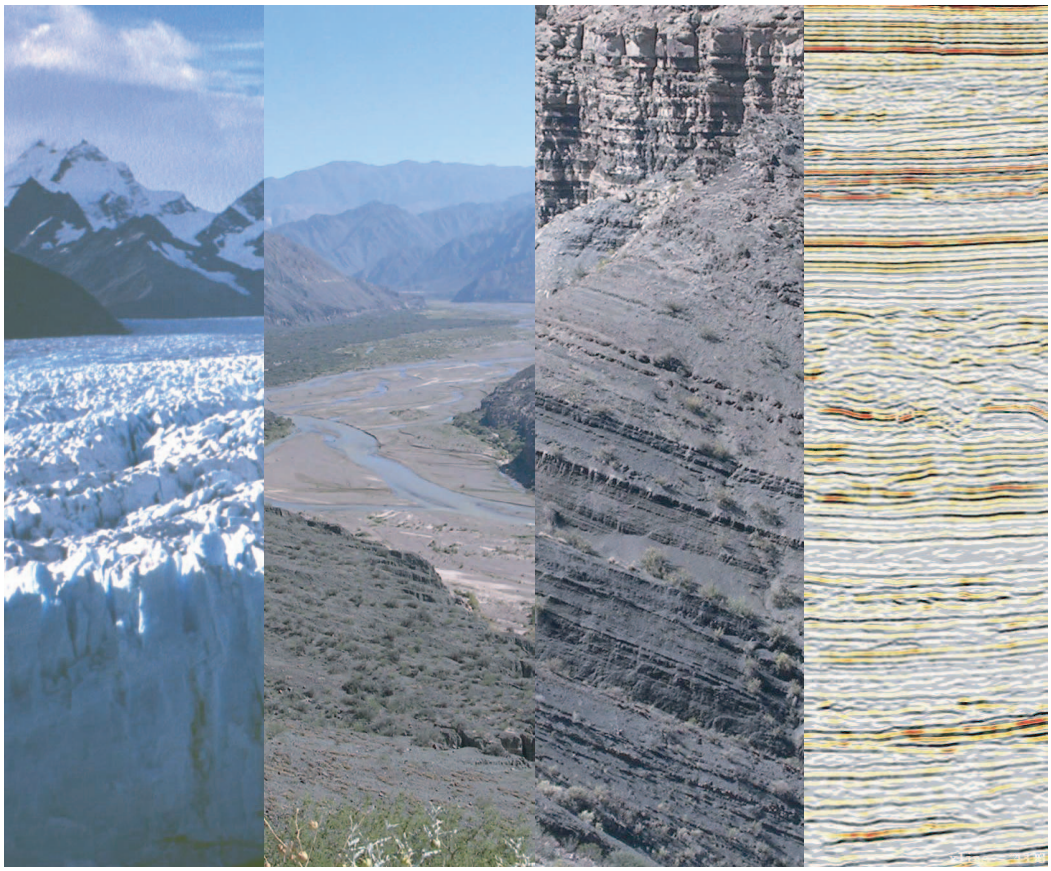
EXTERNAL CONTROLS ON DEEP-WATER DEPOSITIONAL SYSTEMS



Edited by:
BEN KNELLER
BG Professor of Geology, Department of Geology and Petroleum Geology, University of Aberdeen, AB24 3UE, U.K.
OLE J. MARTINSEN
StatoilHydro ASA, Technology and New Energy, Research Centre, P.O. Box 7200, NO-5020 Bergen, Norway
AND
BILL McCAFFREY
University of Leeds, School of Earth Sciences, Leeds, LS2 9JT, U.K.

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THE CONGO DEEP-SEA FAN AS AN ARCHIVE OF QUATERNARY CHANGE IN AFRICA AND THE EASTERN TROPICAL SOUTH ATLANTIC (A REVIEW)

LYDIE M. DUPONT
MARUM - Center for Marine Environmental Sciences, University of Bremen, Leobenerstr, D-28359 Bremen, Germany
e-mail: dupont@uni-bremen.de

Abstract: A wide variety of proxies has been applied to study the terrestrial input in the Congo deep-sea fan area, the composition of its overlying waters, and the land–ocean interactions of the past 1 to 2 million years. These proxies include stable isotopes of foraminifers, total organic carbon (TOC), alkenone-derived sea-surface temperatures (SST), biomarker content and compound-specific stable isotopes, element composition, clay minerals, pollen and spores, dinoflagellate cysts, diatom valves, and opal. Not only the sedimentation in the deep-sea fan but also the productivity of the overlying waters is strongly influenced by the Congo River discharge and its fluctuations depending on the strength of the monsoon. SST and marine productivity are further affected by wind- and river-induced upwelling. A direct relation between SST, precipitation in the Congo Basin, vegetation cover, chemical weathering, and runoff could be established for the past 200 thousand years. Increase of mean global ice volume between 1000 and 500 ka suppressed the precession forcing of trade-wind zonality and monsoonal river runoff, leading to a higher production of nonsilica marine organisms compared to diatoms, and increased eolian transport of terrigenous material.

Key words: Congo deep-sea fan, paleoclimate, African monsoon, Quaternary

INTRODUCTION

The Congo River, with an average discharge of ~ 45 x 10^{13} m^3 s^{-1}, is the second largest river in the world, draining the heart of Africa (Fig. 1; Eisma and Van Bennekom, 1978). The suspension load at the Congo River mouth is relatively low and consists largely of kaolinite, quartz, organic matter, and iron hydroxides (Eisma et al., 1978). About half of the suspended matter carried seaward by the river is deposited in the estuary, at the head of the canyon, and in the mangrove swamps north and south of the main channel. Only less than 5% of the suspended material reaches the deep sea (Eisma et al., 1978). The resulting deep-sea fan system consists of sediments that have been built up by the river. These sediments are instrumental in the study of climatic and environmental developments on large parts of the African continent in relation to the tropical South Atlantic. The aim of this paper is to give a short overview of the work that has been done in the past decades on Quaternary sediments of the Congo deep-sea fan, to show what proxies have been used, and to mention some typical interactions between the Congo River and the South Atlantic.

