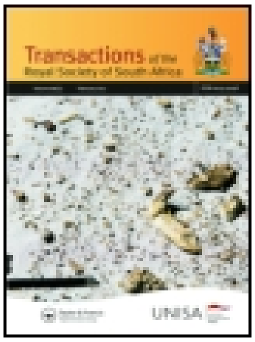

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CHEMICAL OCEANOGRAPHY AND MARINE GEOSCIENCE OFF SOUTHERN AFRICA: PAST DISCOVERIES IN THE POST-GILCHRIST ERA, AND FUTURE PROSPECTS

G. W. Bailey & J. Rogers

CHEMICAL OCEANOGRAPHY AND MARINE GEOSCIENCE OFF SOUTHERN AFRICA: PAST DISCOVERIES IN THE POST-GILCHRIST ERA, AND FUTURE PROSPECTS

By

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SUMMARY

In 1895/96, John D. F. Gilchrist was appointed marine biologist to the Cape Colony. During voyages extending as far as Walvis Bay and Maputo, he initiated studies of the marine geology and chemical oceanography of the shelf while mapping substrata for new demersal fishing grounds. The shelf sediments off the East Coast are controlled by wave processes along the inner shelf and by the poleward-flowing Agulhas Current along the outer shelf. In contrast, South Coast sediments of the eastern Agulhas Bank consist of wave-dominated, landward-coarsening modern (Holocene) terrigenous muds to sands on the inner shelf and relict wave-dominated shelly sands on the outer shelf, deposited during Pleistocene lowstands within glacial (hypothermal) periods. The Agulhas Current also appears to exert a controlling influence over the nutrient chemistry and, hence, primary productivity, on the East and South Coast margins. The surface waters of the Agulhas Current are nutrient-poor and most East Coast areas are consequently considerably less productive than their West Coast counterparts at the same latitude, but the underlying South Indian Central Water (SICW) is nutrient-rich. Recent findings suggest that the Agulhas Current may induce upwelling of nutrient-rich bottom water derived from SICW at sites such as the Natal Bight and off Port Alfred by kinematic upwelling, so enhancing the nutrient content of surface waters and increasing the potential for primary production there. A second physical process, which is also thought to be related to interaction of the Agulhas Current and bottom topography, is the dynamic shelf-edge upwelling of SICW onto the shelf along portions of the South Coast where the shelf is wider. It is uncertain whether this is continuous in space or time, but it is possible that the process may prime bottom waters for wind-induced upwelling in the south-western lee of capes along the South Coast. On the West Coast, the outer-shelf sediment consists of Holocene planktonic-foraminiferal ooze, reflecting the dominating influence of the equatorward-flowing Benguela Current. The middle-shelf sediment often consists of glauconitic sand, whereas the sediment of the inner shelf usually has a landward-coarsening and -thickening wedge of terrigenous muds to sands. Wind-induced upwelling is the dominant West Coast physical process of relevance to the sedimentology and chemistry of the inner shelf and overlying waters. In the southern Benguela this is seasonal, resulting in seasonal variability in the abundance of nutrients and the resultant productivity of surface waters and associated biogeochemical processes, such as the appearance of oxygen-depleted bottom water. There is a northward decrease in the seasonality of these physical and biogeochemical processes along the West Coast, which is reflected in an increase in the reducing nature of the underlying organic-rich sediments between St Helena Bay and Walvis Bay. In the deep-sea environment of the Cape Basin, the clockwise poleward flow of both the Antarctic Bottom Water (AABW) and the North Atlantic Deep Water (NADW) is reflected in a major zone of erosion of the sea floor, mantled by abundant ferromanganese nodules, at the foot of the continental rise, which is fed by margin-perpendicular slumps, debris flows and canyon-fed turbidity currents. The currents, driven by Coriolis Force, both swing left (east) into the Agulhas Passage between the Agulhas Bank and the Agulhas Plateau, before parting company in the Transkei Basin, where the AABW is forced eastwards by the northeast-shallowing contours of the Natal Valley. The E-W-orientated Agulhas Drift, a contourite drift, is being deposited on the left (north) side of the AABW. The NADW then heads into the Natal Valley to deposit margin-parallel contourite drifts at the foot of the continental slope as far north as Durban, where the Central Terrace and then the Mozambique Ridge steer the NADW first east and then south back to the mouth of the Natal Valley.

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INTRODUCTION

In 1895/96, John D. F. Gilchrist was appointed marine biologist to the Department of Agriculture of the Cape Colony (Brown, 1997). His main interest was the demersal fishing potential of the continental shelf off the Cape, but he had a broad scientific interest and also investigated the benthic fauna as a whole and attempted to integrate his biological information with environmental factors such as sea temperature and salinity (Gilchrist, 1902), currents (Gilchrist, 1904) and sedimentology (Gilchrist, 1914). No-one can claim that Gilchrist was a pioneer in this regard because the Cape had already been visited by the *Challenger* Expedition (1873-1896) some 20 years prior to his appointment, and sediment composition and the physical and chemical characteristics of the water column were among the parameters investigated. Nevertheless, it is obvious that he began a tradition of multi-disciplinary science which has persisted to this day in local marine science.

As part of his drive to establish new demersal fisheries, Gilchrist undertook a series of research cruises aboard the *Pieter Faure* at the turn of the century. To locate potential fishing grounds, he used, *inter alia*, grab samples. He ventured as far east as the sole grounds off Mossel Bay (Figure 1). In the course of this work he mapped the inner-shelf mudbelt on the eastern Agulhas Bank (Gilchrist, 1914), which even today remains the focus of a sustainable sole fishery (Zoutendyk, 1973; Zoutendyk & Duvenhage, 1989; Le Clus *et al.*, 1994, 1996). He later expanded his research on board the *Pickle* as far up the east coast as Durban and the then Lourenço Marques (now Maputo) and up the west coast as far as Walvis Bay (Brown, 1997).

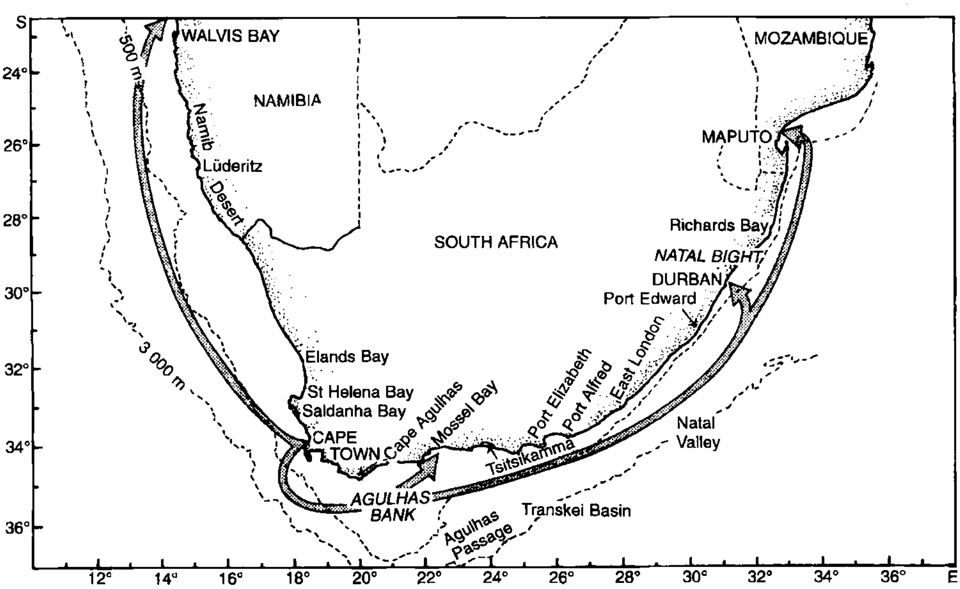

Figure 1. Location chart showing southern Africa, Gilchrist's study area and the major geographical features mentioned in text.

Between the world wars, marine biologists used the *Pickle* to sample and map the sediments of the sea floor, establishing the major divide between the organic-poor sediments off the East Coast and on the eastern Agulhas Bank and the organic-rich sediment west of Cape Agulhas and up the west coast to Namibia (Marchand, 1928; Von Bonde, 1928; Copenhagen, 1934, 1953a,b).

This review of southern African research into marine chemistry and geology, following Gilchrist's work, covers the area from Durban to Walvis Bay, in common with the theme of this suite of papers. Gilchrist's research did not appear to have included chemical pollution studies, nor did he appear to have conducted estuarine research, so these topics are excluded from this paper.

