Chapter 20

Steps toward Drier Climatic Conditions in Northwestern Africa during the Upper Pliocene

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This chapter deals with vegetational and climatic change in northwestern Africa during the Lower and the Upper Pliocene, from 3.7 to 1.7 million years (myr). Northwestern Africa is now characterized by aridity and covered by deserts and dry vegetation. A 200 m-long marine pollen record from the Ocean Drilling Program (ODP) Site 658, at 21°N and 19°W, reveals cyclic fluctuations and long-term variations in vegetation and continental climate. So far, it is the best Upper Pliocene pollen record for this part of Africa in terms of resolution and time coverage.

Marine records have an advantage over terrestrial ones, because they frequently cover long sedimentation periods, fit into a firm global stratigraphy, and have strict time control. Deep-sea pollen records contain grains that have been transported long distances. Consequently, they integrate the vegetation record of a large area and contain an impoverished pollen flora that represents only those plants that produce much pollen. These features make marine palynology a suitable tool for studying large vegetation zones over long periods. Additionally, terrestrial chronology relative to oceanic chronology can be established on the same material.

After introducing ODP Site 658 record, we focus on the long-term variations and on the comparison of two periods from the Late Pliocene, one between 3.5 and 3.2 myr and the other between 2.2 and 1.7 myr. Both periods show strong short-term fluctuations of climate but differ in the timing and extent of the response of the vegetation, as indicated by cross-correlation of pollen influx values with insolation values and oxygen isotopes. A full description of the palynology of ODP Site 658 is given in Dupont et al. (1989) and Leroy and Dupont (1994).

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Sedimentology

ODP Site 658 (leg 108) is situated northwest of Africa (fig. 20.1) at a water depth of 2,263 m on the continental slope 160 km west of Cape Blanc. It is located below an important near-shore upwelling cell induced by the trade winds. Its position at a terrace of the continental slope between two major canyon systems restricts to a minimum disturbance of the sediment record by lateral down-slope transport (Ruddiman et al., 1988). A hiatus spanning the Lower Pleistocene separates the upper 100 m of sediment covering the Brunhes chron from the lower 200 m covering the late Lower and Upper Pliocene (Sarnthein and Tiedemann, 1989). The high sedimentation rate, due to high organic production in the upwelling zone combined with high Saharan dust influx, provides a Plio-Pleistocene record of high quality in which bioturbation hardly obscures the fine-scale resolution up to 1,000 years (Tiedemann et al., 1989).

Chronology

The time scale of the sequence (figs. 20.2–20.5) is provided by biostratigraphy, paleomagnetism, and oxygen isotope stratigraphy (Ruddiman et al., 1988; Sarnthein and Tiedemann, 1989; Tiedemann, 1991). The ages of the isotope stages of ODP Site 658 are derived by comparison with ODP site 659 (18°N, 21°W; Tiedemann, pers. comm.). The orbitally tuned time scale of ODP 659 reaches back 5 myr (Tiedemann et al., 1994). The ages of the ODP Site 659 time scale are similar to the independent calibrations of Shackleton et al. (1990) on Pacific sediments (ODP Site 677) and of Hilgen (1991) on Mediterranean sapropels. Therefore, the ages of ODP Site 659, and thus of ODP Site 658, are consistently 130 kyr older than those obtained by Raymo et al. (1989) from the Deep Sea Drilling Project (DSDP) Site 607 in the North Atlantic. Correlation of ODP Site 658 with ODP Site 659 and DSDP Site 607 reveals a hiatus at 158 m, spanning the period from 2.25 to 2.46 myr, and several coring gaps (Tiedemann, 1991). The time resolution of the Pliocene pollen record of ODP Site 658 (using 401 samples) exceeds 1 sample per 5 thousand years (kyr), except for the gaps mentioned, and spans the period from 3.7 to 1.7 myr.

Wind Transport of Pollen into the Marine Sediments

Presently, at latitudes between 19°N and 21°N, the climatically sensitive vegetation of the Sahel gives way to the desert (fig. 20.1). In the adjacent East Atlantic, at 21°N, ODP Site 658 id located where northeasterly trade winds are overlaid by the mid-tropospheric African Easterly Jet (AEJ), namely the summer maximum of the Saharan Air Layer. Trade winds transport pollen from their source areas in the Mediterranean and the Sahara to the marine site (Hooghiemstra et al., 1986). Strong, heat-induced squall lines bring dust and pollen from the Sahel and the southern Sahara into altitudes of the AEJ (1,000–5,000 m). Then, the AEJ carries pollen from latitudes between 16°N and 20°N westward and northward over the Atlantic.