THE MODERN CONGO DEEP-SEA FAN IN THE TROPICAL SOUTHEAST ATLANTIC

Under the influence of the outflow of the Congo River, a deep-sea fan has developed at the foot of the continental slope of the northern Angola Basin. The fan is fed via the Congo deep-sea canyon, which eroded deeply into the continental shelf and slope. The canyon directly connects the river to the deep sea (Savoye et al., 2000). The present sediment flux of the Congo River into the deep ocean is estimated between 30 and 40 million metric tons per year (Jansen, 1990). The river canyon system traps a large part of the river-borne sand and silt fraction, essentially starving the shelf and slope of coarse detritus (Jansen et al., 1984), but a significant portion of the suspended sediment load is carried along shore northwestwards (Giresse et al., 1981).

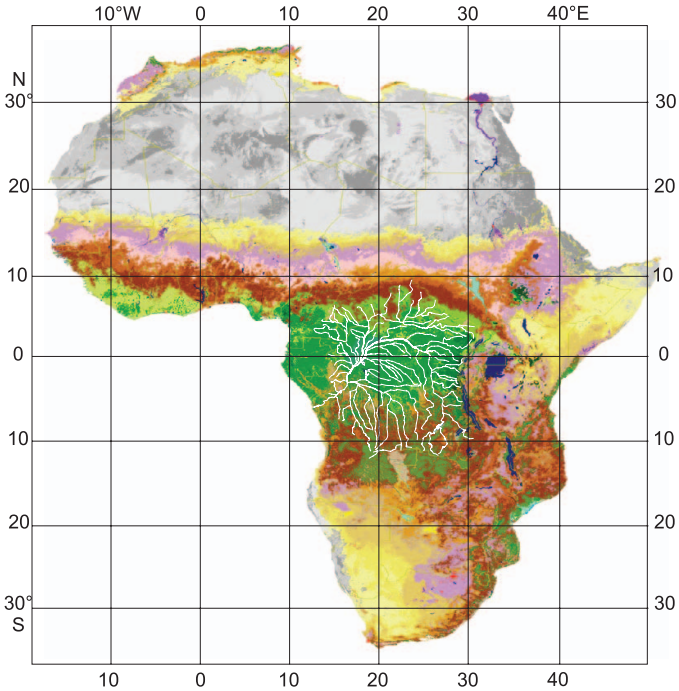

FIG. 1.—Satellite image of the vegetation of Africa derived from a land-cover classification produced with data acquired in 2000 from the VEGETATION instrument onboard the SPOT4 satellite with additional data from the radar instruments onboard the ERS and JERS satellites (Mayaux et al., 2004). Closed forest in dark green, savannahs in shades of brown, grasslands in light purple, semi-deserts in yellow, and deserts in gray. The Congo River system is highlighted. Its drainage area covers most of the central rain forest area of Africa.

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Oceanographic Setting

The freshwater outflow of the Congo River forms a plume which is detectable up to 800 km from the river mouth (Van Bennekom and Berger, 1984). The rapid freshwater flow, forced by a narrow estuary (Fig. 2), induces upwelling of subsurface ocean water rich in nutrients, resulting in high rates of primary productivity.

The Benguela Ocean Current, the South Equatorial Counter Current, and the Angola Current together form the eastern South Atlantic cyclonic gyre (Fig. 2; Peterson and Stramma, 1991; Schneider et al., 1995; Schneider et al., 1997). North of the Congo freshwater plume, at about the equator, upwelled colder waters of the Equatorial Under Current form a front with the warm waters of the Bight of Biafra. South of the Congo River mouth, between 10° and 16° S, the interaction between the eastward-flowing South Equatorial Counter Current, the southward-flowing Angola Current, and the northwestward-flowing Benguela Ocean Current creates a complex pattern of upwelling of nutrient-rich subsurface waters into the euphotic zone. At the southern end, between 15° and 17° S, the Angola–Benguela Front is situated at the convergence between the warm Angola Current and the cold Benguela Coastal Current, which is a coastal northward branch of the Benguela Ocean Current (Meeuwis and Lutjeharms, 1990).

The South Atlantic gyre circulation is masked by a wind-driven surface layer 10 to 20 m thick. The wind field over the Southeast Atlantic is dominated by the southeast trade winds. North of the Angola–Benguela Front, the winds turn clockwise due to the increasing influence of the continental heating on central Africa, which induces the onshore-directed African monsoon. The Angola–Benguela Front is closely linked to the shift in