EVOLUTION OF THE CONTINENTAL MARGIN

In order to set the scene, it is necessary to focus first on the geological evolution of the continental margin. The shape and present bathymetry of the continental margin off South Africa is the result of a long, complex and globally unique geological history since the Early Cretaceous break-up of Gondwana. A history of the endeavours of numerous marine geoscientists, both local and international, to unravel this history can be found in the comprehensive review by Rogers and Bremner (1997), and a masterly synthesis of the data is found in the book *Mesozoic and Tertiary Geology of Southern Africa* by Dingle *et al.* (1983). In essence, the continental margin off the East Coast and on the eastern Agulhas Bank is a sheared margin, which used to lie adjacent to the elongate Falkland Plateau, the Falkland Islands lying south of Cape Agulhas and the tip of the plateau lying off Durban (Dingle & Scrutton, 1974; Dingle, 1992a; Ben-Avraham *et al.*, 1997; Ben-Avraham, 1995). Shearing started in the Early Cretaceous, about 130 million years ago, the tip of the Falkland Plateau eventually clearing the southern tip of the Agulhas Bank in the Late Cretaceous about 80 million years ago. During the same period, a classic passive margin, created by simple tensional rifting between South America and the west coast of South Africa, led to the birth of the South Atlantic Ocean, initially relatively stagnant until southerly access to the open ocean was made possible when the tip of the Falkland Plateau moved west of the Agulhas Bank and when the zip-like opening of the South Atlantic Ocean broke through northwards to the earlier-evolved North Atlantic Ocean. During these fundamental plate-tectonic movements of the latest 3% of geological time, erosion of the subcontinent has caused vast quantities of terrigenous (land-derived) sediment, thousands of metres thick, to be deposited along the continental margin (Dingle, 1971, 1973a,b; Dingle *et al.*, 1978; Dingle & Hendey, 1984), with considerable potential for oil and gas (Broad & Mills, 1993).

Teleconnections have been very important in the palaeoceanographic history of the continental margin of southern Africa (Kennett, 1982). The next major plate-tectonic milestone was the oceanographic isolation of Antarctica and the consequent birth of the modern oceanic systems in the Oligocene Epoch about 40 million years ago (less than 1% of geological time). The chief significance for marine scientific studies off southern Africa was the development of the Benguela ecosystem in the late Miocene, less than 10 million years ago (Siesser, 1980) and the concurrent aridification of the Namib Desert (Siesser, 1978).

As rates of terrigenous sedimentation slowed in the Late Tertiary, a veneer of limestones, hundreds of metres thick, was deposited on the terrigenous mudstones and sandstones of the

Cretaceous and the Early Tertiary. Numerous fluctuations of sea level caused the physical disruption of partially consolidated calcareous sediment, initially in an outer-shelf setting during a Highstand, then in a surf-zone environment during a Lowstand, and again in an outer-shelf setting during a subsequent Highstand. As a result, vast areas of the continental shelf west of Port Elizabeth, especially the outer shelf, are underlain by an intraformational conglomerate, the gravel-size clasts being intraclasts of now well-cemented planktonic-foraminiferal limestone, the sand-size grains being mainly of glauconite and quartz and the matrix being the carbonate fluorapatite, francolite. Parker (1975) described the petrology, geochemistry and paragenesis of these abundant intraformational glauconitic phosphorite conglomerates. Although they were first found off Cape Town during the pioneering voyage of H.M.S. *Challenger* late last century (Murray & Renard, 1891; Dingle, 1974), they have also been found off Morocco, Florida, California and New Zealand (e.g. Baturin, 1982) and, thanks to tectonic uplift, similar, but now subaerially weathered, phosphorite conglomerates are exposed in the Maltese Islands (Pedley & Bennett, 1985), especially on the island of Gozo.

The geologically rapid and frequent sea-level fluctuations of the Quaternary Period in the past 2 million years caused sea level to oscillate between its present level and about 130 m below present sea level. This had the effect of shifting the coastline laterally between Highstand and Lowstand positions, causing geologically rapid variations in the base levels of rivers and varying the locus of the high-energy surf zone. Where the shelf-break today lies shallower than 130 m, i.e. off the East Coast, the Lowstand coastline lay along the upper continental slope and rivers eroding down to this Lowstand base level extended their valleys seawards right across the shelf to the slope. This led to the acceleration of the development of submarine canyons on the slope, which often only enlarge by the process of headward retreat, with frequent slumping. A plethora of canyons has been recorded on the slope north of Durban by Bang (1968), and fewer but larger canyons have been mapped by Dingle and Robson (1985) between East London and Port Elizabeth. Submarine canyons become even rarer farther west, but the largest one, the margin-oblique Cape Canyon off Saldanha Bay, has been described in detail by Simpson & Forder (1968).

Where the shelf-break is deeper than 130 m, i.e. west of East London, the zone of lateral movement of the Quaternary coastline was restricted to the shelf (Dingle & Rogers, 1972). In that case, numerous wave-cut platforms and occasional wave-cut cliffs were formed, especially off Namaqualand and Namibia, and the gullies associated with them form potential traps for gem-quality diamonds (De Decker, 1987, 1988).

The most geologically recent recovery of sea level was from a Latest Pleistocene Lowstand about 20 000 years Before Present (yBP) during the Flandrian Transgression which, off the West Coast in particular, has caused the deposition of a thin (often <1 m thick), but distinctive, fining-upward transgressive sequence. Diamond-bearing relict gravels are overlain by muddy terrigenous fine sand. A final consequence of Quaternary palaeoclimatic variations was the equatorward shift of climatic belts during hypothermal (glacial) Lowstand events, symbolized by the delivery of ice-rafted clasts, as large as boulders, to the continental margin of the west coast (Needham, 1962).

Having focused on the geological evolution of the continental margin, we shall now concentrate on the Holocene sedimentology of the shelf, which is portrayed in a series of maps by Birch *et al.* (1986) and Bremner *et al.* (1986).

THE EAST-COAST MARGIN OF SOUTH AFRICA

HOLOCENE SEDIMENTOLOGY

The continental margin off the East Coast (Figure 1) owes its narrowness and shallowness to its sheared origin, as described above. Its Holocene sedimentology has been studied intensively, mainly by Flemming (1980), Flemming & Hay (1988) and Martin & Flemming (1988), who mapped ocean-current-driven bedforms along the outer shelf (Figure 2) via closely spaced side-scan sonar surveys complemented by grab-sampling of the sediment. Flemming (1980) concluded that energy levels are so high along most of the margin that the high proportion of terrigenous mud (silt and clay), delivered to the margin by rivers fed by a high-rainfall climate, is swept off the margin to be deposited in the Natal Valley. The Agulhas Current reaches velocities of 250 cm s^{-1} off East London over the outer shelf below wave base, and waves cause high energy levels over the inner shelf above wave base. As a result, terrigenous sand dominates the inner shelf along the shoreface (Zone A in Figure 2), and calcareous sand dominates the outer shelf in a wide variety of bedforms (Zone B in Figure 2). These bedforms, including current-perpendicular sand waves up to 17 m high and 700 m long and current-parallel sand ribbons, are similar to the bedforms mapped in the tide-dominated English Channel by Kenyon & Stride (1970). Although the bedforms normally indicate a poleward movement of the Agulhas Current, the presence of equatorward eddies, e.g. just south of Durban, is reflected in the under-

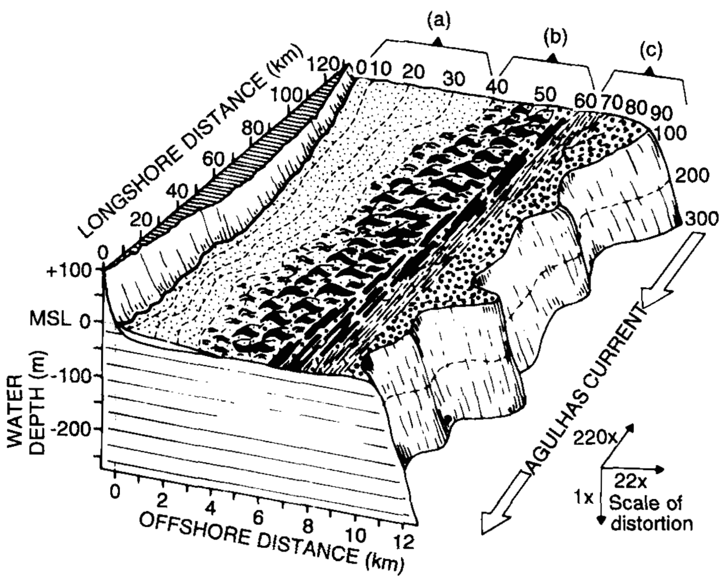

Figure 2. Schematic block diagram of a continental-shelf section summarizing the major physiographic features of the Southeast African continental margin: (a) the wave-dominated nearshore sediment wedge; (b) the current-controlled central-shelf sandstream; (c) the sand-depleted outer-shelf gravel pavement. Reprinted from *Sedimentary Geology*, **26**, pp. 179-205. Flemming, B.W. 1980. Sand transport and bedform patterns on the continental shelf between Durban and Port Elizabeth (southeast African continental margin). With kind permission of Elsevier Science - NL, Sara Burgerhartstraat 25, 1055 KV Amsterdam, The Netherlands.

lying bedforms, the different subregimes being separated by "bedload partings", the same term used in tide-dominated regions. These dynamics of this powerful, yet stable, western-boundary current are discussed by Lutjeharms & De Ruijter (1996). Ramsay (1994) has subsequently conducted an intensive small-boat and diving study of the narrow and shallow continental margin just north of Richards Bay (Figure 1), focusing on the zonation of corals (Ramsay & Mason, 1990) on the remnants of coast-parallel ridges of Pleistocene aeolianite, eroded during the Flandrian Transgression, sand waves under the Agulhas Current (Ramsay *et al.*, 1996) and the diveable head of one of the submarine canyons described by Bang (1968).

