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17. THE ANGOLA-BENGUELA UPWELLING SYSTEM: PALEOCEANOGRAPHIC SYNTHESIS OF SHIPBOARD RESULTS FROM LEG 175[1]

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ABSTRACT

Thirteen sites were occupied during Ocean Drilling Program Leg 175 along southwestern Africa, starting with the Congo Fan in the north and ending off the Cape of Good Hope. North of the Walvis Ridge, penetration was limited because of safety concerns. Sediments from the Congo Fan are rich in opal. Maximum rates of sedimentation were found at holes drilled off Lobito (Angola), with rates as high as 60 cm/k.y. because of high terrigenous influx from a rising coast. On the Walvis Ridge and in the Walvis Bay, organic matter–rich calcareous clays were recovered. The highest organic content, the most vigorous development of methane and carbon dioxide, and abundant noxious gases were found at Site 1084, located off Lüderitz, Namibia. The sites occupied off the Cape of Good Hope are characterized by calcareous oozes.

Organic matter abundance, diatom accumulation, and composition of benthic faunas, among other indicators, are the most important tools for the reconstruction of the productivity history of the Angola-Benguela upwelling system. Problems arising include (1) the origin of the Matuyama Opal Maximum, centered near 2.2 Ma, (2) the question of phase relationships between diatom productivity and organic matter supply, and (3) the role of precessional effects in the modulation of productivity as a function of latitude. Regarding the first problem, it emerged that the maximum supply of diatoms is linked to incursions of both warm pelagic water and Antarctic water during the early Matuyama, presumably resulting in the formation of chaotic frontal zones. Coastal upwelling dominates after the maximum. Thus, opal deposition goes through an optimum situation within the latest Pliocene. We hypothesize that increased silicate concentrations in subsurface waters made this optimum possible. As the Benguela Current became stronger in the Quaternary, a more vigorous flow of underlying Antarctic Intermediate Water increased ventilation of the thermocline off southwestern Africa, thereby helping to decrease the silicate content of subsurface waters. Observations during Leg 75 regarding glacial/interglacial cycles on the Walvis Ridge (that warming is accompanied by increased opal deposition) support our hypothesis. Precessional effects are of great importance in the productivity history recorded on the Congo Fan (as seen in color cycles). The sensitivity of the depositional system off the Congo to precessional forcing apparently is especially high within the Milankovitch Chron (last third of the Quaternary).

INTRODUCTION AND OVERVIEW

Ocean Drilling Program (ODP) Leg 175, the “Benguela Leg,” set out to drill as many as four or five transects off the western coast of Africa, beginning off the Congo River, just south of the equator, and ending in the Southern Cape Basin, just north of the Cape of Good Hope. Eight sites were planned for the leg; 13 were in fact drilled (Fig. 1), and 8003 m of core were recovered. Our goal is to reconstruct the late Neogene history of the Benguela Current and the associated upwelling regimes. These regimes constitute one of the few great upwelling regions of the world. Like other eastern boundary upwelling systems studied during recent ODP legs (Peru and California), the Angola-Benguela regimes are characterized by organic-rich sediments that contain an excellent record of productivity history, which can be read on a very fine scale. In addition, this environment provides a prime setting for natural experiments in diagenesis.

The individual transects reflect a compromise between geographic coverage, accessibility, and time constraints. Off the Congo River and off Angola (where active exploration for offshore hydrocarbons is taking place), drilling was limited to maximally 200 m below sea floor (mbsf) for safety reasons (six sites). On the Walvis Ridge and off Namibia and South Africa, we drilled to advanced hydraulic piston (APC) refusal (two sites) or down to between 400 and 600 mbsf (five sites). This overall drilling strategy resulted in the recovery of Quaternary records north of the Walvis Ridge and upper Neogene records on and south of the ridge. In the south, a number of sites include upper Miocene sediments; Site 1087 (the last drilled) includes upper Eocene sediments, but the record is not continuous in the lower section.

The hemipelagic sediments off the Congo (Sites 1075, 1076, and 1077) are dominated by diatomaceous, partially carbonate-bearing clays. Two shallow-water sites off Lobito (Angola) have extremely high sedimentation rates and contain silty clays (Sites 1078 and 1079). Site 1080, drilled off the Kunene River (Angola), contains diatomaceous clays (the section is disturbed). The sites on the Walvis Ridge and in the Walvis Basin (Sites 1081, 1082, and 1083) contain calcareous clays, which are diatom rich in the upper Pliocene and lower Quaternary sections. Site 1084, off Lüderitz, contains sections with extremely high organic carbon content. The southern sites (1085, 1086, and 1087) near the Cape of Good Hope have pelagic calcareous oozes.

The major aim of the expedition was to provide the basis for reconstruction of productivity variations in the South Atlantic, off western Africa, as a means to obtain clues for the history of the Benguela Current, which is the eastern boundary current for the Subtropical Gyre of the South Atlantic (Fig. 2). The Benguela Current originates near the Cape of Good Hope, fed by the South Atlantic Current and, to some degree, by the Agulhas Current. It moves parallel to the coast off southwest Africa and Namibia, but turns westward at the latitude of the Walvis Ridge and merges with the South Equatorial Current. A front develops over the coastal portion of the Walvis Ridge (the Angola-Benguela Front, see Fig. 2) and moves north and south

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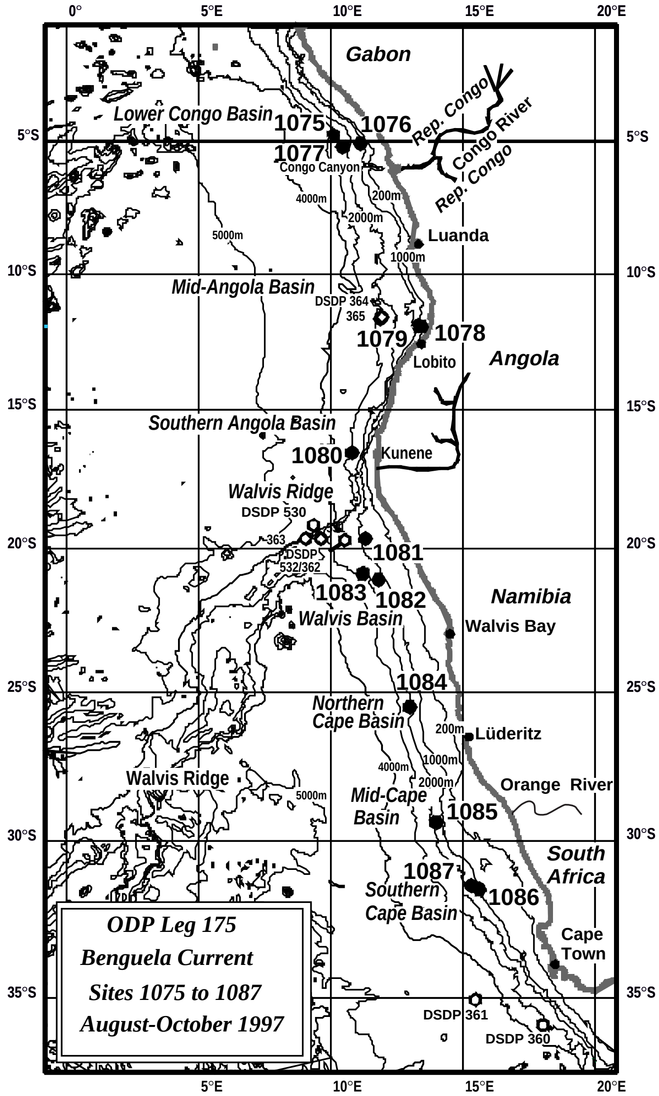

Figure 1. Overview showing locations of Leg 175 drill sites (ODP Sites 1075–1087), as well as DSDP sites drilled earlier (DSDP Sites 360–365 and 530–532).

with the seasons (through ~5°). To the north, sluggish cyclonic circulation marks the Angola Basin, which results in offshore upwelling (the Angola Dome). This region has high nutrient contents in subsurface waters and a strong oxygen minimum.

Productivity is low within the Subtropical Gyre (Fig. 3). It is high along the entire coastal region of southwestern Africa as a result of upwelling and vertical mixing. Areas of especially high productivity within this belt occur both north and south of the Walvis Ridge. To the north, the outflow of the Congo River provides offshore estuarine-type circulation, whereby the dispersing freshwater layer entrains nutrient-rich waters from below the mixed layer. Off Angola, waters rising within the Angola Dome provide nutrients to surface waters, raising the general level of productivity. South of the Walvis Ridge, vigorous wind-driven upwelling interacting with the northward flow of the Benguela Current dominate production dynamics.

The Benguela Current plays a key role in the heat transfer from the South Atlantic to the North Atlantic, which, in turn, dominates climate developments in the Northern Hemisphere in the late Neogene (see articles in Wefer et al., 1996a). The principle of heat transfer is simple: warm surface waters and relatively warm subsurface waters move across the equator, from south to north, to balance the deep return flow of cold waters within the North Atlantic Deep Water (NADW). This results in major heat export from the South Atlantic to the North Atlantic (Woods, 1981; Gordon, 1986; Berger et al., 1987; Broecker and Denton, 1989). Of special interest in this context is the import of warm subtropical waters from the Indian Ocean, around the Cape of Good Hope (Gordon, 1985). The sediments recovered from the Southern Cape Basin will be crucial in reconstructing the history of this process.

Both ocean currents and winds transfer heat from the South Atlantic to the North Atlantic. Warm, moist, tropical air moves across the equator toward the northerly Intertropical Convergence Zone. As a result of this energy transfer, evaporation is greatly increased in the North Atlantic, which produces high-salinity surface waters. Upon cooling in northern latitudes, these waters sink to great depth and return to the south within the NADW. The process started roughly 10 m.y. ago, as seen in a drop in the carbonate compensation depth in the North Atlantic at that time and in other indicators (opal deposition and stable isotopes; summarized in Berger and Wefer, 1996).

The results of Leg 175 thus far provide much encouragement regarding the opportunities for detailed reconstructions of productivity histories all along the southern rim of western Africa. High sedimentation rates in most of the sites will facilitate the task. Initial results highlighted here show that productivity involves a different mix of processes in each major region. Nevertheless, long-term changes in these various regions show some striking coherencies. On orbital scales, evidence for cyclic sedimentation similarly suggests large-scale forcing acting on linked subsystems. The Congo sites, recording tropical wind and runoff, provide a window into the interplay of monsoon and trade winds and the response of the African interior. The Walvis and Lüderitz sites monitor the Benguela system proper. The Cape of Good Hope sites help keep track of the warm-water influx from the Indian Ocean through the late Neogene. Establishing the linkage between these major parts of the Angola-Benguela system is the main task yet ahead.

THE MAJOR PROVINCES

Geology

The southwest African margin, which formed the target area for Leg 175, is represented by three major geologic provinces: (1) the northern margin, where salt tectonics is important; (2) the Walvis Ridge intersection, where hot-spot-derived basalt abuts the continent; and (3) the southern margin, which is a “normal” passive margin, without major salt deposits, large fan deposits, or volcanism.

The fact that salt deposits are present north of the Walvis Ridge greatly affected the choice of targets for Leg 175. Salt accumulated in the early rifting stage of the South Atlantic in Aptian–Albian times when the Walvis Ridge was part of a barrier preventing free exchange of a proto-Brazil-Angola Basin with the open ocean (see Deep Sea Drilling Project [DSDP] Leg 40 report; Bolli, Ryan, et al., 1978). Throughout the late Cretaceous and to the present, salt tectonism has helped shape the morphology of both seafloor and coastal regions and has dominated regional sedimentation patterns. Salt domes and ridges provide convenient barriers for the development of sedimentary basins (which aids in preserving undisturbed sequences). However, they also provide conditions favorable for hydrocarbon accumulation, given organic-rich sediments of Cretaceous age, at the bottom of a thick sediment sequence. In recent years, the offshore petroleum potential of salt-dome structures has attracted much attention. This potential limits exploration for scientific purposes when using riserless drilling.

The Walvis Ridge continues to the present to act as a major barrier to deep-water flow, thus influencing deep-sea sedimentation in the Angola Basin throughout the Cenozoic. This influence may be of some significance in the deepest sites occupied north of the Walvis Ridge (Sites 1075 and 1080). The main difference between the north-

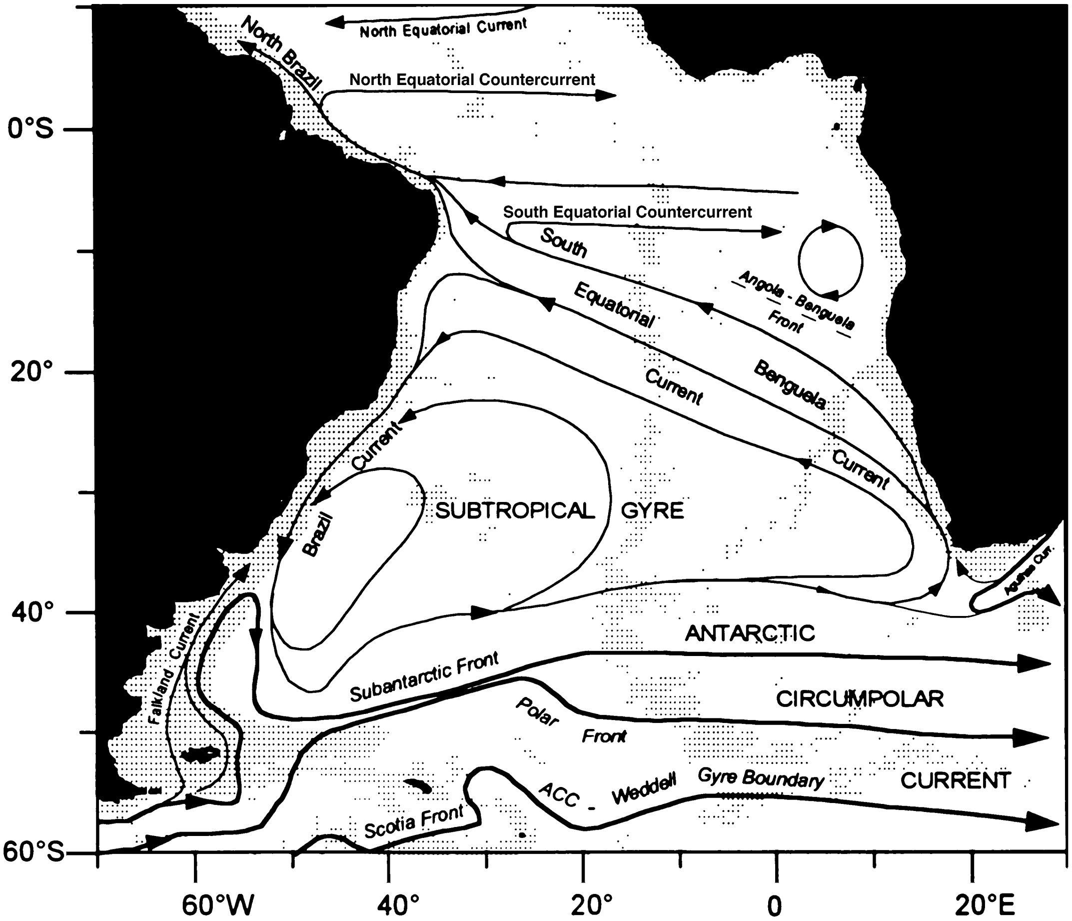

Figure 2. Surface currents of the South Atlantic. Sources: Peterson and Stramma (1991) and Tomczak and Godfrey (1994). From Berger and Wefer (1996).

