure correlation is by the Emsian marine fauna in the Fox Bay Formation and in the lower two-thirds of the Bokkeveld Group. We choose the option that provides a consistent trend of the isopachs, such that the Fox Bay and Port Stephens Formations are correlated with the Bokkeveld Group, and the Monte Maria Formation is correlated with the Witteberg Group (Fig. 5, B and C), while at the same time allowing for the possibility of Table Mountain Group equivalents (Fig. 5A).

(b) The strongly cleaved Lafonian Diamictite, 350–850 m

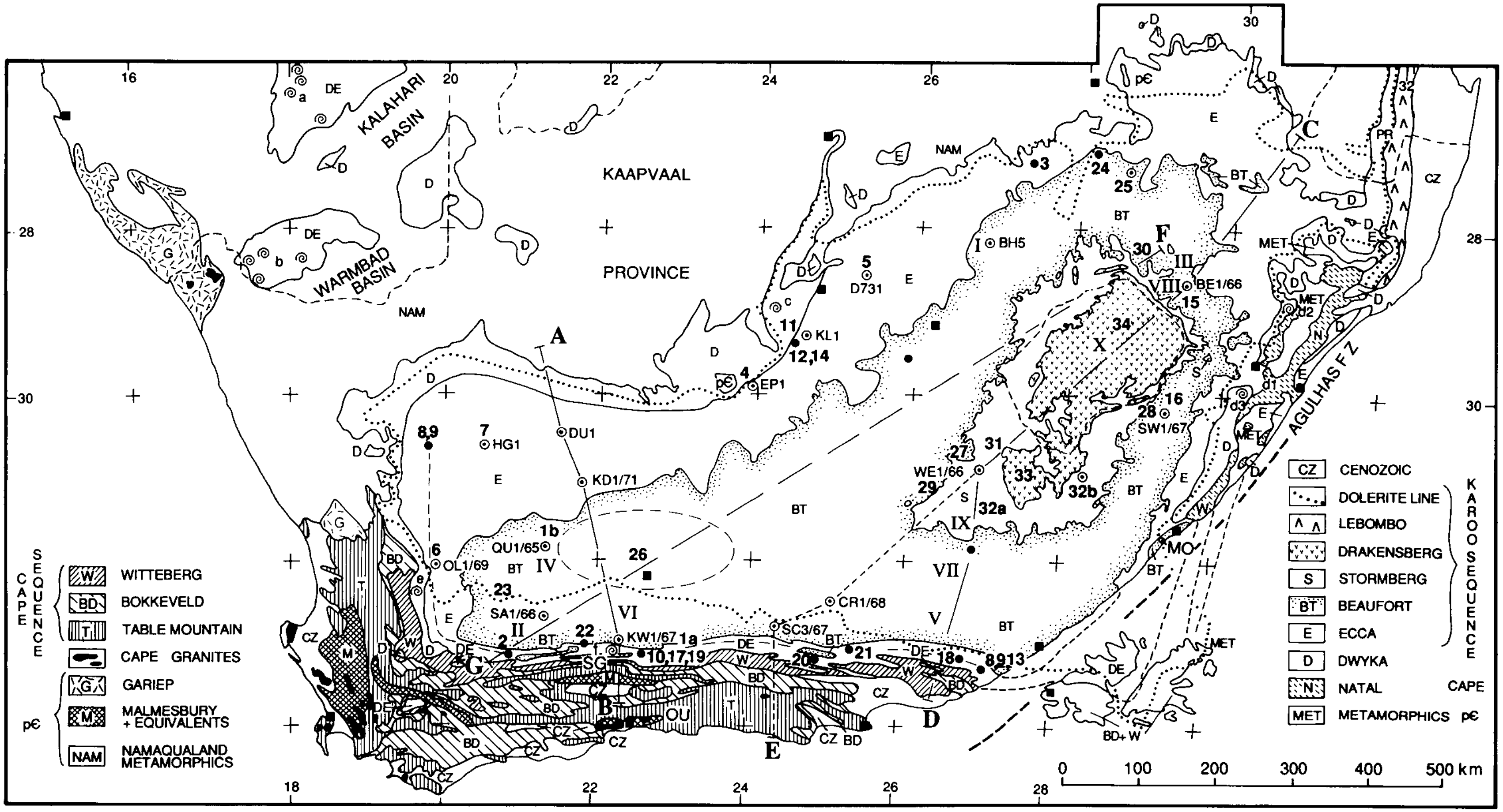


Figure 1. Solid geology of the Karoo Basin (the Karoo Sequence) and the underlying Natal Group in the northeast and the Cape Supergroup in the south (Cape Sequence) and, in turn, the pre-Cape basement, from Geological Map of the Republic of South Africa (1970, 1984) and Kent (1980). Zenithal equal-area meridional projection (Haughton, 1969). Strata dip into the basin except those along the southeastern coast, between 31.5°S and 32.5°S, including an outlier of Molteno Formation (MO), which are involved in the eastern limb of an anticline or in a horst. Also shown are the location of the stratigraphic cross section FG of Figure 10; stratigraphic columns I–X of Figure 8, A–C; AB and CD and boreholes (bullseye) of Figure 2; the time-space diagram CE of Figures 3 and 7; the localities (filled circles and numerals 1–34) with volcanic and volcanogenic material (Tables 2 and 3); and localities of the Dwyka Formation and Prince Albert Formation with marine fossils, shown by coils (McLachlan and Anderson, 1973, 1975) (Table 1): a, western Kalahari Basin; b, southwestern Kalahari (Warmbad); c, north-central Karoo Basin (Douglas); d, northeastern—Pietermaritzburg region; e, western—Tankwa River (actually without invertebrates but correlated with the others by its contained biota); and f, southern—shark and marine microfossils. OU—Outeniqua Mountains, SG—Swartberg Mountains. The Falkland Islands are reconstructed according to the scheme of Adie (1952a) and Mitchell et al. (1986) immediately southeast of the Agulhas Fracture Zone off the Transkei coast. Possible connections through the 1.0 Ga metamorphics, the Bokkeveld and Witteberg equivalents, and the Dwyka and Ecca equivalents are drawn to the mainland. The filled squares represent towns.

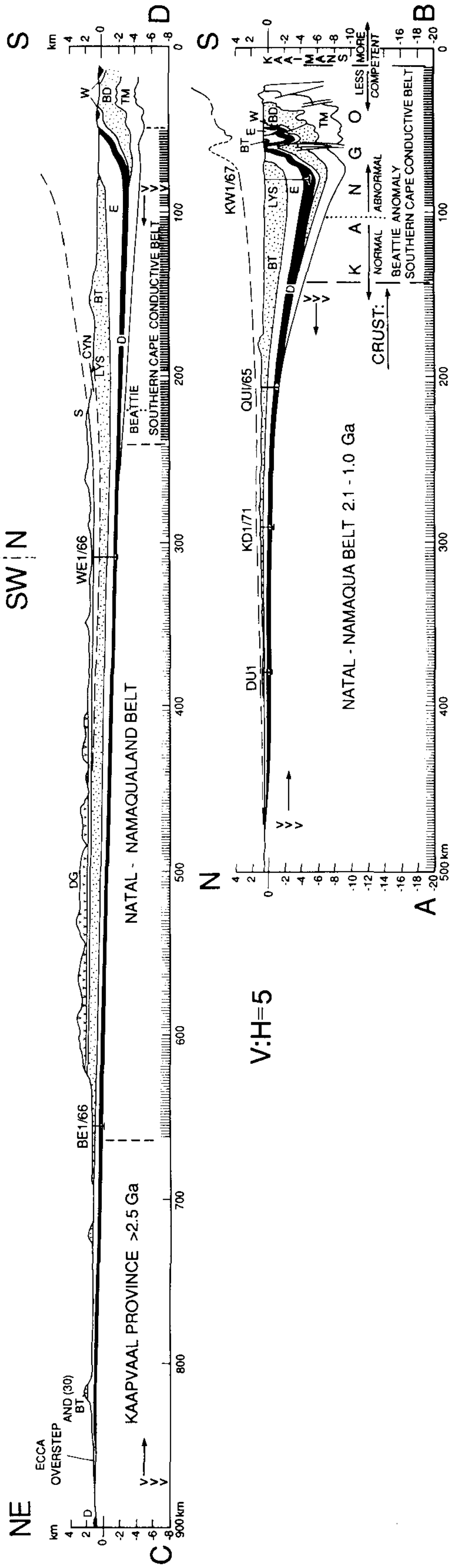


Figure 2. Cross sections AB and CD, located in Fig. 1. Compiled from information in Winter and Venter (1970), augmented by Anderson (1977, charts 1 and 2) and Söhnge and Hälbich (1983). Beaufort Group in south restored (dashes) after Rowsell and de Swardt (1976, p. 84). BD—Bokkeveld, BT—Beaufort, D—Dwyka, DG—Drakensberg, E—Ecca, S—Stormberg, TM—Table Mountain, W—Witteberg. Boundary between *Cynognathus* (CYN) and *Lystrosaurus* (LYS) zones shown by dashed line. V's indicate limit of dolerite intrusions, which have been subtracted from the sections.

of massive gray and brown diamictite, with clasts up to 7 m and stratified intercalations of sandstone and shale, is slightly disconformable to the underlying quartzites, in the same way as the equivalent Dwyka Formation (Adie, 1952a, 1952b; Visser, 1987) (*see* Fig. 11 in a following section) disconformably overlies the Witteberg Group (Du Toit, 1937, p. 119). The conformably overlying sequence (Port Sussex Formation, Terra Mota Sandstone, and Bay of Harbours, Choiseul Sound, Brenton Loch, and West Lafonian Beds) is about 3,000 m thick and comprises gray interbedded shale and sandstone with *Glossopteris*. Adie (1952b) correlated this sequence by the plant fossils with the Ecca and Beaufort Groups. The lack in this sequence of the tetrapods and of the red pigment characteristic of the Beaufort Group suggests to us that the sequence is related to the Ecca Group only. Both have a comparable thickness (*see* Fig. 12 in a following section).

(c) Dolerite dykes cut the Devonian Port Stephens–Monte Maria sequence on West Falkland and the Permian sequence on an island east of Lafonia. As cited by Mitchell et al. (1986), the West Falkland dykes have yielded a K-Ar date of 192 ± 10 Ma, which lies near the old end of the radiometric age range of the Karoo Dolerite (Kent, 1980, p. 566) and the Drakensberg Volcanics. Fig. 1 shows the extension of the Dolerite line to the Falkland Islands.

The Early Jurassic dolerite postdates the Gondwanide deformations. In the Falklands, field evidence indicates the ages of deformation to be Early Permian, shown by the cleaved diamictite, and within the interval Late Permian to Early Jurassic; in southern Africa the deformations are dated as Early Permian, Late Permian, and mid-Triassic (Fig. 3).

In summary, the geologic history of the Falkland Islands followed a course parallel with that of the Cape Fold Belt and the southern crop of the Karoo Basin except that deposition in the Falklands started later, in the Devonian.

Adie's (1952a, b) reconstruction is confirmed by J.E.A. Marshall (1994).

PRE-GONDWANAN HISTORY

Pre-Cape geology

The pre-Cape geology of southern Africa (Fig. 4) comprises (1) the Archean (>2.5 Ga) Kaapvaal Province, (2) the Early-Middle Proterozoic (2.1–1.0 Ga) Namaqua-Natal Belt, and (3) the following Late Proterozoic and epi-Late Proterozoic/Cambrian (1.0–0.5 Ga) belts: (a) Southern Cape Conductive Belt and Beattie Anomaly; (b) the overlapping Saldanian Province, including the Malmesbury Group and the possible equivalents of the Gamtoos Formation and the Kaaimans and Kango Groups, intruded by the Cape Granite; (c) the Gariep Province; (d) Nama and Vanrhynsdorp Basins; and (e) the correlates of the Gariep near Vanrhynsdorp. De Beer et al. (1982) interpreted the Namaqua-Natal Belt as an Andean chain generated behind a trench that terminated 0.8–1.0 Ga and the Southern Cape Conductive Belt (SCCB) as

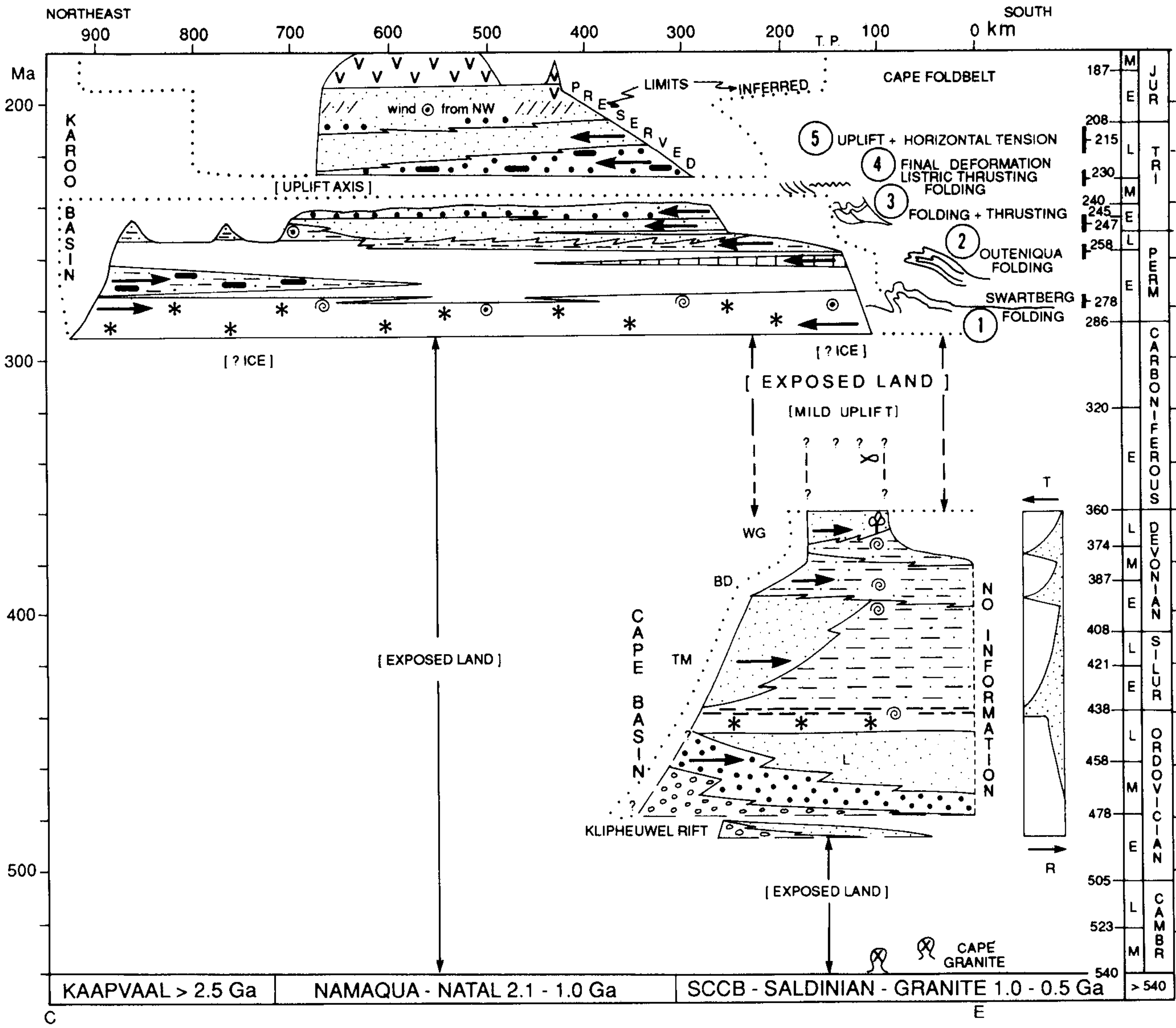


Figure 3. Time-space diagram for the interval 540–180 Ma, located in Figure 1 (line CE); <300 Ma condensed from Figure 7. The youngest reliable age of the Cape Granite Suite is 525 Ma (Kent, 1980, p. 483). The oldest reliable age of the Cape Supergroup is latest Ordovician or Hirnantian (Tankard et al., 1982, p. 335; Theron and Loock, 1989, p. 730) and the base possibly extends to the Early Ordovician. Here we arbitrarily take the base as Middle Ordovician, with the Klipheuwel Formation stretching into the Early Ordovician. The uppermost Table Mountain Group is Pragian/Emsian, the Bokkeveld Group is Emsian and Givetian/Frasnian, and the Witteberg Group is Late Devonian (Boucot et al., 1983; Anderson and Anderson, 1985, p. 20; and other authors cited in Theron and Loock 1989, p. 730). The exposed top of the Cape Supergroup (Witteberg Group) is probably no younger than latest Devonian (Anderson and Anderson, 1985, p. 20), contrary to Gardiner's (1969) view that fish indicate late Early Carboniferous (Visean), as shown by the queries. *See* Figure 7 for symbols, with these additional abbreviations and symbols for the Cape Basin: TM—Table Mountain Group, BD—Bokkeveld Group, WG—Witteberg Group; age-diagnostic megaplants in the Witteberg; environments—alluvial fans (open circles), littoral sediment (L), transgression (T), and regression (R).

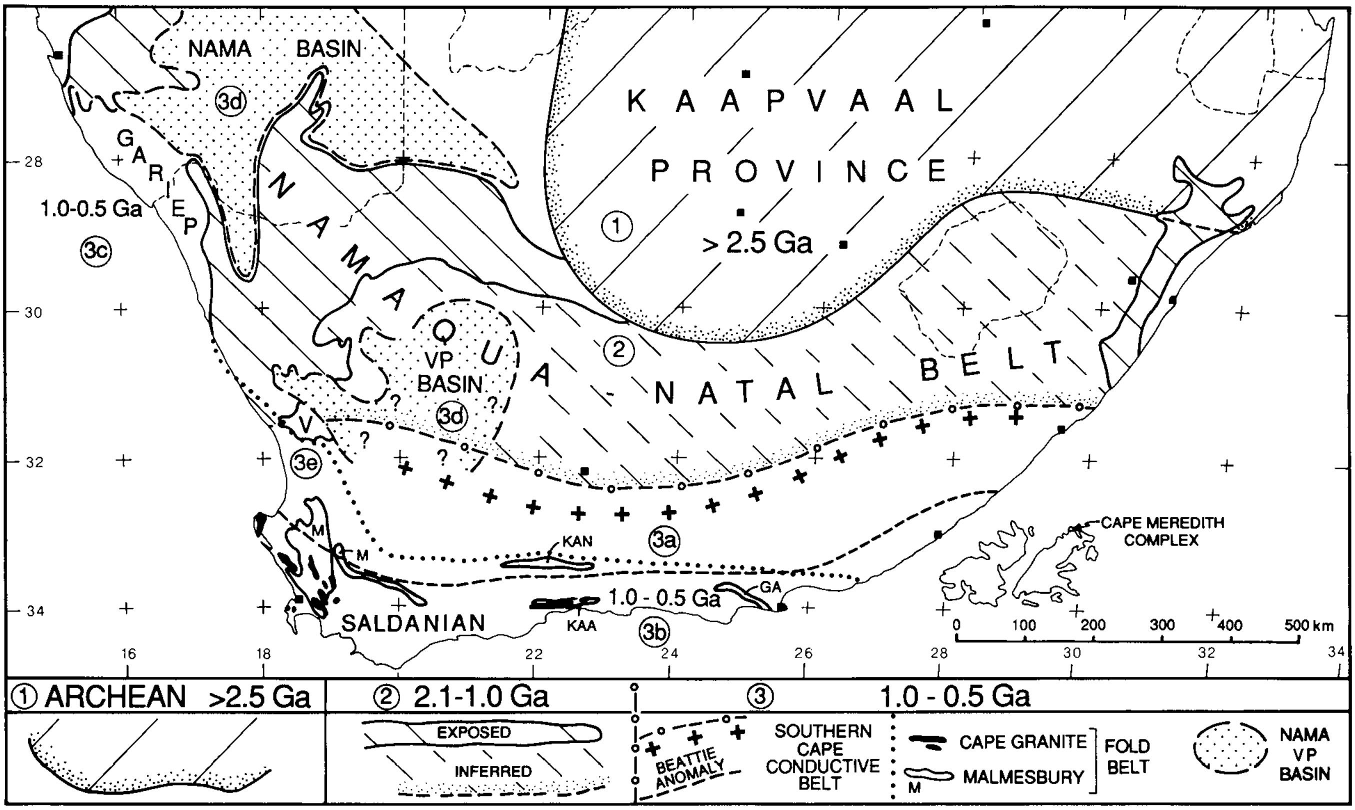


Figure 4. Pre-Cape geology. Precambrian provinces: (1) the Archean (>2.5 Ga) Kaapvaal Province (Hartnady et al., 1985), (2) the Early-Middle Proterozoic (2.1–1.0 Ga) Namaqua-Natal Belt (Tankard et al., 1982), (3) the Late Proterozoic and epi-Late Proterozoic/Cambrian (1.0–0.5 Ga): (a) Southern Cape Conductive Belt and Beattie Anomaly (de Beer et al., 1982); (b) the Saldanian Province (Tankard et al., 1982), including the Malmesbury Group and the possible equivalents of the Gamtoos Formation (GA) and the Kaaimans (KAA) and Kango (KAN) Groups, intruded by the Cape Granite, mapped from Haughton (1969) and Kent (1980); (c) the Gariep Province; (d) the Nama and Vanrhynsdorp (VP) Basins (Hälbich and Hartnady, 1985; Tankard et al., 1982); and (e) the rocks near Vanrhynsdorp (V) correlated with the Gariep (Germs and Gresse, 1991; Tankard et al., 1982). Falkland Islands reconstruction off the Transkei coast from Adie (1952a) and Mitchell et al. (1986), showing the location of the 1.0 Ga Cape Meredith Complex (Rex and Tanner, 1982).

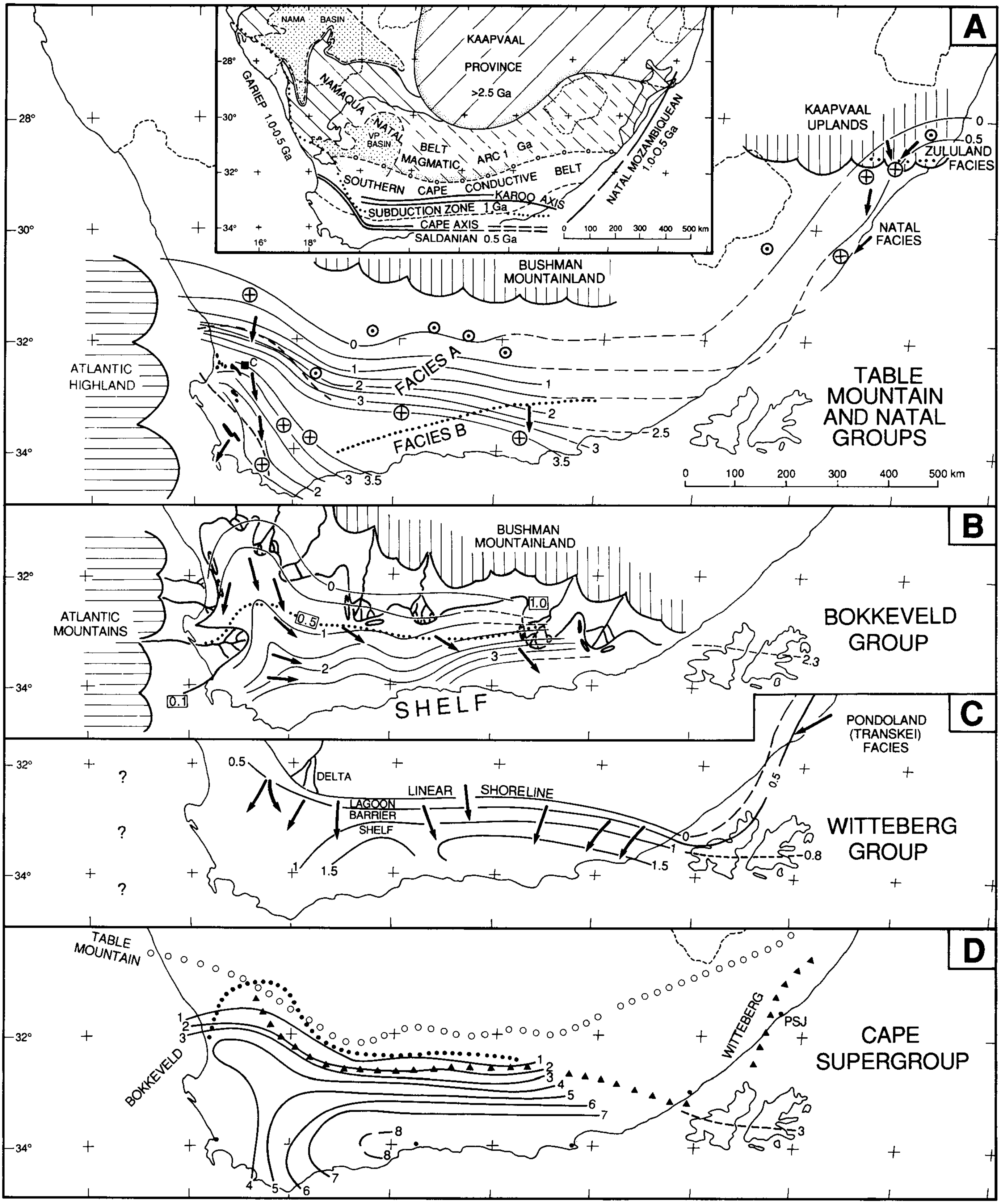
Figure 5. Pre-Gondwanan geology: Cape Supergroup of Ordovician-Devonian (and possibly Early Carboniferous) age. Inset: basement (from Fig. 4) of 1.0–0.5 Ga foldbelts and the reworked Mozambique Province wrapped around the Namaqua-Natal Belt (2.1–1.0 Ga) and Kaapvaal Province (>2.5 Ga). Superimposed on the deep structure are the depositional axes of the Cape Supergroup (Fig. 5D) and of the early Karoo: Dwyka, Ecca, Beaufort (*see* Fig. 13B).

A. Table Mountain and Natal Groups (Tankard et al., 1982; Hobday and Mathew, 1974; Hobday and Von Brunn, 1979). Isopachs (km) (Visser, 1974), from boreholes (circled dot) and field sections (circled cross); prominent paleocurrents from Visser (1974), Hobday and Mathew (1974), Hobday and Von Brunn (1979), and Turner (1990); facies and depositional environments from Visser (1974), Hobday and Von Brunn (1979), Tankard et al. (1982), Turner (1990), Fuller (1985), Shone (1987), Thamm (1987), Marshall (1988), and Thomas et al. (1992). In the western Cape, the solid black denotes outcrops of the Klipheuwel Formation (Kent, 1980, p. 493), and the broken lines denote the edges of the valley in which the Piekenierskloof Formation was deposited east of a western provenance area that Rust (1973, p. 252) called the Atlantic Highland and southwest of the Bushman Mountainland. C—Citrusdal.

B. Bokkeveld Group of Early-Middle Devonian age. Isopachs (km) from Rust (1973), extended to the 2.3-km-thick Fox Bay and Port Stephens Formations of the Falkland Islands, paleocurrents and sand-shale ratios (dotted line denotes the 0.5 value) from J. N. Theron (1970), depositional environments from Tankard et al. (1982), and paleogeography from Theron and Loock (1989).

C. Witteberg Group of Middle and Late Devonian (and possibly Early Carboniferous) age. Environments, isopachs (km), and flow pattern from Theron and Loock (1989). The 0.8 km isopach in the Falkland Islands refers to the Monte Maria Formation, and the data point of the 0.5 km isopach in the northeast is the Pondoland (Transkei) quartz arenite (Visser, 1974).

D. Cape Supergroup. Isopachs (km) summed from A, B, and C. Zero isopach of Table Mountain Group indicated by line of open circles, of Bokkeveld Group by filled circles, and of Witteberg Group by triangles. The zero isopach of the Witteberg Group is extended past Port St Johns (PSJ) to accommodate the occurrence of a Late Devonian megaplant in the Pondoland quartz arenite.


A
NAMA BASIN
KAAPVAAL PROVINCE >2.5 Ga
GARIEP 1.0-0.5 Ga
NAMAQUA NATAL BELT
VP BASIN
MAGMATIC ARC 1 Ga
SOUTHERN CAPE CONDUCTIVE BELT
KAROO AXIS
SUBDUCTION ZONE 1 Ga
CAPE AXIS
SALDANIAN 0.5 Ga
NATAL MOZAMBIQUEAN 1.0-0.5 Ga
0 100 200 300 400 500 km
KAAPVAAL UPLANDS
ZULULAND FACIES
NATAL FACIES
BUSHMAN MOUNTAINLAND
ATLANTIC HIGHLAND
FACIES A
FACIES B
TABLE MOUNTAIN AND NATAL GROUPS
0 100 200 300 400 500 km
B
BUSHMAN MOUNTAINLAND
ATLANTIC MOUNTAINS
BOKKEVELD GROUP
SHELF
C
PONDOLAND (TRANSKEI) FACIES
DELTA
LINEAR SHORELINE
LAGOON
BARRIER
SHELF
WITTEBERG GROUP
D
TABLE MOUNTAIN
BOKKEVELD
WITTEBERG
PSJ
CAPE SUPERGROUP
28°
30°
32°
34°

serpentinized basalt obducted against the Namaqua-Natal Belt at the termination of subduction. The overlapping Saldanian Province was deformed further and intruded by granites (0.6–0.5 Ga) during the final closing of a marginal sea. In this manner, the Pan-African fold belts—the Gariep on the west, the Saldanian on the south, and the reworked Natal-Mozambiquean on the east—became wrapped around the cratonic nucleus of the Namaqua-Natal Belt and the Kaapvaal Province. Subsequent extensions and compressions of this anisotropic lithosphere determined depositional structural axes of the succeeding Cape and Karoo Basins. In particular, the weak crust of the SCCB determined the location of the Cape Fold Belt. As described later, this is unlike the situation elsewhere along the Paleo-Pacific margin, where deformation was located along and landward of the weak zone along the magmatic arc. This different location of the foreland basin of the Karoo, distal to the arc, is consistent with the apparently small volume of volcanogenic material found in the Karoo Basin fill. *Note:* A geoscience transect of Southern Africa (Hälbich, 1993) was published when this work was in press.

Cape geology

Table Mountain Group. Preferential subsidence of the 1.0–0.5 Ga foldbelts determined the site of the depositional axis of the Ordovician-Devonian Cape Basin (Fig. 5, inset): a main W–E trend along the Saldanian Province, and branches to the NW (north of Cape Town) and NE (Natal).

According to Tankard et al. (1982, p. 12, 14),

> During the Early Paleozoic southern Africa lay at the heart of Gondwana, bounded in the west by South America, in the south by the Falkland Plateau, and to the east by Antarctica. Abortive rifting around the southern and eastern fringe of the Kalahari Province resulted in accumulations of continental and marine clastic successions, known as the Cape Supergroup, in elongate troughs in the southern Cape and Natal. . . . Up to 8 km of sediment accumulated in the Cape basin [Fig. 5D]. The lower 4 km of quartz arenites, mudstones, and conglomerates in the Table Mountain Group [Fig. 5A] record terrestrial and shallow-marine environments and intermittent northward transgression of the Cape sea during the Ordovician and Early Devonian. Prolonged periods of tectonic and eustatic stability are reflected in quartz arenites up to 2,100 m thick, representing one of the greatest known accumulations of quartz sand (Visser, 1974). . . . The Natal embayment developed along a trend parallel to the Pan African Mozambique Province to the north. Proximal coarse alluvial sediments were deposited at the rugged northern end of the embayment, which opened southward into a tide-dominated marine reentrant where considerable thicknesses of marine quartz sand accumulated.

Visser (1974) subdivided the Cape Supergroup of the Cape Province into two facies (Fig. 5A), A, fluvial-coastal plain-beach-neritic facies and latest Ordovician glacigenic facies) in the north and west, and B, beach-neritic facies in the south and east. From the base upward, facies A comprises 1,000 m of alluvial fan to fluvial conglomerate and coarse-grained sandstone (Piekenierskloof Formation) (thicknesses and formations from Tankard et al., 1982, p. 335); 440 m of paralic interbedded quartz arenite, siltstone, and mudstone, with trace fossils (Graafwater); 1,800 m of open-beach quartz arenite with quartz pebbles and trace fossils (Peninsula); 120 m of glacigene sandstone, conglomerate, and diamictite (Pakhuis), deposited during the Winterhoek glaciation (Tankard et al., 1982, p. 345–348); 140 m of neritic fine-grained sandstone, siltstone, and mudstone, with marine invertebrates, conodonts (Theron et al., 1990), and chitinozoans (Cramer et al., 1974) of latest Ordovician or Hirnantian age (Cedarberg); and 1,100 m of open-beach coarse-grained quartz arenite, with trace fossils (Nardouw). Lacking the basal conglomerate of A, facies B starts with 2,150 m of the open-beach Peninsula Formation and is succeeded by 50 m of the neritic Cedarberg Formation, 640 m of open-beach sandstone, and finally 150 m of the Baviaanskloof Formation: neritic shale, mudstone, and quartz arenite, with Pragian/Emsian marine invertebrates (Theron and Loock, 1989).

The basal formation in the west, the Piekenierskloof Formation, is thickest where it overlies the Klipheuwel Formation (solid black in Fig. 5A), another alluvial fan to fluvial deposit, 2,000 m thick, that wedges out to the north. The Klipheuwel Formation unconformably overlies Malmesbury metasediments and Cape granites.

> It becomes progressively less deformed upward, and in its uppermost parts it is probably a facies equivalent of the basal Cape Supergroup. . . . The Klipheuwel succession is envisaged as a series of coalescing and stacked alluvial-fan and interlobe deposits of southward-flowing braided fluvial systems. The coarseness and poor rounding of the conglomerates, their low degree of sorting, and the high proportion of clay matrix suggest limited distances of transportation and local debris flows in a block-faulted terrain such as commonly marks the culminating phase of orogenesis (cf. the Triassic rift basins of the Appalachians) (Tankard et al., 1982, p. 333). [Cross-dip azimuths are widely dispersed about a southeastward mean.] The variety of interrelated facies types and the fan-shaped paleocurrent distribution of the upper Klipheuwel and Piekenierskloof Formations reflect downstream changes in alluvial processes associated with decreasing gradients. High relief was probably maintained along the northern margin of the basin by progressive subsidence relative to adjoining fault-bounded highlands (Tankard et al., 1982, p. 337).

The southeast-trending valley (Rust, 1973) is shown between the broken lines in Fig. 5A. The common southeast trend of the Klipheuwel and Piekenierskloof Formations and their overlap near Citrusdal (32.5°S, 19°E) near the axis of deposition of the entire Table Mountain Group suggests to us that rift-valley grabens (Klipheuwel and Piekenierskloof rifts, *see* Fig. 3) were the site of early crustal extension ("the steer's head") that was followed by down-flexure of the rift shoulders (Atlantic Highland and Bushman Mountainland, Rust, 1973) to accumulate the more widely distributed Graafwater and younger formations ("the horns").

The preponderance of quartz arenite in the Table Mountain Group reflects its source in the interior of Gondwanaland, as do the Ordovician turbidites of southeast Australia (Powell, 1984, p. 293), both indicating deep denudation of the surface of interior Gondwanaland with its maximum apatite fission-track age of 500 Ma (A. Gleadow, personal communication, 1992).

Natal Group. The Natal Group comprises a marked north-south zonation of the facies (Fig. 5A). In Zululand, a boulder conglomerate was deposited in intermontane valleys in the Kaapvaal uplands and passed southward in Natal to red arkosic sandstone deposited in braided channels. Lacking age-diagnostic fossils, the Natal Group was identified as equivalent to the early Paleozoic Table Mountain Group on the basis of similar lithofacies and ichnofacies (Tankard et al., 1982, p. 348), confirmed by Thomas et al.'s (1992) interpretation of Ar-Ar isotopic dates of authigenic muscovite as indicating an age of about 490 Ma, and accordingly we show the Natal Group on the same map as the Table Mountain Group (Fig. 5A).

At about 31°S in Pondoland (Transkei) and southernmost Natal, south of a basement high at 30°30′S (the Dweshula High mentioned by Thomas et al., 1992), clean quartz arenite deposited on a storm- and tide-dominated marine shelf (Visser, 1974; Hobday and Mathew, 1974; Hobday and Von Brunn, 1979; Tankard et al., 1982; Marshall, 1988) was thought to have been part of the Natal Group until Anderson and Anderson (1985, p. 21 and 91) described a megaplant fossil in a quarry 5 km west of Port St Johns (Lock, 1973; Kent, 1980, p. 530) as a new taxon of Late Devonian Lycophyta, but unlike any known species from the Cape sequence. We follow Thomas et al.'s (1992) view that the Pondoland arenite may be equivalent to the lower Witteberg Group (Fig. 5C), and we draw the zero isopach of the Witteberg Group west of Port St Johns (Fig. 5D).

Bokkeveld and Witteberg Groups. In the southern part of the Cape Province, the predominantly arenitic Table Mountain Group is succeeded by the predominantly argillaceous Bokkeveld and Witteberg Groups. The Bokkeveld Group (Fig. 5B) comprises a northern facies of five or six upward-coarsening fluvial-deltaic wedges (sand:shale ratio of 1.0) that pass southward, across the 0.5 sand:shale line (dotted) into a southern shelf facies of homogeneous mudstone to subgraywacke (ratio 0.1). During its time span of 20 m.y., the Bokkeveld Group accumulated at least 3.5 km of sediment at a mean rate of 175 m/m.y. This was about five times the rate of the equally thick but 100-m.y.-long Table Mountain Group and about twice the rate of the 1.5 km thick and equally long Witteberg Group. The southeast-trending depositional axis of what Theron and Loock (1989) called the Clanwilliam Bay, bounded on the west by the Atlantic Mountains, implied by Tankard et al. (1982, figs. 5.10–5.13) from the absence of marine rocks in adjacent South America, and on the north by the Bushman Mountainland (J. N. Theron, 1970, 1972, p. 135), merged eastward into the east-trending depression, both features inherited from the Table Mountain Group. Theron and Loock (1989, p. 733–735) note that

> The marked, almost instantaneous, change from a few thousand metres of supermature sand to between 1500 to 4000 m of predominantly muddy sediments, evidently without marked variation of provenance, climate or environment, indicates that the accelerated downwarp of the Bokkeveld basin was matched by simultaneous increase in the rate of sedimentation because the proximal and medial Bokkeveld sediments certainly do not display the characteristics of deep water deposits. The rapid rate of filling evidently prevented appreciable sorting and halted the process whereby previously most of the fine grained sediments escaped from the basin. Bokkeveld deposition therefore represents a period of cyclic deposition in a marginal cratonic basin and the lateral continuity of the arenitic entities are ascribed to the coalescence of various drainage systems through current and wave action. . . .
>
> The shallowing of the Cape Basin as a whole during the Givetian, as revealed by the upper Bokkeveld units, continued during deposition of the overlying Frasnian sediments of the Witteberg Group [Fig. 5C]. Extensively bioturbated mudstone, siltstone and sandstone with desiccation cracks and rill marks characterize the basal Witteberg units . . . and some thin intercalated shale horizons have yielded marine bivalves, brachiopods and trilobites (Boucot et al., 1983). In the western part of the basin upward coarsening to an extensive sheet-like quartz arenite sequence . . . as well as similar vertical cyclical stacking of litho units as in the Bokkeveld Group, exists. . . . Laterally these . . . units merge with 5 formations in the eastern part of the basin. . . . This medium to coarse grained, cross-bedded, predominantly quartz arenite succession varies from less than 140 m in the west to 850 m eastward. . . . The main basin in broad outline consisted of two major depressions approximately similarly disposed as during the Bokkeveld cycle. . . . The main provenance was still to the north but the limited outcrops to the west and south at present prohibit clarity on the configuration or distribution of these borderlands. Consideration of the paleo ice-flow of the basal Dwyka tillite and its clast composition, however, indicate highland to the southwest undergoing erosion and an eastward directed paleoslope at the "onset of glaciation." . . . The Witteberg basin at its termination was reduced to only about one-third its original size and can best be described as an open ended marginal intracratonic basin in which shelf deposition took place.