MARINE CHEMISTRY

The nutrient chemistry of the Natal Bight (Figure 1) and adjacent coast was investigated by Carter & D'Aubrey (1988), who found that average surface values of shelf waters off Richards Bay, Durban and Port Edward were elevated in concentrations of nitrate, phosphate and silicate relative to nutrient-poor Agulhas Current waters offshore (Figures 3, 4 & 5). Although the nutrients at those shelf sites were variable and low by West Coast standards, the authors did find the highest maxima off Richards Bay, where it has been proposed by Lutjeharms *et al.* (1989a) that nutrient-rich subsurface South Indian Central Water is periodically upwelled in the Natal Bight as a result of kinematic upwelling induced by the Agulhas Current, a process unrelated to local wind-forcing. The reduced importance attached to research into the chemical oceanography of this portion of the coast is apparent when one compares the effort expended on such research along the south and west coast margins of South Africa.

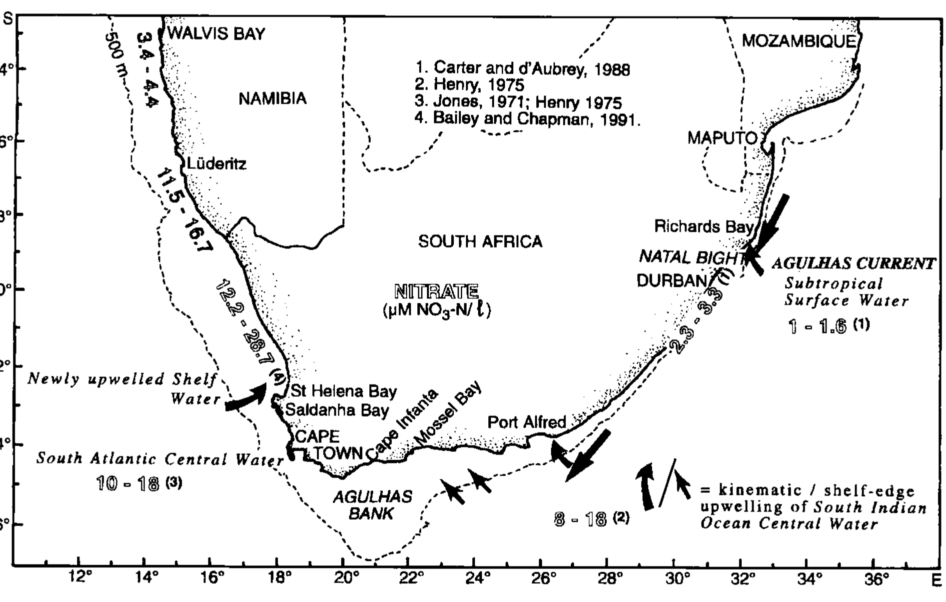

Figure 3: Average sea surface and offshore source water distribution of nitrate around southern Africa, as per text.

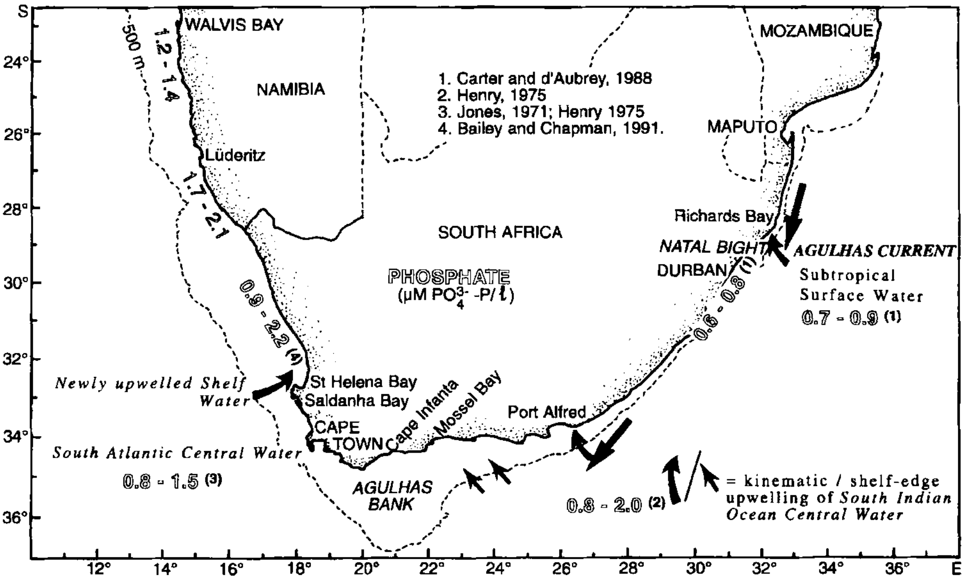

Figure 4. Average sea surface and offshore source water distribution of phosphate around southern Africa, as per text.

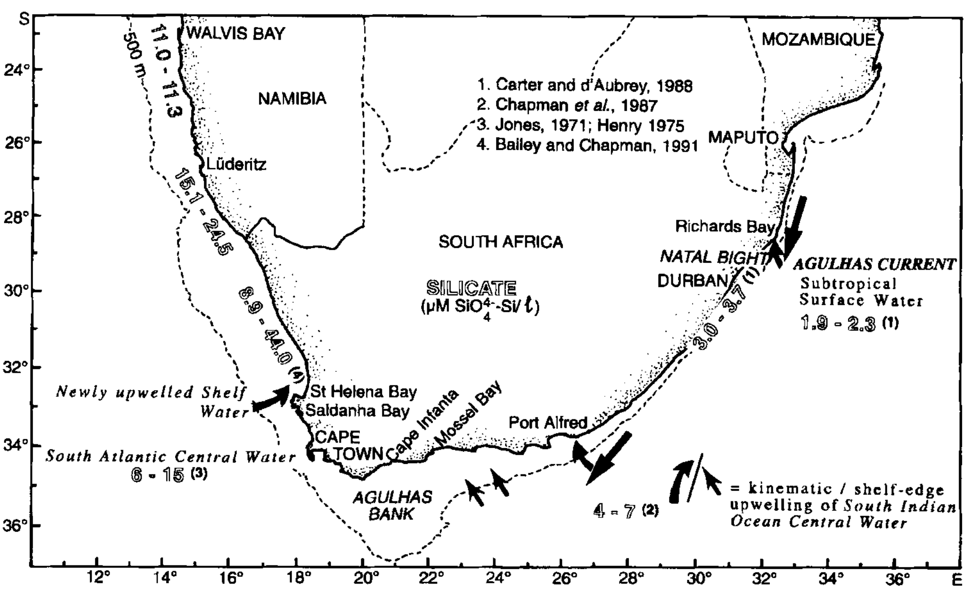

Figure 5. Average sea surface and offshore source water distribution of silicate around southern Africa, as per text.

THE SOUTH-COAST MARGIN OF SOUTH AFRICA

HOLOCENE SEDIMENTOLOGY

West of Port Elizabeth, the Agulhas Current ceases to dominate the shelf, and sediments on the broad eastern Agulhas Bank (Figures 6, 7 and 8) provide an excellent example of the effect of Quaternary sea-level fluctuations on shelf sediments. Biogenic shelly sands (Figure 8), rich in bivalve fragments bored by endolithic algae and fragments of the skeletons of the colonial organisms, bryozoa, dominate the outer shelf (Siesser, 1972a). Polewards of the high-temperature, high-salinity subtropical zones, where non-skeletal grains such as ooids and where hermatypic (reef-building) corals can develop, South Africa is in a broad regime of *foramol* carbonates, derived from the dominant components of foraminifera and mollusca (Lees & Buller, 1972). However, an additional term, *bryomol* sediments (Bone & James, 1993; Henrich *et al.*, 1995) has been used to describe the calcareous sediments off the south coast of Australia (Wass *et al.*, 1970; James *et al.*, 1992), and the term is clearly also applicable to the eastern Agulhas Bank. Today these *relict* sediments, relict of an earlier Lowstand high energy depositional environment (Emery, 1968) are regarded as *palimpsest* (Swift *et al.*, 1971) because, despite a primary origin in a Late Pleistocene higher energy Lowstand setting, they also contain modern (Holocene) planktonic and benthic foraminifera and are affected by modern storms and by landward incursions of the modern-day Agulhas Current.

The middle-shelf sediments are equally relict of higher-energy Lowstand environments, but their higher content of often well-rounded quartz grains, their distinctive well-sorted particle-size-distributions and their occasional association with well-rounded quartzite cobbles, is clearer evidence of a Lowstand beach or upper shoreface (Rogers, 1971). The inner shelf of the eastern Agulhas Bank is today receiving, from local rivers, terrigenous sediment, which is deposited as a coast-parallel mudbelt below wave base and as a nearshore sand prism along the shoreface above wave base (Figure 6). Therefore, the Mossgas pipeline had to traverse the middle shelf's relict/palimpsest sands, *en route* to the coast just west of Mossel Bay, via the terrigenous mudbelt and, finally, the nearshore sand prism with its modern Highstand surf zone.

A detailed study of the Holocene ostracods of the eastern Agulhas Bank has been completed by Conway-Physick (1995). The distribution of the sand-size valves of these arthropods is linked both to variations in substratum and to variations in the physical and chemical oceanography of the bottom water.