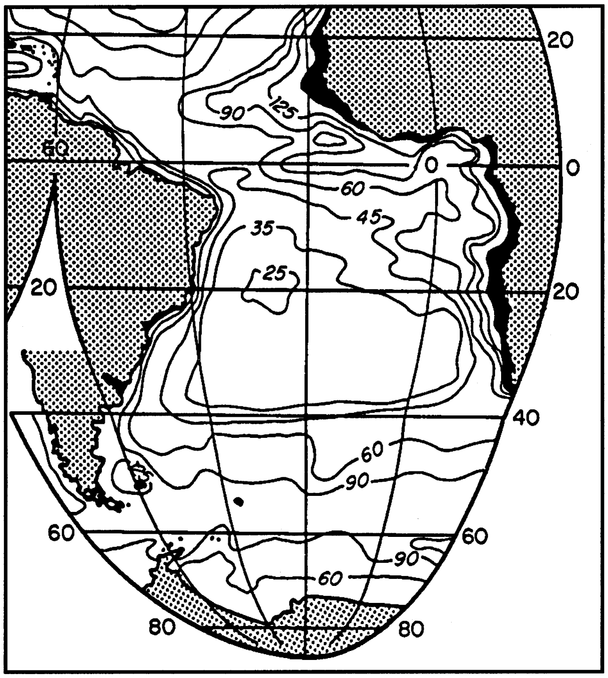

Figure 3. Productivity map of the South Atlantic ("Dahlem" map), based on a compilation of available information up to 1987, including satellite observations on ocean color. Numbers are productivity in grams of carbon per square meter per year (gC/m^2/y). From Berger et al. (1989, p. 453).

ern and southern provinces results from the fact that the Benguela Current turns northwest above the Walvis Ridge to feed the South Equatorial Current (Figs. 2, 4). Thus, the large-scale dynamics of production of organic matter and opal are fundamentally different north and south of the Walvis Ridge. We refer to the region on and south of the ridge as part of the "Benguela Current system" in contrast to the northern area, which belongs to the "Angola regime." The two are separated by the Angola-Benguela Front (ABF; Fig. 4), a frontal zone lying between 16° and 17°S, where the poleward-flowing Angola Current meets the equatorward-flowing Benguela Current (Shannon, 1985).

The Sites

As previously mentioned, the 13 sites occupied during Leg 175 are readily grouped into transects exploring the record of different environments off the coast of southwestern Africa. These groupings are (1) The Congo transect (Sites 1075, 1076, and 1077); (2) the Angola transect (Sites 1078, 1079, and 1080); (3) the Walvis transect (Sites 1081, 1082, and 1083), which includes DSDP Site 532; (4) the Lüderitz Site 1084, which is unique in its position next to an intense upwelling cell; and (5) the Cape transect (Sites 1085, 1086, and 1087). The Walvis, Lüderitz, and Cape of Good Hope sites make up the Benguela set, which contains the history of the Benguela Current and the associated coastal upwelling regime.

An important result of the expedition is the fact that so many of the sections recovered show continuous sedimentation at high rates of accumulation (see Wefer et al., Chap. 16, this volume). Several conditions are responsible for this finding: high rates of supply from high productivity and terrigenous contributions, favorable sites of

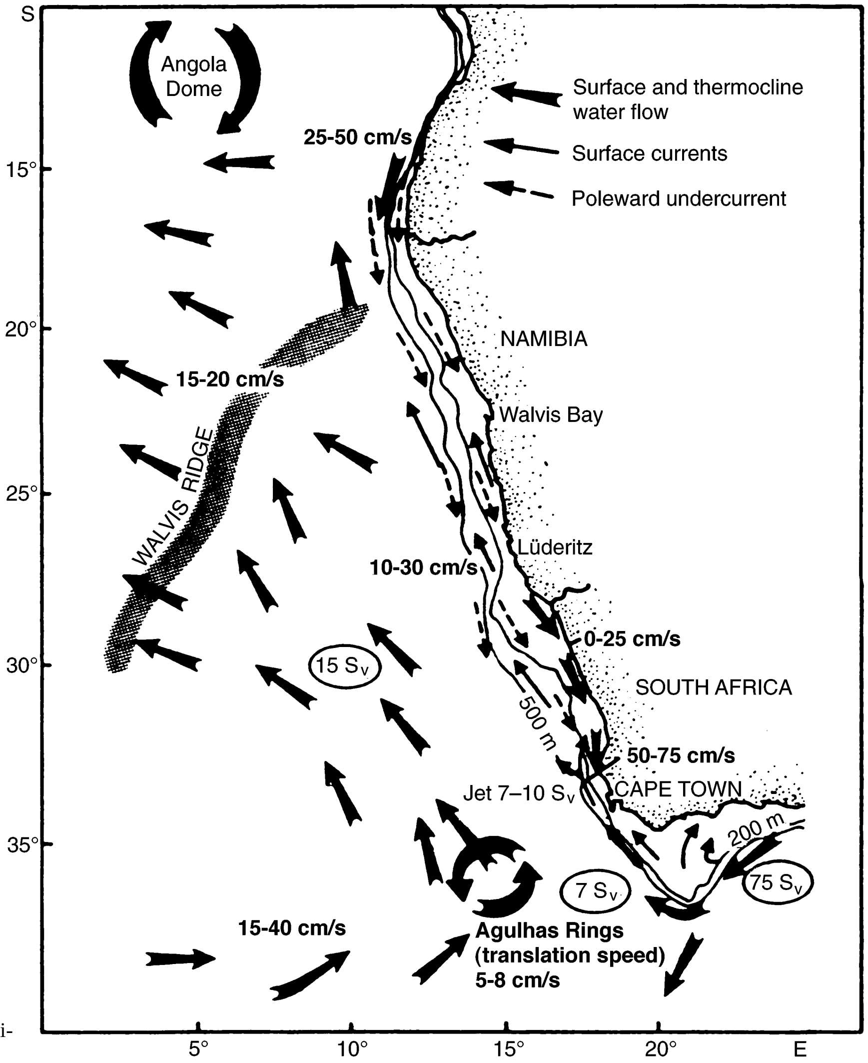

Figure 4. Strategic position of the Walvis Ridge with respect to the Benguela Current system. Current speeds refer to surface values. Transports (circled) refer to total transport above 1500 db (i.e., includes Antarctic Intermediate Water). From Shannon and Nelson (1996).

deposition through salt tectonics (north of the Walvis Ridge), and a tectonically quiet setting (in the Cape Basin). This is not to imply that sediments are undisturbed, as a rule, along this margin. They are not. However, it was possible to find stratigraphically useful sections based on well-prepared site selection.

The major environmental provinces and their sedimentary records may be characterized as follows.

Congo Transect

The regional environment in the Congo Fan region is dominated by three major influences: (1) the freshwater input from the Congo River (the second largest river in the world), (2) seasonal coastal upwelling and associated filaments and eddies moving offshore, and (3) incursions of open-ocean waters, especially from the South Equatorial Countercurrent. According to Jansen (1985), river-induced phytoplankton activity extends ~160 km beyond the shelf edge, which would affect all three sites drilled. Much of the regionally enhanced productivity is river related. However, divergence and doming and glacial/interglacial changes in the dynamics of the South Equatorial Countercurrent and the Benguela Current may be just as important. In the site closest to shore, the effects of seasonal coastal upwelling should be superimposed on the riverine effects. Late Quaternary Congo Fan sediments have exceptionally high opal content (Müller and Schneider, 1993), ~10 times higher than in the slope sediments recovered from anywhere else off southwestern Africa. Fluctuations in the opal content are controlled by large-scale climatic patterns, as is evident from the presence of Milankovitch cycles (cryosphere cycles of 41-k.y. and 100-k.y. periodicity and wind-system cycles of 23-k.y. and 19-k.y. periodicity; see Schneider et al., 1997). The Congo transect provides a window into the climatic history of western tropical Africa.

The hemipelagic sediments in this province are dominated by diatomaceous, partially carbonate-bearing clays. Sedimentation rates are typically between 15 and 20 cm/k.y. for the late Quaternary and are close to 10 cm/k.y. for the early Quaternary. Presumably, terrigenous sediment supply increased with the onset of the large-amplitude 100-k.y. climate- and sea-level cycles 650 k.y. ago.

Angola Transect

The mid-Angola region has surprisingly low productivity compared with adjacent upwelling areas to the north and south (Wefer et al., 1988). Upwelling is seasonal and comparatively weak; opal accumulation is extremely modest for this coastal environment. The two shallow-water sites off Lobito (Sites 1078 and 1079,) have silty clays accumulating at extremely high sedimentation rates, with maximum values of 60 cm/k.y. at Site 1078 and nearly 40 cm/k.y. at Site 1079. Sediments are supplied by an actively eroding coast that is presumably being uplifted by salt tectonics. Site 1080 was drilled off the

Kunene River (Angola). It is located near the northernmost coastal upwelling cell along the southwestern margin. Sediments consist of diatom-bearing and diatom-rich silty clays that are accumulating at a rate near 10 cm/k.y. However, the late Quaternary section is greatly attenuated. Drilling was terminated after a dolomite layer was hit because of slow progress.

Walvis Transect

The Walvis Ridge provides a large shallow area favorable for the preservation of carbonate. Also, it is situated at a crucial latitude where the Benguela Current turns westward into the open sea (Fig. 4). Thus, the ridge is the major monitoring region for the history of the Benguela Current. It was the target for drilling during two earlier legs, whose sites are part of the transect (Leg 40, Site 362; Bolli, Ryan, et al., 1978; and Leg 75, Site 532; Shipboard Scientific Party, 1984). The DSDP sites are well off the coast but contain an upwelling signal which has been transported outward from its coastal zone of origin by the eddies and filaments of the Benguela Current. The DSDP sites produced evidence for cyclic sedimentation from varying carbonate dissolution, productivity, and terrigenous sediment supply. Site 1081 extends this transect toward the coast where upwelling is strong. Sediments recovered (from Sites 1081, 1082, and 1083) consist of calcareous clays, which are especially rich in diatoms in the upper Pliocene and lower Quaternary sections (Matuyama Opal Maximum [MOM]). Sedimentation rates are typically between 5 and 10 cm/k.y., with an apparent minimum in the middle portion of the Pliocene section.

Lüderitz Site (1084)

Lüderitz Bay, on the Namibian shelf, is in the center of the Benguela upwelling region, which is characterized by a series of upwelling cells between the Cape of Good Hope and the Kunene River mouth. The Lüderitz cell is the largest and most active of these (Duncombe Rae et al., 1992). It vigorously sheds eddies and filaments into the coastal Benguela Current. Poleward subsurface flow brings nutrient-rich waters southward to this location from the Walvis Bay area, whereas upwelling is induced by winds and the northward-flowing Benguela Current, which approaches close to the coast thanks to a narrow shelf (Fig. 4). Drilling at Site 1084, off Lüderitz, recovered sediments with the highest organic carbon contents of any site occupied (as much as 20%). Diagenetic activity, as reflected in the presence of methane and carbon dioxide and in the rapid reduction of sulfate within interstitial waters, is extremely intense; alkalinity values were the second highest ever measured in sediments recovered by DSDP or ODP. (The highest were found off Peru, during Leg 112; Suess, von Huene, et al., 1988, 1990.) The central portion of the sediment column recovered (upper Pliocene to lower Pleistocene) consists of diatom-bearing clay to diatomaceous clay and diatom ooze sandwiched between nannofossil clay and ooze of early Pliocene and late Pleistocene age. Black organic-rich layers are prominent throughout the section. Sedimentation rates are typically between 10 and 20 cm/k.y., with the younger sediments having the higher rates of accumulation.

Cape Transect

The southernmost sites of Leg 175 (1085, 1086, and 1087), near the Cape of Good Hope, have pelagic calcareous oozes, mainly nannofossil oozes, but with high proportions of foraminifers in some areas (especially at Site 1086). Diatoms, radiolarians, and other opaline fossils generally are rare or absent, except in sediments corresponding to the MOM where abundances are distinctly higher. These sites are excellently situated to monitor the fluctuating influence of Southern Ocean water, including intermediate water, and the import of warm water from the Indian Ocean. Sedimentation rates typically vary between 2 and 7 cm/k.y. at all three sites.

Benguela Transect

The Walvis transect, Lüderitz site, and Cape of Good Hope transect form one coherent megatransect for the Benguela Current system. Indications are that the important trends and events in the history of this system are recorded simultaneously along the entire transect. A reconstruction of latitudinal migrations of elements of the Benguela upwelling system (and the associated South Atlantic high-pressure cell) will be of special interest.

THE RECORD OF PRODUCTIVITY

The record of productivity of the Angola-Benguela upwelling system resides in a number of indicators, most prominently in organic matter and opal accumulation, and in the various chemical changes driven by bacterial activities and other diagenetic reactions. On the basis of these indicators, the sites can be ranked according to the overall productivity of overlying waters, and trends in productivity can be discerned.

Starting in the late Miocene, the strength of the Benguela Current has continuously increased. This is apparent in the history of eastern boundary upwelling in the South Atlantic (Siesser, 1980; Meyers et al., 1983). The record of organic matter deposition in the Angola Basin and on the Walvis Ridge suggests that rates of upwelling accelerated near 6 Ma and near 3 Ma, but held steady (or decreased somewhat) within the Quaternary (Fig. 5).

A general increase in deposition of organic carbon is evident at all sites on and south of the Walvis Ridge (Fig. 6; north of the ridge, penetration is insufficient to say). There is some indication for the steps seen earlier at 6 Ma (Site 1082) and 3 Ma (Sites 1081, 1082, and 1084). However, substantial variability exists, and the widely spaced sampling intervals make it difficult to recognize any steps. Within the Quaternary record, no clear trends are apparent. Maximum values in sediments of late Quaternary age in the sites north of the Walvis Ridge may be sampling artifacts (extremes are more likely where sampling is dense, other factors being equal). The early Quaternary maximum suggested in the DSDP data of Meyers et al. (1983; Fig. 5) is seen at Site 1081 and, perhaps, Site 1083, but not at Sites 1082 and 1084. Site 1085 also has a maximum value in the early Quaternary.

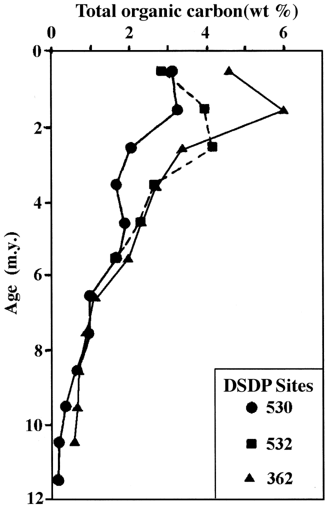

Figure 5. Organic carbon content at DSDP Sites 530, 532, and 362 in the Angola Basin and on the Walvis Ridge (from Meyers et al., 1983).

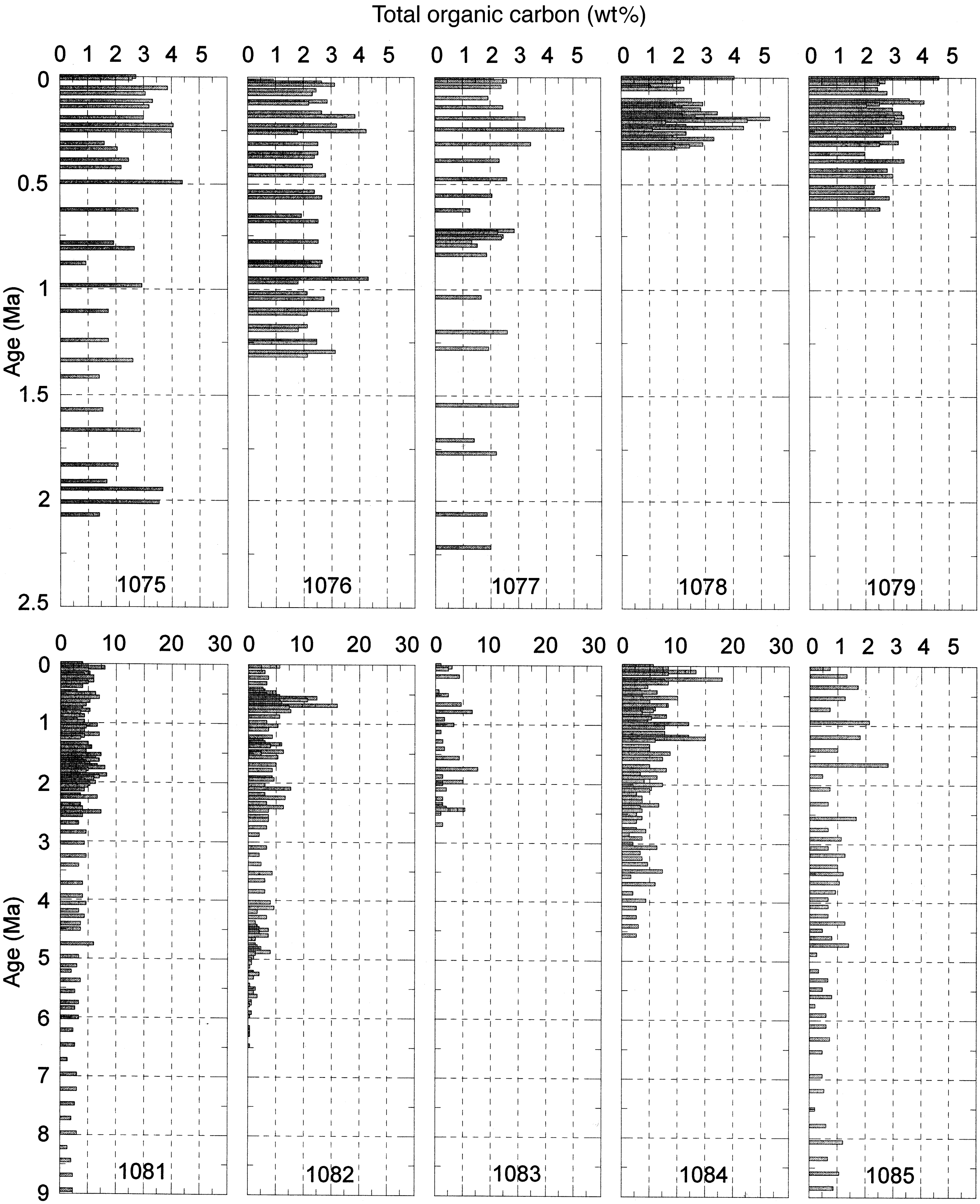

Figure 6. Abundance of total organic carbon at Leg 175 Sites 1075–1085, as measured on board. Note differences in scale (see “Organic Geochemistry” section in the “Sites 1075–1085” chapters, this volume). 1 = trace; 2 = rare; 3 = frequent; 4 = common; and 5 = abundant.

