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Pliocene-Quaternary upwelling in the Southeastern Atlantic may reflect changes in water mass production

William W. Hay

GEOMAR, Wischhofstrasse 1-3, D-24148 Kiel, Germany, and Department of Geological Sciences, CIRES, and Museum, University of Colorado, Boulder, CO 80309, USA.

ABSTRACT

Key words: Upwelling; Pliocene; Quaternary; Atlantic; water masses; opaline silica; organic carbon.

The sediments recovered at Deep Sea Drilling Project Sites 362 and 532 on Walvis Ridge Abutment Plateau and at Site 530 in the southeastern Angola Basin record long-term changes in the rates of upwelling. Deposition of opaline silica and organic carbon increased from latest Miocene to latest Pliocene then declined to present. The sediments display light-dark cycles. The dark cycles contain more terrigenous material and represent glacials. During the Late Miocene the productivity maxima were characteristic of glacial maxima in the Antarctic. Since the beginning of the Pliocene productivity maxima have occurred during interglacials. The most likely causes of these changes are:

1) desiccation and reflooding of the Mediterranean. The desiccation drew the ITCZ to its most northerly position. After reflooding the Mediterranean had a positive fresh-water balance until about 2.5 Ma, when it changed to its present negative balance and lagoonal circulation. The period during which productivity increased along the southwest African margin corresponds to the time when the Mediterranean had a positive fresh-water balance and estuarine circulation. During this time the Mediterranean supplied no intermediate water to the North Atlantic. The decline in productivity off southwest Africa corresponds to the time when lagoonal circulation developed in the Mediterranean and, as at present, its outflow forms a major intermediate water mass. During glacials the more dilute saline Mediterranean outflow resulted in the expansion of nutrient-poor North Atlantic Intermediate Water (NAIW) at a higher level in the ocean. The NAIW replaced AAIW in the South Atlantic during glacials. Upwelling along Southwest Africa may have increased as a result of increased wind stress, but the upwelled water was NAIW, and did not result in increased productivity.

2) growth of the Antarctic and Northern Hemisphere ice caps. During the Late Miocene growth of the Antarctic ice cap forced northward migration of the subtropical highs and Intertropical Convergence Zone (ITCZ). These changes in atmospheric circulation may have initiated productive upwelling over the Walvis Abutment Plateau. As Northern Hemisphere glaciation was initiated, the Earth changed from a unipolar to a bipolar glaciated state. This forced southward migration of the ITCZ and an increase in the intensity of the southeast trade winds.

3) closing of the Central American Straits. The resulting salinization of the North Atlantic forced increased production of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). The production of NADW resulted in nutrient export from the North Atlantic and development of the contrast between nutrient-rich southern and nutrient-poor northern intermediate and deep water masses.

The combination of all these changes is probably responsible for the observed pattern of change in productivity. Hay and Brock's (1992) explanation of lessened productivity during glacials being due to upwelling of nutrient-poor NAIW rather than AAIW remains a viable hypothesis.

INTRODUCTION

Sites 362 and 532, drilled during Legs 40 and 75 of the Deep Sea Drilling Project (DSDP) on the Abutment Plateau where Walvis Ridge joins the continental margin, record long- and short-term changes in upwelling-related productivity. Site 532 was a reoccupation of Site 362 in an attempt to recover a more complete section using hydraulic piston coring. Site 532 penetrated a sequence of late Neogene sediments recording both short and long-term changes in upwelling of nutrient-rich waters. The changes in abundance of sedimentary components indicative of upwelling have been discussed by Hay, Sibuet*et al.* (1984) and Hay and Brock (1992). Opaline silica, regarded as the best indicator of intensity of upwelling of nutrient-rich waters, increased sharply from the late Miocene to the latest Pliocene and then declined to present values during the Pleistocene. The proportion of opaline silica in the sediment also increased from negligible in the late Miocene to almost 30% in the latest Pliocene and declined to 3% in the Pleistocene. The diatom-rich deposits encountered on Walvis Ridge and in the southern Angola Basin reflect an increase and then decline of upwelling of waters with a complete complement of nutrients (PO_4, NO_3, H_4SiO_4) from beneath the surface mixed layer (Calvert, 1974; Diester-Haass, 1978, 1983; Calvert & Price, 1983). Figure 1 shows the average accumulation

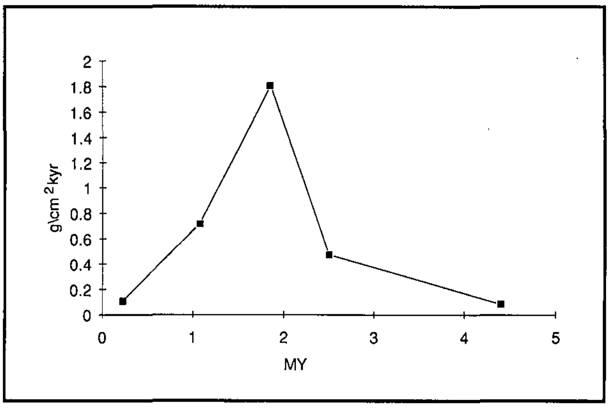

Fig. 1 — Average accumulation rates for opaline silica calculated from the sediments preserved at DSDP Site 532 for the intervals defined by nannofossil biostratigraphy (Hay & Sibuet *et al.*, 1984; Steinmetz *et al.*, 1984; Steinmetz & Stradner, 1984).

rates for opaline silica at DSDP Site 532 for the intervals defined by nannofossil biostratigraphy (Hay, Sibuet*et al.*, 1984; Steinmetz *et al.*, 1984; Steinmetz and Stradner, 1984). Superimposed on this long-term trend are shorter-term cyclic variations in the carbonate, organic carbon and opal content of the sediments, commonly referred to in the literature as dark-light cycles. The length of these cycles cannot be determined with accuracy, but they are in the range of Milankovitch orbital forcing. The light cycles are relatively carbonate-rich (Dean*et al.*, 1984; Gardner*et al.*, 1984; Dean & Gardner, 1985) and have been interpreted as representing interglacial high stands of sea-level (Gardner *et al.*, 1984). Studies by Diester-Haass (1985a, 1985b, 1988), Diester-Haass *et al.* (1986, 1990), and Diester-Haass & Rothe (1987) have shown that in the pre-Pliocene sediments the glacial (dark) cycles are enriched in opaline silica, but in the younger sediments opaline silica is less abundant in the dark cycles and enriched in the light cycles.

DSDP Site 530 in the southeastern Angola Basin contains a similar sequence but the stratigraphy is interrupted by turbidity currents and debris flows. Its record has been compared to that at Site 532 by Hay & Brock (1992) and will not be discussed here.

