Glacial-interglacial oceanography of the southeastern atlantic Ocean and the paleoclimate of west central Africa

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SUMMARY : The sediments of the NE Angola basin are siliceous oozes, rich in organic carbon. They are subdivided in pelagic and hemipelagic deposits, turbidites and debris-flow deposits. The calcium carbonate concentrations are primarily controlled by dissolution, but reflect also periods of high primary production. Biogenic opal is abundant because it has unusually high Al concentrations, which reduces its solubility. The surface hydrography is reflected by the distribution of marine diatoms, planktonic Foraminifera and Radiolaria.

Downcore studies of microfossils and oxygen isotopes indicate that during glacial periods the surface waters were somewhat colder than today. The coastal branch of the Benguela Current penetrated deeper into the region, causing coastal and oceanic upwelling and increase of primary production as is demonstrated by investigations of microfossils and biogenic opal.

During glacials, the mass accumulation rates were high due to a large terrigenous input which reflects continental aridity in tropical Africa. The fluvial supply of kaolinite and poorly crystallized smectite decreased in favour of well crystallized smectite, a product of more arid weathering, and eolian illite from the south, probably the Namibian desert. This source produces also phytoliths. The Zaïre River, on the contrary, supplies both phytoliths and freshwater diatoms. Therefore, the ratio of phytoliths to freshwater diatoms is regarded as an aridity index. For the last 20 ky it corresponds closely with the known climatic events in Africa. In general, the paleoclimatic signals above indicate aridity during glacial stages.

A long-term change, about 400-350 ky BP, from more arid to more humid conditions forms the expression of the global mid-Brunhes climatic shift.

I - INTRODUCTION

The Atlantic Ocean off west central Africa is a complex region with a variety of sometimes interdependent environmental processes. The surface hydrography is dominated by the east equatorial circulation system. Superimposed on this system is the influence of the Zaïre or Congo River which supplies freshwater, nutrients and sediments to the ocean. As a result the sediments contain messages of both the marine and the continental environment, and offer the opportunity to combine oceanographic and climatic information. The deep-sea sediments, therefore, are a potential source of knowledge of the climate of the adjacent part of Africa.

This contribution gives a brief outline of the hydrography and geology, and a description of the recent sedimentation in relation to oceanic phenomena and terrigenous signals. Hereupon follows an overview of the applications of the knowledge of the actual processes to the Quaternary glacial-interglacial paleoceanography and paleoclimate.

II - HYDROGRAPHY AND GEOLOGICAL OUTLINE

1°) Hydrography

The south equatorial Atlantic environment off Africa is greatly influenced by the presence of the river Zaïre, or Congo. Draining an area of 3.7 million km^2, the greater part of equatorial Africa, the Zaïre River is the second largest river in the world with an average yearly discharge of 1.3 x 10^{12} m^3 y^{-1} (Eisma and Van Bennekom, 1978 ; Peters, 1978). A plume of Zaïre water stretches 800 km westward into the Atlantic Ocean (fig. 5a). Below and around the plume, the (sub)surface water circulation is controlled by the interaction of three major currents, the northward Benguela Current, deflected westward at 20°S by the eastward South Equatorial Counter Current and Equatorial Under Current (sometimes called Lomosonov Current), which causes a

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complicated pattern of fronts, gyres and domes (Van Bennekom and Berger, 1984). Coastal branches of the Benguela Current continue northward, in May at least to 13°S and during the southern winter even further north (Giresse, 1980 ; Van Bennekom and Berger, 1984).

Nutrient-rich shallow subsurface water is brought into the euphotic zone, especially south of the Zaïre plume, resulting in an increase in primary production. The shelf is incised by a deep submarine canyon which is unique in that it has eroded back into the estuary. In the river mouth it is over 400 m deep, which gives ocean water easy access to the narrow estuary. This configuration forces a rapid outflow of river water in a thin, sharply bounded turbid layer 10 m thick (Eisma and Van Bennekom, 1978) and causes a displacement of the river-induced phytoplankton production to a narrow zone outside the estuary in waters with salinities of about 30 ‰ (Van Bennekom et al., 1978 ; Cadée, 1978 ; Cadée, 1984).

The deep water circulation of the Angola Basin is distinguished from the circulation in the other Atlantic oceanic basins by the near absence of Antarctic Bottom water (AABW) which is supplied in only small amounts over the sills in the Romanche Fracture Zone from the north and in Walvis Ridge from the south (Van Bennekom and Berger, 1984).

2°) Zaïre sediment supply

The sediment supply of the Zaïre River is partly in the form of suspended matter : the total flux is estimated at 31 x 10^9 kg y^{-1} (Gibbs, 1967) to 40 x 10^9 kg y^{-1} (Eisma and Kalf, 1984), organic matter included. From the suspension data by Eisma and Kalf an inorganic supply to the ocean floor of 14-29 x 10^9 kg y^{-1} can be calculated, of which less than 11 x 10^9 kg y^{-1} reaches the deep ocean via the Zaïre low-salinity plume. In the estuary 14-18 x 10^9 kg y^{-1} settles and joins the river bed load. This bed-load is estimated at 50 x 10^6 m3 y^{-1} by Peters (1978), and from his data I calculated this volume to be equivalent to 13 x 10^9 kg y^{-1} of dry sand. These two amounts of bed load, together about 30 x 10^9 kg y^{-1}, are eventually transported into the Angola Basin through the canyon, fan channels and deep waters by turbidity currents and bottom nepheloid layers (Jansen et al., 1984b ; Pak et al., 1984 ; Van Weering and Van Iperen, 1984). The total sediment flux to the deep ocean, estimated from the transport measurements in the river and estuary, is therefore 30-40 x 10^9 kg y^{-1}. This amount is to be compared with a Holocene mass accumulation rate (MAR) of inorganic material calculated from the data in Jansen et al. (1984b) of about 4 x 10^9 kg y^{-1} (free of carbonate and biogenic opal). No satisfactory explanation is available for this difference. Regarding the pattern of the MAR isolines (fig. 1) it seems improbable that only