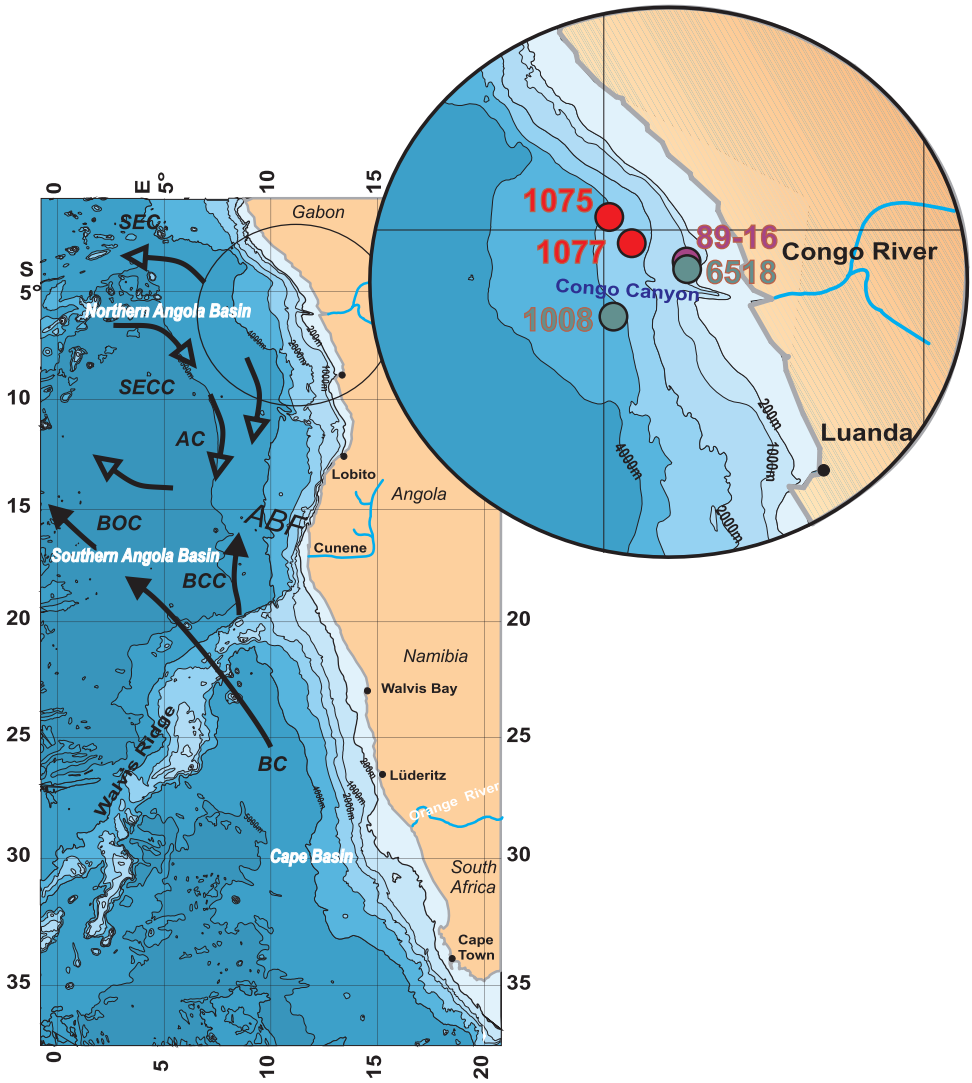

FIG. 2.—Map of the eastern South Atlantic Ocean and a detail of the Congo deep-sea fan system. The numbers refer to coring sites of the Netherlands Institute of Sea Research (89-16), the Department of Geosciences of the University of Bremen (1008 and 6518), and the Ocean Drilling Program (1075 and 1077), on which sediments most of the mentioned studies have been carried out. Surface currents over the Angola Basin: SECC, South Equatorial Counter Current; AC, Angola Current; BCC, Benguela Coastal Current; BOC, Benguela Ocean Current; BC, Benguela Current; ABF, Angola–Benguela Front.

the direction of the zonal component of the southeast trade winds (Shannon and Nelson, 1996; Kim et al., 2003).

Iperen et al. (1987) could relate the diatom distribution in surface sediment samples of the Congo deep-sea fan to the hydrographic conditions. They distinguish four groups associated with ocean surface conditions. Group 1, dubbed the Plume group, consists of planktic and meroplanktic diatom species indicating the overlying waters of the Congo River plume. Schefuß et al. (2004) found large concentrations of diatom lipids in these sediments. Groups 2 and 3, composed of *Thalassionema nitzchioides* and *Chaetoceros* resting spores, respectively, are associated with high productivity. Group 4 is formed by a mixture of subtropical and tropical species, and is related to the warm waters of the Southern Equatorial Counter Current. Group 4 consists of diatom species mostly described as subtropical; its distribution is restricted to East Atlantic waters south of the Congo River mouth.

Pathways of Terrigenous Material into the Congo Deep-Sea Fan

The distribution patterns of well-preserved terrigenous components in the marine surface sediments of the Angola Basin reflect pathways of particle transport into the ocean. The distribution of freshwater diatoms indicates that they are brought in by turbidity currents and river discharge, while the distribution of phytoliths (siliceous bodies of the leaves of vascular plants, particularly abundant in grasses) suggests that they are transported mainly by the southeast trade winds (Iperen et al., 1987). In the northern Angola Basin, transport of pollen from the tropical rain forest by the rivers dominates (Dupont and Wyputta, 2003), although there are indications of long-range transport of pollen from the Angolan mountainous forest by the southeast trade winds to the distal parts of the Congo deep-sea fan (Dupont et al., 2007). Also the distribution of terrestrial organic compounds in marine surface sediments reveals their main pathways to the ocean (Schefuß et al., 2003; Schefuß et al., 2004). The discharge of the Congo River supplies the sediments mainly with organic material from C3 plants. The distribution of the wax concentration (*n*-alkane concentration normalized to total organic carbon) in the Angola Basin indicates primarily transport by the southeast trade winds (Fig. 3; Schefuß et al., 2003).

Constituents of the wax layer on the leaves of terrestrial plants (*n*-alkanes) are easily removed from the leaf surface by rain or wind and are common organic components of eolian dust. The wax layers on the leaves are much thicker on plants from arid to semiarid climates than on the leaves of evergreen rain forest and swamp forest species of the Congo Basin, which explains the preferred wind transport of their components.

