Wefer, G., Berger, W.H., Richter, C., et al., 1998
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1. INTRODUCTION: BACKGROUND, SCIENTIFIC OBJECTIVES, AND PRINCIPAL RESULTS FOR LEG 175 (BENGUELA CURRENT AND ANGOLA-BENGUELA UPWELLING SYSTEMS)[1]

Shipboard Scientific Party[2]

ABSTRACT

During Leg 175, 13 sites were occupied off the western coast of Africa (Congo, Angola, Namibia, and South Africa) and 40 holes were drilled using advanced hydraulic piston coring and the extended core barrel method. The goal is to reconstruct the late Neogene history of the Benguela Current and the associated upwelling regimes between 5° and 32°S. The area investigated contains one of the great upwelling regions of the world, intermediate in intensity between the systems off Peru and California. The Angola-Benguela Current system (ABC-system) with its associated upwelling regions is characterized by organic-rich sediments that contain an outstanding record of productivity history, which can be read on a very fine scale. In addition, this environment provides an excellent setting for natural experiments in diagenesis.

The individual transects selected for drilling within the ABC-system reflect a compromise among geographic coverage, accessibility, quality of sedimentary record, and time constraints. Variations in productivity are generated in different ways, within different geographic settings (off the Congo, near the Angola Dome, at the Walvis Ridge, and in the upwelling cells south of the ridge). One of the major goals is to document fluctuations in productivity in these different settings in relationship to large-scale climatic change within the late Neogene, including the onset of glacial cycles in the Northern Hemisphere. Another major goal is to tie fluctuations in oceanic conditions with the corresponding changes in climate on the adjacent continent.

Most of the drilled sites have high sedimentation rates (~100 m/m.y.), which offers an opportunity to develop detailed paleoceanographic records with a resolution close to 1000 yr. Sediments are largely diatomaceous and carbonate-rich clays with variable (and occasionally very high) organic carbon contents. Analysis of these sediments will greatly extend and refine the results concerning paleoceanography and paleoclimate of the late Neogene that were provided by Deep Sea Drilling Project Sites 362 and 532.

The northernmost sites (1075, 1076, and 1077) contain the record of sediment supply by the Congo River, intercalated with the oceanic record. Pollen, freshwater diatoms, phytoliths, and clay minerals will provide clues to climatic change in the drainage basin of the Congo. Fluctuations in the accumulation of pelagic diatoms and marine organic matter track the changes in productivity in this peri-estuarine environment.

Sedimentation patterns at Sites 1078 and 1079 are greatly influenced by changes in intensity of the upwelling around the Angola Dome. The two sites show extremely high rates of accumulation, which presumably are caused by the supply of silt from vigorous coastal erosion (as seen in the morphology of the coast around Lobito).

Sediments from Site 1081 contain a record of variation in the seasonal coastal upwelling near the northern boundary of the string of coastal upwelling cells off Namibia and South Africa (southwest Africa upwelling cells). This record is closely related to the southeasterly winds driving the Benguela Current, which is documented (in part) in the supply of dust from the Namib Desert.

Sites 1082, 1083, and, especially, 1084 lie close to the major upwelling centers along southwest Africa with year-round upwelling activity. Thus, these sites directly record the variability in the intensity of coastal upwelling mainly through the eddies and filaments that form at the centers, pass over the sites, and generate high export production here.

The three sites in the southern part of the Cape Basin (Sites 1085, 1086, and 1087) document the history of the Benguela Current near its point of origin and contain a record of the influence of warm water from the Indian Ocean, brought by the Agulhas Current. Also, these sites contain evidence for incursions of cold antarctic waters, which apparently reached a maximum near the Pliocene/Pleistocene boundary.

Preliminary results focus on the interplay between high-latitude and low-latitude Milankovitch forcing (obliquity vs. precession), the role of the 100-k.y. oscillation, the effects of the mid-Pleistocene climate step (near 920 ka) on upwelling and African climate, the nature of the late Pliocene–early Pleistocene productivity maximum, the onset of enhanced upwelling at the beginning of the late Pliocene (near 3 Ma), and the implications of changes in productivity and sediment supply for diagenesis, which affects the interpretation of seismic profiles. Concerning the last item, dolomite layers were found to be abundant at certain sites, whereas evidence for clathrates was lacking at all sites.

UPWELLING AND CLIMATE

The ocean's role in climatic change through heat transport and control of carbon dioxide is increasingly being recognized. This new awareness and the urgency that must be accorded to the attempt to understand the mechanisms of climatic change have led to the initiation of large integrated efforts in physical and chemical oceanography. Likewise, the potential of using the oceanic record to understand climatic change has received increased attention in recent years (CLIMAP, 1976; COSOD II, 1987). The Angola-Benguela Currents (ABC-system) with its associated upwelling regimes need to be studied because of their importance in the global ocean–carbon cycle and their capacity to provide for comparison with the systems off Peru and California.

By comparing these systems with one another, we shall learn which elements of a system are peculiar and which have general validity through time and on a global scale. To further these goals, the *JOIDES Resolution* occupied 13 sites off the southwestern coast of Africa (Fig. 1) for drilling with the advanced hydraulic piston corer (APC) and the extended core barrel (XCB). The sediments recovered during Leg 175 contain the record of climatic change and productivity variation of the ABC-system, with emphasis on the late Neogene.

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[1] Wefer, G., Berger, W.H., Richter, C., et al., 1998. *Proc. ODP, Init. Repts.,* 175: College Station, TX (Ocean Drilling Program).

[2] Shipboard Scientific Party is given in the list preceding the Table of Contents.

Eastern boundary upwelling is strongly involved in the marine carbon cycle. This process helps set the partial pressure of carbon dioxide (pCO_2) both by "biological pumping" (removal of carbon from surface waters to deep waters) and by "biological dumping" (removal of organic carbon to sediments; e.g., Berger and Keir, 1984; Sundquist and Broecker, 1985; Boyle, 1988; Sarnthein et al., 1988; Berger et al., 1989). It is now generally thought that the efficiency of biological pumping (Broecker, 1982) is a crucial factor for the explanation of short-term fluctuations in atmospheric CO_2, as seen in ice cores. However, the effect is probably insufficient in magnitude to serve as the sole or main cause. Biological dumping also has to be considered, as well as the accumulation and redissolution of carbonate. That evidence from sediments is relevant to the reconstruction of atmospheric CO_2 is shown in the good correlation between productivity indices in a core from the eastern equatorial Pacific and the ice-core record of pCO_2 (Fig. 2). Likewise, there is good correlation between the ice-core record and estimates of CO_2 pressure in surface water from a core taken off Angola (Fig. 3).

With respect to Neogene climate steps, Vincent and Berger (1985) have postulated that carbon dumping by coastal upwelling is responsible for rapid changes in the general level of atmospheric pCO_2. They propose climatic preconditioning by upwelling-induced carbon extraction from the ocean-atmosphere system for the beginning of the modern ice-cap–dominated world. Their argument is based on the observation that carbon isotopes in deep-sea benthic foraminifers become enriched in ^{13}C just when organic-rich phosphatic sediments begin to accumulate around the Pacific margins (Fig. 4). In this view, eastern boundary upwelling, and therefore upwelling off Angola, Namibia, and South Africa, has global implications for the long-term history of the carbon cycle and climate and for the evolution of life and biogeography on land and in the sea.

If we are to assess the effects of changes in productivity on the CO_2 content of the atmosphere, the interrelationships among ocean circulation, nutrient transport, and the sedimentation of organic compounds and carbonate must be established for each of the important productivity regions. Before Leg 175, little information was available on upwelling fluctuations off Angola and Namibia—except for the late Quaternary period.

The most important period for understanding the workings of the present system is the time since the late Miocene. Within this period, we see the evolution of the present planetary orography, the buildup of ice caps on both poles, the development of modern wind and upwelling regimes, and the stepwise increase in North Atlantic Deep Water (NADW) production, which dominates the style of deep circu-

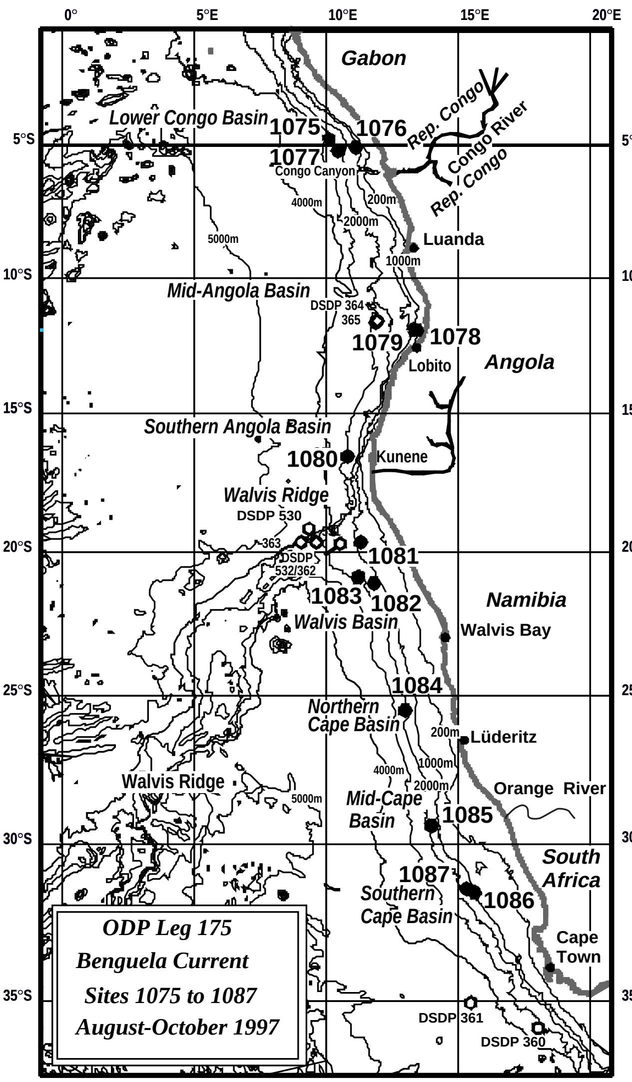

Figure 1. Overview map showing sites drilled during Leg 175.

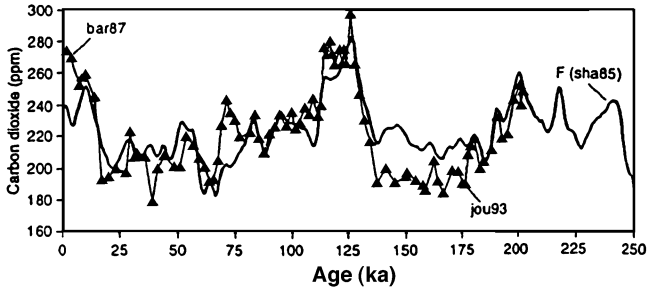

Figure 2. Carbon dioxide concentrations (solid triangles; bar87 and jou93) in the Vostok ice core from Antarctica (Barnola et al., 1987; Jouzel et al., 1993) and eastern tropical Pacific (difference between the $\delta^{13}C$ values of planktonic and benthic foraminifers (thick line; F [sha85]); Shackleton and Pisias, 1985), show that ocean productivity and atmospheric CO_2 tend to vary together. Time scale of Barnola et al. (1987) is adjusted to the one of Shackleton and Pisias (1985) by correlation of the deuterium signal in the ice with the oxygen-isotope signal in the sediment (from Berger et al., 1996).

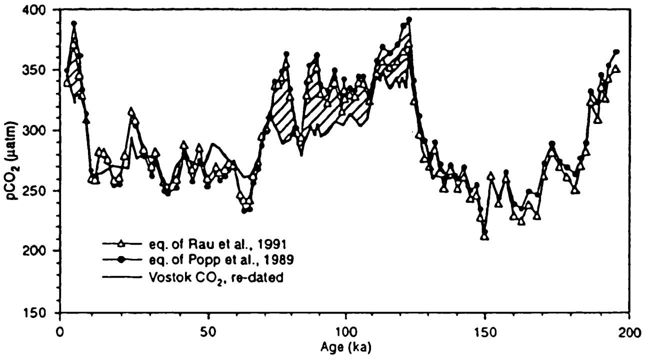

Figure 3. Comparison of the ice-core CO_2 record of Barnola et al. (1987) with surface-water pCO_2 estimates for Geosciences Bremen (GeoB) Core 1016-3, using the conversion for $\delta^{13}C$ of organic matter to CO_2 pressure proposed by Popp et al. (1989) and Rau et al. (1991; eq. = equation). Time scale of Vostok ice core is adjusted for best fit. Hatched pattern = misfit (from Müller et al., 1994).