Long-term Variation

We define *long-term variation* (fig. 20.2) as one that lasts over a period of several hundred thousand to a few million years and *short-term variation* as one that lasts up to one hundred thousand years.

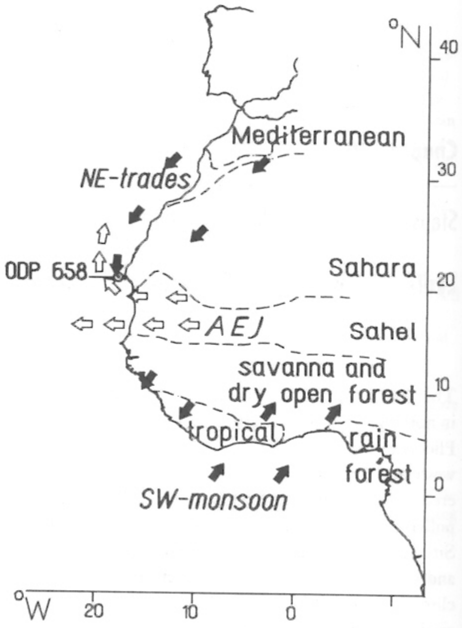


Fig. 20.1. Location of ODP Site 658, at 21°N 19°W; surface winds—northeasterly trades and southwesterly monsoon (black arrows), the mid-tropospheric African Easterly Jet (AEJ, open arrows); and the modern position of the main northwest-African vegetation zones—Mediterranean, Mediterranean Steppes, Sahara, Sahel, savanna and dry open forest, tropical rain forest.

River Discharge. For the Pliocene and the Pleistocene, the sedimentology of ODP Site 658 shows dust transport into the Atlantic by winds (trades and the African Easterly Jet) as well as clay transport by rivers (Tiedemann et al., 1989; Tiedemann, 1991). Quartz content and siliciclastics (eolian dust > 6 μm) indicate wind vigor, whereas the clay content illustrates the importance of river discharge to the formation of the sediment. The declining percentage maxima of Cyperaceae in the ODP Site 658 pollen record (fig. 20.4) confirms the conclusion drawn from sedimentary analysis (Tiedemann, 1991) of persistent river discharge before 3.4 myr followed by subsequent decline. Generally, river-borne pollen seems numerous until 2.97 myr (Leroy and Dupont, 1994). Thereafter, transport of pollen grains by river discharge is insignificant, which is comparable to the modern situation (Hooghiemstra, 1989; Dupont and Agwu, 1991).

Mangrove Swamps and Tropical Forests. A humid and probably warm climate prevailed before 3.5 myr. According to the percentage average of *Rhizophora* pollen that exceeds 4 percent (fig. 20.2), mangrove swamps were growing near Cape Blanc around 3.70 myr, probably accompanying a paleoriver. At present, 10 percent *Rhizophora* pollen grains are found at the mouth of the Senegal River, which is 5° to the south (Dupont and