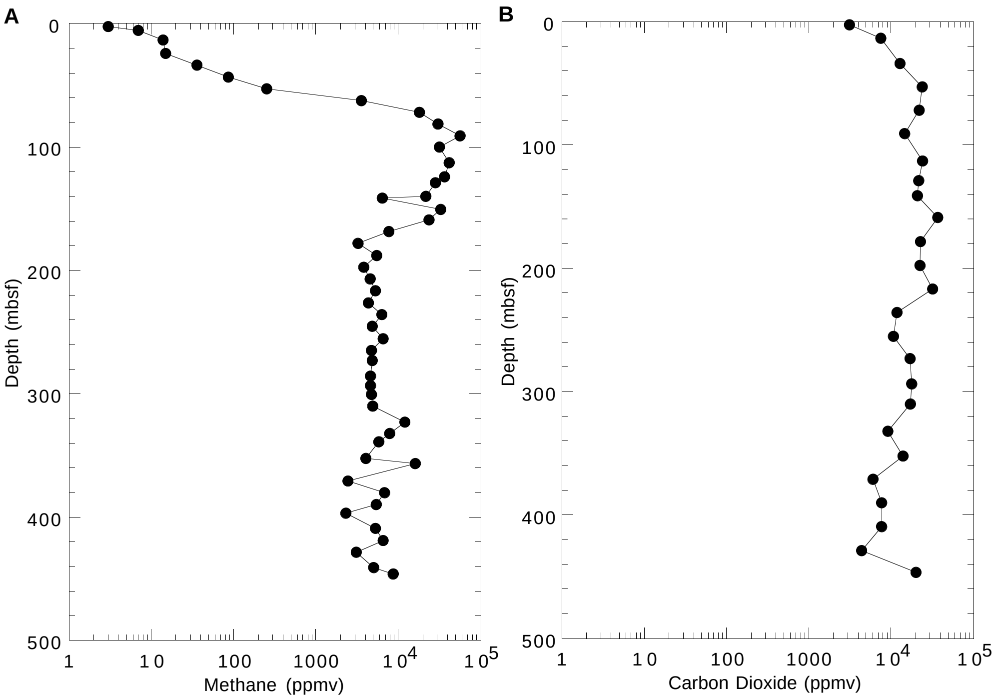

Figure 7. Contents of (**A**) methane and (**B**) carbon dioxide in sediments from Site 1081, based on headspace measurements made on board (see "Organic Geochemistry" section, "Site 1081" chapter, this volume).

The overall trend of increasing organic carbon deposition is difficult to interpret in any detail. Decay of organic matter continues deep within the sediment, so that a trend toward lower values with depth below seafloor is expected from diagenesis alone. The most obvious sign of decay of organic matter at depth was the high gas content of hemipelagic sediments. Biogenic methane and carbon dioxide were roughly equally important at most sites, based on headspace measurements (Fig. 7). The methane production only sets in after the available sulfate in interstitial waters has been used up for oxidation of organic matter. Carbon dioxide is generated throughout the zone of bacterial activity. The presence of a methane maximum (100 to 150 m at Site 1081) suggests that the rate of destruction of organic matter decreases considerably below 125 m.

The high gas content in most of the cores recovered during Leg 175 made handling and measuring physical properties difficult. However, it also kept sediments from compacting as quickly as they might have otherwise, thus allowing much faster drilling than anticipated. The site with the highest TOC values is Site 1084, off Lüderitz, at the edge of the most active Namibian upwelling cell. Its sediments showed extremely high diagenetic activity (with a mixture of malodorous gases emanating from the cores, in addition to methane and carbon dioxide).

The rapid reduction of sulfate in the uppermost part of the sediment column attests to the vigorous activity of bacteria within the sediment (Fig. 8), as do the extremely high ammonia values in the interstitial waters, especially at Site 1084. High alkalinity of interstitial water results from these processes, which leads to the precipitation of carbonates including dolomites. Intense degradation of organic matter is also indicated by the rapid increase of phosphate values below the seafloor. Formation of apatite and other phosphatic minerals presumably accounts for the decrease of phosphate values at depth. Apparently, dissolved silicate values are similarly constrained, but at a rather well-defined range of values (near 1000 µM), suggesting precipitation of Opal CT or uptake by clay minerals. This indicates that diatoms also are subject to long-term destruction.

Given the pore-water measurements concerning sulfate, ammonia, phosphate, and silicate, we can rank of the Leg 175 sites in terms of the intensity of organic-driven diagenesis. We use reported values at 10 mbsf, as well as the depth at which the sulfate ion drops below 1 mM. Sulfate, ammonia, and phosphate values correlate well among the sites (r is between 0.7 and 0.8). However, the correlation between the silicate values and the other variables is rather poor. Thus, the intensity of organic-driven reactions will not predict silicate values well (also illustrated in Fig. 8).

The ranking of the sites in terms of intensity of diagenetic reactions (driven by organic matter supply) is as follows: (1) Site 1084; (2) Site 1078; (3) Site 1076; (4) Site 1077; (5) Site 1083; (6) Site 1082; (7) Site 1075; (8) Site 1079; (9) Site 1085; (10) Site 1081; (11) Site 1087; and (12) Site 1086. Site 1080 is not ranked. The first six sites in this list have intense diagenesis and may be considered "high-productivity" sites.

The ranking in terms of dissolved silicate at 10 mbsf is as follows: (1) Site 1075; (2) Site 1083; (3) Site 1082; (4) Site 1084; (5) Site 1077; (6) Site 1076; (7) Site 1081; (8) Site 1085; (9) Site 1078; (10) Site 1087; (11) Site 1086; and (12) Site 1079. Site 1080 is not ranked. The first six sites in this list show elevated levels of silicate and may be considered "high-opal" sites.

Sites that appear in the first six ranks of both lists are (1) Site 1084; (2) Site 1083; (3) Site 1076; (4) Site 1077; and (5) Site 1082.

Sites that appear in the last six ranks of both lists are (1) Site 1079; (2) Site 1085; (3) Site 1081; (4) Site 1087; and (5) Site 1086.

Thus, on the whole, high-productivity sites also tend to be high-opal sites, although this is by no means a strict correspondence. The low-productivity low-opal sites compose the set of pelagic carbonates, except for Site 1079, off Lobito, with its high rate of terrigenous sediment accumulation.

The ranking given above, being derived from indices dependent on reactions within the upper ~50 m of the sediment column, refers to Quaternary conditions. Concerning the abundance of diatoms within Quaternary sediments, it is seen that the high-opal sites (as identified by dissolved silicate in pore waters) are the high-diatom sites as well. The exact rank order depends on which criteria are used (average diatom abundance, last 2 m.y., or maximum abundance, for example). In any event, Sites 1075, 1082, 1083, and 1084 would be at the top. As mentioned, the Congo Fan (Sites 1075, 1076, and 1077) was identified previously as a region of high opal deposition (as mentioned above). River supply and peri-estuarine pumping of silicate-rich subsurface waters are the processes responsible for high opal deposition. Sites 1082, 1083, and 1084 reflect the effects of coastal upwelling and associated eddies and filaments penetrating the Benguela Current.

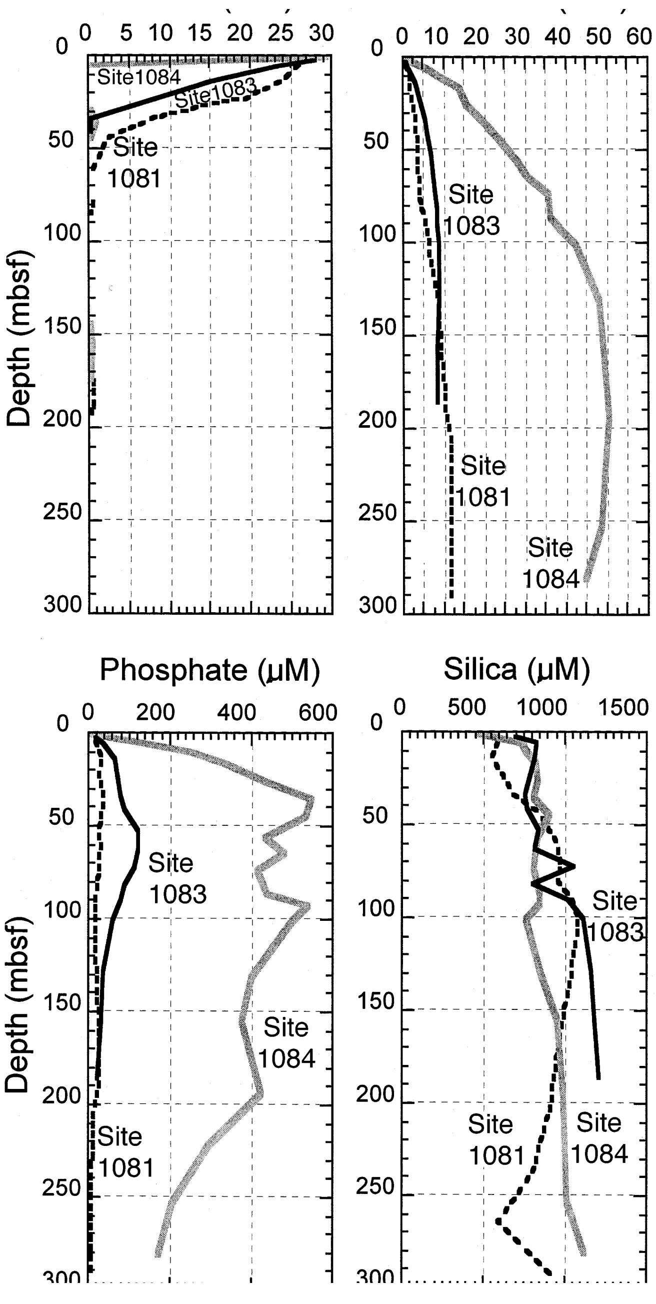

Figure 8. Chemistry of interstitial waters from Sites 1081, 1083, and 1084, as measured on board, indicating high productivity of overlying waters. Note the extreme values at Site 1084, off Lüderitz (see "Inorganic Geochemistry" section, "Site 1084" chapter, this volume).

All sites on and south of the Walvis Ridge tend to show a maximum abundance of diatoms near and just before 2 Ma. This is the MOM, first discovered on the Walvis Ridge by Leg 75 scientists (Shipboard Scientific Party, 1984). We confirm it here as a phenomenon common to the entire Benguela upwelling system and explore it in some detail.

CARBONATE DEPOSITION

Much of the hemipelagic sediments and most of the pelagic sediments recovered during Leg 175 consist of calcareous nannofossils with various admixtures of foraminifers. The varying carbonate content at any one site reflects production in overlying waters (and benthic production), dilution with noncarbonate particles, and dissolution. In most cases, dissolution is the process most responsible for the variations seen. This is true even in rather shallow water depths, as at Site 1081 (805 m). At this site, abundances of calcareous fossils, although tracking one another, have no correlation with those of siliceous fossils (Fig. 9).

Two factors dominate preservation (or dissolution) of calcareous fossils: the saturation of waters in contact with the seafloor, which provides the boundary conditions, and the diagenetic reactions within the uppermost sediment, which determine the chemistry of pore waters in contact with the calcareous particles. In low-productivity situations, deep-water properties are important, and their changes are recorded in terms of fluctuations in preservation. In environments characterized by high production, diagenetic processes will dominate, so that deep-water properties will imprint less prominently on the sediment.

What we expect to see regarding the deep-water environment is an overall trend of increased carbonate preservation since the Miocene carbonate crisis ~12 m.y. ago (Fig. 10). This crisis, which represents an excursion of the pelagic carbonate compensation depth (CCD) to elevations close to the crest of the Mid-Atlantic Ridge, was first iden-

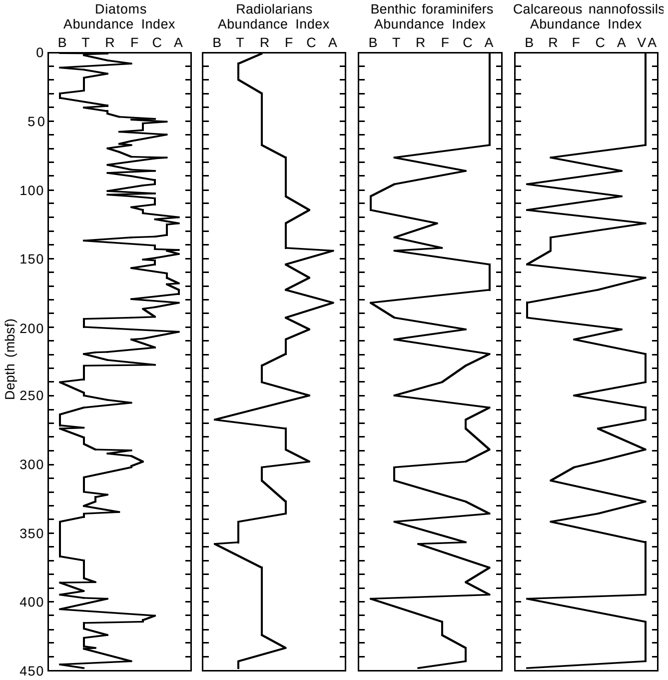

Figure 9. Abundance estimates for siliceous and calcareous fossils in core-catcher samples from Site 1081. B = barren; T = trace; R = rare; F = few; C = common; A = abundant; and VA = very abundant.

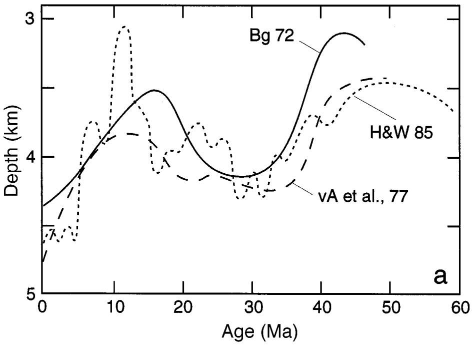

Figure 10. Reconstruction of CCD variations in the South Atlantic, based on backtracking of drilling sites, by various authors (Bg 72, after Berger, 1972; vA et al., 77, after van Andel et al., 1977; H&W 85, after Hsü and Wright, 1985). From Berger and Wefer (1996).

tified in the South Atlantic based on results from DSDP Leg 3 (Fig. 10, "Bg72"; Berger, 1972). Subsequent expeditions allowed considerable refinement (Fig. 10, "H&W85"; Hsü and Wright, 1985). The drop of the CCD since the beginning of the late Miocene largely represents the increased intensity of NADW production. Seafloor bathed by NADW preserves carbonate, whereas seafloor bathed by Antarctic Bottom Water does not. The turning up of NADW some 10 m.y. ago is likewise recorded in the overall switch of opal deposition out of the North Atlantic into the North Pacific (Keller and Barron, 1983; Woodruff and Savin, 1989).

The available data do not show the late Neogene trend of increased deep-water carbonate preservation (Figs. 11–13). There is one exception: at Site 1085 (1713 m), carbonate values are distinctly low, (between 9 and 8 Ma), and they rise to a high level shortly after. Site 1086 (at 794 m) is too shallow to trace deep-water properties; carbonate data for Site 1087 (at 1386 m) are not yet available.