CIRCULATION OF THE SOUTH ATLANTIC OCEAN

Until recently it was thought that the circulation in the South Atlantic had the form of a single large subquadrate anticyclonic gyre, as had been indicated by Schott (1942). The east side of this gyre is commonly known as the Southeast Trade Wind Drift or Benguela Current. This diverges from the Benguela Coastal Current that flows northward on the Namibian shelf (Dietrich, 1957). It was thought that the Benguela Current left the African coast to turn west at or north of Cabo Frio but more recent analysis has shown that the anticyclonic gyre of the South Atlantic has a triangular form, and the Benguela Current leaves the coast well south of Cabo Frio (Peterson & Stramma, 1991), as shown in Figure 2. It has also been found that there is a smaller cyclonic gyre in the northeast South Atlantic that includes the Angola Dome (Peterson & Stramma, 1991; Gordon & Bosley, 1991). The eastern side of this cyclonic gyre is the southward-flowing Angola Coastal Current. Eddies are generated where the Benguela and Angola Coastal Currents meet. The cyclonic eddies containing upwelled water with diatoms and radiolarians drift offshore, and sterile anticyclonic eddies of tropical water drift inshore (Hart & Currie, 1960; Hagen *et al.*, 1981). Diester-Haass (1985a, 1985b, 1988), Diester-Haass *et al.* (1986, 1990), and Diester-Haass and Rothe (1987) have considered the cyclonic eddies to be the source of the biogenic silica deposited on the Walvis Ridge Abutment Plateau. They suggested that the weakening of productivity during glacials is due to a northward shift of the latitude at which the Benguela Current leaves the coast. This now seems unlikely because Winter and Martin (1990) have shown that the subtropical convergence separating the Circumantarctic Current (West Wind Drift) from the subtropical gyres of the South Atlantic and southern Indian Oceans did not move northward far enough to shut off flow of the Agulhas Current around the tip of Africa during the glacials.

The nutrient-rich waters upwelled along the southwest African margin are derived from Antarctic Intermediate Water. After reviewing the different kinds of upwelling mechanisms that might play a role in introducing nutrient-rich waters to the eastern Walvis Ridge and southern Angola Basin, Hay & Brock (19) concluded that both the long-term increase and decrease of biogenic silica production and the changes from interglacial to glacial cycles may reflect upwelling of waters of differing nutrient content. In this paper I explore how changes in the subthermocline water masses might have caused the long-term and interglacial-glacial variations in fertility of the upwelled waters.

THE MAJOR WATER MASSES OF THE ATLANTIC

Rooth (1982) noted that the circulation of the tropical-subtropical ocean is broken into basin-wide anticyclonic gyres that lie between the extremes of zonal wind stress and the equator. At present the ocean is thermally stratified, and the effect of the wind stress is concentrated in the surface mixed layer. Surface layers of warm water in the tropics and subtropics lie above and adjacent to the much larger body of cold water. The warm surface layers are separated

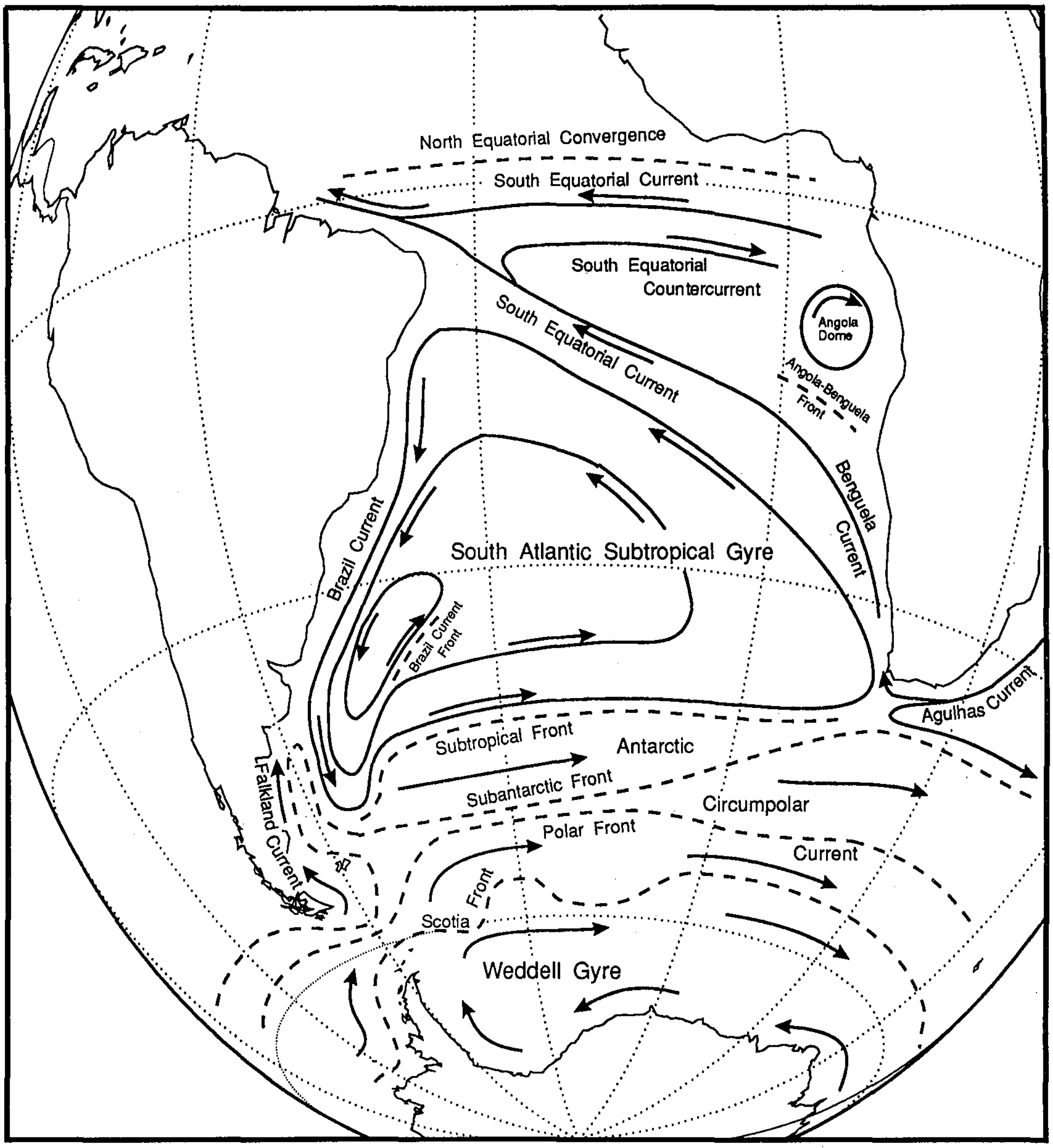

Fig. 2 — Circulation of surface currents and convergences (fronts) in the South Atlantic (after Peterson & Stramma, 1991, modified). Convergences (fronts) are indicated by dashed lines. Solid lines are current streamlines.

from each other and from the cold polar surface layer by oceanic fronts. The fronts are sites of convergence; the water flows into the convergences from both sides and sinks. The convergences are induced by increasing meridional Ekman transport resulting from increased meridional wind stress, as shown schematically in Figure 3. The water masses of the South Atlantic formed along the convergences are shown in Fig. 4.

In the absence of other forces the poleward heat transport in the oceans should not extend beyond the subtropical oceanic convergence bounding the anticyclonic gyres at 45° N and S latitude. It is only the deep thermohaline circulation, through which significant quantities of dense water sink in the polar regions to form deep water, that allows ocean waters to be diverted from the tropical-subtropical anticyclonic gyres to the higher latitude cyclonic gyres and thereby to transport heat by surface currents to higher latitudes. The effect of the thermohaline circulation is most strongly felt in the North Atlantic, where some 8 to 10 Sverdrups (1 Sverdrup = 10^6 m^3s^{-1}) of surface water sink in the Norwegian-Greenland and Labrador Seas. This "hole in the surface ocean" causes diversion of a large part of the flow of the North Atlantic Drift to the north into the Norwegian-Greenland Sea, resulting a significant oceanic heat transport north of 45° N and amelioration of the climate of Europe (Hay, 1993).

