Mid-Pleistocene environmental change in tropical Africa began as early as 1.05 Ma

L.M. Dupont*
B. Donner
R. Schneider
G. Wefer
Geosciences Bremen, P.O. Box 330440, D-28334 Bremen, Germany

ABSTRACT

Palynological records from the Congo fan reveal environmental change in equatorial Africa occurring 1.05 Ma ago, 100 k.y. before the mid-Pleistocene climatic shift at 0.9 Ma. Prior to 1.05 Ma, a glacial-interglacial rhythm is not obvious in the African vegetation variation. Afterwards, *Podocarpus* spread in the mountains of central Africa mainly during glacials and Congo River discharge decreased. The sequence of vegetation variation associated with the mid-Pleistocene glacials and interglacials differed from that observed during the late Pleistocene. Between 0.9 and 0.6 Ma, interglacials were characterized by warm dry conditions and glacials were characterized by cool humid conditions, while during the past 0.2 Ma glacials were cold and dry and interglacials warm and humid. Our data indicate that before the Northern Hemisphere ice caps dramatically increased in size (0.9–0.6 Ma), low-latitude climate forcing and response in the tropics played an important role in the initiation of 100 k.y. ice-age cycles. During the mid to late Pleistocene, however, the climate conditions in the tropics were increasingly influenced by the glacial-interglacial variations of continental ice sheets.

Keywords: pollen, dinoflagellates, mid-Pleistocene climatic shift, tropical Africa, vegetation.

INTRODUCTION

An increase in the amplitude between ice mass buildup and melting associated with the dominance of the 100 k.y. cycle changed the global climate pattern ca. 0.9 Ma (e.g., Berger and Wefer, 1992; Berger and Jansen, 1994; Mudelsee and Stattegger, 1997). The 100 k.y. cycle might be related to the isostatic rebound, the sluggishness of large ice caps, and/or the modulation by the eccentricity of the precession cycle (e.g. Pollard, 1983). Berger and Jansen (1994) emphasized the role of unidirectional modifications of land morphology by ice erosion in the Arctic for the 100 k.y. cyclicity to become the dominant climate system response to orbital forcing. Alternatively, a gradual long-term decline of atmospheric CO_2 levels induced by tectonic processes could also help to explain the growth of larger ice sheets (see Raymo, 1997, and references therein).

The buildup of excess ice and resulting lower sea levels during ice ages increased the positive feedback of CO_2 forcing and/or amplification (e.g., upwelling-related burial of organic carbon and carbonate removal from the shelves to the deep sea during glacials decrease atmospheric CO_2 concentrations and reduce the greenhouse effect). It thus increased the influence of the ocean circulation on global climate in the course of the Quaternary (Berger and Jansen, 1994).

Changes in the vegetation cover, particularly in the tropics, influence the climate by their direct impact on albedo and soil moisture affecting the net radiation and heat budget as well as the hydrological cycle (Textier et al., 1997). The effects of lowered atmospheric CO_2 are partly countered by a decrease in terrestrial plant mass (Crowley, 1995). That is, changes in the vegetation have a positive feedback on temperature and precipitation, but a negative feedback on carbon dioxide levels. Importance of the vegetation feedback mechanisms on climate might have changed through the course of the Pleistocene. A

hint of the significant change in the proportions of terrestrial and oceanic carbon reservoirs is provided by a notable shift of the mean ocean $\delta^{13}C$ at 1.0 Ma (Raymo et al., 1997). At about the same time (1.0–0.87 Ma), the tropical forest limit in the Colombian Andes showed a trend toward lower elevations (Hooghiemstra et al., 1993).

To investigate the relative importance of the vegetation feedback mechanism, a better understanding of timing and change in tropical environments is needed. To obtain a record of tropical African vegetation we selected material from Ocean Drilling Program (ODP) Leg 175. The Congo transect of this leg (Sites 1075–1077) provides a window into the monsoon history of western tropical Africa. Deposition patterns at Sites 1075–1077 reflect climatically driven changes in the supply of fluvial material from the Congo, seasonal coastal upwelling, and open-ocean contributions (Schneider et al., 1997; Wefer et al., 1998b). In this study we focused on the variations in tropical vegetation between 1.5 and 0.5 Ma that are related to changes of the West African monsoon system. A record of the equatorial African vegetation cover is provided by analysis of pollen and spores from Site 1075. Accompanying fluctuations in the monsoon precipitation regime induce variations in the Congo River discharge to the eastern equatorial Atlantic. We use dinoflagellate cyst assemblages to track these changes in marine surface conditions off the Congo River mouth.

