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Structural and sedimentary development of the continental margin off southwestern Africa

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The 1800 km divergent continental margin off southwestern Africa lies between two major orthogonal crustal lineaments: the modem Walvis Ridge abutment and the Agulhas Fracture Zone. Secondary lineaments subdivide it into Walvis and Orange sediment basins, and buoyant Lüderitz and Columbine/Agulhas arches. By comparison, the wider conjugate margins of South America suggest that the African side represents the upper-plate fragments of the original, Jurassic South Atlantic rift zone. Oceanic isolation during the early phases of continental separation resulted in a long period (?Hauterivian to late Aptian: 17 Ma) of anoxic marine sedimentation in the palaeo-southeast Atlantic, following the partial infilling of the rift valleys by lavas and continental detritus.

Albian to Oligocene sediments accumulated as huge marine delta/fans adjacent to the Orange River and in the bight of the Walvis Ridge. In the former, particularly rapid oceanward progradation during Santonian to Maastrichtian time was facilitated by continuous slumping on a massive scale. During the latter half of the Cenozoic (when terrigenous sediments were replaced by authigenic and biogenic sediments as the dominant forms), the continental margin off southwestern Africa suffered sediment starvation and there was relatively little accumulation on the shelves, and a nett loss from the deep-sea basins because of erosion.

Introduction

South Atlantic refits figured prominently in formative attempts at continental reconstructions (e.g. Du Toit, 1937). In the modern era, it was Bullard *et al.*'s (1965) computer fit of South Atlantic conjugate margins, allowing quantitative testing for over- and underlap, that enabled plate-tectonists to understand the spreading geometry of this region well before other areas of the globe had been investigated. This led to an early appreciation of the importance of tectonic compartments in the sedimentary history of the South Atlantic, and the roles played by the Equatorial and Falkland Plateau offsets, and the Walvis Ridge/Torres Arch volcanic centres (e.g. Le Pichon and Hayes, 1971; Francheteau and Le Pichon, 1972). In addition, the apparent simplicity and symmetry of the southern South Atlantic encouraged geophysicists to explore its margins and to propose models which were considered typical for passive (divergent) continental-margin development. As a result, the spreading history, magnetic-anomaly patterns and continent-ocean boundary (COB) structures of this region were intensely studied in the 1970s, and an early Cretaceous age established for its opening (e.g. Maxwell *et al.*, 1970; Hoskins *et al.*, 1974; Rabinowitz, 1976; Rabinowitz and LaBrecque, 1979). A good summary of this work was given by Simpson (1977) in the 15th Alex du Toit Memorial Lecture.

The age and facies of the sedimentary succession in the southeast Atlantic ocean basin was first investigated by Emery *et al.* (1975) who established a regional seismic stratigraphy that was subsequently refined by DSDP boreholes at sites 360 and 361 southwest of Cape Town (Bolli *et al.*, 1978). The acoustic-stratigraphic framework, based on seismic reflectors Atlantis II (All) and Davie (D) identified during these two studies, has remained the cornerstone for subsequent regional correlations in the Cape Basin, (e.g. Dingle *et al.*,1983; Emery and Uchupi 1984; Dingle and Robson, 1992). Commercial exploration has resulted in stratigraphies for continental shelf basins south of the Orange River (e.g. Gerrard and Smith, 1984; McMillan, 1990). A recent tectonic and stratigraphic interpretation of commercial seismics for the Namibian sector of the margin has been presented by Maslanyj *et al.* (1992), but this came to hand too late to consider for the present paper.

The continental margin off southwestern Africa lies between two major fractures that are associated with crustal lineaments orthogonally crossing the southern part of the South Atlantic: the Walvis Ridge/Torres Arch, and the Falkland/Agulhas Fracture Zone (Fig. 1). Early reconstructions assumed that rift initiation along this sector of the South Atlantic was geologically instantaneous (e.g. Dietz and Holden, 1970; Francheteau and Le Pichon, 1972), but an interpretation of multichannel seismic records and a reappraisal of Rabinowitz's (1976) magnetic data from the continent-ocean boundary (COB) by Austin and Uchupi (1982), has provided evidence for south-to-north rift propagation (e.g. Martin, 1984). In addition, major crustal fractures recognised across South America can be correlated with structural lineaments related to rifting between South America and southwestern Africa (e.g. Uchupi, 1989; Uchupi and Emery, 1991).

In this paper I will reappraise the Jurassic to Palaeogene sedimentary and tectonic development of the basins between the Walvis Ridge and the Agulhas Fracture Zone, and conclude by emphasising the role played by ocean currents in determining Neogene lithofacies and sediment distribution. It should be noted at this point that I have used the time scales of Harland *et al.* (1982).

Rift and early drift: Jurassic to early Cretaceous

Unternehr *et al.* (1988) have argued for intraplate dislocation along extensions of the Falkland Fracture Zone and the Walvis Ridge/Torres Arch, while further orthogonal subdivisions of this sector of the South Atlantic, originally suggested by Scrutton and Dingle (1977), have been identified by Uchupi and Emery (1991) as "insert basins..parallel to the structural grain of the Palaeozoic terrane accreted onto South America during the Permo-Triassic Gondwanide Orogeny." (Fig. 1). Specifically, these are the major Jurassic-Cretaceous rifts (Salado and Colorado) that lie adjacent to the northern and southern boundaries, respectively, of the Orange Basin (see Dingle *et al.*, 1983).