MARINE CHEMISTRY

South Coast marine chemistry research was not included in Chapman & Shannon's (1985) review, which was restricted to the Benguela upwelling system. Chemical oceanographic research really began along this portion of South Africa's coast with the work of Clowes (1954), who described the distribution of phosphate in waters around South Africa. Although Clowes (1938) earlier described the distribution of both phosphate and silicate in the Southern Ocean from observations made on a voyage of the *Discovery*, it was only much later that samples were analysed for silicate off South Africa. Orren (1963, 1966) described the horizontal and vertical distribution of "reactive" phosphate (orthophosphate) as determined in the South-West Indian Ocean, and he was followed by Mostert (1966), who emphasized the rela-

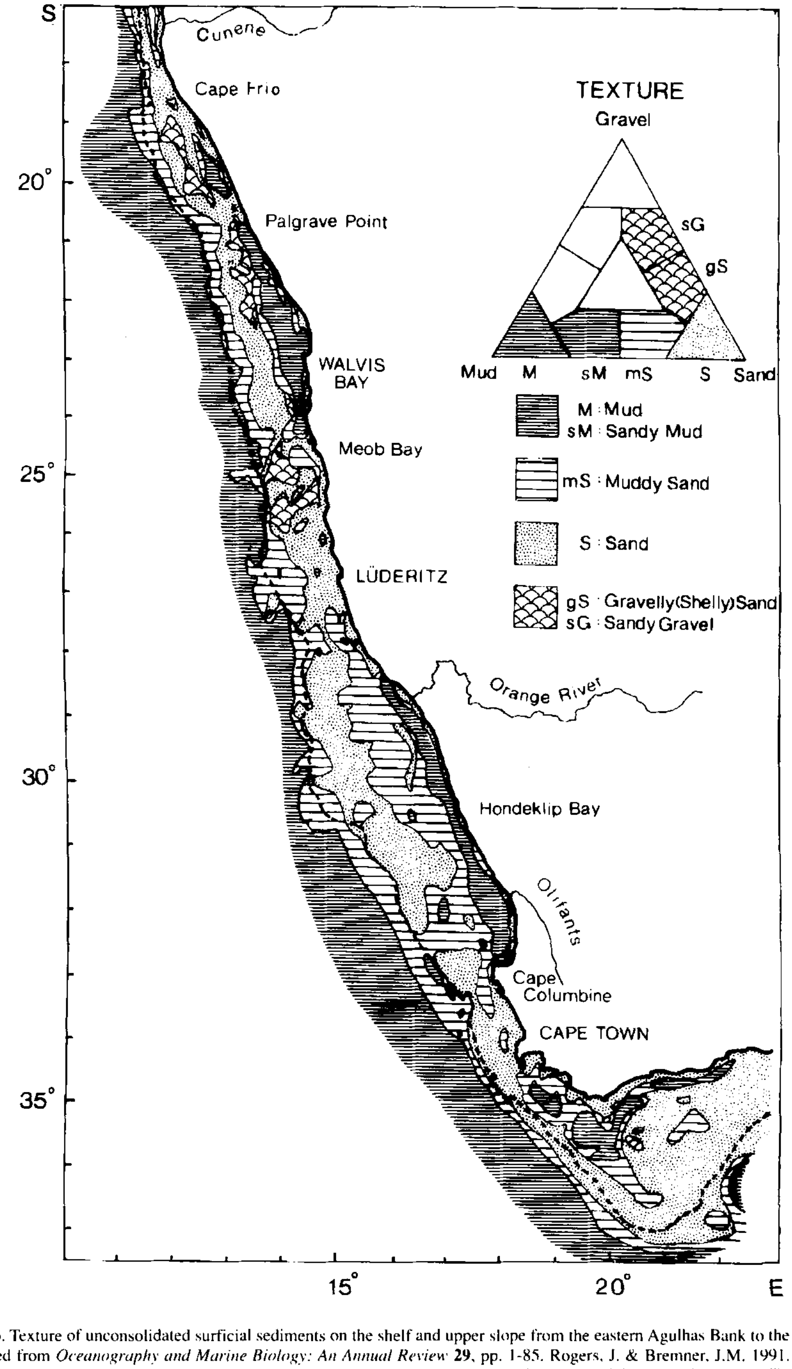

Figure 6. Texture of unconsolidated surficial sediments on the shelf and upper slope from the eastern Agulhas Bank to the Cunene River. Reprinted from *Oceanography and Marine Biology: An Annual Review* **29**, pp. 1-85. Rogers, J. & Bremner, J.M. 1991. The Benguela ecosystem. 7. Marine-geological aspects. With kind permission of Aberdeen University Press and the editor, M. Barnes, The Dunstaffnage Marine Laboratory, Oban, Argyll, Scotland.

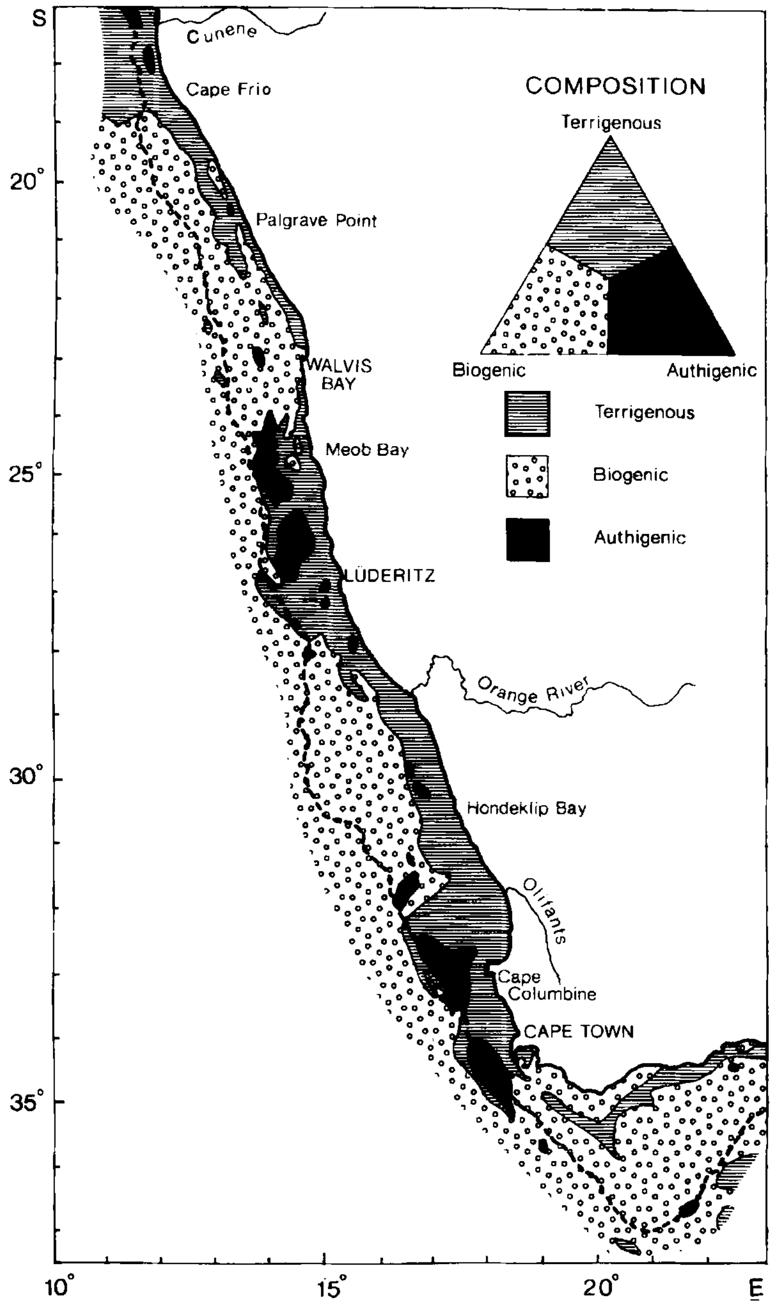

Figure 7. Composition of unconsolidated surficial sediments on the shelf and upper slope from the eastern Agulhas Bank to the Cunene River. Reprinted from *Oceanography and Marine Biology: An Annual Review* **29**, pp. 1-85. Rogers, J. & Bremner, J.M. 1991. The Benguela ecosystem. 7. Marine-geological aspects. With kind permission of Aberdeen University Press and the editor, M. Barnes, The Dunstaffnage Marine Laboratory, Oban, Argyll, Scotland.

tionship between phosphate and dissolved oxygen in the same waters. Until Henry (1975), no-one had conducted widespread analyses of nitrate in local Indian Ocean waters, and silicate was routinely analysed only some time later.

The Agulhas Bank (Figure 1) is formed by the southward extension of the continental shelf to nearly 37°S, south of Africa. It is important from a fisheries point of view, being the main spawning ground of South Africa's pelagically caught clupeids, anchovy *Engraulis capensis* and pilchard *Sardinops sagax* (Crawford, 1980), although this was not realized during the time of Gilchrist. Commercial exploitation of these pelagic species only began in 1943 (Cochrane *et al.*, 1997). Gilchrist did conduct a research cruise to the sole grounds off Mossel Bay, where he located potential fishing grounds by means of grab samples. Le Clus & Roberts (1995) suggested that temporal and spatial variability in the catch rates of Agulhas sole *Austroglossus pectoralis* is caused by changes in availability rather than biomass. They interpreted this to imply that dynamic environmental factors such as bottom temperature or levels of dissolved oxygen were responsible. However, having tested research-cruise-derived catch rates by linear regression and analysis of variance against bottom temperature and dissolved oxygen and depth of the sea bed (a static factor), they found the last of the three is the major factor influencing catch rates, leaving temporal variability in catch rates unexplained. It is possible that untested dynamic environmental factors such as currents or wind cause spatial and temporal changes in availability.