The three major transgressive/regressive events indicated by the appearance of marine fossils (Fig. 3) correspond with the glacio-eustatic transgression at the end-Ordovician (Hirnantian) after the melting of the African ice sheets (Tankard et al., 1982, p. 345–348) and at the Pragian/Emsian start and Givetian/Frasnian peak of the rise in sea level in Euramerica (Johnson et al., 1985, p. 584).

Tectonic setting of the Cape Sequence. The northwest trend of the Clanwilliam Bay in the western part of the Cape Basin denotes an axis of faster sediment accumulation that persisted through the deposition of the Table Mountain Group, the Bokkeveld Group, and possibly the Witteberg Group (Fig. 5A–C). According to Tankard et al. (1982, p. 348), the Natal Group accumulated in an elongate downwarp, the Natal embayment (Fig. 5A), whose axis parallels the present coastline along the trend of the Proterozoic Mozambiquean Province to the north (Fig. 5, inset). Subsidence and concomitant accumulation of sediment along the northwest and northeast branches of the main west-trending Cape axis are believed to have started probably as long ago as the Ordovician and continued to the end of the Devonian, as indicated by the shape of the zero isopachs and reflected in the isopachs of the total Cape Sequence (Fig. 5D and inset).

We interpret the Cape axis and its northwest and northeast branches as axes of extension concentrated along the deep structural boundaries (Fig. 5, inset) between the east-trending 1.0 Ga Namaqua-Natal Belt and the Southern Cape Conductive Belt and the Pan-African (1.0–0.5 Ga) Saldanian Province on the south and between the Namaqua-Natal Belt and the Gariep Province on the present southwestern margin and the Mozambiquean Province on the southeastern margin (Tankard et al., 1982). The provenance of the Cape Sequence was to the northeast (Bushman Mountainland) and west (Atlantic Mountains).

The 600–500 Ma Cape Granites were emplaced during the final closing of a marginal sea, which was followed by the opening of a rifted ocean or a second marginal sea. The Cape Sequence was deposited across this passive margin (Johnson, 1991) throughout the Ordovician to end-Devonian or Early Carboniferous. Only with the Early Permian development of the overlying structural Karoo Basin is evidence of a southern flank and provenance of deposition seen.

GONDWANAN (KAROO) HISTORY

Introduction

Having sketched the pre-Gondwanan history of southern Africa, we now come to a synopsis of the Gondwanan (Permian-Jurassic) geologic history of the craton and its development by the growth of the Cape Fold Belt as part of the foreland basin behind the Panthalassan margin. This account is illustrated by geological maps (Figs. 1, 6, 9) and cross sections (Figs. 2 and 10), a time-space diagram (Fig. 7), stratigraphic columns (Fig. 8), and paleogeographic and paleotectonic maps (Figs. 11–14).

Setting

Following a lacuna that lasted all but the latest part of the Carboniferous, the succeeding Karoo Sequence, together with the other parts of the Gondwana Facies of the Gondwanaland Province of the newly formed Pangea (Veevers, 1988), started accumulating sediment in the initial sags and grabens of the Pangean cratonic platform during the latest Carboniferous (Gzelian, Eastern Australian palynological stage 2) (Veevers, 1989). The realm of subsidence in southern Africa, hitherto confined to the southern tip, spread northward to the equator (Fig. 6). Subsidence was effected by two tectonic processes (Rust, 1975): (1) the Karoo tectono-sedimentary terrain was warped into basins (Karoo, Kalahari, Congo, Gabon) and intervening swells, and (2) the Zambezian terrain was faulted into graben-type depositories. In the Early Permian, renewed sinking of the denser material in the northern part of the SCCB between the lighter material north and south of it, together with uplift by folding in the south, initiated the Karoo structural basin. Later in the Permian and Triassic, the SCCB marked the site (south of the Beattie Anomaly, Hälbich et al., 1983) (*see* Fig. 2) of intense thrusting and folding of the less competent crust (de Beer, 1983, Hälbich, 1983). The site of the deformation of the Karoo Basin was therefore determined by the inherited structure.

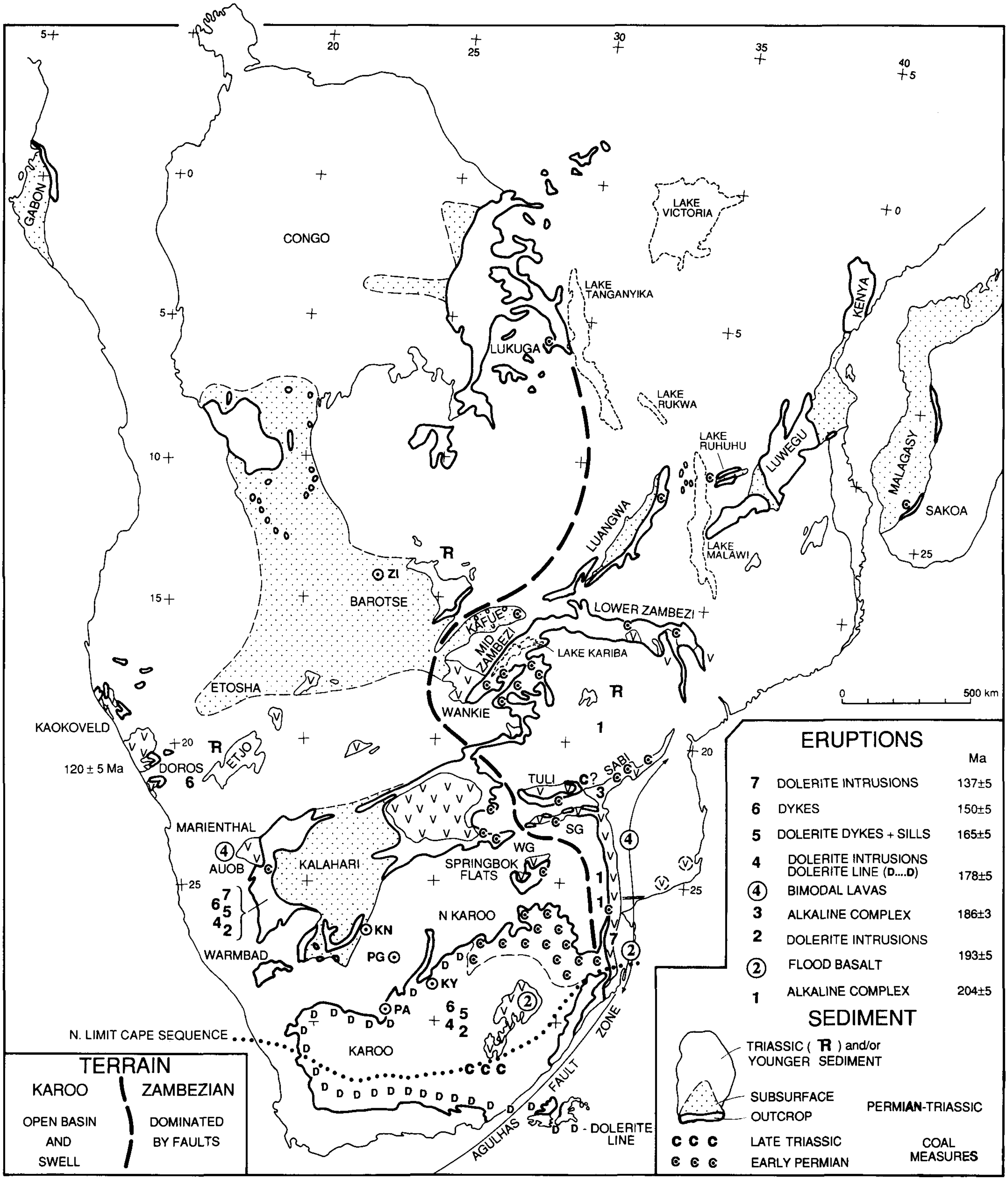
Karoo Sequence

The correlation of the latest Carboniferous to Jurassic formations of southern Africa is given in Figure 21 (Appendix 2), and shown in the time-space diagrams (Figs. 3, 7). In brief, deposition started in the latest Carboniferous (Gzelian or 290 Ma) and continued through the Permian into the Early Triassic; after a Middle Triassic lacuna, deposition resumed in the Late Triassic and Early Jurassic, and concluded with the widespread intrusion of dolerite and extrusion of basalt in the Early and Middle Jurassic.

The major units in the Karoo Basin are now discussed in ascending order: Dwyka Formation, Ecca Group, Beaufort Group, Stormberg Group, and Drakensberg Group.

Dwyka Formation. This account of the Dwyka Formation

Figure 6. Gondwana (Karoo) basins of Africa south of the Equator, with Malagasy and Falkland Islands in restored positions, showing distribution of Permian and Triassic (and younger) sediment and Jurassic and Cretaceous lavas and intrusions. From de Wit et al. (1988), augmented by information on (1) position of Falkland Islands, as detailed above; (2) distribution of Permian sediment (Frakes and Crowell, 1970; Anderson, 1977, map 2; Kent, 1980; Truswell, 1980; Reimann, 1986), including coal measures (Ryan and Whitfield, 1979; Kreuser and Semkiwa, 1987); (3) distribution of Late Triassic sediment, including coal measures (Dingle et al., 1983; Visser, 1984); (4) the dolerite line in the Karoo Basin and Falkland Islands, from Figure 1; (5) Karoo magmatic events, lavas (circled numbers) and intrusions, according to Fitch and Miller (1984): 1—early events about 204 ± 5 Ma, 2—major about 193 ± 5 Ma, 3—minor about 186 ± 3 Ma, 4—major about 178 ± 5 Ma, 5—events about 165 ± 5 Ma, 6—about 150 ± 5 Ma, 7—about 137 ± 5 Ma, post-Karoo Etendeka lavas about 120 ± 5 Ma; subsurface lavas (circled) in Mozambique from Dingle et al. (1983); and (6) Karoo and Zambezian tectono-sedimentary terrains, from Rust (1975). Heterolithic breccias containing up to 70% of basalt xenoliths occur at Kolonkwaren (KN), Prieska (PA), and Postmarburg (PG) (Eales et al., 1984, p. 3), and xenoliths sampling the entire Karoo column above the Dwyka occur in the Kimberley (KY) pipe (Truswell, 1977). ZI marks the township of Zambesi in the Barotse Basin of western Zambia in the region of a subsurface occurrence of a 2-m-thick arkose and mudstone in which acritarchs of suspected early Paleozoic age were found (Reimann, 1986).


GABON
CONGO
LAKE VICTORIA
LAKE TANGANYIKA
LUKUGA
LAKE RUKWA
LAKE RUHUHU
LUWEGU
KENYA
MALAGASY
SAKOA
LUANGWA
LAKE MALAWI
BAROTSE
ZI
KAFUE
MID ZAMBEZI
LOWER ZAMBEZI
LAKE KARIBA
WANKIE
ETOSHA
KAOKOVELD
120 ± 5 Ma
DOROS
ETJO
TULI
SABI
SG
WG
MARIENTHAL
AUOB
KALAHARI
SPRINGBOK FLATS
N KAROO
KN
PG
KY
PA
WARMBAD
KAROO
N. LIMIT CAPE SEQUENCE
AGULHAS FAULT ZONE
D - DOLERITE LINE
0 500 km
TERRAIN
KAROO
ZAMBEZIAN
OPEN BASIN AND SWELL
DOMINATED BY FAULTS
ERUPTIONS
Ma
7 DOLERITE INTRUSIONS 137±5
6 DYKES 150±5
5 DOLERITE DYKES + SILLS 165±5
4 DOLERITE INTRUSIONS
DOLERITE LINE (D....D) 178±5
4 BIMODAL LAVAS
3 ALKALINE COMPLEX 186±3
2 DOLERITE INTRUSIONS
2 FLOOD BASALT 193±5
1 ALKALINE COMPLEX 204±5
SEDIMENT
TRIASSIC (R) and/or YOUNGER SEDIMENT
SUBSURFACE
OUTCROP
PERMIAN-TRIASSIC
C C C LATE TRIASSIC
C C C EARLY PERMIAN
COAL MEASURES

is derived from the monumental work of J.N.J. Visser and colleagues, as summarized in Visser (1979, 1989, 1990).

The Cape Fold Belt comprises an easterly trending southern branch and a northwesterly trending western branch that meet in the southwesterly trending syntaxis (Fig. 13A). Following mild uplift and erosion during the Carboniferous lacuna, the Witteberg Group was disconformably overlain by the Dwyka Formation along the present southern crop of the Karoo Basin. From east to west in the Southern Branch, the Dwyka Formation steps across the youngest preserved Witteberg Group (Dirkskraal Formation) at Willowmore (23°30′E) down 500 m of stratigraphic relief to the top of the Waaipoort Formation at 23°00′E and continues at this level to Touws River; from here the line of section swings to north and south,

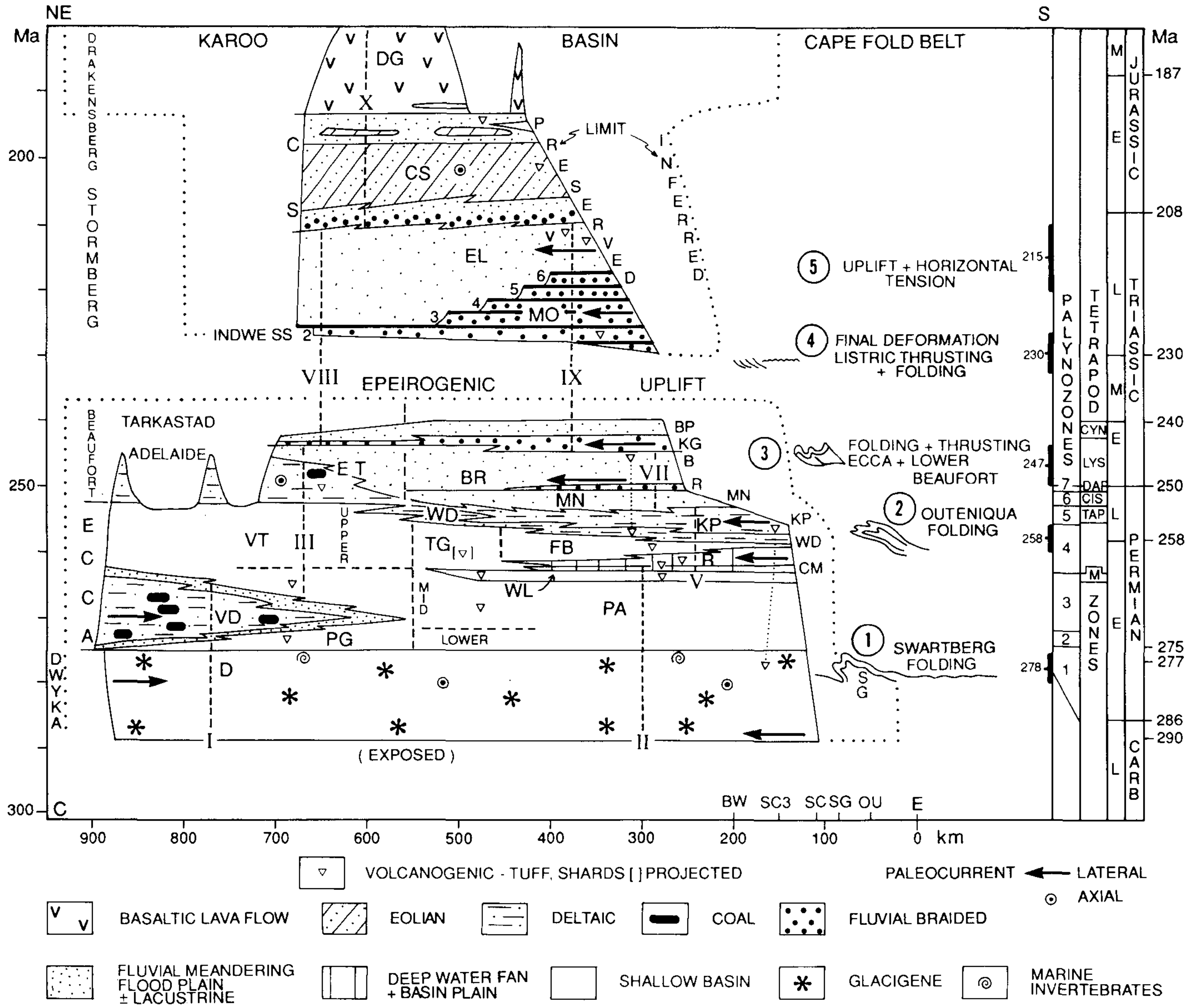


Figure 7. Distribution in time and space of latest Carboniferous, Permian, Triassic, and Jurassic lithostratigraphic units and environments, located on Figure 1 (line CE). Correlation from Fig. 21. Abbreviations: BP—Burgersdorp, BR—Balfour, CM—Collingham, CS—Clarens, D—Dwyka, DG—Drakensberg, EL—Elliot, ET—Estcourt, FB—Fort Brown, KG—Katberg, KP—Koonap, MN—Middleton, MO—Molteno, PA—Prince Albert, PG—Pietermaritzburg, R—Ripon, TG—Tierberg, VD—Vryheid, VT—Volksrust, WD—Waterford, WL—Whitehill. Stratigraphic columns of Figure 8, except IV and VI in the southwest part of the basin, located by fine broken line. Paleocurrents from the side (from data in Figs. 11–14) shown by arrow, southward in the Dwyka and Vryheid of the northern Karoo, northward elsewhere except along the axis (westward) in the upper Dwyka and the Estcourt (Botha and Linström, 1978); northwesterly wind in the Clarens Formation (Visser, 1984) shown by a circled dot. Upward-fining cycles 1–6 of Molteno Formation (Fig. 8, part IX) from Turner (1983, fig. 3). Folding, thrusting, and uplift of the Cape Fold Belt from Hälbich et al. (1983, table 13.3). Localities projected into section are OU—Outeniqua Mountains, SG—Swartberg Mountains, SC—south crop, SC3—drillhole SC3/67, BW—Beaufort West.

and the Dwyka Formation steps down another 500 m of stratigraphic relief to cross the Witpoort Formation (Loock and Visser 1985, p. 168). According to de Beer (1990, p. 585),

> Uppermost Witteberg units (Kweekvlei and Floriskraal Formations) occur below Dwyka tillite in two down-faulted grabens situated well into the Western Branch. . . . Erosion of upper Witteberg sediment apparently resulted from uplift of the basin rim to the north and south of the hinge-line of the early Karoo depository, or from a general lowering of sea level. The available field evidence is insufficient to prove uplift along a N-trending zone during post-Witteberg/pre-glaciation times in the west. . . .
>
> No evidence demonstrating independent folding of the Witteberg Group before erosion of its upper part, or before deposition of the Dwyka glacials, could be found in the Tankwa Karoo [west]. Dwyka tillite of the Swartruggens Mountain Range is folded about the same NW–SE axes displayed in the immediately underlying Witpoort Formation. This, together with the points made in the previous paragraph, removes the two cornerstones of the pre-Dwyka folding hypothesis.

Farther south, at 19.5°E, 33.8°S, an outlier of the Dwyka and Ecca rests on the Witteberg (Fig. 1). To the north, the Dwyka Formation steps across the Cape Sequence and the Namaqua-Natal Belt to reach the Kaapvaal Province and beyond (Wopfner and Kreuser, 1986) in an expansion of deposition deep into the interior Karoo terrain to the present Equator (Fig. 6).

The Dwyka Formation was deposited as a sheet of glacial sediment that thickened away from a ragged edge in the contemporary Cargonian Highlands, as indicated by the areas of basement overlapped by the Ecca Group (black on Fig. 11 and double line on Fig. 12), into the Karoo Basin on the south and southwest and into the Kalahari Basin on the north and west. The ice flowed westward into the Kalahari Basin and southwestward (through or across the denuded Atlantic Mountains) into an inferred shallow sea. For the first time, sediment was shed to the northwest from an upland, probably from the rising folds of the Cape Fold Belt. In the Karoo Basin, the sediment merged with the drainage from the north in a westward axis. The Karoo Basin has a platform facies association in the south (70% massive diamictite, 22% bedded diamictite, and 8% mudrock), exemplified by Fig. 8A, part II, and a valley facies association in the north (21% massive diamictite, 37% bedded diamictite, and 42% mudrock, half of which contains ice-rafted debris) (Fig. 8A, part I). A third facies association, glacial debris reworked by water into breccia, conglomerate, and sandstone, represents deposition in upland areas by the removal of fines. A sequence of nine sedimentation units in the southern part of the basin was deposited from ice lobes that flowed from the north, east, and south. Features of the ice lobes—grounded or afloat, level of sediment transport, and basal thermal condition—eventually controlled deposition.

A vital control was sea level. Firm evidence of marine deposition (Table 1) is provided by the marine invertebrates (brachiopods, bivalves, cephalopods) of the *Eurydesma* zone in the basal Prince Albert Formation (formerly called the upper Dwyka Shales) in the Kalahari Basin (localities a and b, Figs. 1 and 11). Marine microfossils (arenaceous foraminiferids, radiolarians, and sponge spicules) occur also in the Kalahari Basin, and in the Karoo Basin (topmost Dwyka Formation) at Douglas, locality c, correlated by McLachlan and Anderson (1973, p. 45) with the Kalahari Basin on the basis of Sakmarian fish (*Namaichthys schroederi*) and spores, in the Dwyka Formation of the Pietermaritzburg area (localities d1–3), and with a shark at the boundary between the Dwyka Formation and Prince Albert Formation at Zwartskraal (locality f). The palaeoniscid fishes and coprolites (probably from sharks) associated with the invertebrates at Douglas are found alone in the topmost Dwyka Formation at Tankwa River (locality e), which is inferred to be marine. The familiar association of glendonite concretions in the *Eurydesma* zone of Eastern Australia, as in the Woody Island Siltstone of Tasmania (Clarke and Forsyth, 1989, p. 298), is found also at Douglas (McLachlan and Anderson, 1973), although *Eurydesma* has not been found.

Possible marine indicators are the acritarch *Mycrhystridium* at the base of the Dwyka Formation of the southwest Karoo (Anderson, 1977, p. 51–53). Geochemical research, however, indicates that "the geochemistry of the glacial and related rocks [organic carbon:total sulfur ratio, Fe:Mn ratio] does not give positive evidence for marine conditions in the Dwyka Basin . . . [except] the geochemistry of the mudrocks immediately overlying the glacial beds indicates marine conditions which are confirmed by the palaeontology (Visser, 1989, p. 383).

All this evidence suggests to us the following events:

(1) During the Tastubian a single marine transgression or group of multiple transgressions (comparable to the 20 or so in the Quaternary) crossed the Karoo Basin from west to east during deposition of the topmost Dwyka Formation and the overlying basal Prince Albert and Pietermaritzburg Formations as a local manifestation of the glacioeustatic *Eurydesma* transgression (Dickins, 1984; Veevers and Powell, 1987); in our opinion, Visser's (1990) basal Prince Albert transgression is simply a component of the multiple *Eurydesma* transgression, which we regard as a single stepped rise of sea level in southern Africa during the Tastubian.

(2) Mudrock units traceable over distances of up to 400 km and interpretable as interglacial deposits (Visser 1989, p. 381) were deposited in lakes, as depicted by Visser (1987, fig. 9), and not in the sea, as shown by the dotted lines in figure 6 of Visser (1989).

(3) The rise of sea level corresponded to the disintegration of the ice sheets in the Gondwanaland province (Visser, 1989, p. 387); the return of this melt-water to the ocean (glacio-eustatic) thus caused, at least in part, the sea-level rise. The transgression in the Karoo Basin was possibly augmented by concomitant subsidence of the shelf (Visser, 1991a), generated by the first extensional phase of Pangean history (Veevers, 1990).

Figure 8A–C (on the following three pages). Representative stratigraphic columns through the Karoo sequence showing lithology and depositional environment; symbols and abbreviations key beneath columns I and II. Thickness in meters. Columns located in the map (Fig. 1), cross section FG (*see* Fig. 10), and time-space diagram (Fig. 7).

A: I. Northeast. Dwyka from Visser (1986) and Visser and Kingsley (1982), marine fossils from Table 1; Ecca Group: Pietermaritzburg (PG) and Vryheid, from Borehole 5 in Van Vuuren and Cole (1979).

II. Southwest. Dwyka from Visser (1986, 1988); lower part of Ecca Group: Prince Albert (PA) and Whitehill (WL) from Visser and Loock (1978) and Cole and McLachlan (1991), who correlate the Whitehill Formation with the upper Vryheid Formation. I and II represent deposition (Dwyka Formation) from a retreating ice sheet interrupted by at least one re-advance (Visser, 1982), followed by suspension settling of argillite (Prince Albert/Pietermaritzburg) in the deglacial flooded basin (Visser, 1987), culminating in the deposition of carbonaceous shale (Whitehill) on an anoxic basin floor caused by the growth of cyanobacterial mats (Cole and McLachlan, 1991). In the northeast part of the basin, postglacial rebound of the source areas resulted in the progradation of a clastic wedge (Vryheid) (Van Vuuren and Cole, 1979).

III. Northeast. Upper part of Ecca Group: Volksrust from Cadle and Hobday (1977), Visser and Loock (1978), and Van Vuuren and Cole (1979). Lower part of Beaufort Group: Estcourt from Botha and Linström (1978), Hobday (1978), and Tankard et al. (1982, p. 392). All from Borehole BE1/66. Represents the second progradation (above the Vryheid/Pietermaritzburg couplet) in the northeast.

B: IV. Southwest. Upper part of Ecca Group: Collingham (CM) from Viljoen (1993, unpublished), Vischkuil and Laingsburg from Viljoen (1993, unpublished), Visser and Loock (1978) and Visser et al. (1980); Fort Brown from Visser and Loock (1978) and Visser et al. (1980); Waterford from Visser et al. (1980), Jordaan (1981), and Rubidge (1988), nonmarine bivalves from Cooper and Kensley (1984). This is a thick regressive sequence deposited in an initially deep trough or foredeep (Tankard et al., 1982, p. 379) that shoaled during the deposition of the Fort Brown and Waterford Formations.

V. Southeast. Upper part of Ecca Group and base of Beaufort Group. Collingham and Ripon from Kingsley (1977, 1981) and Viljoen (in preparation); Fort Brown and Koonap from Kingsley (1977, 1981). A thicker facies equivalent of IV.

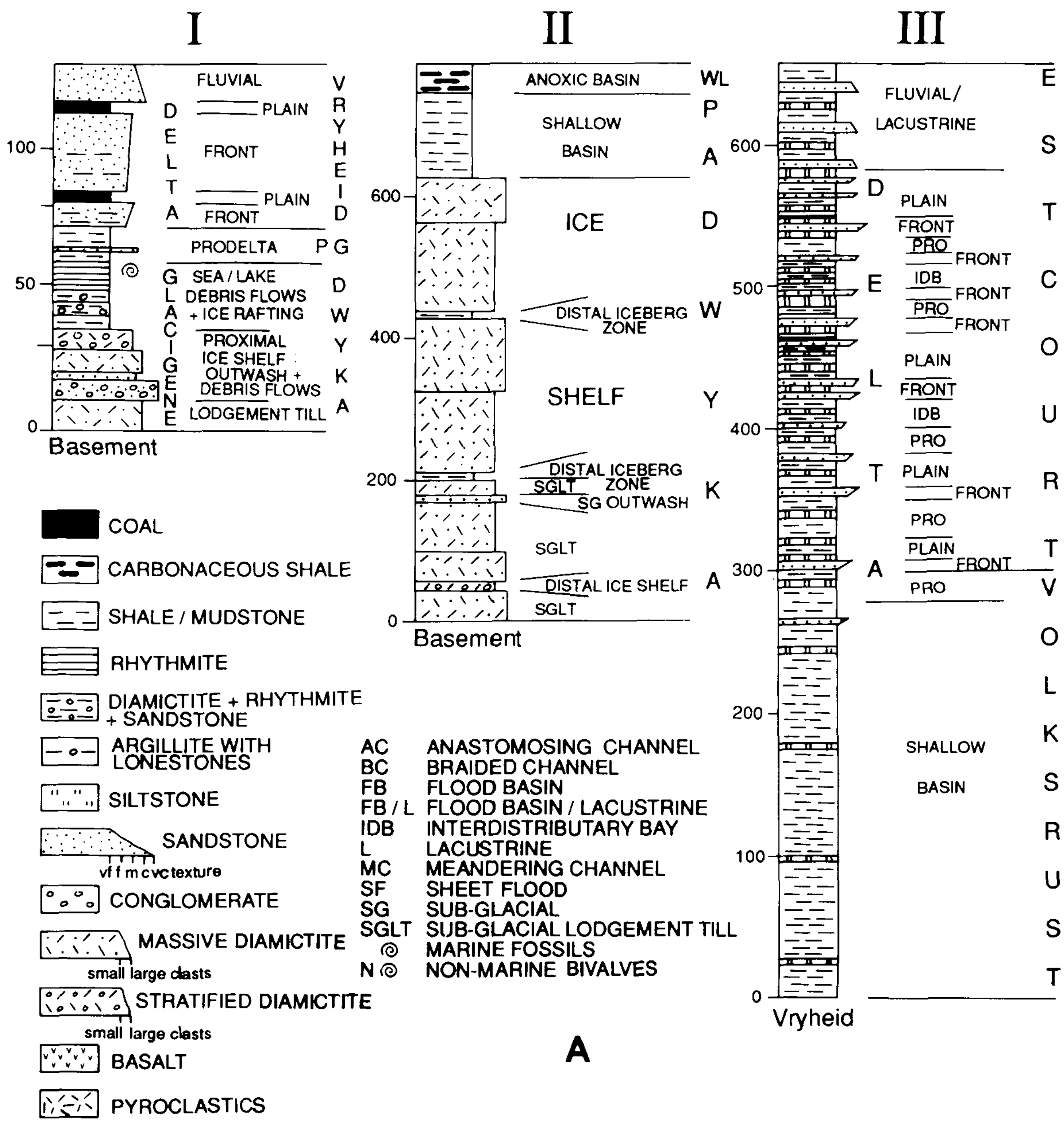
VI. Southwest. Beaufort Group. Abrahamskraal from Stear (1980, 1985), Jordaan (1981), Turner (1981), Rubidge (1988), and Cole and Wipplinger (1991); Teekloof from Stear (1980, 1985), Turner (1981), and Cole and Wipplinger (in preparation). Initial progradation of fluvial deposits over a delta, followed by decreasing fluvial energy as a result of denudation of the source area (Turner, 1985). The fluvial channels range from low- to high-sinuosity (Stear, 1980, 1985) and the sandstones cluster into packages (Stear, 1980; Cole and Wipplinger, 1991).

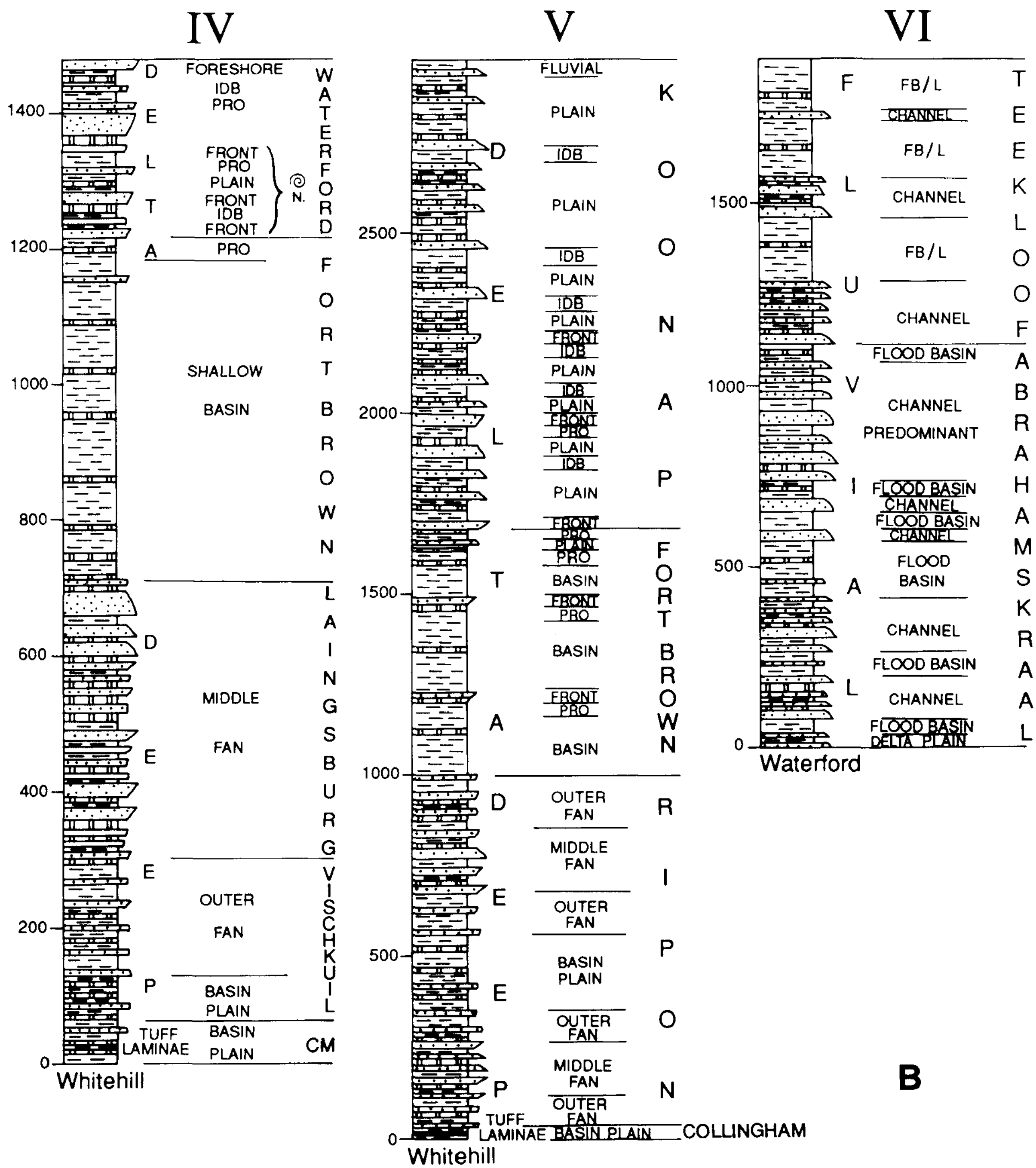
C: VII. Southeast. Middle part of Beaufort Group. Middleton from Visser and Dukas (1979) and Kingsley (1981); Balfour from Visser and Dukas (1979), Stavrakis (1980), Turner (1981), and Hiller and Stavrakis (1984). Similar to VI but the migration of the depositional system sourceward due to a decrease in fluvial energy has been interrupted by high-energy influxes at the base and near the top of the Balfour Formation (Visser and Dukas, 1979).

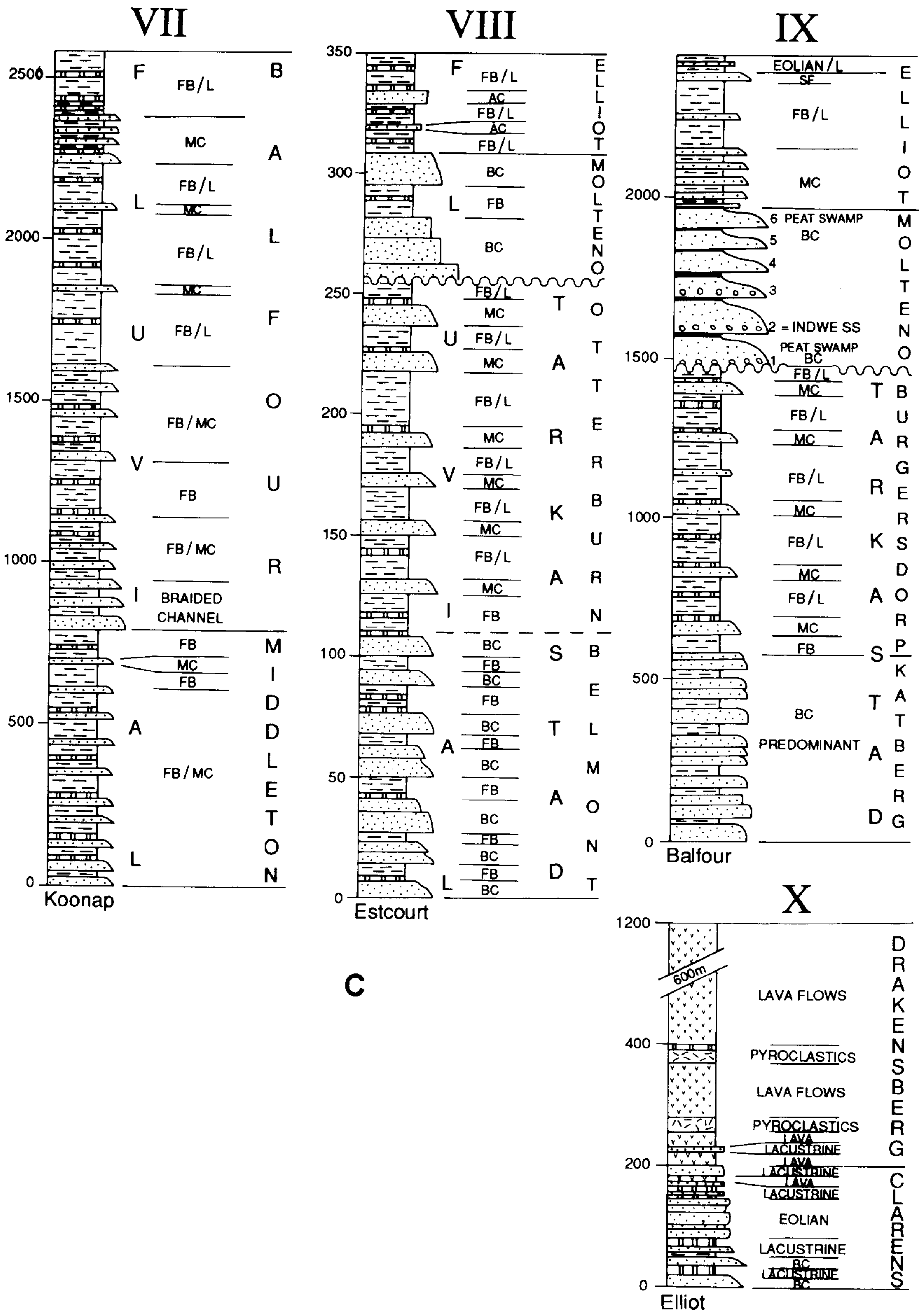
VIII. Northeast. Upper part of Beaufort Group unconformably overlain by the Stormberg Group. Tarkastad from Botha and Linström (1978), Hiller and Stavrakis (1984), and Turner (1986); Molteno cycle 2 or Indwe Sandstone member from Eriksson (1984) and Turner (1983, 1986); Elliot from Eriksson (1985) and Turner (1986). Two northward influxes of fluvial sediments from episodes of tectonic uplift (Hiller and Stavrakis, 1984, p. 2). Each influx was followed by sourceward migration of the distal, fine-grained facies as the source area was progressively denuded.

IX. Southeast. Upper part of Beaufort Group unconformably overlain by the Stormberg Group. Katberg from Visser and Dukas (1979), Stavrakis (1980), and Hiller and Stavrakis (1984); Burgersdorp from Stavrakis (1980) and Hiller and Stavrakis (1984); composite section of Molteno across southern outcrop, showing fining-upward sequences 1–6, from Turner (1975, 1977, 1983, fig. 3); Elliot from Visser and Botha (1980) and Tankard et al. (1982). Similar to VIII except the Molteno Formation contains coal at the top of coarse-grained facies that indicates at least three phases of provenance uplift (Turner, 1983).

X. Northeast. Drakensberg Group and uppermost Stormberg Group. Clarens from Beukes (1970), Eriksson (1979), and Tankard et al. (1982, p. 397); Drakensberg from Lock et al. (1974), Tankard et al. (1982, p. 400), and Visser (1984). Deposition in a desert environment subject to ephemeral floods, followed by lava flows that are interlayered with pyroclastics in the lower third of the Drakensberg.