Figure 2 shows the structural framework of the Jurassic rifts in the southern proto-South Atlantic. Of note on the margin off southwestern Africa are:

1. the relatively small extent of the marginal basins (Walvis and Orange);
2. wide zones of buoyant basement (Lüderitz and Columbine/Agulhas arches) adjacent to the basin;
3. lack of insert basins projecting into the African continent;
4. the closeness of the basins' inner margin to the present coast.

A feature of this rift geometry is the asymmetry of basin disposition, which results in a particularly wide continental margin off Argentina and Uruguay (i.e. south of the Pelotas/Walvis basin), with large margin-parallel, as well as cross-margin (insert) basins. First noted by Dingle *et al.* (1983), a plausible explanation for this arrangement has been proposed by Uchupi and Emery (1991) (Fig. 3) based upon Klitgord *et al.*'s (1988) model for the divergent margin off eastern USA. Here, the trace of the master fault lies in the vicinity of the present Argentinian coastline.

Final continental separation occurred at the locus of the fault block polarity change, a position attained by migration of the upwarp in the asthenosphere as the lithosphere of the overlying upper-plate progressively stretched and thinned. This resulted in the spreading ridge lying closer to the coast of Africa and adjacent to relatively narrow, steep-sided basins on the upper-plate. Also, on the African side, buoyant granite cratons under the Lüderitz and Columbine/Agulhas arches resisted subsidence, with only the crust under the Orange and Walvis basins stretching and thinning significantly.

Maslanyj *et al.* (1992) have interpreted the tectonic style of the Namibian margin in terms of the simple shear model of Wernicke (1985).

Lithofacies in these rift basins was restricted to acidic lavas and continental deposits (e.g. Urien *et al.*, 1976; Gerrard and Smith, 1980; Malumian and Ramos, 1984), with marine sediments known only from peripheral areas: Neuquen basin in western Argentina, and on the collapsed section of the Cape Fold Belt, to the north of the Falkland/Agulhas Fracture Zone (Fig. 2). Extensive basic lavas of mid-Jurassic age (161-173 Ma) occur on the craton northeast of Lüderitz (Hoachanas), while interbedded ash and lavas of probable mid-late Jurassic age occur in the southeast, immediately to the north of the Falkland/Agulhas Fracture Zone (see summary in Dingle *et al.* ,1983; p112-113, 187-189, Table 36; Fig. 192).

Possibly through a combination of south-to-north rift propagation and differential lateral movement along orthogonal lineaments, the oldest sea-floor magnetic anomalies young from M9-10 (131 Ma, Valanginian/Hauterivian boundary) immediately north of the Agulhas Fracture Zone, to M4 (127 Ma, Hauterivian) in the sector between the Orange River and the Walvis Ridge (Fig. 4). These ages are close to those originally proposed by Larson and Ladd (1973), but the recognition of the COB off southwestern Africa has been a contentious issue (see Austin and Uchupi, 1982, and compare with Gerrard and Smith, 1984), and clearly is crucial to assessing the age of opening of the various sectors. In particular, the age of the oldest ocean crust adjacent to the northern Orange and the Walvis basins is uncertain.

The concept of a drift onset (or break -up) unconformity, that marks the change in lithofacies and basin tectonism accompanying the progression from rifting to drifting, was first propounded by Falvey (1974) and has been widely accepted. Gerrard and Smith (1984), equate this event with SOEKOR seismic Horizon R in the Orange Basin (Fig. 5; Dingle *et al.*, 1983). In view of the diachronism of the COB discussed above, the age of Horizon R (or equivalent) can be expected to vary by as much as 4 Ma between the Falkland Fracture Zone and the Walvis Ridge. The age of the oldest marine sediments, which in the distal parts of the margin are typically associated with the break-up unconformity (Falvey, 1974), depends on the time at which marine conditions were established in the newly created ocean basin. In view of the palaeogeography of the southeast Atlantic, this event could have been delayed by several million years. The only date available is from DSDP site 361, where Bolli *et al.* (1978, p. 68) identified early Aptian marine sediments 36-86 m (estimated from seismic profiles) above crust that lay 220 km west of the COB at the time of their deposition. In other words, a minimum age for marine sediments associated with the break-up unconformity in the southern part of the Cape Basin is early Aptian.