Visual comparison of carbonate stratigraphies at the sites on and south of the Walvis Ridge indicate a number of low-value intervals, which can be interpreted as periods of enhanced dissolution (Fig. 11). The first of these, going back in time, is between 0.6 and 0.7 Ma and is perhaps associated with glacial Stage 16. The second is centered between 1.7 and 2 Ma, marking the onset of the Quaternary. Lack of detailed sampling prevents identification of other, older events. There is a long-term trend toward lower values, from 6 to 2 Ma, seen at Sites 1081 and 1082. Presumably, this trend parallels increased productivity (and carbon dioxide production within sediments). Also, there is an overall increase in carbonate values throughout the Quaternary period, suggesting a general decrease in productivity or an increase in intermediate water and upper deep-water saturation.

Nannofossil abundances show striking variability at some sites (the Congo transect, Site 1081). Site 1081 has a nearly barren zone within the lower Pliocene section; at Site 1082, a similar zone is centered on 3 Ma. This suggests high organic productivity at the boundary between the early and late Pliocene, just before the MOM. A shorter barren zone is seen at Site 1081, near 1.5 to 1.6 Ma. Also, at Site 1075, there is such a zone at the base of the section recovered between 2 and 1.5 Ma. Abundance estimates are not sensitive enough, nor sampling dense enough, to provide more detail on dissolution zones or trends.

Benthic foraminiferal abundances show some of the same patterns as carbonate percentages and nannofossils. Again, there are low values in the early Quaternary (Sites 1075, 1077, 1081, and 1083) and around 3 Ma (Sites 1081 and 1084). Observations on the preservation of planktonic foraminifers at Site 1084 support the general impression that calcareous fossils are dissolved in those sections where productivity is high. The lack of sensitivity of the abundance index and the wide spacing of samples make it difficult to extract a more detailed dissolution stratigraphy.

In summary, there is some indication that there were two extended dissolution pulses, one centered near 3 Ma, the other in the early Quaternary. It is likely that these were connected to times of high productivity. If so, this would suggest that productivity decreased somewhat throughout the late Quaternary (as also suggested by the diatom record; see Fig. 14). Organic matter abundance would not necessarily show this reduction in productivity (Fig. 6) because of diagenetic processes that result in an overall decreasing preservation of organic matter with depth below seafloor, which yields a false pattern of productivity increase within the Quaternary.

THE MATUYAMA OPAL MAXIMUM

Several Leg 175 sites show a distinct opal maximum within the upper Pliocene and lower Quaternary, spanning the lower half of the Matuyama reversed polarity Chron (Sites 1081, 1082, 1084, and 1085; see Fig. 14). Detailed onboard studies reveal that the maximum abundance of diatoms is reached within the early Matuyama Chron, centered on ~2.2 Ma (Fig. 15). At Site 1084, near the most active upwelling cell of the Benguela Current system, the diatom maximum owes its existence to a vigorous proliferation of *Thalassiothrix* and other pelagic species, in addition to the *Chaetoceros* spores typical for coastal upwelling. A mixture of warm-water and cold-water pelagic forms and of upwelling species suggests frontal developments and intense mixing in this region during the late Pliocene. At Site 1084, the rich supply of diatoms resulted in the development of diatom mats, reminiscent of those reported from the eastern equatorial Pacific (Kemp and Baldauf, 1993).

Patterns are similar for the Walvis sites, as mentioned earlier, except that the cold-water component is somewhat weaker and diatom mats did not develop (or were not noted). A maximum abundance of diatoms centered near the Pliocene/Pleistocene boundary was earlier reported for DSDP Site 532 by Leg 75 scientists (Fig. 16). This site is located on the Walvis Ridge at 1131 m water depth and was cored by the APC (Dean et al., 1984; Gardner et al., 1984). The patterns recorded at this site for carbonate, organic carbon, and diatoms yield valuable clues for the interpretation of the MOM (Fig. 16). From inspection, it appears that organic carbon and diatom abundances do not show similar trends (dilution effects may play a role in decreasing any correlation). Both the lowest and highest values for organic carbon are measured in the upper Pleistocene sediment, when diatom abundances are well off the maximum. On the whole, carbonate increases within the upper Pleistocene sediment, with the onset of large-amplitude ice-age cycles (i.e., after the mid-Pleistocene climate shift).

The late Pleistocene increase in carbonate values is here interpreted as a decrease in productivity by the arguments given above. A strong negative correlation between carbonate and organic carbon (which sets in just after the diatom maximum) supports this interpretation. As productivity decreases, the silicate supply diminishes more rapidly than the phosphate supply, a pattern that is common in most regions of the ocean (Herzfeld and Berger, 1993; Berger and Lange, in press). Significantly, opal deposition is reduced during glacials at this site (Diester-Haass, 1985), even though upwelling activity has most likely increased (Oberhänsli, 1991). What this means is that the intense late Pleistocene glacial conditions take the system beyond the optimum for opal deposition, which occurs at an intermediate stage of cooling.

Fundamentally, then, the Benguela Current system responded to cooling in the Pliocene with increased upwelling (and increased diatom deposition). However, when cooling passed a certain threshold, upwelling becomes less efficient in pumping nutrients into the photic

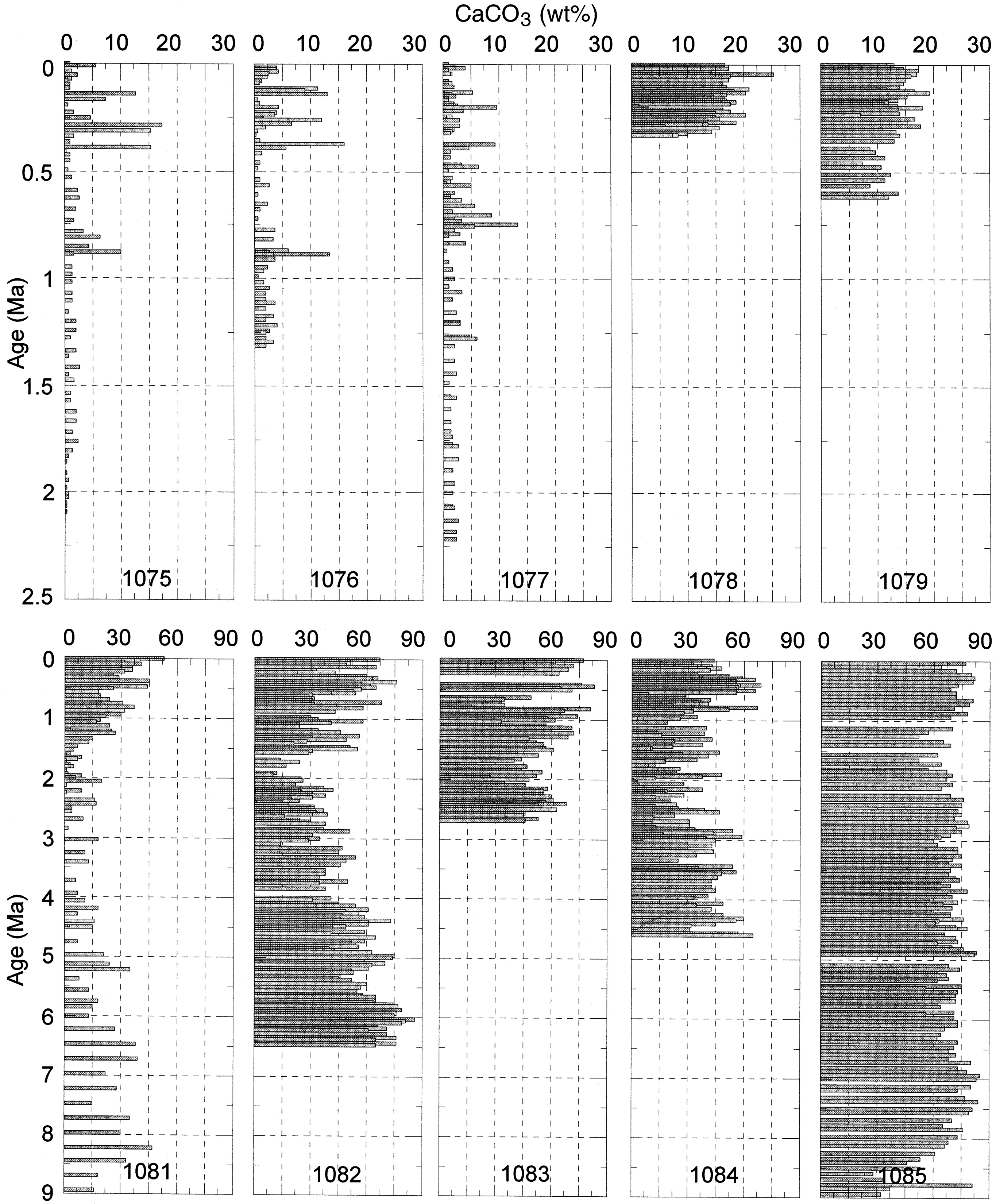

Figure 11. Carbonate percentages at Sites 1075–1085, measured during Leg 175 (see "Organic Geochemistry" sections of the individual site chapters, this volume).

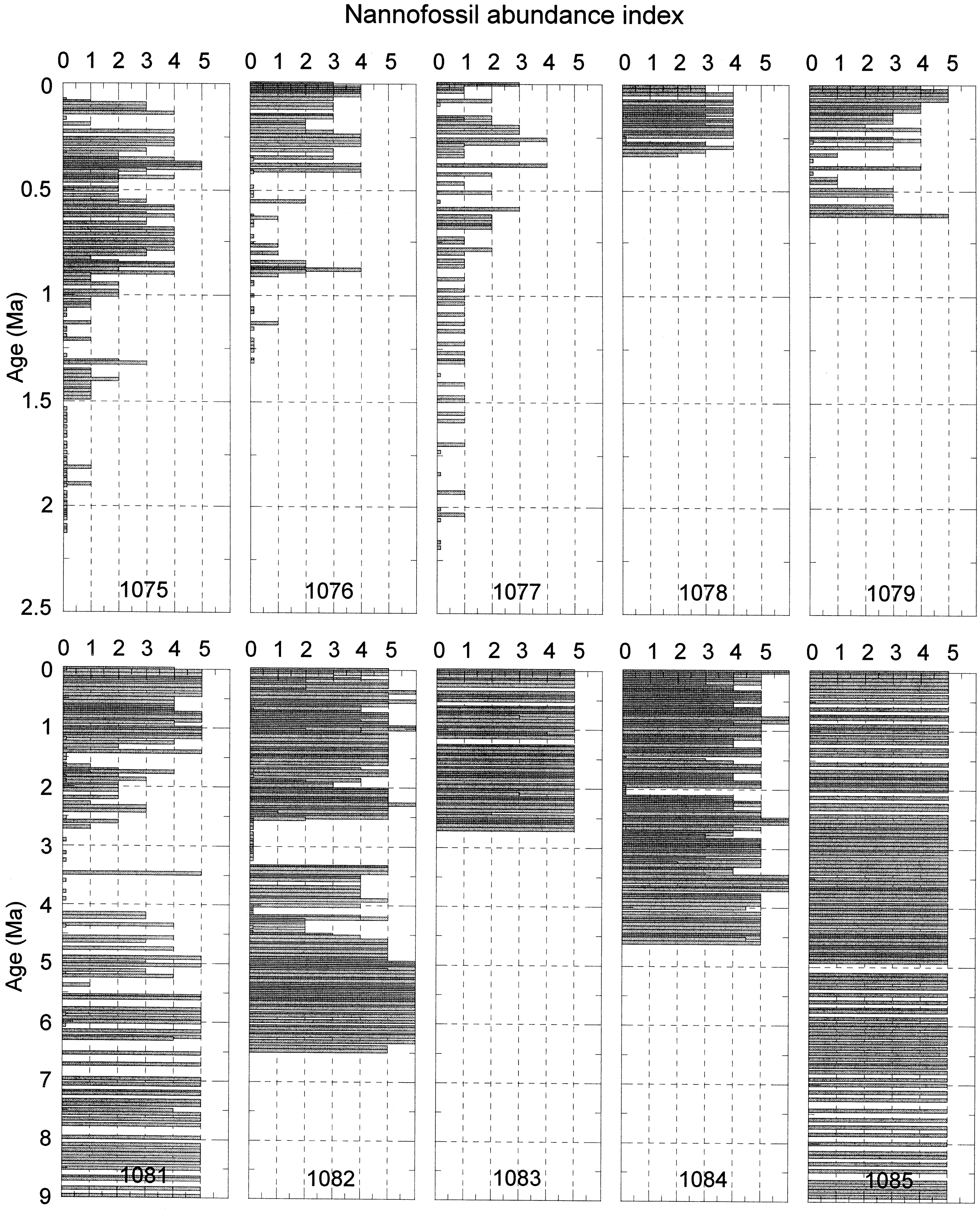

Figure 12. Nannofossil abundances estimated from smear slides for Sites 1075–1085. Abundance indices 1–5 same as in Figure 6.

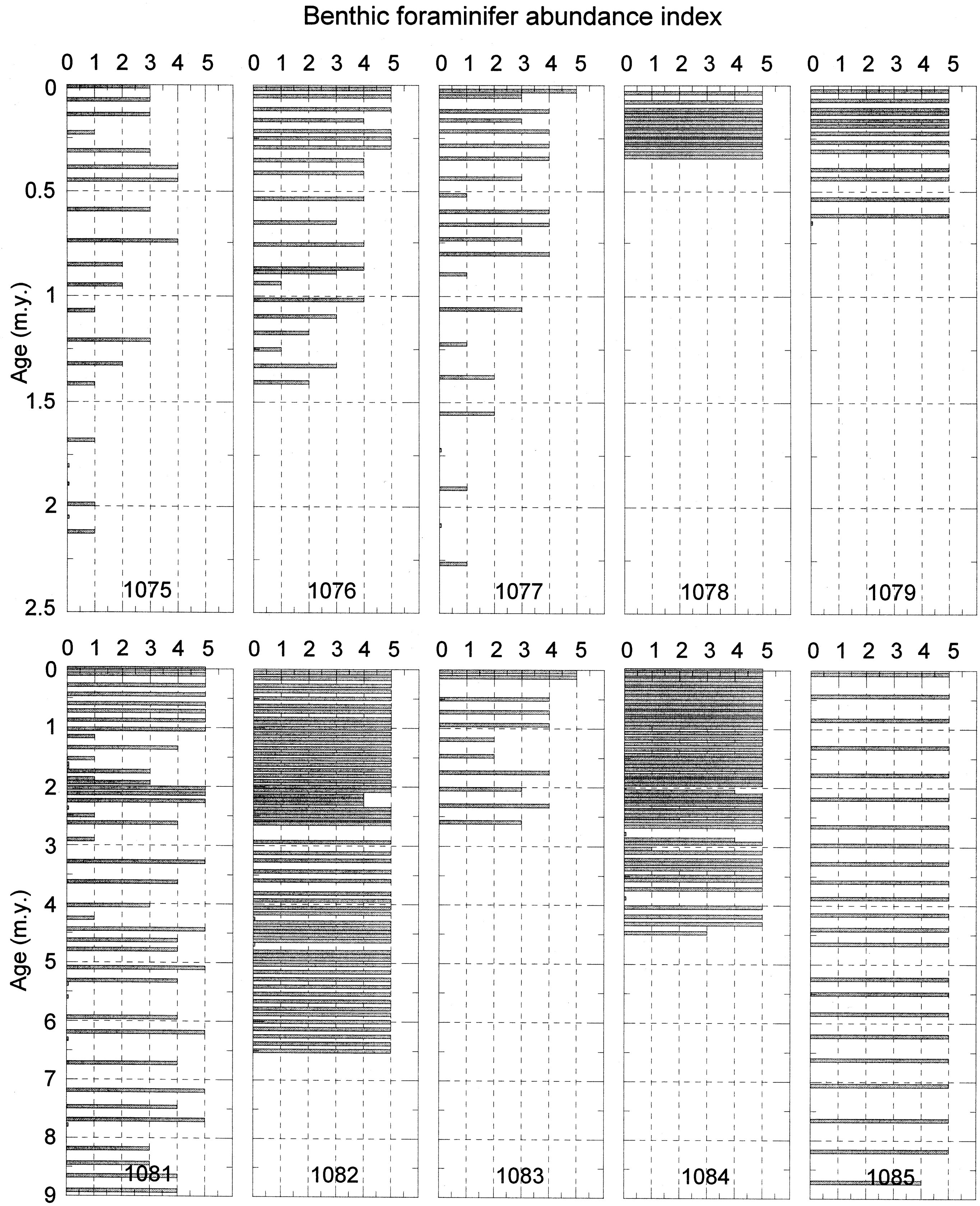

Figure 13. Benthic foraminiferal abundances estimated on board from core-catcher samples from Sites 1075–1085. Abundance indices 1–5 same as in Figure 6.