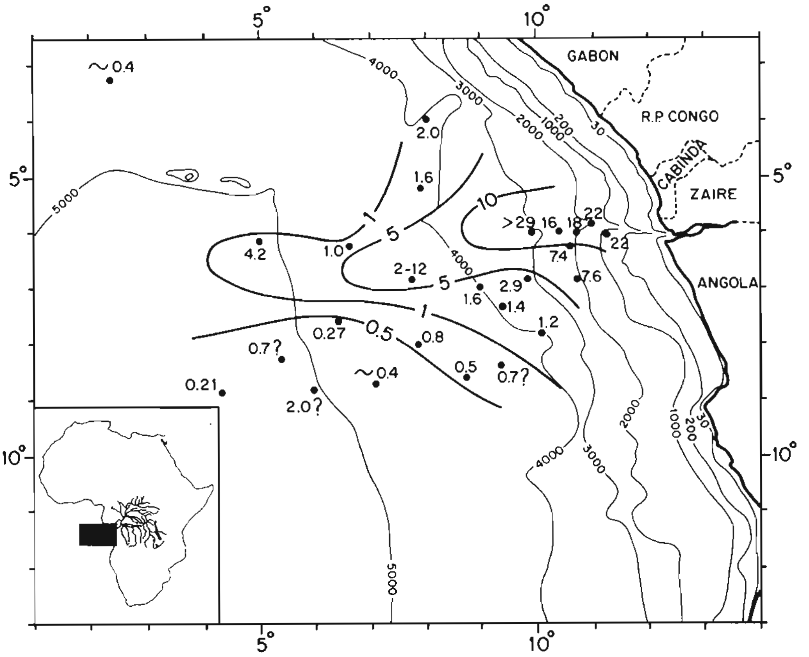

Figure 1 : Recent non-carbonate mass accumulation rates (g cm^{-2} ky^{-1}) in the Zaïre deep-sea fan area (Jansen et al., 1984b ; Jansen et al., 1989).

about 10% of Zaïre River sediment is being deposited in the deep-sea fan. It may be that the river data, which were yielded from instantaneous surveys, are not representative for the last several thousands of years which are mirrored in the fan data.

A significant portion of the Zaïre suspended sediment load is carried to the northwest by longshore drift resulting from dominant ocean waves from southwestern directions, and is subsequently deposited on the Cabinda Congo-Gabon continental shelf (Giresse et al., 1981 ; Jansen et al., 1984a ; Moguedet, 1988 ; Giresse et al., this volume, p. 71). It is estimated that more than 8 x 10^9 kg y^{-1} of inorganic material follows this path (Eisma and Kalf, 1984).

3°) Geological outline

At about 2700 m water depth the canyon merges into a typical fan valley, and the sediment supplied by the river has built a deep-sea fan extending over 1000 km westward into the Angola Basin (Heezen et al., 1964 ; Shepard and Emery, 1973). The maximum age of the fan is determined by the initial opening of the South Atlantic Ocean, where the oldest oceanic crust, identified near South Africa, is of Early Cretaceous age or 130 My old (Larson and Ladd, 1973 ; Rabinowitz, 1976 ; Rabinowitz and La Brecque, 1979). At the latitude of the Zaïre fan the spreading of the ocean floor started a few My later (Ojeda, 1982). In the young ocean north of Walvis Ridge and Rio Grande Rise it was followed by important salt accumulation during the Middle Aptian, which later resulted in extensive zones of diapiric structures along the continental margins of Angola, Zaïre, Cabinda, Congo and Gabon in the east and Brazil in the west (Rabinowitz and La Brecque, 1979 ; Reyment, 1980).

The deposition in front of the Zaïre River mouth was greatest in the period following the opening of the ocean; 40% of the total post-salt sequence dates to the Albian (108 My to 95 My BP) and 70% of the sediments were already supplied before the Cretaceous-Tertiary transition 66 My BP (Jansen, 1985a). Hiatuses occur in the Cenomanian deposits, at the Cretaceous Tertiary boundary, and in the Late Eocene-Oligocene and Late Miocene deposits. The latter three hiatuses are correlated with unconformities on the shelf which separate seismic units of different tectonic character (Jansen et al., 1984a ; Jansen, 1985a). The correlation indicates that the hiatuses were at least partly caused by large-scale tectonic processes in west equatorial Africa and not exclusively by low global sea levels (Vail et al., 1977).

III - RECENT SEDIMENTATION

1°) Sedimentary structures

The sediments of the fan region are siliceous oozes, rich in organic carbon (up to 5% weight), and with an inorganic component that mainly consists of terrigenous clay minerals (Jansen et al., 1984b ; Van der Gaast and Jansen, 1984 ; Jansen, 1985b).