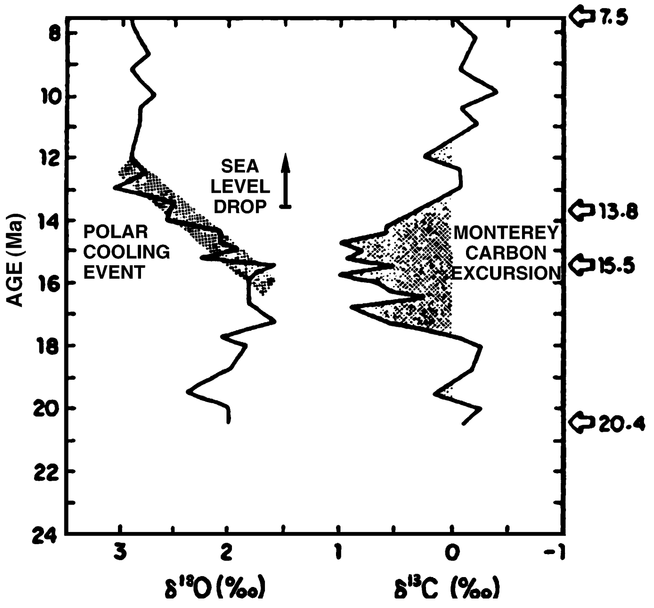

Figure 4. Relationship between δ^{18}O and δ^{13}C records of benthic foraminifers at DSDP Site 216 in the tropical Indian Ocean. It suggests that extraction of organic carbon in upwelling regions during Monterey time eventually resulted in cooling because of downdraw of atmospheric pCO_2 (from Berger, 1985; after Vincent and Berger, 1985).

lation in the ocean. The present system is characterized by a strong 100-k.y. climatic cycle, beginning at ~700 ka (Berger et al., 1996). High-amplitude fluctuations associated with buildup and decay of northern ice sheets began at ~2.8 Ma (Shackleton et al., 1984; Hodell and Venz, 1992; see Fig. 5).

REGIONAL SETTING

The ABC-system is one of the five or six great upwelling regions in the world. It extends over a considerable portion of the western margin of South Africa, with productivity values >180 gC/m^2/yr (black areas in Fig. 6). It is characterized by organic-rich sediments containing an excellent record of productivity history, which, in turn, is closely tied in with the regional dynamics of circulation, mixing, and upwelling, as seen in the oxygenation of thermocline waters (Fig. 7). In addition, this environment provides an excellent setting for "natural experiments" in diagenesis, especially concerning the genesis of economically important resources such as petroleum and phosphate.

Upwelling off southwest Africa is centered, at present, on the inner shelf and at the shelf edge. The Benguela Current flows roughly parallel to the coast and within ~180 km of it south of 25°S, and then turns to the west over the Walvis Ridge (WR) between 23°and 20°S (Stramma and Peterson, 1989; Fig. 8). At about 20°S, warm, tropical water masses from the north meet the cold Benguela Current water. Eddies of cold, upwelled water contain radiolarian and diatom skeletons, which are transported from the upwelling area to the northern slope of the WR where they have been sampled at Deep Sea Drilling Project (DSDP) Sites 532 (Hay, Sibuet, et al., 1984) and 362 (Bolli, Ryan, et al., 1978).

According to previous studies, eddies formed farther north during the Last Glacial Maximum (LGM). The Benguela Current stayed close to the coast and flowed over the WR to reach the Angola Basin, only bearing to the west at ~17°S. Sediments deposited at Site 532 during the LGM apparently confirm the postulated absence of upwelling eddies by showing very low abundances of opal skeletons (Hay, Sibuet, et al., 1984; Diester-Haass, 1985). Upwelling may have continued to occur near the African shelf, but the Benguela Current then did not transport that upwelling signal to the WR. However, from the distribution of foraminiferal assemblages at Site 532, it appears that, under glacial conditions, the northeastern WR was, in fact, characterized by intensified upwelling and a westward expansion of

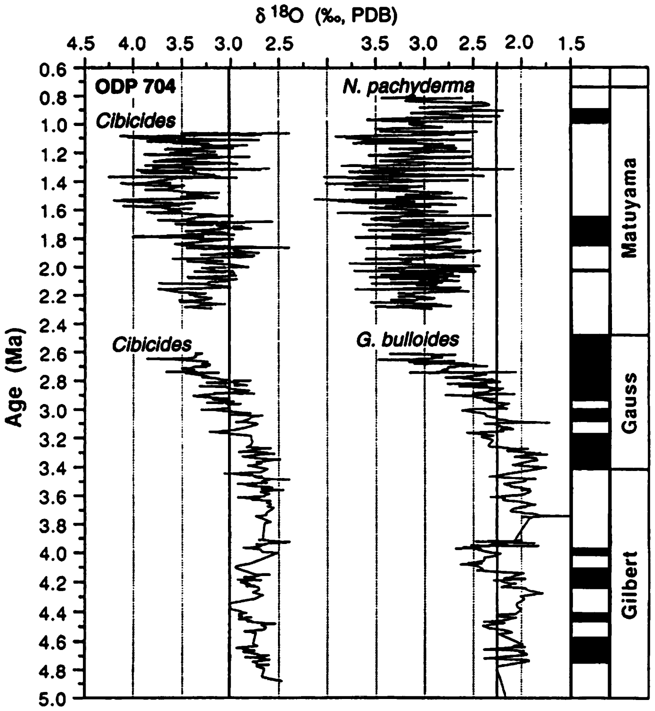

Figure 5. The cooling step observed between 3 and 2.5 Ma (as seen in the shift to more positive values of δ^{18}O) marks a change toward greater instability of climate, as seen in increased fluctuations of δ^{18}O values of planktonic foraminifers (*Neogloboquadrina pachyderma* and *Globigerina bulloides*) and benthic foraminifers (*Cibicides* spp.) sampled near the boundary between the South Atlantic and Southern Oceans (from Hodell and Venz, 1992).

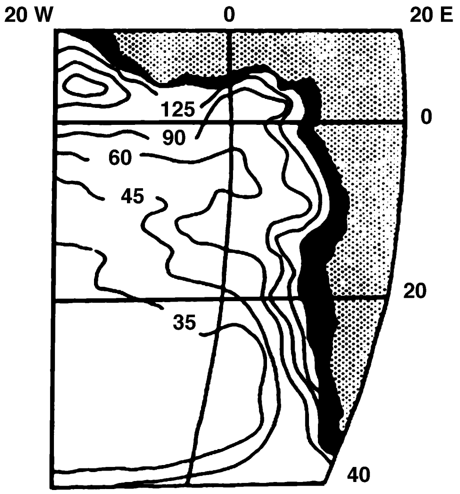

Figure 6. Angola-Namibia upwelling system off southern Africa, as seen in productivity distributions (modified from Berger, 1989). Numbers represent the primary production in grams of carbon per square meter per year (gC/m^2/yr); black areas have primary production values >180 gC/m^2/yr.

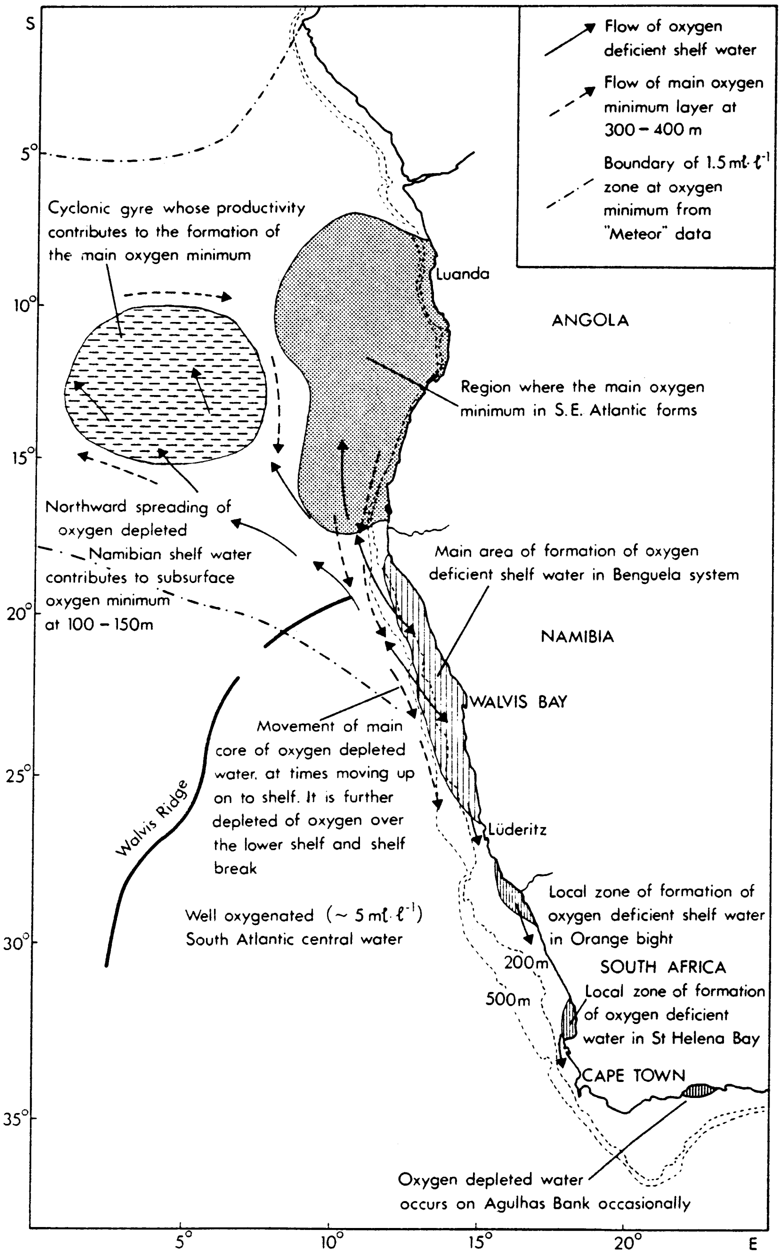

Figure 7. Conceptual model showing areas where low-oxygen water is formed in the southeast Atlantic and the inferred movement of this water (dashed arrows; modified from Chapman and Shannon, 1987).

coastal upwelling cells during the last 500 k.y. (Oberhänsli, 1991). The issue of contrasting models of glacial/interglacial upwelling dynamics in this region is unresolved. It hinges on the question of why opaline fossils show contrary abundance variations with respect to the productivity record from other proxy indicators.

The results from Sites 362 and 532 can be used to reconstruct, tentatively, the evolution of the Benguela Current during the past 10 m.y. This evolution is characterized, on the whole, by increasing rates of accumulation of organic carbon (C_{org}). In addition, there are indications from changing correlations among percent carbonate, percent C_{org}, and diatom abundance that the dynamics of the system undergo stepwise modifications. In this connection, as well, a distinct opal maximum centered near the Pliocene/Pleistocene boundary is of great interest (Fig. 9). The nature of this opal maximum is not clear; perhaps, it is a response to the migration of the polar front to a more northern position.

The evolution of the climate of the Northern Hemisphere, particularly that of northern Europe, is linked to the exchange of heat between the South Atlantic and the North Atlantic Oceans (Fig. 10). Operating over long distances, this energy transport is involved in the control of global climate patterns including the growth and wasting of polar ice caps. In today's world, a net heat transfer from the South Atlantic to the North Atlantic exists in currents above the thermocline (Fig. 11). A part of the heat contribution from the South Atlantic is believed to originate from the Indian Ocean via the Agulhas Current. Water masses from the Agulhas Current—warm eddies produced within the Agulhas Retroflection—are swept up by the Benguela Current and moved northward. Northward and southward shifts of the Southern Ocean polar front constrict or expand, respectively, the interchange of heat from the Indian Ocean to the South Atlantic (McIntyre et al., 1989). This interchange presumably has a drastic impact on the heat budget of the Benguela Current system and, consequently, that of the entire Atlantic Ocean. Such variations in heat transfer should appear as changes in the course and intensity of currents and productivity regimes and should be recorded in the sediments accumulating along the southwest African margin.