The warmest waters of the Atlantic, 27-28° C, occur in the western equatorial Atlantic. Polewards across the tropical-subtropical gyres of the Atlantic, the temperatures decline to 12° C at the Subtropical Convergence near 40° S and along its less well developed northern hemisphere counterpart.

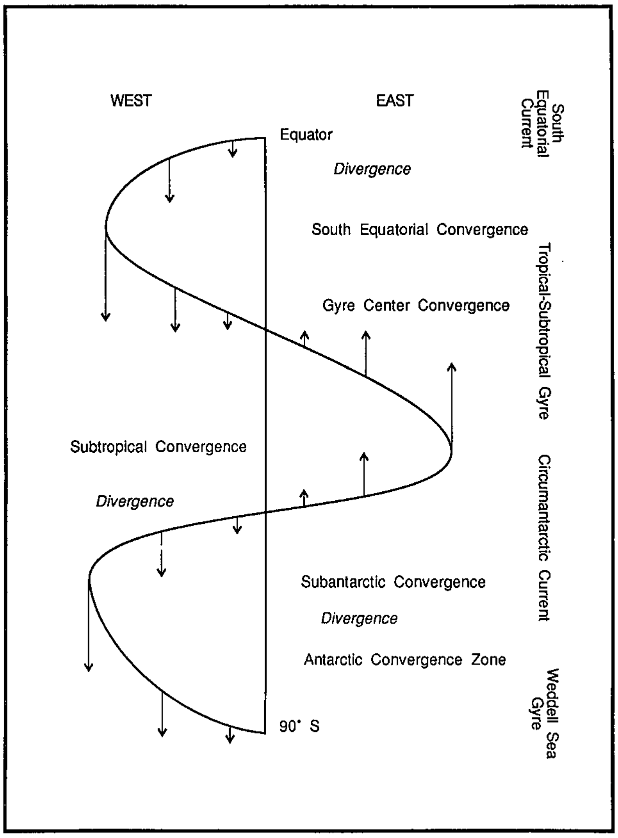

Fig. 3 — Schematic diagram of zonal (E-W) wind stress and meridional (N-S) Ekman transport of the surface mixed layer in the southern hemisphere. Relative magnitude of the zonal wind stress is indicated by the solid curve. Relative magnitude of the meridional Ekman transport is indicated by the length of the arrows. Major current systems and belts of convergence and divergence are indicated.

Salinities follow the precipitation-evaporation balance. They are lowest on the equator and in the Arctic (<34.0). The salinities in the centers of the tropical-subtropical gyres of the Atlantic reach >37.2. A body of water with intermediate temperature (12° to 4° C) and salinities of 34.0-34.5, termed Subantarctic Surface Water, occupies the region between the Subtropical and Antarctic Convergences or Fronts. The region includes an intermediate Subantarctic Convergence or Front.

Beneath the warmer waters of the tropical-subtropical gyres, the decline in temperature from 18° to 5° C defines the main oceanic thermocline; it occurs within and immediately below water masses termed the Central Waters of the oceans, shown in Fig. 4. Iselin (1939) suggested that the Central Waters form from water sinking in the region along the Subtropical convergence. The deeper part of the Central Waters in the South Atlantic, Indian and Pacific Oceans has temperatures and salinities characteristic of the Subantarctic Surface Waters (SASW) between the Subtropical and Antarctic Fronts.

The SASW between the Subantarctic and Antarctic Fronts is the surface outcrop of the lower part of the main ocean thermocline. The Antarctic Convergence, also known as the Antarctic Polar Front, separates the SASW from the cold, nearly isothermal (-1° to 3°), low salinity (<34.4) Antarctic Surface Water (AASW) that surrounds the continent. It was originally thought that the Subtropical, Subantarctic and Antarctic Convergences were well-defined and stable, but as more becomes known about the Southern Ocean it is increasingly apparent that they are highly variable in form and position. They are more properly systems rather than sites of convergence. Circumpolar Deep Water (CPDW), with temperatures from 0° to 2.5° C and salinities from 34.6 to 34.8 lies beneath the SASW.

Under the influence of the prevailing westerly winds that blow around the world at 50° S uninterrupted by topographic obstructions, the Antarctic Circumpolar Current (West Wind Drift) extends from the surface to the ocean floor and carries these waters from west to east; it has a zonal transport of about 150 Sv and a vertical transport of 70 Sv (Nowlin & Klinck, 1986). The rapid vertical motions mean that nutrient-rich waters have a short residence in the photic zone, and consequently only a small fraction of the nutrients (30%) are utilized by phytoplankton (Oeschger*et al.*, 1984) before being returned to the depths.

The cold, low salinity water sinking at the Antarctic Polar Front spreads northward beneath the main thermocline as Antarctic Intermediate Water (AAIW), as shown in Fig. 4. Its global volume flux is in the order of 10 Sv (1 Sv = 1 Sverdrup = $10^6 m^{-3} s^{-1}$) (Gordon & Taylor, 1975).

The two nearly circumglobal convergence systems of the southern hemisphere effectively isolate the circumantarctic water from the rest of the world's surface waters. As a result, the circumantarctic water has lesser density differences. During the winter, it develops an extensive cover of sea-ice, promoting the formation of Antarctic Bottom Water (AABW). The sea-ice breaks up and melts during the summer. The layer of AASW, best developed in the summer after melting of the ice pack, has temperatures between 0°and 4° C and salinities < 34.4. It may be up to 200 m thick. It is underlain by Antarctic Winter Water (AAWW) which is colder (down to -2° C) and has salinities < 34.5. AAWW may extend to the surface during winter.

Mediterranean Outflow Water (MOW) is the densest water entering a major ocean basin (Krause*t al.*, 1978). As it flows down the slope from the Straits of Gibraltar it entrains Atlantic interior water and the mixture spreads out at a depth of about 1.5 km as sterile Mediterranean Water (MW), shown in Figure 5. Some of this relatively warm saline water contributes to the formation of NADW in the GIN (Greenland-Iceland-Norwegian) Sea and in the interior of the North Atlantic (Reid, 1979; Peterson & Rooth, 1976; Broecker & Takahashi, 1980).

NADW, mixing with other waters along the way, returns to the surface in the Antarctic Divergence south of the Antarctic Polar Front. The fraction that goes north becomes slightly freshened by the excess of precipitation over evaporation but remains cold. At the Antarctic Convergence