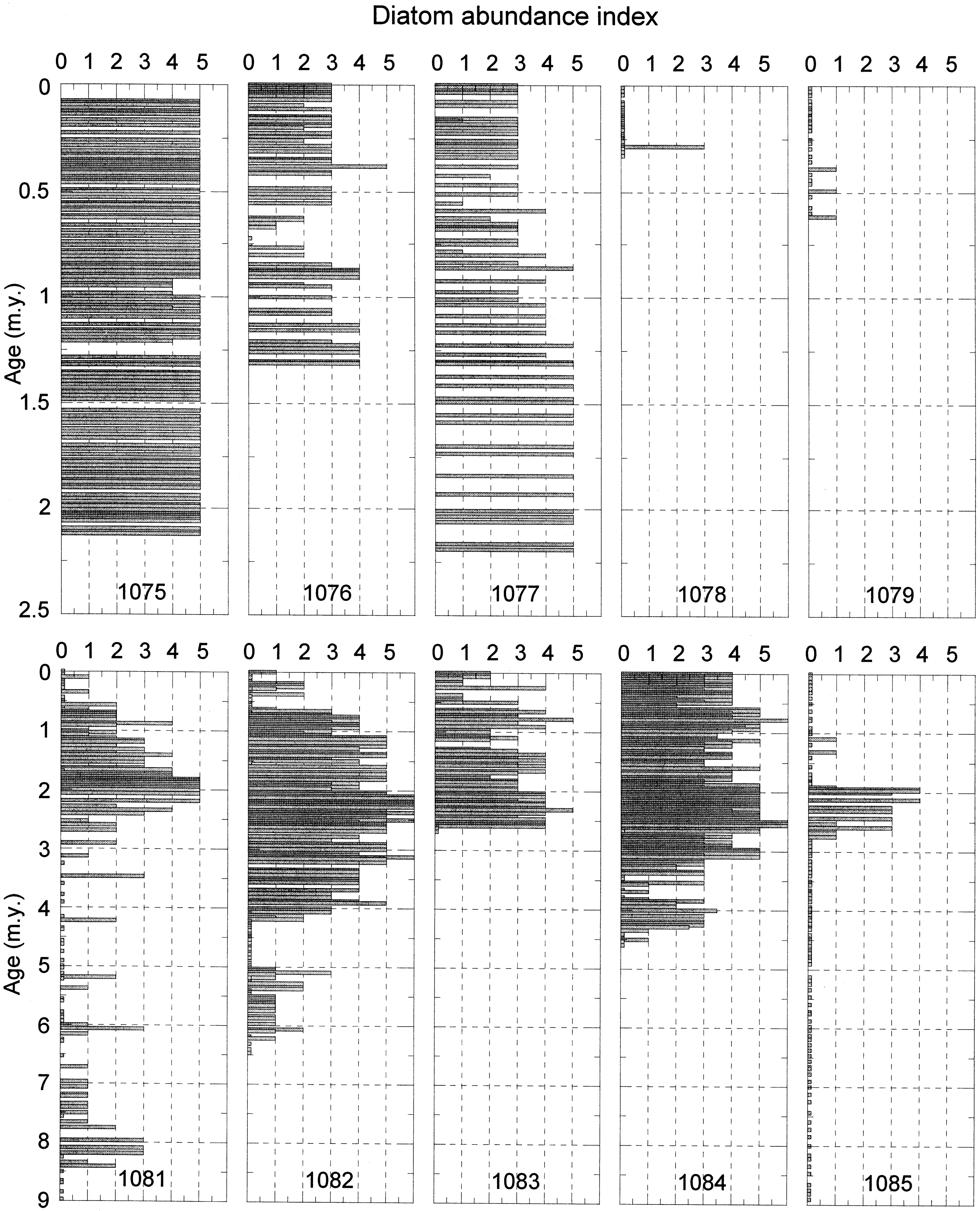

Figure 14. Diatom abundance recorded in smear slides for Sites 1075–1085. Abundance indices 1–5 same as in Figure 6.

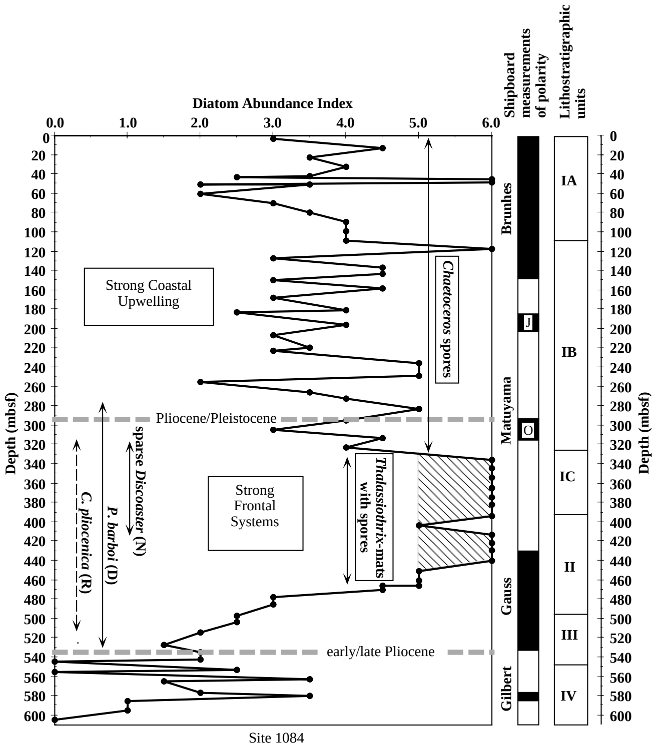

Figure 15. Estimates of diatom abundances at Site 1084 based on smear-slide examination. Abundance indices 1–5 same as in Figure 6.

layer. This drop in efficiency is likely tied to the nutrient content of subsurface waters (that is, to thermocline fertility), as suggested by Hay and Brock (1992). The passing of the system through and beyond a silica optimum would also explain why the correlation between temperature and opal abundance changes sign sometime within the Pliocene, as reported by Diester-Haass et al. (1992). On the warm side of the optimum, cooling produces additional upwelling and hence increases diatom supply to the seafloor. On the cold side of the optimum, cooling removes silicate from the thermocline, canceling any effects of increasing upwelling.

Why should "excess" cooling lead to a lowered silicate content in the Benguela Current system? The answer must lie within the processes supplying silicate (and phosphate) to the Benguela Current system. At present, maximum silicate and phosphate values in subsurface waters are found not within the Benguela Current system, but off Angola, well north of the Walvis Ridge. From there, nutrient-rich waters are brought southward along the upper slope with a poleward undercurrent, at least to the latitude of Lüderitz (Fig. 4). This mechanism of nutrient supply was identified by Hart and Currie (1960), who found evidence of a subsurface current with extremely low oxygen content flowing poleward along the edge of the continental shelf ("compensation current"). The current is centered at ~200–300 m depth and appears to be the replacement source for upwelled water (Shannon, 1985). That a strong oxygen minimum with high silica content does not build up within the Benguela Current system (we assume) is because ventilation by intermediate water currents prevents this: the poleward flow is restricted to a narrow band along the shelf and upper slope (it may be severely curtailed once sea level drops below the shelf edge). If such ventilation runs parallel to the strength of the Benguela Current (as seems reasonable), then intensification of the Benguela Current (and of the underlying northward-flowing intermediate water) would simultaneously result in decreasing the strength of the oxygen minimum, first off South Africa, and then off Namibia. In the extreme, only the region off Angola would continue to collect high-nutrient subsurface waters. Indeed, the correlation between opal deposition and organic matter deposition remains strongly positive off the Congo through glacial/interglacial cycles (Schneider et al., 1997).

The effects of increased intermediate-water currents on upper slope sediments may be seen at Site 1086. Here, the upper Quaternary record is missing entirely, and the upper part of the section (upper Pliocene to Pleistocene) is foraminifer rich; that is, it appears to be winnowed.

In summary, there is evidence for increased Pleistocene intermediate-water flow along the upper slope below the Benguela Current. Relaxing these currents (through general warming) should allow the Angolan oxygen minimum to expand southward. This could provide for increased opal productivity despite a decrease in coastal upwelling. This type of trade-off, we suggest, explains why there is a MOM in the early phase of the ice-age fluctuations.

BENTHIC FORAMINIFERS AS PRODUCTIVITY INDICATORS

The traditional indicators of productivity, organic matter and opal abundance, are strongly influenced by diagenesis, which complicates interpretations. To obtain additional clues to changes in productivity, we turn to benthic foraminifers. Benthic organisms live on the food provided by the export from overlying waters. The amount and nature of this export is reflected in the abundance and species composition of benthic foraminifers (Douglas and Woodruff, 1981; Woodruff, 1985; Lutze et al., 1986; Hermelin and Shimmield, 1990; Hermelin, 1992; Burke et al., 1993; Herguera and Berger, 1994; Loubere, 1994; Thomas et al., 1995). Unfortunately, the abundance of benthic foraminifers in many of the sites is largely controlled by carbonate preservation, as discussed above. We next explore the possibility that despite this handicap, species composition retains valuable information regarding trends in productivity.

The diversity of a benthic assemblage is sensitive to food supply: organic-rich environments tend to show reduced diversity but high abundance (Phleger and Soutar, 1973; Douglas and Woodruff, 1981; Hermelin and Shimmield, 1995). A simple index of diversity (which minimizes the effects from sample size) is the inverse of the percentage of the most abundant species. The distribution of this index shows minimal values for Sites 1081, 1083, and 1084. Maximum values are calculated for Sites 1076 and 1085 (Fig. 17) and in the other two pelagic sites (1086 and 1087; not shown in the figure). However, comparison with the ranking of sites in terms of productivity shows no clear relationship. In the cores south of the Walvis Ridge, there is a tendency for higher values to occur in sediments older than 3 Ma. This would agree with the proposition of lower productivity before the late Pliocene. However, there is no sign of recovery of diversity in the late Quaternary, for which we postulate lowered productivity. Thus, from these data, it appears that the late Quaternary productivity reduction applies only to opal, not to organic matter.

We plot the patterns for four taxa: *Bulimina* spp., *Bolivina* spp., *Uvigerina* spp., and *Cibicidoides* spp. The first two have long been recognized as forms abundant in high-productivity regions in coastal environments, such as off California (Uchio, 1960; Douglas and Woodruff, 1981). The presence of *Uvigerina* may indicate elevated levels of productivity (Lutze et al., 1986; Hermelin and Shimmield, 1990, 1995) and also has been tied to low-oxygen conditions in a pelagic setting (Burke et al., 1993). Different species within this genus apparently have different preferences (Berger et al., 1987). *Cibicidoides* is considered neutral with respect to productivity, at least with respect to its relative abundance (Berger and Herguera, 1992).

The genus *Bulimina* comprises several species (*B. aculeata, B. exilis, B. marginata, B. mexicana,* and *B. truncana*), which appear to have more or less similar distributional patterns. Maximum values

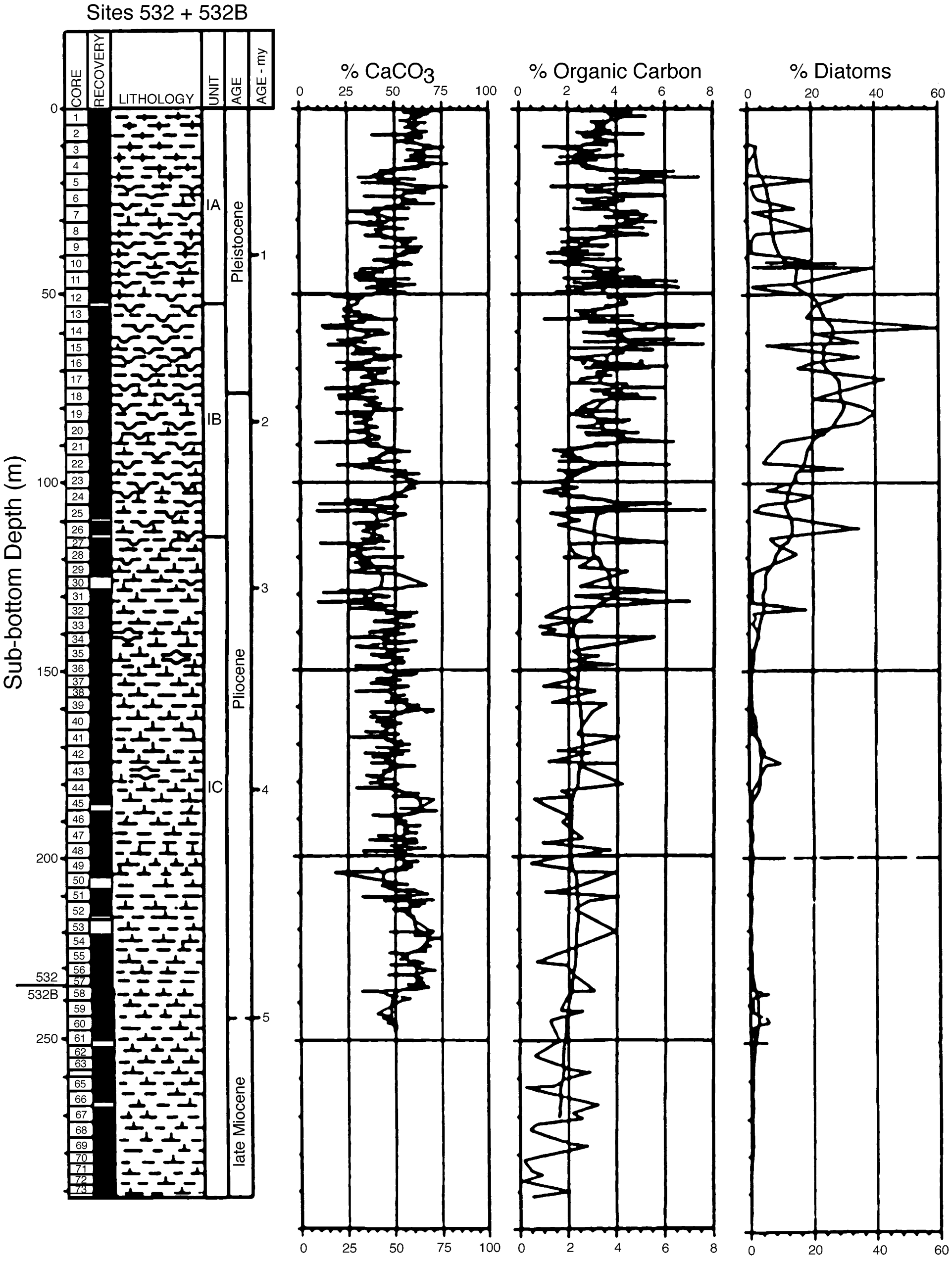

Figure 16. Late Neogene patterns of biogenous sedimentation on the Walvis Ridge in the Benguela Current system. Note the overall trend in diatom abundance, showing the Matuyama Opal Maximum. From Dean and Gardner (1985) and Hay and Brock (1992).

occur at the Lüderitz site (1084) and in two of the Walvis sites (1082 and 1081), but not in the third (Site 1083). The high percentages appear within the Quaternary record (Fig. 18). There is a drop in the upper Quaternary section at Site 1081. High values also characterize many samples from the Congo Sites 1076 and 1077, but not from Site 1075. The patterns suggest that this taxon tracks high productivity in pulsing upwelling systems associated with strong oxygen minima. It prefers shallower areas within the set of Leg 175 sites; that is, areas with a strong influence from coastal upwelling. This agrees well with results from the upwelling area in the Arabian Sea (Hermelin and Shimmield, 1990). If this interpretation is correct, coastal upwelling effects within the Benguela Current system (Walvis and Lüderitz sites) increased greatly from the late Miocene to the Quaternary, with a possible maximum in late Pliocene to early Quaternary time.

