Marine - terrestrial interaction of climate changes in West Equatorial Africa of the last 190,000 years.

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Abstract

Palynological investigation of a marine piston core GeoB 1008-3 (6°35'S/10°19'E) from the highly productive area off the Congo fan provides a dinoflagellate cyst record reflecting marine surface water conditions during the last 190 ka and a pollen record of the vegetation changes in Central Africa induced by climatic fluctuations for the same period. The freshwater discharge of the Congo river is related to the intensity of the West African monsoon. During warmer and more humid phases, dinoflagellate cyst flux decreased in relation to lower productivity and increased freshwater input in the eastern South Atlantic. At the same time on the continent, the rain forest expanded. During the cooler interstadials of Stage 5, the Afromontane forest represented by *Podocarpus* pollen expanded to lower altitudes and occupied former areas of rain forest during periods showing intermediate levels for sea surface temperatures and river discharge. During the colder and more arid phases of glacial Stages 6 and 2, when freshwater run-off into the Gulf of Guinea decreased, dinoflagellate cysts were much more abundant. However, Stage 4 shows high levels of river discharge and a moderate dinoflagellate cyst flux coupled to low sea-surface temperatures of the eastern South Atlantic, while Stage 3 shows moderately high pollen percentages of the rain forest during phases with fluctuating fresh-water discharge and very low sea-surface temperatures. High sea levels at the beginning of the Last Interglacial and the Holocene favoured the expansion of mangroves.

Keywords: Dinoflagellate cysts, pollen, Congo river discharge, palaeo-precipitation, marine productivity, salinity fluctuations, eastern equatorial Atlantic

Introduction

Trade winds and monsoon circulation control the climate of West Africa. The surface wind field over the Angola Basin and the Gulf of Guinea is dominated by the SE-trade winds, that change their direction from SE to SW thereby becoming the SW-monsoon that penetrates far into the continent during boreal summer. In boreal winter, atmospheric circulation reverses over the continent when NE trade-winds blow over Africa and the adjacent subtropical Atlantic and reach the Gulf of Guinea (Leroux 1983; Hastenrath 1992).

Monsoon circulation results from the differing heat capacities of land and water: sensible heating warms land surfaces much more rapidly than the ocean mixed layer. Over West Africa, summer heating over central North Africa during boreal summer drives the inflow of moisture-laden air from the adjacent eastern equatorial Atlantic. Strong trade winds of the Southern Hemisphere cross the equator and penetrate into central Africa. The monsoon delivers precipitation deep into central subtropical Africa. Variations of the monsoon, however, are strongly coupled to sea surface temperature fluctuations of the Indian Ocean (Kutzbach & Street-Perrot 1985; Kutzbach 1987; Prell & Kutzbach 1987).

Additional influence on the West African monsoon is from the North Atlantic Ocean. General circulation model experiments of DeMenocal & Rind (1993) indicate that cooler North Atlantic sea surface temperatures (SST's) reduce the monsoonal inflow into North Africa and decrease surface air temperature by 2 to 4°C and precipitation up to 1 mm/day. Summer southwest African monsoon winds are reduced by the same high-pressure cell over the North Atlantic strengthening the winter NE trade-wind circulation over northwestern Africa. The precipitation decreases over Africa can be related to increased surface air outflow from the region owing to the thermal effects of the cooler North Atlantic SST's (DeMenocal & Rind 1993).

Because of the influence of different oceanic regions on the strength of the monsoon, its response to climatic variation is highly complicated. On the one hand, there is the influence of the SST's of the North Atlantic in response to glacial-interglacial variation and obliquity, while, on the other hand, there is the direct response of continental heating to insolation and the precessional controlled SST's of the eastern equatorial Atlantic (McIntyre et al. 1989; Schneider et al. 1995; Mix & Morey 1996; Schneider et al. 1996) and of the Indian Ocean. Glacial-interglacial high latitude variation intermingles with the response to low-latitude precessional insolation (DeMenocal 1995).

By comparing terrestrial and oceanographic proxy data from a core off the mouth of the Congo river, we try to identify the direct influence of the SST of the eastern equatorial Atlantic on the climate of west equatorial Africa (Congo basin and surroundings) for the last 190 ka. To this purpose, a new dinoflagellate cyst diagram is presented from the Congo fan (core station GeoB 1008) and compared with a pollen diagram from the same locality (Jahns 1996). The present study continues and extends investigations about the vegetation changes in western equatorial Africa to the south. Changes in palaeo-precipitation can be inferred from shifts in vegetation zones. The dinoflagellate cyst record holds information about marine surface production and salinity variation as a result of river induced upwelling and oceanic/coastal upwelling as well as oscillations of the Congo freshwater discharge. A firm land-sea correlation is established by the combined records of dinoflagellate cysts and terrestrial palynomorphs from the same samples. Additional information is provided by alkenone-derived palaeo-SST’s (Schneider et al. 1995) and by Al/K-ratios indicating chemical wheathering conditions on the continent (Schneider et al, 1997).

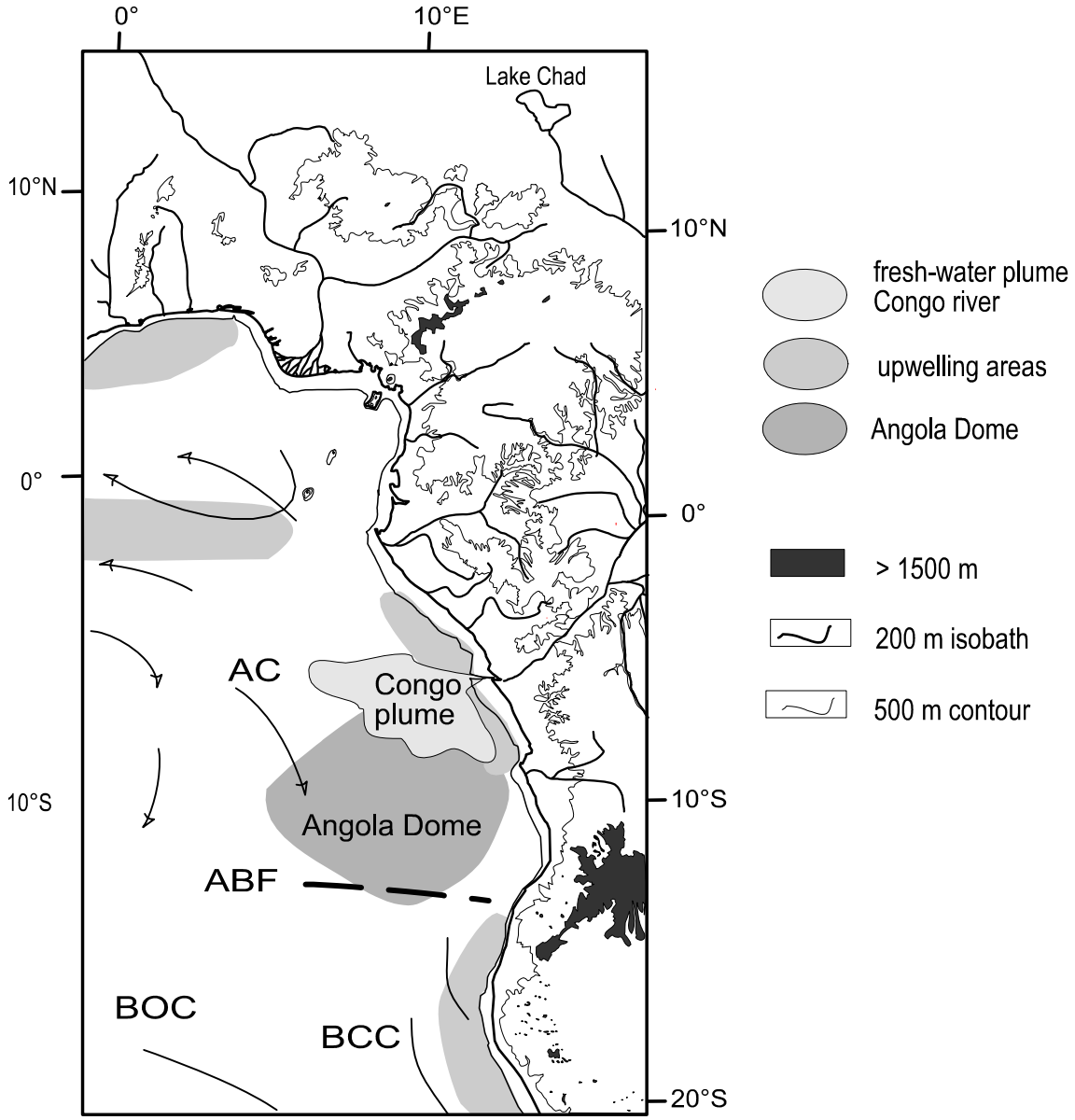

Figure 1: Ocean currents (AC = Angola Current, BOC = Benguela Ocean Current, BCC = Benguela Coastal Current, ABF = Angola-Benguela Front), upwelling areas, area of the Congo fresh water plume, area of the Angola Dome where isotherms bow up to the surface in a dome like shape, 500 and 1500 m contours and the 200 m isobath, river systems.