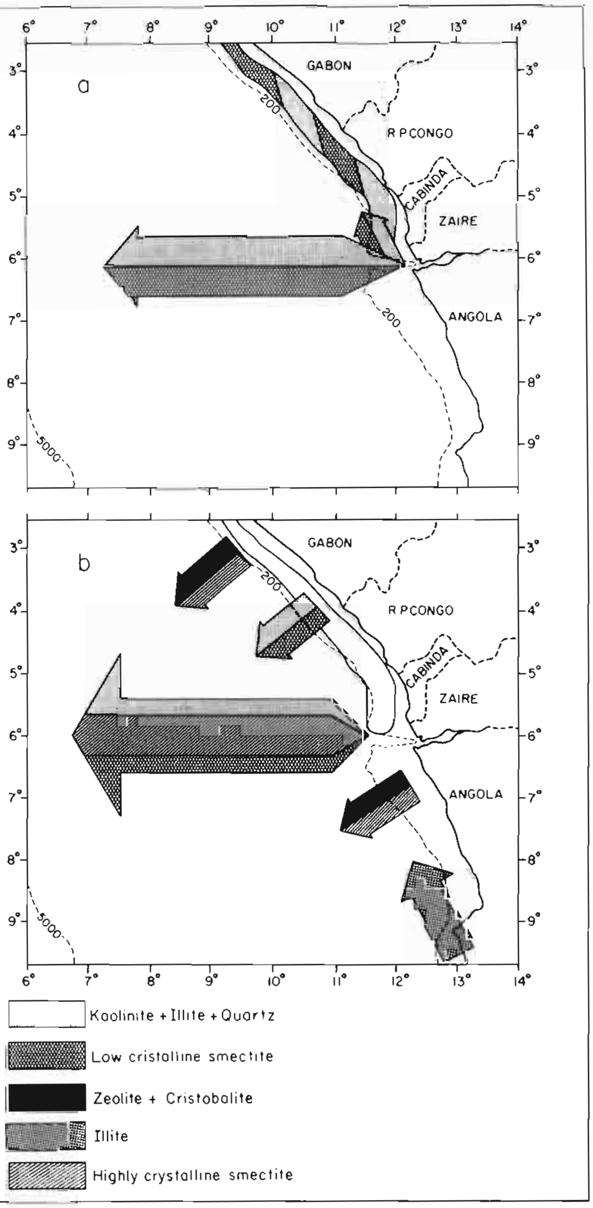

Figure 2 : Model of mineral deposition in the region of the Zaïre deep-sea fan (Van der Gaast and Jansen, 1984) ; a : During Holocene and interglacial times ; b : During glacial times.

Based on the sedimentary structures, the surface sediments can be divided into : (1) fine-grained turbidites, located in the central fan area and roughly coinciding with the lobe of mass accumulation rates larger than about 5 g cm^{-2} ky^{-1} (fig. 1), (2) pelagic and hemipelagic deposits, on the continental slope, in the outer fan and at greater depths (included the homogeneous deposits named by Van Weering and Van Iperen, 1984) and (3) debris-flow deposits, as found in a core from the upper fan near the canyon mouth. The turbidites comprise thinly laminated silts and graded and ungraded silts (carbonate particles included) and clays, the inorganic component of the hemipelagic and pelagic deposits consists almost entirely of clay particles < 2 µm (Jansen et al., 1984b; Van Weering and Van Iperen, 1984).

In all these deposits ichnofossils, or trace fossils occur, structures produced by the boring and trailing activity of benthic organisms. Different associations of these ichnofossils are found to be characteristic of hemipelagic deposits on the shelf and slope or deposits of greater depths. If the turbidites are thicker than 8 cm, they may kill all borrowing organisms. The ichnofossil associations show that after the passage of a lethal turbidite complete recolonisation will take about 1000 years (O.P. Werver and P.J. Pestman, unpublished data).

2°) Terrigenous and shelf-derived deposits

The surface sediments are an admixture of oceanic, terrigenous and shelf deposits (fig. 2a). The terrigenous components are well recognized in the turbidites which show that the supply from the Zaïre River consists of kaolinite, poorly crystallized smectite, quartz and minor amounts of illite/ mica and gibbsite (Van der Gaast and Jansen, 1984). Another source of illite in the Angola Basin is atmospheric dust originating from the Namibian desert (Bornhold and Summerhayes, 1977; Van der Gaast and Jansen, 1984), dust which is also recognizable by its Sr and Rb isotope composition (Biscaye et al., 1974). The continental shelf is the source of well cristallized smectite and admixtures of zeolite and cristobalite originating from Tertiary opal-rich layers (Van der Gaast and Jansen, 1984 ; Moguedet, 1988 ; Giresse et al., this volume, p. 71 ; Giresse and Kouyoumontzakis, this volume, p. 106). The radioisotope ^{10}Be is generally regarded as of oceanic origin, its settling being mainly controlled by biologic scavenging (Mangini et al., 1984). There is, however, a significant linear relation between ^{10}Be accumulation rates and terrigenous mass accumulation rates, which indicates that there is also a terrigenous source of ^{10}Be. The relation is best explained by a terrigenous ^{10}Be supply modified by biologic scavenging (Jansen et al., 1987a).

Organic components of continental origin are fresh-water diatoms, phytoliths, plant fragments and organic matter with δ13C values to -27 ‰ (Jansen et al., 1984b ; Mikkelsen, 1984 ; Van Iperen et al., 1987 ; Gasse et al., 1988 ; Jansen et al., 1989). The terrigenous carbon arrives at the ocean floor with a delay of about 1000 years which is the average difference between the ^{14}C age of carbonate and organic carbon in the same samples (Jansen et al., 1984b).

In the hemipelagic and pelagic environment, terrigenous and shelfderived components form a considerable part of the surface sediment outside the central fan. Their contribution to the sediments is large at the base of the continental slope and decreases oceanwards as is also demonstrated by the map of the mass accumulation rates (fig. 1).

3°) Oceanic components

The oceanic component consists of calcareous and siliceous microfossils and marine organic matter. The calcium carbonate and biogenic silica (opal) concentrations are determined by the combined action of biologic production of carbonate and opal, dissolution in the sea water and on the ocean floor, and dilution with other components. The map of carbonate accumulation rates, in which the effect of dilution is eliminated, displays two trends : a decrease with greater depths and a lobe of high rates in the central fan region (fig. 1). The decrease with increasing water depth is primarily due to dissolution of calcium carbonate to the water column. In the western Atlantic basins and the Cape Basin the carbonate lysocline, the level of rapid increase in dissolution, is associated with the top of the Antarctic Bottom Water (AABW) because AABW is undersaturated with carbonate (Berger, 1968). In the Angola Basin, however, where AABW is nearly absent (Van Bennekom and Berger, 1984), there is a sharp increase in the degree of dissolution at 4700-4900 m (Thunell, 1982 ; Van Leeuwen, 1988). Accordingly, the carbonate lysocline can be placed at approximately 4800 m. The level of complete carbonate dissolution, the carbonate compensation depth (CCD), is situated at approximately 5600 m (Jansen et al., 1984b ; Jansen, 1985b).