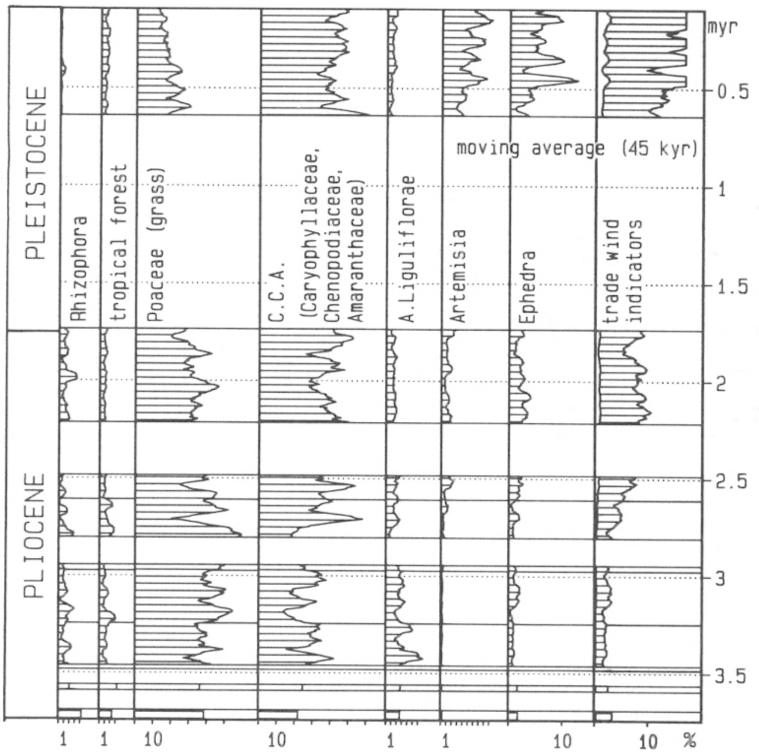


Fig. 20.2. Long-term trends in the pollen record of ODP Site 658. Plots of a moving average over nine successive pollen spectra expressed as percentages of the pollen total and interpolated at steps of 5 kyr: *Rhizophora* (mangrove tree), sum of tropical forest elements (dry open and wet lowland forest; Guinean and Sudanian vegetation zones), Poaceae (grasses), CCA (the sum of Caryophyllaceae and Amaranthaceae-Chenopodiaceae), Asteraceae Liguliflorae (A. Liguliflorae), *Artemisia*, *Ephedra*, and trade-wind indicators (sum of *Artemisia, Ephedra,* Mediterranean elements, and A. Liguliflorae). The horizontal axis of each curve starts at 0 and increases from left to right. Time scale in myr on the vertical axis.

Agwu, 1991). Percentages of the sum of pollen from Sudanian and Guinean vegetation, that is, wooded savanna, woodland, and tropical forest, repeatedly exceed 5 percent, indicating that forest and savanna had a distribution at least as far as 21°N during those periods. This latitude is 5° to 10° farther to the north than the modern situation (Dupont and Agwu, 1991). Before 3.5 myr, and between 3.25 and 2.6 myr, percentage averages of tropical forest element (>2 percent) indicate a northern extent of tropical forests that probably shifted southward after 2.6 myr.

The Development of a Desert in the Western Sahara. High pollen percentages of Poaceae (grasses) in the lower part of the sequence indicate that extensive savannas were already present in the Lower Pliocene (fig. 20.2). After 2.8 myr, a declining trend in percentage averages of Poaceae indicates a reduction of savanna vegetation (including wooded savanna and dry, open forest), probably as a result of the development of a desert in the western Sahara. Percentages of Asteraceae Liguliflorae reach high values before 3.2 myr but decline to low values afterward (fig. 20.3). Nowadays, many species of the A.

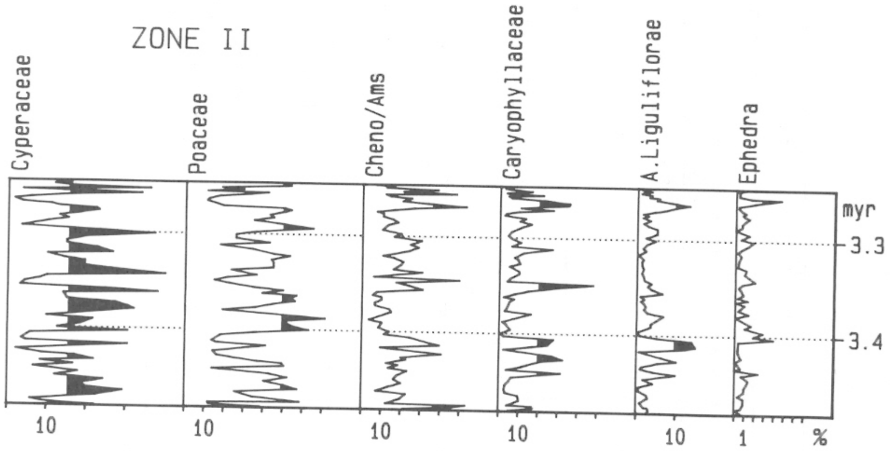


Fig. 20.3. Short-term fluctuations in the pollen record of ODP Site 658 between 3.5 and 3.2 myr (Zone II). Plots of six selected pollen taxa expressed as percentages of total pollen: Cyperaceae, Poaceae, Chenopodiaceae-Amaranthaceae (Cheno/Ams), Caryophyllaceae, A. Liguliflorae, and *Ephedra*. The horizontal axis of each curve starts at 0 and increases from left to right.