Laboratory cultures of the coccolithorid species *Emiliania huxleyi* as well as studies of modern plankton, sediment-trap material, and surface sediments established a relationship between the saturation index of C37-alkenones produced by coccolithophorids and the temperature of the water in which the coccolithophorids were growing (Prahl et al. 1988; Brassell 1993). Biological studies show that coccolithophorids bloom in offshore surface waters off SW Africa above a well developed thermocline (Giraudeau et al. 1993). Sediment-trap experiments on the Walvis Ridge revealed that alkenones were exported from the surface waters throughout the years, with two prominent maxima during austral spring and fall. Alkenone-derived palaeo-SST's, therefore, most likely reflect annual average temperatures of the mixed layer (Schneider et al. 1995).

Fluctuations in the ratios of Al/K and kaolinite/feldspar are attributed to changes in the composition of the Congo river particulate sediment load, assuming the river outfall to be the major source for kaolinite in the Angola Basin sediments (Eisma et al. 1978; Sholkovitz et al.

1978). Because kaolinite and feldspar strongly differ in their aluminium content, most of the variation in the Al/K-ratio reflects variation in the kaolinite/feldspar-ratio with which it generally covaries. Changes in the Al/K-ratio in Congo fan sediments can be considered in terms of weathering of the central African hinterland, whereby high Al/K-ratios correspond to intensified chemical weathering (Schneider et al. 1997).

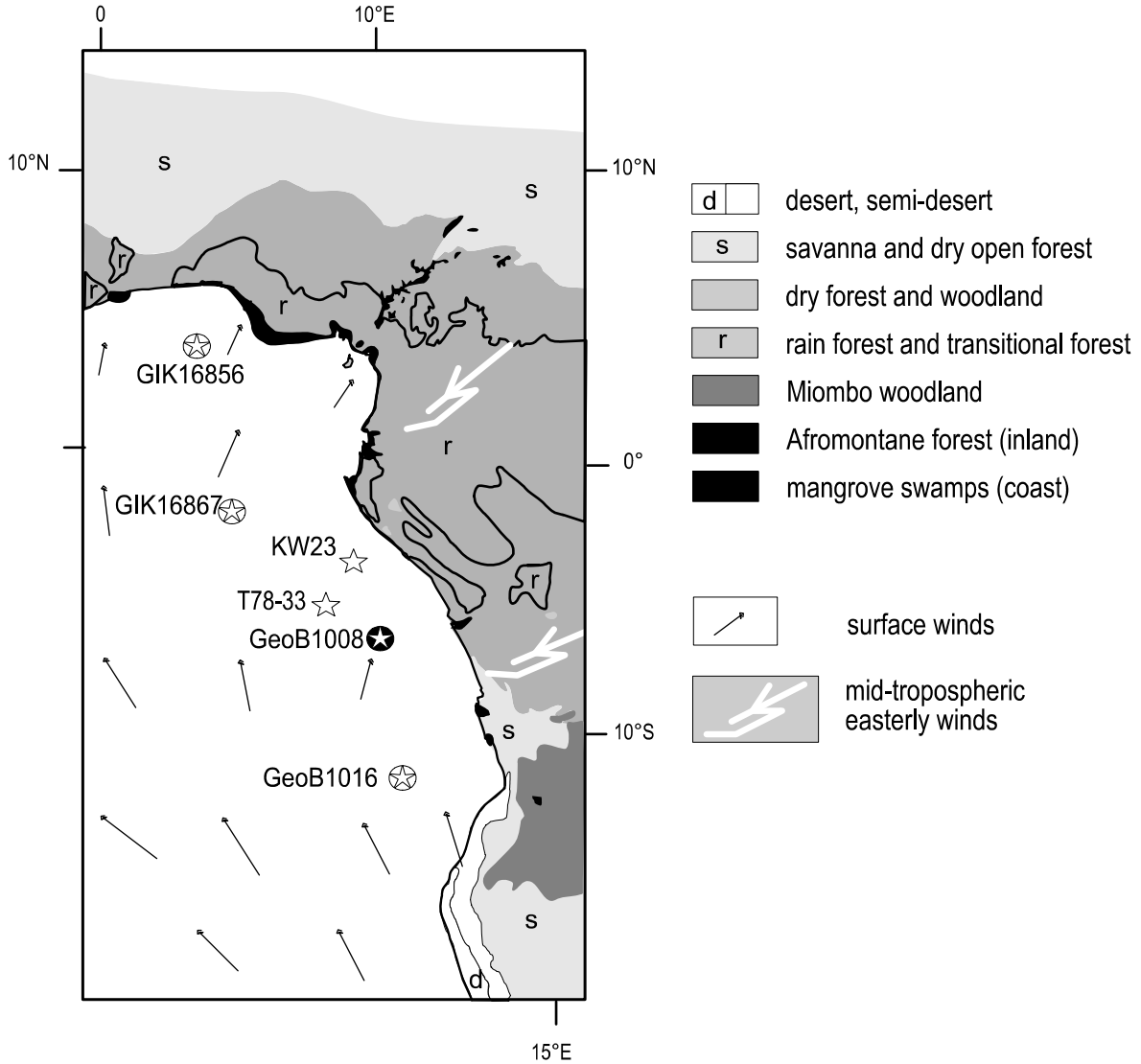

Figure 2: Phytogeographical zones, location of the cores mentioned in the text, general direction of surface and mid-tropospheric winds. The black areas in Cameroon and Angola denote Afrmontane forest; those along the coast denote mangrove swamps.

Present oceanographic setting

The surface waters off the Congo mouth are dominated by southward flowing warm surface and sub-surface currents: Angola current and South Equatorial Counter-Current. The Angola Dome and the cyclonic-gyre circulation of the SE Atlantic, which transports warm equatorial waters southward through the Angola Current, influence the region. A small amount of northward flowing cold sub-surface waters from the Benguela Coastal Current also reaches the core station. However, the main front between the warm surface waters of the Angola Current from the north and the cold surface waters of the Benguela Coastal Current from the south - called the Angola-Benguela Front - is situated farther south, between 12 and 14°S (Fig. 1). The area is charaterized by high productivity caused by oceanic, river-induced, and

coastal seasonal upwelling. (van Bennekom & Berger 1984; Berger et al. 1989; Stramma & Peterson 1989; Peterson & Stramma 1991).

The sediments from the Congo fan are hemipelagic mud mainly consisting of terrigenous silty clays with biogenic calcium carbonates. Jansen (1990) recognises three sources of terrigenous material in the deep-sea fan of the Congo: 1) suspended supply from the Congo containing pollen and fresh-water diatoms, 2) atmospheric dust also containing pollen and phytoliths, and 3) continental shelf derived deposits that decrease oceanwards. Most of the particulate terrigenous suspended and bed load of the Congo river is directly channelled to the deep Angola Basin via the Congo Canyon (Jansen et al. 1984; Schneider 1991). As a consequence, the upper fan north and south of the canyon is free of turbidites and has only two to three times higher sedimentation rates than the continental margin off Angola (Schneider 1991). The Congo fan core used in this study is located ca. 200 km from the coast and should not be influenced by coastal sedimentation processes (Schneider et al. 1997).

Although the sediment input into the Angola Basin is relatively small, the freshwater discharge by the Congo river is huge. The dissolved Congo river load is dominated by silica, while absolute dissolved concentrations of Ca, Na, Sr, K, Ba, and Rb are remarkably low compared to other rivers (Dupré et al. 1996). Freshwater influence is well demonstrated by reduced surface salinity as far as in the eastern Gulf of Guinea (Kolesnikov 1973).

The area at present exhibits highest average primary production rates in the tropical eastern South Atlantic (Berger & Wefer 1991). It has been shown that biological productivity off the Congo river is characterised by very high diatom production, in a plume reaching out into the open ocean by about 800 km (van Bennekom & Berger 1984; Van Iperen et al. 1987).