Figure 6 is a palaeogeography for mid-Cretaceous time (say late Aptian), when the Falkland Plateau barrier still lay across the southern exit to the opening oceanic basin. In terms of the stratigraphy of the sections in Figure 5, Figure 6 relates to time prior to Horizon All (= P of SOEKOR: McMillan 1990), which was dated as late Aptian by Bolli *et al.* (1978) at DSDP 361. With the exception of sediment thicknesses and some intuitive feel for lithofacies based on P-wave velocity measurements (e.g. Hoskins *et al.*, 1974; Goslin and Sibuet, 1975; Fig. 5), no data are available on the post-drift fill of the sediment accumulations in the Walvis Basin, and adjacent to the Lüderitz Arch. In contrast, the Kudu boreholes, which lie on the outer edge of the modem continental shelf, provide data on the litho- and biostratigraphy in the Orange Basin. Here, there was a sharp change in the depositional environment across Horizon All from an organic-rich lithofacies with abundant planktonic, but sparse benthic faunas below, to diverse abyssal assemblages above (McMillan, 1990). This is a remarkably similar succession to that found at DSDP 361 (organic carbon range 0.1 - 14.6%), which was deposited close to the spreading ridge 7° (750 km) farther south. Proximal facies within the Orange Basin comprise red beds and aeolian sands interbedded with various amygdaloidal basalts and tuffs (e.g. Wickens and McLachlan, 1990). Contemporaneous marine sedimentation on the relatively shallow Falkland Plateau produced similarly organic carbon-rich Aptian sediments (5.3 - 5.8% Corg) (Barker *et al.*,1977; Lorenzo and Mutter, 1988; see Dingle *et al.*, 1983 for summary).

Onshore, early Cretaceous aeolian sands and various volcanics are widespread in coastal Namibia, ranging from the thick Walvis Ridge/Torres Arch basalts (Etendeka lavas [132-108 Ma] and Etjo Sandstones) in the north, to the small-scale Lüderitz alkaline intrusives in the south (130 Ma) (see Dingle *et al.*, 1983, Table 36).

Termination of the early drift stage in the southeast Atlantic coincided with the separation of the Falkland Plateau from the southern tip of Africa. Theoretically, it would have been at this point that the southeast Atlantic was flushed by oxygenated waters from the southwest Indian Ocean. However, the two events did not coincide, presumably because deep fracture channels between the two continental units allowed entry of abyssal waters into the Cape Basin before the continental areas had finally separated. As mentioned above, the oceanic event, represented by horizon. All, occurred in the late Aptian (ca. 114 - 115 Ma), but dating the tec-

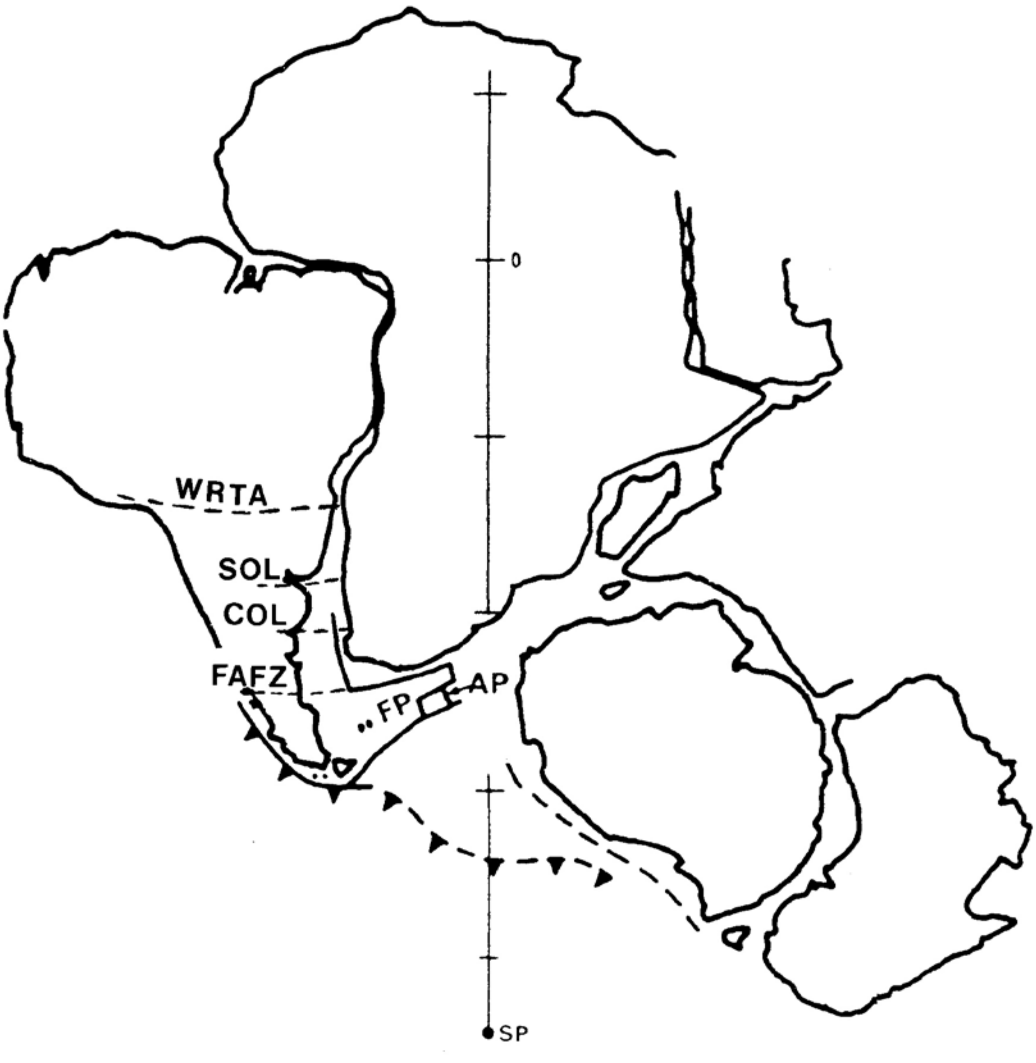


Figure 1: Jurassic Gondwana reconstruction showing lineaments affecting the southeast Atlantic Ocean. WRTA = Walvis Ridge/Torres Arch. SOL = Solado/Orange line, COL = Colorado/Orange line, FAFZ = Falkland/Agulhas Fracture Zone. FP = Falkland Plateau, AP = Agulhas Plateau, SP = south pole. After Dingle *et al.* (1983), Unternehr *et al.* (1988), Uchupi and Emery (1991)