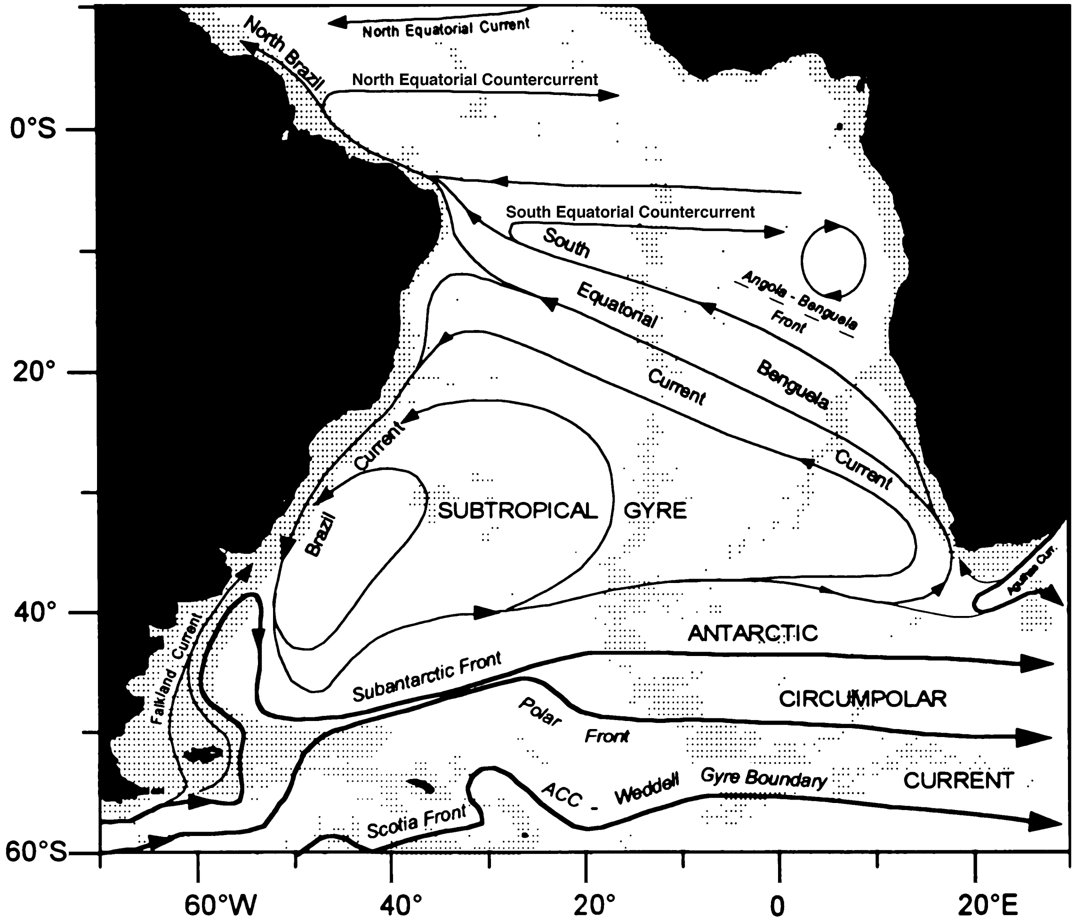

Figure 8. Schematic representation of the large-scale, upper level geostrophic currents and fronts in the South Atlantic Ocean. After Peterson and Stramma (1991), with minor additions from other compilations. ACC = Antarctic Circumpolar Current.

An important element of the heat transfer dynamics is the deep-circulation pattern. Traditionally, the focus in reconstructing this pattern has been on the properties and boundaries of NADW-related water masses, as seen in the $\delta^{13}C$ of benthic foraminifers. The emphasis has been on glacial-to-interglacial contrast (Fig. 12). This contrast shows that NADW production was greatly reduced during glacial periods (also reflected in the pattern of carbonate preservation). More recent studies have added much detail to this story (summarized in Bickert and Wefer, 1996; see Fig. 13). It appears that the strength of the NADW is reflected in the differences between eastern and western basins and in gradients within the eastern basin. Information on associated changes at depths above the NADW has been sparse. It must be assumed that the strength of the nutrient maximum underlying the Benguela upwelling regions (Fig. 14) is somehow coupled to the evolution of NADW, which, in turn, influences the dynamics of intermediate water-mass formation to the south. At this point, we do not know how the different cycles are related, so little or nothing can be said about causal relationships.

Paleoceanographic interpretations regarding the history of the Benguela Current are derived mainly from a single location off the southwestern coast of Africa (Site 532) and must be considered preliminary. Given the indications that the axis and the intensity of the Benguela Current have changed over the past 15 m.y. and that productivity has fluctuated with glacial/interglacial cycles, confirmation and refinement of these ideas are needed. Although sites in the Cape and Angola Basins and on the WR were occupied during DSDP Legs 40, 74, and 75, these sites are situated too far offshore to provide the required information regarding processes in the eastern boundary system. Sites 362 and 532 on the WR receive an indirect record of near-coastal upwelling from material transported to their location by the Benguela Current. Furthermore, modern coring technology (APC and XCB) allows for high-resolution studies by avoiding much of the drilling disturbance present in the Leg 40 cores. Such high-resolution work is crucial if the dynamics of upwelling are to be captured back to the Miocene on a scale of glacial/interglacial cycles. Information from the Leg 175 array of sites situated in the Southern and Mid-Cape Basins (SCB and MCB, respectively), on the WR, and in the Southern Angola Basin (SAB) allow the construction of a coherent picture.

SCIENTIFIC OBJECTIVES

The results from DSDP Sites 362 and 532 suggest that there has been a general northward migration of the Benguela Current upwelling system during the last 14 m.y. Because the shape of the South Atlantic Ocean has not changed appreciably during this time, the changes in the upwelling system must reflect large-scale, perhaps global, changes in ocean circulation. Leg 175 focused primarily on the paleoceanographic and paleoclimatic aspects of the area. However, there is interest in investigating samples from the upwelling area off Angola and Namibia with regard to early diagenetic processes taking place in this unique environment. Possible work includes study of the formation of dolomite (Baker and Kastner, 1981; Kulm et al., 1984; Kelts and McKenzie, 1982, and other articles in Garrison et al., 1984) and phosphorite (Calvert and Price, 1983). We

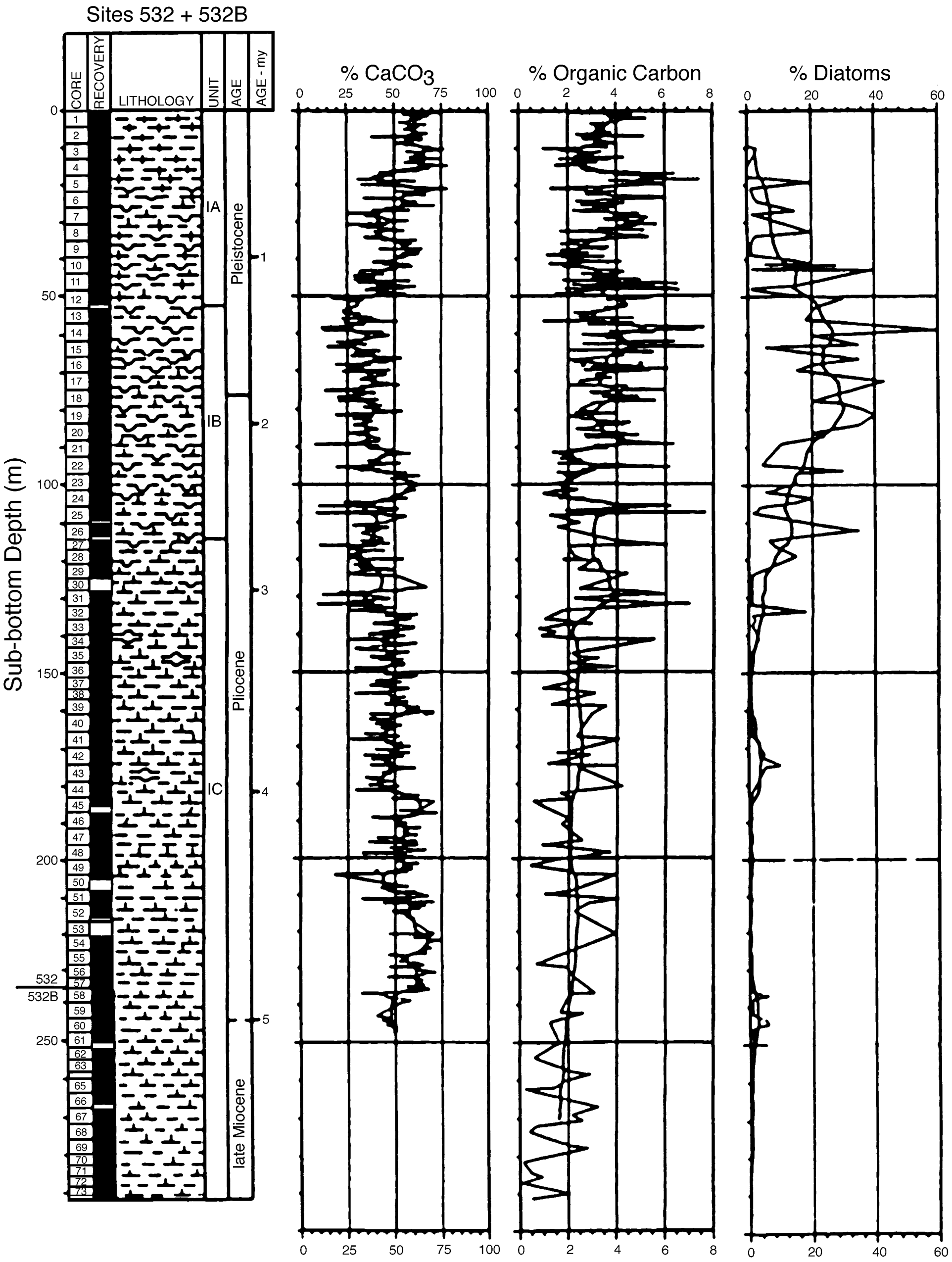

Figure 9. Depositional cycles in biogenous sediments on the Walvis Ridge, in the Benguela Current system. Note overall trend in diatom abundance, with a maximum near the Pliocene/Pleistocene boundary (after Dean and Gardner, 1985, and Hay and Brock, 1992).

also hope to examine the organic matter type and distribution as a function of time and climatic cycles.

Important goals of Leg 175 include the following:

1. Determine the history of the Benguela Current for the late Neogene. Of special interest is the changing response to orbital forcing, as seen in spectral amplitudes and phase relationships of various proxies (e.g., McIntyre et al., 1989; Schneider, 1991; Berger and Wefer, 1996a, 1996b; Jansen et al., 1996; Schneider et al., 1996; Wefer et al., 1996).
2. Study the history of upwelling productivity off Angola and Namibia and the influence of the Congo River, thereby extending available information about the late Quaternary (Bremner, 1983; Jansen et al., 1996) to earlier periods. The history of opal deposition off the Congo River is of interest (Schneider, 1991), as well as the origin of cycles of carbonate, organic matter deposition, and diatoms in each region.
3. Determine what kind of oceanographic changes (regarding the Agulhas Current, polar front position, Equatorial Current, and Brazil–Argentine Currents) occur simultaneously with the shifting of the Benguela Current. Quaternary studies, in conjunction with results from physical oceanography (Wefer et al., 1996), can help refine the nature of such shifts. Results from Ocean Drilling Program (ODP) Legs 108, 114, and 177 are useful in defining the past equatorial and polar boundaries of the Benguela Current. The final aim is to reconstruct the late Neogene paleocirculation pattern of the South Atlantic Ocean to evaluate implications for the glacial/interglacial heat bal-

ance through time between the South and North Atlantic Oceans. Of special interest is the identification of changes in modes of circulation, as seen in changes in correlations between proxy variables, as a function of time.