I
II
III
FLUVIAL
PLAIN
FRONT
PLAIN
FRONT
DELTA
VRYHEID
PRODELTA
P G
SEA / LAKE
DEBRIS FLOWS
+ ICE RAFTING
PROXIMAL
ICE SHELF
OUTWASH +
DEBRIS FLOWS
LODGEMENT TILL
GLACIGENE
DWYKA
Basement
ANOXIC BASIN
WL
SHALLOW
BASIN
PA
ICE
DISTAL ICEBERG ZONE
SHELF
SGLT
SG OUTWASH
DISTAL ICE SHELF
DWYKA
EDELTA
FLUVIAL/
LACUSTRINE
PLAIN
FRONT
PRO
IDB
SHALLOW
BASIN
ESTCOURT
VOLKSRUST
Vryheid
COAL
CARBONACEOUS SHALE
SHALE / MUDSTONE
RHYTHMITE
DIAMICTITE + RHYTHMITE + SANDSTONE
ARGILLITE WITH LONESTONES
SILTSTONE
SANDSTONE
vf f m c vc texture
CONGLOMERATE
MASSIVE DIAMICTITE
small large clasts
STRATIFIED DIAMICTITE
small large clasts
BASALT
PYROCLASTICS
AC ANASTOMOSING CHANNEL
BC BRAIDED CHANNEL
FB FLOOD BASIN
FB / L FLOOD BASIN / LACUSTRINE
IDB INTERDISTRIBUTARY BAY
L LACUSTRINE
MC MEANDERING CHANNEL
SF SHEET FLOOD
SG SUB-GLACIAL
SGLT SUB-GLACIAL LODGEMENT TILL
MARINE FOSSILS
N NON-MARINE BIVALVES
A


IV
V
VI
DELTA
FORESHORE
IDB
PRO
FRONT
PRO
PLAIN
FRONT
IDB
FRONT
PRO
N.
WATERFORD
FORT BROWN
SHALLOW
BASIN
LAINGSBURG
DEEP
MIDDLE
FAN
OUTER
FAN
VISCHKUIL
BASIN
PLAIN
TUFF
LAMINAE
BASIN
PLAIN
CM
Whitehill
FLUVIAL
PLAIN
KOONAP
FORT BROWN
BASIN
RIPON
OUTER
FAN
MIDDLE
FAN
BASIN
PLAIN
COLLINGHAM
FB/L
CHANNEL
FLOOD BASIN
CHANNEL PREDOMINANT
DELTA PLAIN
FLUVIAL
TEEKLOOF ABRAHAMSKRAAL
Waterford
B


VII
VIII
IX
X
Koonap
Estcourt
Balfour
Elliot
C
2500
2000
1500
1000
500
0
F
L
U
V
I
A
L
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
FB/MC
FB
FB/MC
BRAIDED CHANNEL
FB
MC
FB
FB/MC
B A L F O U R
M I D D L E T O N
350
300
250
200
150
100
50
0
F
L
U
V
I
A
L
FB/L
AC
FB/L
AC
FB/L
BC
FB
BC
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
MC
FB
BC
FB
BC
FB
BC
FB
BC
FB
BC
FB
BC
FB
BC
E L L I O T
M O L T E N O
T A R K A S T A D
T O T T E R B U R N
B E L M O N T
2000
1500
1000
500
0
EOLIAN/L
SF
FB/L
MC
6 PEAT SWAMP
BC
5
4
3
2 = INDWE SS
PEAT SWAMP
BC
1
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
MC
FB/L
MC
FB
BC
PREDOMINANT
E L L I O T
M O L T E N O
T A R K A S T A D
B U R G E R S D O R P
K A T B E R G
1200
600m
400
200
0
LAVA FLOWS
PYROCLASTICS
LAVA FLOWS
PYROCLASTICS
LAVA
LACUSTRINE
LAVA
LACUSTRINE
LAVA
LACUSTRINE
EOLIAN
LACUSTRINE
BC
LACUSTRINE
BC
D R A K E N S B E R G
C L A R E N S

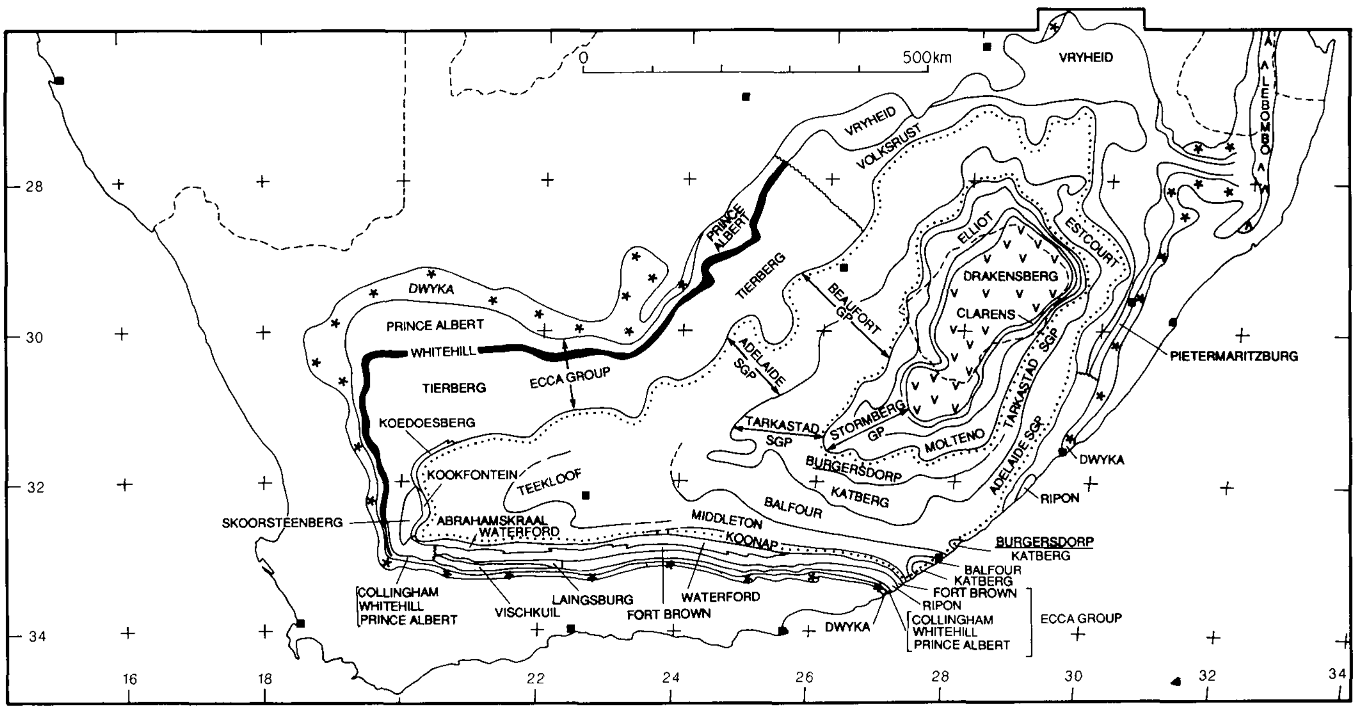


Figure 9. Schematic map distribution of formations in the main Karoo Basin, adapted from Kent (1980, p. 560) as updated by M. R. Johnson (personal communication, 1990). Also shown are subgroups (SGP) and groups (GP).

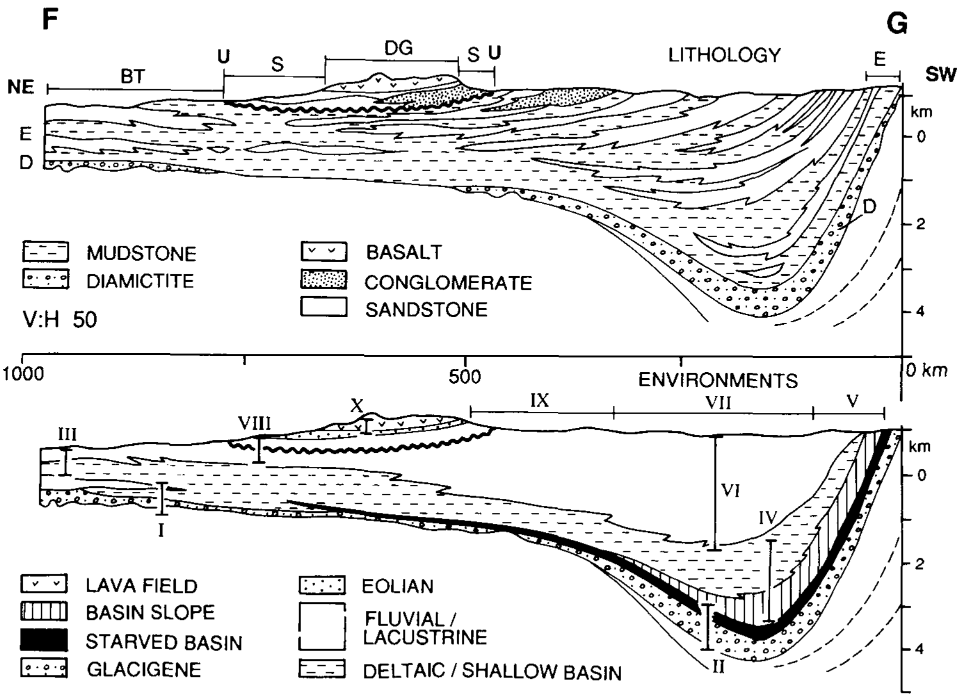


Figure 10. Stratigraphic cross section, located on Figure 1, showing lithology (top) and depositional environments (below) of the Karoo Sequence, modified from fig. 11-2 of Tankard et al. (1982). The lower figure shows also the location (actual or projected) of the stratigraphic columns of Figures 8, A–C. BT—Beaufort, DG—Drakensberg, D—Dwyka, E—Ecca, S—Stormberg, U—unconformity.

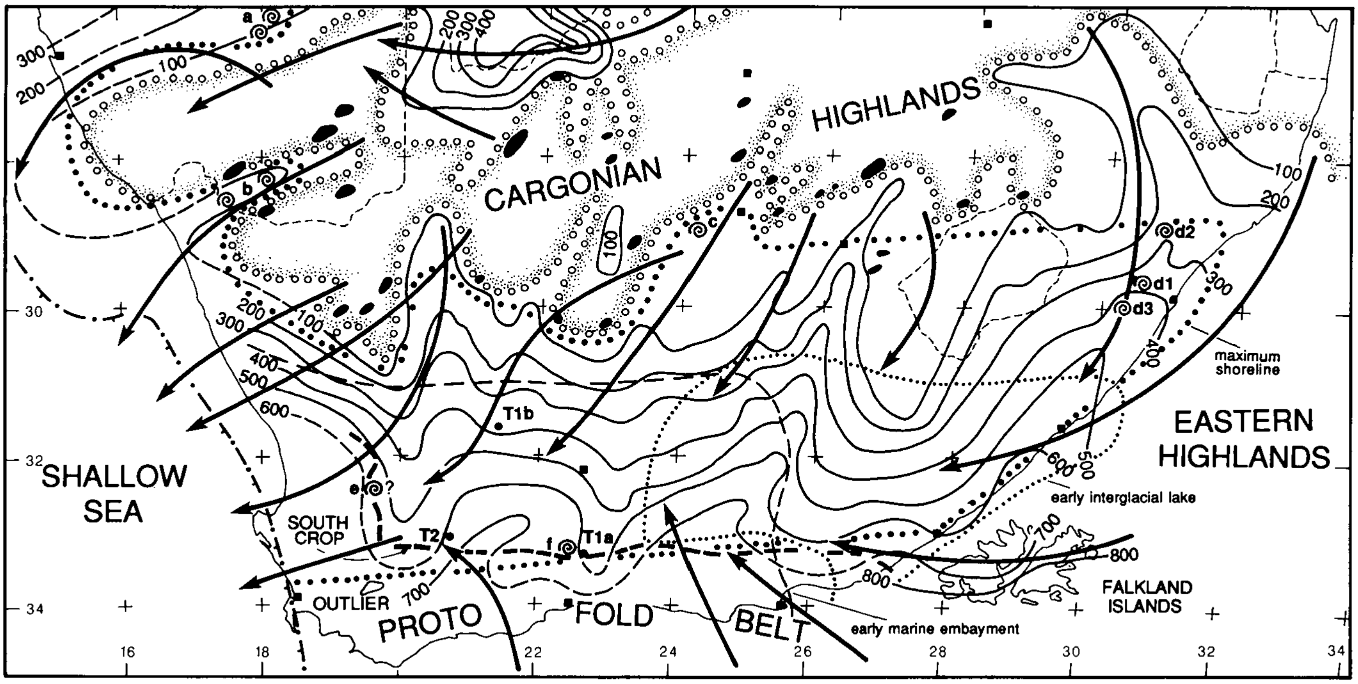


Figure 11. Maximum glaciation (latest Carboniferous/earliest Permian, Gzelian and early Tastubian: 290–277 Ma) in the Kalahari Basin (north of 28°S) and the Karoo Basin (Dwyka Formation), and on the Falkland Islands (Lafonian Diamictite), from Visser (1987, fig. 9), and additionally our interpretation of the Tastubian marine shoreline. Falkland Islands replotted from Mitchell et al. (1986). Shown are isopachs (m), the location (within the Cargonian Highlands) of uplands where younger rocks overlap the glacial deposits (solid), a westward axial ice flow (arrows) during maximum glaciation when the ice sheet was still grounded around a marine embayment (light dashed line) (Visser, 1989, fig. 6), and an early interglacial lake in the east (light dotted line). Coils indicate the location of Tastubian marine invertebrates at localities a and b in the Prince Albert Formation (McLachlan and Anderson, 1973, 1975), at d of marine microfossils in the Dwyka Formation, at c and e of associated fossils, and at f of a shark with radiolarians and arenaceous foraminiferids, as shown also on Figure 1. Heavy dotted line indicates our interpretation of the maximum advance of the Tastubian shoreline, which, limited to the area of known marine fossils, does not include the Falkland Islands. T1a, T1b, and T2 mark the location of tuff in the upper Dwyka Formation (277 Ma) (Table 2). The south crop is indicated by the heavy broken line.

(4) The subsequent fall of sea level in the previously glaciated areas of Gondwanaland (Argentina, southern Africa, India, southern Australia) was due to isostatic rebound.

Our conclusions, broadly in agreement with Visser's (1989, p. 387) history of the Karoo ice sheets, are as follows:

(a) Grounded ice streams from the Cargonian Highlands in the north and from highlands in the south coalesced at the present latitude, 33°S, and flowed westward to a presumed shoreline along the present west coast (heavy broken barbed line in Fig. 11).

(b) During at least two interglacials the basin axis was occupied by a lake (light dotted line in Fig. 11, after Visser, 1987, fig. 9) or a marine embayment (dashed line in Fig. 11).

(c) With the rise of sea level in the Tastubian, the ice sheet flowed through valleys on the southern flank of the Cargonian Highlands at a grounding line (heavy dotted line in Fig. 11) floating as an ice shelf over the basin axis, as suggested also by Von Brunn and Gravenor (1983).

(d) The rapid disintegration of the ice shelf and sheet was followed by an equally rapid isostatic rebound of the areas of formerly grounded ice and regression of the shoreline well past its original position somewhere in the west.

(e) Deposition after the Dwyka Formation and basal Prince Albert and Pietermaritzburg Formations was mainly nonmarine. From time to time the water may have been brackish to form a layer beneath the surface freshwater (cf. the Caspian Sea, Yassini, 1987) as a holdover from the Dwyka/Prince Albert sea, as suggested by phosphatic nodules (Visser, 1991b) and glauconite in the Vryheid coal measures (Van Vuuren and Cole, 1979, p. 109) and the geochemistry of mudrocks in the Ecca and Beaufort Groups (Marchant, 1978; Zawada, 1988; Visser, 1989). But an effectively open connection with the world ocean

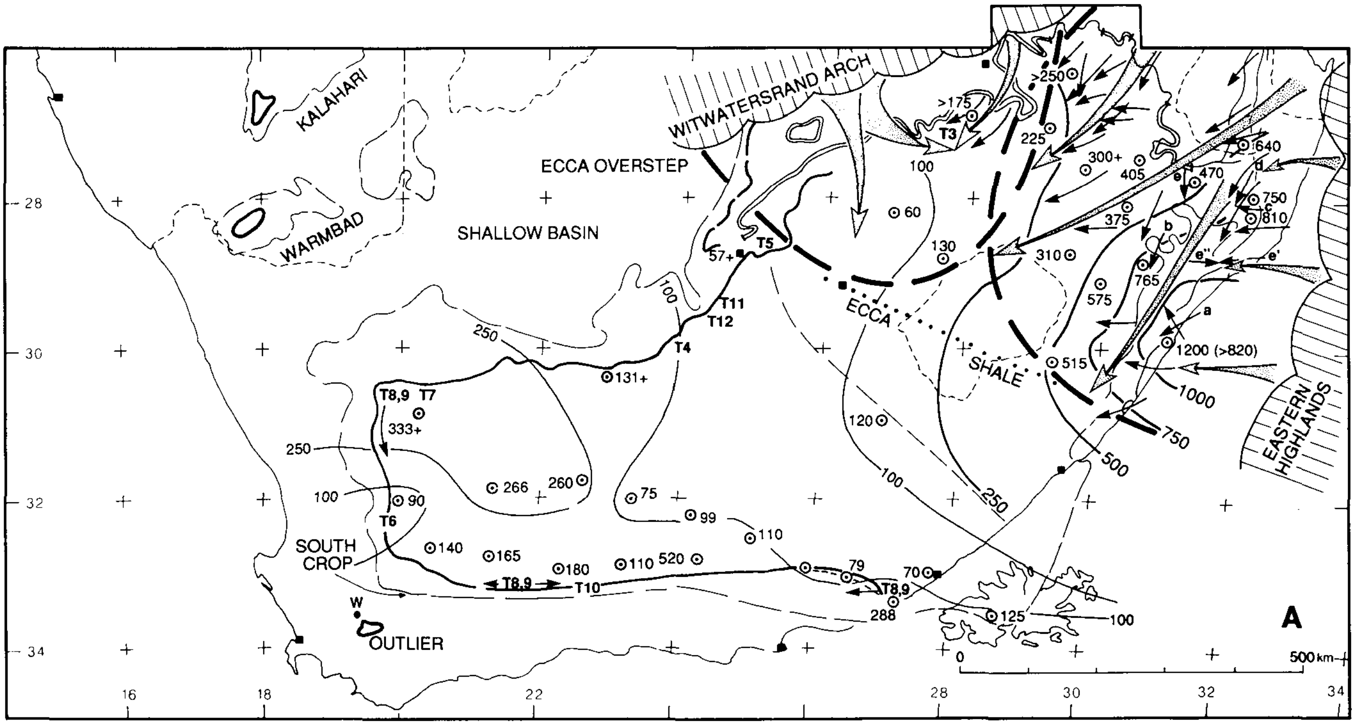
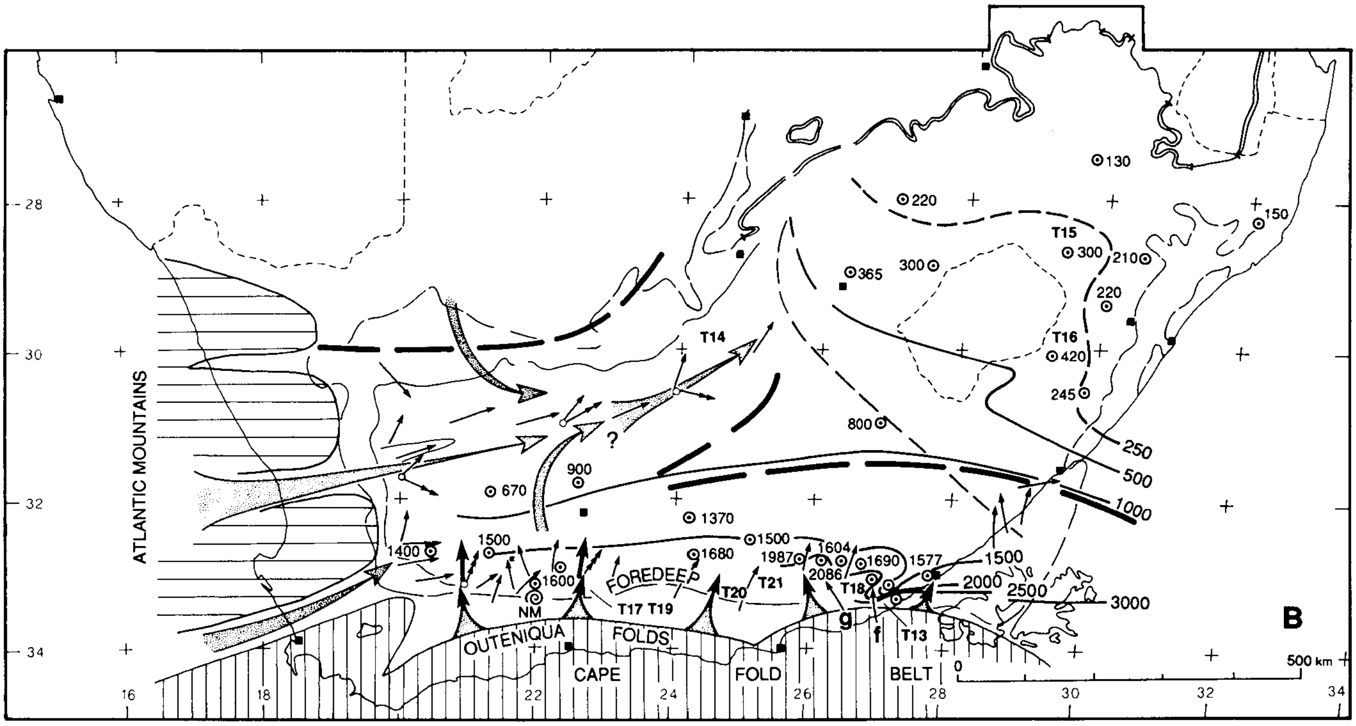


Figure 12 (on this and facing page). Early Permian (late Tastubian–Kalinovian: 275–255 Ma) Ecca Group. The double line denotes the northern feather edge of the Ecca Group that oversteps the Dwyka Formation to rest on basement.

A. Lower Ecca (palynozones 2 and 3). Whitehill Formation (denoted by the solid line, McLachlan and Anderson, 1977; Cole and McLachlan, 1991) and Prince Albert Shale in west and south, and equivalent Vryheid Formation and Pietermaritzburg Shale in north and east. Heavy dotted line denotes the southern limit of sand from the northeast and heavy broken lines the delta complex lobes from the Witwatersrand Arch and the Eastern Highlands (Van Vuuren and Cole, 1979, p. 103, 110). Isopachs (m) from thicknesses of Whitehill Shale + Prince Albert Shale ("Upper Dwyka shales") and Pietermaritzburg ("Lower Ecca shales") + Vryheid Formation ("Middle Ecca") from Anderson (1977, chart 1), Winter and Venter (1970), and unpublished data from D. I. Cole, augmented by thicknesses of Whitehill and Prince Albert on south crop east of 26°E from Kingsley (1979, table 1), and of the presumed equivalent Black Rock member of the Falkland Islands (Frakes and Crowell, 1967, p. 41). Thickness of Whitehill Formation (80 m) at Worcester (W) outlier from Cole and McLachlan (1991). In the north only the first-order isopach trends are shown; details of the valley-fill geometry of the Vryheid Formation are given by Van Vuuren and Cole (1979, figs. 15 and 17). Paleoflow (stippled arrow) from paleocurrents (in north and east only) from Ryan and Whitfield (1979) shown by plain arrow, others by (a) Vryheid Formation (Taverner-Smith, 1982), (b) Vryheid (Middle Ecca) deltaic deposits (Hobday, 1973), (c) Ecca Group (Whateley, 1980), (d) Vryheid Formation (Whateley, 1980), (e) Ecca Group (Hobday et al., 1975), (e′) Vryheid, early flow WNW, later flow (e″) eastward (Mason and Taverner-Smith, 1978).

B. Upper Ecca (palynozone 4), comprising the interval between the Whitehill Formation and the Beaufort Group in the south (Waterford/Fort Brown/Ripon/Laingsburg/Vischkuil/Collingham), the Tierberg, Skorsteenberg, Kookfontein, and Koedoesberg Formations in the northwest, and the Volksrust Shale in the northeast. Isopachs (m) from thicknesses of palynozone 4 in Anderson's (1977) chart 1, except for the south crop east of 26°E, from Kingsley (1979, table 1), and the 3,000-m-thick sequence above the Lafonian Diamictite on the Falkland Islands, from Frakes and Crowell (1967). Paleocurrents from Ryan and Whitfield (1979) except (f) Ripon Formation and (g) Fort Brown Formation (Kingsley, 1979, 1981), and the six localities marked with a circle (Visser et al., 1980), including two from subaqueous fans (heavy arrow), four from the lower delta plain (single-tipped arrows), four from the upper delta plain (double-tipped arrow), and two from the undifferentiated delta plain (triple-tipped arrow). The coil indicates the locality near Prince Albert of the nonmarine (NM) bivalves in the Waterford Formation (Cooper and Kensley, 1984).



ceased after the Tastubian, and southern Africa has remained above or beyond the sea to the present day, as shown by the lack of indubitably marine sediment.

Three tectonic events took place during deposition of the Dwyka Formation: (1) Clast type and ice-flow direction indicate that there was a change to the high ground ("proto fold belt") of the southern epiclastic provenance (Visser, 1993); this was a reversal of slope from that during Cape deposition. (2) The first juvenile volcanogenic material in the form of siliceous tuff beds in outcropping mudrock appeared within diamictite of the upper Dwyka Formation of the south crop north of Klaarstrom, about 100 km south of Beaufort West (Table 2, 1a). This is the first sign in the Karoo Basin of the activity of the magmatic zone along the Panthalassan margin, presumably well south of the Cape Fold Belt, which itself lacks contemporaneous magmatic rocks. And (3) the first movements in the Cape Fold Belt were manifested in the Swartberg folding dated at 278 ± 2 Ma (Hälbich et al., 1983, table 13.3). These events (Figs. 3 and 7) foreshadow the subsequent development of the orogen that delimits the southern edge of the Karoo structural basin.

Ecca Group. This account of the Ecca Group is derived from data given mainly by Anderson (1977), Van Vuuren and Cole (1979), Anderson and McLachlan (1979), McLachlan (1973, 1977), Visser et al. (1980), Tankard et al. (1982), Cole and McLachlan (1991), and Cole et al. (1990).

Following the collapse and melting of the Dwyka ice sheet and the concomitant marine transgression (probably due to a combination of shelf subsidence and glacio-eustatic rise in sea level), the formerly glaciated ground rebounded isostatically to form uplands. The Cargonian Highlands in the northeast (Fig. 11) became the Witwatersrand Arch (Ryan and Whitfield, 1979), and the Eastern Highlands persisted in the east (Fig. 12A). The first folding of the Cape Orogeny, the Swartberg event, dated by the 278 ± 2 Ma recrystallization cleavage in the Cedarberg Formation (Hälbich et al., 1983), probably took place during the deposition of the upper part of the Dwyka Formation (Fig. 7). The event was probably deep-seated because no major facies changes indicate uplift and shedding of sediment in the upper Dwyka and lower Ecca in the basin adjacent to the Cape Fold Belt. The basin stretched southward across the site of the Cape Fold Belt at least to the proto fold belt during Dwyka deposition, possibly as far as a magmatic belt along the Panthalassan margin (Visser, 1987, 1991b). It was not until the second, Outeniqua, folding event dated at 258 ± 2 Ma (Hälbich et al., 1983) that the Cape Fold Belt became a major provenance for Karoo sediment, initially supplying the sand and mud of the upper Ecca Group. The lowermost part of the Ecca Group (Prince Albert, Whitehill, Pietermaritzburg, and Vryheid Formations) conformably succeeded the Dwyka Formation except in the northeast where the Vryheid Formation overstepped the valley-fill deposits of the Dwyka to rest directly on basement (double lines in Fig. 12A).

The question of the marine or nonmarine character of the

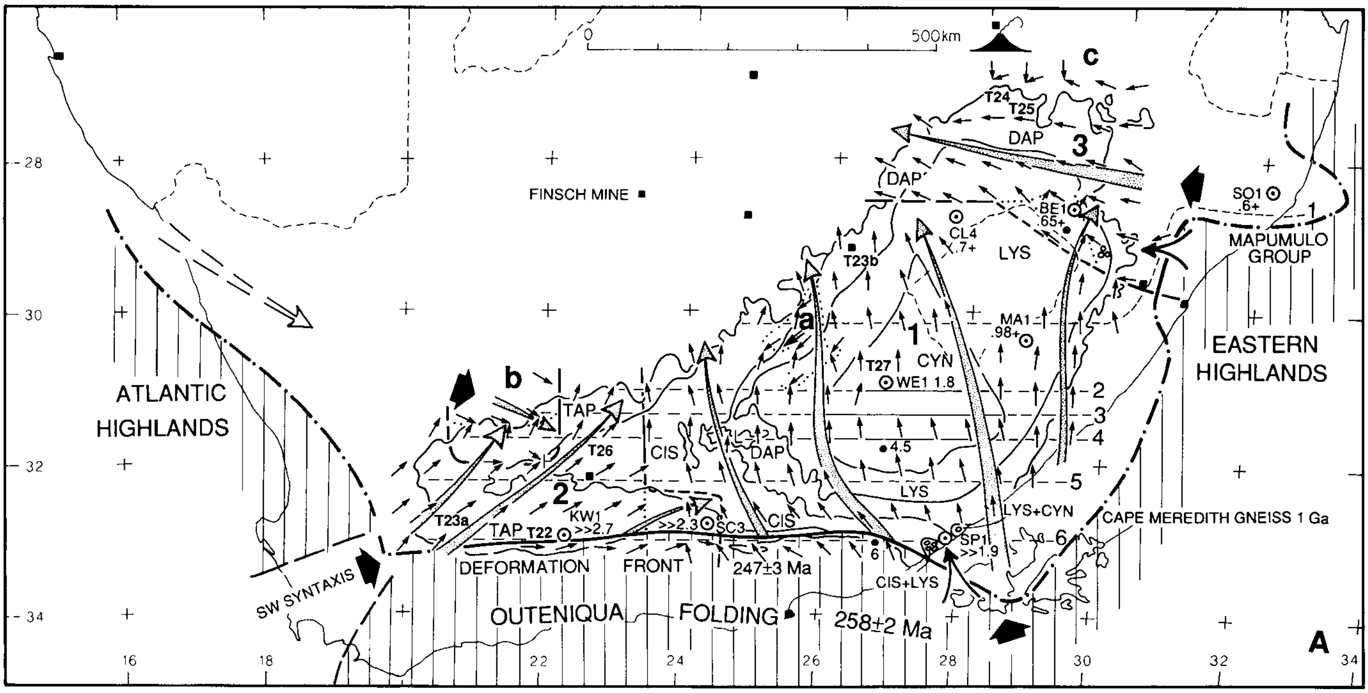
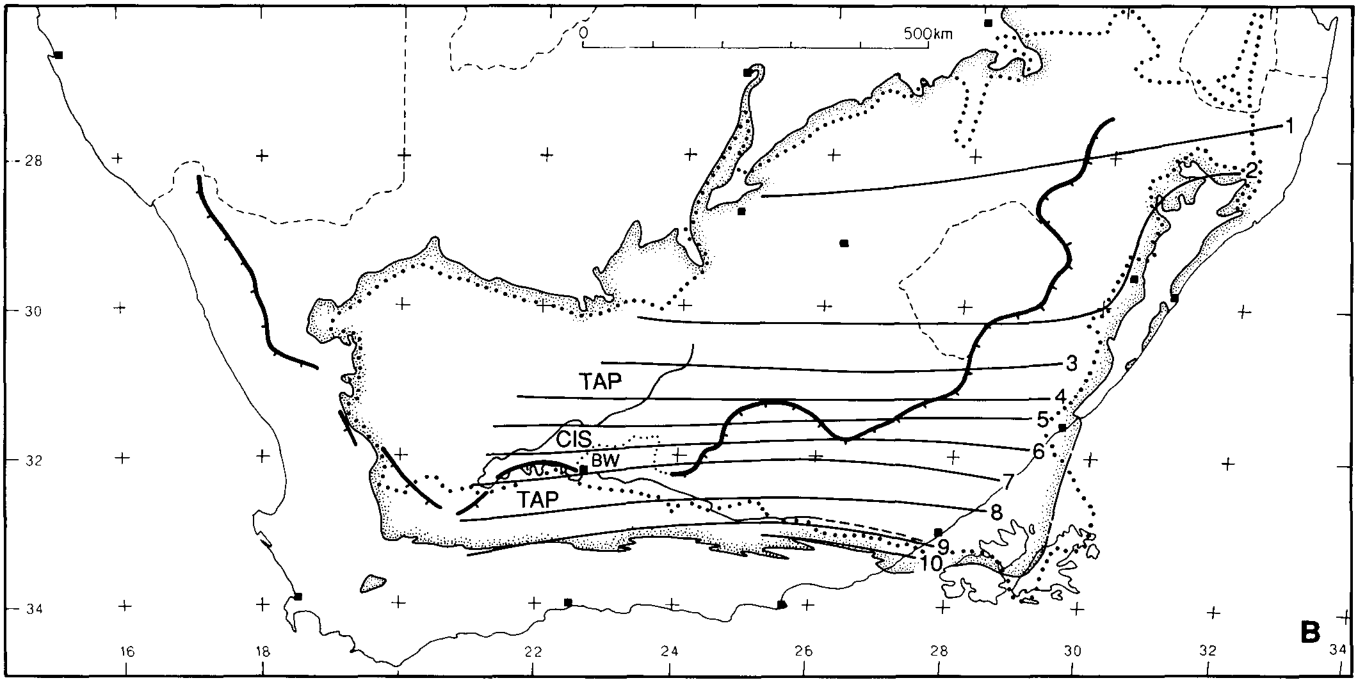


Figure 13 (on this and facing page). A. Late Permian (Sosnovian and Tatarian) and Early Triassic (Scythian) (250–240 Ma) Beaufort Group. Isopachs (km) from drill-hole (circled dot) data (Winter and Venter, 1970, fig. 12, dolerite-free thickness) and inferred original thickness on southern outcrop (filled circle) from Rowsell and de Swardt (1976, p. 84). Tetrapod zones west of 26°E and south of 31°S from Keyser and Smith (1979), rest from Kitching (1970), whose terminology is retained: TAP-*Tapinocephalus,* CIS-*Cistecephalus,* DAP-*Daptocephalus,* LYS-*Lystrosaurus,* CYN-*Cynognathus.* Paleocurrents, from Cole and Wipplinger (1991), are moving averages for each 1° × 1° square progressing in steps of ½°; the vector means were calculated from 13,000 readings taken principally from Theron (1975) and augmented from Botha and Linström (1978), Cole (1980), Hiller and Stavrakis (1980), Kingsley (1970, 1979), Kingsley and Theron (1964), Stavrakis (1980), Turner (1978, 1986), and Visser and Dukas (1979), together with unpublished data from D. I. Cole and various theses and reports. Single arrows show range of paleocurrent directions in each of domains 1–3 (areas of overlap shown by broken and dotted lines) and in enclaves a and b; broad arrows show the general direction of sediment transport. Deformation front of Cape Fold Belt (heavy line) during Beaufort deposition (and deformation) about the southwestern (SW) syntaxis from Söhnge (1983), to the east (with dates) from Hälbich et al. (1983), and on the Falkland Islands from Adie (1952a). Dot-and-dashed line marks foot of highlands. Rudites (circles) in the Katberg Sandstone on the coast near 28°E and in the Belmont Sandstone near the Mooi River from Theron (1975, p. 65). The ash-flow tuff at T24 and T25 probably had a local volcanic source in the northern Karoo Basin. All others had a southern source.

B. Total isopachs (km) of the Dwyka Formation and Ecca and Beaufort Groups, summed from Figs. 11, 12, and 13A. Also shown are the dolerite line (dotted, from Fig. 1), the boundary between the *Cistecephalus* (CIS) and *Tapinocephalus* (TAP) zones (from part A), approximating the boundary between the Teekloof and Abrahamskraal Formations in the west and the Middleton and Koonap Formations in the east, and the Great Escarpment (barred line, from Dingle et al. 1983, fig. 169). BW—Beaufort West (township).

Ecca Group above its marine base is not resolved, and we present the evidence now before continuing the description. From a review of the fossils in the Ecca Group, McLachlan (1973, p. 10) concluded that the water in which the Ecca was deposited "was normally fresh. Certain lines of evidence (the glauconite bands, spinose acritarchs and sponge spicules) suggest that the water was at times saline, but the lack of recognizable marine faunas indicates that a connection with the oceans was unlikely." The only indubitably marine invertebrate recorded from the Ecca Group, an ammonite said to have been from the Vryheid coal measures, was shown to be grossly displaced (McLachlan, 1977). As related above, the marine invertebrates in the upper Dywka Formation and basal Prince Albert Formation constitute the only convincing evi-



dence of a Permian sea in southern Africa. The water in the later Ecca basin, after the withdrawal of the sea at the end of the Tastubian, may have been brackish to form a dense layer beneath the surface fresh water, and this would reconcile Marchant's (1978) conclusion that the concentration of Ni, Zn, and Cu in organic separations of the Ecca shale favors deposition in saline water. Zawada (1988) used the concentration of Rb, B, V, and Cu, and adsorbable Mg^{2+} and Ca^{2+} to show that the Ecca Group mudrocks were probably deposited in fresh or brackish water. According to Van Vuuren and Cole (1979, p. 109), the glauconite in the Ecca Group is confined to the transgressive top of two of the regressive cycles (B2 and C) of the Vryheid Formation in the 1-m thick poorly sorted sandstone on top of fluvial sandstone. They cite another occurrence of glauconite in South Africa in the soil and calcrete of modern salt pans, in a setting possibly comparable with the occurrence of casts of gypsum in the dolostone of the Whitehill Formation (McLachlan and Anderson, 1977, p. 93). The essential paleogeographic distinction is between the marine and nonmarine realms. Saline water is not uniquely marine, as signified by the term *salina* for a class of lake, but freshwater is uniquely nonmarine.

We believe that the water of the Ecca basin was brackish to fresh except in the northeast, where the fluvial parts of the Vryheid Formation were wholly fresh. Later, as a result of the shrinking of the basin due to uplift along the Cape Fold Belt and an influx of deltaic sediment, the environment became entirely nonmarine. In the southwest, the nonmarine sediments form the uppermost units of the Ecca Group: the Koedoesberg and Waterford Formations (Fig. 9). The Waterford Formation contains endemic freshwater or nonmarine bivalves (Cooper, 1979; Cooper and Kensley, 1984). Cooper (1979) and Cooper and Kensley (1984) pointed out the connection with the nonmarine fauna of the Estrada Nova Formation of the Parana Basin of South America, which was deposited in an isolated body of brackish water likened by Runnegar and Newell (1971) to the Caspian Sea, a vast lake filled with fresh to brackish water, and isolated from the ocean. In the northern Caspian Sea, fresh surface water from the Volga delta flows over the brackish lake water to form a permanent stratification, and the deeper (>800 m) floor in the central and southern parts is anoxic (Yassini, 1987, fig. 5, table 1).

The Ecca Group is divided into lower and upper sequences. The lower sequence comprises the Prince Albert, Whitehill, Pietermaritzburg, and Vryheid Formations; the upper comprises the Collingham, Vischkuil, Laingsburg, Ripon, Fort Brown, Tierberg, Volksrust, Skoorsteenberg, Kookfontein, Koedesberg, and Waterford Formations (Figs. 7 and 9; Kent, 1980, fig. 7.3.3).