Lutjeharms *et al.* (1996) have proposed that the Agulhas Bank may be divided into three distinct provinces from a nutrient chemistry point of view (Figures 3, 4 & 5). The deep eastern Agulhas Bank is dominated by nutrient-poor Subtropical Surface Water advected in by the Agulhas Current from the east, whereas the western Agulhas Bank experiences nutrient-rich South Atlantic Central Water associated with the Benguela upwelling system to the west. The division is roughly in line with that proposed by Largier *et al.* (1992). A third province is the portion of the eastern Agulhas Bank shallower than 200 m influenced by nutrient-rich bottom water (Chapman & Largier, 1989).

Nutrient-poor Subtropical Surface Water is advected in by the Agulhas Current and may penetrate some distance onto the eastern Agulhas Bank (Henry, 1975). Lutjeharms *et al.* (1989b) have suggested that incursions of nutrient-poor Subtropical Surface Water onto the shelf occur as a result of frontal instabilities of the Agulhas Current. Goschen & Schumann (1988) conducted a summer survey of the nutrient chemistry of the eastern and central Agulhas Bank and found low concentrations of silicate and nitrate of < 2 and < 1 $\mu mol.\ell^{-1}$ respectively, beyond the shelf break, in accordance with average concentrations indicated for surface waters of the Agulhas Current in Figures 3 & 5.

The western Agulhas Bank has been found by Boyd *et al.* (1985), Largier *et al.* (1992) and Boyd & Shillington (1994) to be characterized by higher concentrations of nutrients in upwelled surface waters at the shelf edge outside of winter (nitrate exceeded 15 $\mu mol.\ell^{-1}$ at times in summer). During winter, surface nitrate concentrations were moderate (2-5 $\mu mol.\ell^{-1}$) over a wide area, as a result of wind-induced turbulent mixing.

Inshore portions of the eastern Agulhas Bank are important for the Agulhas sole fishery and for the jig fishery for chokka squid *Loligo vulgaris reynaudii* (see Cochrane *et al.*, 1997). It is noticeable that enhanced euphotic-zone nutrients have been reported for some inshore sites by Lutjeharms *et al.* (1996), who ascribe this to coastal upwelling, in addition to fluvial

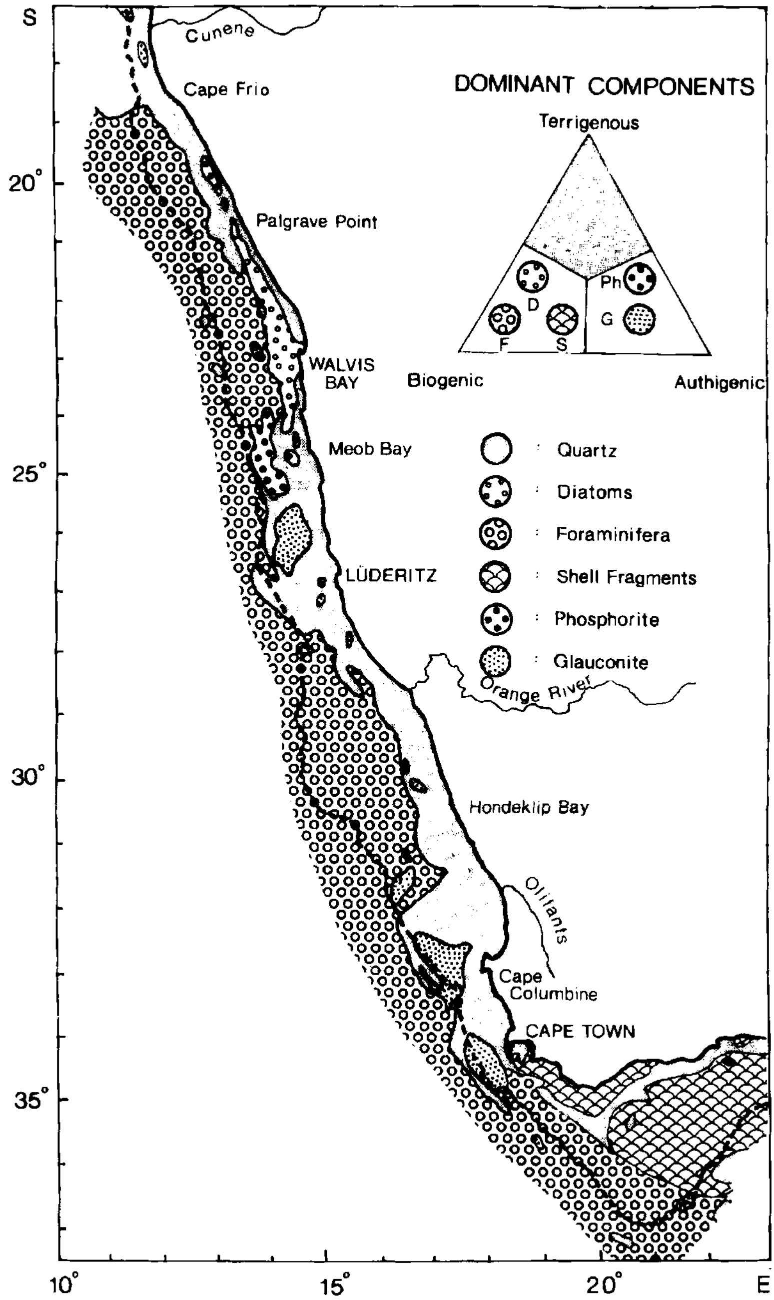

Figure 8. Dominant sand-size components of unconsolidated surficial sediments on the shelf and upper slope from the eastern Agulhas Bank to the Cunene River. Reprinted from *Oceanography and Marine Biology: An Annual Review* **29**, pp. 1-85. Rogers, J. & Bremner, J.M. 1991. The Benguela ecosystem. 7. Marine-geological aspects. With kind permission of Aberdeen University Press and the editor, M. Barnes, The Dunstaffnage Marine Laboratory, Oban, Argyll, Scotland.

and anthropogenic input at localized sites. Increased nutrient concentrations may be expected in surface waters in the lee of prominent capes along the South Coast where there may be intermittent, localized upwelling (Schumann *et al.*, 1982). Chapman & Largier (1989) confirmed that the source of this upwelling water is in fact subsurface nutrient-rich Indian Ocean Central Water, but the mechanism by which this water is advected onto the inner shelf is currently subject to debate. Shannon (1966) proposed dynamic upwelling by the Agulhas Current, a suggestion later supported by Chapman & Largier (1989), who assumed that this occurred along the length of the shelf edge. Lutjeharms and Meyer (submitted) have, however, suggested that the bottom water originates instead at the far eastern extremity of the Agulhas Bank, in the Port Alfred upwelling cell, and then advects in, along the shelf in a south-westward direction.

In accord with the increased abundance of nitrates in the euphotic zone over the western Agulhas Bank, Probyn *et al.* (1995) found higher f-ratios there than over the eastern Agulhas Bank, where productivity was based to a greater degree on regenerated nitrogen such as ammonium and urea. The same authors also revealed that there is discrimination as to the source of nitrogen utilized by phytoplankton in the vertical sense too. When there is a subsurface chlorophyll maximum, as frequently occurs over the Agulhas Bank, this constitutes a nutrient trap which limits the diffusive flux of nitrate across the nitracline into the Upper Mixed Layer (UML). Under such conditions, the subsurface chlorophyll maximum is fuelled to a large degree by nitrate, whereas production in the UML is driven predominantly by regenerated nitrogen.

The seasonal pattern of nutrient distribution has been described by Eagle & Orren (1985) from repeated 100-km transects conducted south of Cape Infanta between 1974 and 1979.

The deep-sea region south of Africa has been described in a number of cruises to the Agulhas Retroflection area (Chapman *et al.*, 1987; Gordon *et al.*, 1987, 1992; Chapman, 1988; Fine *et al.*, 1988). Chapman *et al.* (1987) described the distribution of nutrients, dissolved oxygen and chlorophyll *a* as observed during November/December 1983, and showed that these parameters could effectively be used as indicators of frontal systems and water masses in the area. The lowest concentrations of all parameters were found in the zone between the Agulhas Current and the Agulhas Return Current, whereas the Subtropical Convergence zone exhibited the highest nutrient levels. Gordon *et al.* (1992) used dissolved oxygen and chlorofluoromethane-11 and -12 (CFM-11 and CFM-12) tracer data together with CTD data to show that, within the thermocline stratum (9-14°C) and within the underlying Antarctic Intermediate Water, there is significant input of South Atlantic water into the Indian Ocean south of Africa. Some of this input folds back at the Agulhas Retroflection area to re-enter the South Atlantic via the Benguela Current (see later), and the remainder passes into the Indian Ocean.

THE WEST COAST MARGIN OF SOUTH AFRICA

HOLOCENE SEDIMENTOLOGY

Regional studies by Russian marine geologists culminated in the work of Senin (1974), who recognized a broad climatic zonality to the sediments off the west coast of Africa. Starting at a dividing line south-east of Cape Agulhas, he recognized a Southern Arid Zone off South

Africa and Namibia, an Equatorial Zone off Angola and Zaire and a Northern Arid Zone off West Africa. The sediments of Senin's (1974) Southern Arid Zone are characterized by a high proportion of biogenic components, mainly planktonic foraminifera, especially on the outer shelf, enhanced (>2%) organic-matter values and, off Namibia, an extensive inner-shelf deposit of diatomaceous ooze (Figure 8).