4. Assess the relationships between changes in the ABC-system and changes in climates of western South Africa. For example, how is the origin of the Namib Desert related to the initiation and intensification of upwelling off southwest Africa? Sites close to the continent probably contain enough information (clay minerals, grain size of terrigenous material, pollen, phytoliths, and freshwater diatoms) to allow reconstruction of continental climatic changes and to determine whether these changes are synchronous with oceanographic changes.

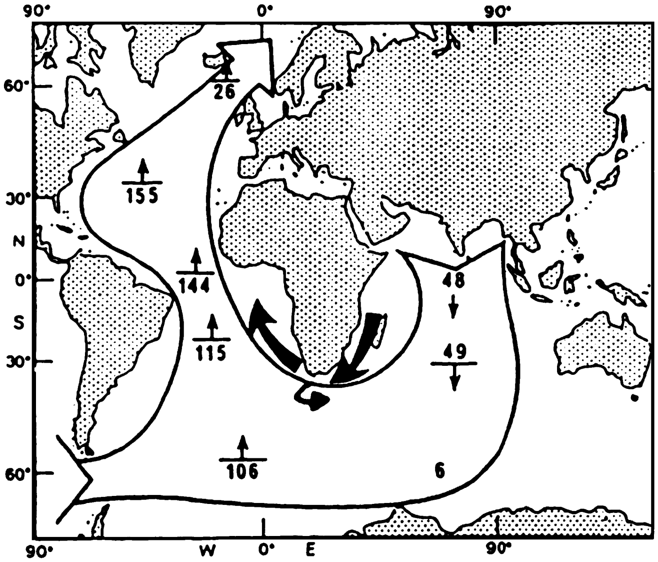

Figure 10. Meridional heat transport in the Indian and Atlantic Oceans (in 10^{13} W; modified from Woods, 1981). Note the major transfer of heat from the Indian Ocean to the Atlantic Ocean, around the Cape of Good Hope, which can be modulated through time by changing the position of the Subantarctic Frontal system.

5. Examine the effect, if any, of sea-level changes on sedimentation below the Benguela Current. Published eustatic sea-level curves (Haq et al., 1987) will be useful for this purpose.
6. Study early diagenetic processes in environments with very high organic carbon and opal contents for comparison with studies undertaken during Leg 46 in the Gulf of California (Curray, Moore, et al., 1982) and Leg 112 off Peru (Suess, von Huene, et al., 1990). The sediments deposited below the upwelling areas off the Peru margin are deposited in forearc basins in a disturbed tectonic setting, whereas sedimentation off Angola and Namibia occurs on a steadily sinking passive margin with quite stable conditions.

These goals guided the planning of Leg 175. On 12 August 1997, the *JOIDES Resolution* set out from Las Palmas (Canary Islands) with a course for the first site (1075) off the Congo River. During the 57-day expedition, we occupied 13 sites (Fig. 1) and drilled 40 holes. Overall penetration totaled 8210.5 m, with 8003.2 m of recovery (Table 1). On 9 October 1997, the vessel entered the port of Cape Town, South Africa, ending the leg.

DRILLING STRATEGY

During Leg 175, the *JOIDES Resolution* drilled 13 sites as part of a latitudinal transect between 5°and 32°S. All but one site (1080) yielded excellent sections with virtually complete recovery (Fig. 15). Off the Congo and Angola, drilling was restricted to the upper 200 m (or 120 m) for safety reasons. Other proposed sites off Angola (downslope of Site 1079) were taken off the list altogether during final review. Sedimentation rates typically are near 100 m/m.y.; thus,

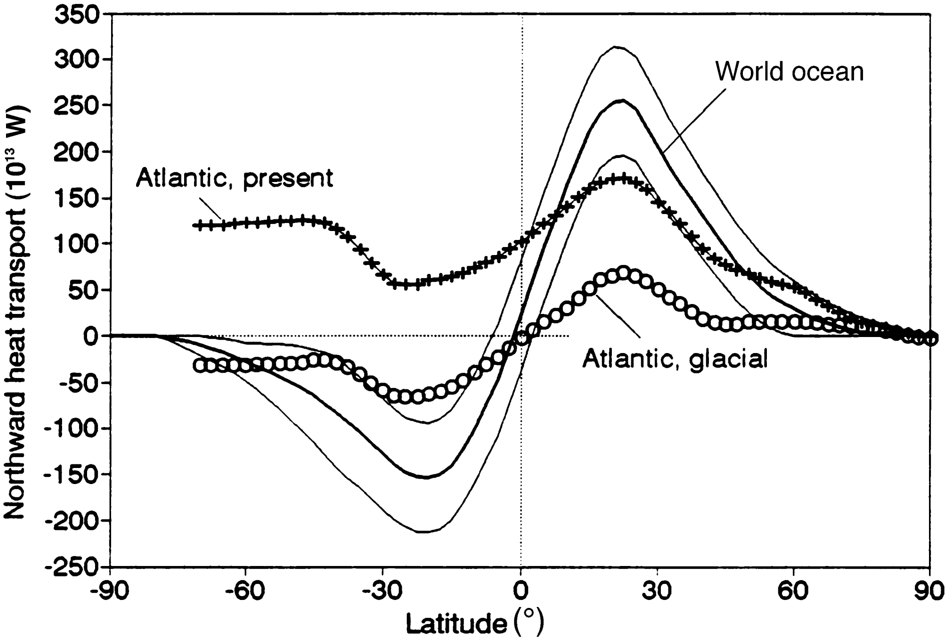

Figure 11. Estimates for annual heat transports for the present world ocean (thick solid line; thin solid lines = approximate error bounds) and for the Atlantic (present conditions and LGM as labeled). From Berger and Wefer (1996a); modified after Miller and Russell (1989). Note the anomalous pattern for the present-day South Atlantic Ocean and the more symmetrical pattern for glacial conditions.

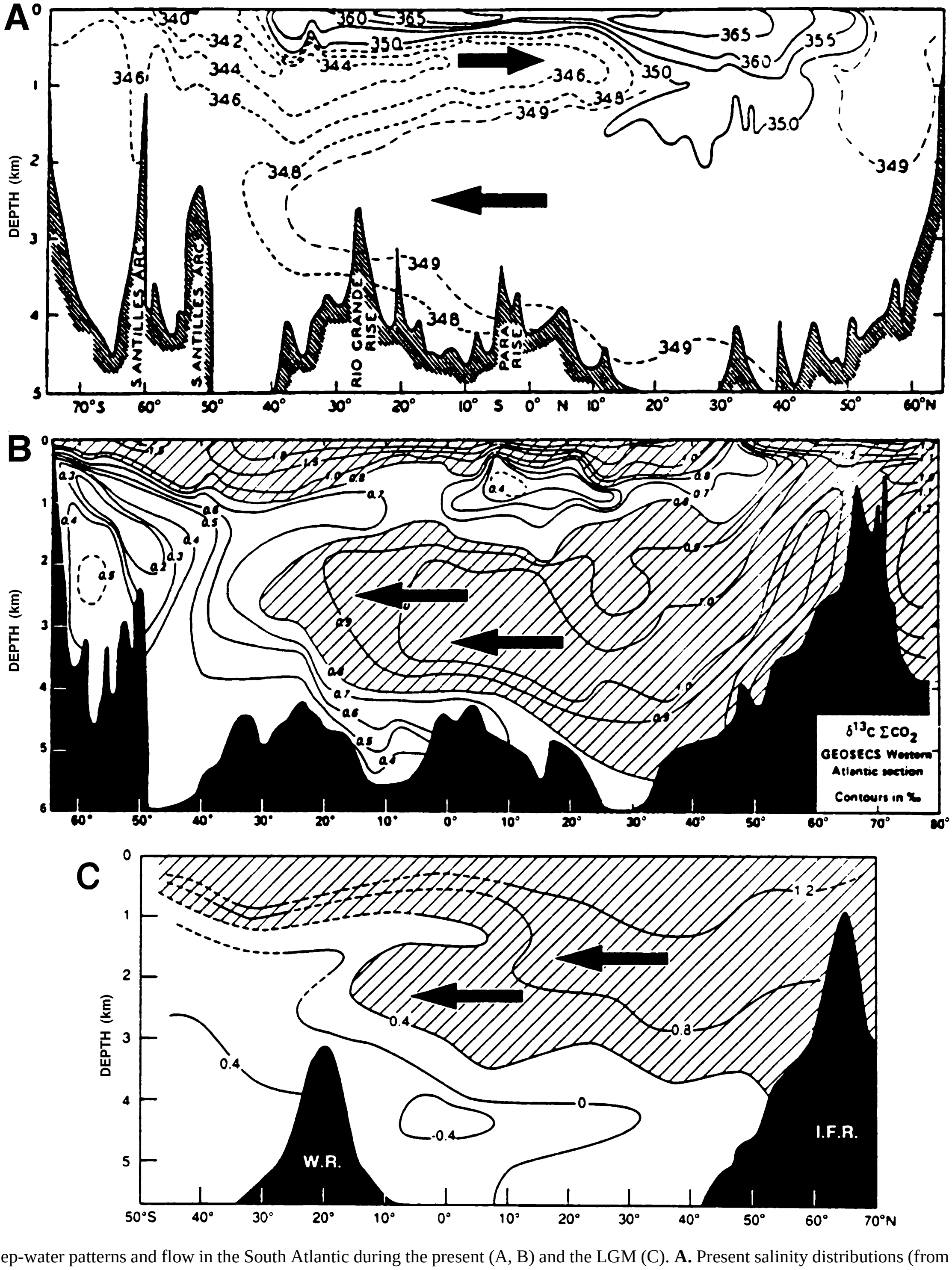

Figure 12. Deep-water patterns and flow in the South Atlantic during the present (A, B) and the LGM (C). **A.** Present salinity distributions (from Sverdrup et al., 1942). **B.** Distribution of δ^{13}C values in dissolved inorganic carbon (from Kroopnick, 1980). **C.** Distribution of δ^{13}C values in dissolved inorganic carbon 20 k.y. ago, inferred from δ^{13}C values in benthic foraminifers of that age (from Berger and Wefer, 1996a; after Duplessy et al., 1988, and Sarnthein et al., 1994).

drilling at the shallow sites to the north of WR recovered sediments mainly of Quaternary age, with occasional penetration into the late Pliocene (Sites 1075 and 1077; see Fig. 16). On and south of WR, several sites had penetration to 600 meters below seafloor (mbsf). From these deeper sites, sediments dating back to the middle Miocene were recovered in continuous stratigraphic sections, and sediments as old as the Oligocene were recovered where sections were incomplete (Fig. 16).