Lower Ecca. In the Sakmarian and Artinskian palynozones 2 and 3 (see Fig. 21 in Appendix 2), the lower Ecca sequence of shale was deposited over the Dwyka Formation in an initially shallow marine and then a shallow brackish-water basin (Visser, 1991b). In the south the shale is called the Prince Albert Formation. It is overlain by the 50-m-thick white-weathering ("white band") pyritic and carbonaceous Whitehill Formation with occasional chert lenses (Fig. 8A, part II; Cole and McLachlan, 1991), with its age in the *Mesosaurus* zone. The Whitehill Formation extends north-northwestward through the Warmbad and Kalahari basins (Fig. 12A) to South America where it is called the Iratí Formation

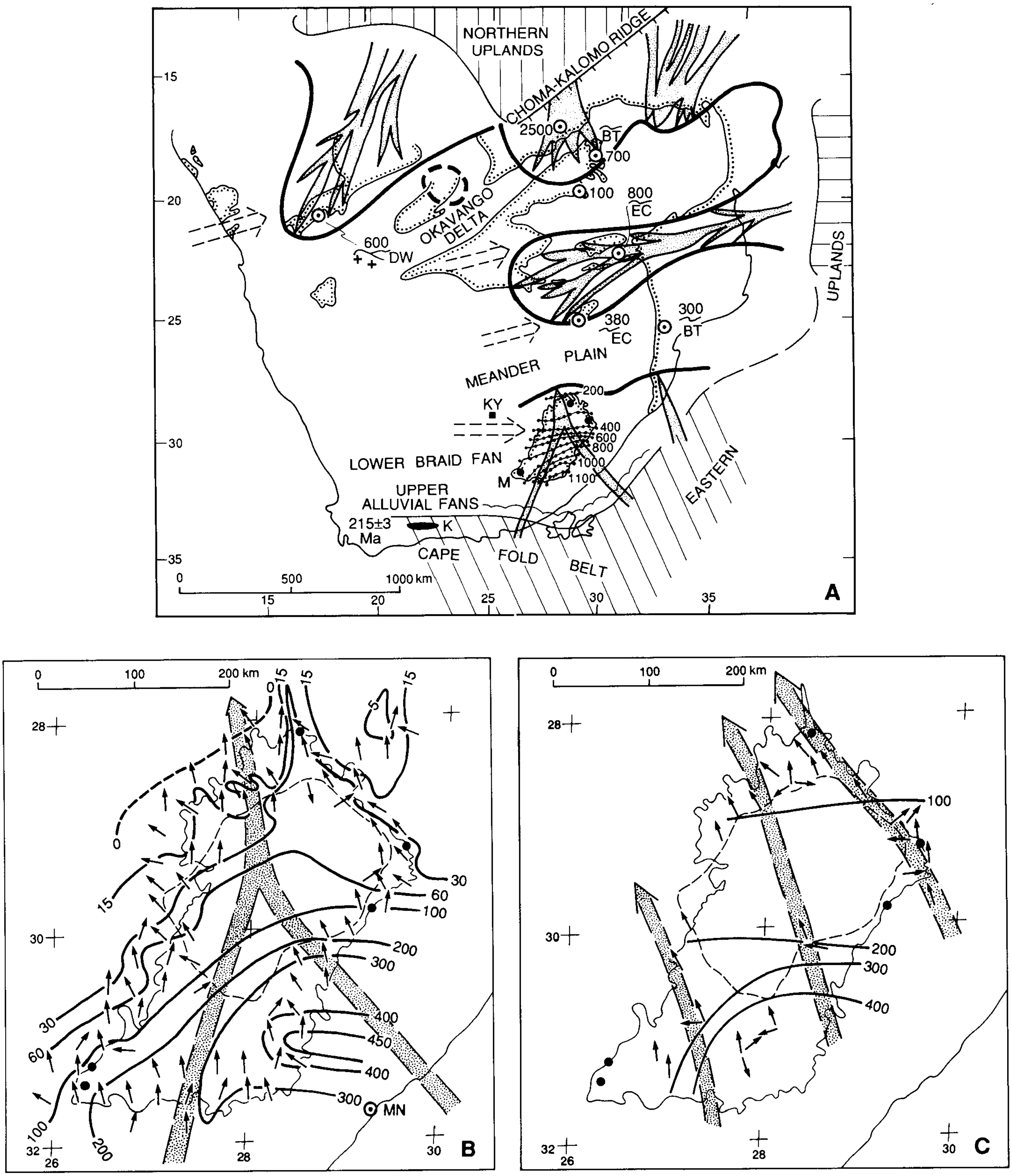

NORTHERN UPLANDS
CHOMA-KALOMO RIDGE
2500
BT
700
100
800 EC
OKAVANGO DELTA
600 DW
380 EC
300 BT
UPLANDS
MEANDER PLAIN
KY
200
400
600
800
1000
1100
LOWER BRAID FAN
M
UPPER ALLUVIAL FANS
215±3 Ma
K
CAPE FOLD BELT
EASTERN
0 500 1000 km
A
0 100 200 km
0
15
5
30
60
100
200
300
400
450
MN
B
C

Figure 14. A. Late Triassic–Early Jurassic (Carnian-Pliensbachian: 230–193 Ma) Stormberg Group and equivalents, and overlying volcanics (outlined by parallel full and dotted lines), from Visser (1984, figs. 13 and 20). Sediment thickness (m) at encircled dots is greatest at 2500 m in the Gwenbe district of Zambia in front of the paleoscarp of the Choma-Kalomo granitic ridge (Taverner-Smith, 1962; Rust, 1975). Disconformably underlying rocks are Beaufort equivalent (BT), Ecca (EC), Dwyka (DW), and Precambrian (++). Source areas are ruled. In the recess between the Cape Fold Belt and Eastern Uplands, fluvial facies belts thin downslope from upper alluvial fans (not preserved, from Turner, 1983, fig. 7) through lower braid fans (northern limit of prograding cycle 2 or Indwe Sandstone Member of the Molteno Formation) to meander plains (Elliot Formation), which retrograded 300 km southward during Molteno cycle 6. Isopachs (m) in the Lesotho region from Dingle et al. (1983), and major lines of fluvial sediment transport from Figure 14B. Solid dots in Molteno outcrop indicate clasts >30 cm long, including the 75-cm block of Witteberg quartzite (Table 5) near Molteno township (M). K—Kango inlier with a retrogressive metamorphic date of 215 ± 3 Ma. KY—Kimberley. Other lobate fluvial systems from east and north, from Visser (1984). Broad broken arrows indicate pattern of the winds from which the Clarens Formation (Beukes, 1970) and equivalents (Visser, 1984, fig. 18) were deposited.

B. Late Triassic (Carnian–early Norian) Molteno Formation exposed within the Lesotho mesa. Isopachs (m) and mean maximum length of clasts >30 cm (dot) from Turner (1984) and vector mean cross-bedding azimuths for 89 sample sectors (5,800 measurements at 540 localities) and derived sediment transport pattern, from Turner (1977). MN—Mngazana, an isolated outcrop of Molteno Formation (Dingle et al., 1983, fig. 108).

C. Late Triassic (late Norian) Elliot Formation exposed within the Lesotho mesa. Isopachs (m) from Dingle et al. (1983, fig. 16B). Paleocurrents in northeast (vector means of 63 measurements at 9 localities) from Eriksson (1985) and elsewhere (about 500 measurements at 22 localities) from Botha (1967), indicating a pattern of sediment transport (broad arrows) from the south-southeast.

(Anderson and McLachlan, 1979). In the northeast, the basal shale is called the Pietermaritzburg Formation, and it is overlain by a regressive-transgressive fluvio-deltaic wedge called the Vryheid Formation (Fig. 8A, part I). The productive coal measures of the Karoo coal province (Hobday, 1987) were deposited on the delta plain of this delta complex. In parts of the north, the Vryheid Formation itself steps across both Pietermaritzburg Shale and the Dwyka Formation to rest on basement and drapes the original Dwyka glacial valleys (Van Vuuren and Cole, 1979, figs. 15 and 17). Van Vuuren and Cole (1979) recognize eight individual cycles of delta progradation that shale out by the dotted line in Figure 12A. We interpret the paleocurrents as showing two overlapping delta complexes. The one in the northwest was sourced from the Witwatersrand Arch and is no thicker than 250 m. The complex in the east was sourced from the Eastern Highlands and is at least 1,000 m thick along an axis located on the present coastline in the position of the former Natal trough of the Cape Supergroup. "The abundance of coarse-grained clastics, the increase in the total sand content of the Vryheid Formation and the increase in the number of recognisable cycles of sedimentation toward the east indicate that the Eastern Highlands were a much more active source than the Witwatersrand Arch" (Van Vuuren and Cole, 1979, p. 110).

Southwest of the line of shale-out (Fig. 12A), the Prince Albert and the Whitehill Formations together thin to <100 m toward the southeast and in a smaller area to the southwest, with the thickest sequence (333+ m) in the west-north-west. Variations in thickness are due partly to the diachronous contact between the Dwyka and Prince Albert Formations. The mud at the base of the Prince Albert Formation was deposited from suspension as the distal part of the glacigenic sediment deposited from tidewater glaciers (Visser, 1982, 1989). The thin sequence in the southwest coincides with the Cape Fold Belt syntaxis, interpreted by de Beer (1990) as a basin swell that rose during the first (278 ± 2 Ma) folding event. A similar situation may have applied in the corresponding syntaxis centered on the restored Falkland Islands (Fig. 12A). The overlying Whitehill Formation thickens to 70 m in the west-north-west and to 80 m in the outlier near Worcester (Cole and McLachlan, 1991), and both trends presumably extended to the proposed South Atlantic embayment that connected the Karoo and Paraná Basins (Oelofsen and Araujo, 1987).

Upper Ecca. During palynozone 4 (Fig. 12B), the situation was reversed. Thick sandy sediment came wholly from the south and west, and the northeastern area of the former Vryheid delta complexes was covered by a shale (Volksrust Formation) that wedged out to the northeast. By the end of Ecca deposition, the brackish lake was almost filled with sediment to become the broad fluvial plain of the Beaufort Group (Smith, 1990).

In the south and west, the Upper Ecca comprises regressive deposits that grade upward through deepwater (<500 m) (Visser and Loock, 1978) subaqueous fans to a delta complex (Cole et al., 1990; Kingsley, 1981). In the southwest (Fig. 8B, part IV), the formations in ascending order are the Collingham, 60 m of interlaminated tuffaceous siltstone and shale; the Vischkuil, 250 m of shale, siltstone, and sandstone of the basin plain and outer fan; the Laingsburg, 400 m of almost equal amounts of shale and sandstone of the middle fan; 500 m of the Fort Brown, deposited in a shallow basin and pro-delta plain; and the Waterford, 250 m of delta-front and pro-delta sandstone and shale that contains nonmarine endemic bivalves. In the southeast (Fig. 8B, part V), the Upper Ecca, almost twice as thick as it is in the west (Fig. 12B), comprises the basin-plain Collingham Formation, the outer-middle fan Ripon Formation, and the outer-deltaic Fort Brown Formation. A third regressive sequence is present in a smaller area in the western part of the basin. It comprises the basin-plain Collingham and Tierberg Formations, which are overlain by 200 m of sandstone and shale corresponding to the subaqueous fan Skoorsteenberg Formation, in turn succeeded by rhythmically bedded, pro-delta mudrock of the Kookfontein Formation, and

TABLE 1. FOSSIL INDICATORS OF MARINE AND NONMARINE ENVIRONMENTS IN THE KAROO AND NEIGHBORING BASINS

Indicator	Reliability	Formation/Group	Locality*	Reference†
		MARINE ENVIRONMENTS		
Marine invertebrates	High	Prince Albert	a W. Kalahari	1
		(formerly Dwyka Shales)	b Warmbad	1
Marine microfossils	High	Dwyka	d1 Ashburton	2
			d2 Tugela Rand	2
			d3 Mkomazi	2
Fish, coprolites	Low	Topmost Dwyka	c Douglas	2
			e Tankwa R.	2
Shark, marine microfossils	High	Ecca/Dwyka	f Zwartskraal	3
Acritarchs	Low	Basal Dwyka	S Karoo	1
			Vaal R.	4
Glauconite	Low	Ecca (Vryheid)	northeast	4
		NON-MARINE ENVIRONMENTS		
Nonmarine bivalves	High	Waterford	Prince Albert	5

*Letters refer to designations used in Figure 11.
†1 = McLachlan and Anderson, 1973; 2 = Von Brunn and Gravenor, 1983, p. 203; 3 = Oelofsen, 1986; 4 = Anderson, 1977, p. 51; 5 = Cooper and Kensley, 1984.

finally by delta-front and delta-plain sandstone of the Koedoesberg Formation (Fig. 9; Cole et al., 1990, p. 6).

The Upper Ecca Group represents the first pulse of thick sediment shed into the foredeep from the rising proto-Cape Fold Belt, which underwent a second deformation, the Outeniqua folding, at 258 ± 2 Ma (Häblich et al., 1983, table 13.3) toward the end of Ecca deposition. Folding probably began earlier than its climax (de Beer, 1991) during rapid subsidence of the shallow floor of the Whitehill basin. With continued subsidence outstripping deposition, the foredeep reached a maximum depth of about 500 m during the deposition of the subaqueous fans (Visser and Loock, 1978). The isopachs now parallel the strike of the Cape Fold Belt, with the thickest known section near the coast and on the Falkland Islands, interpreted as lying at the immediate foot of the Cape Fold Belt. In the west, sediment was transported down an east-north-eastward paleoslope. A Tankwa sub-basin was separated from a southern Laingsburg sub-basin by a basin-floor swell located along the line of the Cape Fold Belt syntaxis (Cole et al., 1990, p. 6; de Beer, 1990). Sediment in the Tankwa sub-basin was probably derived by consequent drainage down the flank of the resurgent Atlantic Mountains that expanded eastward to the Western Branch of the Cape Fold Belt (de Beer, 1990). Across the syntaxis in the Laingsburg sub-basin and the rest of the foredeep, sediment was derived by consequent drainage from the Southern Branch of the Cape Fold Belt (Fig. 12B). The Atlantic Mountains temporarily interrupted or restricted the previous Tastubian upper Dwyka/basal Prince Albert marine and Artinskian Lower Ecca brackish-lacustrine connection between southern Africa and South America. A connection was restored during the growth of the early Kazanian Waterford-Estrada Nova lake with its endemic bivalves.

Beaufort Group. This account of the Beaufort Group is derived from data given mainly by Anderson (1977), Tankard et al. (1982), Dingle et al. (1983), Cole and Wipplinger (1991), and the works of B. R. Turner that are listed in the References Cited section.

Following the filling of the Ecca basin by deltas that prograded initially southwestward from the northeast and then northward from the south, a much greater volume of sediment from the faster rising Cape Fold Belt prograded diachronously northward in rivers that flowed across the floor of the former brackish to freshwater basin down a 500-km-long piedmont flank into a westward-sloping axis of sediment transport (Fig. 13A). During 15 million years of deposition, the piedmont wedge reached an estimated thickness of 6 km at the south crop. The rapid northward thinning of the Beaufort Group is effected by a combination of younging of the Ecca/Beaufort boundary and deeper erosion of upper Beaufort strata before deposition of the Late Triassic Molteno Formation (Fig. 7). The mud and sand are commonly red, due to the well-drained, hence highly oxidized, fluvial slope on which they were deposited as well as to the onset of a warmer and seasonal global climate. The related poverty of palynomorphs—Anderson

TABLE 2. VOLCANIGENIC MATERIAL IN THE TASTUBIAN TO SCYTHIAN PART OF THE KAROO BASIN INDICATING COEVAL DISTAL VULCANICITY EXCEPT THE PROXIMAL 24 AND 25*

Unit	Locality	Material	Reference
27. Burgersdorp	Herschel	Laumontite	Fuller, 1970
Burgersdorp†	**Bf 21**	**44 %**	
Katberg	**Bf 2**	**48 %**	
Balfour	**Bf 16, 17, 20**	**84 %**	
Middleton	**Bf 7, 8**	**72 %**	
Koonap	**Bf 10**	**61 %**	
26. Lower Beaufort (Teekloof, Abrahamskraal)	SW Karoo	i. Shards ii. Sand-sized clasts of alkaline trachyte iii. Drop-like bodies of trachyte iv. Volcanic quartz v. Laumontite	Ho-Tun, 1979 Turner, 1978
25. Lower Beaufort	Blydschap near Frankfort	Ash-flow tuff with pumice lapilli	Keyser and Zawada, 1988
24. Lower Beaufort	Oranje near Heilbron	Ash-flow tuff	Keyser and Zawada, 1988
23. Lower Beaufort Adelaide Subgroup	SW Karoo Edenburg	(a) Shards (b) Shards	Le Roux, 1985 Le Roux, 1985
Waterford	**E3**	**50 %**	
Ripon	**E2, 5**	**56 %**	
22. Base of Beaufort	Prince Albert Road	Shards in silicified tuff	Martini, 1974
21. Fort Brown	Geelhoutboom	Crystal (plagioclase) tuff	Lock and Johnson, 1974
20. Fort Brown	13 km N of Wolwefontein	Shards in felsitic groundmass (SA 10)	Appendix 1; Figure 20D
19. Base Collingham	Remhoogte	Shards plus volcanic quartz Shards (SA 15)	Elliot and Watts, 1974 Appendix 1, Figure 20B
18. Base Collingham	Ecca Pass	Shards (SA 7a)	Appendix 1, Figure 20C
17. Base Collingham Matjiesfontein chert	Remhoogte	Tuff (SA 14c)	Appendix 1; Figure 20E
16. Base Volksrust	SW1/67	Tuff (K-bentonite)	Viljoen, 1990
15. Base Volksrust	BE1/66	Tuff (K-bentonite)	Viljoen, 1990
14. Base Tierberg	Hopetown	Altered tuff (illite-mont. claystone)	McLachlan and Jonker, 1990
13. "Volcanic interval" in Collingham	South Crop	Shards, metabentonite	Lock and Wilson, 1975
12. Whitehill	Hopetown	Altered tuff (illite-mont. claystone)	McLachlan and Jonker, 1990
11. Whitehill	KL1, Hopetown	Shards in crystal tuff	McLachlan and Jonker, 1990
10. Whitehill	Remhoogte	Shards (SA 16a)	Appendix 1, Figure 20A
9. Whitehill	South Crop	Shards in dolostones	McLachlan and Anderson, 1977
8. Base Beaufort to top of Prince Albert	South Crop	Ash beds plus laumontite	Martini, 1974
7. Tierberg to Prince Albert	HG1	Tuff (K-bentonites)	Viljoen, 1990
6. Prince Albert ("Upper Dwyka Shales")	OL1/69	"Volcanoclastic material"	Rowsell and de Swardt, 1976, p. 121
5. Prince Albert	D731	Shards in ash beds	McLachlan and Jonker, 1990
4. Prince Albert	EP1	Shards in claystone	McLachlan and Jonker, 1990
3. Pietermaritzburg	Koppies	Altered ash (mont. claystone)	Schmidt, 1976
2. Laingsburg–Prince Albert	Laingsburg	Tuff beds (K-bentonite)	Viljoen, 1990
1b. Vischkuil–upper Dwyka	QU1/65	Tuff beds (K-bentonite)	Viljoen, 1990
1a. Upper Dwyka	Klaarstrom	Tuff beds (K-bentonite)	Viljoen (1993, unpublished)

*Arranged in stratigraphic order. Located in Figures 1, 7, and 21, and illustrated in Figure 20.
†Supplementary data (**bold**), from Johnson, 1991, Table 2, are selected from those southeastern Karoo Basin sandstones with >44% volcanic rock fragments (Fig. 15C). Whether these fragments are derived from juvenile (coeval) pyroclastics or from ancient (pre-Permian) volcanic rocks is unknown, and their inclusion here as pyroclastics is tentative.

(1977) was unable to zone the Early Triassic upper part of the Beaufort Group because it yielded few palynomorphs—is compensated for by the diversity and abundance of tetrapods, which are grouped into five zones (Fig. 13A). The Beaufort Group is exposed over the entire Karoo Basin except in Lesotho where it is covered by the Stormberg Group, and this large outcrop has provided the wealth of paleocurrent vectors shown in Figure 13A. It extended also northwest at least as far as the Finsch mine, 140 km west-northwest of Kimberley, as indicated by xenoliths in a kimberlite pipe (Visser, 1972). The Beaufort Group is subdivided into two parts: the Adelaide Subgroup of greenish gray and grayish-red mudstone and sandstone overlain by the Tarkastad Subgroup with more sandstone and red mudstone (Kent, 1980, p. 538).

Adelaide Subgroup. In the southwest (Fig. 8B, part VI), the Waterford delta is succeeded by the fluvial channel and flood basin deposits of the Abrahamskraal and Teekloof Formations. The channels, which contain uranium (Ryan and Whitfield, 1979), range from low- to high-sinuosity, and the fluvial energy decreases upward due to denudation of the source area (Turner, 1985). In the southeast (Fig. 8A, parts V and VII), the Fort Brown delta is continued upward by the Koonap Formation and then succeeded by the fluvial Middleton Formation and Balfour Formation, which is punctuated by the coarse influx of braided channels at the base. In the northeast (Fig. 8A, part III), the lacustrine Volksrust Shale is succeeded by the Estcourt Formation of deltaic sediment, including thin coal measures (unique in the Beaufort), capped by fluvial-lacustrine sediment (Tankard et al., 1982, p. 393–394).

Tarkastad Subgroup. The Tarkastad Subgroup corresponds to the Early Triassic *Lystrosaurus* and *Cynognathus* tetrapod zones. A strong pulse of fluvial braided channel sandstone is represented by the 500–1,000-m-thick proximal Katberg Formation in the southeast (Fig. 8C, part IX) (Hiller and Stavrakis, 1980, 1984) and 100-m-thick distal Belmont Formation in the northeast (Figs. 7, 8C, part VIII), overlain by the fluvial meandering-channel Burgersdorp Formation and flood basin–lacustrine Otterburn Formation, the tops of which are exposed at the low-angle unconformity at the base of the Late Triassic Molteno Formation. The pulse is concomitant with folding and thrusting along the front of the Cape Fold Belt, involving older Beaufort strata, and dated by Hälbich et al. (1983) as 247 ± 3 Ma (latest Permian) (Fig. 7).

Paleocurrent analysis. The paleocurrent vectors were measured from the exposed parts of the Beaufort Group that range through five tetrapod zones (Fig. 13A). The vectors have been grouped into three domains of uniform trend: (1) a large N to NNW domain covering the entire outcrop except the extreme west and north, centered on the *Cynognathus* zone and sampled from all five zones, with an enclave (a) with SW trend on the northwest; (2) a small NE domain in the west, sampled from the *Tapinocephalus* and *Cistecephalus* zones, with a small area (b) of SE-E trend on its northern edge, restricted to the *Tapinocephalus* zone; and (3) a small WNW-W-WSW domain in the far north, from the *Daptocephalus* and *Lystrosaurus* zones, with an enclave (c) of southerly trend in the extreme north (Keyser and Zawada, 1988). The paleocurrent patterns apply to specific units or groups of units within the Beaufort Group. The southeastern domain 1, encompassing the entire Beaufort Group from the Koonap Formation to the Burgersdorp Formation (Fig. 7), has a consistent northerly paleocurrent. The paleoslope arrows radiate from a focus near the proposed southeastern syntaxis of the Cape Fold Belt as do those of domain 2 from the southwestern syntaxis (de Beer, 1990). The syntaxes reflect the intersections of the pre-Cape (1.0–0.5 Ga) basement trends of the east-west Saldanian strike with the southwesterly Natal-Mozambiquean strike on the east, and with the southeasterly strike of the Gariep trend on the west (Fig. 5, inset). During deposition of the Beaufort Group, the Saldanian trend was paralleled by the growing Cape Fold Belt of the Outeniqua folds and the deformation front, which incorporated previously deposited Karoo sediment up to the Adelaide Subgroup. The Natal trend is paralleled by the Cape Meredith–Mapumulo trend, which is identified as a resurgent Eastern Highlands (Fig. 12A). The Mapumulo Group of the Natal Metamorphic Province, about 1 Ga old, is specifically identified as a proximal source of the angular to subrounded clasts (<19 cm across) of garnetiferous gneiss, red granite, milky quartz, and large microclines in the Belmont Formation at Mooi River (circles) (Theron, 1975). To the south-south-east, the Falkland Islands are specifically identified as a proximal source of the Katberg Formation near East London (circles), which contains pebble clasts (<12 cm across) of lignite and silicified wood (from the Devonian or Permian or both) and a distal source of the gneiss pebbles (from the 1 Ga Cape Meredith gneiss). The Gariep trend is paralleled by the Western Branch of the Cape Fold Belt (de Beer, 1990), which is identified as the resurgent Atlantic Mountains (Fig. 12B). The source of paleocurrent domain 2 was probably the Baviaanshoek and Hex River anticlinoria of the southwestern syntaxis, and that of enclave b the more distant northwest (de Beer, 1990).

In the northernmost part of the basin, the west-trending arrows of domain 3 are interpreted as showing sediment funneled through a gap or saddle in the Eastern Highlands along an axial paleoslope parallel to the Mapumulo piedmont and at a high angle to the flank slope of the Cape piedmont. This entry point of sediment from the east echoes the situation that pertained during deposition of the Lower Ecca Group (Fig. 12A). Another echo, of the Lower Ecca drainage axial to the Witwatersrand Arch (Fig. 12B), is the southerly drainage in enclave c. The southwesterly drainage in enclave a spans the *Daptocephalus* zone and probably part of the *Lystrosaurus* zone in the central and southern Orange Free State (Kingsley and Theron, 1964). This drainage system was responsible for the deposition of coarse arkose derived from an intrabasinal upland of Precambrian granite and sedimentary inliers. Coarse arkose of the southwesterly drainage interfingered with fine-grained sandstone of the major N to NNW drainage (Kingsley and Theron, 1964).

Summary of the lower Karoo Sequence. The lower part of the Karoo Sequence—the Dwyka, Ecca, and Beaufort—was deposited continuously during the Permian and Early Triassic. The cross-sectional wedge shape of the lower Karoo (Fig. 13B) has two parts: (1) a steep inclined part, at most 250 km long, from the 10-km isopach at the front of the Cape Fold Belt at about 33°S to the 3-km isopach, and thence (2) a low inclined part, at least 500 km long, from the 3-km to the 1-km isopach. The steep part of the wedge is the foredeep of the foreland basin, seen in section in Fig. 2, south of QU1/65 in AB, and south of WE1/66 in CD.

The upper part of the sequence—the Stormberg Group (Molteno, Elliot, and Clarens Formations) and the Drakensberg Group—is separated from the lower Karoo by a lacuna that occupies the entire Middle Triassic. The disconformity between the lower and upper Karoo is underlain by the Tarkastad Subgroup that ranges from the *Cynognathus* zone over most of the area (Burgersdorp Formation; Welman et al., 1991) to the *Lystrosaurus* zone in the extreme north (Otterburn Formation); it is overlain by successively younger cycles of the Molteno Sandstone so that the Indwe Sandstone Member, the second cycle in the south, oversteps the *Cynognathus* zone to rest on the *Lystrosaurus* zone in the north (Dingle et al., 1983, fig. 20) (Fig. 2, CD; Fig. 7). An epeirogenic uplift brought all southern Africa (including the axis of the Karoo Basin) above base level to produce the Middle Triassic lacuna by erosion down to the *Lystrosaurus* zone. At the end of the Middle Triassic (230 ± 3 Ma), the Cape Fold Belt was deformed for the last time by listric thrusting and folding (Hälbich et al., 1983). At about this time, its piedmont was depressed below base level at about 32°S to resume deposition in the form of the initial formation of the Stormberg Group, the Carnian (230–225 Ma) Molteno Formation.

Stormberg Group. This account of the Stormberg Group is derived mainly from data given by Rust (1975), Dingle et al. (1983), Visser (1984), and Turner (1977, 1983, 1984).

The relaxation of the Middle Triassic plateau uplift by depression of the region north of the terminally deformed Cape Fold Belt along an axis at the Tropic of Capricorn resulted in the deposition of the Stormberg Group in lobes of fluvial (Molteno and Elliot Formations) and eolian-lacustrine (Clarens Formation) sediment (Fig. 7).

Molteno and Elliot Formations. The Molteno Formation, dated as Carnian–early Norian from its megaflora (Anderson and Anderson, 1983), disconformably overlies the Beaufort Group above the Middle Triassic lacuna and is conformably overlain (and in the north overstepped) by the Elliot Formation. The following description is drawn from Turner (1983). Of the six fining-upward cycles of the Molteno Formation (Fig. 8C, part IX), the first prograded some 100 km northward of the southern edge of outcrop; the second, called the Indwe Sandstone Member, prograded at least to the northern edge of outcrop (Fig. 8C, part VIII); the remaining cycles 3–6 receded toward the southern edge (Fig. 7) and are followed by the downslope facies equivalent, the Elliot Formation, which itself finally receded southward beyond the southern edge to replace the entire Molteno Formation. The Molteno and Elliot Formations thin northward individually (Fig. 14B and C) and collectively with the Clarens Formation as the Stormberg Group (Fig. 14A). The marked thinning of the Molteno Formation north of 30°S is due to the wedge-out of the northward extensive Indwe Sandstone Member.

A typical fining-upward sequence of the Molteno Formation comprises, from the base upward:

(1) A mainly matrix-supported conglomerate set in a pebbly very coarse feldspathic sandstone, 5–120 cm thick. Extraformational clasts are sparse (most are found in the Indwe Sandstone member) and are predominantly quartzite, including the 75-cm-long clast of the Witteberg Group at Molteno (Fig. 14A, and *see* Table 5 in a following section); clast size decreases from the southeast to northwest (Fig. 14B) except at the northern edge where the high caliber of clasts is interpreted as due to a funneling of braid channels into a single main channel (Turner, 1984, fig. 5).

(2) Coarse to very coarse multilateral and multistoried sandstone (feldspathic lithic arenite), which forms laterally extensive sheets from 30 to 120 m thick. Trough crossbedding predominates, in cosets up to 1.5 m thick and 6 m long; crossbedding indicates a north-northwest paleoslope except for sequence 1, to the north-northeast.

(3) Finer-grained lenticular sandstone and siltstone, <12 m thick; flat laminated with primary current lineation and minor ripple cross-lamination.

(4) Lenticular and impersistent shale and coal, up to 6 m thick. The shale contains the *Dicroidium* flora (Anderson and Anderson, 1983), specimens of which are most abundant in cycle 2, least in cycles 1 and 6; tree trunks of *Dadoxylon,* some in living position, are fossilized in this and the underlying facies. The coal is lenticular in stringers and seams, thickest in cycle 1, barely developed in cycles 5 and 6; it is up to 4.3 m thick in the Indwe Seam, a composite of equal parts of coal and shale/fireclay (Turner, 1971; Dingle et al., 1983). We interpret tonsteins in the coal measures in the southeast (Heinemann and Buhmann, 1987) as the first sign of proximal Karoo vulcanicity (Table 3).

Turner (1983) interprets the fining-upward sequences as deposits of a braided fluvial system. The basal conglomerate was deposited as a channel lag by a single high-energy short-lived event, probably high seasonal rainfall and the failure of earth- or ice-dammed lakes in the source area. The overlying trough crossbedded sandstone is attributed to dune migration within channels, and the finer-grained sandstone and siltstone deposited from waning bedload and suspension-load currents as a consequence of channel shifting, abandonment, and overbank flooding. The shale was deposited by vertical accretion from overbank floods. "Standing bodies of water on the allu-

TABLE 3. LATE TRIASSIC TO EARLY AND MIDDLE JURASSIC PROXIMAL KAROO VOLCANICITY

Unit	Locality	Material	Reference
34. Lesotho lavas, Karoo dykes	Karoo Basin	Basalt, dolerite	Eales et al., 1984
33. Clarens	Barkly East	Pyroclastics and basalt	Lock et al., 1974
32. Clarens and Elliot	Dordrecht **a** Maclear **b**	Basalt and breccia	Eales et al., 1984, p. 6
31. Clarens and Elliot	Herschel	Laumontite (altered volcanic glass)	Fuller, 1970
30. Elliot	Golden Gate	Glass shards	Bristow and Saggerson, 1983a, p. 1027
29. Elliot	Jamestown	Bentonite	Eales et al., 1984, p. 6
28. Molteno	Maluti	Tonsteins	Heinemann and Buhmann, 1987

vial plain became the locus of plant growth giving rise to thin, *in situ* coals whose development and preservation was encouraged by the abundant though seasonal rainfall, and maintenance of a high water table" (Turner, 1983, p. 82).

Turner (1983) concluded that the Molteno Formation was deposited by perennial high-energy braided streams that drained an extensive alluvial plain on the lower slopes of an alluvial fan complex. In Figure 14A, we show the inferred distribution of the (since eroded) upper alluvial fans and the downslope lower braid fan of the Molteno Formation at its most extensive development in the Indwe Sandstone member. Still further downslope is the meander plain (Elliot Formation) that receded sourceward after the deposition of the Indwe Sandstone member and finally, in the basin axis but transverse to the inferred Eastern Uplands, a fluvial system flowing westward along the present Tropic of Capricorn.

The *Dicroidium* flora and *Dadoxylon* with growth rings suggest a cool temperate climate with marked seasonal rainfall. "The feldspars include both fresh and altered varieties . . . suggesting an uplifted or fault-blocked igneous terrain of high-relief undergoing rapid erosion with mechanical weathering dominant over chemical weathering" (Turner, 1983, p. 83).

The Elliot Formation, formerly the Red Beds Stage, was deposited in the lower tract of the transverse fluvial system. The section that overlies cycle 6 of the Molteno Formation in the south (Fig. 8C, part IX, from Visser and Botha, 1980) is 460 m thick and comprises three parts: (1) a lower interval (0–200 m) of stacked multistoried crossbedded medium-grained sandstone with alternating fine-grained sandstone and mudstone, interpreted as deposited in a meandering channel and flood plain; (2) a middle interval (200–400 m) of alternating very fine-grained sandstone and red mudstone with CO_3 concretions, interpreted as deposits of a flood basin; and (3) an upper interval (400–460 m) of alternating crossbedded fine-grained sandstone and red silty mudstone with CO_3 concretions and conchostracans, deposited in flood fans reworked by the wind in eolian dunes. According to Turner (1972), the lower boundary of the Elliot Formation is denoted by a combination of abundant reptile remains, persistent red mudstone, no carbonaceous shale, and a low sandstone:shale ratio. In the Elliot Formation, the ubiquitous crossbeds in the underlying Molteno Formation give way to sporadic ones, which indicate a north-northwest paleoslope (Fig. 14C).

In the north, the 40-m-thick Elliot Formation oversteps the outlapping Indwe Sandstone member of the Molteno Formation (Fig. 8C, VIII) to rest on the Otterburn Formation of the Beaufort Group (Botha, 1967; Turner, 1983, fig. 2), and comprises alternating floodbasin-lacustrine and anastomosing channel deposits (Eriksson, 1985).

Bentonites and glass shards (Table 3) indicate a second early phase of proximal Karoo vulcanicity.

Clarens Formation. The Clarens Formation (Fig. 8C, X), formerly the Cave Sandstone, passes upward from the Elliot Formation "at the point where red and purple mudstones and crossbedded sandstones become subordinate to lighter and 'massive' sandstones and grey/green shales" (Dingle et al., 1983, p. 48). The Clarens Formation is a sequence, from the base upward, of three units (Beukes, 1970; Eriksson, 1979; Tankard et al., 1982, p. 397–399):

(I) Planar crossbedded braided-channel medium- to coarse-grained sandstone, up to 50 m thick in the Natal Drakensberg, alternating elsewhere with lacustrine siltstone that contains fish, crustaceans, and dinosaurs. According to Eriksson (1979), the unit was deposited in converging wadi systems.

(II) Fine-grained sandstone in crossbeds up to 10 m high deposited by straight-crested transverse eolian dunes and in crossbeds up to 3 m high deposited by barchan dunes. The unit is up to 60 m thick in the north and was deposited from westerly winds that redistributed sand from the Elliot Formation and older formations.

(III) An alternation of (I) (but without the coarse-grained braided-channel sandstone) and (II), and toward the top lenses of basalt and pyroclastics (Table 3).

Summary of Stormberg Group. According to Turner (1986), the Stormberg Group has a modern analogue in the central Australian Lake Eyre basin, an arid aggrading internal drainage basin flanked by eolian dunes, in which braided and anastomosing channel sand (Rust, 1981) gives way downslope to the lacustrine mud of Lake Eyre (Veevers and Rundle, 1979).

> However, Lake Eyre was warm and wet during deposition of the relict braided sand sheets and tectonism had little influence whereas cool wet tectonically active conditions prevailed during deposition of the equivalent coarse braided channel subfacies in the Karoo sequence. Furthermore, the Lake Eyre channels are essentially braided and ephemeral whereas in the Karoo sequence braided bedload channels passed downslope into low-sinuosity mixed-load channels, both of which were probably perennial. These in turn passed distally into ephemeral low-sinuosity channels and lacustrine flood flats (Turner, 1986, p. 251–252).

Another model is the Okavango Delta of northwest Botswana (Fig. 14A), which "has an important bearing on patterns of fluvial sedimentation in arid regions since it shows many characteristics of temperate, well-vegetated anastomosed fluvial systems despite its location in the Kalahari Desert" (Turner, 1986, p. 231).

The Stormberg Group is now limited to the Lesotho mesa and the nearby Mngazana area at the recess between the Cape Fold Belt and Eastern Uplands but probably extended wider in the Karoo Basin, as suggested by the possible occurrence in the Cretaceous (94–86 Ma) (Dawson,1989, p. 331) Kimberley pipe of all units (Ecca through Drakensberg) above the outcropping Dwyka (Fig. 14A) (Truswell, 1977, p. 172). Within its preserved limits, the entire Stormberg Group thins northwestward and northward from a maximum known thickness of 1,100 m in the southern part of the recess to 200 m in the north (Fig. 14A). The Stormberg Group started to accumulate during the subsidence in the Karoo Basin that accompanied the fourth diastrophic event in the Cape Fold Belt (final deformation and listric thrusting and folding) (Fig. 7). Turner (1983, fig. 6) interpreted the three pulses of upward-fining deposition in the Molteno and Elliot Formations complex as follows: cycle 1 follows initial uplift/denudation and scarp retreat; cycle 2 (Indwe Sandstone) of maximum progradation follows maximum uplift/denudation and scarp retreat; and cycles 3–6 follow lowering of the basin margin by back-faulting so that the equivalent Elliot Formation retrogrades southward over the Molteno Formation. A regressive metamorphic age of 215 ± 3 Ma in metabasic rocks of the basement Kango Group (K in Fig. 14A) is interpreted by Hälbich et al. (1983, table 13.3) as registering uplift and horizontal tension in the Cape Fold Belt, and it correlates with the final phase of braidplain deposition at the base of the Clarens Formation (Fig. 7). Basin subsidence in the north, in front of the Northern Uplands, including the upfaulted Choma-Kalomo Ridge and downfaulted mid-Zambezi valley, produced a similar set of contemporaneous strata on the northern flank of the wide basin, which had a west-sloping axis along the present Tropic. The chief factor in the accumulation of the Stormberg Group and its equivalents in southern Africa was differential subsidence of the Middle Triassic plateau. Thrusting was important in elevating the source area of the Cape Fold Belt and depressing the coupled foredeep of the Karoo Basin, although the amount of subsidence, measured in hundreds of meters, was much less than the kilometers during the Beaufort deposition. Subsidence over a wider area to the north locally produced a sediment thickness of 2,500 m and was unrelated to this mechanism. In the tectonic synthesis, we suggest that wider subsidence was due to the release of Pangean heat during the Carnian (Veevers, 1989), coincident with the first appearance of proximal Karoo vulcanicity in the Molteno Formation (Table 3).