After diatoms, dinoflagellates form the second main group of marine phytoplankton. During their life cycle, dinoflagellate algae form non-motile cysts whith sporopollenin-like walls which fossilise very well. Different cyst types show preferences in water depth, salinity levels, temperatures and nutrient levels. They have been used as tracers of marine conditions (e.g. Reid 1977; Wall et al. 1977; Harland 1983; Morzadec-Kerfourn 1983; Bujak 1984; Duffield & Stein 1986; Turon & Londeix 1988; Mudie et al. 1990; Edwards & Andrle 1992; De Vernal et al. 1992; Marret 1994 a, b; Versteegh 1995).

Dale & Dale (1996 and Dale pers. comm. 1996) studied dinoflagellate cysts from the surface sediments of the Congo deep-sea fan and its surroundings. They concluded that opportunistic species like *Operculodinium centrocarpum* and species that normally prefer neritic environments are more abundant in sediments under the fresh water plume than elsewhere in the area where oceanic conditions prevail. These authors proposed that the massive freshwater discharge could extent neritic-like conditions further out into the ocean. The occurrence of neritic dinoflagellate cysts at the oceanic Site GIK16867 (2°12'S/5°6'E), such as *Operculodinium centrocarpum* and *Spiniferites* during Stages 1, 5a, 5c, and Stage 5e, may be explained along these lines and would indicate a decrease in salinity of the surface waters of the eastern Gulf of Guinea, as a result of increased precipitation and intensified fresh-water discharge from the continent. Also percentage maxima of *Lingulodinium machaerophorum* seem to record larger nutrient availability and/or seasonal salinity fluctuations (Dupont et al. 1998).

Enhanced fresh water supply and lower surface salinity is coupled to enhanced nutrient supply of the Congo river stimulating the primary production in the first place of diatoms (Van Iperen et al. 1987), but also that of dinoflagellates.

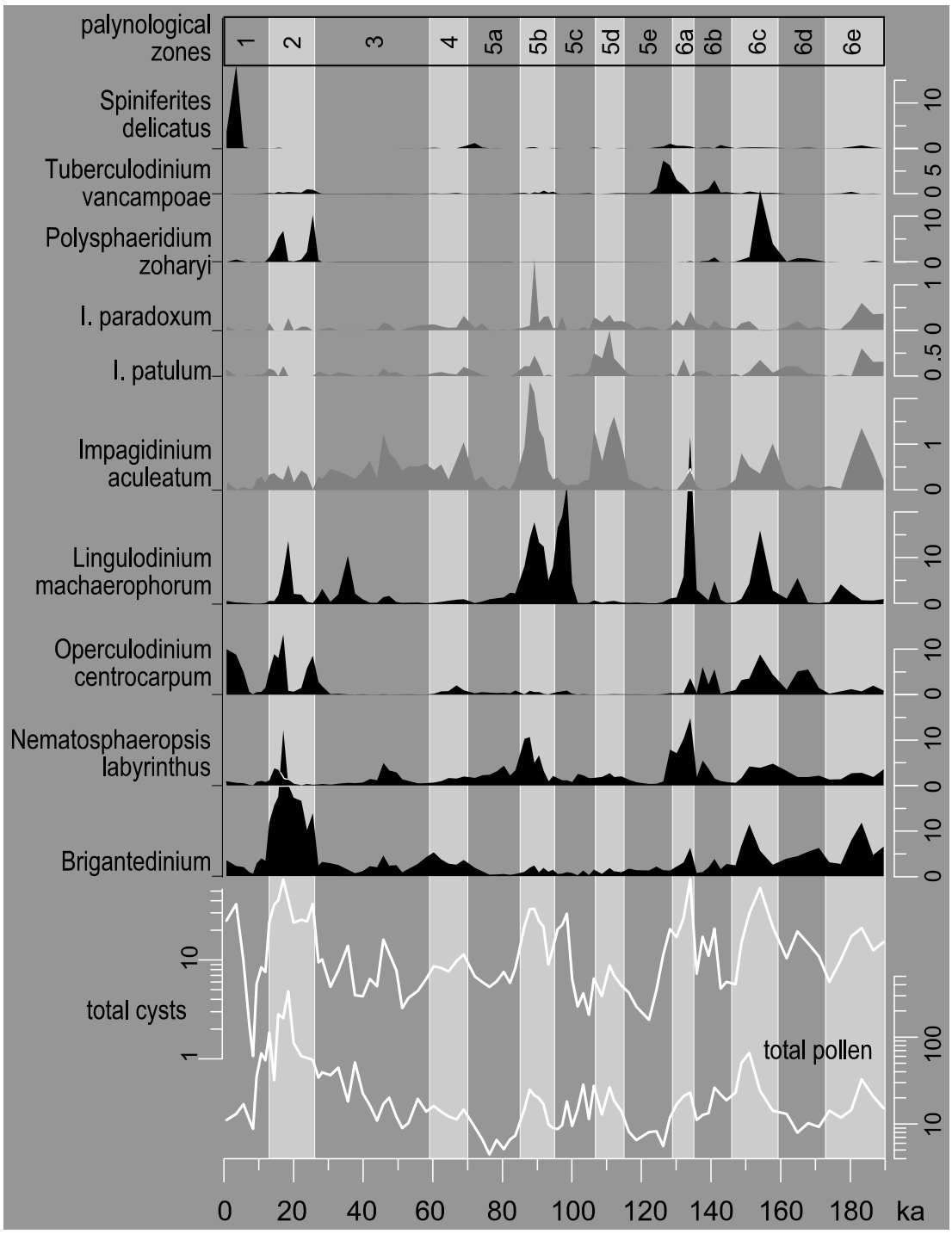

Figure 3: Accumulation rates in sediments of GeoB 1008; total pollen flux and dinoflagellate cyst flux of selected cyst taxa (analyst Anneke Schmüser). Scales of total pollen flux (left) and total dinoflagellate cyst flux (right) are logaritmic. Other scales are linear. Scales for *Impagidinium* are ten times enlarged.

Previous marine palynological studies

Today, the area east of the Gulf of Guinea is covered by the Guineo-Congolian rain forest bordered to the north and south by transitional forest, savanna, and dry forest (Fig. 2). Afromontane forest is restricted in West Africa to the mountains of Cameroon and the Huambo mountains in Angola. East of the Congo basin it grows on the Ruwenzori-Kivu massif. Mangrove swamps are growing along the coast and along river mouths (Knapp 1973; Schnell 1976, 1977; White 1983).

There are no terrestrial pollen records in West Africa covering a full glacial-interglacial cycle. The longer terrestrial cores, in Ghana, Cameroon, and Congo maximally cover the last 25 ka (Maley 1987; Brenac 1987; Elenga et al. 1994). Therefore, we use marine cores to reconstruct the vegetation changes that took place from the end of Stage 6 till the Holocene. Although the time resolution of marine pollen diagrams is generally not as high as that of terrestrial diagrams, marine records normally register palaeoecological data from a larger region and over a longer time span. Previous palynological investigations of marine cores from the East Equatorial Atlantic that include the Late Pleistocene are known from Marret (1994a) and Dupont et al. (1998) at the position of 2°12'S/5°6'E, from Dupont & Weinelt (1996) at the position of 4°48'N/3°24'E off the Niger delta, and from Bengo & Maley (1991) at the position of 4°46'S/9°17'E off the continental shelf of Gabon (Fig. 2).

The northern site (GIK16856), located near the Niger delta, is partly influenced by freshwater discharge and sediment load from the Niger river. Much pollen is river borne, especially pollen of Poaceae (grasses) and Cyperaceae. The core provides information about the expansion of the lowland rain forest, mangroves and sea level fluctuations on the northern coast of the Gulf of Guinea for the last 150 ka. Dinoflagellate cyst associations vary with the extension of the continental shelf (Dupont & Weinelt 1996).

The site at 2°12'S/5°6'E (GIK16867) gives information about the development of Afromontane forests in the Guinean mountains for the last 700,000 years. Pollen and spores are mostly transported by wind to this site. Dinoflagellate cyst abundance is generally correlated to periods with strong winds. Furthermore, the dinoflagellate cyst record of the site is influenced by changes in freshwater discharge of the Congo river. During cold and arid periods, for instance Stages 6 an 2, the distribution of lowland rain forest was reduced. Forest extension was recorded for the warm and humid Stages 5 and 1 (Marret 1994a; Dupont et al. 1998). The Afromontane forest (*Podocarpus*) expanded somewhat during the glacial Stage 6 and strongly during the cooler periods of Stage 5 (Dupont et al. 1996).