Sites are located in the Lower Congo Basin (LCB; Sites 1075, 1076, and 1077), Mid-Angola Basin (MAB; Sites 1078 and 1079), Southern Angola Basin (SAB; Site 1080), Walvis Ridge (WR; Site 1081), Walvis Basin (WB; Sites 1082 and 1083), Northern Cape Basin (NCB; Site 1084), Mid-Cape Basin (MCB; Site 1085), and Southern Cape Basin (SCB; Sites 1086 and 1087; also see Fig. 1). Depth transects were achieved in four areas: LCB with three sites, MAB with two sites, WR/WB transect with three sites, and SCB with

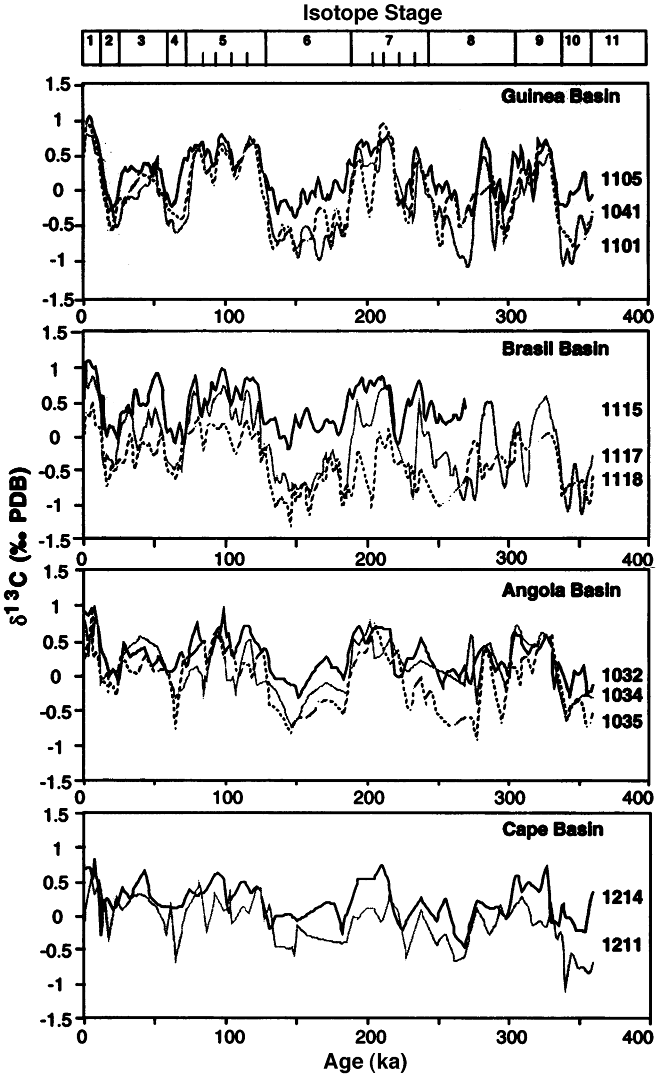

Figure 13. Plot of carbon-isotope records, measured on the benthic foraminiferal taxon *Cibicidoides wuellerstorfi,* as a function of time (from Bickert and Wefer, 1996). Numbers refer to core labels in the Geosciences Bremen collections.

two sites. These transects will allow the assessment of offshore gradients in productivity and sediment transport, as well as depth-related effects. Drilling of APC sections (usually the uppermost 200 to 250 m) was done in triplicate (or in duplicate where time constraints required it) so that complete stratigraphic sections could be spliced together from the neighboring holes, each of which has gaps or disturbed sections between successive cores.

SURVEY OF SITES DRILLED

Lower Congo Basin (LCB), Sites 1075, 1076, and 1077

The three LCB sites sampled a complex environment dominated by riverine input, seasonal coastal upwelling, and incursions from the South Equatorial Countercurrent (Fig. 8). Although these three sites represent the same depositional environment, they are located at varying distances from the shelf break, in different water depths, and at different positions with respect to the Congo Canyon and Congo Fan area (Fig. 17).

Site 1075 (APC to 207.2 mbsf) is the deep-water site on the transect (at 3007 m). Sediments consist of greenish gray diatomaceous clay and nannofossil-bearing diatomaceous clay. Calcium carbonate contents generally are <2.5 wt%; thus, paleoclimatic reconstructions will have to rely largely on siliceous microfossils. Nevertheless, it should be possible to generate an oxygen-isotope stratigraphy, in combination with Site 1077. Sedimentation rates are 100 m/m.y. on average. We expected to find methane (CH_4) clathrates at this site because of the high-productivity setting and the presence of a bottom-simulating reflector at 500 mbsf, as seen in high-resolution seismic profiles. The stability field for CH_4 clathrates, given the temperature gradient of 45°C/km, would suggest a transition from ice to gas near that depth. However, we found no evidence for substantial clathrate abundance at this or any other Leg 175 site. (Such clathrates should have lowered chlorinity in interstitial waters upon melting.) Here and elsewhere in Leg 175 sites, gas was abundant. Consequently, small holes were drilled along the core liners to allow the gas to escape and to prevent the sediment from being pushed out the ends of the liners. About one-half of the gas was CH_4; the other half, CO_2.

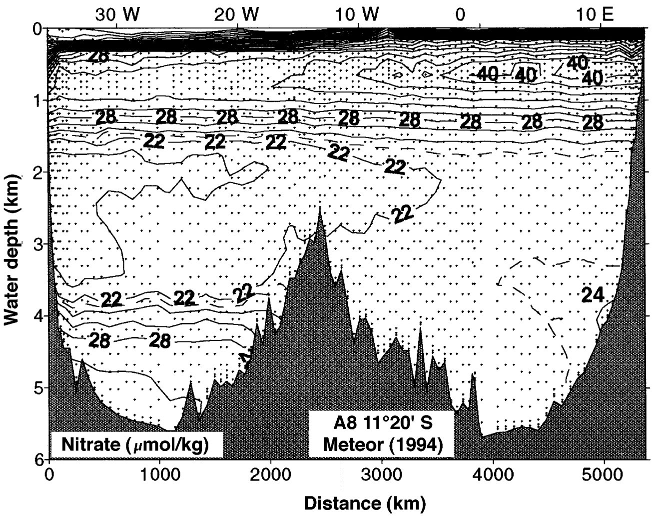

Figure 14. Zonal section of nitrate concentrations at 11°20′S between Brazil and Angola (from Siedler et al., 1996).

Site 1076 is the shallow-water site of the transect (at 1402 m). The record Congo River sedimentation (Fig. 17) was recovered from this site, and it will tie Congo River activity in with coastal upwelling and eastern tropical ocean dynamics. The changing ratio between direct river input and reworked shelf sediments will be of special interest when reconstructing terrigenous input. Sediments consist of organic carbon–rich olive-gray clay and greenish gray clay. Sedimentation rates vary between 50 and 210 m/m.y. The average concentration of total organic carbon (TOC) is 2.6 wt%, which is rather high for ocean margin areas. There is much evidence of reworked material.

Site 1077 is the intermediate site on the Congo transect (at 2394 m). Sediments are composed of greenish gray diatom-rich, diatom-bearing, nannofossil-bearing, and nannofossil-rich clay. Calcium carbonate values vary between 0.8 and 13.2 wt%. In parts of the section, preservation of calcareous fossils is excellent, as indicated by the presence of pteropods. Hole 1077A was logged (202–74 mbsf) with a limited suite of sensors to test for the presence of gas hydrate, for core-log integration, and to obtain proxy records for paleoclimatic change. The presence of Milankovitch-related cyclicity is apparent from comparison of logging records with standard isotope stratigraphies.

Mid-Angola Basin (MAB), Sites 1078 and 1079

The MAB sites, off the Bight of Angola near 12°S, were drilled to provide information on “most nearly normal” margin sedimentation,

Table 1. Summary table of holes drilled during Leg 175.

Hole	Latitude	Longitude	Water depth (mbsl)	Number of cores	Interval cored (m)	Core recovery (m)	Percent recovered (%)	Age of oldest sediment
1075A	4°47.1198′S	10°4.4989′E	2995.7	22	201.00	213.75	106.3	late Pliocene
1075B	4°47.1197′S	10°4.5025′E	2995.2	22	204.50	215.03	105.1	
1075C	4°47.1206′S	10°4.5100′E	2995.5	22	207.20	213.47	103.0	
Site 1075 totals:				66	612.70	642.25	104.8	
1076A	5°4.1316′S	11°6.0917′E	1404.2	22	204.30	217.47	106.4	early Pleistocene
1076B	5°4.1344′S	11°6.0922′E	1402.1	7	60.90	25.87	42.5	
1076C	5°4.1309′S	11°6.1048′E	1402.4	22	203.10	216.80	106.7	
1076D	5°4.1312′S	11°6.1150′E	1401.0	12	113.50	118.41	104.3	
Site 1076 totals:				63	581.80	578.55	99.4	
1077A	5°10.7969′S	10°26.1960′E	2380.0	22	204.50	208.99	102.2	early Pleistocene
1077B	5°10.7977′S	10°26.1831′E	2381.2	22	205.10	211.53	103.1	
1077C	5°10.7995′S	10°26.1687′E	2385.2	3	22.80	16.46	72.2	
Site 1077 totals:				47	432.40	436.98	101.1	
1078A	11°55.2145′S	13°24.0134′E	427.2	9	77.10	70.28	91.2	late Pleistocene
1078B	11°55.2318′S	13°24.0172′E	426.1	14	130.10	125.80	96.7	
1078C	11°55.2474′S	13°24.0161′E	426.0	18	165.20	149.58	90.5	
1078D	11°55.2661′S	13°24.0165′E	427.4	14	126.80	116.71	92.0	
Site 1078 totals:				55	499.20	462.37	92.6	
1079A	11°55.7785′S	13°18.5433′E	737.9	14	121.00	124.61	103.0	late Pleistocene
1079B	11°55.7676′S	13°18.5393′E	738.2	14	128.30	129.70	101.1	
1079C	11°55.7969′S	13°18.5607′E	737.9	14	126.80	129.90	102.4	
Site 1079 totals:				42	376.10	384.21	102.2	
1080A	16°33.5803′S	10°49.2029′E	2765.8	7	52.10	55.57	106.7	early Pleistocene
1080B	16°33.5963′S	10°49.2043′E	2767.9	5	38.20	40.06	104.9	
Site 1080 totals:				12	90.30	95.63	105.9	
1081A	19°37.1818′S	11°19.1598′E	794.1	49	452.70	393.48	86.9	late Miocene
1081B	19°37.1981′S	11°19.1588′E	793.1	21	187.60	195.87	104.4	
1081C	19°37.2128′S	11°19.1620′E	793.8	17	155.20	160.94	103.7	
Site 1081 totals:				87	795.50	750.29	94.3	
1082A	21°5.6373′S	11°49.2361′E	1279.3	64	600.60	502.01	83.6	late Miocene
1082B	21°5.6517′S	11°49.2326′E	1280.4	14	127.00	133.17	104.9	
1082C	21°5.6690′S	11°49.2342′E	1282.1	24	202.00	217.83	107.8	
Site 1082 totals:				102	929.60	853.01	91.8	
1083A	20°53.6841′S	11°13.0720′E	2178.1	22	201.30	185.32	92.1	late Pliocene
1083B	20°53.7004′S	11°13.0738′E	2183.1	22	202.30	206.41	102.0	
1083C	20°53.7138′S	11°13.0734′E	2178.9	1	9.50	9.78	102.9	
1083D	20°53.7138′S	11°13.0734′E	2178.3	21	196.10	201.94	103.0	
Site 1083 totals:				66	609.20	603.45	99.1	
1084A	25°30.8345′S	13°1.6668′E	1991.9	65	605.00	511.56	84.6	early Pliocene
1084B	25°30.8206′S	13°1.6665′E	1992.8	20	182.80	186.60	102.1	
1084C	25°30.8037′S	13°1.6670′E	1991.8	22	207.60	217.82	104.9	
Site 1084 totals:				107	995.40	915.98	92.0	
1085A	29°22.4665′S	13°59.4064′E	1713.2	64	604.00	594.39	98.4	middle Miocene
1085B	29°22.4657′S	13°59.3898′E	1713.0	35	321.20	326.51	101.7	
Site 1085 totals:				99	925.20	920.90	99.5	
1086A	31°33.1608′S	15°39.6235′E	781.1	22	206.20	211.09	102.4	late Miocene
1086B	31°33.1588′S	15°39.6047′E	784.5	23	208.50	212.09	101.7	
Site 1086 totals:				45	414.70	423.18	102.0	
1087A	31°27.8813′S	15°18.6541′E	1371.6	27	255.20	252.38	98.9	
1087B	31°27.8975′S	15°18.6541′E	1371.8	8	72.50	74.83	103.2	
1087C	31°27.9137′S	15°18.6541′E	1374.2	53	491.90	478.30	97.2	early Oligocene/ late Eocene
1087D	31°27.9299′S	15°18.6541′E	1383.5	15	128.80	130.92	101.6	
Site 1087 totals:				103	948.40	936.43	98.7	
Leg 175 totals:				894	8210.50	8003.23	97.5	

being influenced neither by riverine input nor by sustained coastal upwelling activity. Productivity in this region is greatly influenced by variations in the Angola Dome; that is, oceanic upwelling (see Jansen et al., 1996; Fig. 18). Upwelling activity is seasonal, and productivity is not particularly high compared with adjacent regions (Schneider, 1991). This setting allows maximum expression of a pelagic signal in the regional high-productivity record.