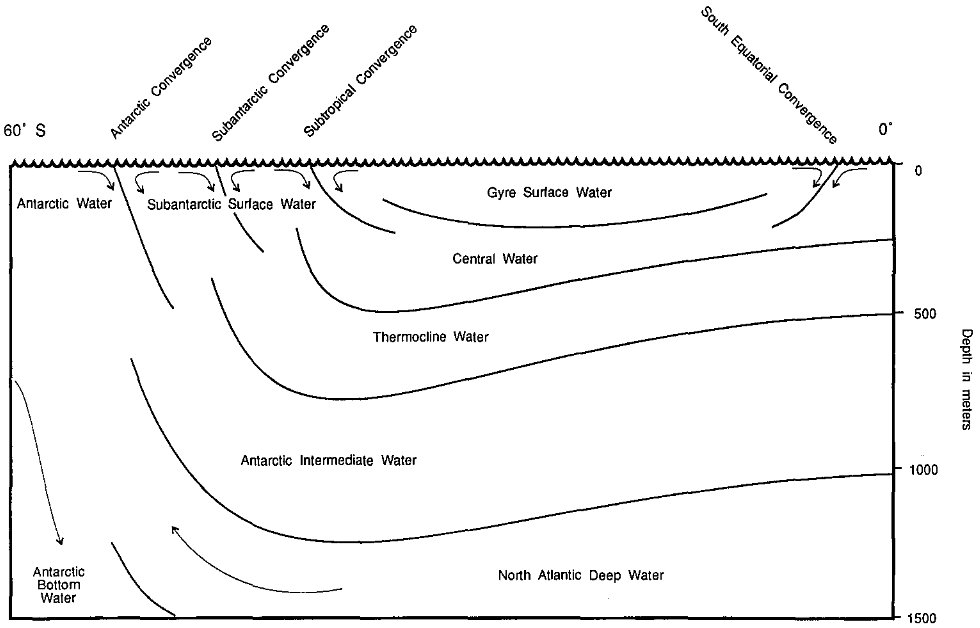

Fig. 4 — Schematic diagram of major water masses in the upper part of the South Atlantic Ocean, showing their relation to major surface convergences.

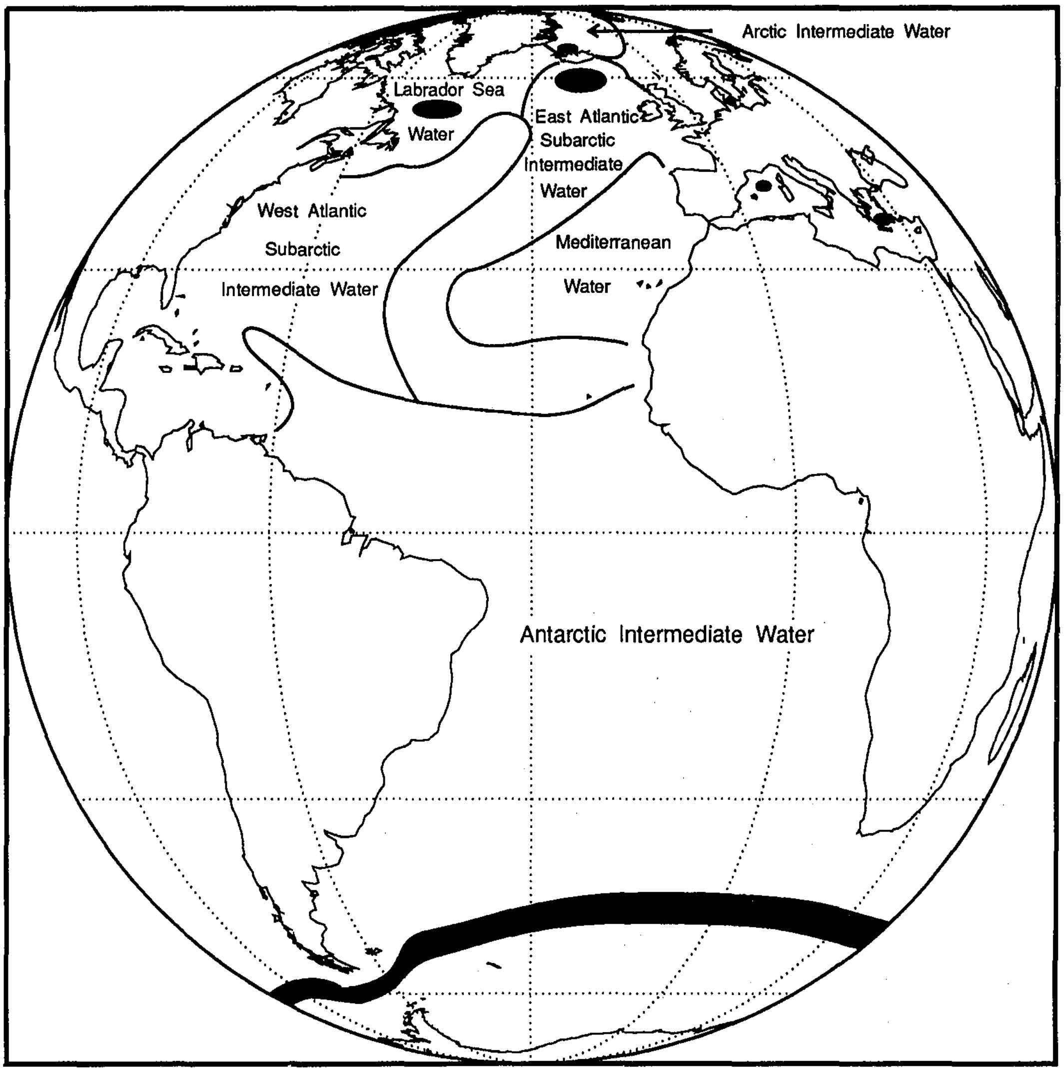

Fig. 5 — Major intermediate water masses of the Atlantic Ocean. Their sources are indicated by black ellipses or bands (after Brown *et al.*, 1989, modified).

it sinks beneath the SASW to form AAIW. This South Atlantic AAIW is the ultimate source of the nutrients upwelled along the Namibian margin. Its core is deepest, 900 m, at 30° S, and gradually rises to 650 m at 20° S off southwest Africa. The fraction of NADW that flows south becomes involved in the formation of Antarctic Bottom Water (AABW).

THE LONG- AND SHORT-TERM CHANGES IN PRODUCTIVITY

Because of the greater meridional temperature gradients, it is generally assumed that winds were stronger during the glacials and weaker during the interglacials, and it follows that wind-driven upwelling should be stronger during glacials. In fact, in most upwelling regions biological productivity did increase during glacials (Pedersen and Calvert, 1990) as a direct result of the increased wind stress. A number of authors had assumed that upwelling increased off southwest Africa during the glacials (CLIMAP, 1976; Morley & Hays, 1979; van Zinderen-Bakker, 1980), but Diester-Haass (1985a, 1985b, 1988), Diester-Haass *et al.* (1986, 1990), and Diester-Haass & Rothe (1987) found that although the accumulation of opaline silica is greatest during glacials in the sediments more than 5.2 m.y. old, the accumulation of opaline silica is greatest during the interglacials of Pliocene and Quaternary. Since the Messinian the South Atlantic has behaved differently from most upwelling areas.