MATERIAL AND METHODS

The three 200-m-deep holes at ODP Site 1075 (4°79′S, 10°8′E) were drilled at a water depth of 2996 m and contained greenish gray to olive-gray, partly nannofossil-bearing, diatomaceous clays. The two 200-m-deep holes and one ~20-m-deep hole at Site 1077 (5°18′S, 10°44′E) were drilled upslope at a water depth of 2380 m and contained diatom-rich, diatom-bearing, nannofossil-bearing, and nannofossil-rich clays. A composite depth profile was compiled for each site using magnetic susceptibility and the Red/Blue ratio (650/450 nm) of

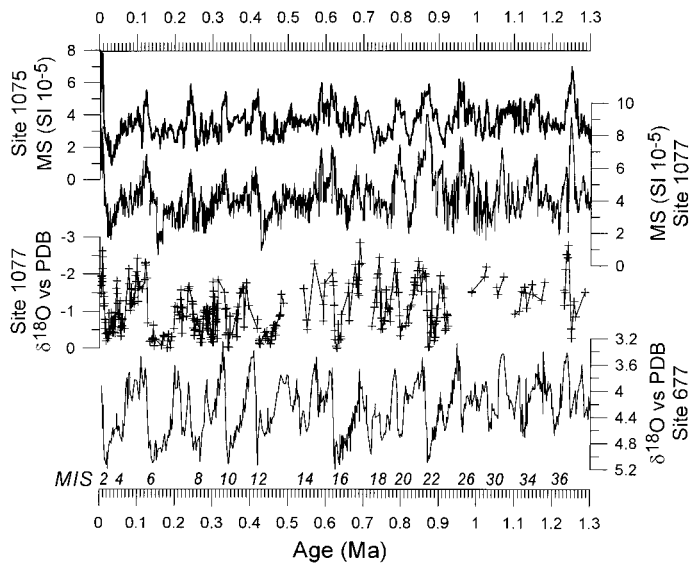*E-mail: E-mail: dupont@uni-bremen.de.

Figure 1. Isotope stratigraphy for Ocean Drilling Program (ODP) Sites 1077 and 1075. Top, shipboard magnetic susceptibility of Sites 1077 and 1075 (Wefer et al., 1998a). Bottom, oxygen isotopes of benthic foraminifera of Site 677 (Shackleton et al., 1990). MIS, marine (oxygen) isotope stage. PDB is Peedee belemnite.

color reflectance (Wefer et al., 1998a). Stable oxygen isotopes were measured on handpicked specimens of the planktic foraminifera *Globigerinoides ruber* (pink) from Site 1077 using a FINNIGAN MAT 251 and an automated Kiel carbonate preparation line. For the palynological study, samples were treated with HCl and HF. Residual clay and fine organic debris were removed by ultrasonic sieving over a polyamid fabric (mesh 8 × 3 μm). Total pollen and spore counts were between 633 and 16 per sample; total cyst counts were between 868 and 80 per sample. Percentages were calculated only in cases where the counts exceeded 100.

Berger et al. (1998) constructed an age model for Site 1075 using magnetic susceptibility. To confirm this age model, we correlated Sites 1075 and 1077 using magnetic susceptibility records (Wefer et al.,

1998a). Site 1077 had a better carbonate preservation, which allowed construction of an isotope stratigraphy (Fig. 1) based on isotopes of planktic foraminifera (only *G. ruber* is consistently present at Site 1077). The results were compared to a benthic oxygen isotope reference curve, in this case from the eastern Pacific ODP Site 677 (Shackleton et al., 1990). The oxygen isotope curve from Site 1077 shows gaps for marine isotope stage (MIS) 13, MIS 25–28, and MIS 36.[1]

POLLEN AND SPORES

More than 250 different pollen taxa recording the vegetation of the Congo River drainage basin and surrounding mountains have been distinguished. Pollen taxa, mostly determined to genus level, are lumped into four groups based primarily on vegetation data of White (1983). The groups comprise pollen taxa representing elements of (1) the tropical rain forest, (2) the semideciduous tropical forest, (3) savanna and woodland trees, and (4) the dry open vegetation of semideserts and deserts.