Only two sites were occupied at relatively shallow depths (Site 1078 [438 m] and Site 1079 [749 m]) and with penetration limited to 200 and 120 m, respectively. Coring was by APC. Sediments consist of gray silty clay with varying amounts of nannofossils and foraminifers. In parts of the sections, extremely high sedimentation rates (as much as 600 m/m.y.) are present. Much of the material responsible for the high rates may be delivered by coastal erosion. Steep soft-rock cliffs near Lobito, seen during the visit to that port, bear witness to vigorous uplift and erosion along the coast.

At Site 1078, dolomite concretions were first encountered during Leg 175. They are between 3 and 7 cm thick and are present at various depths. Laminated intervals are present in parts of the sections (in one case cemented by dolomite) and point to sporadic expansion of anoxic conditions. A shallow sulfate reduction zone (complete reduction by 30 mbsf) and high TOC content (2.5 wt%) indicate high pri-

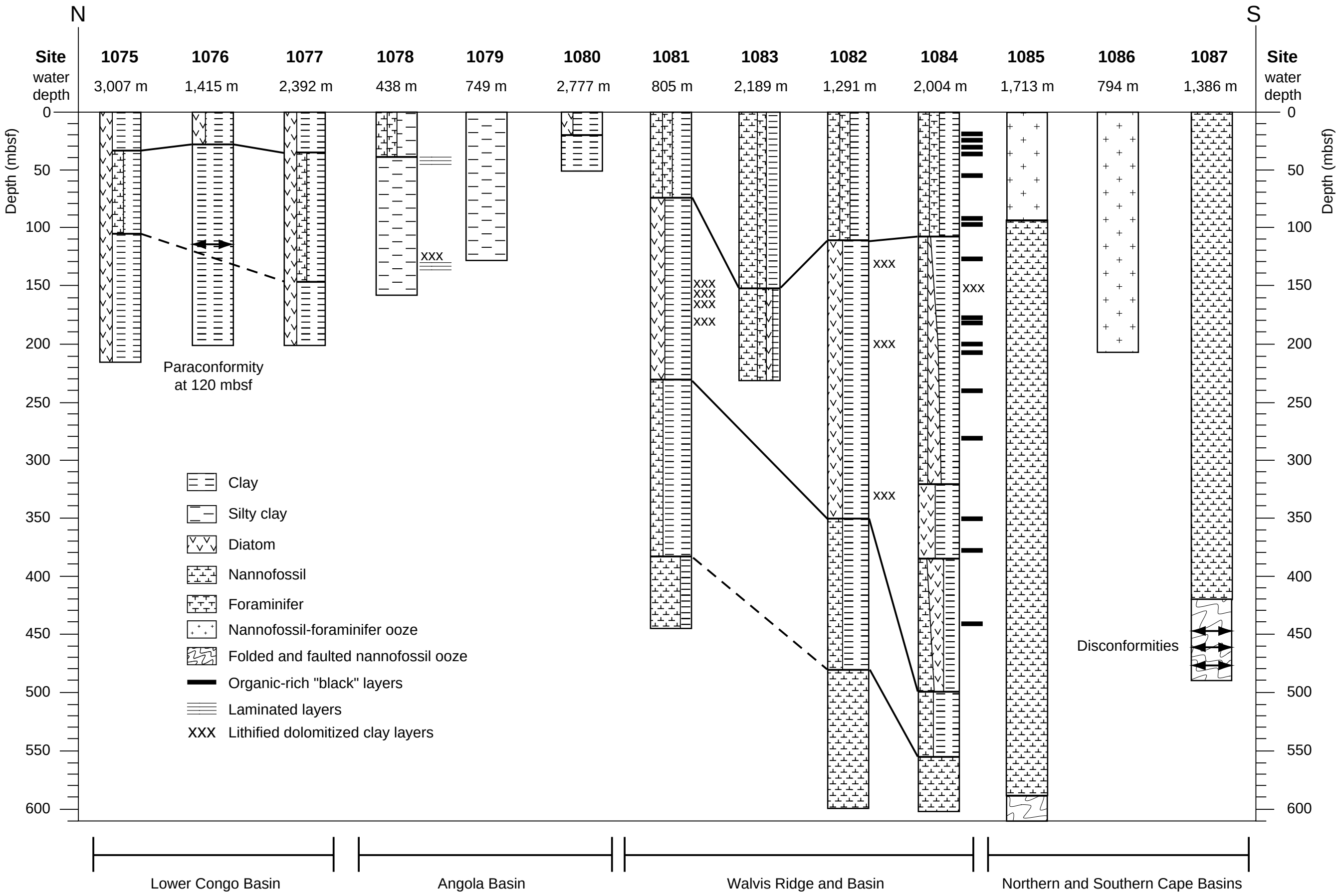

Figure 15. Lithologic units plotted against sediment depth (from Pufahl et al., Chap. 18, this volume).

mary productivity. Together with Site 1079, this site will provide information on the changing position of the Angola-Benguela Front and on the upwelling activity at the Angola Dome.

Site 1079, outside the Bight of Angola, has 60% lower sedimentation rates than Site 1078. Sediments are uniform olive-gray silty clays with varying amounts of nannofossils and foraminifers. TOC content averages 3 wt%, which is somewhat higher than at Site 1078 (less dilution by terrigenous material). Sulfate reduction goes to completion at 50 m.

Southern Angola Basin (SAB), Site 1080

Site 1080, off the Kunene River, is positioned to sample the northern end of the Angola-Namibia upwelling region and for tying shifts in the Benguela Current system to changes in climate in the African hinterland, as reflected in wind-borne dust. Coring at this site proceeded only to 52 mbsf (Hole 1080A) and 38 mbsf (Hole 1080B). Hard dolomite layers resisted drilling at these depths. Because of this, the considerable disturbance of the section, and poor preservation of calcareous fossils, shown by preliminary stratigraphy, drilling was terminated to save time for alternate sites. Sediments from Site 1080 are composed of greenish gray diatom-bearing, diatom-rich silty clays with varying abundances of nannofossils and foraminifers.

Walvis Group (Walvis Ridge/Walvis Bay [WR/WB]), Sites 1081, 1082, and 1083

The Walvis group consists of the three Leg 175 sites on WR and in WB, as well as DSDP Sites 532 and 362 (Legs 75 and 40), which were drilled at a 1300-m water depth. The DSDP sites are seaward of the upwelling center but contain an upwelling signal, which has been transported (as eddies and filaments) by the Benguela Current. Glacial/interglacial cycles are represented as carbonate dissolution cycles, productivity cycles, and continental sedimentation cycles. The transect, located above the regional calcite compensation depth in a passive margin area with high sedimentation rates, can provide high-resolution records for the reconstruction of climatic processes and sea-level change. The phase relationships between carbonate and opal cycles were previously used to propose reconstructions of the path of the Benguela Current (Fig. 19).

Site 1081 (at 760 m) is the shallow-water site of the group. Sediments consist of gray clays, which contain varying amounts of diatoms, nannofossils, foraminifers, and radiolarians. Authigenic minerals, such as glauconite, framboidal pyrite, and dolomite, are present. Sedimentation rates are high, varying between 70 and 150 m/m.y.

Site 1082 (at 1290 m) is intermediate in depth and directly comparable to the DSDP sites farther offshore. Cyclic sedimentation is well developed and spans the last 5.8 m.y. Sediments are composed of green clays containing varying abundances of diatoms, nannofossils, foraminifers, and radiolarians.

Site 1083 (at 2190 m) is the deep-water site in the Walvis group. It has a hemipelagic section going back to 2.6 Ma. Sediments consist of clayey nannofossil ooze. Sedimentation rates vary between 60 and 140 m/m.y. Productivity changes are reflected in dark–light color cycles throughout the drilled sequence.

Northern Cape Basin (NCB), Site 1084

Site 1084, off Lüderitz Bay, will help document the stepwise and fluctuating northward migration of the Benguela Current system from the Miocene to the Quaternary periods, as well as the fluctua-

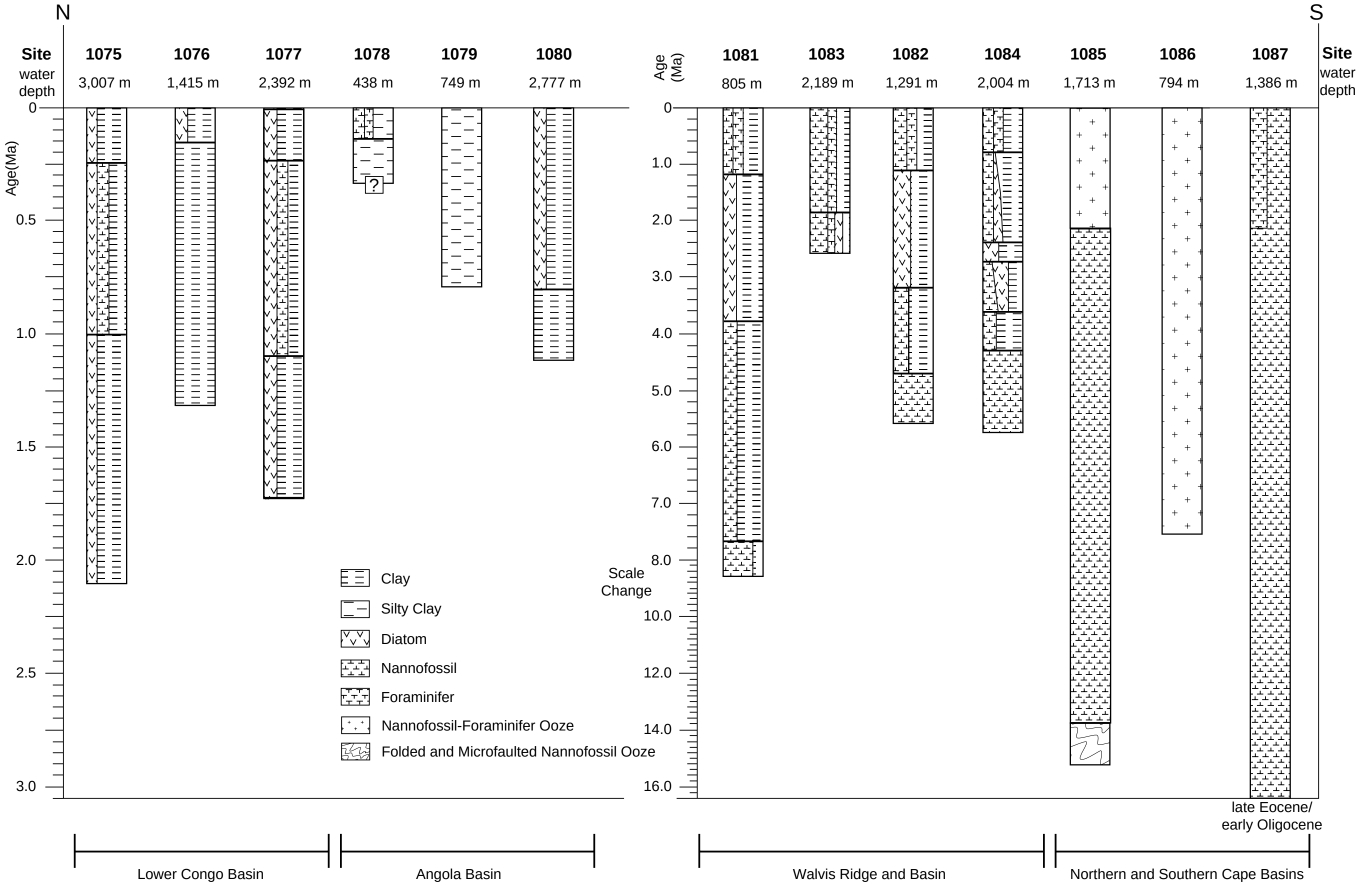

Figure 16. Lithologic units plotted against age (from Pufahl et al., Chap. 18, this volume).

tions in intensity of coastal upwelling in the nearby upwelling center. Such fluctuations are expected to coincide with the movement of the Angola-Benguela Front through coupling via the strength of the trade-wind system. A close tie-in between pelagic and terrigenous sedimentation within the slope record should allow oceanic changes to be matched with continental climate changes. Previous work in this area has documented anaerobic, in part varved, sedimentation in the upper margin region (for a summary, see Dingle et al., 1987; Summerhayes et al., 1995).