Liguliflorae grow in the Mediterranean area, but only a few of them grow in the savannas south of the Sahara. This may be a reflection of a westward extension of the desert driving a wedge in the distribution of A. Liguliflorae species. From 2.7 myr on, percentage averages of CCA (the sum of Caryophyllaceae, Chenopodiaceae, and Amaranthaceae) reach high values (around 40 percent), comparable to those of the Brunhes chron record indicating aridity in northwestern Africa. Mean percentages of *Ephedra* and *Artemisia* during the Pliocene are five times lower than those of the Upper Pleistocene, indicating that arid periods were even shorter and/or milder during the Pliocene.

The pollen record of the Brunhes chron registered, through the African Easterly Jet, latitudinal shifts of up to 10° for desert and wooded grassland. In particular, time-transgressive percentage maxima of Cyperaceae, Poaceae, CCA, *Artemisia*, and *Ephedra* (Dupont and Hooghiemstra, 1989; Dupont et al., 1989) reflect shifting of the desert-savanna boundary (Saharan-Sahelian boundary). We interpret each maximum as a southward extension of the desert and, therefore, as a reflection of drier climate. A few shifts were recorded before 3 myr, but they occur regularly from 2.6 myr onward (fig. 20.5). We conclude that by this time a desert established in the western Sahara. This desert built a permanent though shifting boundary with the savanna south of it.

Trade Winds. An estimation of trade-wind vigor is given by the sum of those pollen taxa that have their main source areas in the northern Sahara and North Africa: *Ephedra*, *Artemisia*, and *Pinus*, as well as A. Liguliflorae for periods after 2.9 myr. Generally, the strength of the trades was much lower during the Pliocene than during the Upper Pleistocene. Trade winds were very weak until 3.2 myr, resulting in low transport of pollen from North Africa. At 3.26 myr, however, trade-wind vigor probably increased for a short period. Then, at 3.2, 2.8, and 2.6 myr, the level of trade-wind strength increases stepwise (fig. 20.2). During the final Pliocene, trade winds are rather strong, with the exception of the period between 1.87 and 1.85 myr, when oxygen isotopes indicate reduced extension of ice sheets. The record of trade-wind indicators corroborates the estimates of wind strength by grain-size analysis of ODP Site 658, ODP Site 659, and DSDP Site 397, showing an increase of the trade winds from 3.2 to 2.6 myr (Tiedemann et al., 1989; Tiedemann, 1991).