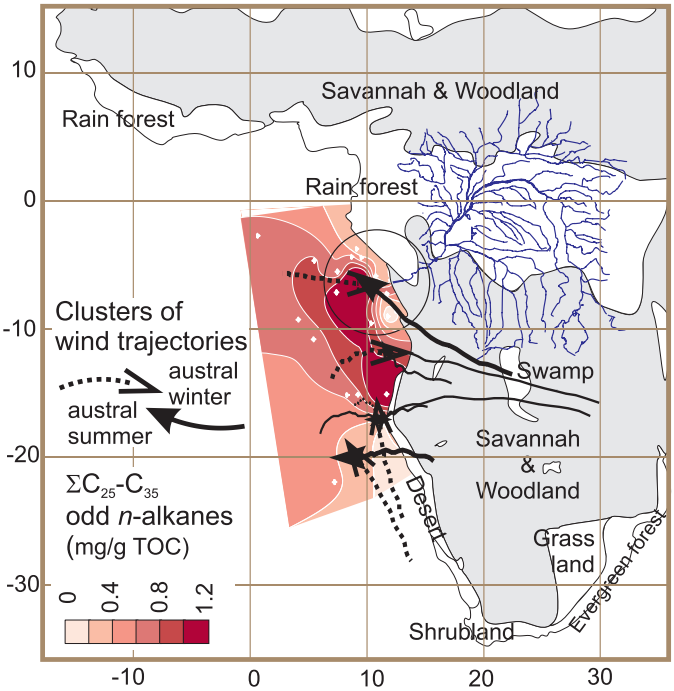

FIG. 3.—Distribution of odd *n*-alkanes of plant waxes in marine surface sediments of the Southeast Atlantic (adapted after Schefuß et al., 2003). White crosses denote the location of the samples. Arrows denote clusters of back trajectories for austral summer (December, January, February, dashed arrows) and austral winter (June, July, August, solid arrows) to four specified locations in the Southeast Atlantic (adapted after Dupont and Wyputta, 2003). Gray areas on the continent indicate the extent of savannah and woodland vegetation. The main tributaries of the Congo River are shown. The distribution of wax components indicates that they are transported primarily by southeasterly winds from the dry areas in southern Africa during the austral winter season.

DEPOSITIONAL SYSTEM OF THE CONGO DEEP-SEA FAN DURING A GLACIAL–INTERGLACIAL CYCLE

Holocene to Pliocene sediments of the northern Angola Basin are composed of moderately bioturbated, greenish gray and olive gray glauconite-rich clay, diatomaceous clay, and nannofossil-rich clay (Pufahl et al., 1998). Sedimentation is dominated by the rain-out of suspended clay derived from the Congo River and by pelagic settling of biogenic debris (Giresse et al., 1982; Bongo-Passi et al., 1988). Nutrient load and river-induced upwelling result in organic-rich sediments (2–3 wt%), in which sulfate reduction leads to complete removal of sulfate in the upper 30 m. Correspondingly, pyrite is ubiquitous and carbonate preservation is poor. A relationship between organic-matter degradation and $CaCO_3$ dissolution is indicated by pore-water studies on sediments of an ODP slope transect just north of the Congo Canyon (Murray et al., 1998).

Berger et al. (1998) concisely formulated the complex processes and interactions that are to be considered in assessing the sediments of the Congo deep-sea fan: "The depositional system includes the sediment-producing drainage basin of the Congo River; the river transport; the redistribution processes, including possible intermediate storage on the shelf; and marine processes … [which] include productivity patterns of both the open ocean and the coastal ocean, as well as changing carbonate chemistry of deep waters" (Berger et al., 1998, p. 565). In the following, I briefly review some methods and techniques that have been employed trying to understand the system.

Estimates of Marine Productivity

Ocean productivity relates to the hydrographic situation, which is influenced by ocean currents, wind stress, and nutrient supply either by upwelling (thermocline depth) or fluvial input. To study marine productivity and export productivity in particular, several proxies, such as carbonate content, total organic carbon, opal content, and accumulation rates of diatom valves

and dinoflagellate cysts have been used. Fluctuations in paleoproductivity proxies for the past 200 thousand years from core GeoB 1008-3, located south of the Congo canyon (Fig. 4), are discussed briefly in this section.

Using carbonate stratigraphy, Jansen et al. (1984) inferred increased carbonate production during interglacial periods of the late Quaternary. However, deposition of carbonate depends not only on its production but also on its preservation in the sediment, which in turn depends on the carbonate saturation of the deep waters. This carbonate saturation is linked to the water mass and is a function of water age and deep ocean circulation. Generally, carbonate saturation is less in glacial stages than in interglacial ones. The increased carbonate production during interglacial periods is, therefore, emphasized by reduced dissolution of carbonate compared to glacial stages. This relationship breaks down in the organic-rich sediments, where carbonate preservation is poor in interglacial periods.