West of Cape Agulhas, outer-shelf sediments are dominated by biogenic sediment, but, in contrast with those of the eastern Agulhas Bank, they are planktonic-foraminiferal oozes (Figure 8) rather than bryomol sands. Middle-shelf sediments are often very rich in the dark green authigenic mineral, glauconite (Figure 8), but intensive research by Birch (1979 a) has shown that the pellets are sand-size intraclasts of silt- and clay-size sediment rich in the clay mineral, illite, that alters authigenically to glauconite and calcite, that alters to the phosphate mineral, francolite (carbonate fluorapatite). He therefore coined the term "mixed glauconite/apatite pellets" to express the reality of a fine admixture of two minerals within each pellet. It is a tribute to the accuracy of the engravings within *Deep-Sea Deposits* by Murray & Renard (1891) that their illustrations of these pellets in colour are not only unique, but even show gradations in mineral proportions e.g. the darker green, glauconite-rich interiors of the pellets and the lighter green, apatite-rich rims. Birch (1979b) also reported dark brown phosphorite pellets, which are much more abundant off Namibia (Bremner & Rogers, 1990; Figure 8). Gilchrist (1922) produced a plate depicting "manganese nodules and fossil bones" trawled up south-west of Dassen Island in approximately 500 m of water. It is probable from their appearance that these were phosphorite clasts, because manganese nodules are generally found at far greater depths.

Economically viable deposits of gem-quality diamonds have been prospected for several years and are now being mined in selective areas by a variety of concessionaires along the landward part of the middle shelf, in water depths of 120 - 130 m off Namaqualand and southern Namibia. De Beers Marine have been involved for the longest time and work from a fleet of specially modified vessels. The deposits are at the base of the fining-upward transgressive sequence mentioned previously, the Holocene terrigenous muddy fine sand forming a thin overburden over the orebody.

The inner shelf between Cape Agulhas and St Helena Bay (Figure 7) is unusual in that the pre-Mesozoic bedrock has a strong influence on the bathymetry of the inner shelf. The Table Mountain Group sandstones between Cape Agulhas and Cape Town produce a very rugged relief on the inner shelf. In contrast the more easily weathered shales of the younger Bokkeveld Group and the older Malmesbury Group form low-relief topography and allowed considerable coastal erosion, which led to the formation of the local bays. Granite forms residual corestone pinnacles in the immediate vicinity of Cape Town and off the coastline between Saldanha Bay and Cape Columbine (Figure 6). Malmesbury Group shales underlie Table Bay and crop out in Robben Island, stretching farther north towards the granite of Dassen Island. The abundance of rock outcrops has led to a rich variety of benthos, which contribute calcareous and, to a much lesser extent, siliceous skeletal fragments to the sediment between the outcrops.

Between St Helena Bay and the Orange River, off the coast of Namaqualand (Figure 6), the pre-Mesozoic bedrock outcrop is much narrower than farther south, and it is often seaward-convex. Diamondiferous gravels are exploited along this part of the inner shelf, landward of a terrigenous mudbelt (Figure 6) extending southwards from the muddy prodelta of the Orange (Rogers, 1977; Bremner *et al.*, 1990), seawards of the terrigenous very fine sand of the delta front.

The equivalent of the terrigenous mudbelt off Namibia is the world-famous belt of diatomaceous ooze (Figures 6, 7 & 8; Bremner, 1980a), rich in Holocene concretionary phosphorite (Bremner, 1980b) along its landward margin and rich in organic matter and associated trace metals along its seaward margin (Bremner, 1983).

A suite of papers has recently appeared (Dingle *et al.*, 1989, 1990; Dingle & Lord, 1990; Giraudeau, 1992, 1993; Dingle, 1992b, 1993, 1995; Dingle & Giraudeau, 1993; Dingle & Nelson, 1993; Giraudeau & Rogers, 1994) on the Holocene micropalaeontology of the ostracods, foraminifera and coccoliths on the continental margin off the West Coast and their relationship to oceanographic parameters. The general conclusion is that the microfossil and nannofossil assemblages in the modern sediments off South Africa and southern Namibia are different from those off northern Namibia, confirming the work of other marine scientists that there is a broad subdivision into a southern Benguela region south of Lüderitz and a northern Benguela region between Lüderitz and the Cunene River (Figure 8). In addition, each region can be subdivided into subregions by applying a multivariate analysis to the data. This research has recently been extended into the modern water column by Giraudeau *et al.* (1993) and Giraudeau & Bailey (1995). In addition, Dingle *et al.* (1996) have used the new data to show that Pleistocene sediments off Namibia have a micropalaeontological signature that more closely resembles Holocene sediments off the Cape Peninsula.

MARINE CHEMISTRY

Chapman & Shannon (1985) reviewed research on the chemical oceanography of the Benguela ecosystem, starting with publications emanating from the research cruises to the South-East Atlantic by the *Meteor* (Wattenberg, 1929) and *Discovery* (Clowes, 1938), and ending with nutrient and oxygen dynamics associated with the Cape Upwelling Experiment (Shannon *et al.*, 1984, 1986, 1992; Bailey & Chapman, 1985). Gilchrist's work was not among the list of references published in that review, but it is known that he conducted research into all disciplines of oceanography, including chemical oceanography and marine geology.

The St Helena Bay shelf region has been intensively studied (Bailey & Chapman, 1991; Chapman & Bailey, 1991; Cochrane *et al.*, 1991), no doubt because of the commercially important fisheries for pelagic fish (pilchard, anchovy and round herring *Etrumeus whiteheadi*) and rock lobster (*Jasus lalandii*). A local hydrological station grid was intensively sampled on a monthly basis between 1950 and 1967, resulting in papers on the hydrology and chemistry and the implications for plankton assemblages in the area (Clowes, 1954; Buys, 1959; Shannon, 1966) and a treatise on the origin of oxygen-depleted subsurface waters (De Decker, 1970). During the 1966 cruise of H.M.S. *Hecla* to the southern Benguela, a zonal transect was made off St Helena Bay and the nutrient and dissolved oxygen distribution between Cape Town and the Orange River mouth was described by Jones (1971).

Rather than revisiting the entire Benguela chemical oceanography review by Chapman & Shannon (1985) and the references therein, this review now focuses on research over the past decade, which has become more process-orientated and less descriptive in nature.

Oxygen dynamics

Oxygen-deficient water ($<2\ m\ell O_2\ell^{-1}$; Bailey, 1991), is a widely reported phenomenon in the Benguela upwelling system (Copenhagen, 1953b; De Decker, 1970; Bailey, 1979; Boyd, 1981; Chapman, 1983; Chapman & Shannon, 1987). Bailey (1991) discussed the oxygen dynamics of the Benguela upwelling system and showed that, on the equatorward side of all but the most southerly of the Benguela upwelling centres, there is an oxygen-deficient water mass which develops as a result of an imbalance in the supply and demand for dissolved oxygen in the Bottom Mixed Layer (BML). Uptake of oxygen occurs in response to sedimentation of particulate organic material derived from primary production in the euphotic zone. Oxygen-deficient bottom waters are a semi-permanent feature in the vicinity of Walvis Bay, but there is a southward increase in seasonality (Figure 9), in accord with the seasonality of upwelling and phytoplankton biomass at these sites. Bailey (1991) has discussed the interchange between water and sediment chemistry, which controls the temporal and spatial extent of oxygen-deficient bottom waters along this portion of the southern African coast.

Nutrient dynamics

Several physical and biological processes affect the distribution of chemical parameters such as oxygen and nutrients. The flux of nutrients to the euphotic zone by wind-induced upwelling has been discussed by Bailey (1985) and Bailey & Chapman (1985). Chapman & Shannon (1985) and Bailey (1987) described how current reversals, associated with coastal trapped waves, may lead to enhanced supply. Brown & Hutchings (1987) and Hutchings *et al.* (1995) examined the injection of new nutrients at upwelling centres in response to pulsed wind events. They concluded that there is an optimal frequency of wind events for dominance of large-celled phytoplankton and that the nutrient supply rate and factors such as phytoplankton seed populations, stratification and mixing with mature water, determine whether new production is exported to the sediments or fisheries.

In addition to the control exerted over dissolved oxygen dynamics by the interplay between water and sediment chemistry, processes such as benthic pelagic coupling also control nutrient dynamics. For much of the year the West Coast shelf environmental functions as a two-layer system separated by an intense thermocline. The euphotic zone, because of the activity of phytoplankton, is rich in dissolved oxygen but depleted in nutrients. In the bottom mixed layer the reverse applies because of regenerative processes.

An analysis of the available data reveals that West Coast surface nutrients are subject to considerable spatial variability (Figures 3, 4 and 5). This is particularly evident in the case of nitrates near Walvis Bay (Figure 3), probably as a result of denitrification. This has important implications for potential new production and to applicability of the Redfield ratio in such regions.

The supply of nutrients to the bottom mixed layer via regeneration from organic-rich sediments and exchange across the sea-sediment interface has been discussed by Bailey (1987). Waldron (1985) demonstrated that, during quiescent conditions, turbulent and diffusive vertical mixing processes are important mechanisms in the supply of nutrients to the euphotic zone.