Drakensberg Group and Lebombo Group. The Lesotho mesa is capped by 1,400 m of Jurassic basaltic flood lavas called the Drakensberg Group that were fed by a complex of dykes and sills called the Karoo dolerite (Eales et al., 1984, p. 9) in the culmination of proximal Karoo vulcanicity. The Karoo dolerite extends over all but the southern edge of the Karoo basin, as delimited by the dolerite line on Fig. 1, implying an original extension of the Drakensberg Volcanics in the Karoo Basin out to the present edge of outcrop and beyond, as shown by abundant basalt xenoliths within younger diatremes at Postmasburg, 150 km WNW of Kimberley (Eales et al., 1984, p. 3) before the plateau surface was worn back during the later Mesozoic and Cenozoic to the present remnant of Lesotho. Sedimentary basins north of the Karoo Basin are capped by lavas or intruded by dolerite of the same Jurassic age; Namibia additionally has lavas of Early Cretaceous age (Figs. 6 and 14A); to the east, the Transantarctic Mountains (*see* Chapter 4) and Tasmania (Hergt et al., 1989, p. 377) contain a similar volcanic sequence of Ferrar-Tasmanian dolerite feeding the surface lavas of the Kirkpatrick Basalt–Ida Bay basalt; to the west, the Amazon Basin contains equally voluminous (340,000 km^3) Late Triassic and Jurassic dolerite (Mosmann et al., 1986); the Paraná (Serra Geral) basalt is Early Cretaceous, all comprising a low-Ti province (Cox, 1988). The flood basalts reflect an enormous drain on the Pangean heat store, between the earlier phases of sagging and rifting and the final phase of seafloor spreading (Veevers, 1989).

Sources of information on the Drakensberg Group drawn on here are Dingle et al. (1983), Bristow and Saggerson (1983a, 1983b), Visser (1984), Eales et al. (1984), and Fitch and Miller (1984).

The Drakensberg Group comprises lava flows interlayered in the basal third with pyroclastics and thin lacustrine sediment (Fig. 8C, part X). At the base, about 200 individual shield volcanoes and explosive vents are known from all but the northeastern part of the Lesotho mesa (Dingle et al., 1983, p. 56). At a well-mapped example in the Moshesh's Ford area near Barkly East, 200 m of basaltic vent fill and extra-vent effusive and ejected material overlie a surface with 100 m relief in the Clarens Formation (Lock et al., 1974). Interlayered with the volcanics are lenses of lacustrine sandstone, most no more than 10 m thick except an exceptional one 130 m thick and 25 km long (Eales et al., 1984, p. 6, 8). Other evidence for aqueous environments comes from the presence of pillow lava. Above the basal section is the Lesotho Formation, a monotonous succession of amygdaloidal basalt lava flows, nearly all of which are of the pahoehoe type. Thicknesses of individual flows range from 0.5 to 50 m (Eales et al., 1984, p. 8), and the aggregate thickness to the exposed top is 1,400 m. The basalt is tholeiitic. Rare silicic lavas in the andesite-dacite range are encountered in the lower part of the Drakensberg Group. "Thus in the north-east Cape, a feature of the overall development of the Karoo igneous events is that the earliest eruptions were characterized by diversity in style and composition of the erupted products. This later evolved into widespread and regular effusion of compositionally monotonous lavas which built the bulk of the volcanic pile" (Eales et al., 1984, p. 8).

The subvolcanic complex of dolerite dykes, sills, "bell-jar intrusions" and irregular bodies that intruded the Karoo sediments represents the feeder channels for the overlying lavas, as shown unequivocally by major and trace element compositional data (Eales et al., 1984, table 1). Within the limits of the dolerite line that skirts basement and the southern edge of the Karoo Basin (Fig. 1), the greatest concentration of dolerite (dolerite:sediment ratio of >0.5) lies in an elliptical zone that trends northeast across northern Lesotho; the dolerite sheets "seem to terminate at a critical distance of a few thousand feet below the basalts" (Winter and Venter, 1970). Dingle et al. (1983, p. 64) explain this observation and the stratigraphic distribution of sills in the Beaufort and Molteno, dolerite plugs in the Molteno, tuff in the Elliot, agglomerate and lava in the Clarens, and pyroclastics and lava at the base of the Drakensberg Group and lava above by the following sequence of events: (1) earliest upward movement of magma in the Late Triassic to produce explosive activity; we believe the Molteno tonsteins (28 in Table 3) are the first sign of proximal Karoo vulcanicity; (2) during Late Triassic–Early Jurassic Elliot and Clarens deposition, an increased scale of upward movement of magma in sills 1 to 2 km beneath the surface, degassing of the magma, and contact with ground water produced explosive action and created diatremes (29–33); (3) main eruption of flood basalt by dyke injection in the Early Jurassic (193 ± 5 Ma), followed by a second major injection in the Middle Jurassic (178 ± 5 Ma), as dated by Fitch and Miller (1984).

In the southern part of the basin (Fig. 13B), the CIS/TAP boundary coincides with the dolerite line, indicating that the dolerite sills intrude only the section above the base of the CIS zone. Given that the sills dilated only at a critically lower pressure related to the thickness of the overburden in the Early Jurassic, we infer that sediment at least above the *Tapinocephalus* zone (upper half of Beaufort, Stormberg, and perhaps some of the Drakensberg Group) had accumulated a thickness in the west equal to that in the east and use this as the basis for extending the isopachs westward from the values estimated from the better preserved section south of Lesotho. The coincidence of the dolerite line and the Great Escarpment west of Beaufort West (BW) suggests that backwearing of the plateau in this region has been impeded at the southern limit of the durable dolerite.

Karoo magmatic events extended northward to 15°S. Fitch and Miller (1984, p. 263–264) found the following sequence of events in the Jurassic and Early Cretaceous (Fig. 6): (1) 204 ± 5 Ma: intrusion of isolated alkaline complexes west of the Lebombo line and in Zimbabwe; (2) 193 ± 5 Ma: very rapidly emplaced Lesotho eruptive centers covered by flood basalt that extended along the Lebombo to 25°S, dyke swarms and major intrusions of dolerite in Namibia and Karoo Basin; (3) 186 ± 3 Ma: minor alkaline complex intruded east of Tuli; (4) 178 ± 5 Ma: very rapidly emplaced dolerite intrusions in Namibia and Karoo Basin and bimodal lavas in Lebombo north of 25°S, also Marienthal lavas in Namibia; (5) 165 ± 5 Ma: dolerite dykes and sills in Karoo Basin and Namibia; (6) 150 ± 5 Ma: dykes in Karoo Basin and Namibia, and an intrusive complex in Namibia; (7) 137 ± 5 Ma (Early Cretaceous): a dolerite sill in Lesotho and a syenite complex in Lebombo, and a major group of dolerite intrusions in Namibia.

POST-GONDWANAN HISTORY

Classified as post-Karoo are the 120 ± 5 Ma (Early Cretaceous) Etendeka lavas of the Kaokofeld, the 145–115 Ma (Early Cretaceous) micaceous kimberlites, and the 95–80 Ma (Late Cretaceous) "normal" kimberlites (Dawson, 1989; Allsopp et al., 1989). Deposition of sediment after the Stormberg switched to the continental margins that formed by seafloor spreading (the fourth stage of Pangean heat release) that started about 160 Ma (Middle Jurassic) in the western Indian Ocean and about 130 Ma (Early Cretaceous) in the South Atlantic Ocean with related right-lateral transform motion along the Agulhas Fracture Zone. Dingle et al. (1983) summarize these developments thus:

> By mid-Jurassic times, large complex depocentres had begun to develop along what were later to become the continental margins of southern Africa, and today, mid-Jurassic-Cretaceous sediments are known only from the coastal fringes and under the continental shelf and slope. This radical shift in depocentres from a previous mid-continental location, was accomplished by horst and graben development (taphrogenic tectonics) around the edges of the old cratonic blocks, and ultimately led to the breakup of this part of Gondwanaland [p. 99]. . . . With the exception of the central Kalahari Basin (non-marine), and the wide Zululand-Mozambique coastal plain, all the extensive deposits of Tertiary strata occur on the continental shelf and slope, where cover is complete apart from nearshore areas in the south and west Cape. . . . The west coast Tertiary forms a vast, coast parallel lens along the whole margin from the Walvis Ridge to the Agulhas Fracture Zone. . . . This reflects the cessation of differential crustal subsidence, and the progressively subordinate role played by terrigenous sedimentation since Late Cretaceous times, with the concomitant increase in the importance of biogenic and authigenic sediment production. . . . Tertiary sediment distribution along the east coast was, by contrast, still dominated by major terrigenous input points: Zambezi, Limpopo, and Tugela Rivers [p. 234].

In a review of the work of F. Dixey and L. C. King on the development of the southern African landscape, Partridge and Maud (1987, p. 179) conclude that

> The Great Escarpment [Fig. 13B] was formed following continental rifting, and its survival up to the present as a major topographic feature is, in large measure, a function of the high elevations consequent upon the central position of southern Africa in Gondwanaland prior to this event. . . . The onshore evidence of erosion surfaces is correlated with recent data on offshore sedimentation, and reveals that a single cycle of erosion (interrupted by minor tectonic interludes) prevailed from the time of rifting to the early Miocene. By the end of this period a gentle pediplain (the African surface) extended across most of southern Africa at elevations of 500–600 m. Most erosion and scarp recession occurred during the earlier part of this interval and produced thick late Jurassic and Cretaceous sedimentary sequences, but shelf sedimentation declined during the Tertiary and had virtually ceased by the Oligocene, when interior planation had advanced to a stage where sediment supply to most rivers was minimal. Modest renewed uplift of 150–300 m in the Miocene tilted the continent slightly to the west and initiated a new (Post-African I) landscape cycle. This was accompanied by renewed offshore sedimentation, although at lower rates than during the Cretaceous. The cycle was terminated near the end of the Pliocene, and its relatively short duration resulted in imperfect planation in most areas to levels of no more than 100–300 m below the African surface. A second uplift of major proportions at the end of the Pliocene raised the eastern interior of the sub-continent by as much as 900 m, although much smaller movements characterized the western areas and interior axes of uplift. Major monoclinal warping resulted in the southeastern hinterland. The ensuing Post-African II cycle is manifested chiefly in deep incision of the coastal hinterland and downcutting along major rivers of the interior. Earlier surfaces were severely deformed and dissected, especially in the south-east of the country. Planation was limited to a few areas close to the coast. The resulting sedimentation is evident mainly in the offshore deltas of major rivers owing to the late development of vigorous coastal currents, but a major increase is reflected throughout the deeper ocean basins.

In summary, most of the Karoo Basin was unroofed by scarp retreat in the Late Jurassic and Cretaceous. Renewed uplift in the Miocene (150–300 m) and end-Pliocene (900 m) led to unroofing of the rest of the basin except in the present outlier in Lesotho.

PROVENANCE OF KAROO BASIN SEDIMENTS

Introduction

In the Karoo Basin, paleocurrents inferred from the almost wholly nonmarine or fluvial Karoo sequence indicate the paleoslope of the depositional surface on the flank of a source upland or in the axis between two uplands. The petrology of the coarse fraction of the sediment reflects the petrology of the source area. By these means, authors have distinguished source areas at each of the cardinal points of the compass: (1) the northern cratonic interior of Gondwanaland; (2) an eastern source, now occupied by the continental margin or beyond, possibly a Late Proterozoic fold belt; (3) a southern source, comprising the proximal Cape Fold Belt and an inferred distal convergent Panthalassan magmatic arc; and (4) a western source, now occupied by the continental margin or beyond, possibly a Late Proterozoic foldbelt, as in the east. In studying the foreland basin, our interest centers on the southern distal magmatic source. Estimates of the type of provenance in the south, e.g., magmatic arc, recycled orogen, or continental block (Dickinson and Suczek, 1979), and their age, whether coeval with or older than the sediments, can be made from the petrography of detrital arenites and rudites. Previously published work is supplemented by Cowan's petrographic study of the rock specimens collected by Veevers in 1984 from localities along the southern outcrop of the Karoo Basin (Appendix 1).

To the work mentioned above was added, at the last moment, Johnson's (1991) comprehensive account of sandstone petrography of the southeastern part of the Karoo Basin and preceding Cape Basin, summarized in Figures 15B and 15C. Johnson (1991) reports new finds of abundant volcanic rock fragments in the Ecca Group (Ripon and Waterford Formations) and Beaufort Group (Koonap, Middleton, and Balfour Formations of the Adelaide Subgroup, and the Katberg and Burgersdorp Formations of the Tarkastad Subgroup) (Table 2). Johnson (1991, p. 137) found that "the Ecca Group and Adelaide Subgroup [were derived] from a magmatic arc provenance, and the upper part of the Karoo Sequence [Tarkastad Subgroup, Molteno, Elliot, and Clarens Formations] from a recycled orogenic source (Cape Fold Belt)." He found (p.140) more rock fragments and feldspar than previous workers (Fig. 16 in a following section) for these reasons: (1) "The amount of matrix present in greywackes in particular has often been greatly overestimated in the past, and a great deal of what is called matrix is, in fact, made up of rock fragment grains and minerals larger than 20 microns"; and (2) "By classifying all clear, untwinned grains of the right birefringence as quartz, workers have in the past often ended up grossly underestimating the feldspar content of Karoo sandstones in particular." The age of the magmatic arc source rocks remains uncertain because Johnson (1991) assumed implicitly that the volcanolithic grains are penecontemporaneous with deposition and not derived epiclastically from ancient volcanics. We try to overcome this uncertainty by identifying the unequivocally syndepositional tuffs.

Active volcanic (pyroclastic) provenances

Southern distal Panthalassan margin provenance: Tastubian to Scythian distal vulcanicity (Table 2, Fig. 1). The Karoo Basin, particularly the southern part, contains a minor amount of recognizable juvenile volcanogenic material, mainly in the form of devitrified shards, in the Dwyka Formation (1a and 1b of Table 2), Pietermaritzburg Shale (3), Prince Albert Formation (4–8), Whitehill Formation (9–12), Collingham Formation (13, 17–19), Vischkuil Formation (1), Laingsburg

Formation (2), Fort Brown Formation (20, 21), Tierberg Formation (14), Volksrust Formation (15, 16), Adelaide Subgroup (Lower Beaufort or Abrahamskraal and Teekloof Formations, 23–26), and at the top of the Beaufort Group in the Burgersdorp Formation (27), all located in Fig. 1 and some illustrated in Fig. 20 (Appendix 1). In addition to the almost ubiquitous shards, the material includes sand-sized fragments of tuff crystals (plagioclase and pyroxene) and drop-like bodies, felsite, volcanic quartz, and alkali trachyte, and associated clay minerals regarded as metabentonite, all interpreted as silicic volcanic ash or tuff. In the Ecca and Lower Beaufort of the western part of the southern Karoo Basin, laumontite is the predominant calc-silicate mineral (Martini, 1974; Turner, 1978), and here as well as in the Burgersdorp, Elliot, and Clarens Formations to the east (Fuller, 1970), it is interpreted as derived by load metamorphism of volcanic glass or, as in Antarctica (J. W. Collinson, personal communication, 1988), enhanced by the dolerite acting on volcanogenic precursors. In turn, "the volcanic fragments in the host sandstones and interbedded tuffaceous material [in the uraniferous Lower Beaufort of the southern and central Karoo] suggest a volcanic source for the uranium" (Turner, 1978, p. 844), amended by Cole and Wipplinger (1991) to "some of the uranium." In the Lower Beaufort, the sand-sized fragments make up appreciable to minor amounts of the column and of these "rounded and drop-like bodies (average SiO_2 content 52%) of tuffaceous material . . . ejected from exploding volcanoes whilst still in a plastic or semi-liquid state" may constitute up to 80% of the sand-sized volcanogenic fraction in some of the rocks (Ho-Tun, 1979). A more silicic source magma is indicated by the 1–15% of the detrital quartz fraction being volcanic quartz, including the beta form. Also silicic is the possibly dacitic crystal tuff, 0.5 m thick, in the Fort Brown Formation at Geelhoutboom (Lock and Johnson, 1974), with cm-thick bands of plagioclase crystals (>90%) and quartz (<10%), emplaced ultimately by subaqueous flow as suggested by the mixing of the pyroclastics with the underlying mudstone. Another silicic rock is the felsite groundmass with shard "phenocrysts" in the Fort Brown Formation near Wolwefontein. Within the 50 m-thick "volcanic interval" of Lock and Wilson (1975) in and about the Collingham Formation, some 30–40% consists of yellow mudstone which Lock and Wilson (1975) interpret as a metabentonite containing 30–40% quartz. In Appendix 1 Cowan (*see* Fig. 20E in Appendix 1) interprets the scattered angular plagioclase and quartz grains in a microcrystalline quartz groundmass or matrix of the Matjiesfontein Chert at Remhoogte (SA 14C in Table 7) as a tuff. Also at Remhoogte, at the base of the Collingham Formation, Elliot and Watts (1974) found clasts of quartz and feldspar that may be volcanogenic. Elsewhere in the Ecca and lower Beaufort Groups, the detrital plagioclase is interpreted as derived from low-grade metamorphic rocks (Kingsley, 1981, p. 37).

Viljoen (1987) suggested that the widespread occurrence of albite, quartz, illite, and montmorillonite in the tuffs of the Ecca Group could be the result of the following diagenetic and low-grade metamorphic reactions (Iijima, 1978):

silicic glass + H_2O $\rightarrow$ montmorillonite + opal $\rightarrow$
alkali zeolites + opal-CT + montmorillonite + K^+ $\rightarrow$
analcime + quartz + illite/montmorillonite + K^+ $\rightarrow$
albite + illite + quartz.

The tuffs (K- or meta-bentonites), some of which are multiple fallout units (Viljoen, 1987), occur throughout the Ecca Group and upper Dwyka Formation. When plotted on a Zr/TiO_2 versus Nb/Y diagram, the tuffs are seen to have a rhyolitic to dacitic composition (Viljoen, 1987). Furthermore, chert beds from the Collingham and Abrahamskraal Formations also fall within the rhyolite to dacite fields (Fig. 15A). Using the same technique, McLachlan and Jonker (1990) found that Ecca Group tuffs from the Hopetown and Boshof areas had a wider compositional range from rhyolite to andesite. In the Lower Beaufort of the northern Karoo, two isolated deposits interpreted to be ash-fall tuffs plot within the rhyodacite field but because the tuffs have undergone hydrothermal alteration, Keyser and Zawada (1988) suggest that the original magma was trachyandesite based on the chemical analysis of a less altered volcanic bomb embedded in the tuff.

From all this evidence, it is apparent that the bulk of the volcanogenic material is rhyodacitic, and that it was emplaced by air fall from contemporaneous explosive vulcanicity, lightly modified by subaqueous flow. Redistribution by water was probably least in the Ecca Group, where the volcanogenic silt and sand is concentrated in bands within lacustrine mudstone deposited from suspension on an anaerobic lake floor (McLachlan and Anderson, 1977), analogous to the concentration of tuff bands in coal seams and lacustrine sediments in the Late Permian Newcastle Coal Measures of eastern Australia (McDonnell 1983; Jones et al., 1987). All occurrences are inferred to come from a southern source except the coarse-grained tuffs in the lower Beaufort Group of the northern Karoo Basin (24 and 25 in Table 2, Fig. 13A), for which Keyser and Zawada (1988) suggest a minor local source in the north. Redistribution is greatest in the coarse fluvial sediments of the Lower Beaufort Group. Ho-Tun's (1979) observation that volcanic quartz grains constitute up to 15% of the detrital quartz fraction in part of the Beaufort Group suggests to us that, taking into account the expected much greater dilution of originally pyroclastic material in a fluvial section, the source of the pyroclastics compared to that of the Ecca Group was either more proximal or more copious or both. According to Martini (1974, p. 115), "The generally small size of the volcanic clasts [of the ash beds] is in agreement with a source several hundreds of kilometres away." As to the direction, Martini (1974) pointed to a source south of the southern Karoo Basin and beyond the southern Cape Province and Agulhas Bank, narrowed to the Paleo-Pacific (Panthalassan) margin from Patagonia to West Antarctica, which contains evidence of Permian magmatic activity. Elliot and Watts (1974) independently pointed to the more general Gondwanide Orogen, and Coutinho et al. (1991) suggest a common rhyolitic volcanic source located in central Argentina for the Late Permian ash beds in both the Paraná and Karoo Basins. Johnson (1991, fig. 8) shows the Permian-Triassic magmatic arc some 400 km south of southern Africa.

Viljoen (1987, 1990) and Verwoerd et al. (1990) found that the total thickness of the tuff and the number of tuff beds in the Collingham Formation decreases gradually toward the northeast. This zone of tuffs is still recognizable in stratigraphically equivalent horizons in the northern Karoo Basin at the base of the Volksrust Formation in boreholes BE1/66 (15 in Table 2) and SW1/67 (16) (Viljoen, 1990) and at the base of the Tierberg Formation near Hopetown (14) (McLachlan and Jonker, 1990). The distribution of the tuffs suggests volcanic eruption centers to the south and southwest along the Panthalassan convergent margin (Viljoen, 1990; Verwoerd et al., 1990).

Bristow and Saggerson (1983a, p. 1028) note "the possibility that much of the volcanoclastic material found in the Karoo sediment was derived locally [e.g., from volcanic maars, small vents, and diatremes that weather extremely rapidly], and that the structures from which the material originated were subsequently reworked by erosion." A similar view is expressed by McLachlan and Jonker (1990), who inferred that "volcanoes of Permian age were present within a few hundred kilometres of the tuffs recorded in the northwestern part of the Karoo Basin." A local source is clear for the volcanic material found in the Late Triassic Stormberg Group and in the Beaufort Group of the northern Karoo Basin (24 and 25 in Table 2). But the uniformly fine grain and wide distribution of all the other volcanogenic material, with the possible exception of the crystal tuff in the Whitehill Formation near Hopetown (11), suggest to us that the vents were distant.

The proximal source, particularly that of the lower Beaufort ash-flow tuffs and the Whitehill Formation crystal tuff in the northern Karoo Basin, has a more basic composition than that of the tuffs found in the Dwyka Formation, Ecca Group, and in the lower Beaufort elsewhere. No Permian volcanic vents are known from southern Africa; the only direct evidence of *in situ* contemporaneous igneous activity is a dolerite dated at 260 ± 16 Ma that intrudes the Table Mountain Group in borehole OL1/69 (Fig. 1) (Rowsell and de Swardt, 1976, p. 121).

We conclude that the provenance of the bulk of the Tastubian to Scythian pyroclastic component of the Karoo Basin was located an unknown distance, probably at least several hundred kilometers, south and southwest of southern Africa, presumably on the adjacent sector of the magmatic arc along the convergent margin of Panthalassa/Gondwanaland. The composition of the source was rhyodacite. A minor proximal provenance (of the lapilli trachyandesite tuff of 25) was a volcanic center at or near the northern edge of the Karoo Basin.

Late Triassic to Early and Middle Jurassic proximal Karoo vulcanicity (Table 3, Figs. 1, 6). Bristow and Saggerson (1983a), Visser (1984), and Eales et al. (1984) reviewed the Karoo vulcanicity that extended over a large part of southern Africa. The first occurrence of tuff, in the Molteno Formation (28 of Table 3), was followed by glass shards in the Elliot Formation, and basalt and pyroclastics in the Clarens Formation. Laumontite in both probably originated as volcanic glass (Table 3). The localized coal-tonsteins of the Molteno Formation are thought to represent volcanic ash beds that were rhyolitic in composition (Heinemann and Buhmann, 1987). By about 193 Ma sediment deposition ended with the outpouring of the 1,500-m-thick Drakensberg basaltic lavas and the intrusion of Karoo dolerite that continued intermittently in southern Africa to the Early Cretaceous. For the purpose of this account, it suffices to note that the Mesozoic Karoo vulcanicity, although some of its products such as shards and laumontite were the same as those of the Permian vulcanicity, was proximal and mafic (and in places bimodal: mafic/silicic) whereas the Permian vulcanicity discussed above was mostly distal and silicic with a minor proximal and trachyandesitic contribution.

Provenances indicated by the petrography of the epiclastics

Recycled orogen provenance. A second type of provenance, that of a recycled orogen (Dickinson and Suczek, 1979),

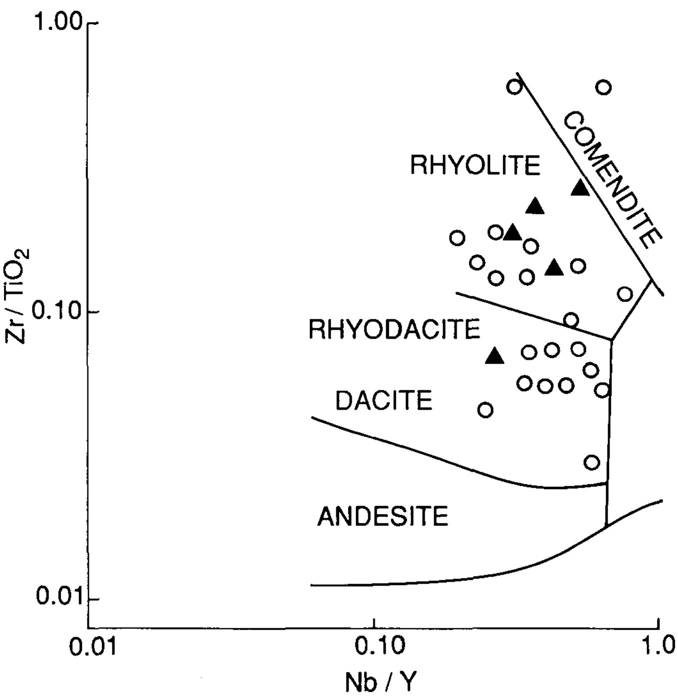
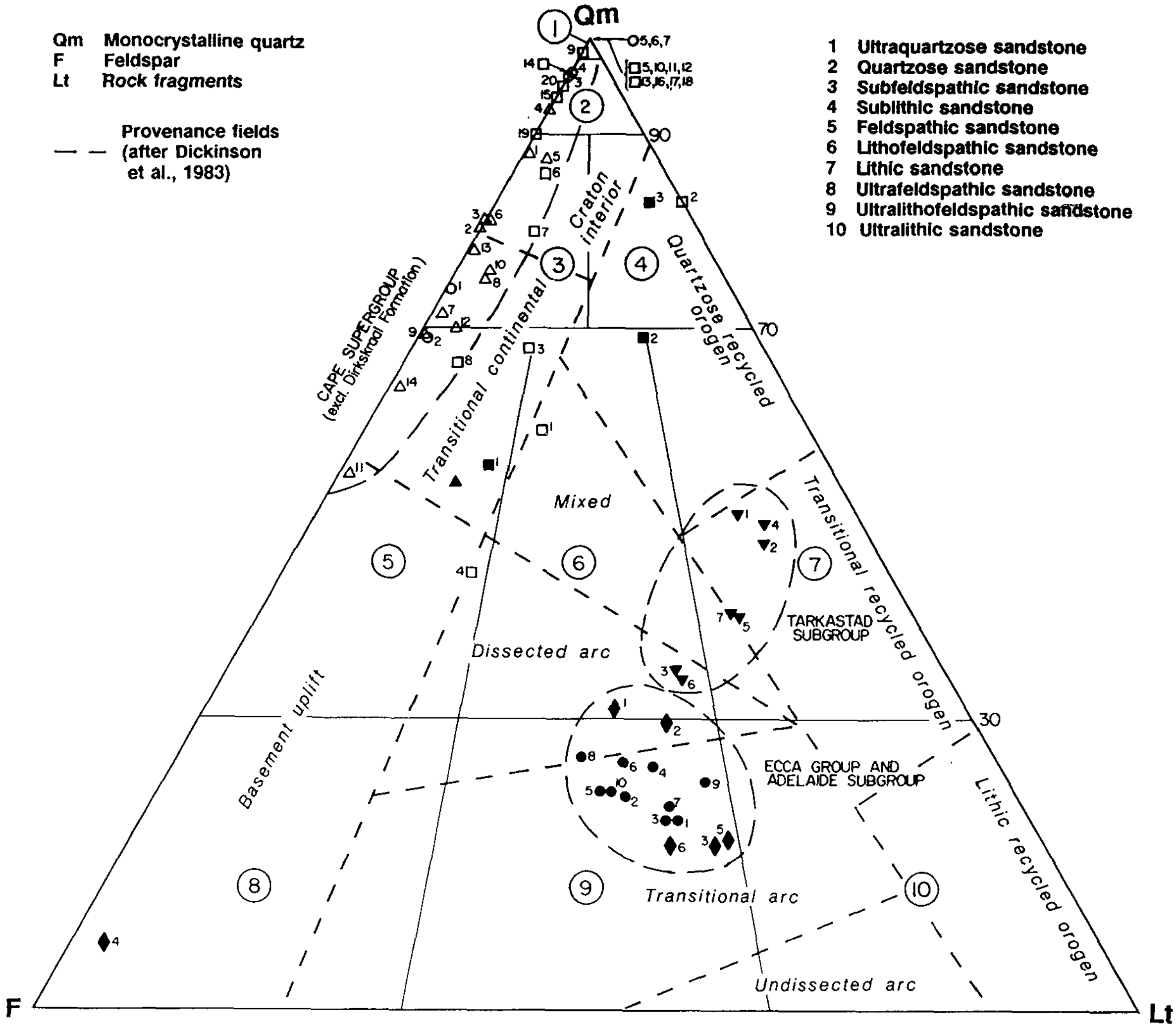


Figure 15A. Zr/TiO_2 versus Nb/Y diagram (format from Winchester and Floyd, 1977) for the tuff (circles) and chert (triangles) in the Early Permian strata of the main Karoo Basin (personal communication from J.H.A. Viljoen, in preparation).



Group	Subgroup	Symbol	Stratigraphic unit[1]	Locality	n
		■ 1	Clarens	C1	3
		■ 2	Elliot	El1	3
		■ 3	Molteno		8
BEAUFORT GROUP	TARKASTAD SUBGROUP	▼ 1	Burgersdorp	Bf 15	5
		▼ 2	Burgersdorp	Bf 21	5
		▼ 3	Katberg (base)	Bf 2	4
		▼ 4	Katberg (top)	Bf 19	3
		▼ 5	Katberg (middle)	Bf 19	8
		▼ 6	Katberg (base)	Bf 19	3
		▼ 7	Katberg (combined)	Bf 19	14
	ADELAIDE SUBGROUP	● 1	Balfour (top)	Bf 3	4
		● 2	Balfour (top)	Bf 9	3
		● 3	Balfour	Bf 12,13,14	9
		● 4	Balfour	Bf 16,17,20	7
		● 5	Middleton (top)	Bf 18	3
		● 6	Middleton	Bf 11	6
		● 7	Middleton	Bf 7,8	4
		● 8	Middleton/Koonap	Bf 4	8
		● 9	Koonap	Bf 5,6	3
		● 10	Koonap	Bf 10	5
ECCA GROUP		♦ 1	Waterford (top)	E 1,3	3
		♦ 2	Waterford (excl. top)	E 1	4
		♦ 3	Waterford	E 3	4
		♦ 4	Ford Brown (tuff)	E 4	1
		♦ 5	Ripon	E 2	7
		♦ 6	Ripon	E 5	10
		▲	Dwyka	E 5	3

Group	Symbol	Stratigraphic unit[1]	Locality	n
WITTEBERG GROUP	□ 1	Dirkskraal	W 1,5	3
	□ 2	Dirkskraal (?)	W 5(?)	1
	□ 3	Dirkskraal	W 7,10	2
	□ 4	Dirkskraal	W 8	3
	□ 5	Swartwaterspoort	W 3,4,9	4
	□ 6	Miller	W 1,4,5	3
	□ 7	Miller	W 8	3
	□ 8	Waaipoort	W 5	2
	□ 9	Floriskraal	W 5	6
	□ 10	Floriskraal	W 9	3
	□ 11	Skitterykloof[2]	W 5	2
	□ 12	Perdepoort[2]	W 5	5
	□ 13	Rooirand[2] (upper)	W 5	7
	□ 14	Rooirand[2] (lower)	W 5	4
	□ 15	Rooirand[2] (base)	W 5	3
	□ 16	Rooirand[2]	W 11,12	10
	□ 17	Weltevrede	W 5	17
	□ 18	Weltevrede	W 6	4
	□ 19	Driekuilen[3]	W 2	2
	□ 20	Driekuilen[3]	W 6	5

Group	Symbol	Stratigraphic unit[1]	Locality	n
BOKKEVELD GROUP	△ 1	Sandpoort	B 5	1
	△ 2	Adolphspoort	B 4	1
	△ 3	Karies	B 5	1
	△ 4	Boplaas (upper)	B 1,2	6
	△ 5	Boplaas (lower)	B 1	2
	△ 6	Boplaas	B 5	4
	△ 7	Hex River	B 2	2
	△ 8	Hex River	B 4	2
	△ 9	Gamka ("arenite facies")	B 2	5
	△ 10	Gamka ("wacke facies")	B 2	4
	△ 11	Gamka ("arenite facies")	B 3	2
	△ 12	Gamka ("wacke facies")	B 3	4
	△ 13	Gamka ("wacke facies")	B 4	3
	△ 14	Gamka	B 6	6
TABLE MOUNTAIN GROUP	○ 1	Kareedouw[4]	T 2,5	5
	○ 2	Baviaanskloof[5]	T 5	3
	○ 3	Skurweberg	T 5	3
	○ 4	Goudini	T 4	2
	○ 5	Peninsula	T 1	5
	○ 6	Peninsula	T 3	12
	○ 7	Peninsula	T 6	5

1 All units are formations except where otherwise indicated
2 Members of Witpoort Formation
3 Member of Weltevrede Formation
4 Member of Baviaanskloof Formation
5 Excluding Kareedouw Member

Figure 15B. Framework mineralogy, provenance fields (after Dickinson et al., 1983) and sandstone classification (after Johnson, 1976) of the southeastern Cape-Karoo Basin, all from Johnson (1991) and reproduced with the permission of the author and the editor of the *South African Journal of Geology*.

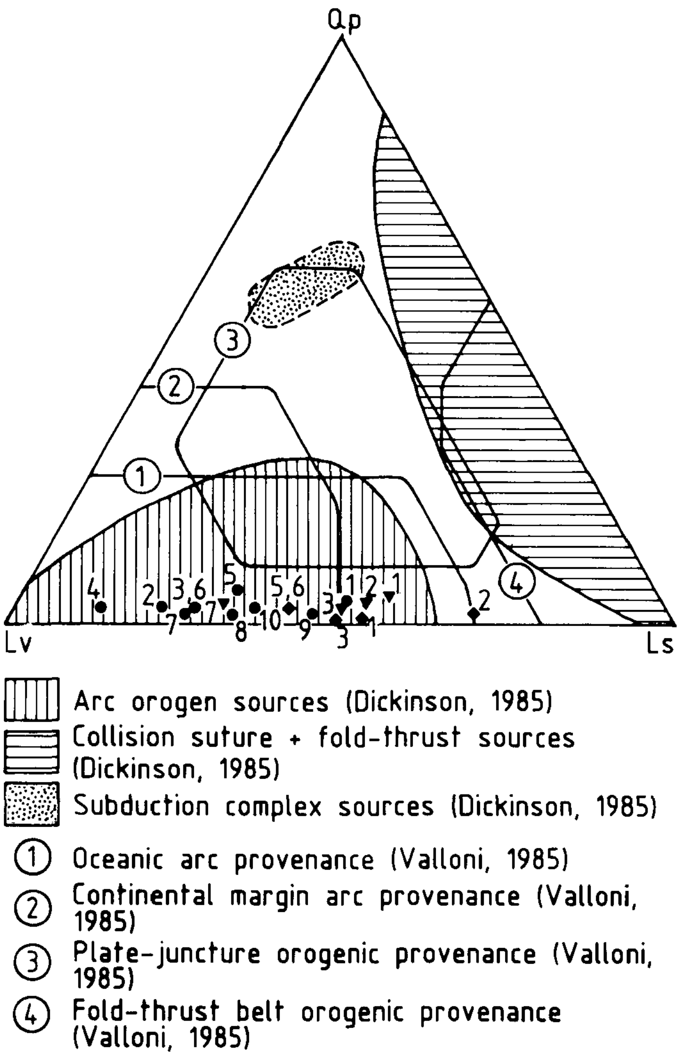


Figure 15C. QpLvLs plot for Ecca Group and Adelaide Subgroup sandstones. Sample symbols and numbers as in Figure 15B. Qp—polycrystalline quartz, Lv—volcanic rock fragments, and Ls—sedimentary and metasedimentary rock fragments. From Johnson (1991), with acknowledgments as above.

is indicated by the framework modes of detrital or epiclastic sandstones in the Karoo Basin (Table 4, Fig. 16), by dated clasts (Table 5), and by the occurrence of garnet (Table 6).

The framework modes of quartz, feldspar, and lithic fragments show that sandstone samples of the Ecca and lower Beaufort Groups are feldspathic litharenite to lithic feldsarenite, those of the Katberg Formation lithic feldsarenite, and those of the Molteno and Elliot Formations quartzose litharenite (Fig. 16, A–C). As noted above, the different petrographic classification of grain types used by Johnson (1991) shifts his samples toward the feldspar and lithic end members into the magmatic arc field (Fig. 15B), whereas the mean modes of the samples plotted in Figure 16D plot in the recycled orogen provenance with the Ecca Group (1) and lower Beaufort Group (2) on the side near the magmatic arc province.

Most of the lithic fragments in the fine-grained plagioclase litharenite near the base of the Ripon Formation (SA 9, Appendix 1, Tables 7 and 8) are felsite with quartz and ?feldspar phenocrysts, as also found in the Beaufort West sample (SA 30, Appendix 1, Tables 7 and 8) and in the other Beaufort rocks reported by Turner (1978, p. 834, "volcanic fragments of predominantly acid character"). The mineral fraction in the Ripon Formation sample is mainly K-feldspar (plagioclase is minor) and mono- or poly-crystalline quartz. From the Ecca and lower Beaufort, Martini (1974, figs. 2–4) described lithic fragments with a felsitic texture with or without phenocrysts and also fragments with trachytic and pilotaxitic textures; and from the lower Beaufort of the northern Karoo, Keyser and Zawada (1988) described lapilli. The felsite grains are interpreted as having been derived originally as pumice from a silicic volcanic province. Unlike the felsite grains in the Sydney Basin, which can be shown to be epiclastic (Chapter 3, Appendix 2), the Karoo pumice grains are too small to indicate whether they were deposited in a porous or a consolidated state before burial. It remains possible therefore that they were derived from the same provenance that provided the air-fall tuffs, but the framework modes suggest another possible source from an older recycled orogen provenance. A paleocurrent analysis of the Beaufort Group (Cole and Wipplinger, 1991) indicates that this provenance may have been located in the region of the Cape Fold Belt south of the Karoo Basin.

Other lithic fragments seen in the collection (Appendix 1, Table 7), besides the recognizable volcanic ash fragments (shards), are granite, quartzite, and an altered plagioclase-rich mafic rock in the Dwyka Formation (SA 5b), and sedimentary chert (banded chalcedony) (*see* Fig. 20F in Appendix 1) in the Fort Brown Formation. Turner (1975) found that the rock fragments in the sandstones of the Molteno Formation comprise quartzite and polycrystalline quartz, probably derived from metamorphic rocks. The mineral fraction is mainly mono- and poly-crystalline quartz and feldspar, with K-feldspar far more abundant than plagioclase and probably derived from granite (Turner, 1975; *see* also Le Roux, 1985).