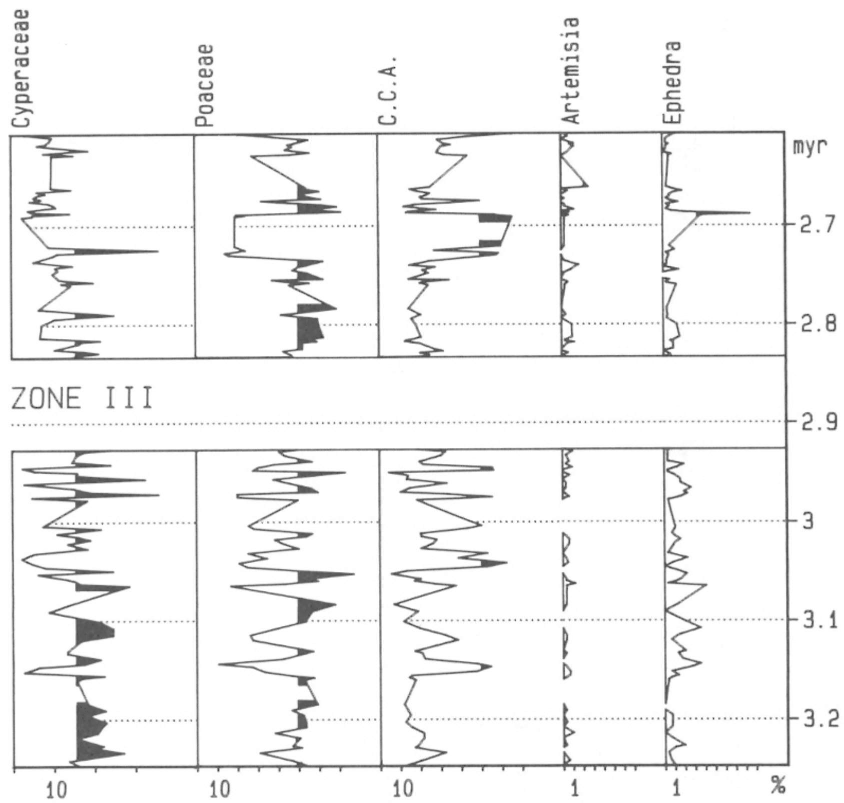


Fig. 20.4. Short-term fluctuations in the pollen record of ODP Site 658 between 3.2 and 2.6 myr (Zone III). Plots of five selected pollen taxa expressed as percentages of total pollen and arranged from left to right in the order of their indication value for climatic conditions at 21°N, from humid to arid: Cyperaceae, Poaceae, CCA (= Carophyllaceae, Chenopodiaceae, and Amaranthaceae), *Artemisia*, and *Ephedra*. The horizontal axis of each curve starts at 0 and increases from left to right. Coring gaps interrupt the record between 2.93 and 2.83 myr, between 2.72 and 2.69 myr, and between 2.66 and 2.63 myr.

Vegetation and Climatic Development before and after 2.5 Million Years

The establishment of desert and the onset of trade winds mark important changes in vegetation and climate of northwestern Africa that correlate with the strong development of ice sheets in the Northern Hemisphere during oxygen isotope stages 100 and 98, around 2.5 myr. In this section, we examine the difference in response of vegetation and climate to orbital forcing by means of spectral analyses of pollen taxa, oxygen isotopes, and insolation for two periods: 3.5–3.2 myr and 2.2–1.7 myr.

The Period between 3.5 and 3.2 myr (Zone II). Five dry phases characterize this period (fig. 20.3). Three of them, at 3.48, 3.35, and 3.26–3.27 myr, show high percentages of Amaranthaceae-Chenopodiaceae pollen (50 percent), indicating arid conditions. Two other dry phases, at 3.44–3.40 and 3.31 myr, are less prominent. Although they show high percentages of Caryophyllaceae, percentages of Amaranthaceae-Chenopodiaceae hardly exceed 40 percent. High percentage values (>10 percent) are found for A. Liguliflorae between 3.44 and 3.40 myr and at ca. 3.27 myr, presenting a unique situation without a modern analogue. The youngest and most

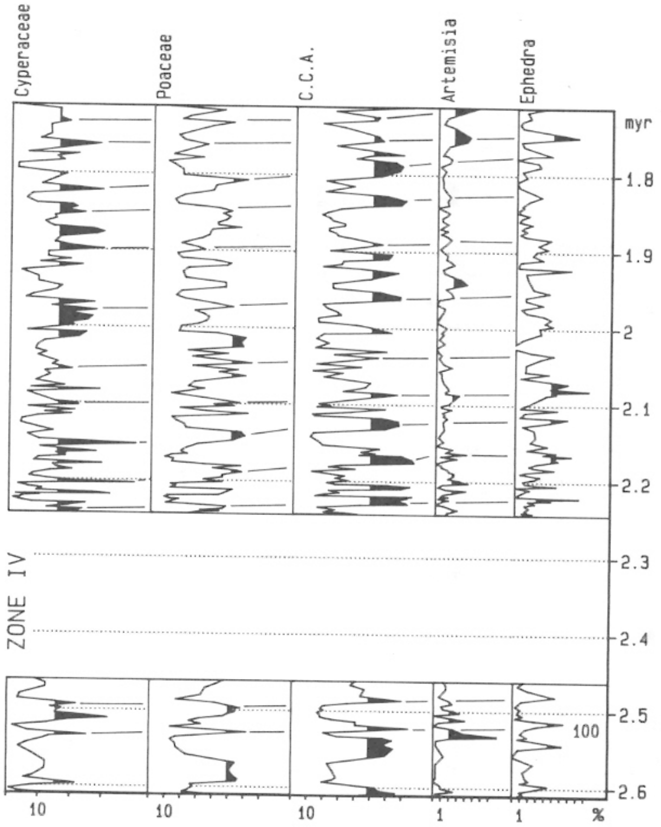


Fig. 20.5. Short-term fluctuations in the pollen record of ODP Site 658 between 2.6 and 1.7 myr (Zone IV). Plots of 5 selected pollen taxa expressed as percentages of total pollen and arranged from left to right in the order of their indication value for climatic conditions at 21°N, from humid to arid: Cyperaceae, Poaceae, CCA (Carophyllaceae, Chenopodiaceae, and Amaranthaceae) *Artemisia,* and *Ephedra.* Bars highlight transgressive maxima indicating a southward shift of the Saharan-Sahelian boundary (desert-savanna boundary). The horizontal axis of each curve starts at 0 and increases from left to right. A sedimentary hiatus interrupts the record from 2.46 to 2.25 myr. Oxygen isotope stage 100 is indicated at the right-hand side.

arid phase shows a percentage maximum of *Ephedra* of 4 percent at 3.26 myr. From the sedimentary record of ODP Site 658, Tiedemann (1991) concluded an increase of eolian activity, especially of the trade winds, around 3.26 myr.