Nitrate and ammonium assimilation by phytoplankton has been measured in the Benguela upwelling system using standard ^{15}N incubation techniques (Probyn, 1985, 1988; Probyn *et al.*, 1990; Waldron & Probyn, 1991, 1992). That research has provided considerable insight into

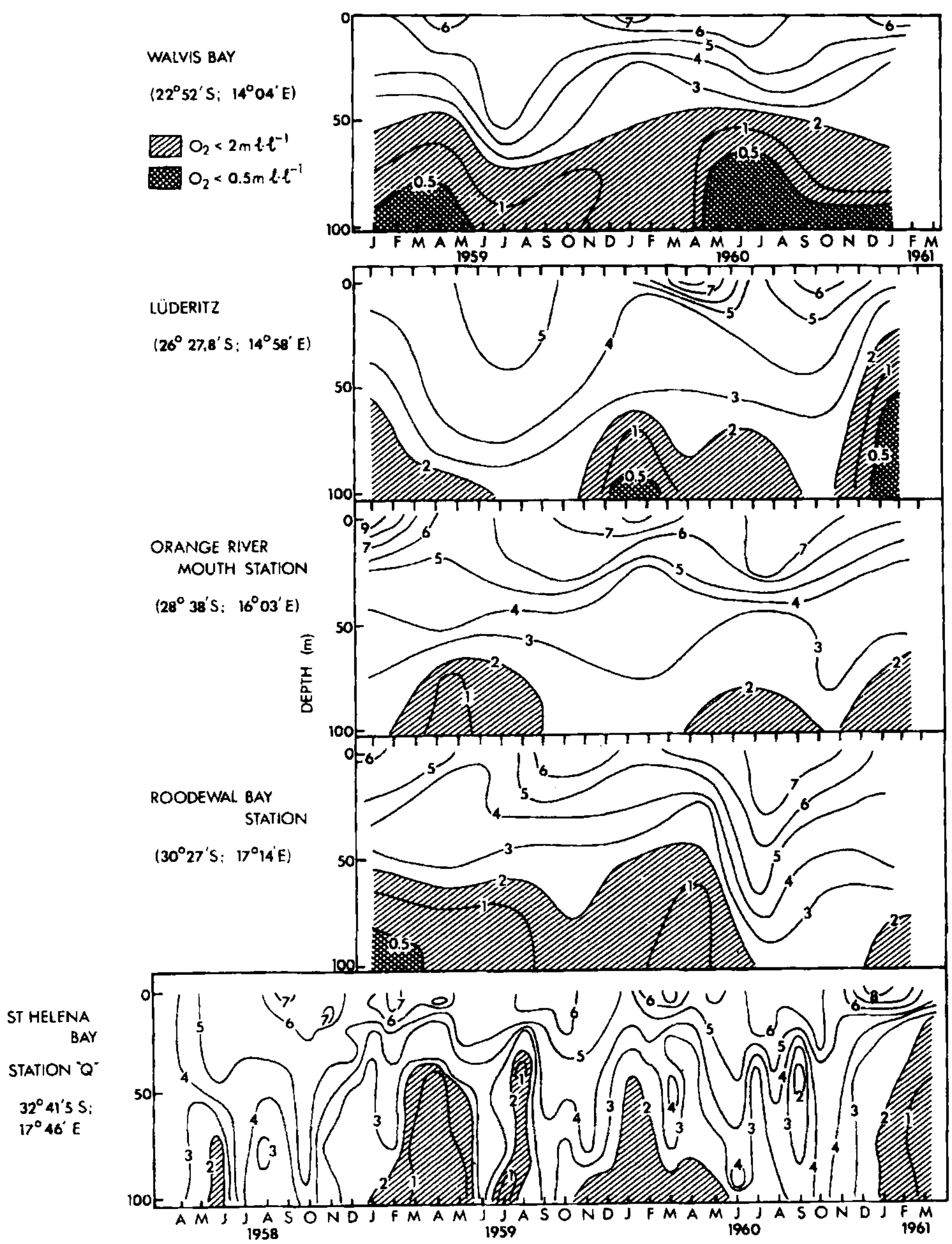

Figure 9. Southward increase in seasonality of the occurrence of oxygen-deficient bottom waters. Stations are all approximately 100 m deep along transects between 23°S and 33°S. Data from SFRI "longline cruises", 1958-1961. Reprinted from *Special Publication of the Geological Society of London* **58**, pp. 171-183. Bailey, G.W. 1991. Organic carbon flux and development of oxygen deficiency on the modern Benguela continental shelf south of 22°S: spatial and temporal variability. With kind permission of the Geological Society of London.

the relative roles of new production (nitrate-based) and regenerated production (ammonium- and urea-based) on a regional basis. Available information was synthesized by Probyn (1992) and compared against other upwelling systems. Using the results of size-fractionated studies, Probyn emphasized the role of large netplankton in new production and hypothesized that the lower than expected pelagic fish yield in the southern Benguela may be caused by dominance by smaller size-classes of phytoplankton.

Related research into potential new production in the Benguela upwelling system has been undertaken by Waldron & Probyn (1992) using satellite-derived sea surface temperature (SST) imagery. This was translated into an estimate of the amount of nitrate available in the euphotic zone from SST-nitrate regression ratios and converted into potential new production in terms of carbon using the Redfield ratio. A novel approach by Waldron (1995) has been the introduction of sea level as a proxy for upwelling, allowing an estimate of annual potential new production to be made for the entire decade 1980/81 to 1989/90. From a combination of satellite imagery and measurements of labelled nitrate uptake beyond the position of the 200 m isobath, Waldron *et al.* (1992) to estimated the proportion of new production in relict upwelled and filament water likely to be exported from the shelf as carbon.

Application of chemical tracers to oceanographic processes

The chemical oceanography of the region and related chemical techniques have recently been used to make inferences about the physical oceanography of the Benguela upwelling system and adjacent deep-sea regions (Table 1). Isotope chemistry has been put to use by Cohen (1988) in reconstructing Holocene SST from the oxygen isotope signal, and the crystal structure and mineralogy of shells of marine molluscs such as *Patella granularis* and *P. granatina* taken from archaeological sites. The oxygen isotope record from samples from Elands Bay cave, north of Saldanha Bay (Figure 1), shows three periods of oxygen isotope enrichment at 10 600, 2 700 and 420 yBP, corresponding with periods of global cooling that would have

Table 1. Application of chemical tracers to oceanographic processes

Application	Reference
Physical processes	
Reconstruction of Holocene SST from oxygen isotope signal, structure in mollusc shells	Cohen, 1988
Interbasin exchange between Indian and South Atlantic Oceans from chlorofluoromethane-11 and -12 tracer distribution	Fine *et al.*, 1988 Gordon *et al.*, 1992 Smythe-Wright *et al.*, 1996
Indian Ocean component in waters entering South Atlantic around the South-Western Cape	Chapman *et al.*, 1987
Poleward undercurrent, continental shelf waves and internal tides interpreted from historical record of sea-bottom temperature, salinity and dissolved oxygen	Dingle & Nelson, 1993
Biological processes	
^{15}N uptake to determine f-ratios	Probyn, 1985, 1988, 1992 Probyn *et al.*, 1990, 1995
$\delta^{13}C$ tracer of foodweb, anchovy diet	Monteiro *et al.*, 1991

influenced the southern Benguela. The oxygen isotope record from mollusc shells from Nelson Bay Cave, east of Mossel Bay (Figure 1) suggest that SSTs over the Agulhas Bank were lower than present for much of the early Holocene, but that at about 6 000 yBP SSTs were higher by up to 2°C.

Chemical tracers such as CFM-11 and CFM-12 (Fine *et al.*, 1988; Gordon *et al.*, 1992; Smythe-Wright *et al.*, 1996) have been used to examine the inter-basin exchange of water between the Indian and South Atlantic Oceans. According to Gordon *et al.* (1992), CTD data and CFM-11, CFM-12 and oxygen-tracer data from the South Atlantic Ventilation Experiment showed that about two-thirds of the thermocline stratum (9-14°C) water and about half of the lower thermocline and AAIW is drawn from the Indian Ocean within the interocean conduit south of Africa. Chapman *et al.* (1987) showed that Agulhas Current water is marked by an oxygen minimum layer at 50-200 m in the Agulhas Retroflection area. This signature, derived in the tropical Indian Ocean, may be used to trace incursions of Agulhas water into the South Atlantic at least as far west as 13°E at the latitude of 34°S.

Chemical tracers have also been used in novel applications which have improved our understanding of biological oceanographic processes in the southern Benguela. This includes the use of ^{15}N incubation techniques by Probyn and his co-workers (Table 1). Monteiro *et al.* (1991) have demonstrated the use of $\delta^{13}C$ as a powerful tool in marine foodweb studies.

QUATERNARY MARINE GEOLOGY FROM THE CAPE BASIN TO THE NATAL VALLEY

Although the flow of Antarctic Bottom Water (AABW) in the southern hemisphere is predominantly northwards, within the Cape Basin it is steered as a contour current in a clockwise pattern, its propensity to swing to the left under the influence of Coriolis Force being frustrated by the Mid-Atlantic Ridge, the Walvis Ridge and the continental margin of Namibia and South Africa. As a result, AABW flows southwards, creating an erosional regional non-conformity along the foot of the continental rise, in tandem with the overlying, south-flowing North Atlantic Deep Water (Tucholke & Embley, 1984; Dingle *et al.*, 1987). Abundant deposits of low-grade ferromanganese nodules, diluted by the ice-rafted detritus (IRD) reported by Needham (1962) have been mapped and sampled along this erosional zone by Rogers (1987, 1995), particularly south of a submarine fan at the foot of the Cape Canyon off Cape Town (Simpson & Forder, 1968). Farther north, the major slumps mapped by Dingle (1980) have spawned major submarine debris flows of foraminiferal ooze from the continental slope, which have buried many of the nodules (Rogers, 1995).