Hay & Brock (1992) suggested that the decrease in productivity over Walvis Ridge during glacials could be

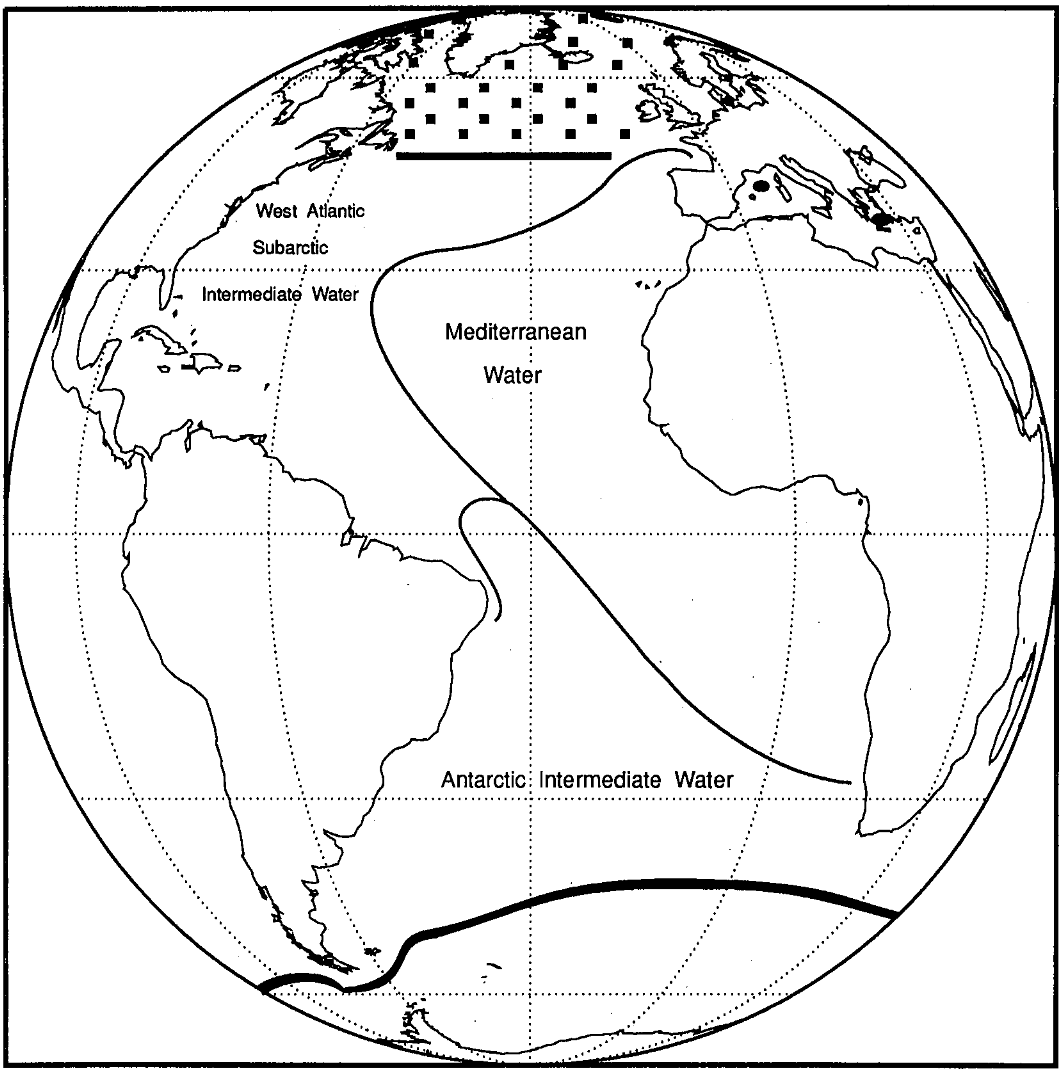

Fig. 6 — Speculative distribution of major intermediate water masses of the Atlantic Ocean during glacial maxima. Permanent sea-ice cover of the northern North Atlantic and GIN Seas indicated by CLIMAP (1976) is indicated by squares. Sources of intermediate water masses are indicated by black bands.

explained in terms of upwelling of less nutrient-rich waters. This could result from replacement of the subthermocline AAIW with a less nutrient-rich intermediate water mass.

CHANGES IN THE NUTRIENT CONTENT OF THE UPWELLED WATER

The major intermediate water masses of the Atlantic Ocean are shown in Fig. 5, along with their sites of formation. Arctic Intermediate Water (AIW) forms in the Arctic and GIN Seas and enters the North Atlantic through the Denmark Strait between Greenland and Iceland. Eastern Atlantic Subarctic Intermediate Water (EASIW) forms from mixtures of water overflowing the Iceland-Scotland Ridge. Labrador Sea Water (LSW) forms in the cyclonic gyre of the Labrador Sea during the winter. Mediterranean Water (MW) is formed by the warm, saline outflow of the Mediterranean mixing with ambient waters of the North Atlantic. Western Atlantic Subarctic Intermediate Water (WASIW) is a mixture of these other North Atlantic Intermediate Water Masses. The largest intermediate water mass in the Atlantic Ocean is AAIW that forms along the Atlantic sector of the circumglobal Subantarctic Front.

The northern and southern Atlantic intermediate waters differ markedly in their nutrient content. The North Atlantic Intermediate Water masses are all nutrient-poor because their sites of formation are far from sites of upwelling, and most of the nutrients have been utilized and already returned to the subpycnocline water by settling as particulate material before the intermediate waters are formed. The most nutrient-depleted water in the North Atlantic is that flowing from the Strait of Gibraltar, MW. AAIW is nutrient-rich because, forming at the Antarctic Front, it includes at its source SASW and Antarctic Circumpolar Water (AACW) that have high preformed (unused) nutrient content (Oeschger *et al.*, 1984; Hay, 1993).

The rate of production of NADW decreases during glacials (Boyle & Keigwin, 1982, 1987; Broecker *et al.*, 1985; Boyle, 1992). Hay & Brock (1992) speculated that if the rate of formation of NADW were reduced, the production of both AAIW and AABW would also slow because NADW mixing into the Antarctic Circumpolar Current and upwelling off the Antarctic promotes their formation. In retrospect, other factors remaining constant, it is more likely that a reduction of production of NADW would reduce the production of AABW which depends on a higher salinity for its formation, and enhance the production of AAIW which is a low salinity water mass. Seasonal sea-ice formation plays a critical role in the formation of NADW at present (Hay, 1993). The reduction of production of NADW is readily understood as a response to permanent ice cover of the GIN Sea and northern North Atlantic, as shown in Figure 6.

Less is known about the circulation of the Mediterranean during glacials. Because of the cooler temperatures and larger fresh water input, the Mediterranean must have a less strongly negative fresh water balance during glacials. This implies that MOW would not be as dense as it is presently, and would not sink as deeply before spreading laterally. The inflow and outflow of water into the Mediterranean Basin is directly related to the fresh water balance, and because of the less negative fresh water balance during a glacial, these flows would be reduced. At present, MOW sinks to a level below the core of AAIW, but during glacials it may more directly compete for the level immediately beneath the Central Waters of the tropical-subtropical gyres and spread over a much larger area as suggested in Figure 6.

The mode of formation of MOW is fundamentally different from that of AAIW. MOW is generated by differentiation of inflowing Atlantic water through the excess evaporation and the cool winter climate in the Mediterranean basin. It is introduced into the North Atlantic at a single point, the Straits of Gibraltar. In contrast, AAIW is formed by convergence of SASW and AACW along the circumglobal Subantarctic Front.

At present AAIW is characterized by low salinities (34.2) and cold temperatures (2-4° C). Its formation involves dilution of upwelling NADW by the large excess of precipitation over evaporation between 40° and 50° S. As suggested above, if other conditions remained equal and the production of NADW were reduced, the dilution could cause the production of AAIW to increase. However, the general reduction of planetary temperatures during the glacial (Emiliani & Ericson, 1991) would result in lessened precipitation over the southern South Atlantic, and this would likely outweigh the effect of reduced NADW production to result in overall reduced production of AAIW during glacials.

Boyle & Keigwin (1987) found that the Cd/Ca ratio in the Caribbean Sea was significantly less during the last glacial than it is today. The Antillean barrier prevents NADW and AABW from entering the Caribbean, so that it is filled by AAIW and WASIW. The data of Boyle and Keigwin (1987) can be interpreted as suggesting that either AAIW in the South Atlantic was nutrient depleted during the last glacial, or that off the Antilles it was replaced by a nutrient-poor intermediate water mass, possibly MW.