The upwelling areas of the Benguela Coastal Current are fed from the thermocline by South Atlantic Central Water, which originates at the Subtropical Convergence Zone by mixing and sinking of subtropical and subantarctic surface waters (Lutjeharms and Valentine, 1987). Filaments of cold, nutrient-rich waters from the coastal upwelling area extend well offshore (as much as ~600 km offshore; Lutjeharms and Stockton, 1987; see Fig. 20). Here, remnants of the filaments mix with low-productivity oceanic water, forming a zone of intermediate productivity. Coastal upwelling is strongly seasonal (Shannon and Nelson, 1996), but response to the seasons differs in the northern Benguela Region (NBR) from that in the southern Benguela Region (SBR; Dingle, 1995). Differences between these regimes are seen in the modern-day planktonic foraminiferal distributions (Giraudeau, 1993; Fig. 21) and have been demonstrated using satellite imaging (Lutjeharms and Meeuwis, 1987). The boundary separating the two regions (Lüderitz Boundary) is the site of maximum upwelling intensity at 26°–27°, with unusually low temperatures persisting throughout the year.

Upwelling in the area north of the Lüderitz Boundary, at the location of Site 1084, shows persistent high productivity and high rates of accumulation of phytoplankton (Brown et al., 1991). Wind speeds are of medium intensity with a wide oceanic and filamentous mixing domain (Lutjeharms and Stockton, 1987). Surface sediments are rich in organics, with a maximum in the inner-shelf belt of diatomaceous ooze off Walvis Bay (Bremner, 1983; Rogers and Bremner, 1991).

Site 1084 has sedimentation rates between 100 and 270 m/m.y., with the highest values within the last 1 m.y. A diatom-rich interval in the uppermost Pliocene sequence also is marked by elevated sedimentation rates. Site 1084's close proximity to the Lüderitz upwelling cell results in well-expressed organic carbon, diatom, and coccolith cycles, via cyclic productivity intensity, as described from the late Quaternary record (Little et al., 1997). Sediments are composed of clay-rich nannofossil diatom ooze, diatomaceous nannofossil ooze, and clay-rich nannofossil ooze. Conspicuous decimeter-thick intervals of dark, organic-rich clay layers are present between 120 and 410 mbsf and are characterized by lower carbonate contents. The biogenic component of the dark layers is commonly dominated by diatom resting spores.

Site 1084 showed intense sulfate reduction in the uppermost few meters and had the second highest ammonia values ever measured for an ODP site. The sediment is unusually gas rich, and the offensive smell produced by outgassing during laboratory studies proved difficult to cope with.

Mid- and Southern Cape Basins (MCB and SCB), Sites 1085, 1086, and 1087

The last three sites occupied during Leg 175 are located in the southern part of the Cape Basin (Fig. 1). They are rather close to the

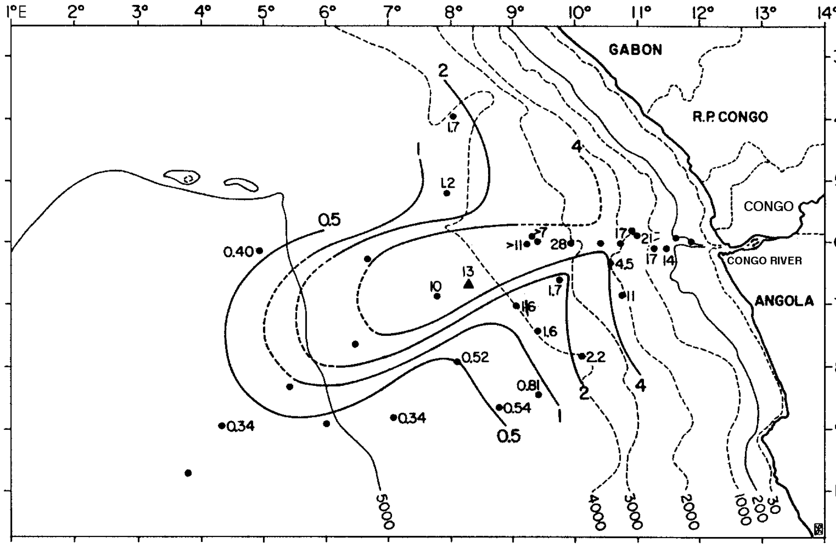

Figure 17. Average noncarbonate sedimentation rates in the Congo Fan area. Rates are in grams per square centimeter per 10^3 yr (from Jansen et al., 1984).

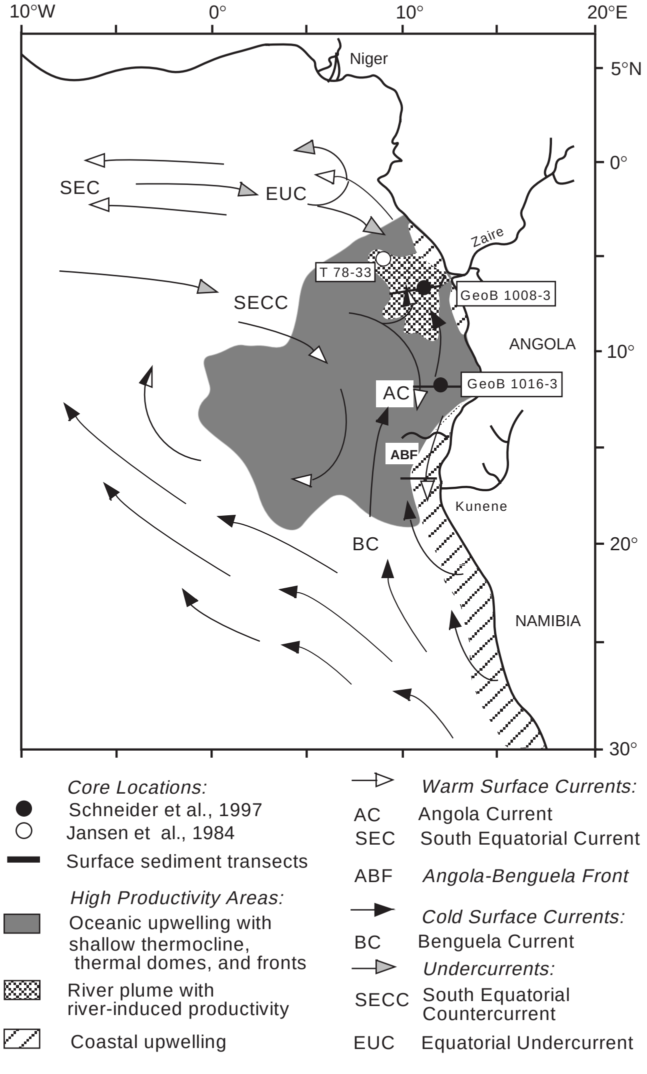

Figure 18. Main surface and subsurface currents and areas with high primary productivity in the southeast South Atlantic (from Schneider et al., 1997). GeoB = Geosciences Bremen.

continent and should be most useful in detecting upwelling signals and clues to changes in continental climate (pollen, clay minerals, and terrigenous silt) and in sea level. Sites 1085, 1086, and 1087 are located within the SBR (Dingle, 1995; see Fig. 21). This region has a highly seasonal upwelling regime, with a maximum in summer, and a restricted mixing domain (Lutjeharms and Meeuwis, 1987; Giraudeau and Rogers, 1994).

Site 1085 is located offshore and to the side of the mouth of the Orange River, which flows year-round and could deliver terrigenous materials to the site. Such an effect should show more clearly during times when the Benguela Current and coastal upwelling activity were less vigorous than they are today. It will be most interesting to compare the results from Site 1085 with those from the more northern Site 362 (Diester-Haass et al., 1990), which is farther from a source of terrigenous input. Together with other sites, especially 1082 and 1084, Site 1085 will help document the path and strength of the Benguela Current from the Miocene to the present, as well as the shoreward and seaward migrations of the upwelling centers along the coast. Because sedimentation rates are more moderate at Site 1085, drilling penetrated into sediments of middle Miocene age so that a complete record of the development of the Benguela Current system should be available.

Site 1086 (at 793 m) is the shallow-water site of the SCB transect. Because of its proximity to the Agulhas Retroflection (Lutjeharms, 1996) and the Subtropical Convergence Zone, we expect to find indications of warm-water incursions in the fauna and flora of the plankton embedded into assemblages typical for temperate and cool conditions. At present, the addition of warm water from the Indian Ocean into the region where the Benguela Current originates (Fig. 22) is an important element of the heat budget of the South Atlantic. Much or all of the Quaternary record is missing at this site, apparently because of winnowing at these shallow depths.

Site 1087 (at 1383 m) is the deep-water site of the transect. For this offshore site, we expect a strong open-ocean influence on sedimentation compared with the more northern sites in the Cape Basin, with their strong imprint of coastal upwelling. This site is located at a crossroads for west-wind drift, the Benguela Current, and the Agulhas Retroflection and should sensitively record the evolution of this complicated system at the point of origin of the Benguela Current.

PRINCIPAL RESULTS

Of the many discoveries made during the expedition, the following are among the most noteworthy:

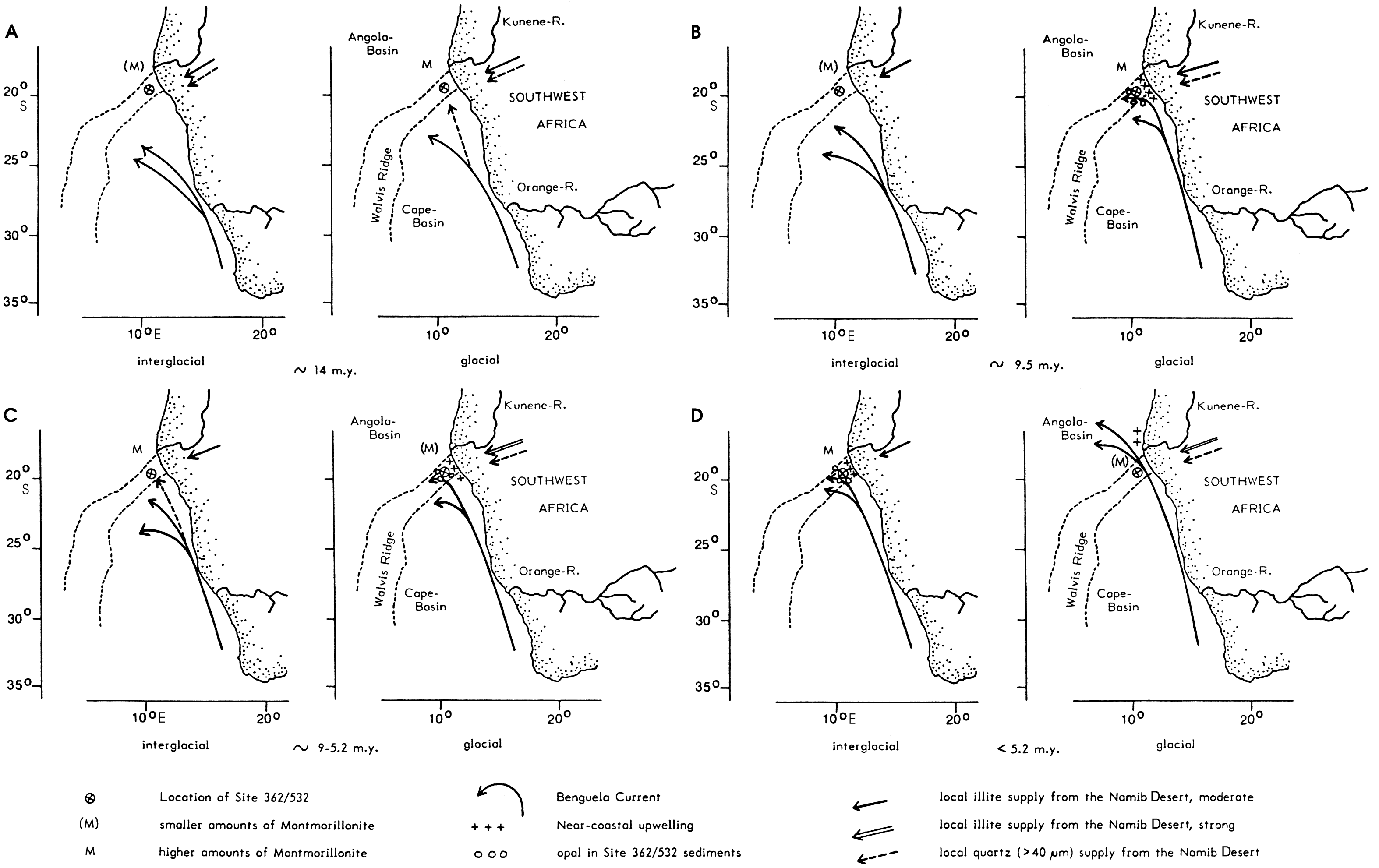

Figure 19. Evolution of the Benguela Current system from ~15 Ma to the present (from Diester-Haass et al., 1990). **A.** ~14 Ma. **B.** ~9.5 Ma. **C.** ~9–5.2 Ma. **D.** <5.2 Ma.