The genus *Bolivina* is represented mainly by *B. seminuda*, *B. pseudoplicata*, and *B. aenarensis*. By far the highest abundances occur at the sites off Lobito (Angola), where *Bolivina* entirely dominates the assemblages (Fig. 19). These are environments of very high accumulation rates of terrigenous sediment, with a seasonal supply of organic matter from coastal upwelling. Furthermore, the dominance of *Bolivina* suggests low oxygen concentrations at the seafloor (Smith, 1963, 1964; Phleger and Soutar, 1973). High percentages of *Bolivina* also are noted in upper Quaternary sediments at Site 1081, where this genus replaces *Bulimina* as the dominant form in a pulse-like fashion. Substantial occurrences in the upper Miocene and lower Pliocene sections at Site 1082 are somewhat puzzling. Apparently, *Bolivina* also thrives here at the expense of *Bulimina*. The patterns suggest that this taxon prefers environments of moderate to high pro-

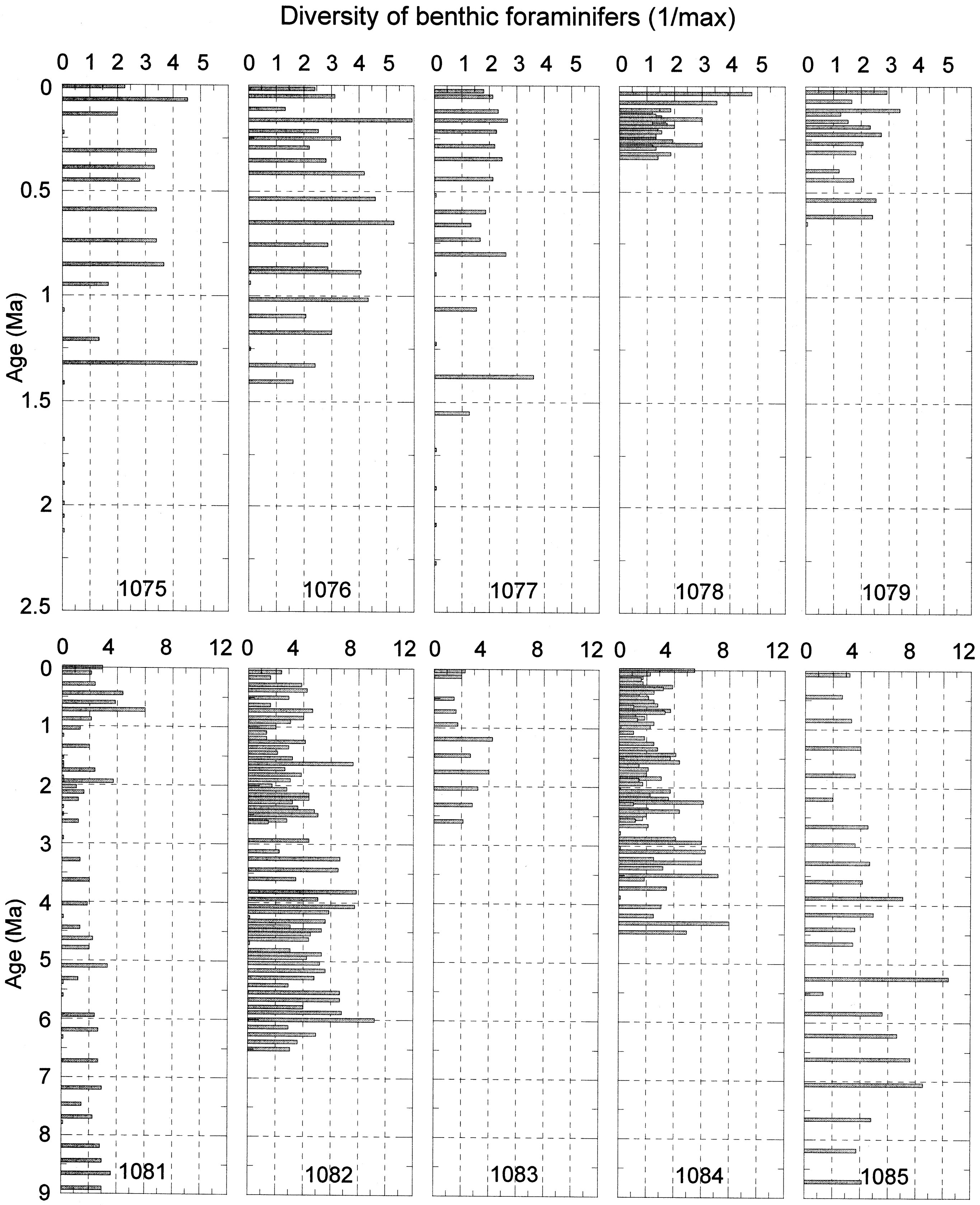

Figure 17. Diversity patterns of benthic foraminifers at Sites 1075–1085. The index is the inverse of the fraction of the most abundant species (e.g., 20% yields the diversity index 5).

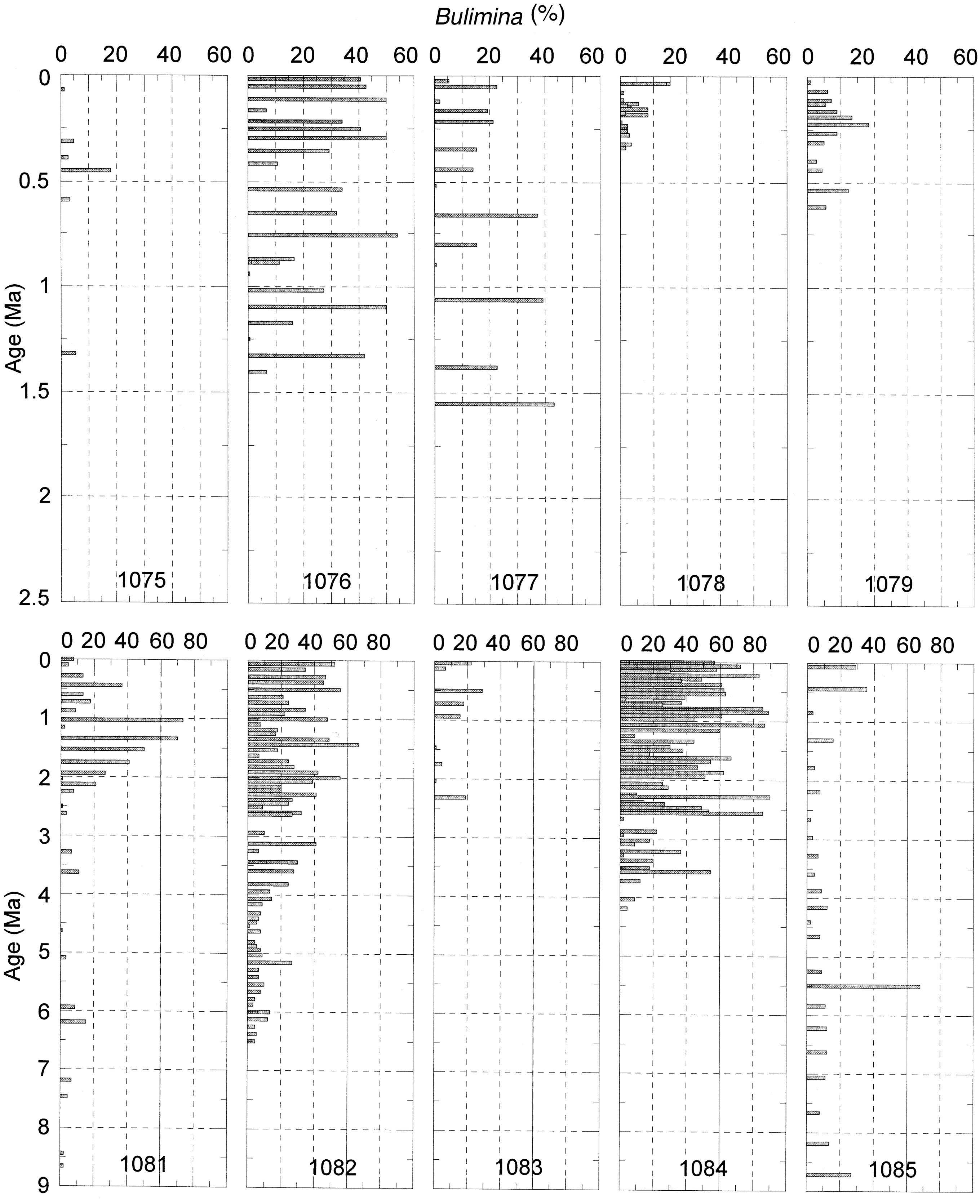

Figure 18. Abundance patterns of the genus *Bulimina* at Sites 1075–1085 according to shipboard analysis of core-catcher samples.

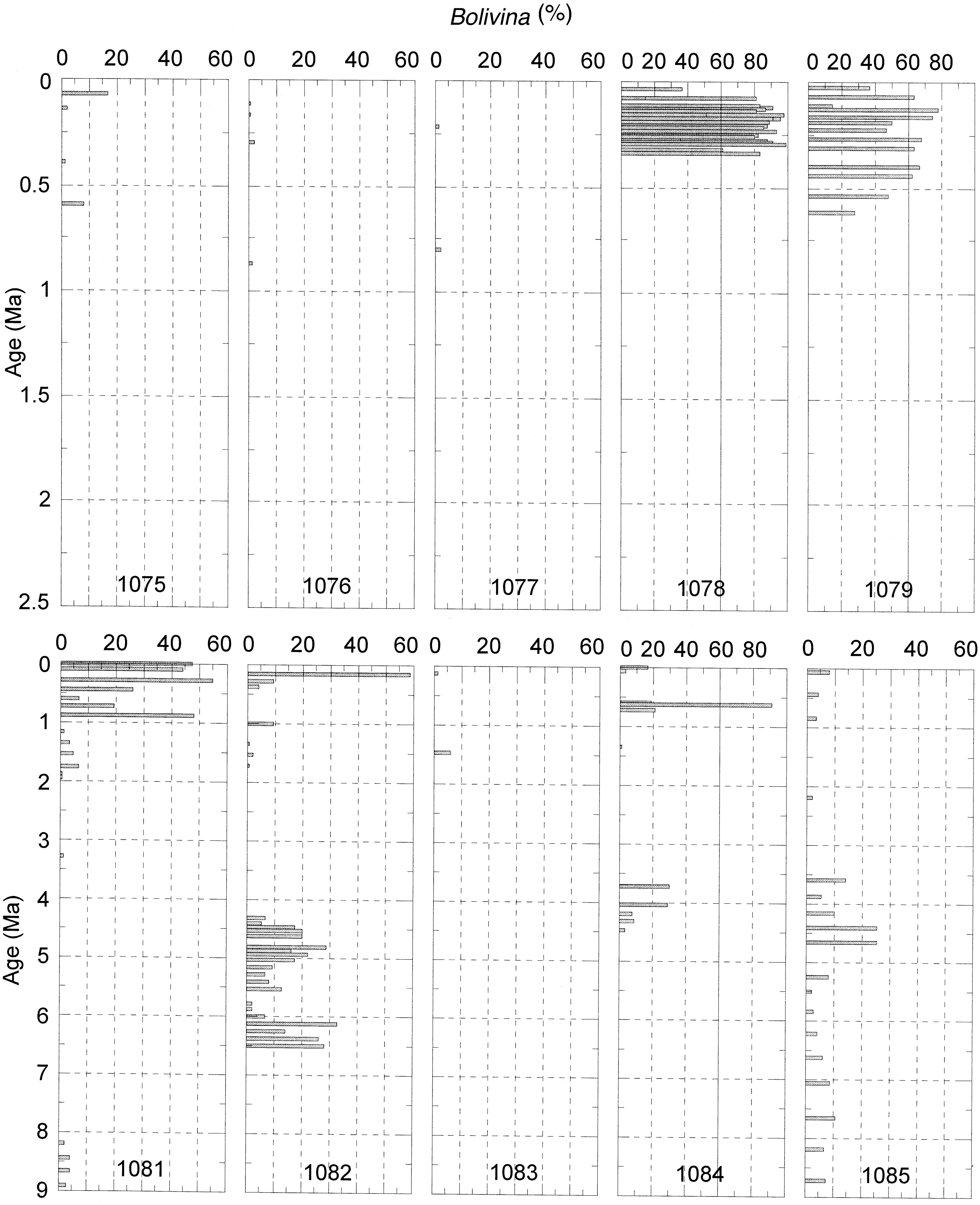

Figure 19. Abundance patterns of the genus *Bolivina* at Sites 1075–1085 according to shipboard analysis of core-catcher samples.

ductivity in a coastal setting and does especially well where influx of terrigenous silts dominate the environment. Occurrences before and after the *Bulimina*-dominated late Neogene sequences (Sites 1081, 1082, and 1084) suggest that productivity went through a maximum centered between 2 and 3 Ma, with *Bolivina* occupying the flanks of that maximum.

The genus *Uvigerina* comprises the species *U. auberiana, U. gallowayi, U. hispida, U. hispidocostata*, and *U. peregrina*. Maxima occur at Site 1081 on the Walvis Ridge (Fig. 20). Among the Benguela set of sites, 1081 ranks low in productivity, but intermediate in opal deposition. It is at the edge of the Angolan oxygen minimum at a rather shallow depth (805 m). The high values for *Uvigerina* would seem to support the notion that this species prefers an environment of moderately elevated productivity in association with an oxygen minimum. If this interpretation is correct, oxygen deficiency is indicated for a period between 3 and 2 Ma on the Walvis Ridge and in the middle of the Quaternary at Site 1082 (Walvis Bay). In the Cape transect, high values occur in the lower Pliocene (Site 1085; other sites not shown because of spotty data) but also in the upper Pliocene (Site 1087). Thus, the distribution of *Uvigerina* would support the notion of an expanded oxygen minimum in the Cape Basin before the Gaussian termination of global warm-climate conditions.

The taxon *Cibicidoides* (also referred to as *Cibicides* and *Planulina* by various authors) comprises the species *C. bradyi*, *C. pachyderma*, and *C. wuellerstorfi*. These forms are of special interest because they serve as carriers of isotopic information for deep-water composition. They are thought to live mainly as epibenthos, avoiding interference from the isotopic composition of interstitial waters (Lutze and Thiel, 1989; review in Wefer and Berger, 1991). *Cibicidoides* is widespread and apparently well adapted to a wide variety of environments. It has substantial presence in the Congo Fan sites (1075, 1076, and 1077) and in the Benguela set (Sites 1081–1087; see Fig. 21). It tends to avoid the environment preferred by *Bolivina* (Sites 1078 and 1079). Maxima occur where the other abundant genera, which are tied to elevated productivity, are not entirely dominant. An interesting situation is shown in the Lüderitz site (1084), where *Cibicidoides* unexpectedly reaches high values within the high-productivity upper Pliocene section. Apparently, it alternates with *Bulimina*, the high-productivity taxon. This suggests that productivity varied considerably at Site 1084 right through the early Matuyama opal maximum. If so, it supports the notion of cyclic upwelling and mixing, as opposed to a continuous strong upwelling (as in the late Quaternary).

In summary, the abundance patterns of benthic foraminiferal species suggest that there is no simple ranking of species with respect to productivity, but that each responds to a mixture of environmental factors. We assume that such factors include sedimentation rate, quantity and quality of organic matter, oxygen supply, and substrate properties. The built-in negative correlation among abundant taxa also makes interpretations difficult. The present analysis by inspection suggests that the presumed productivity maximum associated with the Matuyama opal maximum is real and not just an artifact of diagenetic processes. Also, there are indications of alternating high- and low- productivity periods within and just before the maximum, between 3 and 2 Ma. The hypothesis of an expanded oxygen minimum before the Gaussian climate revolution is supported (albeit mildly).

MILANKOVITCH CYCLES

Much of what we know or guess about long-term changes in productivity is derived from studying glacial/interglacial contrasts and glacial/interglacial cycles. In the area surveyed during Leg 175, 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; see articles in Wefer et al., 1996a). Much detailed work will be necessary to document fluctuations in productivity in these various settings and to tie the fluctuations in oceanic conditions to the corresponding changes in climate on the adjacent continent.