Bengo & Maley (1991) investigated the marine core at 4°46'S/9°17'E (KW23), which spans the last 135,000 years. They described 18 samples taken from an eight meter long sequence only giving a coarse-resolution survey of the vegetation changes west of the Congo basin. Pollen curves of rain forest elements (Caesalpiniaceae) run more or less parallel to the grass percentages and maxima are found in Stages 5e, 5c, and 5a indicating a vegetation pattern of savanna and rain forest during these periods in western Congo that is similar to the modern one. The authors also suggest that during Stages 5d, and 5c, Afromontane forests (*Podocarpus*) replaced the rain forest at altitudes exceeding 600 m.

Material and methods

Gravity core GeoB 1008-3 was obtained during Meteor cruise 6/6 at a position of 6°35'S/10°19'E and a water depth of 3124 m (Wefer et al. 1988). The cores were opened on board and two parallel series of 10 ml syringe samples were taken at 5 cm depth intervals. One sample series was wet sieved for the coarse fraction (> 63 µm) that was used to obtain planktonic foraminifers for measurements of stable oxygen and carbon isotopes. The samples of the second series were measured for their wet weight, freeze dried and then weighed again to obtain the dry bulk density. Afterwards, they were crushed and homogenized, and split into subsamples for elementar analysis (Schneider 1991). The core was resampled for mineralogical and palynological studies later in Bremen.

Oxygen isotopes were measured on handpicked planktonic foraminiferal specimens of *Globigerinoides ruber* and *Globigerina bulloides*. Both curves were used to establish the isotope stratigraphy of GeoB 1008, and its time-scale was reconstructed after the SPECMAP time-scale. Sedimentation rates range between 5 to 8 cm/ka (Schneider 1991; Schneider et al. 1995).

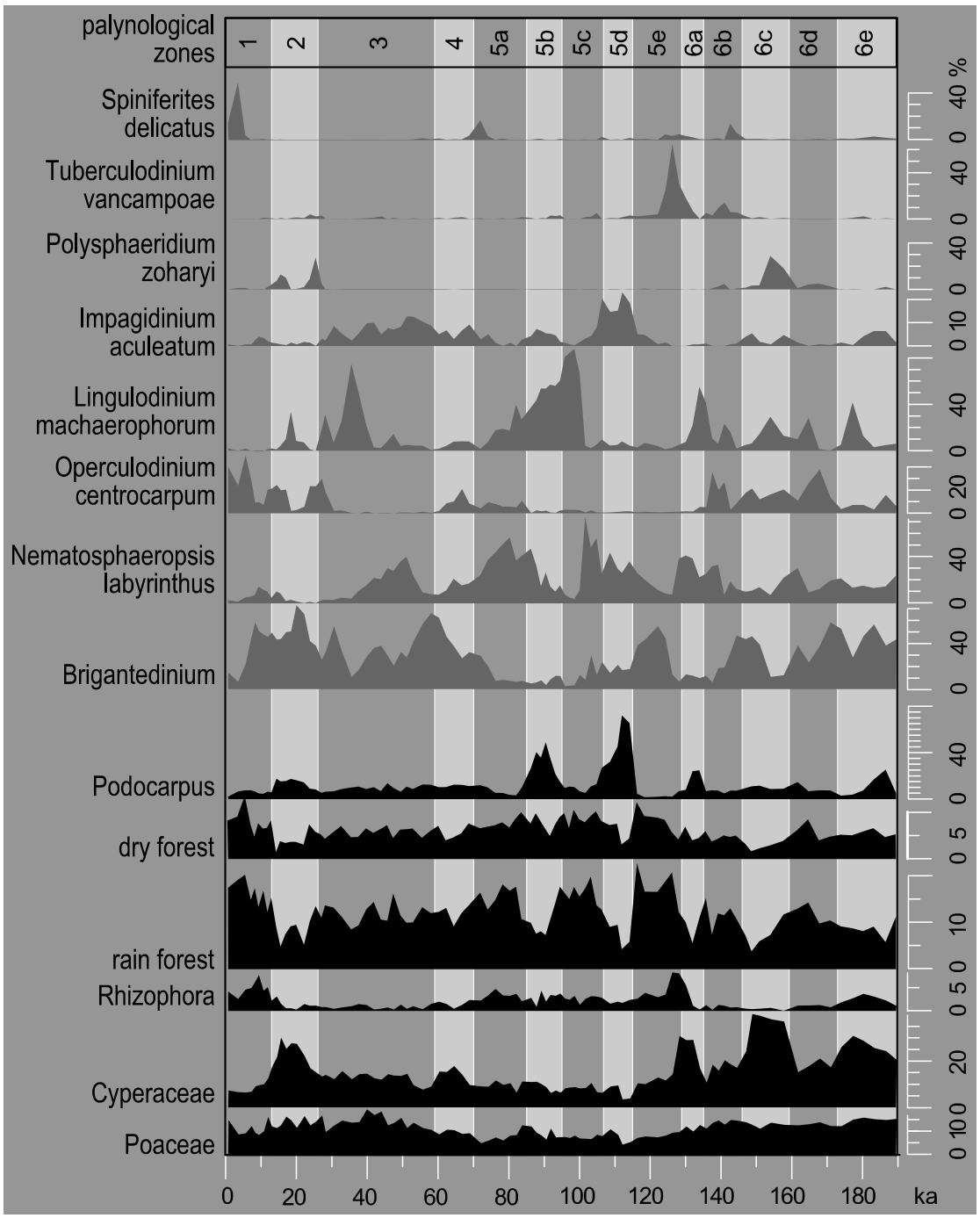

Figure 4: A selection of pollen taxa and groups expressed as percentages of the total of pollen and spores (black shading, analyst Susanne Jahns) and a selection of dinoflagellate cysts expressed as percentages of the total number of cysts (grey shading, analyst Anneke Schmüser).

Samples for palynological analysis with a volume of ca. 20 cm^3 were taken at intervals of 10 to 20 cm. The samples were treated successivly with HCL, HF and ultrasonic sieving. *Lycopodium* spore tablets were added to provide markers grains for concentration measurements. The samples were counted up to a sum of 300 dinoflagellate cysts (Schmüser) and one of 300 pollen grains (Jahns 1996).

Dinoflagellate cysts have been determinated mainly after the reference collection of the Institute of Palaeobotany, Utrecht and after descriptions from literature (among others De Vernal et al. 1992; Marret 1994a). For pollen determination, the reference collection of the Institute of Palynology and Quaternary Science, Göttingen was used supplemented by the literature cited in Dupont & Weinelt (1996). The average sample resolution of the palynological samples is ca. 2 ka.

Table 1: Palynological zones, sample depth, and boundary ages of GeoB1008.

zone	depth (cm)	age (ka)	(sub) zone	depth (cm)	age (ka)	(sub) zone	depth (cm)	age (ka)
1	5-124	0-13	5	525-845	70-129	6	855-1100	129-190
2	139-280	13-26	5a	525-584	79-85	6a	855-875	129-135
3	295-459	26-59	5b	599-660	85-95	6b	885-935	135-146
4	465-510	59-70	5c	670-739	95-107	6c	950-995	146-159
			5d	751-770	107-115	6d	1008-1038	159-173
			5e	780-845	115-129	6e	1048-1100	173-190

Results and interpretation of the dinoflagellate cyst record

This section describes the fluctuations of the dinoflagellate cyst record in detail (Schmüser). In the next section a comparison will be drawn with the pollen record and the Al/K record that already have been described in detail by Jahns (1996) and Schneider et al. (1997), respectively.

The dinoflagellate cyst record consists of flux and percentage diagrams. The flux record is expressed in cysts.a^{-1}.cm^{-2} (Fig. 3); the percentage record is calculated on the total cysts found in each spectrum (Fig. 4). The diagrams are divided into six palynological zones that are fitted to the framework of the oxygen isotope stages (Table 1); zones 6 and 5 are each subdivided into 5 subzones following the zoning in Jahns (1996). The dating follows the $\delta^{18}O$-stratigraphy (Schneider et al. 1995).

Zone 6 (129-190 ka; Isotope Stage 6)

At the beginning of **subzone 6e (173-190 ka)**, *Brigantedinium spp.* (max. 12 cyst.a^{-1}.cm^{-2}; 56%) dominates the dinoflagellate cyst spectra indicating a high nutrient level of the surface waters over the site (Bujak 1984, Mudie et al. 1990, Duffield & Stein 1986). At the same time the occurrence of *Impagidinium aculeatum* (1 cyst.a^{-1}.cm^{-2}; 6%) indicates high salinity under stable oceanic conditions (Marret 1994b). The total dinoflagellate cyst flux is relatively high (max. 21 cyst.a^{-1}.cm^{-2}) giving evidence of high productivity under oceanic conditions. At the end of subzone 6e, the total dinoflagellate cyst flux decreases but for *Lingulodinium machaerophorum* (4 cyst.a^{-1}.cm^{-2}; 42%), which is kown to occur over a broad salinity range (Edwards & Andrle 1992). The dinoflagellate cyst record is explained by initially small river discharge of the Congo increasing at the end of subzone 6e.