Power spectra of all pollen influx curves for the period from 3.5 to 3.2 myr show very little variance at the 23 kyr precession band. Some variance concentrates around the 41 kyr obliquity band for the spectra of Chenopodiaceae-Amaranthaceae, Caryophyllaceae, *Ephedra,* A. Liguliflorae, and Asteraceae Tubuliflorae. The first four groups show significant coherency with the oxygen isotopes of benthic foraminifers (*Cibicidoides wuellerstorfi;* ODP Site 658; Tiedemann, 1991) recording global ice volume and deep-sea temperatures. Only the last group, A. Tubuliflorae, shows significant coherency with the insolation maxima (July, 65°N; Berger and Loutre, 1991).

Coherency between insolation and oxygen isotopes is lacking at the 41 kyr band. From 3.5 to 3.2 myr, there is probably no direct forcing between obliquity and deep-sea temperatures or ice volume as recorded by the oxygen isotopes of benthic foraminifers (Tiedemann et al., 1994). The signal of the A. Tubuliflorae leads the insolation signal. Despite coherency, a forcing relationship between obliquity and A. Tubuliflorae is, therefore, also unlikely. However, the positive correlation of minimum deep-sea temperatures (oxygen isotopes) with pollen influx curves recording drier conditions in northwestern Africa indicates a link between the low deep-sea temperatures and aridity existing well before 3 myr (fig. 20.6A).

The Period between 3.25 and 2.61 myr (Zone III, fig. 20.4). During this intermediate period, humid conditions were reestablished between 3.25 and 3.19 myr, as indicated by high percentages of tropical forest (>2 percent) and Cyperaceae (>15 percent). Afterward, the climate again became progressively drier, and percentages of Cyperaceae declined. During the next part (from 2.97 to 2.61 myr), high percentages of grass pollen (Poaceae up to 70 percent) were followed by percentage maxima of CCA (>50 percent) at 2.73 and 2.69 myr; of *Ephedra* (>5 percent) at 2.69 myr; and the first maximum of *Artemisia* (2 percent) at 2.66 myr. A slight increase in trade-wind strength occurred at 2.76 myr.

The Period between 2.61 and 1.74 myr (Zone IV, fig. 20.5). At 2.60 myr, 2.53 myr, and 2.49 myr (isotope stages 104, 100, and 98, respectively), severe dry periods are recorded by high percentages of *Ephedra* (ca. 3 percent), *Artemisia* (>2 percent), and CCA (>50 percent). They mark the start of a climatic regime in northwestern Africa resembling glacial to interglacial cycles that result in arid-cold and humid-warm phases. These phases show the above described sequence of time-transgressive percentage maxima of Cyperaceae, Poaceae, CCA, *Artemisia,* and *Ephedra* that characterizes the shifting Saharan-Sahelian boundary. Within the period between 2.6 and 1.7 myr, only two extended humid periods occurred, corresponding to the weakly developed isotope stages 76 and 68.

Power spectra of pollen influx values for the period between 2.2 and 1.7 myr show a concentration of variance in the 41 kyr obliquity band. Cross-correlation spectra of *Rhizophora* (mangrove tree), sum of tropical forest elements (Sudanian and Guinean elements), Poaceae (grasses), *Ephedra,* A. Tubuliflorae, Chenopodiaceae-Amaranthaceae, and Caryophyllaceae show coherent phase shifts with insolation as well as with benthic isotopes. The phase shifts of pollen influx versus isotopes are consistent to those of pollen influx relative to insolation (fig. 20.6B). Pollen influx of "wet" elements like *Rhizophora,* Poaceae, and tropical forest lag maximal insolation (65°N, July) by 5 to 7 kyr. Pollen influx of "dry" elements like *Ephedra,* A. Tubuliflorae, Chenopodiaceae-Amaranthaceae, and Caryophyllaceae lag minimal insolation with about the same amount of time. These results strongly suggest forcing by obliquity of northwestern African climate between 2.2 and 1.7 myr.