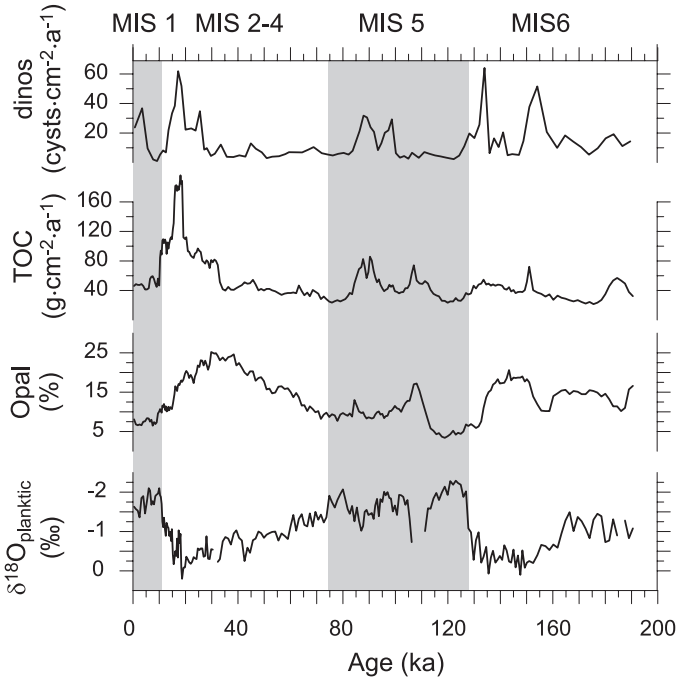

FIG. 4.—Paleoproductivity proxy records of core GeoB 1008-3 at 6° 35' S and 10° 19' E (south of the Congo deep-sea canyon) covering 200 kyr. Gray bars underlie Marine Isotope Stages (MIS) 1 and 5. The age model is constructed by correlating stable oxygen isotope values with SPECMAP (Schneider et al., 1995). From top to bottom. Accumulation rates of total dinoflagellate cysts per cm^2 per year reach maxima during the last glacial maximum and the late part of Marine Isotope Stage 6 (Dupont et al., 1999). Accumulation rates of total organic carbon per cm^2 and year (Schneider et al., 1997) are a function of marine productivity, terrestrial input, and degradation of organic matter in the sediment. Weight percentages of biogenic opal (Schneider et al., 1997) indicate the periods with high silica export production. These records show similar patterns, indicating enhanced marine productivity during glacial stages (MIS 2–4, MIS 6), especially during the later parts of the glacial. Bottom, stable oxygen isotopes of the planktic foraminifer *Globerinoides ruber* pink versus PeeDee Belemnite standard (Schneider et al., 1995).

Late Quaternary Congo Fan sediments are rich in opal, which is the result of additional fluvial supply of dissolved silica during humid climates (Schneider et al., 1997). During colder and more arid glacial conditions, the total paleoproductivity was high because of increased upwelling linked to the increased trade-wind intensity (Fig. 4). In general, opal content and accumulation rates of siliceous microfossils, which is dominated by marine diatom valves and resting spores, indicate higher marine production during glacial periods (Uliana et al., 2001, 2002).

A similar pattern is shown by the accumulation rates of dinoflagellate cysts (Fig. 4; Dupont et al., 1999). However, the accuracy of accumulation rates depends strongly on the resolution and precision of the age model. Moreover, dinoflagellate cysts are susceptible to oxygenic degradation, which would be higher when the deep ocean ventilation is better during periods of vigorous Atlantic overturning circulation. The high cyst accumulation rates at the last glacial maximum and the penultimate glacial maximum probably are a combined effect of increased sedimentation rates and better preservation.

Total organic carbon (TOC) is often used as a first estimate of marine productivity. The TOC signal shows high values during late Quaternary glacial stages in combination with reduced river discharge (Fig. 4; Schneider et al., 1996). However, the TOC signal is a problematic tool for estimating paleoproductivity because the degree of degradation of organic matter and the amount of imported terrestrial organic matter are difficult to quantify. To use TOC as an estimate of oceanic productivity, the marine and terrestrial component must be distinguished. Often the stable carbon isotope ($\delta^{13}C$) signature is used to calculate the autogenic marine organic carbon component and the input of terrestrial organic matter. Values of $\delta^{13}C$ of marine matter are less negative than those of terrestrial matter provided that the terrestrial matter is derived predominantly from C3 plants. The values for derived matter of C4 plants, however, are more similar to the marine ones. A change to enhanced input of material from C4 plants (for instance, tropical grasses) during glacial times would lead to underestimation of the terrestrial input if $\delta^{13}C$ values of TOC are used to estimate the marine terrestrial ratio of organic matter (Holvoeth et al., 2001; Wagner et al. 2003).

Many proxies have been used to study the fluctuations in the marine system. Most of them are associated with marine surface productivity, but none of them can be used unequivocally as a quantitative estimate of marine export productivity. The carbon content in the sediment depends both on export production and on dissolution. TOC is a function not only of marine productivity but also of degradation, and of input of terrestrial carbon. The opal content estimates only the silica production. Content of dinoflagellate cysts is susceptible to oxygenic degradation. Use of accumulation rates depends strongly on the accuracy of the age model, which often lacks the resolution to trace high-frequency fluctuations, and relative abundances are affected by fluctuations in the total terrestrial input diluting the marine signal.

Terrestrial Input

Clay minerals in the Congo deep-sea fan are mainly of terrestrial origin. Three major processes contribute to the clay-mineral assemblage of the Congo deep-sea fan: river discharge, dust supply by the trade winds, and erosion of the exposed shelf during periods of lower sea level (Petschick et al., 1996; Gingele et al., 1998). Clay-mineral tracers of smectite crystallinity and illite chemistry have been used to assess fluctuations in the Congo River freshwater discharge. Smectite crystallinity distinguishes river-induced smectite from that of other sources, and illite

chemistry is used to determine its fluvial or eolian origin. These proxies indicate that river discharge fluctuated in tune with the late Quaternary precessional cycles of the African monsoon (see also next section). Kaolinite/smectite ratios also show precessional variation during interglacials, but the signal is disturbed during glacials, when increased northeast trade winds blow additional eolian kaolinite-rich dust to the area of the Congo fan (Petschick et al., 1996; Gingele et al., 1998).

Organic matter (OM) is an important constituent of the sediments from ODP Site 1075 in the northern Congo fan (for location see Fig. 2). Petrography of these sediments indicates that old (low-reactive) OM from soils and rather fresh (reactive) terrigenous OM are mixed with fresh (highly reactive) marine OM. Increase of terrestrial OM enhances marine productivity, but subsequent enhanced degradation of fresh OM might reduce the TOC in the sediment to a minimum (Holvoeth et al., 2003). Strong increase of river discharge (possibly in the form of flash floods) is suggested by the occurrence of abundant cuticles and remnants of freshwater algae in combination with high values of pollen flux and with increased sedimentation rates in core T89-16 (Marret et al., 2001).