As detailed in Table 6, *garnet* is a common heavy mineral (as is zircon) throughout the entire Karoo Basin sequence and is most abundant in the glacigene Dwyka Formation, where it is distinctly chattermarked, as it is in other Early Permian glacigene deposits in Gondwanaland (Gravenor, 1979). In the underlying Cape Supergroup, the only known occurrence of

TABLE 4. RECYCLED OROGEN PROVENANCE, INDICATED BY QFL COMPOSITION OF EPICLASTIC SANDSTONES IN THE SOUTHERN KAROO BASIN (FIG. 16D)

Unit	Locality	Material	Reference
6. Elliot	Eastern Cape and Witsieshoek	Lithic feldspathic graywacke	Le Roux, 1985
5. Molteno	Molteno outcrop	Quartzose feldsarenite	Turner, 1975
4. Katberg	Queenstown, Kidds Beach	Lithic feldsarenite	Johnson, 1966, *in* Dingle et al., 1983, p. 21
3. Beaufort (Teekloof)	Beaufort West	Lithic feldsarenite (SA 30)	Appendix 1, Table 8
2. L. Beaufort, Ecca	Eastern Cape	Sandstones—90% of detrital feldspar is low-temperature sodic plagioclase from low-grade metamorphics	Kingsley, 1981
1. Ripon	Ecca Pass	Feldspathic litharenite (SA 9)	Appendix 1, Table 8
L. Beaufort, Ecca	Southern Karoo	Graywackes, with volcanic fragments: trachytic, pilotaxitic, and felsitic texture	Martini, 1974

garnet is in the glacigene Pakhuis Formation of the Table Mountain Group (de Villiers and Wardhaugh, 1962). In the modern river sands (mouth of the Orange River, the Crocodile River at Thabazimbi, and the Limpopo River at Messina) that drain the craton north of the Karoo Basin, de Villiers and Wardhaugh (1962) found garnet in greater than trace amounts (>2% of the heavy residue) in one sample only. They concluded that "the resultant rocks would not resemble those portions of the Karroo succession which are characterized by an abundance of garnet in the heavy residue" (de Villiers and Wardhaugh, 1962, p. 105). Within the Karoo Basin provenance itself, de Villiers and Wardhaugh (1962, p. 105) found that "during the present cycle of erosion and deposition of the Karroo sediments, most of the garnet is apparently destroyed." Having eliminated the region north of the Karoo Basin as a provenance of the garnet, de Villiers and Wardhaugh (1962) pointed to a garnet provenance in a southerly extension of Africa of composition similar to that of garnetiferous East Antarctica. Subsequent studies, however, have shown that the northern region was a definite provenance of garnet in the Mooi River Formation (*see* the following discussion) and a probable provenance in the case of the garnet-bearing heavy mineral sands in the Vryheid Formation (Behr, 1986).

Gravenor's (1979) analysis of the heavy mineral suites from Early Permian deposits of South Africa, Australia, and Antarctica, dominated by chattermarked garnet, shows that these garnets underwent a much longer distance of transport, probably as a result of continuous recycling, than the Pleistocene glacial sediments of North America. "The dominance of garnets in the heavy mineral suites was caused by a combination of dissolution of chemically unstable minerals by intrastratal solutions, and mechanical abrasion of the softer minerals" (Gravenor, 1979, p. 1149, 1150). These arguments account for the garnet in the glacigene Pakhuis and Dwyka Formations, but not in the nonglacial part of the Karoo sequence, for which proximity to a voluminous source of garnet is required. The available evidence pinpoints a source for the garnet in one formation only. According to Theron (1975, p. 65; Table 6), cobbles of gneiss in the Mooi River Formation (= Belmont Formation) of Natal contain relatively large amounts of a red garnet, and this kind of rock is common up-paleocurrent 100 km eastward in exposures of the Mapumulo Group in the 1.1 Ga Natal Metamorphic Belt (Fig. 13A). Other formations, in particular the coeval Katberg Formation, shown by paleocurrents to be derived from the south-southeast (Fig. 13A), and the Estcourt Formation, which originated from a source to the east and southeast (Botha and Linström, 1978), could have come from the southern extension of the Natal Belt, perhaps identifiable in the 1.0 Ga Cape Meredith gneiss of the Falkland Islands (Fig. 13A), in the garnetiferous gneiss of the Falkland Plateau (Tarney, 1976), and in the rocks in Dronning Maud Land (2°W to 30°E in Antarctica) that also register the 1.0 Ga tectonic-metamorphic event (Yoshida and Kizaki, 1983).

The age and composition of the proximal sources are best indicated by the rudites. From the list of datable rudite clasts in the southern Karoo Basin in Table 5, we can infer (1) that the southern basal Dwyka Formation came from the south—the nearest known source of the archaeocyathid limestone clasts is Antarctica; (2) that the Katberg Formation came from a province containing granite >390 Ma, and lignite and silicified wood, within the interval Devonian to Permian, both found up-paleocurrent within the Cape Fold Belt, and gneiss of minimum age 535 ± 66 Ma (probably about 1000 Ma) found in the Falkland Plateau (Beckinsdale et al., 1976); and (3) the Molteno Formation came from a proximal province yielding blocks of Witteberg quartzite, available a short distance south of Molteno in the Cape Fold Belt.

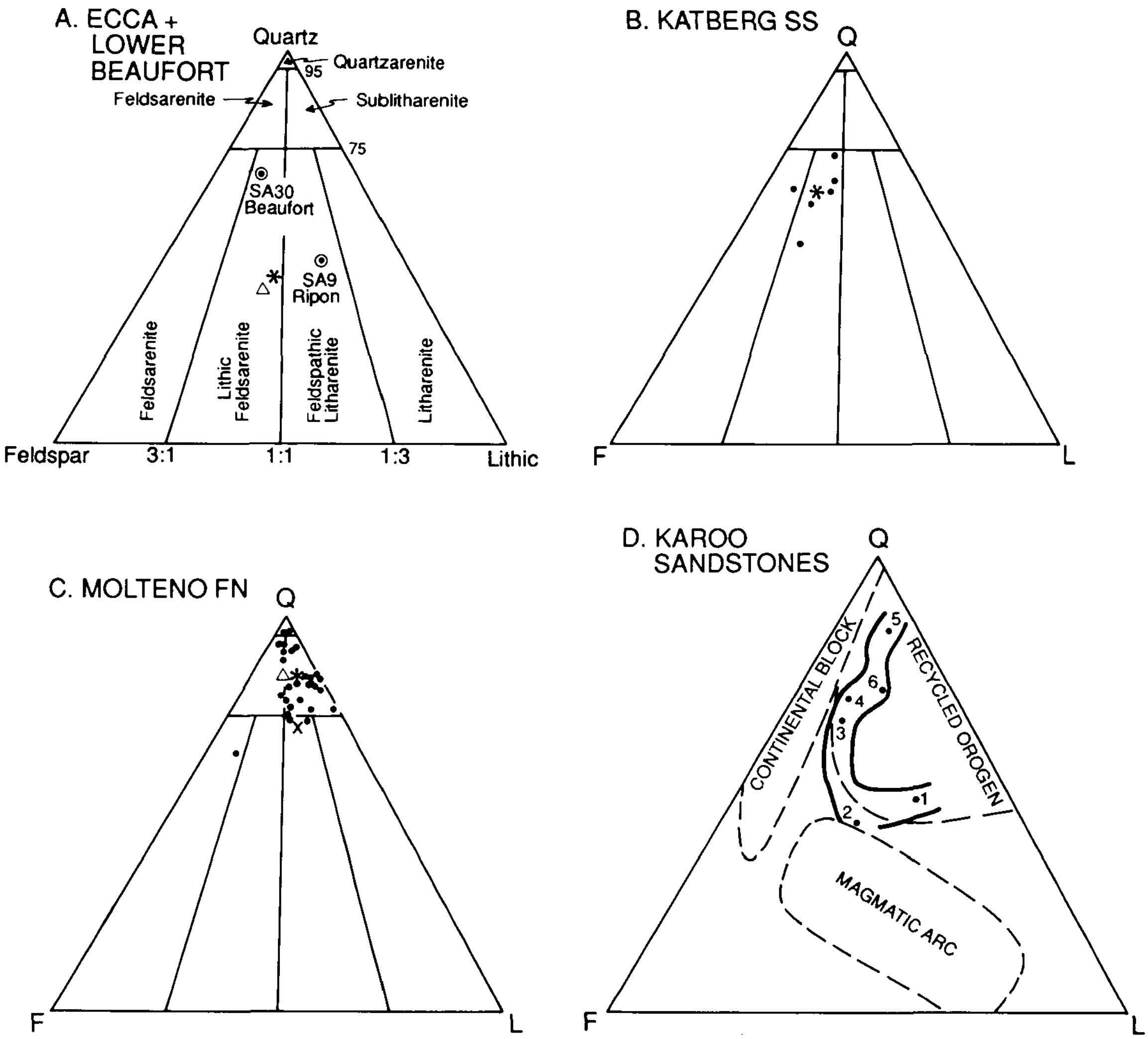


Figure 16. Framework modes of Karoo sandstones plotted on a QFL triangular diagram divided according to Folk et al.'s (1970) scheme, except D, from Dickinson and Suczek (1979). A. Samples SA 9 (Ripon Formation of Ecca Group) and SA 30 (lower Beaufort Group) (Appendix 1) and the mean for the Ecca and lower Beaufort (asterisk) (Kingsley, 1981) and for the lower Beaufort (triangle) (Le Roux, 1985). B. Katberg Formation (upper Beaufort), from Johnson (1966), as given by Dingle et al. (1983 p. 21). The mean is shown by the asterisk. C. Molteno Formation and mean (asterisk) (Turner, 1975), with mean Molteno (triangle) and Elliot Formation (X) from Le Roux (1985). D. Summary. Field of Karoo sandstones represented by 1 (SA9, Ripon Formation), 2 (mean Ecca and Beaufort), 3 (mean Katberg), 4 (SA 30, lower Beaufort), 5 (mean Molteno), 6 (mean Elliot). All lie within the recycled orogen provenance except 2, which lies between this provenance and the magmatic arc provenance.

Other types of provenance, including the northern cratonic provenance. Along the northern feather-edge of the Karoo Basin, paleocurrent directions in the Dwyka Formation, Ecca Group and parts of the Beaufort Group indicate derivation from the northern craton. The large caliber of the abundant glacial stones in the Dwyka (Visser et al., 1986) facilitates the recognition of the proximal cratonic source in the valley fills of the northern Karoo Basin and farther afield, as at Elandsvlei (Table 6), whereas the sand grade of the northern Ecca Group provides a less distinctive clue to the nature of the provenance. The heavy mineral sands in the Vryheid Formation (Behr, 1986) may have been derived from reworked Dwyka Formation to the northwest or from basement. In the Beaufort Group, except the Mooi River Formation, the Belmont/Katberg and Otterburn/Burgersdorp Formations are from the southern provenance. As mentioned already, the rudite of the Mooi River

TABLE 5. DATED RUDITE AND ARENITE CLASTS IN THE SOUTHERN KAROO BASIN

Unit	Locality	Material	Reference
Molteno	Molteno	75-cm-wide clast of Devonian Witteberg quartzite	Rust, 1962; Turner, 1975
Middle Beaufort (Katberg)	East London	Lignite, silicified wood: Permian or older to Devonian	Stavrakis, 1980
Katberg (245 Ma)	Katberg	Granite: K/Ar 390 to 210 Ma min. age*	Elliot and Watts, 1974
Abrahamskraal†	Beaufort West	Detrital zircons: U/Pb 1050 ± 20 Ma	Burger and Coertze, 1977
Dwyka	Gamkapoort to Willowmore	Archaeocyathid limestone: Early Cambrian	Cooper and Oosthuizen, 1974; Oosthuizen, 1981; Visser et al., 1986.

*Possibly an argon loss event (Martin et al., 1981, p. 300).
†The sandstone bearing these grains was deposited from paleocurrents from the southwest, which does not contain this Namaqua-Natal provenance (see Fig. 4). It is possible that the zircons are from reworked Dwyka whose provenance lay northward in the Namaqua-Natal belt.

Formation (= Belmont Formation in Natal) indicates a unique source in the Natal Metamorphic Belt. The Estcourt/Lower Beaufort is from an east-south-east provenance (Botha and Linström, 1978; Cole and Wipplinger, 1991) and a northern provenance in the Heilbron-Frankfort area (Fig. 13A) (Keyser and Zawada, 1988).

Cole and Wipplinger (1991) show that five major paleocurrent directions dominate the Beaufort Group—NE, NNW, ESE, WNW, and SW. The first two suggest derivation of sediment from the Cape Fold Belt region (Recycled Orogen Provenance—*see* previous discussion). The ESE direction indicates transport of sediment from a cratonic provenance centered on Namaqualand, and the WNW direction implies that the Natal Metamorphic Belt was a significant source of Beaufort Group sediment. The SW paleoflow direction was only recently recorded in the Colesberg-Edenburg region (Cole and Wipplinger, 1991). An intrabasinal granitic provenance east of Bloemfontein has been proposed by J. C. Theron (1970).

SYNTHESIS

The analytical data presented above are put together in the form of the series of paleo-tectonic/geographic maps presented in Fig. 17.

Influence of basement structure

Three basement trends (Fig. 17A) existed by the start of pre-Gondwanan (Ordovician-Devonian) deposition. The trends, defined by the 1.0–0.5 Ga foldbelts of weak crust that wrap around the 1 Ga Namaqua-Natal Belt and >2.5 Ga Kaapvaal Province, provide a tub-shaped template that was impressed on succeeding structures up to the Cretaceous breakup of Pangea along the present divergent margins. The pattern is reprinted during the Ordovician-Devonian deposition of the Cape Supergroup in grabens on the northwest and northeast linked by an east-west depositional axis (Fig. 17, B and C) and during the Permian and Triassic development of the Cape Fold Belt along the east-west trend linked with intermittent uplifts to the northwest (Atlantic upland) at a syntaxis around Cape Town and to the northeast (Eastern upland) at a syntaxis in the (restored) Falkland Islands (Fig. 17, D–H). Finally the pattern was exploited to determine the present shape of southern Africa by the dispersal of the neighboring South America. The southeastern margin of South America was dispersed by sea-floor spreading perpendicular to the southwest margin of Africa, and the Falkland Plateau protuberance of South America was dispersed from the southeastern margin of Africa by transform motion along the Agulhas Fracture Zone, after preliminary rotations of subplates including the Falkland Islands and parts of West Antarctica.

Ordovician-Devonian Cape Sequence

Figure 17B shows the initial rift valleys that formed over the Gariep and Mozambiquean trends. In the southwest, the alluvial-fan to braided-river complex of the Klipheuwel and Piekenierskloof Formations occupied the funnel between the proximal Atlantic and Bushman uplands; in the northeast, the Natal valley was filled with a similar complex of alluvial-fan through braided-river to shallow marine shelf that was deposited longitudinally from and within the proximal Kaapvaal uplands. Subsequent down-flexure of the rift shoulders allowed sediment in a coastal plain-marine shelf complex to thicken southward from at least the northern preserved pinchout into a trough axis (marked by the 3.5 km isopachs) that crosses the present south coast. The only other known occurrence of possibly early Paleozoic sediment in southern Africa

TABLE 6. OTHER DATA ON PROVENANCE PETROLOGY, INCLUDING THE OCCURRENCE OF GARNET

Unit	Locality	Material	Reference
Elliot	Natal Drakensberg	Sandstones: sedimentary source, from primary igneous/metamorphic source	Eriksson, 1985
Elliot	Clocolan	**Garnet** and other heavy minerals (HM)	Le Roux, 1969, *fide* Theron, 1975
Molteno	Molteno outcrop	**Garnet** (almandine-spessartite) "from granites, pegmatites, and possibly contact altered siliceous rocks"	Turner, 1975, p. 199
Molteno	Molteno outcrop	Two sources: S—Cape Supergroup quartzites; SE—granitic fault-block terrain of high relief	Turner, 1980
Burgersdorp	Natal Drakensberg	**Garnet**	Botha and Linström, 1978
Belmont	Mooi River	<18 cm clasts: gneiss with red **garnet**, vein quartz, microcline, red granite, quartzite—metamorphic terrane	Theron, 1975, p. 65
Katberg	East London*	Pebbles, HM	Hiller and Stavrakis, 1980
Katberg	Eastern Cape	Quartz-feldspar porphyry and non-porphyritic "lava." Also granite, gneiss, quartzite, sandstone, conglomerate, fossil wood	Johnson, 1976; Theron, 1975
Estcourt	Estcourt/Mooi R.†	Sand grains	Botha and Linström, 1978
Beaufort	Karoo Basin	**Garnet**	Theron, 1975
L. Beaufort and Ecca	E. Cape	Modal analysis, feldspar studies, heavy mineral analysis: low-metamorphic to gneissic terrane	Kingsley, 1979
Ecca	Laingsburg, Harrismith	**Garnet**	Nel, 1962
Vryheid	Bothaville	**Garnet**, zircon from granitic terrane in NW	Behr, 1986
Vryheid	Delmas, Carolina, Muden	**Garnet**	Ryan and Whitfield, 1979; Behr, 1986
Dwyka	N. Karoo, Elandsvlei	Proximal valley source: red quartzite plus stromatolitic dolomite from "Ghaap Plateau" 500 km to NE	Visser et al., 1986
Dwyka	S. outcrop	Diorite, gray limestone with archaeocyathids, from S or SE	Cooper and Oosthuizen, 1974; Visser and Loock, 1982; Visser et al., 1986
Dwyka	Pluto's Vale	Heavy mineral suite flooded with colorless and pink **garnet**	Rust, 1962
Dwyka	Karoo Basin	**Garnet**	de Villiers and Wardhaugh, 1962
Dwyka	Karoo Basin	Chattermarked **garnet**: recycled glacigenic sediment	Gravenor, 1979
Weltevrede (Witteberg)	Willowmore	Rutile, zircon, ilmenite, magnetite, monazite, staurolite, sphene. Namaqua-Natal metamorphic igneous source 100 km to north	Cole and Labuschagne, 1983
Pakhuis	W. Cape	Only known occurrence of **garnet** in Cape Supergroup	de Villiers and Wardhaugh, 1962

*"The pebbles...indicate that the sediments were derived from the weathering and erosion of a granitic or granite gneiss terrane which, in places, was associated with a sedimentary cover and intrusive igneous rocks.... The heavy mineral suite, in which pink **garnet**, magnetite, epidote, sphene and zircon are the most common species, would indicate derivation from a high-grade metamorphic or acid igneous source. The feldspars present in the sandstones, mostly microcline and plagioclase in the albite to andesine range, tend to confirm such a source."

†"The plagioclase and microcline in the sandstones were probably derived from gneissic metamorphic rocks and this conclusion is confirmed by the high garnet content.... The quartz in the sandstones has a typical undulatory extinction, which also points to metamorphic source rocks. The bulk of the material was therefore derived from garnet-bearing basement rocks around the south-eastern and eastern periphery of the Karoo Basin."

TABLE 7. SOUTH AFRICAN ROCK SPECIMENS, ARRANGED STRATIGRAPHICALLY*

Formation/ Locality	SA No.	Description
Beaufort Group, 3 km N of Beaufort West	30	Fine-grained plagioclase litharenite (see Table 8 for point count).
Top Fort Brown, Geelhoutboom	11b	Argillite with very fine quartz fragments.
	11c	Very fine sandstone, with a lithic grain of sedimentary chert (banded chalcedony) (Fig. 20F).
	11d	Argillite similar to 11b and 11c.
Fort Brown, 13 km N of Wolwefontein	10	Tuff of shards in felsitic groundmass, part replaced by carbonate (Fig. 20D).
Basal Ripon Formation, Ecca Pass, 2.4 km past Bain Monument	9	Fine-grained plagioclase litharenite (see Table 8 for point count).
Top Collingham, Ecca Pass	8c, d	Argillite with minor angular quartz grains.
Remhoogte	14–16	
Collingham, Matjiesfontein Chert (MC)	14c	Felsitic groundmass with scattered angular plagioclase and quartz, interpreted as a tuff (Fig. 20E).
	14g	Similar to 14c, some parts replaced by carbonate.
	14h	Similar to 14c and 14g. Replacing mineral (high relief) picks up faint traces of ?vitric shard outlines.
Collingham, 8 m above base	15	Argillite, with curvilinear fragments interpreted as shards with triple junctions (Fig. 20B).
Whitehill	16a	Yellow part of slide is argillite. Black part is vitric tuff with shards replaced by clay (Fig. 20A).
Between MC and Whitehill, 16 km E. of Matjiesfontein	26	Black argillite.
MC at locality 26	27	Laminated microcrystalline quartz with very fine quartz and plagioclase grains.
Whitehill, 1.3 km N of 5	6	Very fine-grained red siltstone. Wavy lamination with truncation surfaces present.
Six m below Whitehill near Laingsburg R. crossing	29	Argillite.
Basal 5-m Collingham, Ecca Pass	7a	Very fine-grained siltstone with devitrified glass shards. Very few detrital grains present. White patches full of shards (Fig. 20C).
	7b	As above but without shards, and replaced locally by carbonate.
	7c	Argillite mostly replaced by carbonate. Black patches show shard-like grains, but too small for positive identification.
	7d	Argillite replaced by carbonate.
		Poorly sorted medium-grained immature sandstone; quartz, and plagioclase, minor microcline. Clasts of granite, quartzite, altered plagioclase-rich (lathwork) mafic rock.

*Volcanogenic material located on Figure 1 and in Table 2.

TABLE 8. MODAL POINT-COUNT PERCENTAGE COMPOSITION OF SANDSTONES*

Category	SA9 Ripon		SA30 Beaufort	
Counts	700		720	
Grainsize	0.17 mm		0.14 mm	
Whole rock quartz	42.7		56.7	
Common		26.1		55.9
Volcanic		1.1		0.0
Polycrystalline		15.2		0.8
Chert/metachert		0.3		0.0
Interstitial	6.4		13.8	
Feldspar	16.7		17.3	
K-feldspar		11.6		5.1
Plagioclase		5.1		12.2
Mica	2.6		3.1	
Heavy mineral	0.1		0.3	
Lithic grains	31.5		8.8	
Volcanic, felsitic		18.4		2.2
Argillite		10.0		6.3
Schist		3.1		0.3
Total	100.0		100.0	
Quartz (Q)	47.0		68.5	
Feldspar (F)	18.4		20.9	
Lithic grains (L)	34.6		10.6	
Total (Q + F + L)	100.0		100.0	

*Categories from Cowan, 1985, after McDonnell, 1983.

is at Zambezi (14.4°S, 22.5°E) (ZI in Fig. 6) (Reimann, 1986), 1,200 km north of the edge of the map area of Fig. 17B.

During the Early and Middle Devonian (Fig. 17C), accelerated subsidence was accompanied by the southward prograding clastic wedge >3.5 km thick of the Bokkeveld Group, shed presumably from the relic Bushman and Atlantic uplands, in the form of "a major trough with marked eastward axial pitch (Agulhas Trough)" (Theron and Loock, 1989, p. 733). In the Late Devonian (Witteberg Group), a linear clastic shoreline developed east of 20°E, and possibly branched northeastward into the Natal trough.

In view of its setting alongside the Paleo-Pacific Ocean, the trough was on the cratonic side of a marginal or back-arc basin behind a magmatic arc, as suggested for the Devonian of the neighboring Antarctica (Bradshaw and Webers, 1988, p. 792) (Fig. 4 in Chap. 7), and of southern South America and the Antarctic Peninsula (Hiller, 1992, fig. 9). In deriving all its epiclastic sediment from the craton, the Cape Basin has the same kind of fill as a passive margin (Johnson, 1991) but the very different tectonic setting of a back-arc basin within a zone of plate convergence.

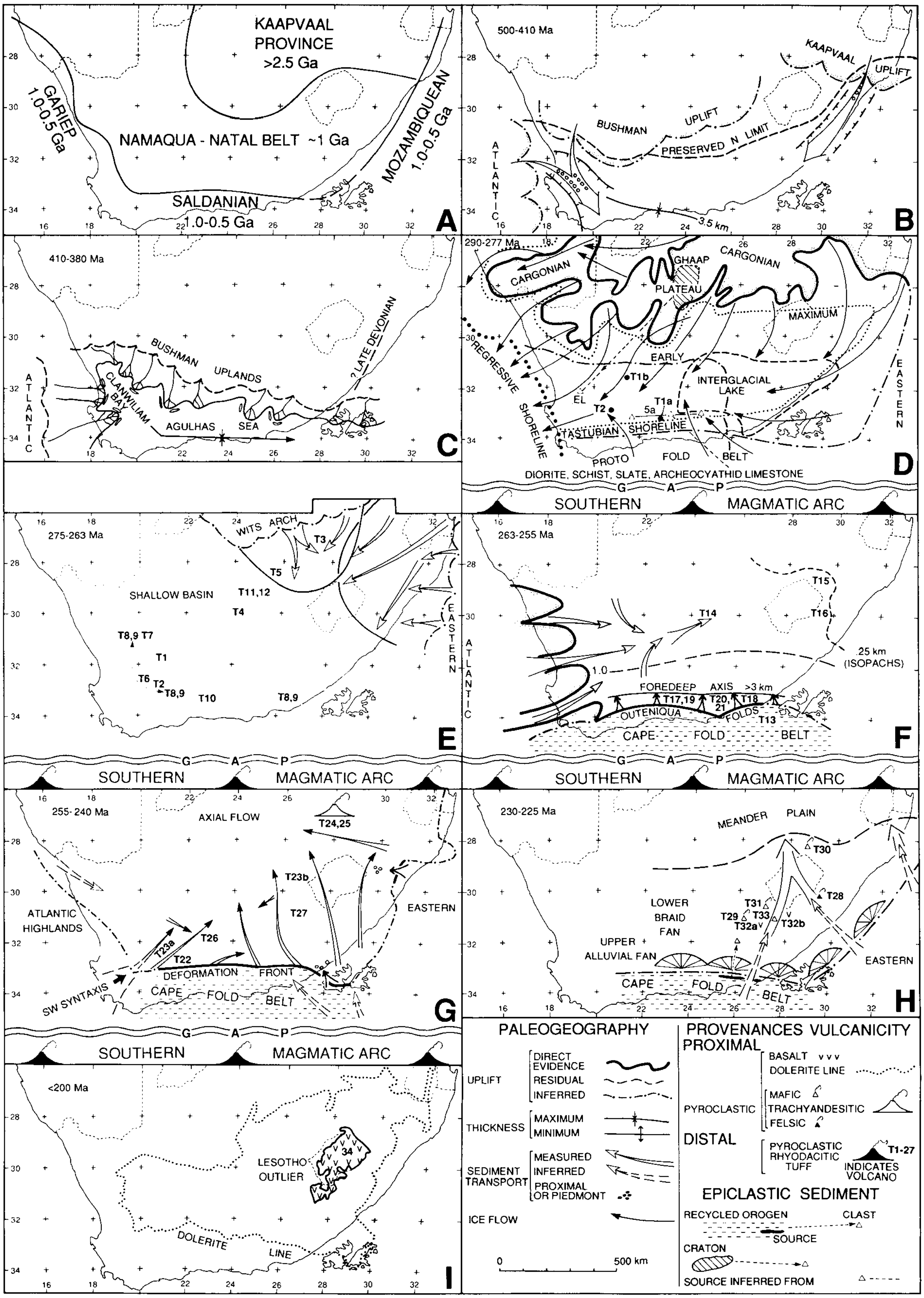
Karoo (Gondwanan) Sequence

Figure 17D shows the following superimposed events at the latest Carboniferous–earliest Permian (290–277 Ma) onset of Karoo deposition: (5) end-Tastubian regressive marine shoreline (heavy dotted line) and tuff; (4) Tastubian marine transgressive shoreline (light dotted line); (3) ice flow during final glaciation (arrows); (2) interglacial lake (heavy broken line); (1) uplands isolated by basin subsidence (stippled line: mapped edge of upland; dot-and-dashed line: inferred edge). T1 and T2 are localities of volcanigenic material, mainly tuff, that indicates coeval distal volcanicity.

The commonest stone in the Dwyka diamictite is granite and gneiss but their occurrence in basement on all sides of the Karoo Basin rules out a specific source area. Distinctive stones in the basal diamictite relatable to source are stromatolitic dolomite and reddish quartzite at Elandsvlei (EL in Fig. 17D) from the Proterozoic of the Ghaap Plateau, and diorite, schist, slate, and archeocyathid limestone (Table 5, a), attributed by default (outcrops are not known in southern Africa) to the south and southeast (Visser et al., 1986).

During the Early Permian (275–263 Ma) deposition of the lower Ecca Group (Fig. 17E), lobes of a delta complex with coal measures overlapped subsiding cratonic uplands in the north (Witwatersrand Arch) and in the east (Eastern uplands) and prograde and shale-out to the southwest into a shallow anoxic basin, which continued to the northwest into South America (Whitehill-Iratí shale basin). A distal magmatic arc is indicated by widespread tuff (1–12 of Table 2).

Figure 17F shows the deposition of the Early/Late Permian (263–255 Ma) Upper Ecca Group of southern Africa and the 3-km-thick equivalent above the Lafonian Diamictite–Black Rock Member on the Falkland Islands. The situation is now reversed from that of the Lower Ecca. Coarse and thick sediment came wholly from the south and west, and the northeastern area of the former delta complexes was covered by a shale (Volksrust Formation). By the end of Ecca deposition, the basin was almost filled with sediment to become the broad fluvial plain of the Beaufort Group. The Upper Ecca represents the first pulse of thick sediment shed into a foredeep from the rising Cape Foldbelt, which underwent a second deformation, the Outeniqua folding, towards the end of Ecca deposition. This foredeep developed by rapid subsidence of the shallow floor of the Whitehill lake to a probable maximum depth of 500 m during the deposition of subaqueous fans. The isopachs parallel the strike of the Cape Fold Belt, and the axis pitches eastward into the thickest known section, near the coast and on the Falkland Islands. In the west, sediment was transported down an east-northeastward paleoslope and was probably derived from two sources: (1) by consequent drainage down the flank of the resurgent Atlantic Mountains, and (2) by axial drainage from the Cape Fold Belt. The Atlantic Mountains temporarily interrupted or restricted the previous Tastubian upper Dwyka margin and Artinskian Lower Ecca


KAAPVAAL
PROVINCE
>2.5 Ga
GARIEP
1.0-0.5 Ga
NAMAQUA - NATAL BELT ~1 Ga
MOZAMBIQUEAN
1.0-0.5 Ga
SALDANIAN
1.0-0.5 Ga
A
500-410 Ma
KAAPVAAL
UPLIFT
BUSHMAN
UPLIFT
PRESERVED N LIMIT
ATLANTIC
3.5 km
B
410-380 Ma
BUSHMAN
UPLANDS
LATE DEVONIAN
CLANWILLIAM BAY
AGULHAS
SEA
ATLANTIC
C
290-277 Ma
CARGONIAN
GHAAP
PLATEAU
CARGONIAN
MAXIMUM
REGRESSIVE
SHORELINE
EARLY
T1b
INTERGLACIAL
LAKE
EL
T2
T1a
5a
TASTUBIAN SHORELINE
PROTO
FOLD
BELT
EASTERN
D
DIORITE, SCHIST, SLATE, ARCHEOCYATHID LIMESTONE
G A P
SOUTHERN
MAGMATIC ARC
275-263 Ma
WITS ARCH
T3
T5
SHALLOW BASIN
T11,12
T4
T8,9 T7
T1
T6
T2
T8,9
T10
T8,9
EASTERN
E
G A P
SOUTHERN
MAGMATIC ARC
263-255 Ma
T15
T14
T16
.25 km
(ISOPACHS)
1.0
ATLANTIC
FOREDEEP AXIS >3 km
T17,19
T20,
21
T18
OUTENIQUA
FOLDS
T13
CAPE FOLD BELT
F
G A P
SOUTHERN
MAGMATIC ARC
255- 240 Ma
AXIAL FLOW
T24,25
T23b
T27
ATLANTIC
HIGHLANDS
EASTERN
T23a
T26
T22
DEFORMATION FRONT
CAPE FOLD BELT
SW SYNTAXIS
G
230-225 Ma
MEANDER PLAIN
T30
T28
LOWER
BRAID
FAN
T31
T29
T33
T32a
T32b
UPPER
ALLUVIAL FAN
EASTERN
CAPE FOLD BELT
H
G A P
SOUTHERN
MAGMATIC ARC
<200 Ma
LESOTHO
OUTLIER
34
DOLERITE
LINE
I
PALEOGEOGRAPHY
UPLIFT
DIRECT
EVIDENCE
RESIDUAL
INFERRED
THICKNESS
MAXIMUM
MINIMUM
SEDIMENT
TRANSPORT
MEASURED
INFERRED
PROXIMAL
OR PIEDMONT
ICE FLOW
0
500 km
PROVENANCES VULCANICITY
PROXIMAL
BASALT v v v
DOLERITE LINE
PYROCLASTIC
MAFIC
TRACHYANDESITIC
FELSIC
DISTAL
PYROCLASTIC
RHYODACITIC
TUFF
T1-27
INDICATES
VOLCANO
EPICLASTIC SEDIMENT
RECYCLED OROGEN
CLAST
SOURCE
CRATON
SOURCE INFERRED FROM

brackish connection between southern Africa and South America that resumed later during the early Kazanian Waterford-Estrada Nova lake with its endemic bivalves.

The framework modes of sandstone in the Ripon Sandstone fall within the recycled orogen field (Fig. 16); the mean of the Ecca and Beaufort Groups (point 2 of Fig. 16) falls between the provenances of the recycled orogen and the magmatic arc, which is represented by widespread tuff (13–21 of Table 2).

Figure 17G shows the Late Permian–Early Triassic (255–240 Ma) deposition of the Beaufort Group. Following the filling of the Ecca basin by northward and eastward prograding deltas, a greater volume of sediment from the faster growing Cape Fold Belt, now including deformed and uplifted early Beaufort strata, prograded diachronously northward in rivers that flowed across the former basin floor down a 500-km-long piedmont flank to an east-trending axis of sediment transport in the northeastern Karoo Basin. During 15 million years of deposition, the piedmont wedge reached an estimated thickness of 6 km at the south crop. The main fan in the southeast radiated from a source region (Theron, 1975) upslope from the syntaxis at the Falkland Islands, as the minor fan in the southwest radiated from a similar syntaxis in the Cape Town–Ceres region. Enclosure of the basin on the northwest is indicated by SE-trending paleocurrents northwest of T26. In the Early Triassic, piedmont conglomerate (circles) was deposited at the foot of uplands in the Falkland Islands and Precambrian Mapumulo Group in the northeast. Proximal sources are an inferred trachyandesite volcanic center near T24, 25, the garnetiferous gneiss of the Mapumulo Group east of the Mooi River (Table 6, g), the Devonian to Permian section of the Cape Fold Belt upcurrent from the Katberg–East London area (Table 5, d), and an inferred granite >390–210 Ma (Table 5, c). The bulk of the Beaufort Group sediment was recycled from the orogen of the Cape Fold Belt (Fig. 16), but sediment from the distal magmatic arc, including rhyodacitic tuff (22, 23, 26, 27 of Table 2), was sufficient to shift the sandstone mode toward the magmatic arc provenance. In the northeastern Karoo Basin, coarse (lapilli) tuff (24–25 of Table 2) indicates a proximal source in a trachyandesitic volcanic center.

Figure 17H shows the Late Triassic deposition of the Molteno Formation, as detailed in Figure 14A. Downslope from the inferred upper fans at the foot of the Cape Fold Belt and the Eastern uplands is a belt of a lower braid fan and then a meander plain. In the Molteno Formation, tonstein (28 of Table 3), derived from a rhyodacitic tuff in turn derived from a proximal source volcano, was followed in the Elliot and Clarens Formations (29–33) by basalt and mafic pyroclastics during the initial stage of *in situ* Karoo vulcanicity.

Figure 17I shows the Early Jurassic Karoo vulcanicity, including the eruption of flood basalt, now worn back to the Lesotho outlier, and the intrusion of dolerite limited by the dotted line.

Figure 17. Paleo-tectonic/geographic maps, showing provenances. Volcanigenic material, mainly tuff that indicates coeval distal vulcanicity during the Permian and Early Triassic, denoted by T1–T23 and T27 (from Table 2); proximal vulcanicity during the Triassic and Jurassic denoted by T24–T25 and T28–T33.

A. Pre-Cape (>2.5–0.5 Ga) basement trends, from Figure 4.

B. Ordovician-Silurian: Table Mountain and Natal Groups, from Figure 5A.

C. Early-Middle Devonian Bokkeveld Group and equivalent in the Falkland Islands, from Figure 5B.

D. Latest Carboniferous–earliest Permian (290–277 Ma) Dwyka Formation in Southern Africa and Lafonian Diamictite on the Falkland Islands, from Figure 11. Magmatic arc in D–G located an unknown distance southward beyond the gap.

E. Early Permian (275–263 Ma) Lower and Middle Ecca Group of southern Africa and Black Rock Member of Falkland Islands, from Figure 12A.

F. Early/Late Permian (263–255 Ma) Upper Ecca Group of southern Africa and the 3-km-thick equivalent above the Lafonian Diamictite/Black Rock Member of the Falkland Islands, from Figure 12B.

G. Late Permian–Early Triassic (255–240 Ma) Beaufort Group, from Figure 13A.

H. Late Triassic (230–225 Ma) Molteno Formation, from Figure 14A.

I. Early Jurassic Karoo vulcanicity.

Setting within southern Africa

The inception of the Karoo Sequence in the latest Carboniferous–earliest Permian corresponded to the relaxation of the Pangean platform in sags and rifts. The regional map of Figure 18 shows the great northward expansion of Gondwanan deposition over the interior of the Gondwanaland province of Pangea beyond that of the confined pre-Gondwanan Cape Sequence. The latest Carboniferous–earliest Permian (290–277 Ma) Dwyka Formation in southern Africa, Lafonian Diamictite on the Falkland Islands, and equivalents northward to 5°N occupied sags in the Karoo (western) terrain, including the Kalahari Basin between the Windhoek and Cargonian uplands and the Karoo Basin between the Cargonian uplands and the proto Cape Fold Belt. The Zambezian terrain (east of the heavy broken line) was affected by faulting of basins during or after deposition or both. Faulting also affected the eastern part of the Kalahari Basin (Visser, 1987) and, in the western terrain, the entire Warmbad Basin (J.N.J. Visser, personal communication, 1992) at the southern part of the Kalahari Basin (Fig. 12A). The equivalents of the Ecca and Beaufort Groups are known from place to place north of the Karoo Basin, but are not so widespread as those of the Dwyka. Only with the renewal of widespread deposition in the Late Triassic and the onset of voluminous proximal Karoo vulcanism in the Jurassic (Fig. 19) were areas in the north newly covered by sediment and lava. Renewed and more extensive deposition in the Late Triassic corresponds to a singularity in Pangean history: terminal compression of fold belts (Cape Fold Belt, Bowen-Sydney Basin) and widespread subsidence, mainly in rifts that prefigured the

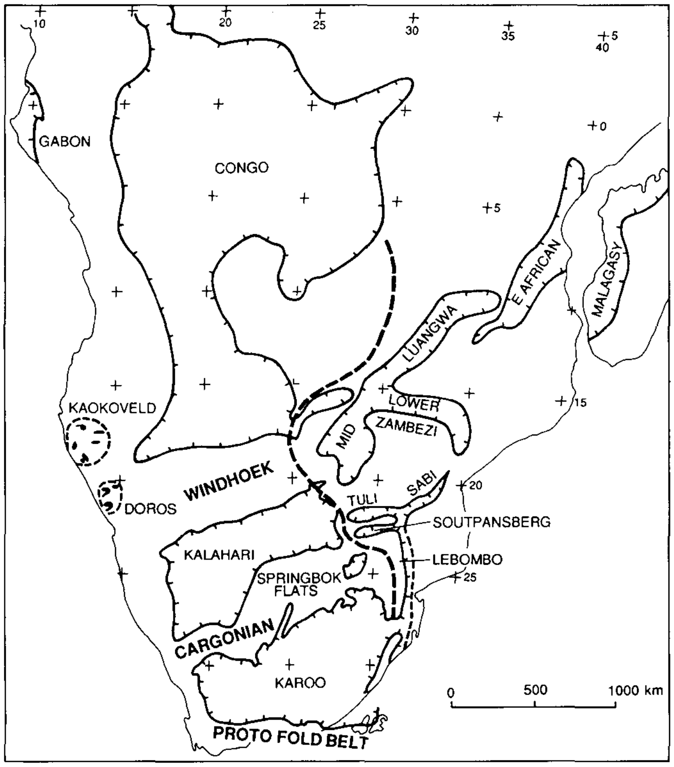


Figure 18. Latest Carboniferous–earliest Permian (290–277 Ma) Dwyka Formation of southern Africa, Lafonian Diamictite of the Falkland Islands, and equivalents northward to 5°N. Map base from Figure 6.

divergent margins of the Atlantic and Indian Ocean regions (Veevers, 1989). The subsequent Karoo vulcanism reflects the increased activity of Pangean hotspots during rifting.