The first two groups, together referred to as tropical lowland forest in Figure 2, include the majority of the taxa, but represent <10% of the total pollen in the sediments of ODP Site 1075. The savanna and woodland trees are also represented by total pollen percentages below 10%. Pollen assemblages of the Afromontane forest are dominated (up to 75%) by *Podocarpus* (yellow wood). The low pollen production of most African tree species (*Podocarpus* is an exception) accounts for their low representation in the total pollen percentages and this is considered in the interpretation of the data. In equatorial Africa, pollen of Cyperaceae (sedges, rushes, and others) and Poaceae (grasses) might have their source areas in the vegetation of swamps along rivers, on water-logged soils, but also from dry open savanna and woodland. *Rhizophora* pollen is imported from the mangrove swamps along the coast.

A strong glacial-interglacial rhythm is absent for the older part of the pollen record (Fig. 2). Between 1.35 and 1.20 Ma the representation of mangroves, tropical lowland forest, and woodland is low. The rep-
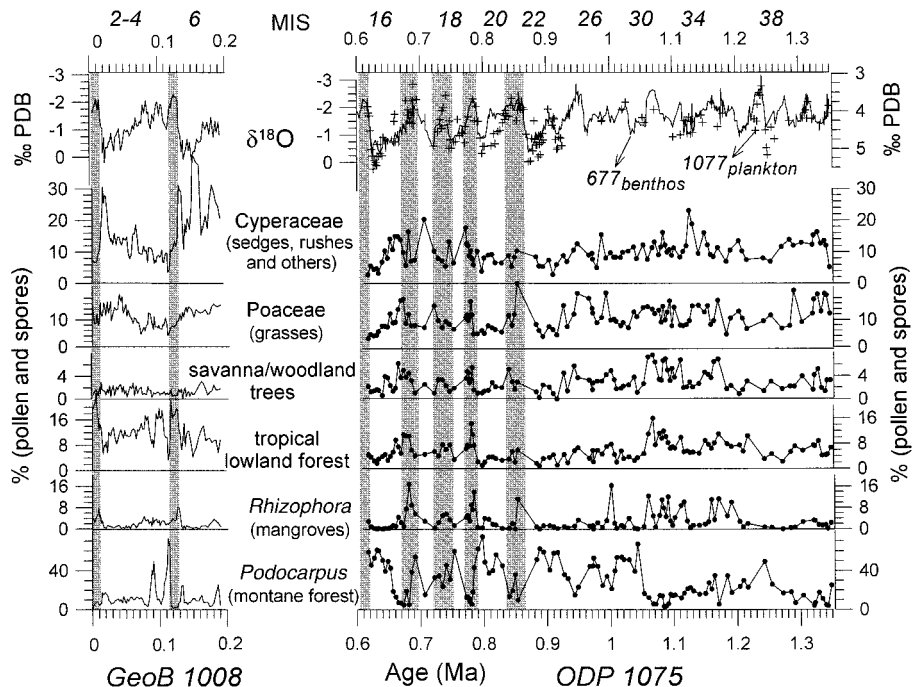

Figure 2. Selected pollen taxa of Sites GeoB 1008 (left; Jahns, 1996) and Ocean Drilling Program (ODP) Site 1075 (right; Dupont, this study) expressed in percent of the total pollen and spores. Top, oxygen isotope curves of GeoB 1008 (left; Schneider et al., 1997) and ODP Sites 677 (solid line; Shackleton et al., 1990) and 1077 (crosses; Donner, this study). Even-numbered glacial marine isotope stages (MIS) are indicated. Interglacial periods after 0.9 Ma are shaded. PDB is Peedee belemnite.

resentation by tropical forest elements shows an increasing trend between 1.20 and 1.05 Ma and pollen percentages for savanna and woodland trees show maximums between 1.15 and 1.05 Ma, while *Podocarpus* percentages decrease. The pollen record of mangrove swamps (*Rhizophora*) also shows numerous maximums between 1.2 and 1.05 Ma. The most prominent change in pollen assemblages occurs at 1.05 Ma. A strong rise in the percentages of *Podocarpus* pollen concomitant with a reduction of woodland and lowland forest pollen indicates extension of the Afromontane forest belt toward lower altitudes, and suggests lower temperatures on the continent. At 0.93 Ma, the amount of grass pollen declined to a lower level, but shows several maximums in the interglacial stages afterward (MIS 21, 19, 17). After 1.05 Ma, the contrast in the pollen spectra between glacial and interglacial stages is more evident, mainly in the *Podocarpus* record, while the other vegetation records exhibit pronounced differences between cold and warm periods after 0.9 Ma.