South of the tip of the Agulhas Bank, the geostrophic currents swing north-eastwards into the Agulhas Passage (Camden-Smith *et al.*, 1981) and on to the Transkei Basin at the southern end of the north-shallowing Natal Valley. There, the AABW is steered to the east by the bathymetry and an E-W orientated contourite drift, the Agulhas Drift, has been deposited (Dingle & Camden-Smith, 1979). This Agulhas Drift was subsequently profiled in finer detail during a major South African research cruise between the Agulhas Plateau and Durban in 1992, aboard the Russian research vessel, the *Professor Logachev*, led by Professor Z. Ben-Avraham. This research resulted in a suite of papers refining the earlier work of Dingle & Robson (1985) and presenting mainly geophysical data on the Mesozoic and Cenozoic turbidites and contourites infilling the Natal Valley and the Transkei Basin (Hartnady *et al.*, 1992; Ben-Avraham *et al.*, 1994), and new data on the continental origin of the Mozambique Ridge (Ben-Avraham *et al.*, 1995). The NADW is shown to have deposited Cenozoic contourite drifts along the foot of the continental slope as far north as Durban, where the NADW is steered eastwards by the Central Terrace and then southeastwards by the Mozambique Ridge towards the Transkei Basin. In an earlier phase, the NADW was able to reach the Mozambique Basin via a rift valley in the Mozambique Ridge, which has since undergone uplift above the level of the NADW (Ben-Avraham *et al.*, 1994). The Mozambique Basin itself is the locus of deposition of the Zambezi Submarine Fan (Kolla *et al.*, 1980) and only south of it are sedimentation rates low enough to allow the formation of the bizarrely-shaped, IRD-riddled ferromanganese nodules described by Hartnady *et al.* (1992) and Rogers (1995).

The marine geology of the sea floor eroded by the Agulhas Current off Durban and the seafloor of southern Mozambique (Figure 1) has been described by Dingle *et al.* (1978), summarizing the research of Martin (1984) and Goodlad (1986).

FUTURE RESEARCH

MARINE CHEMISTRY

The carbon cycle

Hutchings *et al.* (1995) demonstrated how interactions between the physical, chemical and biological dynamics of the coastal upwelling areas may determine the scope for export of organic carbon to the sediments or fisheries. Until recently, little was known about the inorganic carbon pump and whether the Benguela upwelling system is likely to be a net source or sink of carbon dioxide. Monteiro (1996) has given good insight into the problem. This work needs to be expanded, as does the question of the role of dissolved organic carbon in the system.

The iron hypothesis

This hypothesis states that phytoplankton growth and biomass may be limited by low concentrations of available iron (Martin *et al.*, 1994) in regions of the oceans where there is low phytoplankton biomass, despite the presence of abundant other plant nutrients. "New" iron was believed to be supplied by atmospheric input, leading Martin (1990) and others to propose that changes in this source may have led to changes in biological productivity and global climate. Recent findings by Coale *et al.* (1996) demonstrate that biological production in the Equatorial Pacific is not controlled solely by deposition of atmospheric iron, but also by processes which influence the rate of upwelling and the iron concentration in upwelled water. No research has been conducted on this aspect in the Benguela upwelling system. To the north, there is seasonal input of wind-borne dust from the Namib Desert during winter, but also extensive areas of anoxic sediments where benthic fluxes of iron from shallow shelf sediments into upwelling waters may be reduced by available iron being "locked up" as iron pyrite within the sediments.

The information revolution

Society is now firmly on the "third wave", a term coined by Toffler (1980) to indicate social, cultural and economic transformations that have resulted from the information revolution of the 21st century. Similar changes were caused by the industrial revolution of the 18th century and the agricultural revolution 10 000 years ago. According to Brenner (1996), the start of the information revolution may be considered to be 1946, when the first fully electronic computer, or Electronic Numerical Integrator and Computer (ENIAC) was commissioned. This was 50 years after Gilchrist's appointment and 50 yBP. Technology has changed forever from that of Gilchrist's day and is likely to change even more dramatically in the future, with the advent of data-sharing protocols such as the World Wide Web being developed for the Internet in 1990. This raises the possibility of geographically separated colleagues sharing the same database immediately, advancing the potential for collaboration and reducing the need for costly duplication of effort.

MARINE GEOLOGY

Bedrock geology

The bedrock geology of the continental shelf (Dingle, 1971, 1973b; Parker & Siesser, 1972; Siesser, 1972b; Parker, 1975; Dingle & Siesser, 1977; Gentle, 1987), based on the rock samples dredged by the *Thomas B. Davie*, is being refined continually via petrographic study of additional rock samples trawled during demersal research cruises of the F.R.S. *Africana* (Hammond, 1988; Lynham, 1996) and diamond-prospecting operations of De Beers Marine (Edmunds, 1986; Van der Merwe, 1990). This research will be rounded off in the near future and the data added to a database, which has been established using PARADOX at the South African Council for Geoscience. The database includes both the earlier *Thomas B. Davie* suite and the more recent *Africana* suite. Besides refining the bedrock-geology map, a study will be made of ice-rafted erratics, such as granite, banded amphibolite and quartzite from the outer shelf (Hammond, 1988), which are more abundant in the *Africana* suite because trawling operations generally take place on reef-free sediment.

Environmental Impact Assessments

A major Environmental Impact Assessment (EIA) of a diamond concession off southern Namibia has just been completed for De Beers Marine. Draft legislation has been published for the shelf off South Africa, and a flood of EIAs are expected to be completed in the next decade. Being multidisciplinary in nature, these EIAs will provide a considerable quantity of new good-quality data, greatly assisted by the high accuracy of modern position-fixing techniques.

Submersible studies

In late October 1996, Fricke and Bruton undertook research dives of the German-built 2-person submersible *Jago* on the shelf between Saldanha Bay and the mouth of False Bay, south of Cape Town (Figure 1). These complemented earlier research dives in the Tsitsikamma Coastal National Park and off East London (see Figure 1). Intensive surveys were then carried out for De Beers Marine off southern Namibia and off northern Namaqualand. This pioneered a new dimension to marine geological research, the bulk of which has been carried out with no visual control whatsoever. Additional research dives are planned for the *Jago* and, ultimately, this initiative is expected to lead to the construction and utilization of a South African research submersible.

Marine diamonds

The search for economic deposits of marine diamonds in Lowstand drowned beaches of Pleistocene age appears to be expanding exponentially, especially since the new deep-water (200-500 m) D-concessions were awarded. High-quality intensive surveys of the D-concessions have been carried out recently off the west coast from the Cape Canyon northwards to the shelf off Namaqualand, especially by RACAL Surveys utilizing the *Kommodor Therese*. Many vibrocores have been taken along the outer shelf and the upper slope. In addition, vibrocoring of shallower concessions off Namaqualand and Namibia, more recently just north of Lüderitz (Mendes, 1995), will lead to a suite of marine-sedimentological studies linked to the high-resolution (< 0.3 m) CHIRP seismic profiles now available.

International coring programmes

New research on the continental slope by marine geologists of the University of Bremen aboard Germany's research flagship *Meteor* is already bearing fruit in collaboration with South African marine geologists. As the Bremen team is involved in a 12-year study of the Quaternary palaeoceanography of the South Atlantic, a much deeper understanding of this topic is emerging (Schneider *et al.*, 1995; Little *et al.*, in press).

A foretaste of what can be achieved from multidisciplinary studies of cores from the slope is found in a new study by Summerhayes *et al.* (1995) of a core from the upper slope off Walvis Bay in Namibia. Such studies will be carried out on the longest cores of Quaternary marine sediment ever recovered. They were collected in September and October 1996 off southern Africa by an international team, including one of the authors of this paper (JR), of the International Marine Global Changes Study (IMAGES) within the PAGES Project of the International Geosphere Biosphere Programme (IGBP). The new French research vessel, the *Marion Dufresne*, was used to retrieve 23 cores up to 40 m long, which penetrated sediments of the last two glacial-interglacial cycles of the past 300 000 years.

In the ocean basins around South Africa there will shortly be a flurry of international scientific effort, starting at the end of 1997, centred on the drilling vessel *Resolution* of the Ocean Drilling Project (ODP). Two ODP site surveys were completed in 1996, off South Africa's west coast and off Namibia by German marine geoscientists aboard the *Meteor* in January and February and by American marine geoscientists aboard the *Thomas G. Thomson* in February and March.

Methane hydrates and ferromanganese nodules

Ongoing research into the possibility that economic deposits of pollution-free, ice-like methane hydrates exist in ocean-basin sediments of the Natal Valley will be followed up when the proposed survey of South Africa's Exclusive Economic Zone (EEZ) takes place. Earlier studies of deep-ocean ferromanganese nodules will be expanded, particularly off northern

Namaqualand, north of the zone of Pleistocene ice-rafted detritus. Initial planning has already taken place for a joint German-South African research cruise to the Agulhas Plateau, the nearest oceanic plateau to South Africa that requires much more investigation, the earlier studies, such as those of Barrett (1977) being during the pre-GPS (Global Positioning System) era.

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