tonic event is more difficult because it occurred during the mid-Cretaceous magnetically quiet period (83 - 118 Ma). Dingle *et al*. estimated it at 100 Ma (late Albian), and Martin and Hartnady (1986) place it between 93 and 105 Ma. Assuming a constant spreading rate during this period, I calculate it at 98.25 Ma (late Albian) using their data.

Mature drift: late Cretaceous to Palaeogene

Definitive seismic and borehole data have been published only for the Orange Basin, and although significant sedimentary accumulations are indicated farther north (e.g. Goslin *et al*., 1974; Goslin and Sibuet, 1975; Emery *et al*., 1975; Lehner and De Ruiter, 1977), no models summarising sedimentary development within the Walvis Basin and adjacent to the Lüderitz Arch have yet been published. Consequently, speculation can be made only on the basis of analogy with the Orange Basin.

In the latter, throughout late Cretaceous and Palaeogene time, progradation of the continental shelf, slope and rise involving massive transfer of terrigenous detritus onto oceanic crust, proceeded by means of large-scale slumping along a narrow zone of rotational faults located in the vicinity of the shelf edge (Figs 5 and 7). Dingle and Robson (1992) date commencement of rapid up- and outbuilding of the Orange delta/fan as Turonian, and Santonian to Maastrichtian as the period of maximum sediment supply. These increases in terrigenous detritus may correlate with climatic change, and one can speculate on a link with the flux of surface waters from the equatorial Angola Basin accompanying the establishment of shallow water connections across the Walvis Ridge barrier in late Cenomanian-early Turonian time (e.g. Dingle, 1988). Construction of the Orange delta/fan was affected by switches in source point from the Orange River to the Upper.Orange River (late Cretaceous) and back (late Oligocene) (Dingle and Hendey, 1984). This had the effect of periodically shifting the locus of deposition and slumping and it was during the use of the southern exit in the Oligocene that the Cape Canyon and fan were constructed (Fig. 7). A narrow extension of the Orange Basin outer-shelf slump

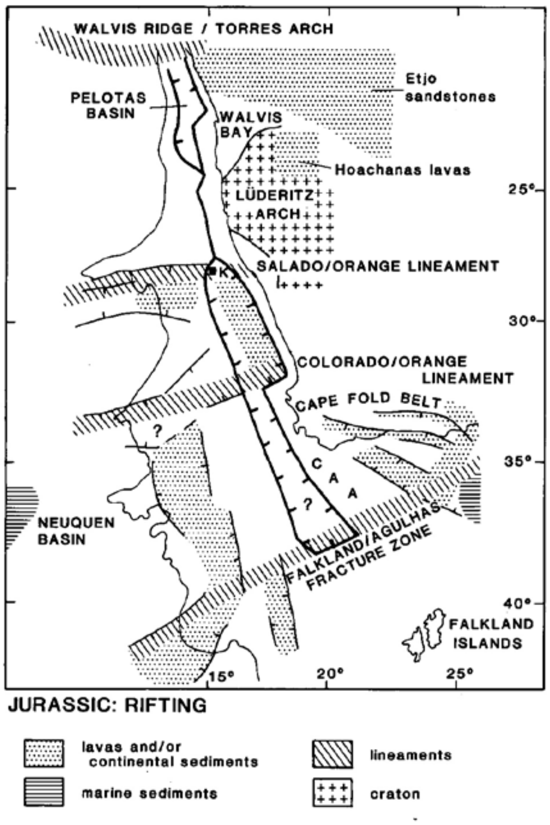


Figure 2: Palaeogeography of late Jurassic rift valleys of the southern South Atlantic. K = Kudu boreholes, CAA = Columbine/Agulhas Arch. Based on Dingle *et al.* (1983), Uchupi (1989), and Uchupi and Emery (1991)