From the pollen record, we infer that *Podocarpus* forest was common during the glacial stages between 1.05 and 0.6 Ma, suggesting that the climate in equatorial Africa became cooler, but remained humid. Interglacial stages between 0.9 and 0.6 Ma, however, exhibit large variations in the vegetation comprising lowland rain forest, savanna and woodland, swamps, and some mountain forest. A trend toward more open swamps is indicated within those mid-Pleistocene interglacial periods. The development of swamps in the Congo basin might be the result of reduced lake areas, which would suggest rather dry interglacial conditions.

In contrast, the late Pleistocene climate cycles (MIS 1 to 6) of cold, dry glacials and warm, wet interglacials differ from that of the mid-Pleistocene scenario (Fig. 2; see also Dupont et al., 2000). The representation of savanna trees and woodland declined and that of tropical lowland forest increased in the late Pleistocene, both in glacials and interglacials. *Podocarpus* forest was abundant only during the cool and humid interstadials of MIS 5 (5c and 5b), and not during the glacial periods (MIS 6, 4–2), as was the case in the middle Pleistocene. According to Jolly and Haxeltine (1997) reduced levels of atmospheric CO_2 during glacials would have handicapped forest growth, particularly in the mountains. During late Pleistocene glacials (MIS 2 and 6), an open vegetation of grassland and swamps probably prevailed, but lowland forest was still present. A strong increase of lowland forest occurred during interglacials (MIS 1 and 5e). The better representation of *Alchornea*, a pioneer tree of the tropical rain forest, suggests that the forest might have been less dense in the late Pleistocene compared to the earlier period.

ORGANIC-WALLED DINOFLAGELLATE CYSTS

More than 30 different cyst taxa have been distinguished. Within the *Spiniferites* group, cysts of *Gonyaulax spinifera* (*Spiniferites delicatus/pachyderma*, *Spiniferites ramosus*, *Spiniferites mirabilis*), cysts of *Gonyaulax digitalis* (*Spiniferites bentorii*), and cysts of *Gonyaulax scrippsae* (*Spiniferites belerius*) were counted. Other taxa that occur include *Nematosphaeropsis labyrinthus*, *Impagidinium aculeatum*, *Ataxiodinium choane*, and *Stelladinium stellatum*.

The dinoflagellate cyst associations at Site 1075 before 1.05 Ma differ in composition from those after 0.9 Ma. The earlier associations are dominated by *Spiniferites* cysts; the later associations show more *N. labyrinthus* and *Impagidinium* cysts. The period between 1.05 and 0.9 Ma exhibits the successive abundance peaks of *S. ramosus*, *S. mirabilis*, *S. bentorii*, *A. choane*, and *St. stellatum* (Fig. 3). This indicates that surface-water conditions prior to 1.05 Ma were significantly different from those after 0.9 Ma and the occurrence of important changes in the hydrographic and/or nutrient conditions of the surface waters over Site 1075.

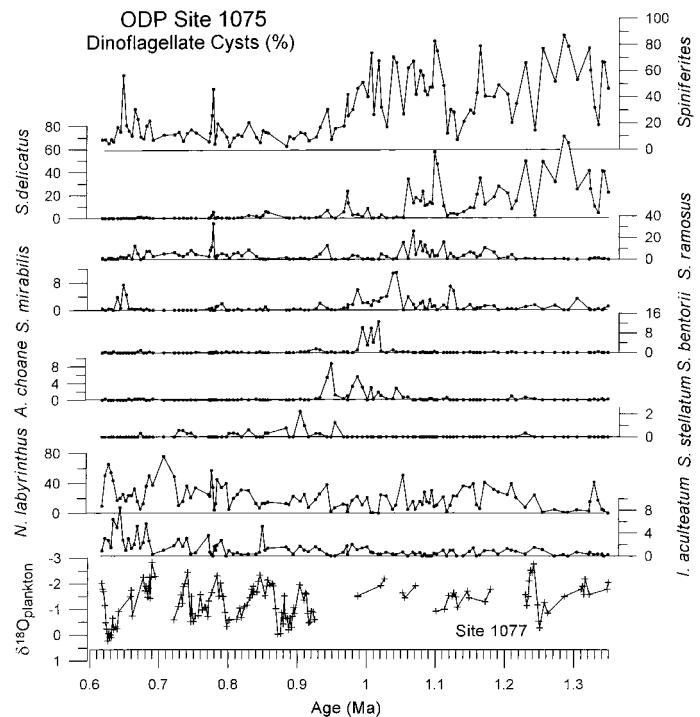Most *Spiniferites* cysts are abundant in slope and shelf sediments.

Figure 3. Selected cyst taxa expressed as percent of total of dinoflagellate cysts. ODP is Ocean Drilling Program; PDB is Peedee belemnite.