In the central fan, carbonate preservation deteriorates because of the strong accumulation of organic matter (Jansen et al., 1984b). Mineralization of buried organic matter produces carbon dioxide, which makes the water more agressive for carbonate. The lobe of large carbonate accumulation rates coincides with an area of poor carbonate preservation (Zachariasse et al., 1984 ; Van

Leeuwen, 1988). This implies that the original biologic production of carbonate has been very high. There is, however, no sign of high phytoplankton production in the Zaïre plume, although dissolved organic carbon (DOC) concentrations are large (Cadée, 1984). This may be due to excretion by zooplankton as suggested by Cadée (1984). If this is true, the lobe of large carbonate accumulation rates is the result of increased zooplankton production rather than primary production (Jansen et al., 1984 ; Jansen, 1985b).

The biogenic opal in the sediments of the northeast Angola Basin has unusually high concentrations of aluminium which has partly substituted for silica. This Al-rich opal has a much lower solubility in sea water than normal opal-A. Some Al is taken up from the high concentrations of dissolved Al in the Zaïre River plume, and the Al concentrations have increased further by selective dissolution of Si and uptake of Al from minerals in the sediment (Van Bennekom et al., 1989).

4°) Microfossils and ocean surface circulation

The distribution of planktonic microfossils in the surface sediments mirrors the hydrography of the surface waters, which is demonstrated by diatoms (Pokras and Molfino, 1986 ; Van Iperen et al., 1987), planktonic Foraminifera (Van Leeuwen, 1988) and Radiolaria (Morley, 1979 ; Morley and Hays, 1979) in core tops. Marine diatoms in particular give a reliable reflection of the overlying water masses (fig. 3). Van Iperen et al. (1987) distinguish 5 different diatom groups : (1) related to the low-salinity river plume, (2) indicating slightly lowered salinity and increased diatom production due to river nutrients and upwelling (corresponding approximately to the factor 3 assemblage of Pokras and Molfino), (3) related to nearshore productive waters due to river-induced upwelling concentrated around the Zaïre river mouth, (4) related to warm and saline ocean water of the South Equatorial Counter Current and Equatorial Under Current (comparable to Pokras and Molfinos factor 1 assemblage), and (5) related to relatively cold and productive water of a coastal branch of the Benguela Current where oceanic upwelling occurs (comparable to the factor 2 assemblage of Pokras and Molfino). The planktonic Foraminifera of this tropical region show 2 major associations, a marginal and a mid-oceanic one which approximately match the 2nd and 4th diatom group, respectively (Van Leeuwen, 1988).

The deep-sea benthic foraminiferal faunas vary primarily with depth which is attributed to vertical gradients in bottom-water temperature and in the amount of organic matter reaching the bottom. Lateral differences may be due to variations in the amount of organic matter at and in the bottom (Van Leeuwen, 1986, 1988).

IV - GLACIAL-INTERGLACIAL PALEOCEANOGRAPHY

1°) Stratigraphy

The Quaternary hemipelagic and pelagic sediments of the Zaïre fan show fluctuations in calcium carbonate concentration which are typical of the entire Atlantic Ocean, high concentrations during warm periods and low concentrations during cold periods (Arrhenius, 1952) (fig. 4a). The fluctuations are generally attributed to variations in carbonate dissolution. The downcore fluctuations are used to define a stratigraphy with stages named conforming to the oxygen isotope stages by Emiliani (1955) and Shackleton and Opdyke (1973). Its time-scale appeared valid for the last 40,000 years as is demonstrated by a series of radiocarbon datings (Jansen et al., 1984b ; Jansen et al., 1989). The stratigraphy has been confirmed by studies of calcareous microfossils (Zachariasse et al., 1984 ; Van Leeuwen, 1988) and siliceous microfossils (Mikkelsen, 1984 ; Bjørklund and Jansen, 1984 ; De Ruiter and Jansen, 1985 ; Jansen and Van Iperen, 198.), oxygenisotope data (Olausson, 1984) and on ^{14}C, ^{10}Be and ^{230}Th-excess dating (Jansen et al., 1984b ; Jansen, 1985 b ; Jansen et al., 1989).

2°) Surface circulation

The lobe of high carbonate accumulation rates has existed during the glacial-interglacial oscillations of the last 250,000 years, although it is not known whether it was also a lobe of glacial carbonate production due to zooplankton production instead of primary production, as is the case today (Jansen et al., 1984b). There are no reasons, however, to believe that during glacials the major controlling factors of this characteristic Zaïre effect, the dimensions of the estuary and the easy access of ocean water, have been very different from the actual conditions. The deep and narrow valley in the Zaïre mouth continues across the shelf and is still a narrow canyon at the shelf break at 120 m water depth. A glacial sea level fall of ca 110 m (Giresse et al., 1981 ; Giresse et al., this volume, p. 71) would have caused an equally narrow and even deeper estuary near the shelf edge, with an easier access of ocean water. It is therefore probable that the Zaïre effect existed during the entire Quaternary, the glacial periods included.