Attempts have been made to estimate the magnitude of Congo River discharge by use of the variation in the iron content of sediments of ODP Site 1075, measured by X-ray fluorescence core scanning. As in the magnetic-susceptibility record, high iron values are expected during humid phases in which the river discharge is high. However, the iron content is influenced by weathering conditions and vegetation cover on the continent as well as by sea-level variations altering the sedimentation pathways for the river sediment load (Jahn et al., 2005).

Iron content and magnetic susceptibility in the Congo fan are also influenced by redistribution of sediment from the shelf to the continental slope and the deep sea, which is dependent on sea-level change and indirectly on global ice volume. Sediments are eroded from the shelf and redistributed on the slope and the Congo deep-sea fan during transgression or sea-level rise. This is illustrated by increased magnetic susceptibility and higher iron content in sediments laid down during terminations and stage transitions (Fig. 5; Dupont et al., 2001; Jahn et al., 2005).

The same effect is seen in the records of mangrove swamps, which in West Africa are dominated by *Rhizophora*. Relative abundance of *Rhizophora* pollen and *Rhizophora*-derived taraxerol in sediments of the Congo fan show maxima during the transgressions of glacial–interglacial transitions (Versteegh et al., 2004). The supply of mangrove materials is a function of the erosion of flooded mangrove swamp on the shelf and—less importantly—the changing extent of the mangrove habitat during sea-level rise (Scourse et al., 2005).

Although the amount of terrestrial input is thus difficult to quantify, terrigenous components in the marine sediments of the Congo fan provide valuable information about change and development on land. Pollen analysis and compound-specific analysis of terrigenous matter reveal changes in the vegetation of the Congo Basin and the surrounding mountains. The tropical rainforest area is susceptible to precipitation variation and has been replaced by more open vegetation in drier periods, notably during full glacial stages (Fig. 6). Probably reed and papyrus swamps replaced swamp forest in the lower parts of the Congo Basin; on higher ground, close-canopy forests receded and open savannah vegetation spread (Jahns, 1996; Maley and Brenac, 1998; Dupont et al., 2001). The $\delta^{13}C$ record of terrestrial plant waxes (*n*-alkanes) indicates an increase in C4 vegetation (including tropical grasses but also papyrus) during dry periods, corroborating inferences from pollen analysis (Schefuß et al., 2003, Rommerskirchen et al., 2006).

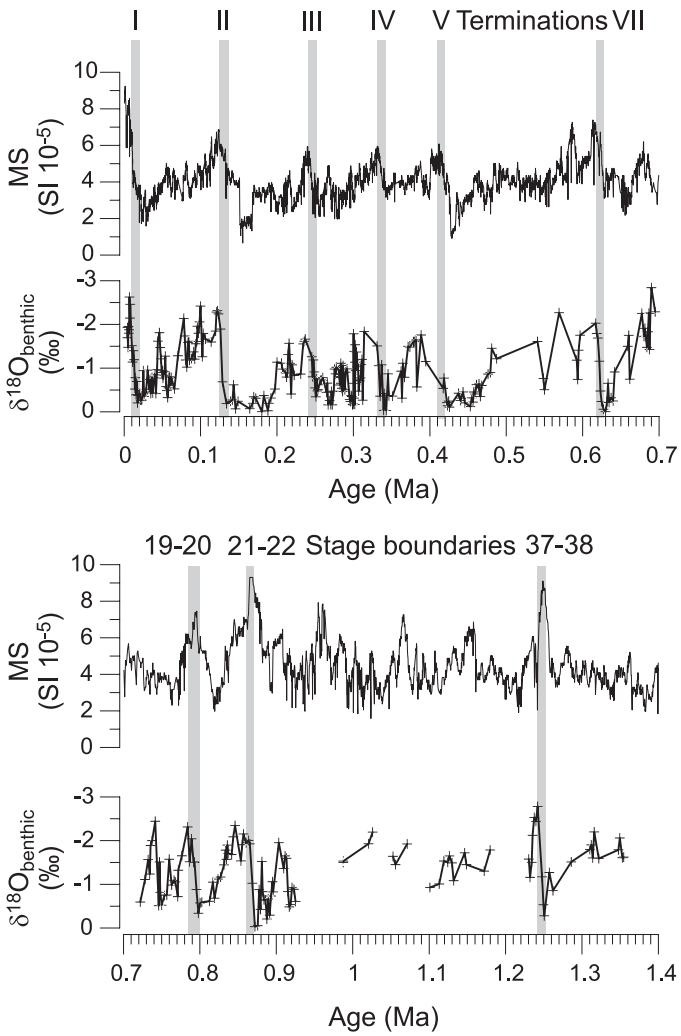

FIG. 5.—Stable oxygen isotopes of benthic foraminifer *Cibicdoides wuellerstiorfi* versus PeeDee Belemnite standard (line and crosses, Dupont et al., 2001) and magnetic susceptibility given in standard units (line, Wefer et al., 1998) for the past 1.4 million years at ODP Site 1077 (4° 79', S 10° 08' E). Gray bars denote terminations (i.e., glacial–interglacial transitions). In the Congo deep-sea fan system, the magnetic susceptibility depends mainly on terrestrial input by the Congo River. Note the early rise of the magnetic susceptibility before the transition from glacial to interglacial, which is attributed to redistribution of terrestrial sediments from the shelf to the slope and deep sea during periods of rapid sea-level rise.