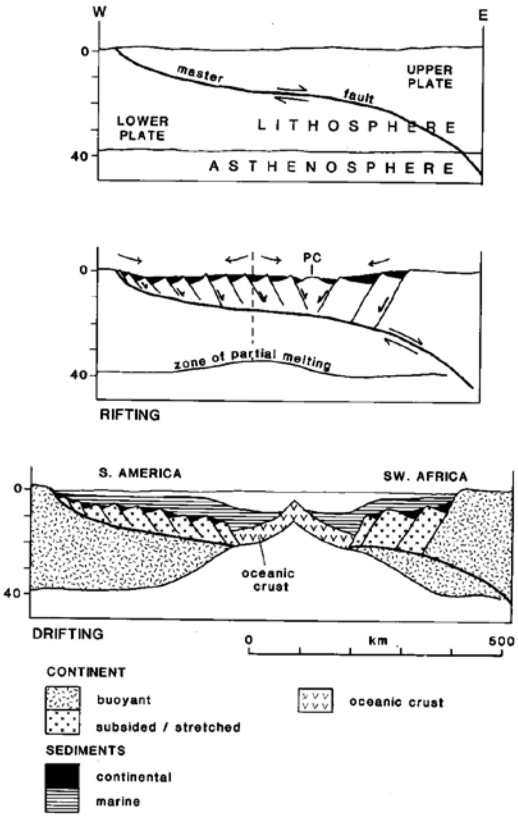


Figure 3: Schematic development of asymmetric divergent continental margins in the southern South Atlantic.
Top panel: location of master fault in initial phase of rifting
Middle panel: development of rift basins as crust on the upper plate stretches and thins. Direction of continental sediment movement (small arrows) and fill (black) is controlled by upwarp which develops over zone of partial melting at base of lithosphere (axis shown by dashed line). This migrates towards the point of rift-fault polarity change, where the stretching and thinning of the upper plate is greatest. The melt zone finally penetrates to the surface at this point, causing continental separation and ocean crust generation. PC = region of fault-block polarity change.
Lower panel: early drift phase and marine sedimentation
Vertical scales are km. Top and middle panels modified from Uchupi and Emery (1991), who based their model on Klitgord *et al.* (1988)

zone occurs along the western side of the Lüderitz Arch (Dingle and Robson, 1992; Fig.7).

In strong contrast to the Orange Basin, seismic coverage of the Walvis Basin (e.g. lines AM-03 and AM-02 in Austin and Uchupi, 1984) shows evidence for slumping within the post-AII Cretaceous interval to be limited to a few disturbed horizons on the middle slope. Figure 7 shows a hypothetical Walvis Basin fan complex constructed by a Kuiseb/Swakop river system.

Throughout the southeast Atlantic sedimentary succession, a prominent seismic reflector straddles the Maastrichtian-Palaeocene boundary. This is Horizon D of Emery *et al.* (1975) (= L of SOEKOR, e.g. McMillan, 1990), which was dated by Bolli *et al.* (1978) at DSDP site 360 on the slope due south of Cape Town. At this deep-water location,

Horizon D coincided with a 23 m brown clay rich in zeolites and fish debris that was deposited below the carbonate compensation depth (CCD). In this respect, it must represent deposition during a short period of more intensive bottom water corrosiveness, because the underlying late-Cretaceous sequence of deep-water shales, which contain no autochthonous calcareous

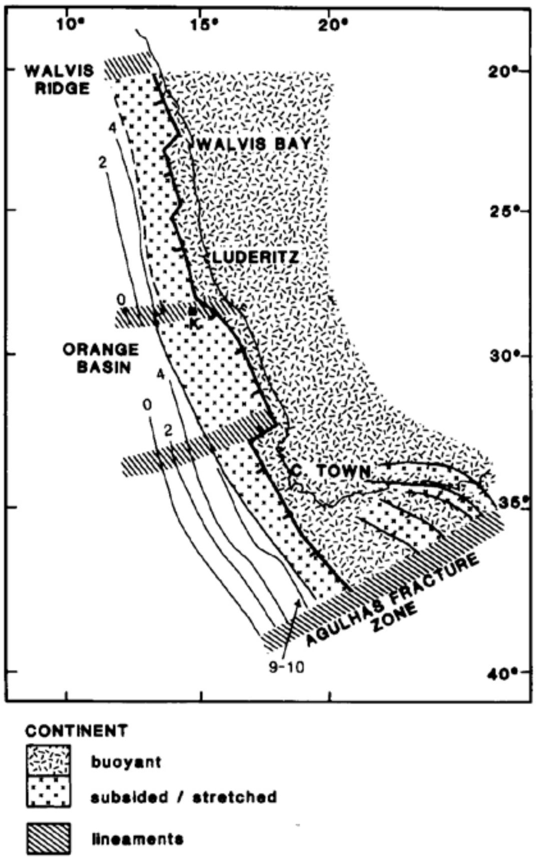


Figure 4: Continent/ocean boundary (COB) structure and age of oceanic magnetic anomalies (MO - M9-10) off southwestern Africa. Lineaments are those from Figure 2. K = Kudu boreholes. Using the time scale of Harland *et al.* (1982), MO is early Aptian (118-119 Ma) and M9-10 is late Valanginian—early Hauterivian (ca. 131 Ma). Based on Dingle *et al.* (1983) and Martin (1984)

planktonic foraminifera and only a sparse fauna of agglutinated benthic foraminifera, are themselves thought to have been deposited beneath the CCD (Bolli *et al.*, 1978).

The Kudu boreholes lie on the outer continental shelf, and in them, Horizon D (L) is represented by an hiatus that spans earliest Maastrichtian to latest Palaeocene time. The hiatus resulted from a period of tectonism (tilting) and erosion of Maastrichtian outer shelf/upper slope sediments, although the thickness of strata removed during this event is not known (McMillan, 1990).