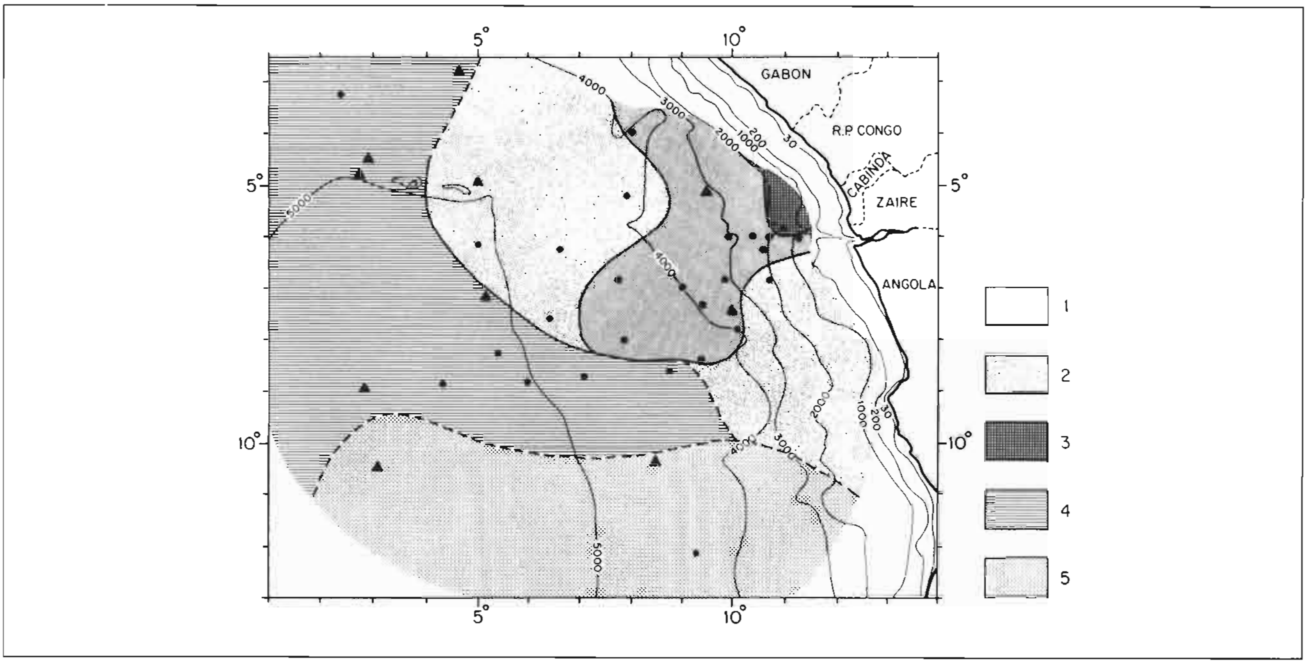

Figure 3 : Distribution of marine diatoms in surface sediments of the Zaïre-fan region (after Van Iperen et al., 1987). Figures in the legend correspond to dominant diatom groups. Broken lines are tentatively inferred from the data of Pokras and Molfino (1986). Data points are from Van Iperen et al. (●) and Pokras and Molfino (▲).

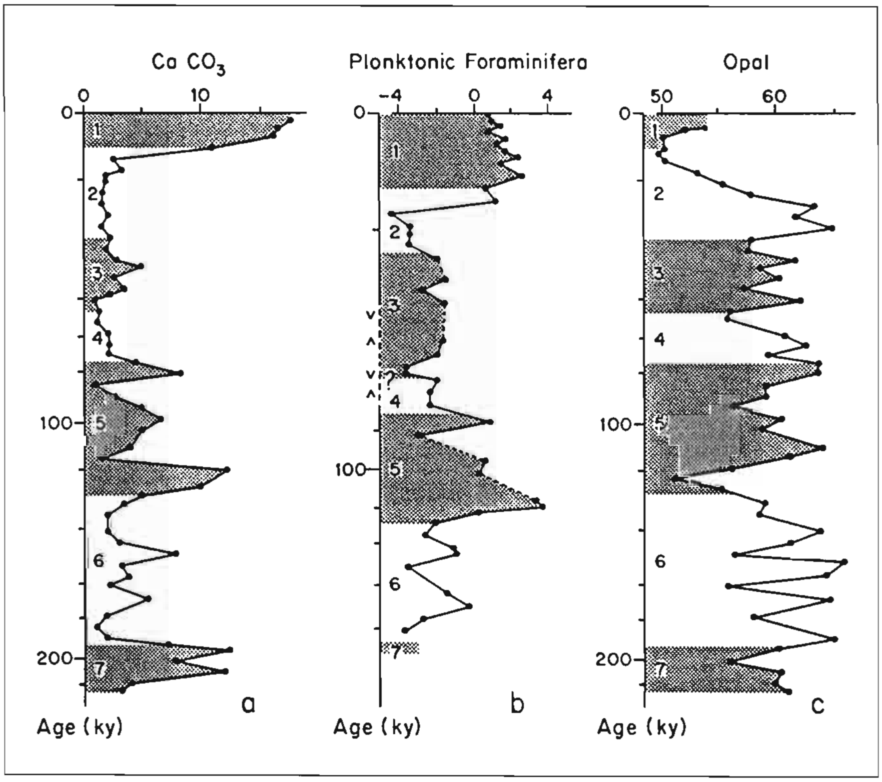

Figure 4 : Paleoceanographic signals in Quaternary sediments of the Zaïre deep-sea fan region ; a : Calcium carbonate concentrations (wt. %) (core T78-33, length 1027 cm, linear depth scale) (Jansen et al., 1984b) ; b : Climate curve based on planktonic Foraminifera data. High values (to the right) indicate interglacial conditions, low values (to the left) glacial conditions, v^ encloses positions of 40 ky and 60 ky marks (core T80-10, length 1681 cm, linear depth scale) (Van Leeuwen, 1988) ; c : Biogenic opal concentrations (wt. % carbonate free) corrected for long-term dissolution (core T78-33, length 1027 cm, linear depth scale) (Jansen and Van der Gaast, 1984).