Also shown in Figure 19 are the axes of drainage (marked b) and maximum thickness of the Permian-Triassic foredeep (marked a) for the following intervals:

(I) Tastubian, at end of Dwyka deposition: As shown in section I, the Dwyka Formation was deposited over a basement that comprised the Kaapvaal Province, the Namaqua-Natal Belt (N-N), the Southern Cape Conductive Belt (SCCB), including the Beattie Anomaly (BA), and the Cape Supergroup. The basin subsided between cratonic uplifts and the growing Swartberg fold in the Cape Supergroup and older rocks (near Y in the section). The axis of iceflow drainage (Ib) lay 80 km north of the maximum thickness of 1 km at Ia (wiggly line).

(II) Kazanian, at the end of Ecca deposition: Sediment encroached northward on the remnant Witwatersrand (WITS) Arch. In the south, the foredeep (IIa for the upper Ecca Group) subsided in front of the growing Outeniqua folds of the Cape Fold Belt and filled with 3.5 km of sediment. The drainage axis (IIb) lay 400 km north of the foredeep.

(III) Early Triassic, at end of Beaufort deposition: The foredeep (IIIa) in front of the further folded and thrusted Cape Fold Belt filled with 6 km of coarse sediment. The drainage axis (IIIb) lay 550 km to the north.

(IV) Late Triassic–Early Jurassic, Stormberg deposition and early part of Karoo vulcanism: The Stormberg Group was deposited during the terminal listric thrusting and epeirogenic uplift of the Cape Fold Belt and Karoo Basin in the south and the onset of rift uplift marked by the Choma-Kalomo Ridge (C-KR) in the north. The drainage basin (IVb) lay 1,000 km from the foot of the foldbelt uplift (IVa), which accumulated at least 1 km of piedmont fans that were subsequently removed during the epeirogenic uplift. The thickest preserved Stormberg equivalent in the north is 2.5 km thick, and was deposited at the foot of the rapidly rising Choma-Kalomo Ridge (C-KR). Karoo vulcanism includes the local volcanic centers in the Stormberg Group and the succeeding flood lava of the Drakensberg Group. To the north, the volcanics have been worn back to smaller outliers or, as in the Lebombo monocline, covered by younger rock. Dolerite intrusions are confined by the dolerite line in the Karoo Basin and (not mapped) within the Kalahari Basin.

As gauged from the vertical datum line in the sections, the foredeep axis shifted 20 km northward from its initial position (I) during Ecca deposition (II) and then a further 40 km northward during Beaufort (III) and Stormberg (IV) deposition by a modest northward encroachment of the deformation front. An initial separation of foredeep (Ia) and drainage (Ib) axes of 80 km increased to 400 km during Ecca deposition, 550 km during Beaufort deposition, and 1,000 km during Stormberg deposition. The increasing separation reflects the widening of the southern depositional flank of the Karoo Basin during the growth of the Cape Fold Belt at the expense of the starved northern cratonic side. Only during Stormberg deposition did the northern craton match the Cape Fold Belt as a source of voluminous sediment. Without this northern source, the drainage axis would have lain even farther than 1,000 km from the Cape Fold Belt.

ACKNOWLEDGMENTS

Veevers acknowledges with thanks the hospitality and guidance given to him by many people during his visit to South Africa in 1984, especially Heidi and John Anderson (Pretoria), Ian McLachlan and Neil Phillips (Johannesburg), Victor Von Brunn (Pietermaritzburg), R. Taverner-Smith and Tom Mason (Durban), Roy Oosthuizen (Klaarstroom), Russell Shone (Port Elizabeth), Richard Dingle and John Rogers (Cape Town), I. W. Hälbich (Stellenbosch), and Johan Loock and Johan Visser (Bloemfontein). Cole acknowledges the help of colleagues Piet Gresse, Hannes Theron, and Jurie Viljoen in commenting on parts of the manuscript. We express our gratitude to the formal reviewers, David Hobday and Johan Visser,

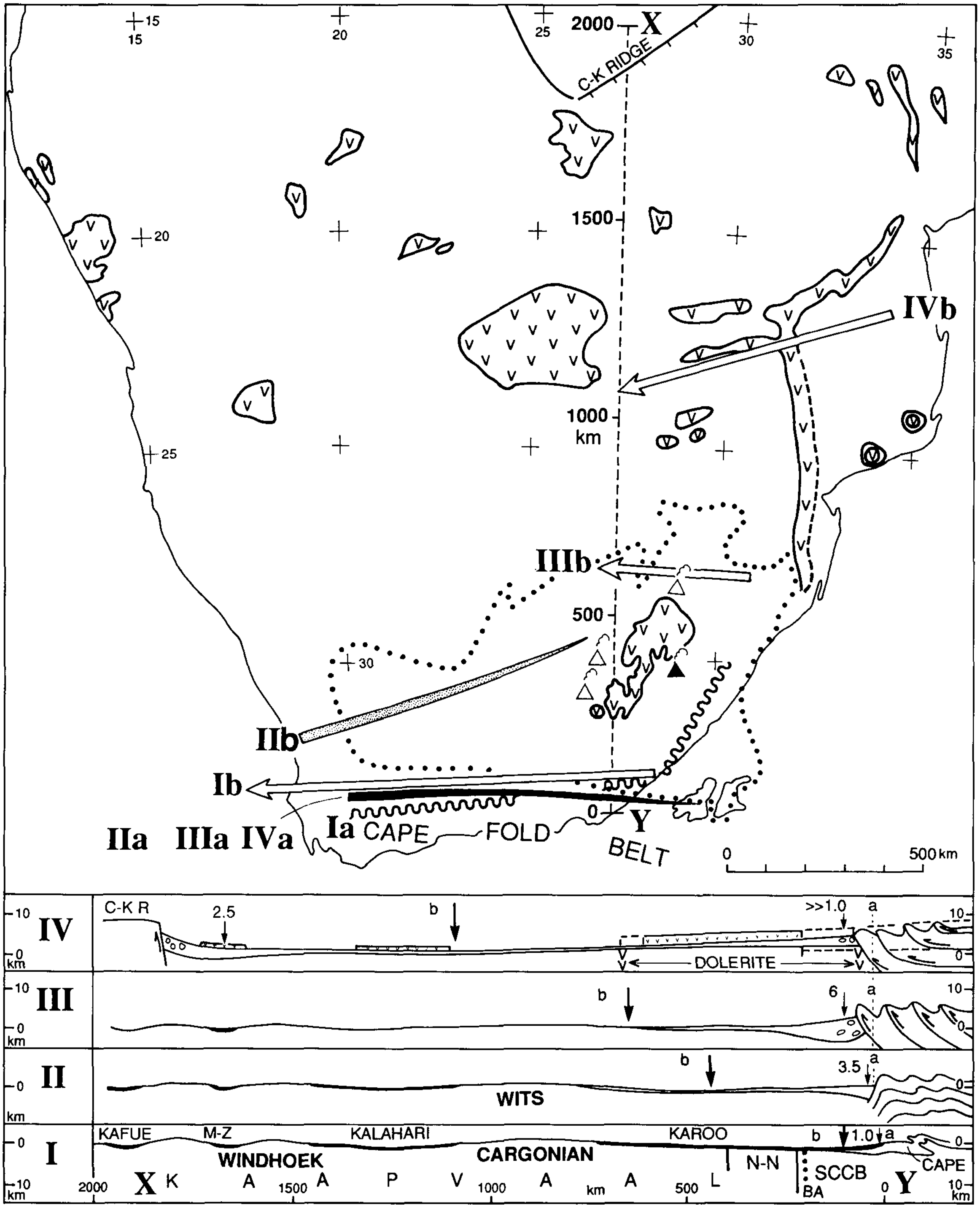


Figure 19. Late Triassic to Middle Jurassic proximal Karoo vulcanicity (V's) (from Figs. 6, 14A, 17H, and 17I), including dolerite (within the dotted line) and, in Mozambique east of the Lebombo monocline, subsurface lavas (doubly encircled V's). Axis of drainage (marked b, open arrows [except stippled II] on map, long arrows on section) and the axis of maximum thickness of the Permian-Triassic foredeep (marked a, solid lines on map, short arrows on the section) for the intervals I–IV, from Figure 17. Restored sections (V:H = 10) along line XY, with sediment <1 km thick shown by solid black. I, end Dwyka; II, end Ecca; III, end Beaufort; IV, Stormberg. BA, Beattie Anomaly; C-K R, Choma-Kalomo Ridge; M-Z, Mid Zambezi, N-N, Namaqua-Natal Belt; SCCB, Southern Cape Conductive Belt; WITS, Witwatersrand Arch.

for their generous and helpful comments on the manuscript. We are grateful to Michael Johnson and the publisher for permission to reproduce one of his figures. The final figures were drafted by Judy Davis.

APPENDIX 1. THIN-SECTION STUDY OF SELECTED SANDSTONES AND SILTSTONES FROM THE KAROO BASIN

E. J. Cowan

Thin sections were cut from rock specimens collected by Veevers in 1984 from localities along the southern crop of the Karoo Basin (Fig. 1, Table 7), including the localities of Elliot and Watts (1974) and Lock and Johnson (1974). Shards were found in the Whitehill Formation (Fig. 20A) and Collingham Formation (Fig. 20B) at Remhoogte, as in Elliot and Watts (1974), and also in the Collingham Formation (Fig. 20C) at Ecca Pass and in the Fort Brown Formation (Fig. 20D) southwest of Waterford. A sample from the Matjiesfontein Chert (Fig. 20E) has a "porphyritic" texture with a groundmass containing feldspar and quartz fragments, all interpreted as a tuff, although in the absence of shards this remains tentative.

Sandstones in the Ripon Formation (SA 9) and Beaufort Group (SA 30) were coarse enough to be point-counted (Table 8) according to the scheme adopted by McDonnell (1983) for Sydney Basin samples.

The sandstones characteristically have fairly abundant feldspar and rather rare nonvolcanic rock fragments, mainly sedimentary chert (Fig. 20F). Nearly all the rock fragments in the point-counted samples are volcanic, but whether they are the same age as or older than deposition cannot be told. As in some sub-labile sandstones of the Sydney Basin, the relatively small amount of volcanic quartz and the abundance instead of common quartz indicate that a volcanic source contributed a small part only of the sand fraction. The volcanogenic lithic fragments indicate that the source contained dacitic/rhyolitic volcanics, again similar to the Sydney Basin sandstones. The lathwork volcanolithic grains found in the Dwyka sample (SA5b) and also in trace amounts in the Late Permian coal measures of the Sydney Basin indicate a minor mafic-intermediate volcanic source.

APPENDIX 2. LATE CARBONIFEROUS–JURASSIC CORRELATION CHART FOR SOUTHERN AFRICA

J. J. Veevers

In Fig. 21 the columns are arranged from south to north through the western or Karoo tectono-sedimentary terrain of open basin and swell structure (Rust, 1975, fig. 38.1) on the left, and from southwest to northeast through the eastern or Zambezian terrain of fault-affected basins (Rust, 1975, fig. 38.1) on the right. The radiometric time scale from Appendix 1, Chapter 3, has the Permian/Triassic boundary calibrated at 250 Ma.

I acknowledge the helpful comments of D. I Cole on a draft of the chart.

Biostratigraphical schemes: Primary anchor points

(1) The Tastubian *Eurydesma* fauna (Dickins, 1961, 1984) of the Kalahari Basin localities a and b (Figs. 1 and 11), correlated by fish and spores (McLachlan and Anderson, 1973, p. 45) with the central Karoo Basin (locality c) (McLachlan and Anderson, 1973, 1975) (Table 1). (2) The early Tatarian (Khachian) and mid-Scythian ammonoid faunas of northern Malagasy (Teichert, 1974, p. 377).

Secondary anchor points

(1) Palynozones 1–4 of the northern Karoo Basin (Anderson, 1977, 1981), tentatively correlated by Truswell (1980, fig. 4) with the eastern Australian palynozones, and firmly correlated by Backhouse's (1991, p. 253–256) palynological study of the Permian Collie Basin, Western Australia, from which this précis is drawn:

> "[In] Anderson's (1977) study of the northern Karoo Basin . . . the taxa are comprehensively illustrated and adequate details are provided of their stratigraphic distribution. The study is based on an apparently uninterrupted succession that ranges from Stage 2 to above the *Didecitriletes ericianus* zone [Eastern Australian lower Stage 5b]. . . . Because Anderson's study is more comprehensive in scope than other studies on Gondwanan Permian basins more attention is given here to comparing it with the Collie Basin sequence and in the systematic section of this report the ranges and morphologies of all biostratigraphically significant taxa present in both basins are compared. . . .
>
> The two basins are most similar in the lower parts of the sequences. Up to the lower part of the *M. trisina* zone [Stage 3b] the only major differences in the distribution of index taxa are the absence, or non-recognition, of *Pseudoreticulatispora confluens* and the absence of *Microbaculispora trisina* below Microfloral Zone 3b in the Karoo Basin. The base of the *P. pseudoreticulata* zone [Stage 3a] corresponds here with the base of Microfloral Zone 2a in the Karoo Basin. The *S. fusus* biohorizon [Collie Basin] [upper 3a], which is correlated here with the first appearance of *Striatopodocarpites cancellatus* in the Karoo Basin, and *P. sinuosus* biohorizon [lower Stage 4] are also recognisable on Anderson's distribution chart. Supporting evidence for these correlations is provided by the ranges of *Praecolpatites ovatus* and *Laevigatosporites colliensis* in the Karoo and Collie Basins. The *D. ericianus* biohorizon [lower Stage 5b/c] is the only Collie Basin datum above the *P. sinuosus* biohorizon that can be recognised in the Karoo sequence. *D. ericianus* is first recorded by Anderson from the base of Microfloral Zone 4d."

After R. Helby (personal communication, 1990), I place the *confluens* zone at the base of Stage 3a (Fig. 44 in Chap. 3); Backhouse (1991) places it between Stages 2 and 3a. With this exception, the correlation of the Karoo zones to those of Eastern Australia in Fig. 21 are taken directly from Backhouse (1991, fig. 10). The *Granulatosporites confluens* zone of Foster and Waterhouse (1988) is found at the top of the Dwyka Formation (Anderson's zone 1), so that the rest of the Dwyka Formation, equivalent to the Stockton Formation of the Collie Basin (Fig. 43 in Chap. 3), is Stage 2.

The 12 palynological analyses of C. MacRae, cited by Visser (1990), generally confirm the correlations that Backhouse (1991) made with Anderson (1977).

(2) The middle to ?lower Sakamena Group of southern Malagasy, correlated to the *L. pellucidus* zone of eastern Australia (Foster, 1979, p. 126; Wright and Askin, 1987).

(3) lower Isalo I, correlated to the *S. speciosus* zone (Carnian and younger) of Dolby and Balme (1976) = late Ladinian and Carnian (Helby et al., 1987).

(4) Molteno Formation correlated by mega- and micro-floras to Ipswich Coal Measures (Carnian–early Norian) of eastern Australia (Anderson and Anderson, 1983, p. 8).

(5) Tetrapod zones, in descending order, from Anderson (1981) and Keyser and Smith (1979), given also in Dingle et al. (1983):

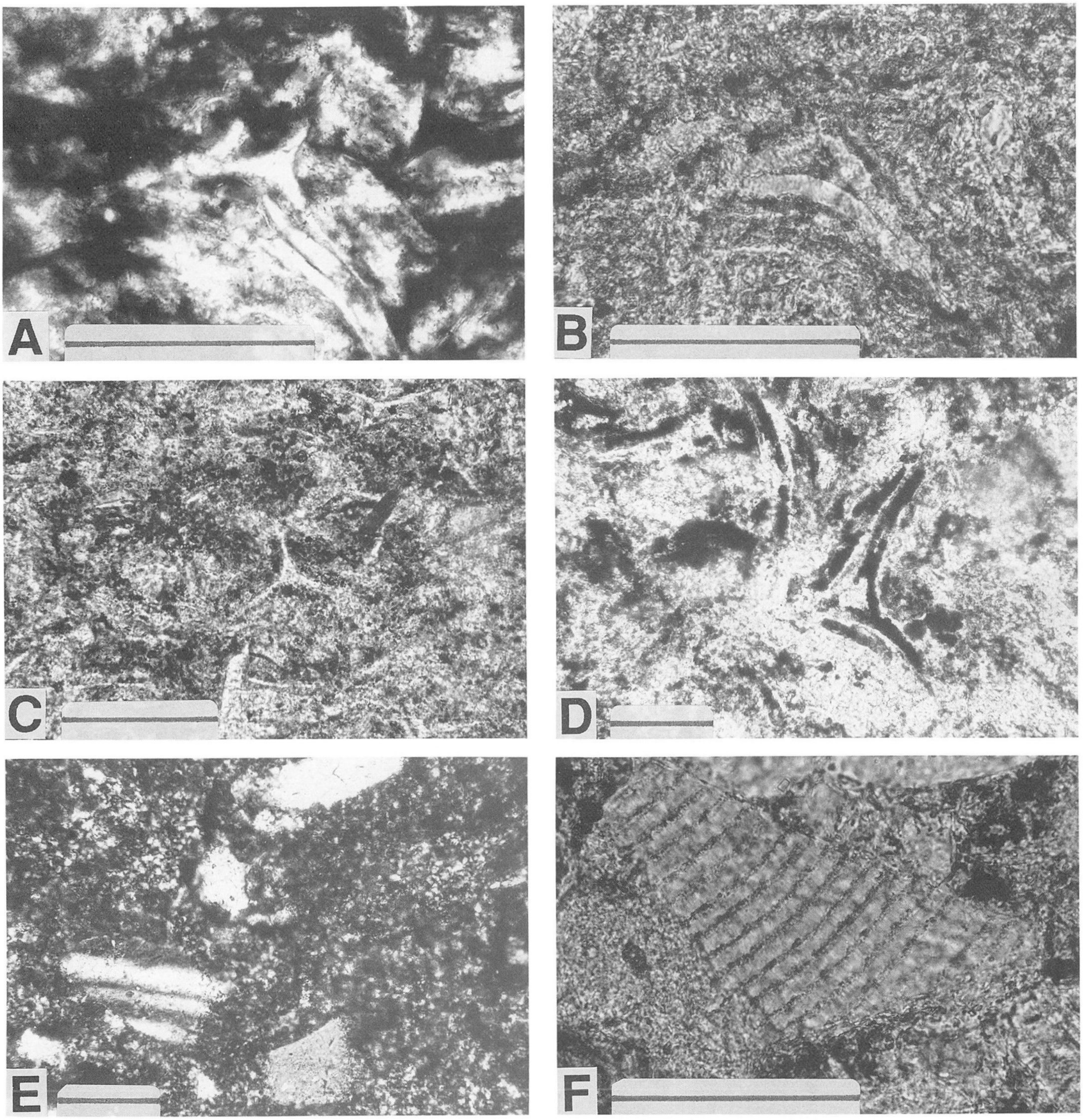


Figure 20. Photomicrographs. The bar scale is 0.1 mm long. A. Vitric tuff with shards replaced by clay, sample SA 16a, Whitehill Formation, Remhoogte. B. Argillite with curvilinear fragments interpreted as shards with triple junctions, SA 15, basal Collingham Formation, Remhoogte. C. Siltstone with devitrified glass shards, SA 7a, basal Collingham Formation, Ecca Pass. D. Tuff of shards in felsitic groundmass partly replaced by carbonate, SA 10, Fort Brown Formation, 13 km north of Wolwefontein. E. Angular feldspar and quartz in a felsitic groundmass, crossed nicols, SA 14c, Matjiesfontein Chert (Collingham Formation), Remhoogte. F. Fine-grained sandstone with a lithic grain of sedimentary chert (banded chalcedony), SA 11c, Fort Brown Formation, Geelhoutboom.

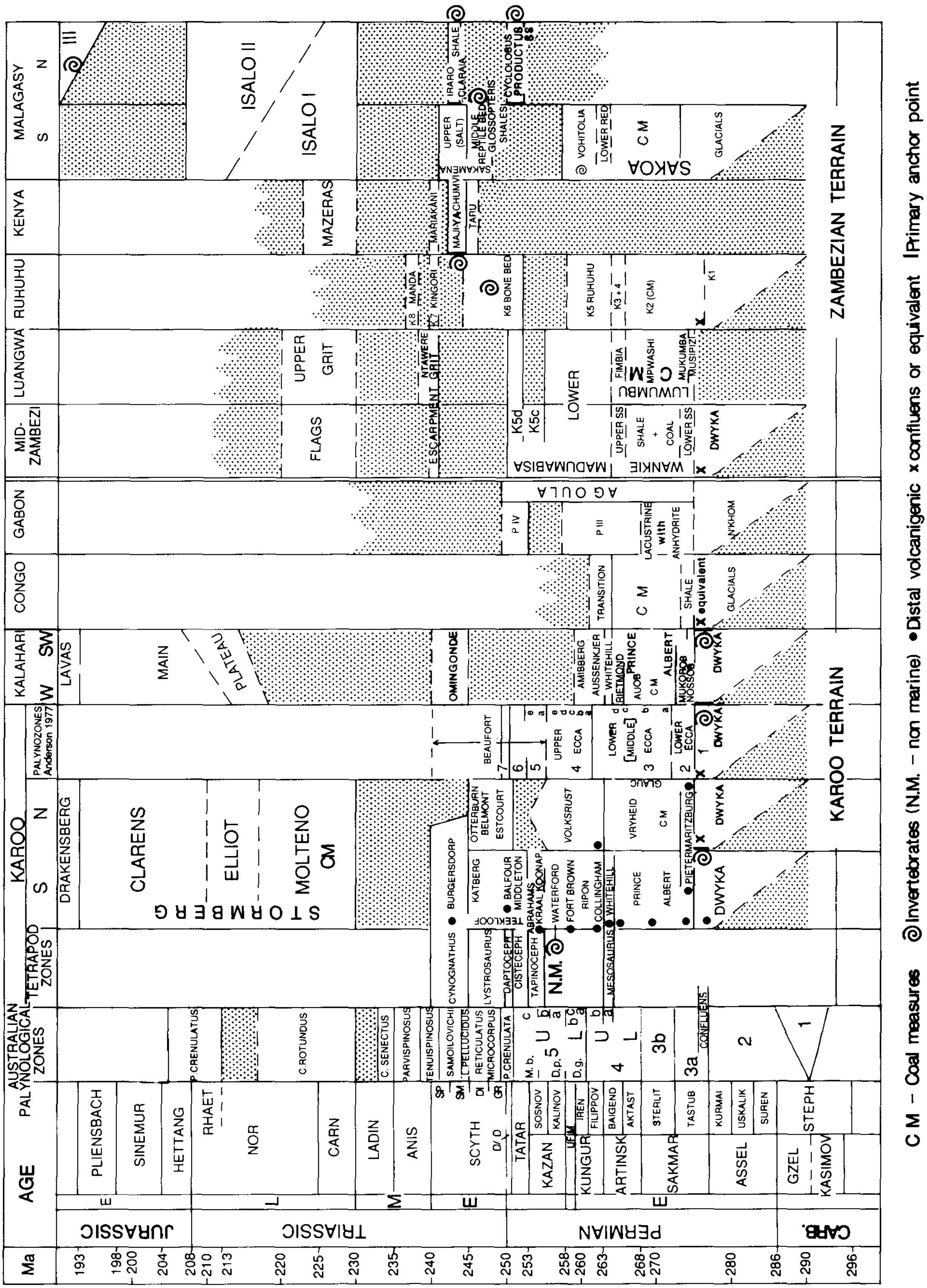


Figure 21. Correlation chart for southern Africa.

Anderson (1981)	Keyser and Smith (1979)
Cynognathus	*Kannemeyeria*
Lystrosaurus	*Lystrosaurus*
Daptocephalus	*Dicynodon lacerticeps*
Cistecephalus	*Aulacephalodon baini* *Tropidostoma microtrema*
Tapinocephalus	*Pristerognathus/Diictodon* Dinocephalian
Mesosaurus	

According to Dingle et al. (1983), the *Cynognathus* Zone is upper Griesbachian, the *Lystrosaurus* Zone all or partly lower Griesbachian, the *Dicynodon lacerticeps* (= *Daptocephalus*) Zone presumably Dorashamian as well as Djulfian (to which it was restricted by Anderson, 1981) because evidence of a lacuna is lacking. Anderson and Cruickshank (1978) date the *Cynognathus* Zone as late Spathian—note the occurrence of *Paratosaurus* of the *Cynognathus* Zone of South Africa (Dingle et al., 1983) in the Gosford Formation and Hawkesbury Sandstone of eastern Australia (Spathian-Anisian, Fig. 44 in Chap. 3). Since evidence of a lacuna between the *Lystrosaurus* and *Cynognathus* Zones is lacking, I extend each zone to the mid-Scythian, so that the *Lystrosaurus* Zone is taken as Griesbachian and Dienerian, and the *Cynognathus* Zone as Smithian and Spathian.

The ages of Anderson's (1981) Karoo zones 5–7 are calibrated by tetrapods.

Basins

North and northeastern Karoo (Anderson, 1981).

Correlation by palynomorphs encompasses the Dwyka to Molteno, except the Katberg and Burgersdorp, correlated by tetrapods.

Dwyka Formation. According to Anderson (1977, p. 43; 1981), palynozone 1 is restricted to the Dwyka Formation. Truswell (1980) tentatively correlated palynozone 1 with East Australian Stage 2, and this was confirmed by Backhouse (1991). Foster and Waterhouse (1988) correlated the Dwyka Formation (?uppermost part) with the *G. confluens* zone, which I regard as early Tastubian or lower Stage 3a. The fish at the top of the Dwyka at Douglas (locality c in Figs. 1 and 11) also indicate Tastubian. The apparent range of the Dwyka (= South African palynozone 1) in the northern and northeastern Karoo and, according to Anderson (1981), in the southern Karoo (and of the glacials in the Congo and mid-Zambezi Basins), is East Australian Stage 2 and lower 3a (shown by the oblique broken line). The overlying palynozone 2 is placed in the later Tastubian or upper Stage 3a. The biostratigraphical ages underpin Visser's (1990, fig. 6) modeled age of Stephanian to Sakmarian, calculated from sedimentation rates, eustatic events, and facies trends.

Ecca Group. According to McLachlan (1977), the ammonoid recorded from the Ecca Series of Natal is not *in situ.* Glauconite is the only physical indicator of a possible marine depositional environment in the northern Karoo Basin, and it occurs in the Vryheid (or Middle Ecca) Formation, in palynozone 3 (Anderson, 1977, chart 2).

Tetrapods. The *Cynognathus* Zone is restricted to the Burgersdorp Formation, which is overlapped by the Stormberg Group northeast of the line between 27°E, 29°S and 29°E, 32°S (Kitching, 1970; Dingle et al., 1983, p. 14, 18, 22). In northwest Natal, the Estcourt Formation is equivalent to the *Daptocephalus* Zone (Keyser and Smith, 1979, p. 12) and possibly also to the *Lystrosaurus* Zone (Dingle et al., 1983, p. 21). The Otterburn Formation also contains *Lystrosaurus* Zone fossils (Dingle et al.,1983, p. 23) and the Belmont Formation lies within the *Lystrosaurus* Zone (Dingle et al., 1983, p. 23). The Molteno Formation is dated by its macro- and micro-floras (Anderson and Anderson, 1983, p. 8).

Southern and central Karoo (Anderson, 1981).

Formations are correlated by the following:

(a) Those palynomorphs not destroyed by the intense deformation and dolerite intrusion experienced in the southern Karoo provide correlation of the Dwyka, Prince Albert, Fort Brown, and Middleton Formations. The age of the Dwyka Formation in the south is poorly constrained (Anderson, 1977, p. 51, 52) but, as noted already, Anderson (1981) sees no reason to regard it as any older or younger than it is in the north. Visser (1990) developed a facies model in which deposition of the Dwyka Formation becomes younger from shelf-ice deposits in the south to valley deposits in the north, but paleontological evidence of diachronous deposition is lacking.

(b) Tetrapods: (i) in the Whitehill Formation, the vertebrate assemblage of the *Mesosaurus* zone is dated by its position at the boundary between palynozones 3 and 4 (Anderson, 1981), equivalent to the middle of Eastern Australian Stage 4 or Baigendian, as found independently by Anderson and Anderson (1985, p. 29). This age in turn dates the Iratí Formation of the Paraná Basin of Brazil, correlated with the Whitehill through its mesosaurid fauna (Oelofsen, 1987). (ii) Waterford (Anderson and Anderson, 1985, p. 28): the nonmarine bivalve assemblage of the Waterford Formation (Cooper and Kensley, 1984) is dated as mid- to late Kazanian (Kalinovian) from its conformable position beneath the tetrapod-bearing (Sosnovian and younger) Beaufort Group; in turn this dates the Estrada Nova Formation of the Paraná Basin of South America, correlated with the Waterford through its nonmarine bivalve fauna, already described by Runnegar and Newell (1971). (iii) Beaufort (Koonap, Abrahamskraal, Teekloof, Middleton, Balfour, Katberg, Burgersdorp) zoned by tetrapods (Keyser and Smith, 1979) over an interval from the Sosnovian through the Scythian, as detailed above.

(c) mega- and micro-flora : Molteno = Ipswich Coal Measures of Eastern Australia (Anderson and Anderson, 1983, p. 8) (*C. rotundus* zone, Carnian-early Norian). We follow Dingle et al. (1983, p. 28, 29) in discounting Stapleton's (1978) view that the age of the Molteno is indistinguishable from that of the Burgersdorp.

(e) superposition and interpolation: (1) Collingham and Ripon between the Whitehill and Waterford; (2) Elliot and Clarens above the Carnian-early Norian Molteno, and at and below the Toarcian (193 ± 5 Ma, Fitch and Miller, 1984) and younger Drakensberg lavas, consistent with the general age indicated by tetrapods (Dingle et al., 1983, p. 17, 43).

Kalahari.

The upper, marine part of the Dwyka is dated as Tastubian (*Eurydesma* fauna of Dickins, 1961, 1984; McLachlan and Anderson, 1973, 1975). Note the occurrence north of Etosha Pan of Anderson's Zone 2 spores from what are called Dwyka Shales (Truswell, 1980, p. 101), probably the Prince Albert Formation. Overlying formations are named from Kent (1980) and dated by Anderson (1981); Omingonde = Burgersdorp according to Anderson and Anderson (1983, chart 13) and Dingle et al. (1983, p. 72), with additionally Plateau and "Main" Sandstones.

Congo.

From Truswell (1980) and Anderson (1981).

Gabon.

From Truswell (1980).

Mid-Zambezi (Zimbabwe), Luangwa (Zambia), Ruhuhu (Tanzania).

From Truswell (1980), Anderson (1981), Anderson and Anderson (1983), and Foster and Waterhouse (1988). Coil = position of Cox's (1936) marine bivalves in the Kidodi area of Tanzania (Furon, 1963, p. 319) now nonmarine (Yemane and Kelts, 1990).

Kenya.

From Anderson and Anderson (1983), and Anderson (1981). Maji-ya-Chumvi with "une intercalation marine à Poissons et *Esthe-*

ria" (Blant, 1973, p. 197), correlated with the mid-Scythian of northern Malagasy.

Malagasy (Boast and Nairn, 1982).

Southern. Sakoa Group: Coal measures (CM) = Anderson's (1977) palynozone 3 (Anderson, 1981, supported by Truswell, 1980, p. 103). Glacials (barren) by superposition regarded (Anderson, 1981) as equivalent to Zone 1 and part of 2. Vohitolia Limestone Member, with brachiopods = Kungurian (Anderson, 1981).

Sakamena Group, lower part: The *Glossopteris* Shales of Furon (1963, p. 358) contain the same marine bivalves (*Modiolopsis stockleyi* Cox and *Gervillia elianae* Cox) as those in northern Tanzania (Furon, 1963, p. 319). Middle Reptile Bed dated by Anderson (1981) as lower Griesbachian (*see* Battail et al., 1987, for paleobiogeographical correlations with mainland Africa). The middle to ?lower parts are equivalent to the *L. pellucidus* zone of Eastern Australia (Foster, 1979, p. 126; Wright and Askin, 1987). The upper part (Bed 6 of Anderson, 1981) is dated as Dienerian/Smithian.

Isalo I: According to Dolby and Balme (1976, p. 127), there is "clear evidence for equating the *S. speciosus* zone to Goubin's Zone IIINA. It may also represent her Zone IIINB but this correlation is less obvious." Dolby and Balme (1976, fig. 10) show Isalo I ranging from top Carnian to base Rhaetian and overlapping Isalo II. Anderson (1981) and Anderson and Anderson (1983) show all the Isalo with marine invertebrates, contrary to all other sources who regard the Isalo as nonmarine except near the top (Isalo III), which, starting in the Toarcian, is dominantly marine. Dolby and Balme (1976, p. 127) find that Rhaetian-Liassic indices appear first in the upper part of Isalo II, from which I regard the top of Isalo II as end-Triassic.

Northern. The sequence starts with the *Productus* sandstone and *Cyclolobus* shale, equivalent to the Khachian Chhidru Formation of the Salt Range (Teichert, 1974, p. 376). Above a disconformity are the *Claraia* shales, beds with ammonoids, and the Iraro Shale with ammonoids at the top, all mid-Scythian according to Teichert (1974, p. 377). According to Anderson (1981), the Isalo is the same age here as in the south.

Age of distal volcanigenic material

Distal volcanigenic material (shown in Fig. 21 by the filled circles) ranges from the earliest Sakmarian or Tastubian (277 Ma) upper Dwyka Formation (1 in Table 2) to the late Scythian (240 Ma) Burgersdorp Formation (27 in Table 2).

Age of coal measures

Coal measures (CM) are restricted to the Sakmarian and Artinskian (277–263 Ma) of the Early Permian, to the Early Triassic (250–247 Ma)*, and to the Carnian (230–225 Ma) of the Late Triassic.

The Early Permian coal measures occur in the following units, from left to right on Fig. 21: Vryheid (Middle Ecca), Auob, unnamed coal measures in the Congo Basin, Wankie, Luwumbu, K2, and Sakoa. The oldest occurrence is in K2, in the Ruhuhu Basin, from the base of the Sakmarian or Tastubian (277 Ma), and the youngest is in the Vryheid and Sakoa, at the top of the Artinskian (263 Ma). Early Triassic* coal layers are restricted to the Estcourt Formation of the Beaufort Group (Fig. 8A, part III). The Late Triassic coal measures are restricted to the Carnian (230–225 Ma) part of the Molteno Formation.

Pre-Permian sequences in southern Africa

The Pre-Permian sequences beneath the Permo-Triassic basins are entirely Precambrian except the 9-km-thick mid-Paleozoic Cape Supergroup (Rust, 1973) beneath the southern Karoo Basin, the 1-km-thick Natal Group beneath the northeastern Karoo Basin, and the thin (2 m) arkose and mudstone tentatively dated as Ordovician-Silurian (Reimann, 1986) beneath the Barotse lobe of the Congo Basin.

*This is in the Estcourt Formation, which, containing *Glossopteris*, is Late Permian (G. J. Retallack, personal communication, 1993).

REFERENCES CITED

Adie, R. J., 1952a, The position of the Falkland Islands in a reconstruction of Gondwanaland: Geological Magazine, v. 89, p. 401–410.

Adie, R. J., 1952b, Representatives of the Gondwana System in the Falkland Islands, *in* Teichert, C., ed., Symposium sur les Séries de Gondwana: Algiers, 19th International Geological Congress, p. 385–392.

Allsopp, H. L., Bristow, J. W., Smith, C. B., Brown, R., Gleadow, A.J.W., Kramers, J. D., and Garvie, O. G., 1989, A summary of radiometric dating methods applicable to kimberlites and related rocks: Geological Society of Australia Special Publication 14, p. 343–357.

Anderson, A. M., and McLachlan, I. R., 1979, The oil-shale potential of the Early Permian White Band Formation in Southern Africa: Geological Society of South Africa Special Publication 6, p. 83–89.

Anderson, J. M., 1977, The biostratigraphy of the Permian and Triassic, Part 3: A review of Gondwana Permian palynology with particular reference to the northern Karoo Basin South Africa: Memoirs of the Botanical Survey of South Africa, v. 41, 67 p., 4 charts, 188 plates.

Anderson, J. M., 1981, World Permo-Triassic correlations: Their biostratigraphic basis, in Cresswell, M. M., and Vella, P., eds., Gondwana Five: Rotterdam, A. A. Balkema, p. 3–10.

Anderson, J. M., and Anderson, H. M., 1983, Palaeoflora of Southern Africa: Molteno Formation Triassic, Volume 1: Rotterdam, A. A. Balkema, 227 p.

Anderson, J. M., and Anderson, H. M., 1985, Palaeoflora of Southern Africa: Prodromus of South African megafloras: Devonian to Lower Cretaceous: Rotterdam, A. A., Balkema, 423 p.

Anderson, J. M., and Cruickshank, A.R.I., 1978, The biostratigraphy of the Permian and Triassic, Part 5: A review of the classification and distribution of Permo-Triassic tetrapods: Palaeontologia Africana, v. 21, p. 15–44.

Backhouse, J., 1991, Permian palynostratigraphy of the Collie Basin, Western Australia: Review of Palaeobotany and Palynology, v. 67, p. 237–314.

Barrett, S. F., and Isaacson, P. E., 1988, Devonian paleogeography of South America, *in* McMillan, N. J., Embry, A. F., and Glass, D. J., eds., Proceedings, International Symposium on the Devonian System, 2nd, Calgary, Volume 1: Regional syntheses: Canadian Society of Petroleum Geologists, p. 655–667.

Battail, R., Beltan, L., and Dutuit, J. M., 1987, Africa and Madagascar during Permo-Triassic time: The evidence of the vertebrate faunas, *in* McKenzie, G. D., ed., Gondwana Six: American Geophysical Union, Geophysical Monograph, v. 41, p. 147–155.

Beckinsdale, R. D., Tarney, J., Darbyshire, D.P.F., and Humm, M. J., 1976, Rb-Sr and K-Ar age determinations on samples of the Falkland Plateau basement at Site 330: Initial Reports of the Deep Sea Drilling Project, v. 36, p. 923–927.

Behr, S. H., 1986, Heavy mineral deposits in the Karoo Sequence, *in* Anhaeusser, C. R., and Maske, S., eds., Mineral deposits of southern Africa, Volumes I and II: Johannesburg, Geological Society of South Africa, p. 2105–2118.

Ben-Avraham, Z., Hartnady, C.J.H., and Malan, J. A., 1993, Early tectonic extension between the Agulhas Bank and the Falkland Plateau due to rotation of the Lafonia microplate: Earth and Planetary Science Letters, v. 117, p. 43–58.

Beukes, N. J., 1970, Stratigraphy and sedimentology of the Cave Sandstone Stage, Karroo System: Proceedings and papers, Gondwana Symposium, 2nd: Johannesburg, p. 321–342.

Blant, G., 1973, Structure et paléogeographie du littoral meridional et oriental de l'Afrique, *in* Blant, G., ed., Sedimentary basins of the African coasts: Paris, Association of African Geological Surveys, p. 193–233.

Boast, J., and Nairn, A.E.M., 1982, An outline of the geology of Madagascar, *in* Nairn, A.E.M., and Stehli, F. G., eds., The ocean basins and margins, Volume 6, The Indian Ocean: New York, Plenum, p. 649–696.