MAJOR PALEOGEOGRAPHIC/ PALEOCLIMATIC CHANGES THAT MIGHT AFFECT INTERMEDIATE WATER PRODUCTION

The Messinian salinity event

During the late Miocene the Mediterranean Basin dried up and at the beginning of the Pliocene filled again with seawater (Hsü *et al.*, 1977; Cita & McKenzie, 1986). While the Mediterranean basins were dry, the Intertropical Convergence Zone (ITCZ) moved north of the present Sahara to 30° N paleolatitude during northern hemisphere summers (Thiedemann *et al.*, 1989; Ruddiman *et al.*, 1989).

At the end of the Messinian upwelling of nutrient-rich waters at the Walvis Ridge Abutment Plateau shifted from maxima during glacials to maxima during interglacials. The coincidence between reflooding of the Mediterranean and the change to maximally productive upwelling during interglacials suggest cause and effect.

According to Rio *et al.* (1990) the Mediterranean had a positive fresh water balance and estuarine circulation until 2.5 Ma. During this time the outflow was on the surface and there was no Mediterranean intermediate water mass in the North Atlantic. In the latest Pliocene the fresh water balance became negative and the present lagoonal circulation was established (Rio *et al.*, 1990). The Mediterranean became a major source of warm saline intermediate water, Mediterranean Water, for the North Atlantic. The Mediterranean outflow, by increasing the salinity of the North Atlantic, enhanced the production of North Atlantic Deep Water, growth of the Antarctic ice cap, and onset of northern hemisphere glaciation.

The onset of Northern Hemisphere glaciation

Flohn (1979) suggested that when the planet had a single ice-covered pole, the contrast between the meridional temperature gradients of the two hemispheres would be greater than it is today. The effect of high ice sheets is to cause a stronger pressure gradient in the troposphere displacing the Intertropical Convergence Zone (ITCZ) into the less glaciated hemisphere. Today the mean annual

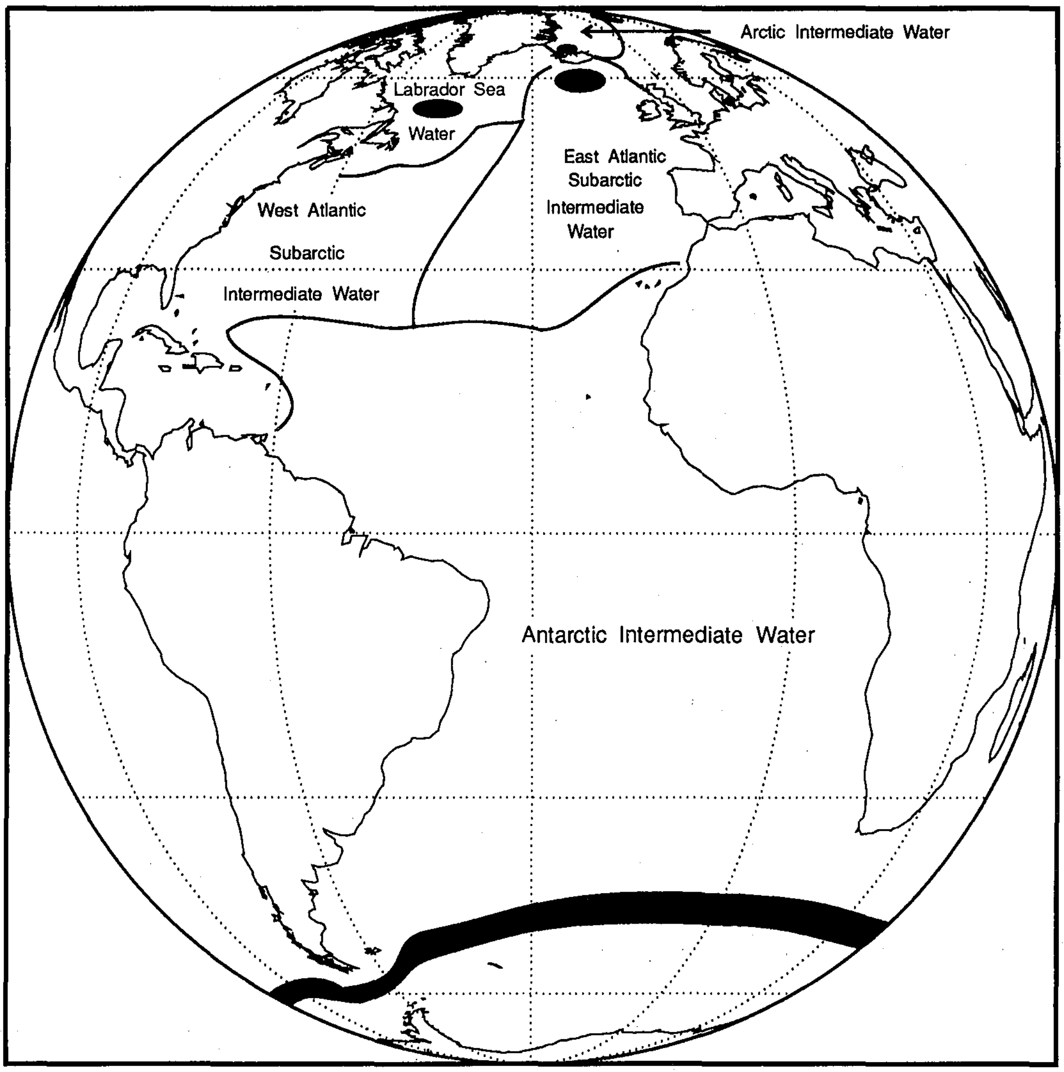

Fig. 7 — Speculative distribution of major intermediate water masses of the Atlantic Ocean during most of the Pliocene when the Mediterranean had a positive fresh-water balance and estuarine circulation providing no dense saline outflow into the Atlantic.

position of the ITCZ (= thermal equator) is about 6° N, and the belt of subtropical highs of the northern hemisphere lies at a higher latitude than that of the southern hemisphere. Prior to 3.4 Ma, the Earth had unipolar glaciation centered on the South Pole and Flohn speculated that the thermal equator lay at about 10° N.

The onset of northern hemisphere glaciation 3.4 million years ago, with periodic formation of ice caps over eastern North America, Scandinavia and Siberia, changed the configuration of the Earth to one having bipolar ice. Since 2.5 Ma the northern hemisphere has alternated between glacial conditions with three 2 km thick ice caps centered on 60° N. During the interglacials only Greenland has an ice cap but sea-ice covers the Arctic Ocean. Flohn (1984) has suggested that these changes would result in a change of the meridional temperature gradients, causing a shift of the ITCZ from its more northerly position during the time of unipolar glaciation to its present average position of 6° N.

For the southwest African coast, the expected effect of the transition from unipolar to bipolar glaciation would be southward migration of the subtropical high over the South Atlantic, strengthening of the longshore wind, and enhanced upwelling. Siesser (1980) concluded that the increased organic carbon and opaline silica content of the sediments since the Miocene reflected the development of a strong southeast trade wind system. This essentially corresponds to Flohn's analysis of what could be expected from the unipolar-bipolar transition.