Downcore studies of planktonic Foraminifera (fig. 4b) indicate that during the glacial periods of the last 150,000 years the surface waters were somewhat cooler than today (Van Leeuwen, 1988). According to the $\delta^{18}0$ values of a hemipelagic core on the continental slope the temperature decrease was at maximum 3°C (Olausson, 1984). Cold Cenguela Current waters are thought to have penetrated deeper into the area due to an intensified surface circulation of the glacial ocean (Gardner and Hays, 1976 ; Morley and Hays, 1979 ; Van Leeuwen, 1988 ; Diester-Haass et al., 1988 ; Jansen and Van Iperen, 198.). The stronger Benguela Current may have pushed the front and gyre system of the interacting water masses northwards (fig. 5b). Coastal upwelling accompanied the coastal branch of the Benguela Current, analogous to the present upwelling of cold Benguela Current water further south, off the Namibian desert (Schuette and Schrader, 1981).

The glacial Benguela Current did not penetrate into the Guinea Basin, in contrast with the inference from paleotemperature analyses of Foraminifera and Radiolaria associations by Gardner and Hays (1976) and Morley and Hays (1979) respectively. Their assemblages, associated with Benguela current water, are not exclusively controlled by surface-water temperatures, but also by nutrient concentrations. Therefore, the amplification of these assemblages in "glacial" sediments of the Guinea Basin points to increased fertility due to oceanic upwelling rather than a temperature fall due to penetration of Benguela Current water (Jansen et al., 1984b ; Jansen, 1985b).

3°) **Paleoproduction**

The primary production was larger in glacials than in interglacial stages. Investigations of diatoms, planktonic Foraminifera and Radiolaria demonstrate an increase of high-fertility species in cold periods which are thought to be caused by coastal and oceanic upwelling in relation to an intensified oceanic circulation (Zachariasse et al., 1984 ; Mikkelsen, 1984 ; Bjørklund and Jansen, 1984 ; Van Leeuwen, 1988 ; Jansen and Van Iperen, 198.). The changes in the benthic Foraminifera are ascribed primarily to variations in the amount of organic matter which arrived at the sea floor as a result of increased production in the surface water masses during cold

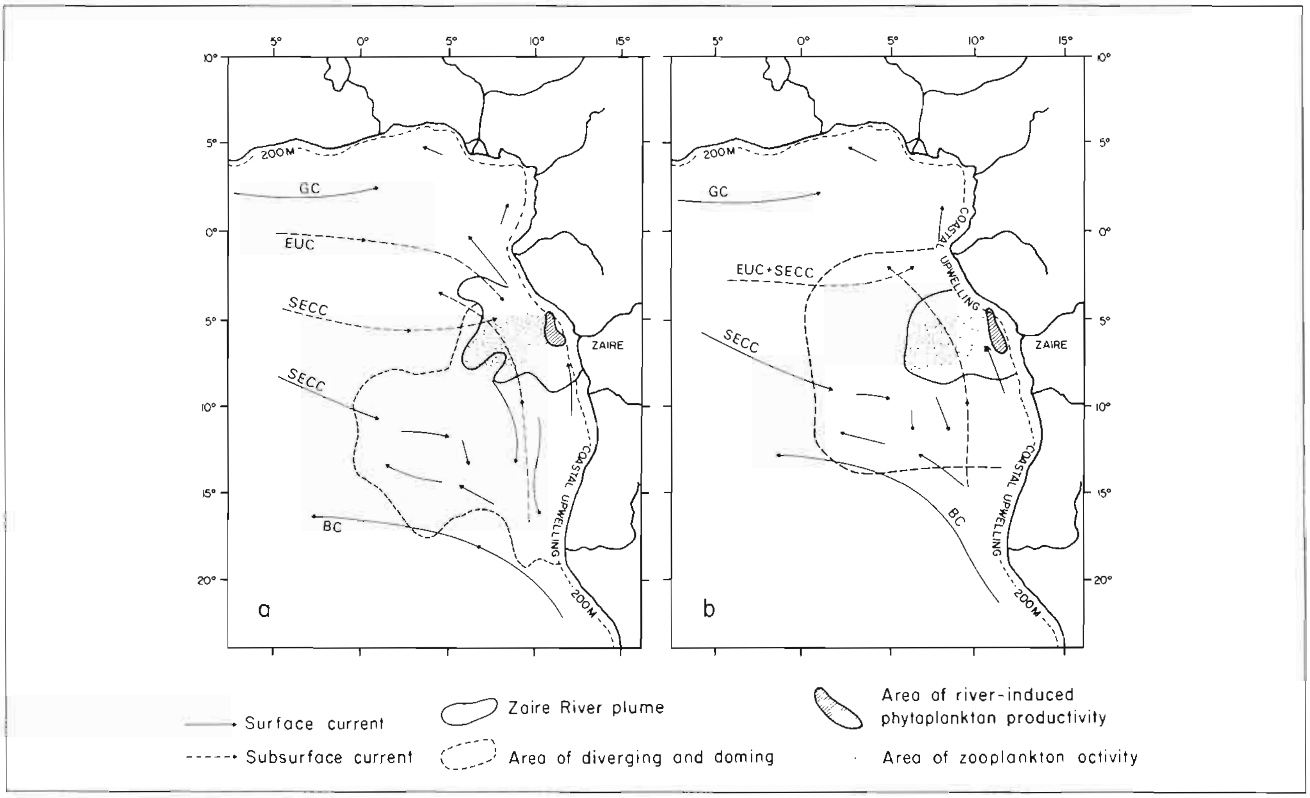

Figure 5 : Generalized oceanic circulation in the eastern Angola Basin ; a : Present circulation (mainly after Van Bennekom and Berger, 1984) ; b : Gacial circultation during isotope stage 2 (after Jansen et al., 1984b) ; BC : Benguela Current ; GC : Guinea Current ; SECC : South Equatorial Counter Current ; EUC : Equatorial Under current.

periods (Van Leeuwen, 1988). At great depths, the bottom water masses were also colder in glacials than today.