S. ramosus may be regarded as an indicator of upwelling conditions (Zonneveld, 1996), which, in this case, would be associated with river-induced upwelling. However, *N. labyrinthus*, which are also cysts of *G. spinifera*, occur in pelagic sediments as well (Marret, 1994; Zonneveld, 1996). *A. choane*, another cyst in the *G. spinifera* group according to Dale (1976), is presently recorded from subpolar to temperate marine sediments (Edwards and Andrle, 1992), but is also found in Pliocene sediments of the Mediterranean (Versteegh, 1997). The occurrence of *Impagidinium*—represented by *I. aculeatum* (cysts of *Gonyaulax* species)—indicates full oceanic conditions (Marret, 1994). Over the Congo fan, *I. aculeatum* cysts usually disappear during periods of increased river discharge (Dupont et al., 1999). We interpret the apparent change in dinoflagellate cyst associations as a successive reduction of the influence of the Congo freshwater plume and river-induced upwelling over the site.

DISCUSSION

With the expansion of *Podocarpus* forest, the change in the vegetation of west equatorial Africa occurring at 1.05 Ma (MIS 30) is strongest during glacials periods. At the same time, the dinoflagellate cyst assemblage west of the Congo River mouth indicates the beginning of the reduction of the river discharge. These environmental changes in tropical Africa precede the mid-Pleistocene climatic shift (Berger and Wefer, 1992) by 100 k.y. and the onset of the ~100 k.y. ice-volume cycles (Berger and Jansen, 1994) by ~300 k.y. It also precedes the ice-volume related change in deep-water circulation (e.g. Raymo et al., 1997).

After 0.9 Ma the decrease in river discharge came to its full extent indicated by the increase of *Impagidinium* associated with a trend toward more open vegetation in tropical Africa during warm and dry interglacials (suggested by the maximums in the record of grasses and Cyperaceae during MIS 21, 19, and 17). This would have affected the feedback mechanisms of the vegetation on the albedo, the hydrological cycle, and the atmospheric CO_2 budget. The reduction of forest in tropical lowland areas during warm periods would decrease the CO_2

uptake and increase the greenhouse effect. However, increase of the albedo would have decreased the heat budget in the tropics during an interglacial phase.

The development in equatorial Africa might be compared to that of the Andes in South America. Between 1.42 and 1.0 Ma, during a period of predominantly cold conditions, the upper Andean forest line showed a rising trend, oscillating from 2200–2600 to 2400–2800 m at the end of the period, reaching its maximum altitude around 1.07 Ma. The first major drop in the upper forest limit is recorded ca. 1.0 Ma (MIS 30), coinciding with the migration of *Alnus* into the region. Between MIS 25 and 22 (0.95–0.85 Ma) the upper forest line dropped again, and oscillated between about 1900 and 3000 m above sea level during MIS 22–19 (Hooghiemstra et al., 1993; Hooghiemstra and Cleef, 1995).

The early climatic change ca. 1.06–1.05 Ma is thus reflected in the vegetation records of both tropical Africa and South America. A decline of the upper forest limit in the Andes and a lowering of the lower limit of the *Podocarpus* forest around the Congo basin indicate a cooling of the equatorial region. The upper forest limit in the Andes during the mid-Pleistocene is probably not yet CO_2 limited (Cowling and Sykes, 1999) because the mountain forest expanded in Africa during the same period. Changes in the vegetation cover may have resulted in increased erosion of land plant material into the ocean after 1.0 Ma, as postulated by Raymo et al. (1997). The vegetation change at tropical latitudes ca. 1.05 Ma, however, cannot be attributed to the onset of severe glaciations of the Northern Hemisphere, because it precedes the first pronounced glacial conditions that occurred between 0.95 and 0.87 Ma (MIS 24–22).

The interval from 1.2 to 0.7 Ma (Croll chron after Berger and Wefer, 1992; Berger and Jansen, 1994) can be viewed as a transitional period from dominant obliquity cycles to the large-amplitude eccentricity cycles of the Milankovitch chron (past 0.7 m.y.). Our data, together with the vegetation changes in South America, imply that already during the early Croll chron tropical climate response to a threshold in climate forcing may be related to low-latitude (semi-)precessional insolation variation (DeMenocal, 1995; Rutherford and D'Hondt, 2000). The climatic feedbacks of terrestrial and tropical environments might have been predominant in this period, before the Northern Hemisphere ice caps increased dramatically in size and influence during the 'mid-Pleistocene revolution'.

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