Subzone 6d (159-173 ka) is also characterised by *Brigantedinium spp.* (4 cyst. a^{-1}.cm^{-2}; average ca. 40%), and a high total dinoflagellate cyst flux (up to 20 cyst.a^{-1}.cm^{-2}) records continously high nutrient levels. Relatively high *Operculodinium centrocarpum* percentages (max. 38%; 5 cyst.a^{-1}.cm^{-2}) during subzone 6d indicate stronger freshwater influence. *O. centrocarpum* is a cosmopolitic species mostly favouring neritc conditions (Edwards & Andrle 1992). Its maximum is followed by a maximum in the curves of *L. machaerophorum* (5 cysts.a^{-1}.cm^{-2}; up to 30%). We interprete the combination as a result of lower and fluctuating salinity of the surface waters, caused by increased freshwater discharge by the Congo river.

During **subzone 6c (146-159 ka)**, fluctuations in nutrient and salinity levels are registered by oscillations of the *Brigantedinium spp.*, *L. machaerophorum*, and *I. aculeatum* curves. The appearence of the estuarine species *Polysphaeridium zoharyi* with values up to 16 cyst.a^{-1}.cm^{-2} (30%) may be the result of an arid and cold climate on the continent (Morzadec-Kerfourn

1983). *P. zoharyi* may have occupied saline estuarine environments on the continental shelf being exposed by low sea-level. Effects of reduced freshwater discharge are shown in high total dinoflagellate cyst flux values (max. 54 cyst.a^{-1}.cm^{-2}).

In **subzone 6b (135-146 ka)** disappear species which need a high salinity level such as *I. aculeatum*. The total dinoflagellate cyst flux (range 6-21 cyst.a^{-1}.cm^{-2}) also decreases and only the opportunistic taxon *O. centrocarpum* (max. 6 cyst.a^{-1}.cm^{-2}; 35%) and the tropical-neritic one *Tuberculodinium vancampoae* (max. 3 cyst.a^{-1}.cm^{-2}; 14%) are abundant (cf. Wall et al. 1977; Harland 1983). The *Brigantedinium spp.* curve drops from 4 to 1 cyst.a^{-1}.cm^{-2} - varying between 46 and 6% - and records declining nutrient levels.

The total dinoflagellate cyst flux (67 cyst.a^{-1}.cm^{-2}) is again very high in **subzone 6a (129-135 ka)**. The most abundant taxa are *Nematosphaeropsis labyrinthus* (max. 15 cyst.a^{-1}.cm^{-2}; 23-41%) which prefers high nutrient levels and oceanic conditions (Turon & Londeix 1988), and *L. machaerophorum* (max. 37 cyst.a^{-1}.cm^{-2}; up to 56%) which probably tolerates salinity fluctuations. The *Brigantedinium spp.* curve shows a minor maximum (6 cyst.a^{-1}.cm^{-2}; 10-12%). We interprete subzone 6a as a period with low freshwater discharge.

Zone 5 (70-129 ka; Isotope Stage 5)

During **subzone 5e (115-129 ka)** the dinoflagellate cyst flux decreases rapidly (from 21 down to 2 cyst.a^{-1}.cm^{-2}). Only the neritic taxon *T. vancampoae* shows an increase (up to 7 cyst.a^{-1}.cm^{-2}; 65%) at the beginning of zone 5e. This can be interpreted as an indication of a strong outflow of the Congo as the result of increased precipitation on the continent. *T. vancampoae* also has a tropical to subtropical preference (Harland 1983). So it may reflect the high surface temperatures of Stage 5e inferred from alkenones (Fig. 5; Schneider et al. 1995). The low *Brigantedinium spp.* flux values (average 1.6 cyst.a^{-1}.cm^{-2}) indicate decreased nutrient levels.

During **subzone 5d (107-115 ka)** the total dinoflagellate cyst flux increases slightly (up to 9 cyst.a^{-1}.cm^{-2}). *N. labyrinthus* (3 cyst.a^{-1}.cm^{-2}; 44%) and *I. aculeatum* (1.6 cyst.a^{-1}.cm^{-2}; 23%) show maxima during this period. Both taxa prefer oceanic conditions. *I. aculeatum* reaches highest values reflecting a higher salinity level. Increased salinity probably is the result of decreased Congo outflow.

The total dinoflagellate cyst assemblage is dominated by *L. machaerophorum* during **subzone 5c (95-107 ka)** and becomes nearly monospecific at the end of subzone 5c (26 cyst.a^{-1}.cm^{-2}; 88%). This unique event is also recorded in the cores GeoB 1016 (Shi, unpublished data) and GIK 16867 (Marret 1994a) indicating a widespread bloom of the dinoflagellate *Lingulodinium polyedrum* that produces the cysts known as *Lingulodinium machaerophorum* (Kokinos & Anderson 1995). Oceanic elements such as *N. labyrinthus* and *I. aculeatum* disappear at that time indicating increase of freshwater discharge.

The occurence of *N. labyrinthus* (max. 11 cyst.a^{-1}.cm^{-2}; up to 47%) and *I. aculeatum* (2 cyst.a^{-1}.cm^{-2}; up to 7%) indicate generally high salinity levels and favourable temperatures during **subzone 5b (85-95 ka)**. Percentages of *I. aculeatum* increase, but not as strongly as in subzone 5d. This may be caused by salinity fluctuations which are reflected by high *L. machaerophorum* values (max. 18 cyst.a^{-1}.cm^{-2}; range from 38-61%). The total dinoflagellate cyst flux (max. 33 cyst.a^{-1}.cm^{-2}) increases which indicates the availability of more nutrients in combination with more oceanic conditions.

The dinoflagellate cyst flux decreases (5-8 cyst.a^{-1}.cm^{-2}) in **subzone 5a (85-70 ka)**. The main taxon is *N. labyrinthus* (2-4 cyst.a^{-1}.cm^{-2}; 25-57%). *L. machaerophorum* shows a declining trend (2-0.1 cyst.a^{-1}.cm^{-2}; range from 40-2%). The extend of the Congo freshwater plume may have been larger in subzone 5a compared to subzone 5b.

Zones 1 - 4 (0-70 ka; Isotope Stages 1 - 4)

Increased occurrence of *I. aculeatum* (1 cyst.a^{-1}.cm^{-2}; 9%) indicates that marine conditions became more oceanic during **zone 4 (59-70 ka)**. Total dinoflagellate cyst flux reaches a value of 11 cyst.a^{-1}.$cm^{-2}$and *Brigantedinium spp.* cysts show for the first time since zone 6a higher values again at the end of zone 4 (5 cyst.a^{-1}.cm^{-2}; 62%). Judging from the dinoflagellate record, nutrient level increased and freshwater influence decreased.

Brigantedinium spp. (1-5 cyst.a^{-1}.cm^{-2}; range from 11-66%) is the main component in most of the dinoflagellate spectra of **zone 3 (29-59 ka)**. The end of zone 3 is characterised by *L. machaerophorum* (max. 11 cyst.a^{-1}.cm^{-2}; 75%). This cannot be explained by the river discharge only, while the continuing presence of *I. aculeatum* (up to 1 cyst.a^{-1}.cm^{-2}; 2-13%) indicates that there is no strong drop in salinity during the period. At the middle of zone 3, *N. labyrinthus* (up to 5 cyst.a^{-1}.cm^{-2}; 40%) appears with higher values. The total dinoflagellate cyst flux is low (6 cyst.a^{-1}.cm^{-2}) except for maxima at 46-49 ka (16 cyst.a^{-1}.cm^{-2}) and at 33 ka (14 cyst.a^{-1}.cm^{-2}).