It is of regional significance that on seismic records from the Walvis Basin, Horizon D can be traced from the continental rise onto the outer shelf (e.g. Emery *et al.*, 1975; Austin and Uchupi, 1982; Fig. 5). Clearly, a latest Cretaceous to earliest Tertiary period of outer margin tectonism, with concomitant changes in deep-sea oceanographic/sedimentary environments, affected the whole of the southeast Cape Basin. Coincident with this event was the previously mentioned switching of the Orange River outlet to what is today the lower Olifants valley (shown as Upper Orange River in Fig. 7). Dingle and Hendey (1984) suggested tectonism accompanied by intrusion of volcanic plugs in the hinterland south of the modem Orange River estuary (68-67 Ma) as a possible cause for this major drainage reorganisation, and the two tectonic events may have been related.

Influence of ocean currents: Miocene to Holocene

The establishment of the modem surface and deep water circulation patterns in the southeast Atlantic had a profound effect on the sedimentary history of the margin off southwestern Africa.

Although there is some evidence for the initiation of nearshore upwelling in a proto-Benguela system in Oligocene time (Siesser, 1978), intense upwelling and hinterland aridification date from the late Miocene (Siesser, 1978; Diester-Haass and Rothe, 1987). Prior to this date, early Miocene shelf microfaunas indicate subtropical water temperatures with faunal links to both east and west Africa (Christison, 1985; Dingle, in preparation).

Modem upwelling cells are quasi-permanent, with seasonal fluctuations in wind stress and surface-water temperatures confined to six well-defined areas between the Kunene River and Cape Town (e.g. Shannon, 1985; Lutjeharms and Meeuwis, 1987; Fig. 8). The cell which exhibits maximum upwelling intensity, and has the largest extent, lies between Lüderitz and a position north of Walvis Bay. Although all the upwell cells have certain common oceanographic characteristics (e.g. relatively low surface temperatures, high organic productivity), each is underlain by bottom sediments that are specific to the cell.

In general terms, the high organic productivity of the surface waters on the modern continental shelf off southwestern Africa, combined with the low terrigenous runoff from an arid hinterland, results in bottom sediments with high biogenic and/or authigenic contents. In the modem situation, the Lüderitz/Walvis cell exhibits the most extreme variations from "normal" continental shelf sedimentation by locally displaying: high organic-matter values, high opaline silica (diatomaceous muds) values, contemporaneous phosphate deposition, and various trace-metal signatures (see Rogers and Bremner (1991) for summary). The biogenical content of the sediments diminishes significantly away from the Lüderitz/Walvis cell, while the terrigenous mud content increases (e.g. south of the Kunene and Orange rivers).

There is no reason to suppose that the oceanographic climate of the west coast, and consequently its depositional environment, has changed significantly since late Miocene times. The only exception may have been during glacial episodes, when low sea levels and modified oceanic and atmospheric circulation would probably have moved the loci of cell upwelling farther offshore and perhaps latitudinally (e.g. equatorward according to Diester-Haass *et al.*, 1988). Consequently, sediments characterised by high biogenic (carbonate, siliceous, organic matter), high authigenic and low tenigenous contents can be expected to have accumulated in continental shelf and upper-slope environments off Namibia during most of Neogene time. Farther south, lower opaline silica and organic carbon values can be predicted in contemporaneous sequences.

In the Cape Basin, clockwise circulation of Antarctic Bottom Water (AABW), constrained by the Walvis Ridge, was established possibly in the early Oligocene (Johnson, 1982). Since late Miocene time it has maintained extensive areas of deep-water erosion or non-deposition (Fig. 8; Tucholke and Embley, 1984), with the development of ferro-manganese fields and omission surfaces over eroded Palaeogene sediments (e.g. Bolli *et al.*, 1978; Dingle *et al.*, 1987). Regional erosion at the foot of the continental slope (Bornhold and Summerhayes, 1977; Tucholke and Embley, 1984; Rogers, 1987) possibly triggered the large-scale continental-slope slumping mapped along the whole of the southwest African margin by Summerhayes *et al.* (1979) and Dingle (1980). Sediment removed during this prolonged period of erosion has been transported out of the Cape Basin by AABW flow and deposited as major bedforms in the southwest Indian Ocean (Dingle and CamdenSmith,1979).

Summary of sedimentation

Figure 9 summarises the sedimentary history of the continental margin off southwestern Africa since continental drifting commenced. It illustrates the similari-