Work completed in preparation for Leg 175 on piston cores has shown that productivity systems are extremely sensitive to climatic change on several time scales. The influence of precessionally modulated seasonal insolation is especially strong in the tropical regions (Schneider et al., 1994, 1996, 1997; Wefer et al., 1996b), as has been known for some time (McIntyre et al., 1989; Molfino and McIntyre, 1990; McIntyre and Molfino, 1996). The effect is still strong at the latitude of the Walvis Ridge (Wefer et al., 1996b). Three factors are sufficient for obtaining a reasonable statistical model of organic carbon accumulation on the Walvis Ridge: (1) the general climatic state of the world, as reflected in a standard oxygen-isotope curve; (2) the precessional effect, as measured by insolation in July at 15°N; and (3) the decay of organic matter during diagenesis.

The example given in Figure 22 is based on total organic carbon (TOC) measurements on Core GeoB 1028 (Geosciences Bremen), located close to DSDP Site 532. The time scale is based on oxygen-isotope stratigraphy (data in Wefer et al., 1996b). The TOC model is of the form

$$TOC = SL^{a} \cdot INS^{(a-1)} \quad a < 1,$$

where *SL* stands for sea level and is expressed as an arbitrary index, a linear transformation of the *G. sacculifer* isotope record in ODP 806 (806sox; Berger et al., 1995). *INS* is the insolation in July at 15°N, expressed as an arbitrary index ranging between 0.5 and 1.5, a linear transformation of the actual irradiation values given in Berger and Loutre (1991). The exponent *a* is taken as $^2/_3$; this defines the weighting of the two explanatory variables as 2 to 1. The resulting calculated curve is shown as TOCcalc and is compared with TOCmeas (model and target; Fig. 22). The difference between model and target, the residual, shows decreasing values with depth in core, indicating the effects of diagenesis. The slope is decreasing with depth, reflecting diminishing rates of decay, with the most active destruction occurring in the uppermost meter of the sediment column. From the nature of the residual, there is a hint that the system is more sensitive toward precession during cold climate states than during warm ones on a 100-k.y. scale.

The appearance of color reflectance data at Site 1075 and subsequently occupied sites invited a search for precessional signals within color cycles. It would be of great interest to document a diminishing influence of precessional power going from the tropics to the Cape of Good Hope.

Unfortunately, the origin of color differences is not entirely clear; varying contents of carbonate and organic matter are involved, as well as other components such as terrigenous supply and authigenic minerals. Also, comparison between different holes at the same site shows that amplitudes of color variation are subject to artifact, such as exposure to air. For example, although Hole 1075A shows increasing amplitudes with depth, Hole 1075C shows the exact opposite in the long-term trend (see “Lithostratigraphy” section, “Site 1075” chapter, this volume). Short-term changes in amplitude presumably are less subject to alteration and may preserve the precessional beats.

To test this idea, we first establish a detailed time scale using magnetic susceptibility (measured continuously on unopened cores). To avoid circular reasoning, we do not use reflectance to establish a scale. Inspection of raw magnetic susceptibility data, combined with previous knowledge about sedimentation rates in the region (Schneider et al., 1994, 1997), suggested a direct correlation with the global oxygen-isotope stratigraphy. The fit is in fact excellent (Fig.

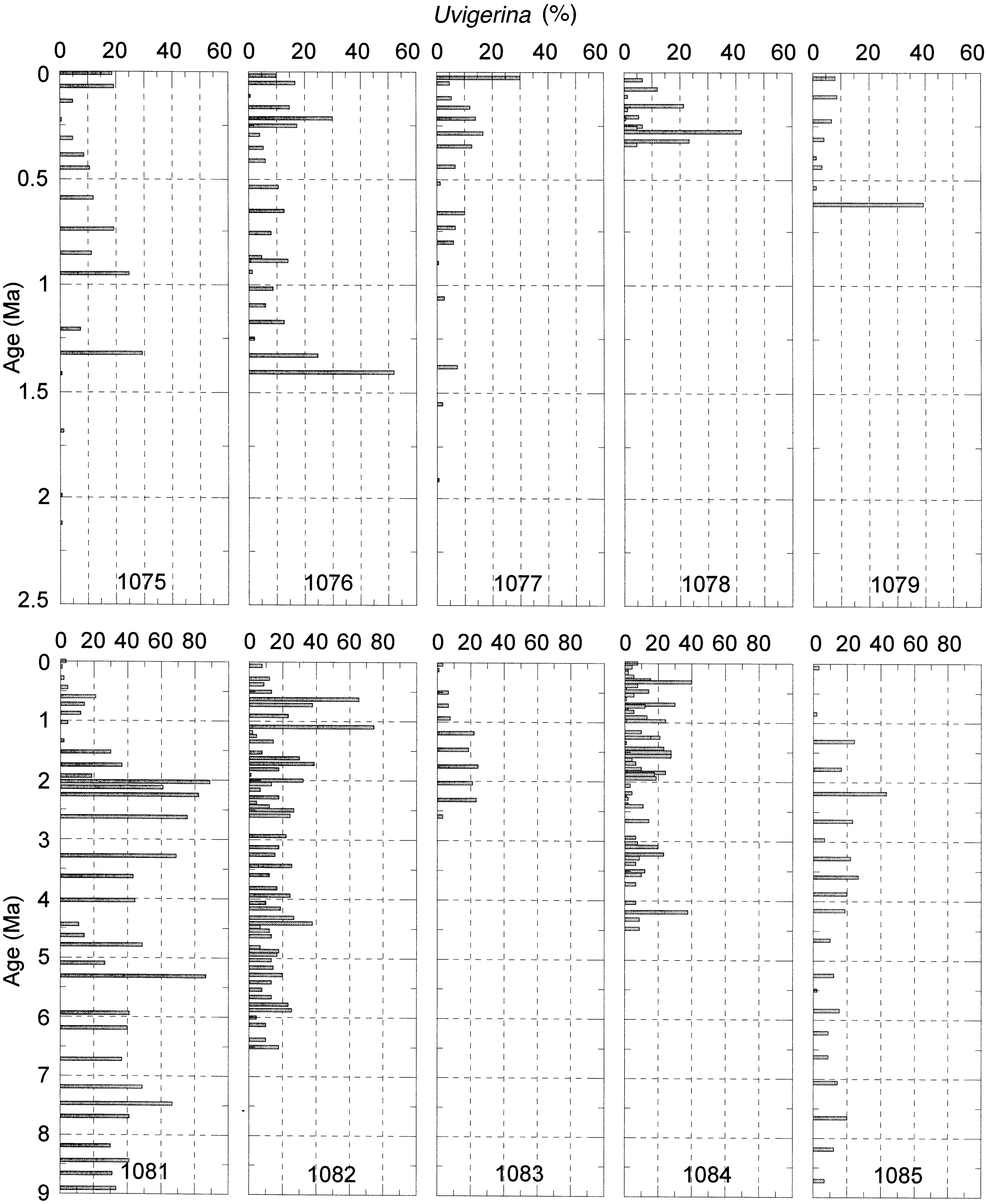

Figure 20. Abundance patterns of the genus *Uvigerina* at Sites 1075–1085 according to shipboard analysis of core-catcher samples.

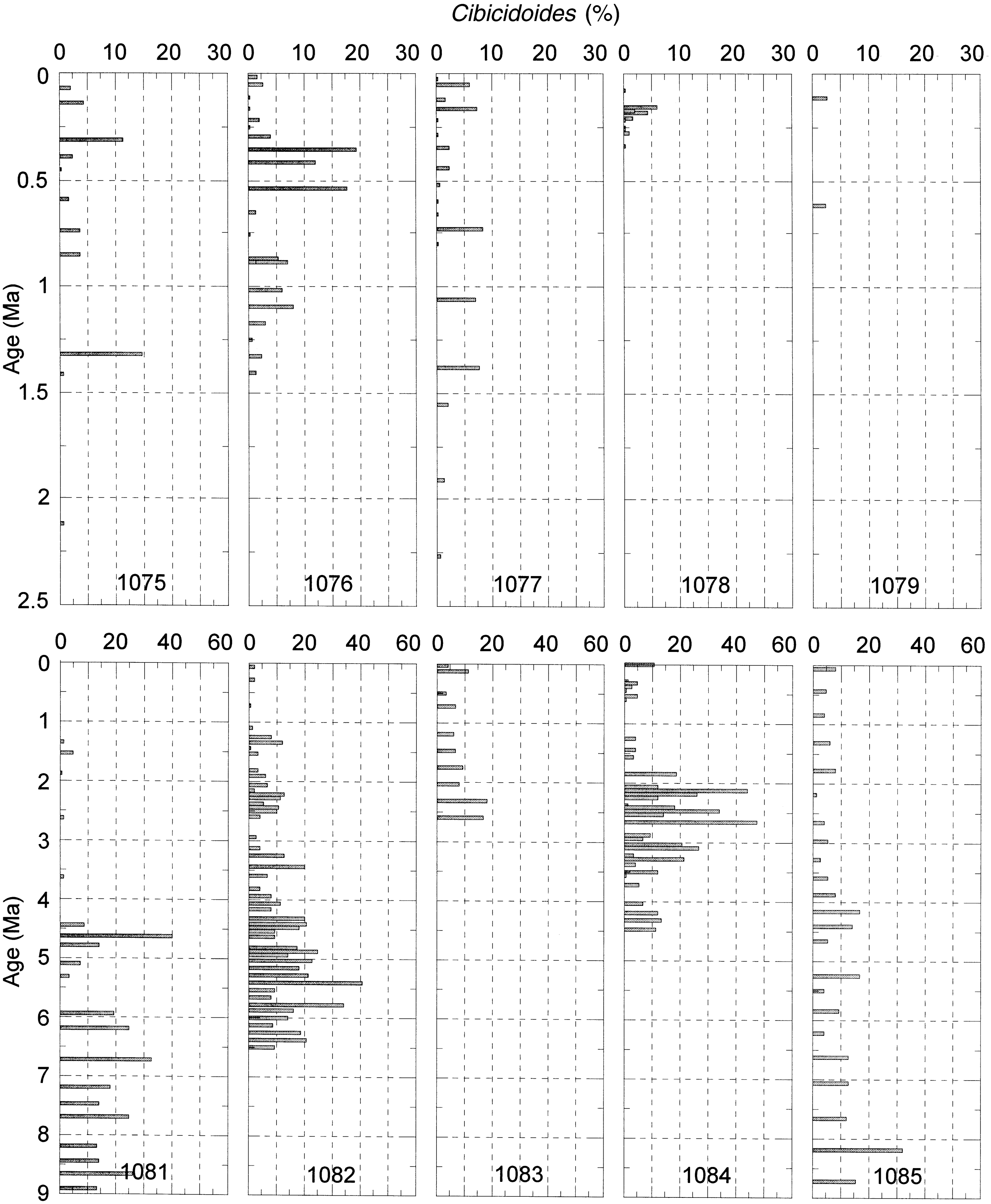

Figure 21. Abundance patterns of the genus *Cibicidoides* at Sites 1075–1085 according to shipboard analysis of core-catcher samples.

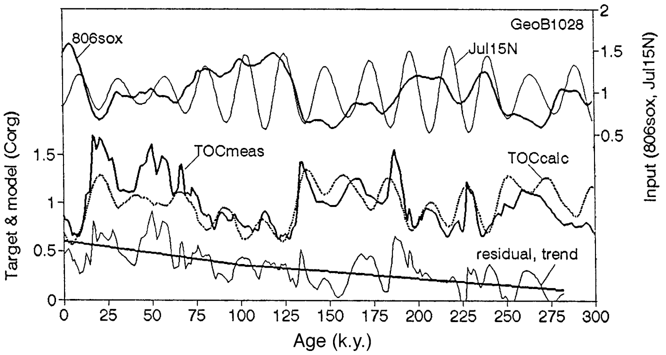

Figure 22. Statistical modeling of TOC content in Core GeoB1028 on the Walvis Ridge (near DSDP Site 523). Input is global sea level, as reflected in a global oxygen-isotope signal (806sox) and seasonal insolation, as reflected in solar energy received during July at 15°N. After accounting for the trend (caused by decay), r^2 is 0.65. Data sources: TOC, Geowissenschaften Bremen; 806sox, Berger et al. (1995); and Jul 15N, Berger and Loutre (1991).

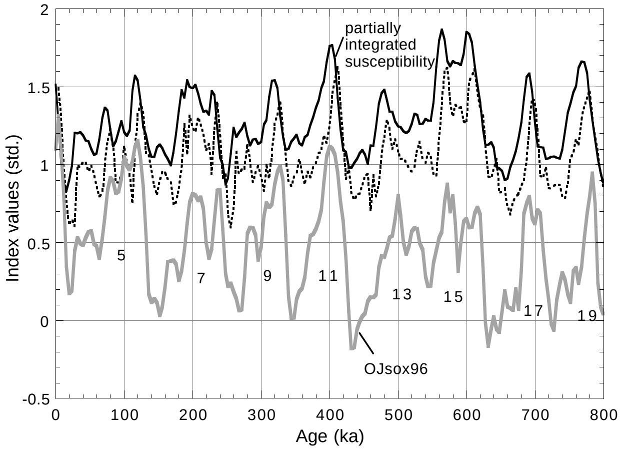

Figure 23. Correlation of magnetic susceptibility ("partially integrated susceptibility") and a global oxygen-isotope curve ("Ojsox96"). Dashed line = magnetic susceptibility. OJsox96, Ontong Java *G. sacculifer* oxygen-isotope curve, as given in Berger et al. (1996).

23), especially if susceptibility data are partially integrated going upward in the sequence (labeled "partially integrated susceptibility" in Fig. 23; for details, see Berger et al., Chap. 22, this volume). The integration assumes that susceptibility is spiked on deglacial transitions and has the effect of smoothing the curve and moving it toward slightly younger ages.

The time scale derived from correlation, in the fashion shown in Fig. 23, places the Brunhes/Matuyama boundary at the correct depth (i.e., just before the susceptibility maximum corresponding to Stage 19 in the correlation). With the time scale established, reflectance data were automatically dated and could be analyzed for precessional information. Results show strong precessional cycles in the red/blue ratio, especially in the last 600 k.y. (Milankovitch Chron) when the 100-k.y. cycle dominates climatic change (Fig. 24). Total reflectance, on the whole, has less prominent precessional information, but more so in the middle Pleistocene (Croll Chron, ~600–1200 k.y.). Although a correspondence of forcing and response is evident for both reflectance and color, the match is not as good as one would hope (perhaps because of the above-mentioned artifact).

Precessional information enters the record through productivity variations because of cyclic fluctuations in the wind field (McIntyre et al., 1989; Molfino and McIntyre, 1990; Schneider et al., 1994, 1996; Jansen et al., 1996; McIntyre and Molfino, 1996; Mix and Morey, 1996; Wefer et al., 1996b). Simulations with a climate model suggest that sea-surface temperature and wind fields respond to changes in seasonal insolation (Kutzbach and Liu, 1997). In particular, modeling indicates that 6000 yr ago, when seasonal contrast was greater than today because of late summer perihelion, sea-surface temperature (SST) was greater in late summer, and winds had a stronger landward component toward North Africa (Fig. 25). A landward component is also suggested for South Africa. The effect of such a change in wind field would be to weaken the trades and hence decrease upwelling in the eastern equatorial Atlantic. Also, the offshore component of flow along the southwestern margin would be weakened, reducing upwelling in the entire Benguela Current system. Whether heat transfer from the South Atlantic to the North Atlantic would increase or decrease is not clear; presumably, there would be a shift from transport by currents to transport by moist winds.

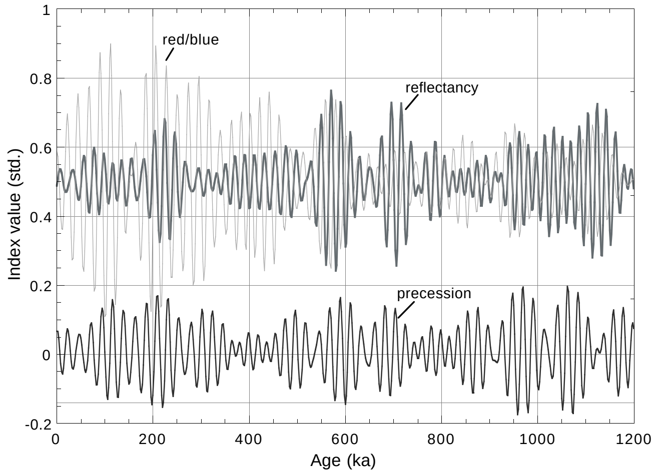

Figure 24. Precessional components of reflectance and color data at Site 1075, dated by matching magnetic susceptibility to a standard oxygen-isotope curve. Note the apparent increase in sensitivity of color to forcing during the last 600 k.y. (forcing is taken as the precessional effect on summer insolation, as given in Berger and Loutre, 1991).