The total dinoflagellate cyst flux (max. 65 cyst.a^{-1}.cm^{-2}) reaches highest values in **zone 2 (13-26 ka).** Also the *Brigantedinium spp.* curve shows its highest values (32 cyst.a^{-1}.cm^{-2}; 73%). We infer, therefore, that the nutrient level of the sea-surface waters is very high. *L. machaerophorum* (up to 14 cyst.a^{-1}.cm^{-2}; 34%) is again interpreted as indication of fluctuating salinity. The curve of *P. zoharyi* shows two maxima that are almost as high as that of zone 6c indicating arid and cold conditions on the continent (at 25 ka 28 cyst.a^{-1}.cm^{-2} and 10%; around 16 ka ca. 12 cyst.a^{-1}.cm^{-2} and 6%). Puzzeling is the increase of *O. centrocarpum* occurring at the beginning and the end of zone 2 (9 and 13 cyst.a^{-1}.cm^{-2}; 23 and 20%). It may indicate increased influence of plume waters just before and after the Last Glacial Maximum. Parallel to the *O. centrocarpum* increase, *I. aculeatum* values are low (less than 1 cyst.a^{-1}.cm^{-2}; 0.5-3%), which hints to low sea surface temperatures along with decreased salinity during this period comparable to those of zone 6.

The dinoflagellate cyst flux decreases (down to 5 cyst.a^{-1}.cm^{-2}) in **zone 1 (0-13 ka)**. However, at the end of zone 1, a peak in the total dinoflagellate cyst flux (37 cyst.a^{-1}.cm^{-2}) of which the main components are *O. centrocarpum* (max. 10 cyst.a^{-1}.cm^{-2}; 50%) and *Spiniferites delicatus* (18 cyst.a^{-1}.cm^{-2}; up to 49%). Both are cysts of neritic species (Marret 1994a) and their occurrence may be explained by increasing sea levels and flooding of the continental shelf in combination with increased river discharge. We infer that marine surface conditions changed in zone 1 to lower salinity.

Comparing different records related to palaeo-precipitation

In Fig. 4, we compare the dinoflagellate cyst record (Schmüser) with the pollen record (Jahns 1996) and in Fig. 5 we compare selected palynological curves with the Al/K record (Schneider et al. 1997). While the dinoflagellate cysts react on the fluctuations in river influence, salinity variations, and fluctuations in nutrient supply, the Al/K ratio is coupled to weathering conditions on the continent and this ratio increases when the terrestrial load of the Congo river is large during periods of intensified rainfall. Pollen percentages of grasses (Poaceae), Cyperaceae, rain forest elements, *Podocarpus* (mountainous element) and others record changes in the vegetation cover east of the marine site and in the Congo basin (Congo, Angola). The extent of the rain forest area depends largely on the available precipitation. However, it is also varying with temperature fluctuations. Lower temperatures cause the mountainous forest to occupy lower altitudes reducing the area of the lowland rain forest.

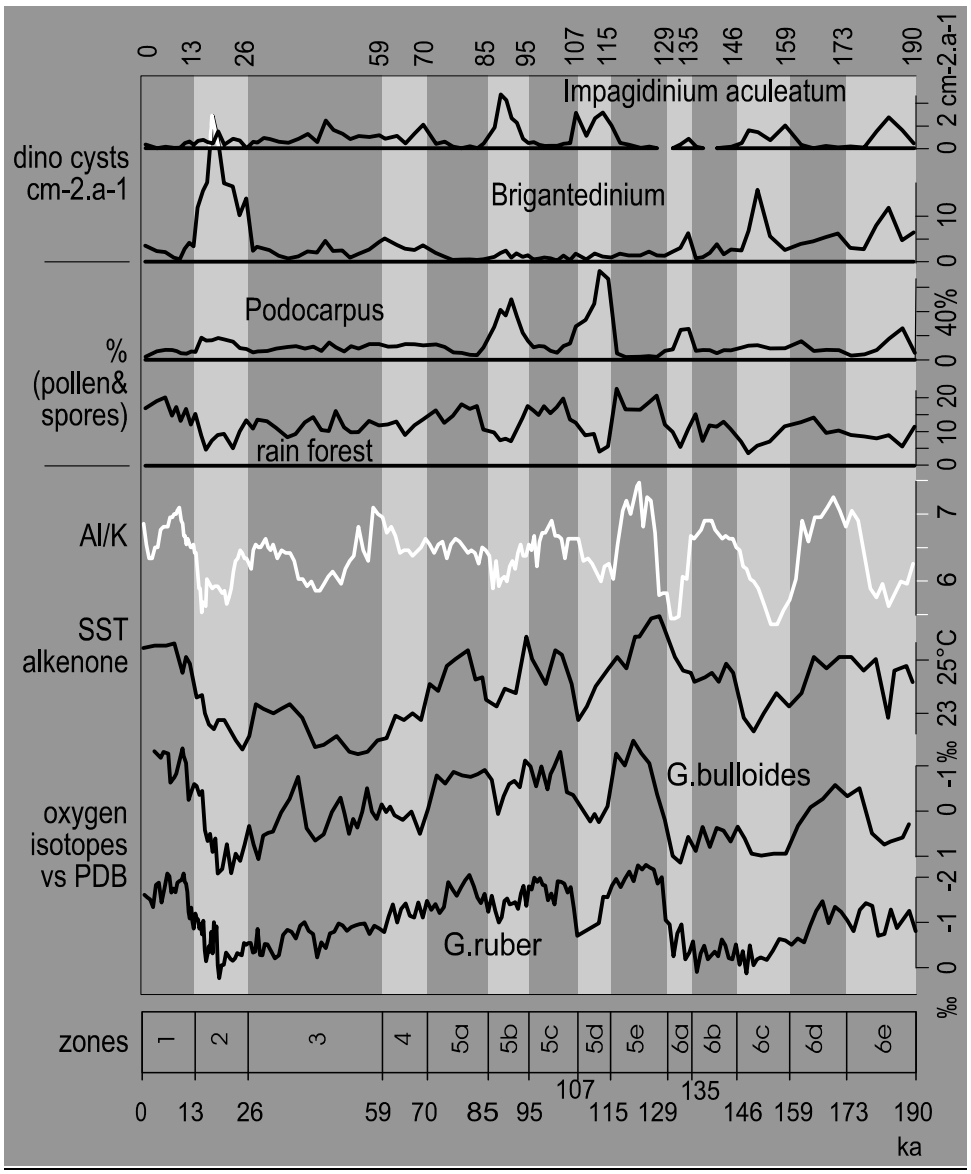

Figure 5: Oxygene isotopes (in ‰ vs. PDB) of the foraminifera *Globigerinoides ruber* (rosa) and *Globigerina bulloides*, SST estimates based on the alkenone saturation index (Schneider et al. 1995), Al/K-ratio (Schneider et al. 1997), pollen percentages of rain forest taxa and of *Podocarpus* (Jahns 1996), cyst flux rates of *Brigantedinium spp.* and *Impagidinium aculeatum* (Schmüser).

Pollen percentages of forest taxa do not reach high values during most of **Stage 6** (Jahns 1996). The relative high pollen percentages of Poaceae (10-16%) and Cyperaceae (20-40%) indicate that large areas are covered with dry open forest and grassland. During the subzones 6e (173-190 ka), 6c (146-159 ka) and 6a (129-135 ka), precipitation probably was even lower than in the intermediate periods as indicated by the reduced pollen percentages of the lowland rain forest (4-12%). The curve of rain forest pollen percentages parallels that of Al/K ratios indicating increased weathering during periods of increased river discharge. The division into five subzones is corroborated by the dinoflagellate cyst record. Increase of the *L. machaerophorum* cyst flux and later that of *O. centrocarpum* are interpreted as the effect of a relative increase of the Congo freshwater plume. Hence, we infer that the regional climate during Stage 6 generally was much drier and colder than today, but included ameliorations in precipitation from 159 to 173 ka and from 135 to 146 ka. *Rhizophora* pollen percentages recording the occurrence of mangrove swamps are low (max. 4%), which is probably the result of low sea-levels during Stage 6. Reduction of mangrove swamps during glacial stages is also reported by Sowunmi (1981), Fredoux & Tastet (1988) and Dupont & Weinelt (1996).

The indicators of open forest and grassland, Poaceae and Cyperaceae decrease at the beginning of **Stage 5**. Simultaneously, the rain forest expands (pollen percentages max. 23%), most strongly during the more humid phases 5e, 5c, and 5a. During the cooler substages 5d and 5b, the Afromontane forest (*Podocarpus* pollen percentages up to 72%) probably replaces the lowland rain forest (min. 4%) at altitudes between 500 and 1500 m (Dupont et al. 1996). The large extension of *Podocarpus* forests during Stages 5d an 5b is unique for the last 190 ka. It indicates lower temperatures as the belt with mountainous vegetation was lower at those times in connection to relatively moist conditions, that is at least not as arid as during full glacial periods of Stages 6 and 1. During those arid stages only a small increase in the representation of *Podocarpus* is recorded. Intermediate climatic conditions are also indicated by slightly reduced SST's (Fig. 5; Schneider et al. 1995) and intermediate values of the Al/K ratio. *Rhizophora* (up to 8%) increases especially at the beginning of Stage 5e, probably as the result of raising sea level at the beginning of Stage 5 maintaining - albeit with fluctuations - through the rest of Stage 5. The correlation between pollen percentages of the rain forest and Al/K ratios persists through Stage 5. However, the dinoflagellate cyst record is rather varied.