MONSOON VARIABILITY IN RELATION TO SEA-SURFACE TEMPERATURES

A major strength of analyzing terrigenous material in marine sediments is that the terrestrial proxies can be directly correlated to the proxies of marine surface-water conditions and that monsoonal land–sea interactions can be studied on the same material. These studies have been carried out at high (centennial) and medium (millennial) temporal resolution, and trends through the Pleistocene have been discussed. A problem in studies at high temporal resolution, however, is that dating of specific compounds revealed the terrestrial organic fraction often to be older

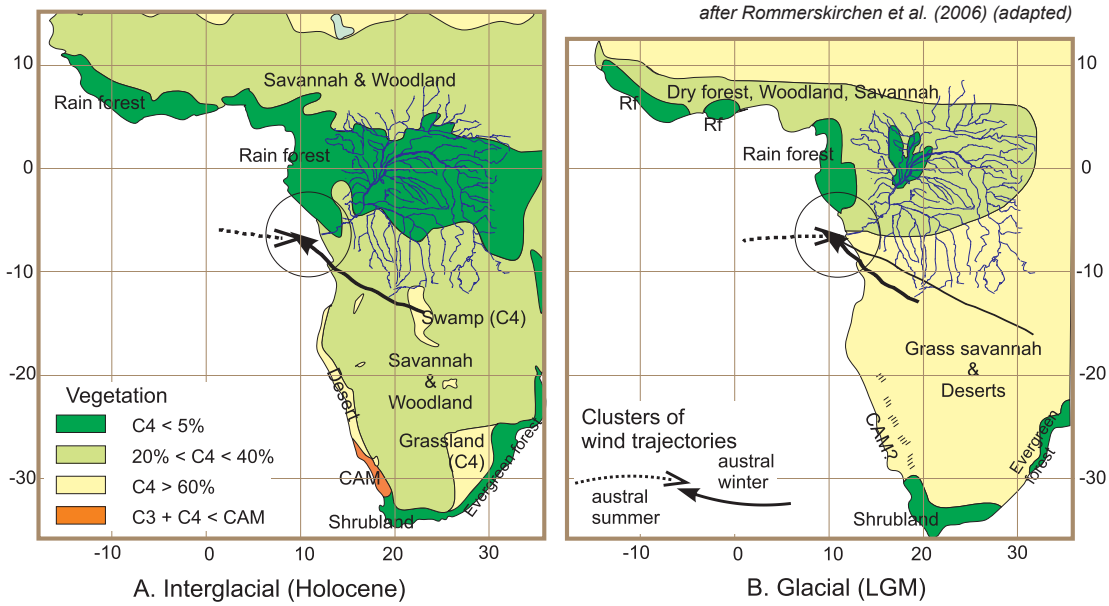

FIG. 6.—Simplified phytogeographical units (color coding/shading according to C4 plant occurrence; see legend) of Holocene and last glacial maximum (LGM) in southwest Africa (after Rommerskirchen et al., 2006) and clusters of wind trajectories (after Dupont and Wyputta, 2003) of the austral summer (December, January, February, dashed arrows) and winter (June, July, August, solid arrows) to core position GeoB 1008-3 at 6° 35' S and 10° 19' E.

than the marine organic fraction and the latter older than the marine calcareous fraction by considerable amounts of time (Mollenhauer et al., 2005).

Nevertheless, Weijers et al. (2007) measured branched tetraether membrane lipids derived from soil bacteria that are thought to be a proxy for continental temperatures on material of GeoB 6518-1 (for location see Fig. 2) covering the past 25 kyr. They compared their continental temperature signal to sea-surface temperatures (SSTs) from the same core, enabling them to evaluate the land–sea temperature difference. The paleo-SSTs have been derived from alkenones produced by haplophyte algae (Schefuß et al., 2005b). Additionally, Schefuß et al. (2005b) used the hydrogen stable-isotope composition of plant-wax lipids from core GeoB6518-1 as an indication of precipitation fluctuations in the terrestrial Congo Basin. Based on these datasets, Weijers et al. (2007) concluded that the thermal pressure gradient expressed as the land–sea temperature difference has had an important control on the precipitation pattern in central Africa over the past 25 kyr.

Superimposed on the glacial interglacial variability, a rhythm with a periodicity of 23 kyr (precession) related to monsoon variability is obvious in many proxies derived from the Congo fan. The strength of the monsoon varies at the precession band, because the heating over central Africa (and Asia) and the land–sea contrast are larger when the irradiation maximum falls in July (Kutzbach, 1987). Obliquity forcing (at periodicities of 41 kyr) is much weaker or lacking.

So SSTs are low during glacials and high during interglacials over the past 200 kyr of core GeoB 1008-3 (for location see Fig. 2), which pattern is superimposed by short-time maxima corresponding to precession minima (Fig. 7). SSTs of the east equatorial South Atlantic depend not only on global SST but also on local (river-induced) upwelling and surface oceanography, which is sensitive to the intensity of the African monsoon (Schneider et al., 1995).

Sediment production and transport in the Congo Basin are a function of monsoon intensity through climate-dependent weathering processes, erosion, and fluvial transport. Clay-mineral records show increased Al-rich illite during interglacials as well as short-time fluctuations corresponding to precession variability (Schneider et al., 1997; Gingele et al., 1998). Variation in the K/Al ratios of core GeoB 1008-3—which is attributed to changes in the kaolinite input by the Congo River—indicates that periods of more intense chemical weathering are promoted by increased monsoonal precipitation in central Africa (Fig. 7; Schneider et al., 1997). Also, relative abundances of tropical-rain-forest pollen from the same core correlate well with both SSTs and K/Al ratios (Fig. 7). The pollen percentages indicate expansion of the rain forest during periods with enhanced rainfall and strong monsoons (Dupont et al., 1999).