The stronger glacial production is corroborated by the biogenic opal in the sediments, with maxima of both concentrations and accumulation rates in glacial intervals (Van der Gaast and Jansen, 1984 ; Jansen and Van der Gaast, 1988) (fig. 4c). Within a zone of 300 km from the coast, carbonate accumulation rates were large during the last glacial stage. The high rates were caused by high carbonate production in the surface waters and also mirror the increased primary production and coastal upwelling induced by the intensified Benguela Current. Superimposed on the ocean-wide carbonate dissolution processes, these large glacial accumulation rates resulted in deviations in the downcore carbonate curves of the continental slope region (Jansen et al., 1984b ; Jansen, 1985b).

Organic carbon concentrations, however, do not give information about paleoproductivity in the area. Generally, the high concentrations appeared to be related to high organic carbon burial rates. Because there is an evident exponential relationship between these burial rates and the total mass accumulation rates, the burial rates are mainly controlled by the degree of decomposition of organic matter in relation to total mass accumulation (Jansen et al., 1984b). There is much debate about the validity of organic carbon concentrations as indicators of paleoproductivity (see Sarnthein et al.,1987, and Arthur et al., 1988).

The larger availability of organic matter during cold periods did not only affect the benthic foraminiferal fauna, it probably changed the entire benthic community as is witnessed by the glacial-interglacial variations in the trace-fossil associations (O.P. Werver and P.J. Pestman, unpublished data).

4°) The benthic environment

The temperature of the bottom waters has varied at least below 3000 m water depths. Cold waters entered the benthic environment during the glacial stages 2 and 4 and the middle of stage 5 (Van Leeuwen, 1988).

Mineralization of the organic matter by bacteria and benthic animals produced dissolved CO2, which made the pore water and bottom water more agressive for carbonate. As a result, the carbonate lysocline and the level of complete carbonate dissolution (CCD) of the sediment at the latitude of the Zaïre mouth rose 1000 m, to about 4000 m and 4400 m, respectively. The apparent interglacial lysocline and CCD approximate closely to the glacial ones. Originally, however, the interglacial dissolution levels must have been close to the present levels because the interglacial hydrographic regimes resemble the present rather than the glacial regimes.

Therefore, it is inferred that postdepositional dissolution in the depth zone above the interglacial-actual lysocline has adapted the interglacial levels to the subsequent glacial hydrographic conditions (Jansen et al., 1984b ; Jansen, 1985b).

Increased degradation of more abundant organic material in glacials is assumed to have also caused higher burial rates of MnC03 (rhodochrosite) during these periods. Long-term alterations in the steady-state systems which produces a subsurface Mn-peak in the sediment may have lead to the existence of this fossil Mn signal (Van der Gaast and Jansen, 1984).

The richness in organic carbon is also a requisite for the formation of ikaite crystals in the sediments of the central Zaïre fan. These very fragile, translucent brown crystals, consisting of hydrated calcium carbonate, release water and transform into calcite at temperatures over 5°C. The presence of ikaite is indicative of a low-temperature, anaerobic, organiccarbon-rich marine environment. Ikaite is probably the precursor of a great number of porous calcite pseudomorphs, and possibly also of many authigenic microcrystalline carbonate nodules in modern and ancient marine environments (Jansen et al., 1987b).

V - PALEOCLIMATE OF WEST CENTRAL AFRICA

1°) Microfossils

The considerable terrigenous input in the marine sediments of the Zaïre-fan region and the availability of continuous pelagic and hemipelagic records form a potential source of knowledge of the continental climate. The retreat of the Zaïre canyon into the river mouth, 33 km deep, allows for the terrigenous signals to enter the oceanic environment with relatively little delay. Altogether, the deep-sea sediments off Angola, Zaïre, Cabinda and R.P. Congo offer an excellent opportunity for the study of climatic history of the adjacent African continent.

Freshwater diatoms may reflect river-flux from humid regions as well as wind-borne transport out of arid