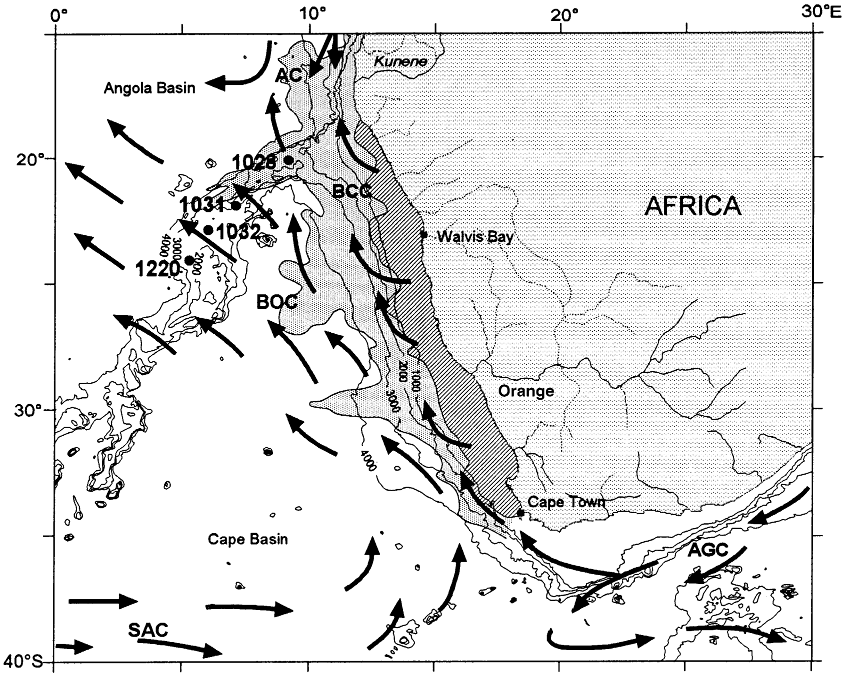

Figure 20. Major upwelling regions off South Africa, with the area of coastal upwelling (hatched pattern) and the extension of the upwelling filaments in the mixing zone between Benguela Coastal Current (BCC) and Benguela Oceanic Current (BOC; dark gray area), during Southern Hemisphere winter (August; from Wefer et al., 1996; modified after Lutjeharms and Stockton, 1987). AC = Angola Current; SAC = South Atlantic Current; and AGC = Agulhas Current. Bold numbers = locations of Geosciences Bremen gravity cores.

1. Evidence for a strong tie-in of variations in productivity in the Angola Basin to fluctuations in the monsoonal activity in North Africa;
2. The presence of a sedimentary record of dry-wet cycles in the drainage basin of the Congo River, located in the heart of Africa;
3. Evidence for large-scale changes in the strength of the Benguela Current;
4. Evidence for considerable increase in the intensity of upwelling off Namibia, which is associated with the great cooling step that initiated Northern Hemisphere glaciation at ~2.8 Ma and with a pronounced maximum in productivity near the Pliocene/Pleistocene boundary; and
5. Evidence for intense chemical activity within the sediments, which leads to the production of gas (CH_4 and CO_2) and the formation of new minerals.

One of the most interesting discoveries, in the context of diagenesis, was the realization that layers of dolomite hard rock form within the soft organic-rich sediment. These layers extend over large areas and greatly impact the ability of sediments to reflect sound. Logging proved the case for the abundance of dolomite layers, which, because of their hardness, were difficult to sample.

In addition, some of the most extreme values for the intensity of sulfate reduction and the production of ammonia ever measured in sediments retrieved by drilling were encountered in a number of holes, especially at Site 1084.

An important result, and a pleasant surprise to many of the scientists on board, is the fact that so many of the sections recovered show continuous sedimentation at high rates of accumulation. Several conditions are responsible for this finding: high rates of supply from high productivity and terrigenous contributions, favorable sites of deposition through salt tectonics (north of WR), and a tectonically quiet setting (in the Cape Basin). This does not imply that, as a rule, sediments are undisturbed along this margin. They are not. A crucial ingredient of finding stratigraphically useful sections is well-prepared site selection. Optimal site selection was possible thanks to high-resolution air-gun profiles collected during two 4-week expeditions mounted for this purpose (the *Sonne* Expedition SO86 in 1993 [Bleil et al., 1995] and the *Meteor* Expedition 34/1 in 1996 [Bleil et al., 1996]). These preparatory expeditions were carried out by the Geosciences Group at Bremen University; processing was done at the Alfred-Wegener Institut for Polar and Marine Research at Bremerhaven.

Stratigraphic continuity also relies on drilling multiple holes using APC technology and on matching the records using detailed core-core correlation. The most important records for splicing proved to be magnetic susceptibility and spectral reflectance, as measured by the Minolta spectrophotometer.

In most cases, the measurement of physical properties was influenced by the high abundance of gas, which produced sediment expansion and created voids and cracks. Consequently, logging had an unusually important role in providing ground truth. Six sites were logged during Leg 175 (Sites 1077, 1081, 1082, 1084, 1085, and 1087). Many different types of measurements were made, including gamma ray, porosity, density, acoustic velocity, electrical resistivity, and magnetic susceptibility. The stability and shape of most of the logged holes were of excellent quality.

Although the high gas content made handling of the cores and measuring physical properties difficult, it also kept sediments from compacting as quickly as they might have otherwise, thus allowing much faster drilling than anticipated. This ultimately resulted in 13 sites being occupied, rather than the planned eight sites. The high rate of core recovery placed special demands on all Leg 175 participants. The stratigraphers, in particular, were called upon to deliver age estimates at an unusual pace. With coccolithophorids as a backbone, as well as magnetic reversals (fortunately still recognizable, despite the high intensity of diagenesis), it was possible to satisfy the demand for operationally relevant information. Backup information came from the other microfossils in due time. Unsurprisingly, diatoms proved to be especially valuable indicators of changes in upwelling intensity.

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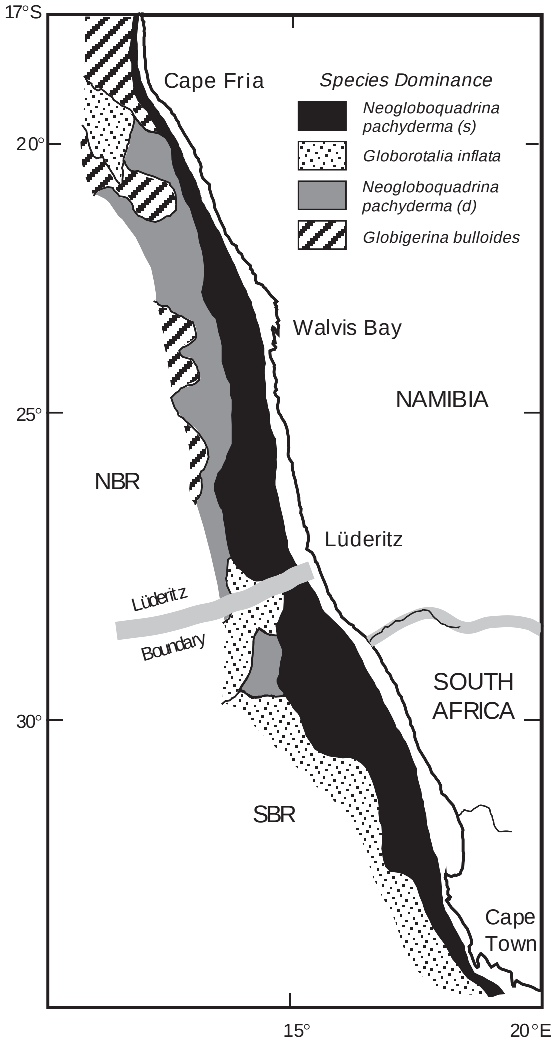

Figure 21. Recent distribution of planktonic foraminifers in the Benguela upwelling system. The Lüderitz Boundary represents the boundary between the northern and southern Benguela regions (NBR and SBR, respectively). From Giraudeau (1993).

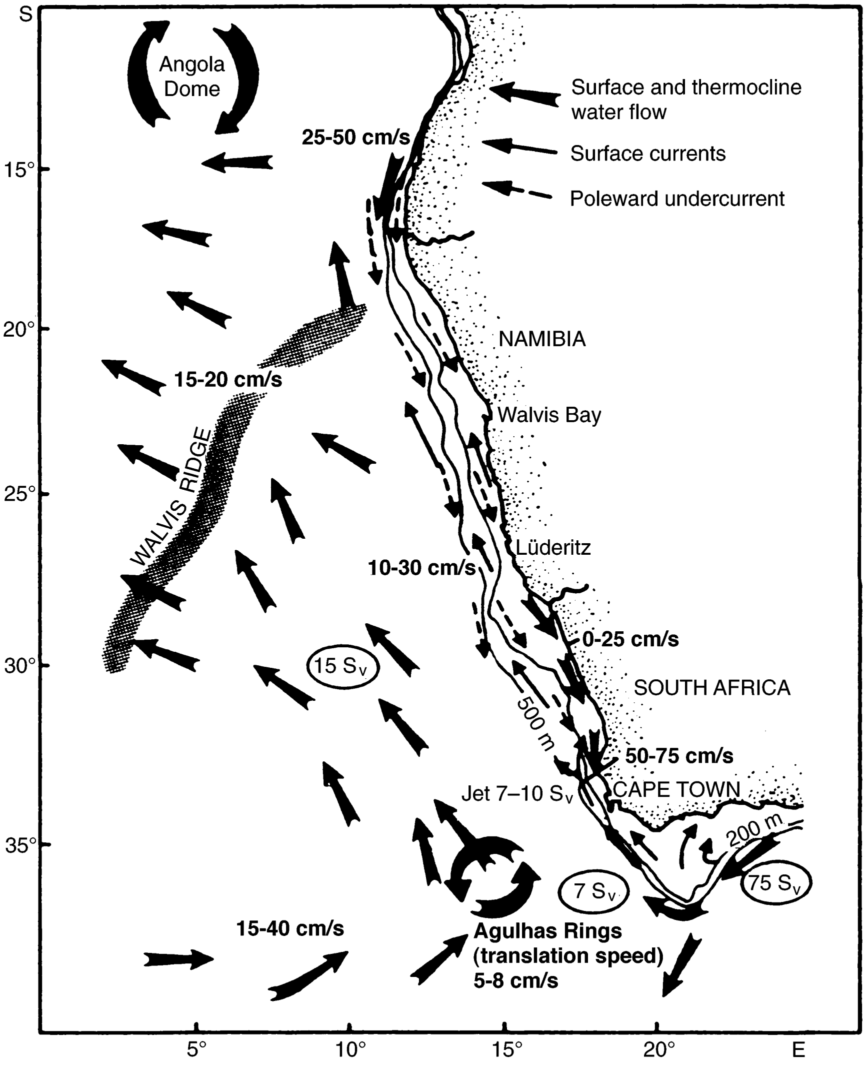

Figure 22. Schematic flow field of surface and thermocline waters. Current speeds refer to surface values from Shannon and Nelson (1996, modified). Transports (circles) refer to total transport above 1500 db (i.e., includes Antarctic Intermediate Water).