Thus, integrated marine and terrestrial evidence from the combined studies of alkenone-derived sea-surface temperatures, K/Al ratios, dinoflagellate cyst assemblages, and relative pollen abundances illustrates the relationship between SST, chemical weathering and runoff, salinity fluctuations of the marine surface waters, and the vegetation in the Congo Basin. Increased Northern Hemisphere insolation during minima in the precession index results in warmer SSTs, heating of central Africa, and strong monsoonal rains, which in turn enhance river discharge, chemical weathering, and expansion of the rain forest.

Through the course of the Pleistocene, fluctuations in the mass accumulation rates of TOC are generally in pace with precession for most of the past 1.7 Myr, and its 100 kyr variability is strong only during the past 500 kyr. Variations in Fe intensity indicating terrigenous input into the Congo deep-sea fan record a 100 kyr rhythm for at least 1.7 Myr and a regularly shifting phase lag with the 23 kyr precession cycle (Jahn et al., 2005). The record suggests that eccentricity modulation of the low-latitude insolation (precession band) directly influenced

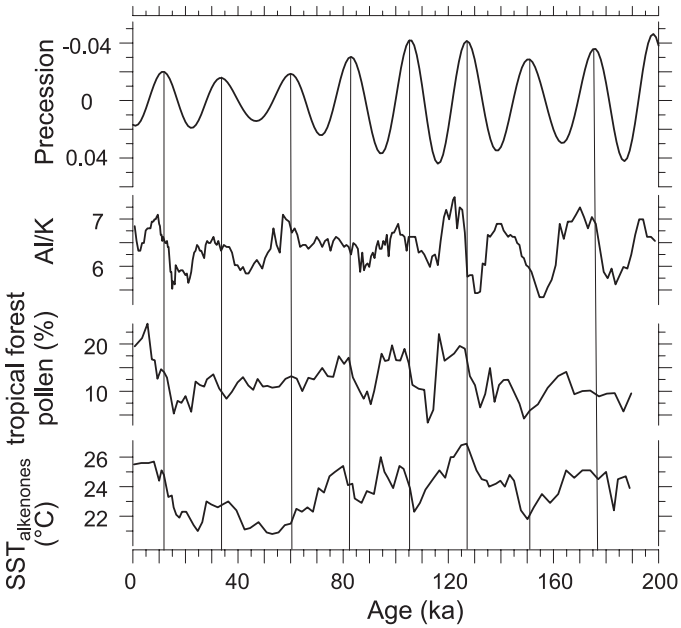

FIG. 7.—Terrestrial and marine records from core GeoB 1008-3 at 6° 35' S and 10° 19' E for the past 200 kyr (same time scale as in Fig. 4). Ratio of Al to K as a proxy for the degree of chemical weathering of clay minerals under humid conditions (Schneider et al., 1995). Relative abundance of pollen from the tropical forest in percentages of total pollen and spores (Jahns, 1996). Sea-surface temperatures (SST) derived from the saturation index of alkenones (Schneider et al., 1995). Top, the precession index after Berger and Loutre (1991). Stronger forcing occurs at minima of precession index. The correlation between the pollen and the clay-mineral record suggests a direct relation between humidity (and river runoff) and the extent of the tropical forest, which is linked to the SSTs of the equatorial South Atlantic. Highest monsoon activity occurs just after the minima in precession index.

the equatorial African monsoon system. Low-latitude climate forcing and response in the tropics might have played an important role in the initiation of the 100 kyr ice-cap cycle (Rutherford and D'Hondt, 2000). Apart from the low-latitude monsoonal variation, records for iron and magnetic susceptibility show additional variation in the see-saw pattern of ice caps, indicating that these records of terrestrial input are influenced by sea-level changes (Fig. 5).

The predominance of low-latitude forcing has been associated with periodic large-river runoff, delivering dissolved silica and terrigenous C3 plant matter into the ocean (Schefuß et al., 2005a). Before the start in the growth of additional global ice mass around 900 ka, precession-band variation was prevalent. The availability of silica led to strong diatom production off the Congo River mouth. After 900 ka, the growing amplitude of the 100 kyr cycle increasingly influenced the tropical environment and the enlarged ice volume increased the strength and zonality of the trade winds. Following the onset of the strong 100 kyr cycles (between 1000 and 500 ka), the wind transport of plant-wax lipids and wind-driven upwelling increased (Schefuß et al., 2003). Over the past 1000 kyr, the ecosystem in the Angola Basin has shown a decreasing importance of diatom productivity relative to other primary producers (due to a lower availability of dissolved silica) and a higher relative importance of wind-driven upwelling (Berger et al., 2002; Schefuß et al., 2005a). The pollen record shows an increase of mountainous elements, in particular during the periods with increased global ice volume after 1050 ka (Dupont et al., 2001). These could well be the result of increased trade winds blowing pollen from the mountain forests of the Angola highlands to the marine sites of the northern Angola Basin.

CONCLUSION

The signals eventually recorded in the sediments of the Congo deep-sea fan system are a mixture of terrestrial and oceanic processes. The processes involved in the depositional system of the Congo deep-sea fan are complex and strongly interlinked. They couple processes dependent on tropical monsoon climate with those dependent on SST and sea-level fluctuations, which fluctuate with changes in global ice volume. The fluctuations on orbital time scales are both linked to low-latitude precession variation (periodicities of 19 and 23 kyr) and, to a lesser extent, high-latitude obliquity variation (41 kyr). To recognize orbital forcing at the 100 kyr periodicity band is complicated, because the signal can be the result of eccentricity modulation of the precession signal or an effect of ice caps that also have a quasi-periodicity of 100 kyr (at least for the past 500 kyr).

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