It seems that large freshwater discharge in Stage 5e resulted in a response of the neritic *T. vancampoae*, while during Stage 5c it resulted in a massive increase of *L. machaerophorum*. The latter occurred to a lesser extend also in Stage 5a. Freshwater diatom assemblages indicate increased Congo discharge especially between 115 and 135 ka (Gasse et al. 1989). The increase of the oceanic *I. aculeatum* cyst flux may have been the result of reduced freshwater outflow in Stages 5d and 5b. Cyst production seems to react unfavourably on lower salinity caused by increased river discharge and a high Al/K ratios correlate with low dinoflagellate cyst flux. During Stage 5c, when *L. machaerophorum* cysts dominate the dinoflagellate record, Al/K-ratios indicate a trend to higher and fluctuating freshwater input.

Dinoflagellate cyst as well as pollen records of Stages 3 and 4 show relatively little fluctuation. A drop in sea level is followed by decreasing *Rhizophora* pollen percentages recording the reduction of mangrove swamps. Increase of the flux of both *Brigantedinium spp.* and *I. aculeatum* during **Stage 4** seems to point to reduced river discharge and increased oceanic productivity. However, the Al/K ratios hardly decline at the beginning of Stage 4 and increase even strongly at the end of the stage. Hence, weathering on the continent seems not to be greatly reduced. The higher pollen percentage values of Poaceae (10%) and Cyperaceae (18%) indicate a change in vegetation to more open forest and grassland. However, percentages of the rain forest (12-13%) decrease only slightly and those of the Afromontane forest maintain at ca. 12%.

The vegetation distribution during **Stage 3** is similar to that of Stage 4. The Al/K-ratio is at about the same level as in Stage 4, but for an interruption during the middle of Stage 3 (ca. 50-40 ka). After that, freshwater diatom assemblages seem to indicate an increase of river discharge between 35 and 40 ka (Gasse et al. 1989) parallel to an increase in the Al/K ratio. During the phase of lower Al/K-ratios, flux values of *Brigantedinium spp.*, *N. labyrinthus*, and *I. aculeatum* slightly increase. Also pollen percentages of Poaceae have high values during the middle period of Stage 3. However, there is no reaction in the curve of forest elements that would indicate fluctuations in precipitation as inferred from both the Al/K and the dinoflagellate record. An explanation that draws on the effects of low sea surface temperatures (Schneider et al. 1995) during the period remains unsatisfactory for two reasons. Low SST's would reduce the amount of moisture of the lower atmosphere and lowering of the atmospheric temperatures in the region should have increased the area of the Afromontane forest.

Exceptional conditions during Stage 3 were also recorded at Site GIK16867 (Marret 1994a; Dupont et al. 1998). An oceanic and tropical environment at that site is reflected by the relative high percentages of *I. aculeatum* and *N. labyrinthus* and the low percentages of *T. vancampoae*. Enhanced productivity of the surface waters situated at the eastern end of the

oceanic upwelling area, is alternately recorded by high percentages of *Brigantedinium spp.* and *N. labyrinthus*. Correlation of high oceanic productivity and enhanced atmospheric circulation is recorded in most of the 700,000-year record. An exception forms Stage 3, when high oceanic productivity occurred under a regime of rather weak atmospheric circulation. Warm and saline surface waters are indicated by percentages of *I. aculeatum*. The combination of high *Brigantedinium spp.* percentages with high *I. aculeatum* percentages may indicate a seasonal input of nutrients during Stage 3.

For **Stage 2**, the correlation between marine and terrestrial records is more straigthforward. The sharp decrease of the representation of the rain forest (down to 5%) correlates with the decline of the Al/K record, both indicating reduced precipitation and reduced weathering on the continent. Existence of open forest and grassland is reflected by higher pollen percentages of Cyperaceae (max. 30%) and continuing high percentages of Poaceae pollen (12-16%). Also the representation of Afromontane forest increases by slightly higher pollen percentages of *Podocarpus* (max. 18%). A dry and cold climate is inferred. The dinoflagellate record indicates high nutrient levels in combination with low sea surface temperatures shown by the alkenone SST's. High nutrient levels may have caused diatom blooms during Stage 2. Extremely high opal accumulation rates indicating a large biogenic opal production and, therefore, high surface productivity and nutrient levels during Stage 2 were found in core T78-33 in the Congo fan region at 5°11’S 7°58’E (Jansen & Van der Gaast 1988).

High humidity during **Stage 1** is indicated by the high percentages of rain forest taxa (max. 20%). Mangroves increase with the sea level rise of the transition between Stages 2 and 1 and *Rhizophora* pollen percentages reach their maximum (8%) in the early Holocene. Al/K ratios increase and so does total dinoflagellate cyst influx. Again, increased fresh water discharge seems unfavourable for the dinoflagellates. Conditions comparable to Substage 5e occur again in Stage 1. Also fresh water diatoms indicate increased Congo discharge (Gasse et al. 1989). At the end of Stage 1, the Al/K ratio corroborates a tendency to lower river discharge reflected in the dinoflagellate record by increased values for *O. centrocarpum* and *S. delicatus*.

The correlation between alkenone derived sea-surface temperatures, river discharge, and rain forest expansion - seen for Stages 6, 5, 2, and 1 (Fig. 5) - may be explained as follows: Warm surface waters of the Gulf of Guinea allow the monsoon to take up more moisture that finds its way back as enlarged fresh-water discharge of the Congo river. The effect of reduced salinity of the surface waters is found in the rarification or disappearance of dinoflagellate cysts of *Impagidinium aculeatum*. Rain forests spread under warm and humid conditions in central Africa, while afromountainous *Podocarpus* forest had their largest extension during cool and moist periods. Full glacial periods (Stages 6 and 2) show a reduced forest cover, increased aridity, and decreased river discharge. Reduced Congo discharge and increased relative aridity in equatorial Africa during Stages 6 and 2 has already been inferred from the ratio of phytoliths to fresh-water diatoms (Jansen et al. 1989).

Table 3: Phase shifts at the frequency 1/23 ka (coherency at the 90% level)

	precession (June, N.H.)	alkenone SST	min. K/Al ratio
min. K/Al ratio	80 ± 25	4 ± 10	0
min. I. aculeatum (flux)	69 ± 12	-12 ± 6	-15 ± 5
rain forest (pol.%)	90 ± 12	13 ± 4	10 ± 10

Spectral analysis

To test the correlation between SST, precipitation and run-off, marine surface salinity, and vegetation in the Congo basin, we carried out a spectral analysis using Welch Overlapping Segment Averaging (WOSA) with two segments, a Hanning window, and a Lomb-Scargle Fourrier transform on inequidistant data (Schulz 1996; Schulz & Stattegger 1997). Beforehand we tested on the existence of harmonic components after Siegel (λ = 0.4, α = 0.01) in four series: K/Al-ratios, alkenone-temperatures, rain forest pollen percentages, and cyst flux of *I. aculeatum.* Average sample interval of the K/Al-data was 1 ka, the other data series have average sample intervals of 2 ka. All series contained harmonic components and all showed significant periodicity in the precessional 23 ka band. The power spectra of the K/Al-ratios, the rain forest pollen percentages, and the *I. aculeatum* fluxes showed ca. 40% of their variance at 23 ka. Only the power spectrum of the alkenone temperatures showed more variance at 100 ka and only 6% of the variance at 23 ka (Fig. 6). All cross-correlated combinations of palaeodata turned out to be coherent at frequencies around 1/23ka (α = 0.10). Phase angles with precessional insolation (June, Northern Hemisphere) ranged between 70 and 90°, the phase shift estimates among each other did not significantly deviate from zero (Table 2).

Spectral analysis indicate that the responses between SST, chemical weathering and run-off, salinity fluctuations of the marine surface waters, and the vegetation in the Congo basin are more or less direct and that a causal relationship between high SST's the tropical southeastern Atlantic, a wet monsoon, more precipitation and run-off, lower salinity of the marine surface waters, and expansion of the rain forest may be postulated. Schneider et al. (1996) concluded that low-latitude insolation in the Northern Hemisphere and changes in the thermal gradient in the Southern Hemisphere can be regarded as primary forcing mechanisms for surface water changes in the eastern South Atlantic.