Closure of the Central American straits

Maier-Reimer *et al.* (1990) used an ocean general circulation model driven by present winds to examine the effect of closure of the Central American Straits. They found that with an open Central American Strait the present slope of the North Atlantic sea surface, a difference of 0.8 m between the Caribbean and the GIN Sea, would disappear. This would greatly reduce the strength of the Gulf Stream. Large scale mixing of Atlantic and Pacific waters would lower the salinity of the Atlantic so that there would be no production of North Atlantic Deep Water.

The coincidence of gradual closure of the Central American Straits and the increase of upwelling intensity on Walvis Ridge Abutment Plateau suggests cause and effect but the relation is probably indirect, through increasing production of North Atlantic Deep Water as salinization of the North Atlantic took place. The increased production of NADW in turn increased the production of AAIW and AABW.

A possible sequence of events

Until the end of the Messinian, the South Atlantic was similar to the South Pacific. The only intermediate water mass was AAIW. The ITCZ was drawn far into the northern hemisphere by desiccation of the Mediterranean, so that waxing and waning of the Antarctic Ice Sheet did not affect its position. The "glacial-interglacial" response of upwelling along the southwest African margin was "normal", with intensification of upwelling of nutrient-rich waters during the glacials.

From the end of the Messinian until 2.5 Ma, the Mediterranean had a positive fresh-water balance and did not contribute intermediate water to the North Atlantic. At the same time, the increasing restriction of the Central American Strait resulted in gradual salinization of the North Atlantic and initiation of the production of NADW from waters flowing over the Greenland-Scotland Ridge. The NADW formed from nutrient-depleted waters, and the effect of its formation and southward flow was to export nutrients from the North Atlantic. This started the "conveyor belt" of Broecker *et al.* (1985), removing nutrients from the North Atlantic and concentrating them in AAIW and AABW. A possible distribution of the intermediate water masses during the time when there was no saline Mediterranean outflow is shown in Figure 7.

At 2.5 Ma the Central American Strait was closed, and the salinization of the North Atlantic increased. Also, at 2.5 Ma the Mediterranean changed from a positive to a negative fresh water balance. The Mediterranean outflow introduced additional salt to the North Atlantic, further enhancing the production of NADW. The increased salinity of the North Atlantic may have played the critical role in the full-scale glaciation of the northern hemisphere by promoting the transport of warm waters to the high latitudes of the GIN Sea where they could supply moisture to feed the growing ice sheets. The increased Mediterranean outflow introduced a major nutrient-depleted water mass into the Atlantic which could compete with the AAIW. During glacials, the Mediterranean water, being relatively less dense than during interglacials, could compete directly with the weakened flow of AAIW and perhaps penetrate far enough south to replace it along the African margin, as suggested in Figure 6.

SUMMARY AND CONCLUSIONS

The changes in productivity recorded at DSDP Site 532 reflect changes in the nutrient content of the upwelled waters. The upwelled waters are presently derived from AAIW, but in the past these may have been replaced by more sterile intermediate water masses formed in the North Atlantic or by Mediterranean outflow.

Three major paleogeographic changes may have produced the changes in oceanic intermediate water formation: 1) the Messinian desiccation of the Mediterranean that ended 5.2 Ma with its reflooding; 2) the onset of northern hemisphere glaciation at 3.4 Ma and intensification at 2.5 Ma; and 3) the gradual closure of the Central American Straits that finally severed the connection between the Atlantic and Pacific at 2.5 Ma.

From the end of the Messinian until 2.5 Ma the Mediterranean had a positive fresh-water balance and estuarine circulation. The dense saline outflow that produces the MW of the North Atlantic did not start until 2.5 Ma when the fresh water balance of the Mediterranean changed from positive to negative and the circulation switched from estuarine to lagoonal.

The production of NADW can be expected to have begun as salinization of the North Atlantic occurred in response to the gradual closing of the Central American Straits, and to have increased markedly as the Mediterranean began to supply saline water to the North Atlantic. NADW exports nutrients from the North Atlantic and creates the contrast between nutrient-rich southern and nutrient-depleted northern intermediate and deep water masses.

The development of northern hemisphere glaciation has strongly affected the production of northern intermediate waters and NADW. During glacials the nutrient-depleted northern intermediate waters may have replaced AAIW along the southwest African margin. Relatively less dense MW formed during glacials could compete directly with AAIW as the major subthermocline water mass. Production of AAIW may have been curtailed during glacials by the lower precipitation on the sea surface resulting from the lower planetary temperature.

Recommendations for further study

More cored sequences penetrating to the Middle Miocene are required to solve the problem of changes in productivity in the South Atlantic. These should include sites to the south and to the north of Walvis Ridge. Studies such as those of Girardeau (1992, 1993) on the Namibian shelf need to be extended to older units to evaluate patterns of productivity and to determine whether the lower productivity during glacials is a regional phenomenon.

A better understanding of the factors influencing the rates of production of intermediate water is essential. This may be best accomplished through sensitivity studies using atmospheric and ocean circulation models.

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REFERENCES

Boyle, E. A. (1992) - Cadmium and $\delta^{13}C$ paleochemical ocean distributions during the stage 2 glacial maximum. *Ann. Rev. Earth. Planet. Sci.*, 20: 245-287.

Boyle, E. A. & Keigwin, L. D. (1982) - Deep circulation of the North Atlantic over the last 200,000 years: geological evidence. *Science*, 218: 784-787.

Boyle, E. A. & Keigwin, L. D. (1987) - North Atlantic thermohaline circulation during the past 20,000 years linked to high-latitude surface temperature. *Nature*, 330: 35-40.

Broecker, W. S.; Peteet, D. M. & Rind, D. (1985) - Does the ocean-atmosphere system have more than one stable mode of operation?. *Nature*, 315: 21-26.

Brown, J.; Colling, A.; Park, D.; Phillips, J.; Rothery, D., & Wright, J. (1989) - Ocean Circulation. *Pergamon Press*, Oxford, 238 p.

Calvert, S. (1974) - Deposition and diagenesis of silica in marine sediment, *in* Hsü, K. J. & Jenkyns, H. C., eds., *International Association of Sedimentologists,* Special Publication 1, Pelagic Sediments. On Land and Under the Sea: 273-299.

Calvert, S. E. & Price, N. B. (1983) - Geochemistry in Namibian shelf sediments, *in* Suess, E. & Thiede, J. eds., NATO Conference Series, Series IV: Marine Sciences 10a, Coastal Upwelling, Its Sediment Record. Part A. Responses of the Sedimentary Regime to Present Coastal Upwelling. New York, *Plenum Press*: 337-375.

Cita, M. B. & McKenzie, J. A. (1986) - The terminal Miocene event, *in* Hsü, K. J., ed., Geodynamics Series, 15, Mesozoic and Cenozoic Oceans. Washington, D.C., *American Geophysical Union*: 123-140.

CLIMAP Project Members (1976) - The surface of the ice-age earth. *Science*, 191: 1131-1137.

Dean, W. E. & Gardner, J. (1985) - Cyclic variations in calcium carbonate and organic carbon in Miocene to Holocene sediments, Walvis Ridge, South Atlantic Ocean, *in* Hsü, K. J. & Weissert, H. J., eds., South Atlantic Paleoceanography. *Cambridge University Press*: 61-78.