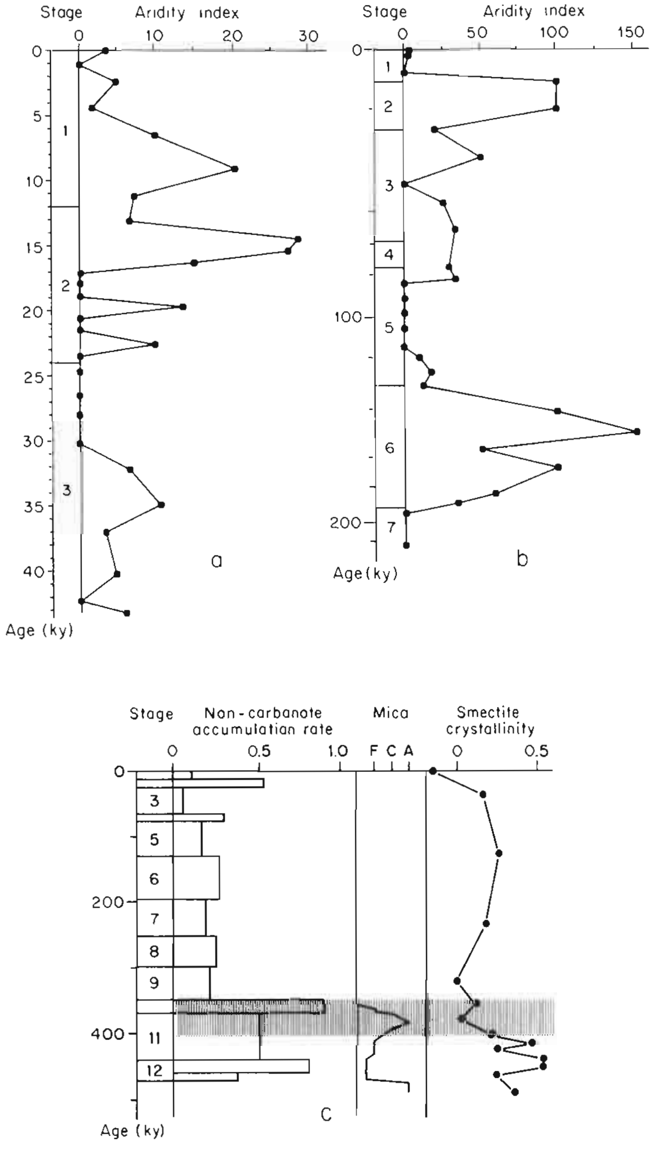

Figure 6 : Paleoclimatic signals of west central Africa in Quaternary sediments of the Zaïre deep-sea fan ; a and b : Aridity index (phytoliths/freshwater diatoms) ; a : core T78-46 (length 1112 cm) ; b : core T78-33 (length 1027 cm, linear depth scale) Jansen et al., 1989). c : The mid-Brunhes climatic shift. Mass accumulation rates (g cm^{-2} ky), mica abundance and smectite crystallinity indicate a long-term shift to more arid conditions in the Zaïre drainage area 400-350 ky ago. Stages are calcium carbonate preservation stages. F, C, and A mean few, common and abundant, respectively (core T78-38, length of described section 634 cm) (Jansen et al., 1986).

regions, while phytoliths are usually regarded as being transported by wind (Parmenter and Folger, 1972 ; Stabell, 1986 ; Gasse et al., 1988). The distribution of the accumulation rates of these two types of siliceous microfossils show that both are supplied by the Zaïre River, but phytoliths also have a southern source, probably the Namibian desert. Therefore, the ratio of phytoliths to freshwater diatoms can be regarded as an aridity index (figs. 6a and 6b). For the last 20,000 years this index corresponds closely with the known-climatic events in tropical Africa. In general, the index indicates that aridity prevailed during glacial climatic stages (Jansen et al., 1989).

In the glacials, most plant fragments were also deposited, they are rare in the Holocene and interglacial sediments. The fragments are generally brown in interglacial intervals, but have a black and burnt appearance in the glacial sediments indicating that frequent conflagrations have taken place (Jansen et al., 1984b ; Mikkelsen, 1984).

2°) **Clay minerals**

The climatic variations also influence the inorganic sediment supply. Arid areas are much more subject to erosion than overgrown humid tropical forests. As a result more sediment was supplied from the Zaïre drainage area during the arid glacials than during the humid interglacials, and the maximum glacial mass accumulation rates are 2-4 times as large as the minimum interglacial rates (Jansen et al., 1984b).

During interglacial stages, like today, the clay-mineral associations were dominated by kaolinite, while during glacial periods the Zaïre River transported more high-crystalline smectites towards the ocean floor (fig. 2). This model fits in well with the generally accepted opinion that kaolinite is a weathering product of igneous rocks in the tropical rain forest. Smectite is thought to indicate contrasting seasons and a pronounced dry season (Singer, 1984). Downcore variations, however, demonstrate that the clay mineral associations are primarily controlled by a hidden contribution of low-crystalline smectite which was high during interglacials and low during glacials. Low-crystalline smectite usually escapes observation by X-ray diffractometry, but can be measured by low-angle powder diffraction (Van der Gaast et al., 1986).

Glacial aridification is also indicated by the increasing contribution of illites which may reflect an expansion of the Namibian desert to the north. Besides, river-bourne components were carried to the continental shelf during interglacials. They were stored, subsequently eroded by glacial shore-line movements, and added to the "glacial" sediments together with highly crystalline smectite and traces of zeolite and cristobalite derived from the shelf (Jansen et al., 1984b ; Van der Gaast and Jansen, 1984 ; Jansen, 1985b).

The climate-related mineralogy is also reflected in the magnetic properties of the hemipelagic and pelagic sediments. The remnant magnetism in the cores is very weak due to pyritization. But a correlation of relatively high mean values for the remanent hysteresis parameters with cold periods suggests that a climate-controlled magnetic relict has escaped pyritization (Van Vreumingen, 1984).

3°) **The mid-Brunhes climatic shift**

A distinct break is observed in the mass accumulation rates and mineralogical composition during the mid-Brunhes (fig. 6c). About 400,000 -350,000 y BP there was a decrease in the terrigenous accumulation and the supply of high-crystalline smectites. The decrease in mass accumulation rates was recorded in all six piston cores that contain sediments of this age. This fan-wide phenomenon reflects a long-term change from more arid to more humid conditions in equatorial Africa (Jansen et al., 1984 ; 1986).

The mid-Brunhes change in the sediments of the Angola Basin is a global change and not a merely regional feature, it is present in all well documented marine and terrestrial climate records available (Jansen et al., 1986). The change appears in two different shapes. Records from the Northern Hemisphere show a trend towards more "glacial" conditions, records from equatorial regions and the Southern Hemisphere, on the contrary, towards more "interglacial" conditions. The data demonstrate that during the early Brunhes the polar fronts in the North Pacific, South Atlantic, and southeast Indian Oceans and the interglacial subtropical fronts in the Canary Basin were all generally situated more to the north. The magnitude of the displacements suggests that climatic and oceanic zones migrated toward the south over a few degrees of latitude after that time.

Some records also show long-term climatic changes 700,000 - 600,000 years ago and possibly 150,000 - 100,000 years ago, in directions, however, opposite to those of the mid-Brunhes shift. Evidence of the latter change comes also from the Zaïre deep-sea fan, where unusually high accumulation rates point to increased aridity in tropical Africa during the stages 4 to 2 (Jansen et al., 1984b). The changes probably form the expression of an asymmetric climatic cycle with a period of about 400,000 y which is forced by the orbital eccentricity cycle of 413,000 y (Jansen et al., 1986).

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