The experiment by Kutzbach and Liu (1997) illustrates how the climate record in Africa will have to be consulted to fully understand the history of upwelling in the Angola-Benguela systems. It is clear from their results that the influence of tropical dynamics will be strong well beyond the tropics. Although we expect that precessional information will tend to dominate in the tropical portion of the Leg 175 megatransect (based on the earlier findings cited), we anticipate a strong precessional signal even off the Cape of Good Hope. As mentioned, the relationships to climatic change on the continent will be of special interest (Jansen et al., 1984).

CONCLUSIONS: CENTRAL ISSUES AND MATUYAMA OPAL MAXIMUM HYPOTHESIS

Inasmuch as upwelling along the southwestern coast of Africa is driven by winds and is closely tied to the strength of the offshore currents, it reflects processes important in the heat transfer from the South Atlantic to the North Atlantic Oceans. However, no simple relationship between productivity and heat transfer can be assumed.

At least two factors introduce important complications. The first is the back pressure developed from a glaciated Northern Hemisphere, which moves the Intertropical Convergence Zone from its northern position toward the equator (Flohn, 1985). The back-pressure problem demands that productivity patterns be reconstructed equally well for the systems off Iberia and northwest Africa for comparison with the southern African regions.

The second factor concerns changes in the nutrient content of subsurface waters feeding the upwelling system (Hay and Brock, 1992;

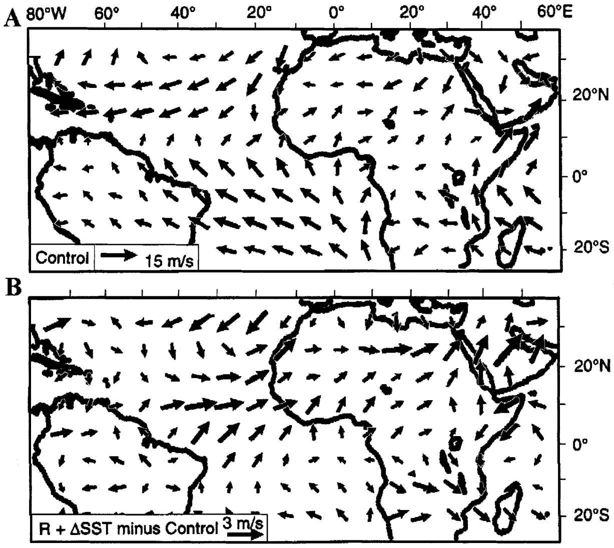

Figure 25. Simulated surface winds for summer months for (**A**) control and (**B**) R + ΔSST minus control. Control = present conditions; R + ΔSST = departure of the situation 6 k.y. ago from the present. Note the change in the wind-speed scale, going from A to B. R = the effects of summer insolation with SST fixed; ΔSST = an adjustment in the model for heating of the sea surface. Simplified from Kutzbach and Liu (1997).

Lange and Berger, 1993; Herguera and Berger, 1994). Changes in nutrient content of subsurface waters ("thermocline fertility") are readily appreciated when comparing depositional rates of opal and organic matter (Berger et al., 1994, 1997; Berger and Wefer, 1996; Schneider et al., 1996, 1997). Thus, great care must be taken to capture both the influence of physical mixing and upwelling (which depend on the wind field) and that of thermocline fertility (which depends on the quality of upper intermediate waters, among other things).

The MOM off southwestern Africa is of special interest in the context of evolution of the Benguela Current and the concomitant development of thermocline fertility. It is centered near 2.2 Ma and follows a rapid increase of diatom productivity near 3 Ma. In its early stage, it is marked by a strong Antarctic component, as well as by an admixture of warm-water forms. After MOM time, diatomaceous remains typical of strong coastal upwelling dominate. This sequence suggests a greater availability of silicate in subsurface waters during the MOM than either before or after. We hypothesize that the MOM marks a time when the Benguela Current (and all other currents interacting with it at its point of origin) were flowing less vigorously than today (Fig. 26). The silicate front (Fig. 27A) was less well developed than in the Quaternary, and subsurface waters were richer in silicate north of 40°S than they are today (e.g., Westall and Fenner, 1990, p. 780). Because the Agulhas Retroflection was less active to the west of the Cape of Good Hope (it depends on the inertia of a strong Agulhas Current), waters of Antarctic origin were entrained sporadically into the region off southwest Africa up to Namibia ("AAE" in Fig. 26B). Poleward undercurrent flow ("PUC" in Fig. 26) was stronger during MOM time, being less opposed than today by the Benguela Current and northward-flowing Antarctic Intermediate Water.

Our scenario (Fig. 26B) suggests a number of tests:

1. During MOM time an increased poleward undercurrent should bring oxygen-deficient waters at intermediate depths to a region farther south than today.
2. A decreased Agulhas Current (and decreased eddy activity) should result in fewer planktonic organisms being imported from the Indian Ocean.

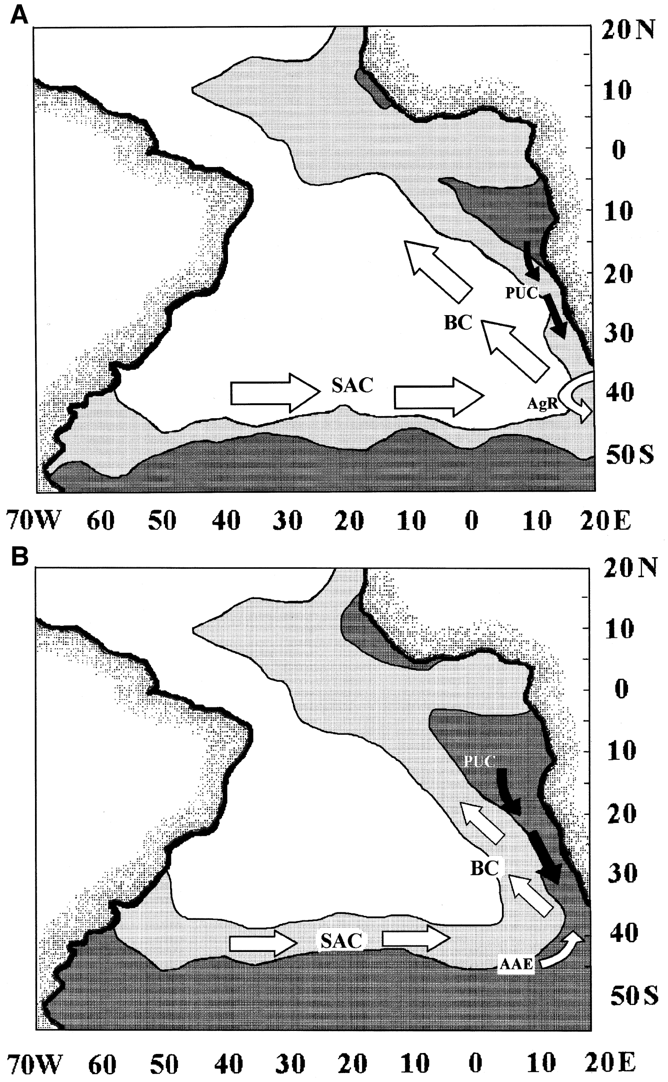

Figure 26. Hypothesis of silicate expansion in subsurface waters during the Matuyama Opal Maximum (MOM). **A.** Present-day distribution patterns of silicate at 100 m (simplified from Herzfeld and Berger, 1993). Gray = silicate content >4 µM/kg; black = >8 µM/kg. **B.** Hypothetical conditions during MOM time, near 2.2 Ma. Currents: SAC = South Atlantic Current, BC = Benguela Current, PUC = Poleward Undercurrent, AgR = Agulhas Retroflection, and AAE = Antarctic water excursions.

3. Warm-water and cold-water forms of all major planktonic organisms in the Cape Basin region should be less well segregated during the MOM than today.

Our hypothesis states that the system goes through an optimum with respect to diatom deposition. It implies that warming moves us closer to the optimum; hence, interglacials should have greater opal deposition on and south of the Walvis Ridge, and indeed they do (Diester-Haass et al., 1990, 1992; Hay and Brock, 1992). Also, north of the ridge, a more normal pattern should be found, with glacial sediment having the greater opal content (as described by Schneider et al., 1996, 1997). Furthermore, before reaching the MOM, more opal should accumulate on and south of the ridge during cold periods because cooling moves the system closer to the optimum. There are indications that this may be so (Diester-Haass et al., 1992; Hay and Brock, 1992).

These distinct patterns on various time scales suggest to us that upwelling is not the only factor controlling opal deposition; the qual-

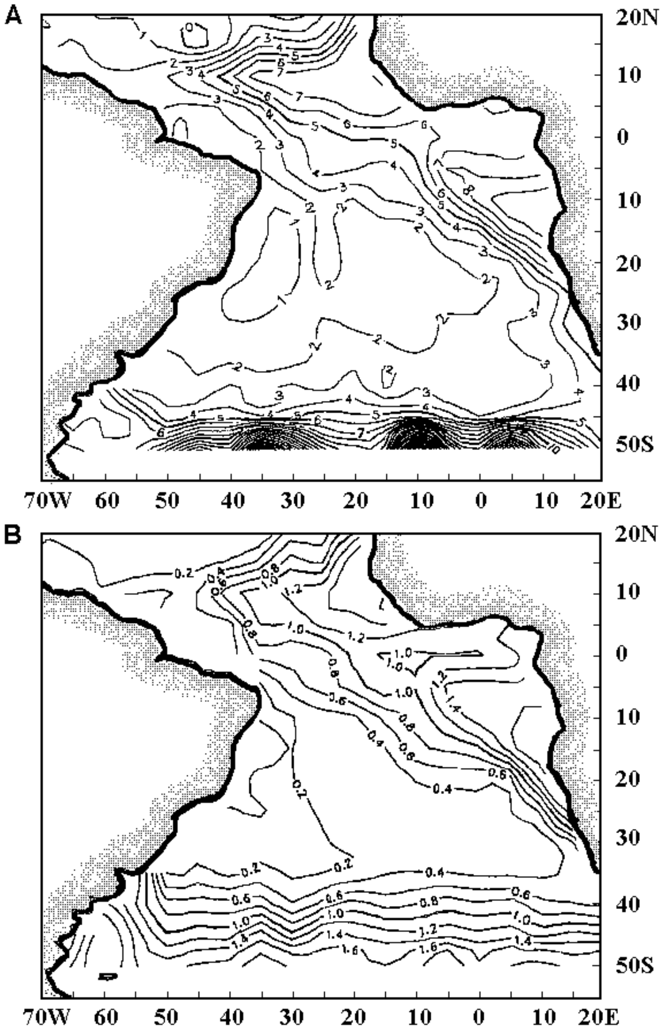

Figure 27. Silicate and phosphate patterns in subsurface waters of the South Atlantic (from Herzfeld and Berger, 1993). **A.** Silicate concentrations at 100-m depth (in µM/kg). **B.** Phosphate concentrations at 100-m depth (in µM/kg).

ity of the upwelled water is equally important (cf. Barron and Baldauf, 1989; Baldauf and Barron, 1990). Increased flow of the Benguela Current presumably parallels increased upwelling; however, it also seems to be associated with processes that decrease the silicate content of waters within the thermocline off southwestern Africa. Analogous observations have been made elsewhere (Berger et al., 1997). Clues to the mechanisms responsible for these patterns will be found in the phase relationships between different productivity proxies and between productivity and the ice-age cycles of temperature and sea level.

The Agulhas Current Retroflection ("AgR" in Fig. 26A) is thought to play a major role in providing warm water to the Benguela Current near its point of origin (Lutjeharms, 1996; Shannon and Nelson, 1996). The Agulhas Current overshoots beyond the Cape of Good Hope and spawns large eddies, which enter the Benguela Current as the Agulhas water turns back toward the Indian Ocean (Fig. 28). The history of the import of Indian Ocean water (some 6 sv at present; 1sv = 10^6 m^3/s) clearly is of great importance to the question of heat transport in the Benguela Current system. We suspect that there is an optimum for warm-water acquisition when the inertia of the Agulhas Current is great enough to inject waters well into the South Atlantic Ocean, but the countervailing currents (South Atlantic Current and Antarctic Circumpolar Current) were not as strong as they are today. It is possible that such optimum injection was contemporaneous with the MOM, in which case our hypothesis would have to be modified to account for sporadic warm-water incursions from the Indian Ocean into the Cape Basin.

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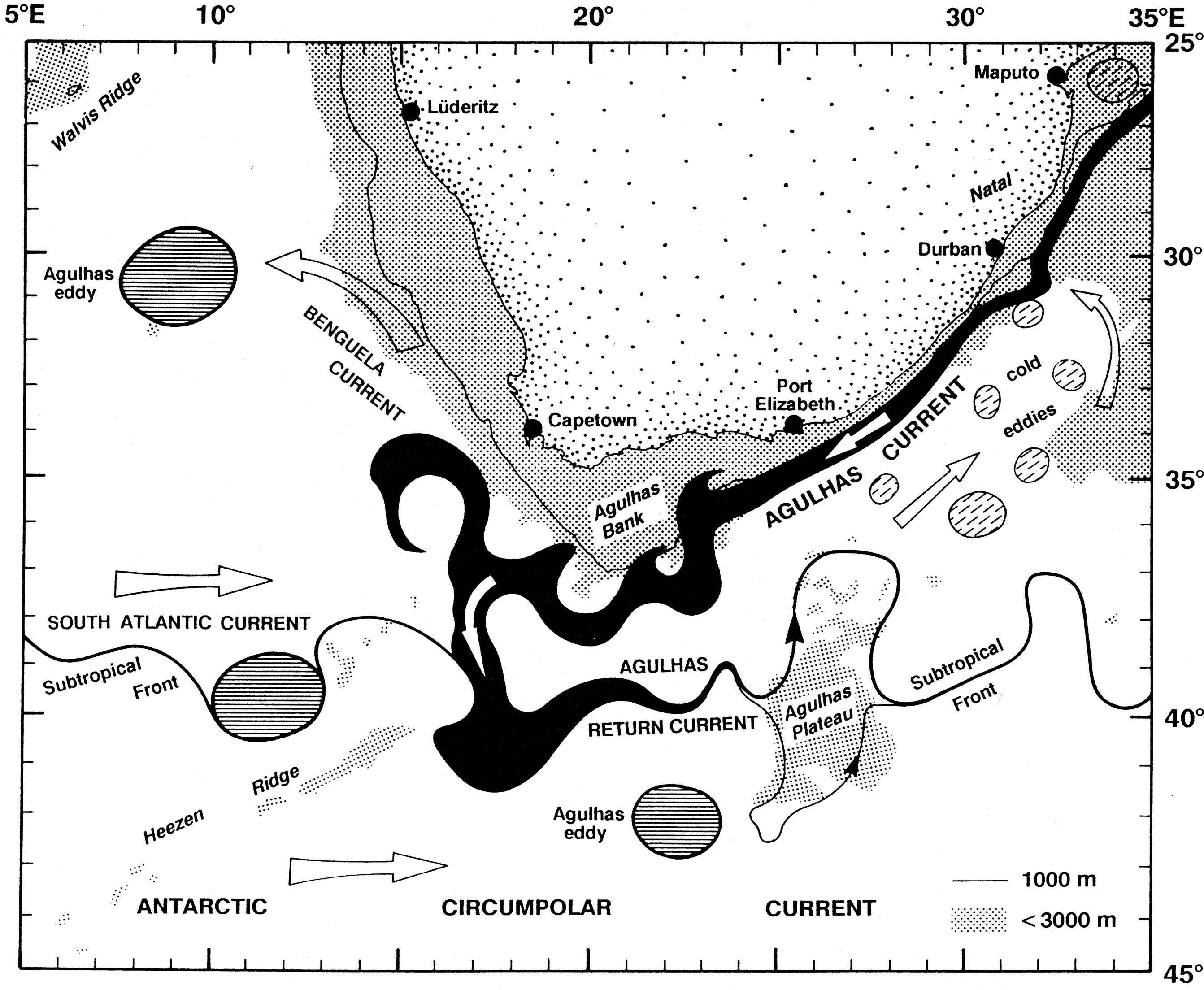

Figure 28. Agulhas Current and Agulhas Retroflection (south of Africa) and associated currents and eddies (from Peterson and Stramma, 1991; after Lutjeharms and van Ballegooyen, 1988).