Botha, B.J.V., 1967, The provenance and depositional environment of the Red Beds Stage of the Karroo System: Proceedings, Conference on Gond-

wana Stratigraphy: Buenos Aires, p. 763–774.
Botha, B.J.V., and Linström, W., 1978, A note on the stratigraphy of the Beaufort Group in North-western Natal: Geological Society of South Africa Transactions, v. 81, p. 35–40.
Boucot, A. J., Brunton, C.H.C., and Theron, J. N., 1983, Implications for the age of South African Devonian rocks in which Tropidoleptus (Brachiopoda) has been found: Geological Magazine, v. 120, p. 51–58.
Bradshaw, M. A., and Webers, G. F., 1988, The Devonian rocks of Antarctica, *in* McMillan, N. J., Embry, A. F., and Glass, D. J., eds., Proceedings, International Symposium on the Devonian System, 2nd, Calgary, Volume 1: Regional syntheses: Canadian Society of Petroleum Geologists, p. 783–795.
Bristow, J. W., and Saggerson, E. P., 1983a, A general account of Karoo vulcanicity in southern Africa: Geologische Rundschau, v. 72, p. 1015–1059.
Bristow, J. W., and Saggerson, E. P., 1983b, A review of Karoo vulcanicity in southern Africa: Bulletin Volcanologique, v. 46, p. 135–159.
Burger, A. J., and Coertze, F. J., 1977, Summary of age determinations carried out during the period April 1974 to March 1975: Annals of the Geological Society of South Africa, v. 11, p. 317–321.
Cadle, A. B., and Hobday, D. K., 1977, A subsurface investigation of the Middle Ecca and Lower Beaufort in Northern Natal and the South-eastern Transvaal: Geological Society of South Africa Transactions, v. 80, p. 111–115.
Clarke, M. J., and Forsyth, S. M., 1989, Late Carboniferous-Triassic: Geological Society of Australia Special Publication 15, 293–338.
Cole, D. I., 1980, Aspects of the sedimentology of some uranium-bearing sandstones in the Beaufort West area, Cape Province: Geological Society of South Africa Transactions, v. 83, p. 375–390.
Cole, D. I., and Labuschagne, L. S., 1983, Shallow-marine placer deposits in the Witteberg Group near Willowmore, Cape Province: Transactions of the Geological Society of South Africa, v. 86, p. 105–116.
Cole, D. I., and McLachlan, I. R., 1991, Oil potential of the Permian Whitehill Shale Formation in the main Karoo basin, South Africa, *in* Ulbrich, H., and Rocha Campos, A. C., eds., Proceedings, Gondwana Seven: São Paulo, Instituto de Geociências, Universidade de São Paulo, p. 379–390.
Cole, D. I., and Wipplinger, P. E., 1991, Uranium and molybdenum occurrences in the Beaufort Group of the main Karoo basin, South Africa, *in* Ulbrich, H., and Rocha Campos, A. C., eds., Proceedings, Gondwana Seven: São Paulo, Brazil, Instituto de Geociências, Universidade de São Paulo, p. 391–406.
Cole, D. I., Smith, R.M.H., and Wickens, H. de V., 1990, Basin-plain to fluvio-lacustrine deposits in the Permian Ecca and Lower Beaufort Groups of the Karoo Sequence, Guidebook, Geocongress 1990: Cape Town, Geological Society of South Africa, p. 1–83.
Cooper, M. R., 1979, Discussion of J. W. Marchant's "The metal contents of organic separates of some Ecca shales": Geological Society of South Africa Transactions, v. 82, p. 275.
Cooper, M. R., and Kensley, B., 1984, Endemic South American Permian bivalve molluscs from the Ecca of South Africa: Journal of Paleontology, v. 58, p. 1360–1363.
Cooper, M. R., and Oosthuizen, R., 1974, Archaeocyatha-bearing erratics from the Dwyka Subgroup (Permo-Carboniferous) and their importance to continental drift: Nature, v. 247, p. 396–398.
Coutinho, J.M.V., Hachiro, J., Coimbra, A. M., and Santos, P. R., 1991, Ash-fall-derived vitroclastic tuffaceous sediments in the Permian of the Parana basin and their provenance, *in* Ulbrich, H., and Rocha Campos, A. C., eds., Proceedings, Gondwana Seven: São Paulo, p. 147–160.
Cowan, E. J., 1985, A basin analysis of the Triassic System, central coastal Sydney Basin [B.Sc. honours thesis]: Sydney, Macquarie University.
Cox, K. G., 1988, The Karoo Province, *in* Macdougall, J. D., ed., Continental flood basalts: Dordrecht, Kluwer, p. 239–271.
Cox, L. R., 1936, Karroo Lamellibranchia from Tanganyika Territory and Madagascar: Quarterly Journal of the Geological Society of London, v. 92, p. 32–57.
Cramer, F. H., Rust, I. C., and de Cramer, M.d.C.R., 1974, Upper Ordovician chitinozoans from the Cedarberg Formation of South Africa: Preliminary note: Geologische Rundschau, v. 63, p. 340–345.
Dawson, J. B., 1989, Geographic and time distribution of kimberlites and lamproites: relationships to tectonic processes: Geological Society of Australia Special Publication 12, 323–342.
de Beer, C. H., 1990, Simultaneous folding in the western and southern branches of the Cape Fold Belt: South African Journal of Geology, v. 93, p. 583–591.
de Beer, C. H., 1991, Author's reply to discussion on "Simultaneous folding in the western and southern branches of the Cape Fold Belt": South African Journal of Geology, v. 94, p. 393–395.
de Beer, J. H., 1983, Geophysical studies in the Southern Cape Province and models of the lithosphere in the Cape Fold Belt: Geological Society of South Africa Special Publication 12, p. 57–64.
de Beer, J. H., van Zijl, J.S.V., and Gough, D. I., 1982, The Southern Cape Conductive Belt (South Africa): Its composition, origin and tectonic significance: Tectonophysics, v. 83, p. 205–225.
de Villiers, J. E., and Wardhaugh, T. G., 1962, A sedimentary petrological study of some sandstones, conglomerates and tillites of the Cape and Karroo Systems: Transactions of the Geological Society of South Africa, v. 65, p. 101–108.
de Wit, M., Jeffery, M., Bergh, H., and Nicolaysen, L., 1988, Geological map of sectors of Gondwana reconstructed to their disposition 150 Ma ago: Tulsa, American Association of Petroleum Geologists, scale 1:10,000,000.
Dickins, J. M., 1961, *Eurydesma* and *Peruvispira* from the Dwyka Beds of South Africa: Palaeontology, v. 4, p. 138–148.
Dickins, J. M., 1984, Late Palaeozoic glaciation: Australian Bureau of Mineral Resources Journal, v. 9, p. 163–169.
Dickinson, W. R., 1985, Interpreting provenance relations from detrital modes of sandstones, *in* Zuffa, G. G., ed., Provenance of arenites: Dordrecht, D. Reidel, p. 333–361.
Dickinson, W. R., and Suczek, C. A., 1979, Plate tectonics and sandstone compositions: American Association of Petroleum Geologists Bulletin 63, p. 2164–2182.
Dickinson, W. R., Beard, L. S., Brakenridge, G. R., Erjavec, J. L., Ferguson, R. C., Inman, K. F., Knepp, R. A., Lindberg, F. A., and Ryberg, P. T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222–235.
Dingle, R. V., Siesser, W. G., and Newton, A. R., 1983, Mesozoic and Tertiary geology of southern Africa: Rotterdam, A. A. Balkema, 375 p.
Dolby, J., and Balme, B. E., 1976, Triassic palynology of the Carnarvon Basin, Western Australia: Reviews of Palaeobotany and Palynology, v. 22, p. 105–168.
Du Toit, A. L., 1937, Our wandering continents: Edinburgh, Oliver and Boyd, 366 p.
Eales, H. V., March, J. S., and Cox, K. G., 1984, The Karoo Igneous Province: An introduction: Geological Society of South Africa Special Publication 13, p. 1–26.
Elliot, D. H., and Watts, D. R., 1974, The nature and origin of volcaniclastic material in some Karoo and Beacon rocks: Geological Society of South Africa Transactions, v. 77, p. 109–111.
Eriksson, P. G., 1979, Mesozoic sheetflow and playa sediments of the Clarens Formation in the Kamberg area of the Natal Drakensberg: Geological Society of South Africa Transactions, v. 82, p. 257–258.
Eriksson, P. G., 1984, A palaeoenvironmental analysis of the Molteno Formation in the Natal Drakensberg: Geological Society of South Africa Transactions, v. 87, p. 237–244.
Eriksson, P. G., 1985, The depositional palaeoenvironment of the Elliot Formation in the Natal Drakensberg and north-eastern Orange Free State: Geological Society of South Africa Transactions, v. 88, p. 19–26.
Fitch, F. J., and Miller, J. A., 1984, Dating Karoo igneous rocks by the conventional K-Ar and $^{40}Ar/^{39}Ar$ age spectrum method: Geological Society

of South Africa Special Publication 13, p. 247–266.

Folk, R. L., Andrews, P. B., and Laws, D. W., 1970, Detrital sedimentary rock classification and nomenclature for use in New Zealand: New Zealand Journal of Geology and Geophysics, v. 13, p. 937–968.

Foster, C. B., 1979, Permian plant microfossils of the Blair Athol Coal Measures and basal Rewan Formation of Queensland: Queensland Geological Survey, Palaeontological Papers, v. 45.

Foster, C. B., and Waterhouse, J. B., 1988, The Granulatosporites confluens Oppel-zone and Early Permian marine faunas from the Grant Formation on the Barbwire Terrace, Canning Basin, Western Australia: Australian Journal of Earth Sciences, v. 35, p. 135–157.

Frakes, L. A., and Crowell, J. C., 1967, Facies and paleogeography of Late Paleozoic diamictite, Falkland Islands: Geological Society of America Bulletin 78, p. 37–58.

Frakes, L. A., and Crowell, J. C., 1970, Late Paleozoic glaciation: II, Africa exclusive of the Karroo Basin: Geological Society of America Bulletin, v. 81, p. 2261–2286.

Fuller, A. O., 1970, The occurrence of laumontite in strata of the Karoo System, South Africa: Proceedings and Papers, Gondwana Symposium, 2nd: Johannesburg, p. 455–456.

Fuller, A. O., 1985, A contribution to the conceptual modelling of pre-Devonian fluvial systems: Geological Society of South Africa Transactions, v. 88, p. 189–194.

Furon, R., 1963, Geology of Africa: Edinburgh, Oliver and Boyd, 377 p.

Gardiner, B. G., 1969, New palaeoniscoid fish from the Witteberg Series of South Africa: Zoological Journal of the Linnean Society, v. 48, p. 423–452.

Geological Map of the Republic of South Africa, 1970: Pretoria, Department of Mines, scale 1:1,000,000.

Geological Map of the Republic of South Africa, 1984: Pretoria, Department of Mineral and Energy Affairs, scale 1:1,000,000.

Germs, G.J.B., and Gresse, P. G., 1991, The foreland basin of the Damara and Gariep orogens in Namaqualand and southern Namibia: Stratigraphic correlations and basin dynamics: South African Journal of Geology, v. 94, p. 159–169.

Gravenor, C. P., 1979, The nature of the Late Paleozoic glaciation in Gondwana as determined from an analysis of garnets and other heavy minerals: Canadian Journal of Earth Sciences, v. 16, p. 1137–1153.

Hälbich, I. W., 1983, A tectogenesis of the Cape Fold Belt (CFB): Geological Society of South Africa Special Publication 12, p. 165–175.

Hälbich, I. W., compiler, 1993, The Cape Fold Belt–Agulhas Bank transect across Gondwana suture, Southern Africa, Washington, D.C., American Geophysical Union, 18 p.

Hälbich, I. W. and Hartnady, C., 1985, Structural correlation on the Swartland Dome between Riebeek-Kasteel, Malmesbury and Moorreesburg: Geological Society of South Africa Field Guide, 11 p.

Hälbich, I. W., Fitch, F. J., and Miller, J. A., 1983, Dating the Cape orogeny, *in* Söhnge, A.P.G., and Hälbich, I. W., eds., Geodynamics of the Cape Fold Belt: Geological Society of South Africa Special Publication 12, p. 149–164.

Hartnady, C., Joubert, P., and Stowe, C., 1985, Proterozoic crustal evolution in southwestern Africa: Episodes, v. 8, p. 236–243.

Haughton, S. H., 1969, Geological history of southern Africa: Johannesburg, Geological Society of South Africa, 535 p.

Heinemann, M., and Buhmann, D., 1987, Coal-tonsteins from the Molteno Formation of the Maluti District, Transkei: South African Journal of Geology, v. 90, p. 296–304.

Helby, R., Morgan, R., and Partridge, A. D., 1987, A palynological zonation of the Australian Mesozoic: Association of Australasian Palaeontologists Memoir 4, p. 1–94.

Hergt, J. M., McDougall, I., Banks, M. R., and Green, D. H., 1989, Jurassic dolerite: Geological Society of Australia Special Publication 15, p. 375–381.

Hiller, N., 1992, The Ordovician system in South Africa: A review, *in* Webby, B. D., and Laurie, J. R., eds., Global perspectives on Ordovician geology: Rotterdam, A. A. Balkema, p. 473–485.

Hiller, N., and Stavrakis, N., 1980, Distal alluvial fan deposits in the Beaufort Group of the eastern Cape Province: Geological Society of South Africa Transactions, v. 83, p. 353–360.

Hiller, N., and Stavrakis, N., 1984, Permo-Triassic fluvial systems in the southeastern Karoo basin, South Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 45, p. 1–21.

Ho-Tun, E., 1979, Volcaniclastic material in lower Beaufort Group, Karoo rocks: Geological Society of South Africa, 18th Congress Abstracts, p. 197–199.

Hobday, D. K., 1973, Middle Ecca deltaic deposits in the Mulden-Tugela Ferry Area of Natal: Transactions of the Geological Society of South Africa, v. 76, p. 309–318.

Hobday, D. K., 1978, Palaeoenvironmental models in the eastern Karoo Basin: Palaeontologia Africana, v. 21, p. 1–13.

Hobday, D. K., 1987, Gondwana coal basins of Australia and South Africa: Tectonic setting, depositional system and resources: Geological Society of London Special Publication 32, p. 219–233.

Hobday, D. K., and Mathew, D., 1974, Depositional environment of the Cape Supergroup in the Transkei: Geological Society of South Africa Transactions, v. 77, p. 223–227.

Hobday, D. K., and Von Brunn, V., 1979, Fluvial sedimentation and paleogeography of an early Paleozoic failed rift, southeastern margin of Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 28, p. 169–184.

Hobday, D. K., Tavener-Smith, R., and Mathew, D., 1975, Markov analysis and the recognition of palaeoenvironments in the Ecca Group near Vryheid, Natal: Geological Society of South Africa Transactions, v. 78, p. 75–82.

Iijima, A., 1978, Geological occurrences of zeolites in marine environments, *in* Sand, L. B., and Mumpton, F. A., eds., Natural zeolites; occurrences, properties, and use: Oxford, Pergamon Press, p. 175–198.

Johnson, J. G., Klapper, G., and Sandberg, C. A., 1985, Devonian eustatic fluctuations in Euramerica: Geological Society of America Bulletin 96, p. 567–587.

Johnson, M. R., 1966, The stratigraphy of the Cape and Karoo Systems in the eastern Cape Province [M.Sc. thesis]: Grahamstown, South Africa, Rhodes University.

Johnson, M. R., 1976, Stratigraphy and sedimentology of the Cape and Karoo sequences in the eastern Cape Province [Ph.D. thesis]: Grahamstown, South Africa, Rhodes University, 336 p.

Johnson, M. R., 1991, Sandstone petrography, provenance and plate tectonic setting in Gondwana context of the southeastern Cape-Karoo Basin: South African Journal of Geology, v. 94, p. 137–154.

Jones, J. G., Conaghan, P. J., and McDonnell, K. L., 1987, Coal measures of an orogenic recess: Late Permian Sydney Basin, Australia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 58, p. 203–219.

Jordaan, M. J., 1981, The Ecca-Beaufort transition in the western parts of the Karoo Basin: Transactions of the Geological Society of South Africa, v. 84, p. 19–25.

Kent, L. E., 1980, Stratigraphy of South Africa, Part 1: Lithostratigraphy of the Republic of South Africa, South West Africa/Namibia, and the Republics of Bophutatswana, Transkei and Venda: Geological Survey of South Africa Handbook, v. 8, 690 p.

Keyser, A. W., and Smith, R.M.H., 1979, Vertebrate biozonation of the Beaufort Group with special reference to the western Karoo Basin: Geological Survey of South Africa Annals, v. 12, p. 1–35.

Keyser, N., and Zawada, P. K., 1988, Two occurrences of ash-flow tuff from the Lower Beaufort Group in the Heilbron-Frankfort area, northern Orange Free State: South African Journal of Geology, v. 91, p. 509–521.

Kingsley, C. S., 1970, Palaeocurrent directions in sandstone and arkose of the Beaufort Series of the Hendrik Verwoerd Dam basin: Geological Survey of South Africa Annals, v. 8, p. 87–88.

Kingsley, C. S., 1977, Stratigraphy and sedimentology of the Ecca Group in the eastern Cape Province, South Africa [Ph.D. thesis]: University of Port Elizabeth, 286 p.

Kingsley, C. S, 1979, Evidence for a southern and southeastern provenance during the Permian in South Africa: Proceedings and Papers, Gondwana Symposium, 4th: Calcutta, p. 683–694.

Kingsley, C. S., 1981, A composite submarine fan-delta-fluvial model for the Ecca and Lower Beaufort Groups of Permian age in the Eastern Cape province, South Africa: Geological Society of South Africa Transactions, v. 84, p. 27–40.

Kingsley, C. S., and Theron, J. C., 1964, Palaeocurrent directions in arkose of the Beaufort Series in the Orange Free State: Geological Survey of South Africa Annals, v. 3, p. 71–74.

Kitching, J. W., 1970, A short review of the Beaufort zoning in South Africa: Proceedings and Papers, Gondwana Symposium, 2nd: Johannesburg, p. 309–312.

Kreuser, T., and Semkiwa, P. M., 1987, Geometry and depositional history of a Karoo (Permian) coal basin (Mchuchuma-Ketewaka) in SW-Tanzania: Neues Jahrbuch fur Geologie und Palaontologie Monatshefte, v. 2, p. 69–98.

Le Roux, J. P., 1985, Palaeochannels and uranium mineralization on the main Karoo basin of South Africa [Ph.D. thesis]: University of Port Elizabeth, 250 p.

Lock, B. E., 1973, The Cape Supergroup in Natal and the northern Transkei: Geological Magazine, v. 110, p. 485–486.

Lock, B. E., and Johnson, M. R., 1974, A crystal tuff from the Ecca Group near Lake Mentz, Eastern Cape province: Geological Society of South Africa Transactions, v. 77, p. 373–374.

Lock, B. E., and Wilson, J. D., 1975, The nature and origin of volcaniclastic material in some Karoo and Beacon rocks: Discussion: Geological Society of South Africa Transactions, v. 78, p. 171.

Lock, B. E., Paverd, A. L., and Broderick, T. J., 1974, Stratigraphy of the Karoo volcanic rocks of the Barkly East district: Geological Society of South Africa Transactions, v. 77, p. 117–129.

Loock, J. C., and Visser, J.N.J., 1985, South Africa, *in* Martinez Diaz, C., ed., The Carboniferous of the world, II: Australia, Indian subcontinent, South Africa, South America, and North Africa: Madrid, Instituto Geológico y Minero de España, p. 167–174.

Marchant, J. W., 1978, The metal contents of organic separates of some Ecca shales: Geological Society of South Africa Transactions, v. 81, p. 173–178.

Marshall, C.G.A., 1988, Some aspects of the Natal Group between Durban and Eshowe: Geological Society of South Africa, 22nd Congress Abstracts, p. 379–382.

Marshall, J.E.A., 1994, The Falkland Islands: A key element in Gondwana paleogeography: Tectonics, v. 13, p. 499–514.

Martin, K. A., Hartnady, C.J.H., and Goodlad, S. W., 1981, A revised fit of South America and south central Africa: Earth and Planetary Science Letters, v. 54, p. 293–305.

Martini, J.E.J., 1974, On the presence of ash beds and volcanic fragments in the Southern Cape Province (South Africa): Geological Society of South Africa Transactions, v. 77, p. 113–116.

Mason, T. R., and Taverner-Smith, R., 1978, A fluvio-deltaic Middle Ecca succession west of Empangeni, Zululand: Geological Society of South Africa Transactions, v. 81, p. 13–22.

McDonnell, K. L., 1983, The Sydney Basin from Late Permian to Middle Triassic, a study focused on the coastal transect [Ph.D. thesis]: Sydney, Macquarie University.

McLachlan, I. R., 1973, Problematic microfossils from the Lower Karoo beds in South Africa: Palaeontologia Africana, v. 15, p. 1–21.

McLachlan, I. R., 1977, An investigation of the Lower Permian Middle Ecca ammonite locality at Alleta, Natal: Palaeontologia Africana, v. 20, p. 53–63.

McLachlan, I. R., and Anderson, A. M., 1973, A review of the evidence for marine conditions in southern Africa during Dwyka times: Palaeontologia Africana, v. 15, p. 37–64.

McLachlan, I. R., and Anderson, A. M., 1975, The age and stratigraphic relationship of the glacial sediments in southern Africa, *in* Campbell, K.S.W., ed., Gondwana Geology: Canberra, Australian National University Press, p. 415–422.

McLachlan, I. R., and Anderson, A. M., 1977, Carbonates, "stromatolites" and tuffs in the Lower Permian White Band Formation: South African Journal of Science, v. 73, p. 92–94.

McLachlan, I. R., and Jonker, J. P., 1990, Tuff beds in the northwestern part of the Karoo Basin: South African Journal of Geology, v. 93, p. 329–338.

Mitchell, C., Taylor, G. K., Cox, K. G., and Shaw, J., 1986, Are the Falkland Islands a rotated microplate?: Nature, v. 319, p. 131–134.

Mosmann, R., Falkenhein, F.U.H., Goncalves, A., and Nepomuceno, F., 1986, Oil and gas potential of the Amazon Paleozoic basins, *in* Halbouty, M. T., ed., Future petroleum provinces of the world: American Association of Petroleum Geologists Memoir 40, p. 207–241.

Nel, H. J., 1962, A petrographic description of the Ecca sediments in the southern Karroo and eastern Orange Free State: Geological Survey of South Africa Annals, v. 1, p. 91–103.

Oelofsen, B. W, 1986, A fossil shark neurocranium from the Permo-Carboniferous (lowermost Ecca Formation) of South Africa, *in* Uyeno, T., Arai, R., Taniuchi, T., and Matsuura, K., eds., Indo-Pacific fish biology: Tokyo, Ichthyological Society of Japan, p. 107–124.

Oelofsen, B. W., 1987, The biostratigraphy and fossils of the Whitehill and Iratí Shale Formations of the Karoo and Parana Basins, *in* McKenzie, G. D., ed., Gondwana Six: American Geophysical Union Geophysical Monograph, v. 41, p. 131–138.

Oelofsen, B. W., and Araujo, D. C., 1987, *Mesosaurus tenuidens* and *Stereosternum tumidum* from the Permian Gondwana of both Southern Africa and South America: South African Journal of Science, v. 83, p. 370–372.

Oosthuizen, R.D.F., 1981, An attempt to determine the provenance of the southern Dwyka from palaeontological evidence: Palaeontologia Africana, v. 24, p. 27–29.

Partridge, T. C., and Maud, R. R., 1987, Geomorphic evolution of southern Africa since the Mesozoic: South African Journal of Geology, v. 90, p. 179–208.

Powell, C. McA., 1984, Uluru regime, *in* Veevers, J. J., ed., Phanerozoic earth history of Australia: Oxford, Clarendon, p. 290–340.

Reimann, K. U., 1986, Prospects for oil and gas in Zimbabwe, Zambia and Botswana: Episodes, v. 9, p. 95–101.

Rex, D. C., and Tanner, P.W.G., 1982, Precambrian age for gneisses at Cape Meredith in the Falkland Islands, *in* Craddock, C., ed., Antarctic Geoscience: Madison, University of Wisconsin Press, p. 107–108.

Rowsell, D. M., and de Swardt, A.M.J., 1976, Diagenesis in Cape and Karoo sediments, South Africa, and its bearing on their hydrocarbon potential: Geological Society of South Africa Transactions, v. 79, p. 81–145.

Rubidge, B., 1988, The palaeontology and palaeoenvironment of the rocks of the Ecca-Beaufort contact in the southern Karoo: Geological Society of South Africa, 22nd Congress Abstracts, p. 521–524.

Runnegar, B., and Newell, N. D., 1971, Caspian-like relict molluscan fauna in the South American Permian: American Museum of Natural History Bulletin 146, p. 1–66.

Rust, B. R., 1981, Sedimentation in an arid-zone anastomosing fluvial system: Journal of Sedimentary Petrology, v. 51, p. 745–755.

Rust, I. C., 1962, On the sedimentation of the Molteno Sandstones in the vicinity of Molteno, C.P.: Annals of the University of Stellenbosch, v. 37, Series A, p. 165–236.

Rust, I. C., 1973, The evolution of the Palaeozoic Cape Basin, southern margin of Africa, *in* Nairn, A.E.M., and Stehli, F. G., eds., The ocean basins and margins, Volume 1: The South Atlantic: Plenum, New York, p. 247–276.

Rust, I. C., 1975, Tectonic and sedimentary framework of Gondwana basins in southern Africa, *in* Campbell, K.S.W., ed., Gondwana geology: Canberra, Australian National University Press, p. 537–564.

Ryan, P. J., and Whitfield, G. G., 1979, Basinal analysis of the Ecca and lowermost Beaufort Beds and associated coal, uranium and heavy mineral beach sand occurrences: Geological Society of South Africa Special

Publication 6, p. 91–101.
Schmidt, E. R., 1976, Clay, *in* Coetzee, C. B., ed., Mineral resources of the Republic of South Africa: Geological Survey of South Africa Handbook, v. 7, p. 275–287.
Shone, R. W., 1987, A resedimented conglomerate and shallow-water turbidite from the Sardinia Bay Formation, Lower Table Mountain Group: South African Journal of Geology, v. 90, p. 86–93.
Smith, R.M.H., 1990, A review of stratigraphy and sedimentary environments of the Karoo Basin of South Africa: Journal of African Earth Sciences, v. 10, p. 117–137.
Söhnge, A.P.G., and Hälbich, I. W., eds., 1983, Geodynamics of the Cape Fold Belt: Geological Society of South Africa Special Publication 12, 184 p.
Stapleton, R. P., 1978, Microflora from a possible Permo-Triassic transition in South Africa: Review of Palaeobotany and Palynology, v. 25, p. 253–258.
Stavrakis, N., 1980, Sedimentation of the Katberg Sandstone and adjacent formations in the south-eastern Karoo Basin: Geological Society of South Africa Transactions, v. 83, p. 361–374.
Stear, W. M., 1980, Channel sandstone and bar morphology of the Beaufort Group uranium district near Beaufort West: Geological Society of South Africa Transactions, v. 83, p. 391–398.
Stear, W. M., 1985, Comparison of the bedform distribution and dynamics of modern and ancient sandy ephemeral flood deposits in the southwestern Karoo region, South Africa: Sedimentary Geology, v. 45, p. 209–230.
Tankard, A. J., Jackson, M.P.A., Eriksson, K. A., Hobday, D. K., and Minter, W.E.L., 1982, Crustal evolution of Southern Africa—3.8 billion years of earth history: New York, Springer-Verlag, 523 p.
Tarney, J., 1976, Petrology, mineralogy, and geochemistry of the Falkland Plateau basement rocks, Site 330, Deep Sea Drilling Project: Initial Reports of the Deep Sea Drilling Project, v. 36, p. 893–927.
Taverner-Smith, R., 1962, Karroo sedimentation in part of the mid-Zambezi valley: Geological Society of South Africa Transactions, v. 65, p. 43–74.
Tavener-Smith, R., 1982, Prograding coastal facies associations in the Vryheid Formation (Permian) at Effingham quarries near Durban, South Africa: Sedimentary Geology, v. 32, p. 111–140.
Teichert, C., 1974, Marine sedimentary environments and their faunas in Gondwana area: American Association of Petroleum Geologists Memoir 23, p. 361–394.
Thamm, A. G., 1987, Palaeoenvironmental significance of clast shape in the Nardouw Formation, Cape Supergroup: South African Journal of Geology, v. 90, p. 94–97.
Theron, J. C., 1970, Some geological aspects of the Beaufort Series in the Orange Free State [Ph.D. thesis]: Bloemfontein, University of the Orange Free State.
Theron, J. C., 1975, Sedimentological evidence for the extension of the African continent southwards during the Late Permian–Early Triassic times, *in* Campbell, K.S.W., ed., Gondwana geology: Canberra, Australian National University Press, p. 61–71.
Theron, J. N., 1970, A stratigraphical study of the Bokkeveld Group: Proceedings and Papers, Gondwana Symposium, 2nd: Johannesburg, p. 197–204.
Theron, J. N., 1972, The stratigraphy and sedimentation of the Bokkeveld Group [D.Sc. thesis]: University of Stellenbosch.
Theron, J. N., and Loock, J. C., 1989, Devonian deltas of the Cape Supergroup, South Africa: Canadian Society of Petroleum Geologists Memoir 14, p. 729–740.
Theron, J. N., Rickards, R. B., and Aldridge, R. J., 1990, Bedding plane assemblages of Promissum pulchrum, a new giant Ashgill conodont from the Table Mountain Group, South Africa: Palaeontology, v. 33, p. 577–594.
Thomas, R. J., 1989, A tale of two tectonic terranes: South African Journal of Geology, v. 92, p. 306–321.
Thomas, R. J., and Mawson, S. A., 1989, Newly discovered outcrops of Proterozoic basement rocks in northeastern Transkei: South African Journal of Geology, v. 92, p. 369–376.
Thomas, R. J., Marshall, C.G.A., Watkeys, M. K., Fitch, F. J., and Miller, J. A., 1992, K/Ar and $^{40}Ar/^{39}Ar$ dating of the Natal Group, southeast Africa: Post Pan-African molasse?: Journal of African Earth Science, v. 15, p. 453–471.
Truswell, E. M., 1980, Permo-Carboniferous palynology of Gondwanaland: Progress and problems in the decade to 1980: Australian Bureau of Mineral Resources Journal v. 5, p. 95–111.
Truswell, J. F., 1977, The geological evolution of South Africa: Cape Town, Purnell, 220 p.
Turner, B. R., 1971, The geology and coal resources of the north-eastern Cape Province: Geological Survey of South Africa Bulletin 52, 74 p.
Turner, B. R., 1972, Revision of the stratigraphic position of cynodonts from the upper part of the Karroo (Gondwana) System of Lesotho: Geological Magazine, v. 109, p. 349–360.
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]: Johannesburg, University of Witwatersrand, 314 p.
Turner, B. R., 1977, Fluviatile cross-bedding patterns in the Upper Triassic Molteno Formation of the Karoo (Gondwana) Supergroup in South Africa and Lesotho: Geological Society of South Africa Transactions, v. 80, p. 241–252.
Turner, B. R., 1978, Sedimentary patterns of uranium mineralisation in the Beaufort Group of the Southern Karoo (Gondwana) Basin South Africa, *in* Miall, A. D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 831–848.
Turner, B. R., 1980, Palaeohydraulics of an Upper Triassic braided river system in the main Karoo Basin, South Africa: Geological Society of South Africa Transactions, v. 83, p. 425–431.
Turner, B. R., 1981, Revised stratigraphy of the Beaufort Group in the Southern Karoo Basin: Palaeontologia Africana, v. 24, p. 87–98.
Turner, B. R., 1983, Braidplain deposition of the Upper Triassic Molteno Formation in the main Karoo (Gondwana) Basin, South Africa: Sedimentology, v. 30, p. 77–89.
Turner, B. R., 1984, Palaeogeographic implications of braid bar deposition in the Triassic Molteno Formation of the eastern Karoo Basin, South Africa: Palaeontologia Africana, v. 25, p. 29–38.
Turner, B. R., 1985, Uranium mineralization in the Karoo basin, South Africa: Economic Geology, v. 80, p. 256–269.
Turner, B. R., 1986, Tectonic and climatic controls on continental depositional facies in the Karoo Basin of northern Natal, South Africa: Sedimentary Geology, v. 46, p. 231–257.
Turner, B. R., 1990, Continental sediments in South Africa: Journal of African Earth Sciences, v. 10, p. 139–149.
Valloni, R., 1985, Reading provenance from modern marine sands, *in* Zuffa, G. G., ed., Provenance of arenites: Dordrecht, D. Reidel, p. 309–332.
Van Vuuren, C. J., and Cole, D. I, 1979, The stratigraphy and depositional environments of the Ecca Group in the northern part of the Karoo basin: Geological Society of South Africa Special Publication 6, p. 103–111.
Veevers, J. J., 1988, Gondwana facies started when Gondwanaland merged in Pangea: Geology, v. 16, p. 732–734.
Veevers, J. J., 1989, Middle/Late Triassic (230 ± 5 Ma) singularity in the stratigraphic and magmatic history of the Pangean heat anomaly: Geology, v. 17, p. 784–787.
Veevers, J. J., 1990, Tectonic-climatic supercycle in the billion-year plate-tectonic eon: Permian Pangean icehouse alternates with Cretaceous dispersed-continents greenhouse: Sedimentary Geology, v. 68, p. 1–16.
Veevers, J. J., and Powell, C. McA., 1987, Late Paleozoic glacial episodes in Gondwanaland reflected in transgressive-regressive depositional sequences in Euramerica: Geological Society of America Bulletin 98, p. 475–487.
Veevers, J. J., and Rundle, A. S., 1979, Channel Country fluvial sands and associated facies of central-eastern Australia: Modern analogues of Mesozoic desert sands of South America: Palaeogeography, Palaeoecology, Palaeoclimatology, v. 26, p. 1–16.

Verwoerd, W. J., Viljoen, J.H.A., and Viljoen, K. S., 1990, Olivine melilites and associated intrusives of the southwestern Cape Province, Guidebook, Geocongress 1990: Cape Town, Geological Society of South Africa, p. 1–60.

Viljoen, J.H.A., 1987, Subaqueous fallout tuffs of the Ecca Group in the Southern Cape Province, *in* Brown, G., and Preston, V. A., compilers, Workshop on pyroclastic volcanism and associated deposits: Pietermaritzburg, Department of Geology and Mineralogy, University of Natal, p. 45–48.

Viljoen, J.H.A., 1990, K-bentonites in the Ecca Group of the south and central Karoo Basin, Abstracts, Geocongress 1990: Cape Town, Geological Society of South Africa, p. 576–579.

Visser, J.N.J., 1972, Sedimentere insluitsels van Karoo-ouderdom in kimberliet van die Finsch-diamantmyn: Suid Africaanse Tydskrift vir Natuurwetenskap, v. 12, p. 32–36.

Visser, J.N.J., 1974, The Table Mountain Group: A study in the deposition of quartz arenites on a stable shelf: Geological Society of South Africa Transactions, v. 77, p. 221–237.

Visser, J.N.J., 1979, Changes in sediment transport direction in the Cape-Karoo basin (Silurian-Triassic) in South Africa: South African Journal of Science, v. 75, p. 72–75.

Visser, J.N.J., 1982, Implications of a diachronous contact between the Dwyka Formation and Ecca Group in the Karoo basin: South African Journal of Science, v. 78, p. 249–251.

Visser, J.N.J., 1984, A review of the Stormberg Group and Drakensberg Volcanics in southern Africa: Palaeontologia Africana, v. 25, p. 5–27.

Visser, J.N.J., 1986, Lateral lithofacies relationships in the glaciogene Dwyka Formation in the eastern and central parts of the Karoo basin: Geological Society of South Africa Transactions, v. 89, p. 373–383.

Visser, J.N.J., 1987, The palaeogeography of part of southwestern Gondwana during the Permo-Carboniferous glaciation: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 61, p. 205–219.

Visser, J.N.J., 1988, Facies interpretation of thick homogeneous diamictite of the Dwyka Formation in the southern Karoo Geological Society of South Africa Congress, 22nd, Abstracts: p. 677–680.

Visser, J.N.J., 1989, The Permo-Carboniferous Dwyka Formation of southern Africa: Deposition by a predominantly subpolar marine ice sheet: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 70, p. 377–391.

Visser, J.N.J., 1990, The age of the late Palaeozoic glacigene deposits in southern Africa: South African Journal of Geology, v. 93, p. 366–375.

Visser, J.N.J., 1991a, Self-destructive collapse of the Permo-Carboniferous marine ice sheet in the Karoo Basin: Evidence from the southern Karoo: South African Journal of Geology, v. 94, p. 255–262.

Visser, J.N.J., 1991b, Geography and climatology of the Late Carboniferous to Jurassic Karoo Basin in south-western Gondwana: Annals of the South African Museum, v. 99, p. 415–431.

Visser, J.N.J., 1993, Sea-level changes in a back-arc–foreland transition: The Late Carboniferous-Permian Karoo Basin of South Africa: Sedimentary Geology, v. 83, p. 115–131.

Visser, J.N.J., and Botha, B.J.V., 1980, Meander channel, point-bar, crevasse splay and aeolian deposits from the Elliot Formation in Barkly Pass, north-eastern Cape: Geological Society of South Africa Transactions, v. 83, p. 55–62.

Visser, J.N.J., and Dukas, B. A., 1979, Upward-fining fluviatile megacycles in the Beaufort Group, north of Graaff-Reinet, Cape Province: Geological Society of South Africa Transactions, v. 82, p. 149–154.

Visser, J.N.J., and Kingsley, C. S., 1982, Upper Carboniferous glacial valley sedimentation in the Karoo Basin, Orange Free State: Transactions of the Geological Society of South Africa, v. 85, p. 71–79.

Visser, J.N.J., and Loock, J. C., 1978, Water depth in the main Karoo Basin, South Africa, during Ecca (Permian) sedimentation: Geological Society of South Africa Transactions, v. 81, p. 185–191.

Visser, J.N.J., and Loock, J. C., 1982, An investigation of the basal Dwyka Tillite in the southern part of the Karoo Basin, South Africa: Geological Society of South Africa Transactions, v. 85, p. 179–187.

Visser, J.N.J., Loock, J. C., and Jordaan, M. J., 1980, Permian deltaic sedimentation in the western half of the Karoo Basin: Geological Society of South Africa Transactions, v. 83, p. 415–424.

Visser, J.N.J., Hall, K. J., and Loock, J. C., 1986, The application of stone counts in the glacigene Permo-Carboniferous Dwyka Formation, South Africa: Sedimentary Geology, v. 46, p. 197–212.

Von Brunn, V., and Gravenor, C. P., 1983, A model for late Dwyka glaciomarine sedimentation in the eastern Karoo Basin: Geological Society of South Africa Transactions, v. 86, p. 199–209.

Welman, J., Groenewald, G. H., and Kitching, J. W., 1991, Confirmation of the occurrence of Cynognathus Zone (Kannemeyeria-Diademodon Assemblage-zone) deposits (uppermost Beaufort Group) in the northeastern Orange Free State, South Africa: South African Journal of Geology, v. 94, p. 245–248.

Whateley, M.K.G., 1980, Deltaic and fluvial deposits of the Ecca Group, Nongoma Graben, Northern Zululand: Geological Society of South Africa Transactions, v. 83, p. 345–351.

Winchester, J. A., and Floyd, P. A., 1977, Geochemical discrimination of different magma series and their differentiation products using immobile elements: Chemical Geology, v. 20, p. 325–343.

Winter, H., and Venter, J. J., 1970, Lithostratigraphic correlation of recent deep boreholes in the Karoo-Cape sequence: Proceedings and papers, Gondwana Symposium, 2nd: Johannesburg, p. 395–408.

Wopfner, H., and Kreuser, T., 1986, Evidence for late Palaeozoic glaciation in southern Tanzania: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 56, p. 259–275.

Wright, R. P., and Askin, R. A., 1987, The Permian-Triassic boundary in the southern Morondava Basin of Madagascar as defined by plant microfossils, *in* McKenzie, G. D., ed., Gondwana Six: American Geophysical Union Geophysical Monograph, v. 41, p. 157–166.

Yassini, I., 1987, Ecology, paleoecology and stratigraphy of ostracodes from Late Pliocene and Quaternary deposits of the south Caspian Sea region in north Iran, *in* McKenzie, K. G., ed., Shallow Tethys 2: Rotterdam, A. A. Balkema, p. 475–497.

Yemane, K., and 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: Journal of African Earth Sciences, v. 10, p. 169–185.

Yoshida, M., and Kizaki, K., 1983, Tectonic situation of Lutzow-Holm Bay in East Antarctica and its significance in Gondwanaland, *in* Oliver, R. L., James, P. R., and Jago, J. B., eds., Antarctic Earth science: Cambridge, England, Cambridge University Press, p. 36–39.

Zawada, P. K., 1988, Trace elements as possible palaeosalinity indicators for the Ecca and Beaufort Group mudrocks in the southwestern Orange Free State: Geological Society of South Africa Transactions, v. 91, p. 18–26.

MANUSCRIPT ACCEPTED BY THE SOCIETY SEPTEMBER 9, 1993

Printed in U.S.A.