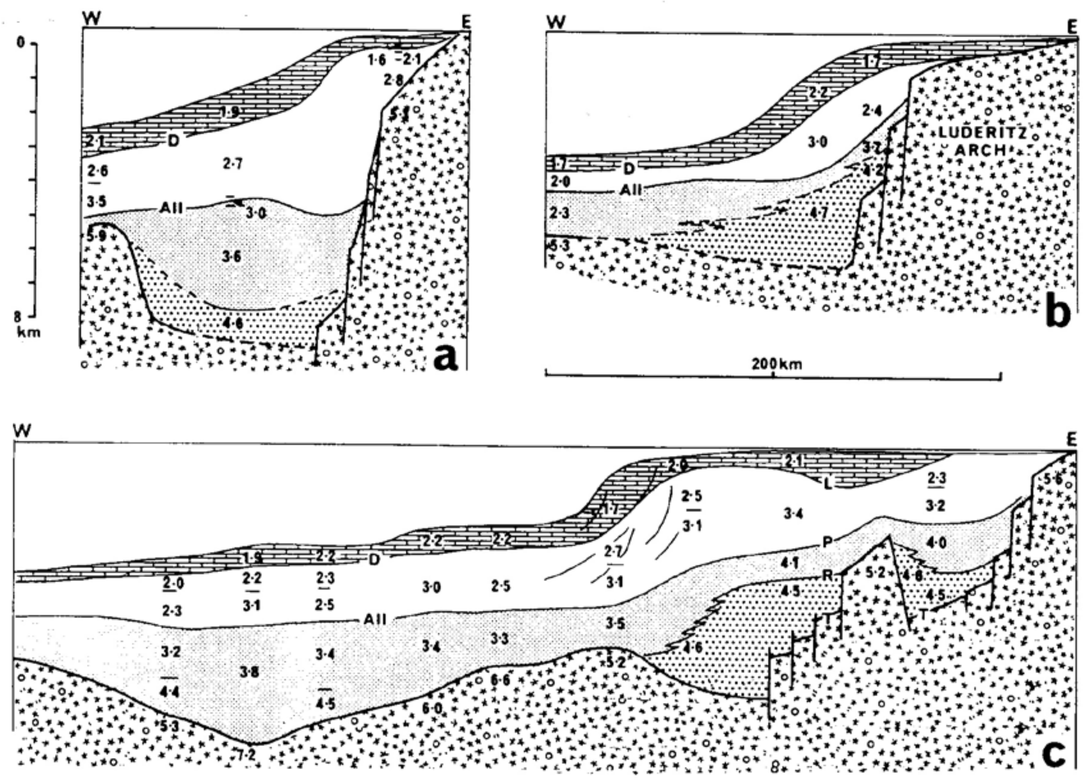


Figure 5: Schematic cross sections: a) Walvis Basin (24°S); b) Lüderitz Arch (27°S); c) Orange Basin (31°S.) Values are seismic refraction P-wave interval velocities. Shading is to identify strata between control seismic horizons R, AII = P, and D = L. See text for explanation of stratigraphc and lithologic significance. From Dingle *et al.* (1983)

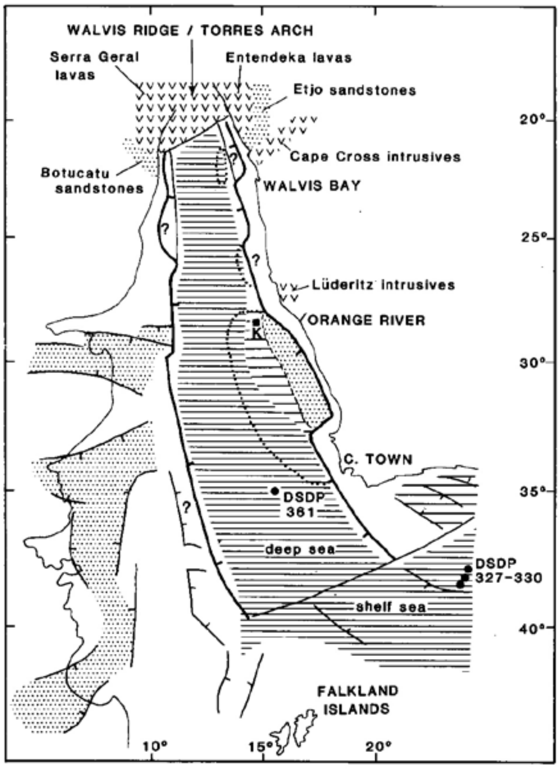
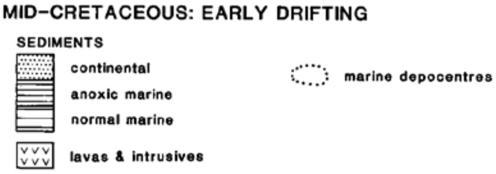


Figure 6 (left): Palaeogeography of Aptian early drift phase. K = Kudu boreholes. After Dingle *et al.* (1983)



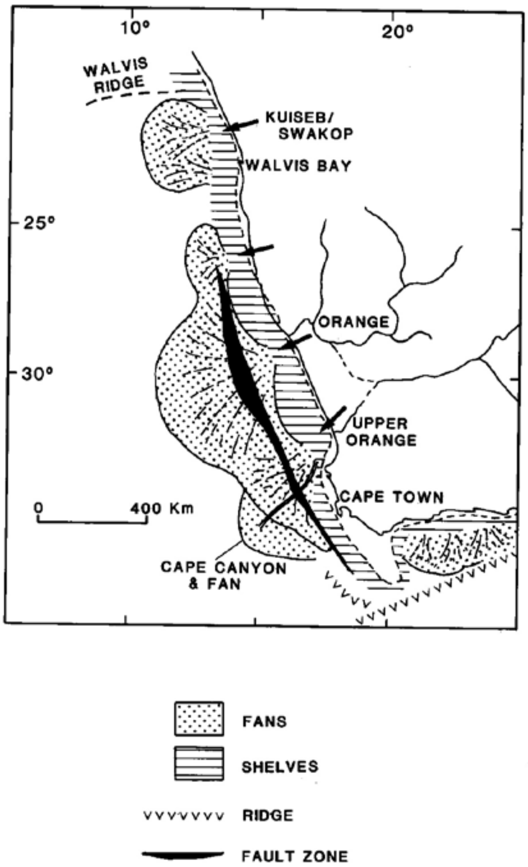


Figure 7: Palaeogeography of late Cretaceous—Palaeogene mature drift stage. The fault zone marks the locus of proximal slump glide planes. Arrows show main sediment input routes