Fluctuations of SST, salinity, river discharge, and rain forest expansion do not follow the same pace as the ice-volume and the glacial stages. Several short-time fluctuations during stages 6 and 5 underline the importance of precessional variation of the monsoon climate corroborating findings of among others McIntyre et al. (1989), and Schneider et al. (1995). Also Prell & Van Campo (1986) inferred from the correlation between pollen and upwelling records from the Arabian Sea of the last 140 ka that stronger monsoons occurring during interglacial intervals are in phase with precession.

Productivity of the surface water as indicated by flux values of the dinoflagellate cyst *Brigantedinium spp.* is more related to glacial-interglacial variation reflecting a stronger Benguela Ocean Current and an intensified South Atlantic cyclonic gyre during times of large global ice volume (Mix & Morey 1996). Records from the Congo fan area of diatoms, planktonic foraminifera, and radiolaria show an increase of high-fertility species in cold periods caused by upwelling in relation to intensified oceanic circulation. The stronger glacial production is corroborated by a maximum accumulation of biogenic opal during Stages 6 and 2 (Jansen et al. 1989; Jansen 1990). Wind transport of fresh water diatoms was found for dry periods at 15-20 and 270 ka (Gasse et al. 1989). Pollen flux in the marine sediments of Site GIK 16867 in the northernmost Angola basin (Dupont et al. 1998) and of Site GeoB 1016 at the Angola margin (Shi & Dupont 1997) may be used as a proxy for wind vigor. It fluctuates in concordance with the glacial-interglacial rhythm and is high during Stages 6, 4, and 2. The short-term monsoonal variation is less prominent in this wind-strength proxy. In contrast, pollen flux of the site under discussion is strongly influenced by the Congo river discharge. Therefore, a correlation of wind strength and pollen flux is not expected at Site GeoB 1008.

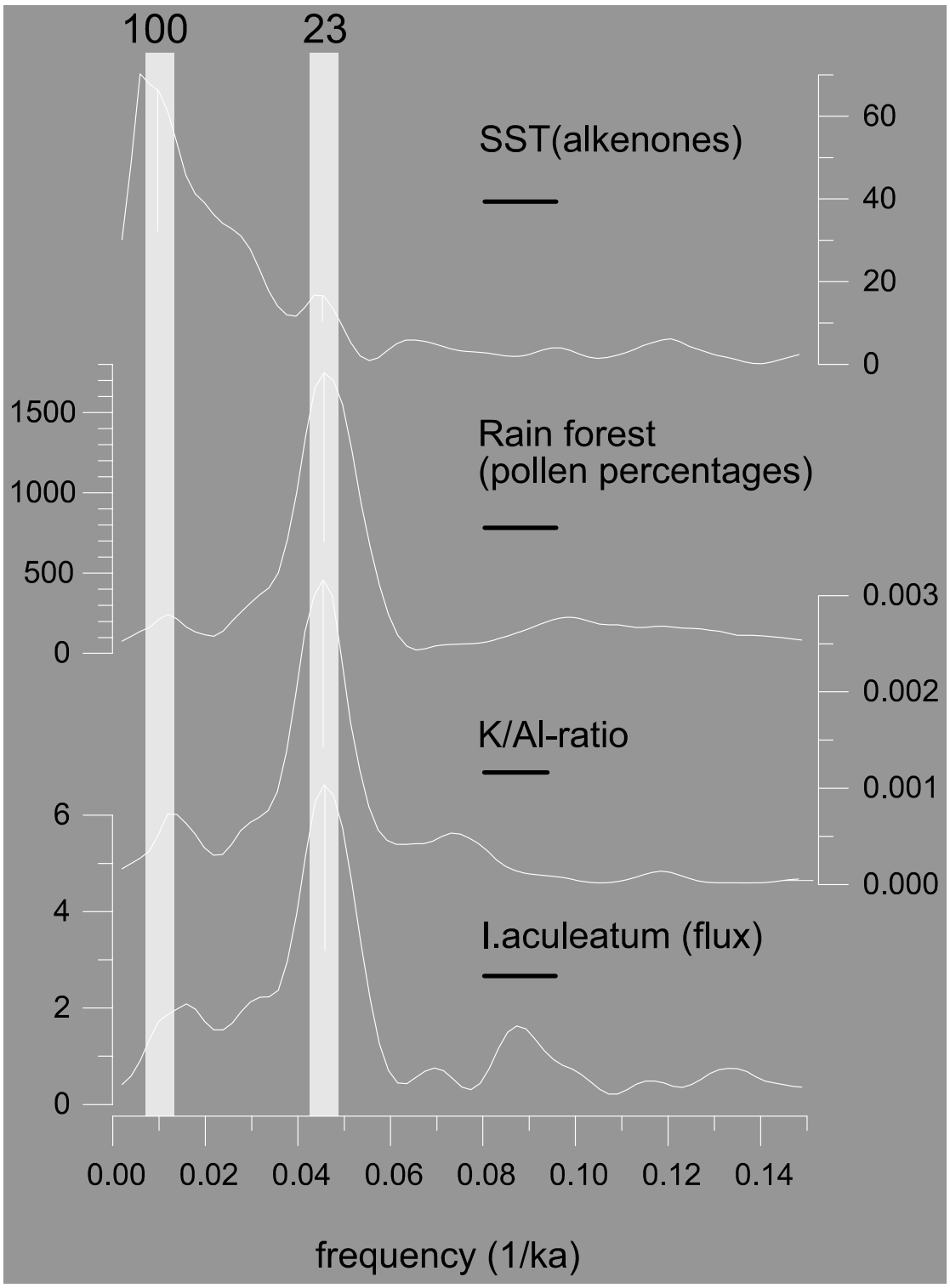

Figure 6: Power spectra of four palaeoclimatic time series (WOSA, Lomb-Scargle Fourier analysis using two segments and a Hanning Window) Lower confidence limits with $\alpha = 0.10$. Horizontal bars indicate bandwidth.

The above described situation holds for Stages 6, 5, 2, and 1. However, Stage 3 and to a lesser extent Stage 4 show a different type of variation. Precessional insolation variation is much weaker than during Stages 6 and 5. During early Stage 3, relative strong winds are contemporaneous with extremely low SST's while humidity on the continent stays comparatively high and fluctuations of the Congo-river discharge are rather small. Also the changes in ocean productivity are less than expected. It seems that during Stages 4 and 3 the

central African climate is decoupled from variation in the Eastern South Atlantic. Another source of humidity for central Africa may be sought in the Indian Ocean.

Conclusions

Palynological investigations were carried out on a marine piston core GeoB 1008-3 from the Congo fan. The resulting dinoflagellate cyst and pollen diagrams cover the last 190 ka with a time resolution of 2 ka. They are compared to the Al/K ratio that is influenced by the weathering conditions on the continent and the fresh water discharge of the Congo river.

During the last 190 ka marine conditions in the area of the Congo plume are characterised by a high nutrient level. The dinoflagellate cyst flux seems to react more sensitive to fluctuations in salinity.

During phases with larger (parts of Stage 6, Substage 5a, beginning and ending of Stage 3) and largest freshwater input (Substage 5e and Stage 1) into the eastern equatorial Atlantic, the dinoflagellate cyst flux decreases strongly. An exception occurred during the humid Substage 5c, when a bloom of the neritic dinoflagellate *Lingulodinium polyedrum* caused a high flux of the cyst *Lingulodinium machaerophorum*.

During the arid and colder Stages 6 and 2, the marine surface conditions are characterised by a high nutrient level combined with a high salinity level indicated by a high total dinoflagellate cyst flux especially of *Brigantedinium spp.* and *Impagidinium aculeatum*.

The climate changed from Stage 6 to Stage 5 to warmer and more humid conditions. During Stage 5, three periods show high freshwater discharge and high monsoon activity (5e, 5c and 5a). Substages 5d and 5b are characterised by cooler but probably not very cold conditions and intermediate humidity as indicated by the records of *Podocarpus*, alkenone derived SST's, and chemical wheathering.

Also during Stage 6, the Al/K ratio shows three phases (denoted as zones 6e, 6c and 6a) corresponding to a reduced representation of the rain forest, in which the influence of freshwater is small due to low precipitation at the continent. During these phases boreal summer insolation is minimal. The opposite conditions prevail in the periods between, zones 6d and 6b, being moister phases with larger Congo river discharge.

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