Dean, W. E.; Hay, W. W. & Sibuet, J.-C. (1984) - Geologic evolution, sedimentation and paleoenvironments of the Angola Basin and adjacent Walvis Ridge: Synthesis of results of Deep Sea Drilling Project Leg 75, *in* Hay, W. W., Sibuet, J.-C., *et al.*, eds., *Initial Reports of the Deep Sea Drilling Project*: Washington, D.C., U.S. Government Printing Office, 75: 509-544.

Diester-Haass, L. (1978) - Sediments as indicators of upwelling, *in* Boje, R. & Tomczak, M., eds., Upwelling Ecosystems. *Springer-Verlag*, Berlin: 261-281.

Diester-Haass, L. (1985a) - Late Quaternary sedimentation on the eastern Walvis Ridge, SE Atlantic (HPC 532 and four piston cores). *Mar. Geol.*, 65: 145-189.

Diester-Haass, L. (1985b) - Late Quaternary upwelling history off southwest Africa (DSDP Leg 75, HPC 532), *in* Hsü, K. J. & Weissert, H. J., eds., South Atlantic Paleoceanography. *Cambridge University Press*: 47-55.

Diester-Haass, L. (1988) - Sea level changes, carbonate dissolution and history of the Benguela Current in the Oligocene-Miocene off southwest Africa. *Mar. Geol.*, 79: 213-242.

Diester-Haass, L., & Rothe, P. (1987) - Plio-Pleistocene sedimentation on the Walvis Ridge, southeast Atlantic (DSDP Leg 75, Site 532) - Influence of surface currents, carbonate dissolution and climate. *Mar. Geol.*, 77: 53-85.

Diester-Haass, L.; Meyers, P. A., & Rothe, P. (1986) - Light-dark cycles in opal-rich sediments near the Plio-Pleistocene boundary, DSDP Site 532, Walvis Ridge continental terrace. *Mar. Geol.*: 1-23.

Dietrich, G. (1957) - Ozeanographische Probleme der deutschen Forschungsfahrten im Internationalen Geophysikalischen Jahr 1957/58. *Deutsche Hydrographische Zeitschrift*, 10: 39-61.

Emiliani, C., & Ericson, D. B. (1991) - The glacial/interglacial temperature range of the surface water of the oceans at low latitudes: *in* Taylor, H. P. Jr.; O'Niel, J. R. & Kaplan, I. R., eds., Stable Isotope Geochemistry. A Tribute to Samuel Epstein. *The Geochemical Society,* Special Publication No. 3: 223-228.

Flohn, H. (1979) - Possible climatic consequences of a man-made global warming: energy systems analysis, *in International Conference on Energy Systems Analysis, Proceedings*, Dublin: 558-568.

Flohn, H. (1984) - Climatic belts in the case of a unipolar glaciation, *in* Mörner, N. A. & Karlen, J., ed., Climatic Changes on a Yearly to Millennial Basis, Proceedings of the Second NATO Symposium on Climatic Changes and Related Problems, Dordrecht, *D. Reidel*: 609-620.

Gardner, J. V.; Dean, W. E. & Wilson, C. R. (1984) - Carbonate and organic carbon cycles and the history of upwelling at Deep Sea Drilling Project Site 532, Walvis Ridge, South Atlantic Ocean, *in* Hay, W. W., Sibuet, J.-C. *et al.*, eds., *Initial Reports of the Deep Sea Drilling Project*, Washington, U.S. Government Printing Office, 75: 905-921.

Girardeau, J. (1992) - Distribution of Recent nannofossils beneath the Benguela system: southwest African continental margin. *Mar. Geol.*, 108: 219-237.

Girardeau, J. (1993) - Planktonic foraminiferal assemblages in surface sediments from the southwest African continental margin. *Mar. Geol.*, 110: 47-62.

Gordon, A. L. & Bosley, K. T. (1991) - Cyclonic gyre in the tropical South Atlantic. *Deep-Sea Res.*, 38, suppl. 1A: S323-S343.

Gordon, A. L. & Taylor, H. W. (1975) - Heat and salt balance within the cold waters of the world ocean, *in* Numerical Models of Ocean Circulation, Washington, D. C., *National Academy of Sciences*: 54-56.

Hagen, E.; Schemainda, R.; Michelsen, N.; Postel, L.; Schulz, S. & Below, M. (1981) - Küstensenkrechten Struktur des Kaltwasserauftriebs vor der Küste Namibias: *Geodätische und geophysikalische Veröffentlichungen*, 36: 1-99.

Hart, T. J. & Currie, R. T. (1960) - The Benguela Current: *Discovery Reports*, 31: 123-298.

Hay, W. W. (1993) - The role of polar deep water formation in global climate change. *Ann. Rev. Earth Planet. Sci.*, 21: 227-254.

Hay, W. W. & Brock, J. C. (1992) - Temporal variation in intensity of upwelling off southwest Africa, *in* Sumerhayes, C. P.; Prell, W. L. & Emeis, K. C., eds., *Geological Society* Special Publication 63, Upwelling Systems. Evolution Since the Early Miocene: 463-497.

Hay, W. W.; Sibuet, J.-C. *et al.* (1984) - Site 532, Walvis Ridge, *in* Hay, W. W.; Sibuet, J.-C. *et al.*, eds., *Initial Reports of the Deep Sea Drilling Project*, 75. Washington, D.C., U.S. Government Printing Office: 295-445.

Hsü, K. J.; Montadert, L.; Bernoulli, D.; Cita, M. B.; Erikson, A.; Garrison, R. B.; Kidd, R. B.; Melieres, F.; Müller, C. & Wright, R. (1977) - History of the Mediterranean salinity crisis. *Nature*, 267: 399-403.

Iselin, C. O'D. (1939) - The influence of vertical and lateral turbulence on the characteristics of the waters at mid-depths. *Transactions of the American Geophysical Union*, 20: 414-417.

Kraus, E. B.; Petersen, W. H. & Rooth, C. G. (1978) - The thermal evolution of the ocean, *in* International Conference, Evolution of Planetary Atmospheres and Climatology of the Earth. *Centre national d'etudes spatiales (France)*: 201-211.

Maier-Reimer, E.; Mikolajewicz, U. & Crowley, T. (1990) - Ocean general circulation model sensitivity experiment with an open Central American isthmus. *Paleoceanography*, 5: 349-366.

Morley, J. J. & Hayes, J. D. (1979) - Comparison of glacial and interglacial oceanographic conditions in the South Atlantic from variations in calcium carbonate and radiolarian distributions. *Quaternary Research*, 12: 396-408.

Nowlin, W. D. Jr. & Klinck, J. M. (1986) - The physics of the Antarctic Circumpolar Current. *Rev. Geophys. Space Phys.*, 24: 469-491.

Oeschger, H.; Beer, J.; Siegenthaler, U.; Stauffer, B.; Dansgaard, W. & Langway, C. C. (1984) - Late glacial climate history from ice cores, *in* Hansen, J. E. & Takahashi, T., eds., Geophysical Monograph 29, Maurice Ewing, 5, Climate Processes and Climate Sensitivity: Washington, D.C., *American Geophysical Union*: 299-306.

Pedersen, T. F. & Calvert, S. (1990) - Anoxia vs. productivity: What controls the formation of organic-carbon-rich sediments and sedimentary rocks?. *AAPG Bull.*, 74: 454-466.

Peterson, W. H. & Rooth, C. (1976) - Formation and exchange of deep water in the Greenland and Norwegian seas. *Deep-Sea Res.*, 23: 273-283.