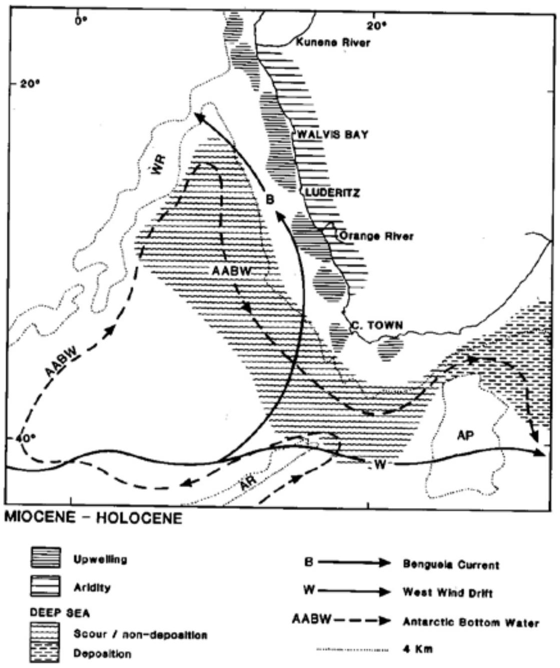


Figure 8: Late-Cenozoic sedimentary regimes and oceanographic climate around southern Africa. Based on Dingle *et al.* (1987), with upwelling cells from Lutjeharms and Meeuwis (1987). AR = Agulhas Ridge, WR = Walvis Ridge, AP = Agulhas Plateau

ties between sedimentation in the southeast Atlantic and southwest Indian Oceans until the establishment of the modem ocean current circulation in the' mid-Tertiary. From this point, there was a divergence in the nature of the sedimentary products on the west and east margins, both on the continental shelves and in the deep ocean basins. This occurred as a result of different deep-sea flow characteristics and hinterland climates. The latter were in turn controlled by the nature of the surface currents and atmospheric cells established on either side of the subcontinent. These are typified by the modem contrasts between the terrigenous sediment starved western margin, and the glut of terrigenous detritus generated by the humid east coast hinterland climate. A further major difference is the relatively high (but so far unquantified) proportion of aeolian detritus injected onto the continental margin by katabatic winds along the northern half of the west coast (e.g. Dingle *et al.*, 1987).

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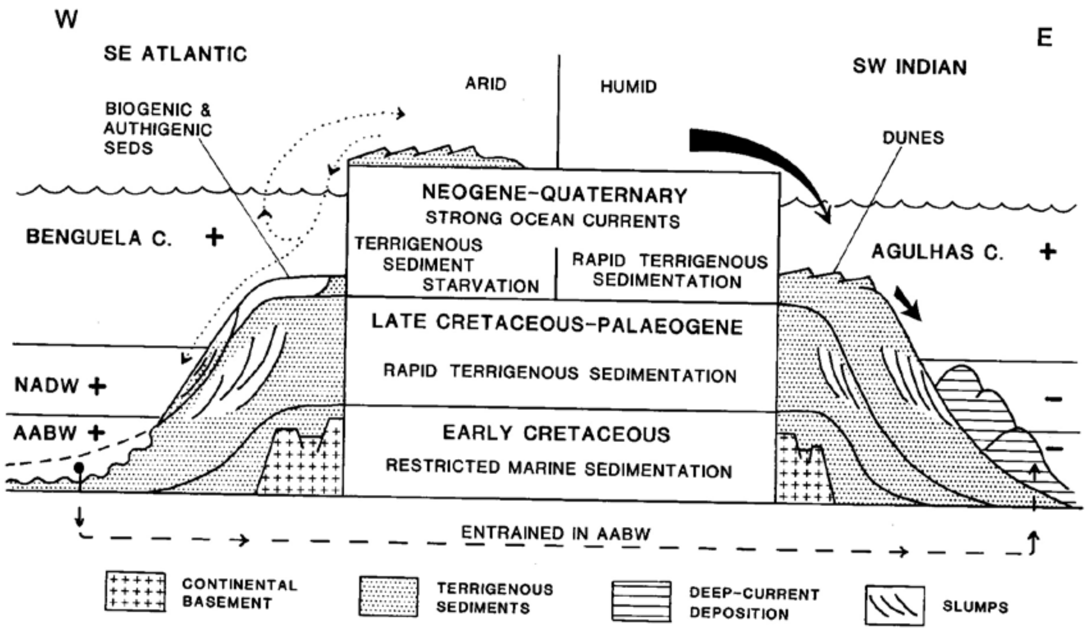

Figure 9: Sedimentary model for the southeast Atlantic and southwest Indian margins and adjacent ocean basins since initiation of continental drift. Arrows show sediment movement (contrast the heavy (thick arrow) and light (dotted) loads). NADW = North Atlantic Deep Water; AABW = Antarctic Bottom Water; Agulhas C = Agulhas Current. + and - indicate water movement out of and into the plane of the diagram, respectively. Wavy line = erosion surface under the AABW core

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