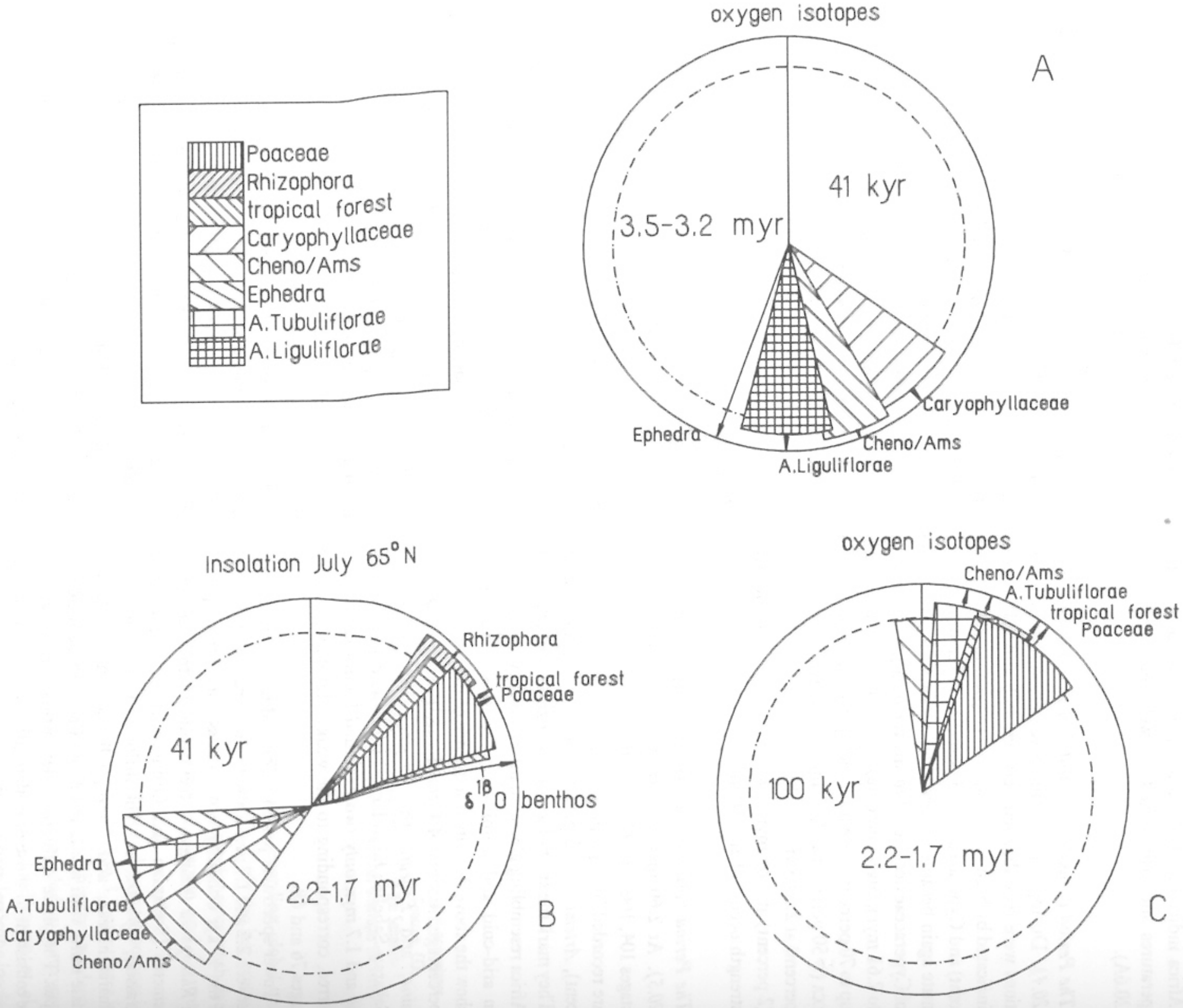
Some of the variance in the power spectra of Chenopodiaceae-Amaranthaceae, A. Tubuliflorae, tropical forest elements, and Poaceae also concentrates around the 100 kyr band (fig. 20.6C). The latter three groups have coherent phase shifts with the oxygen isotopes of *C. wuellerstorfi.* The lag between the influx values of the "dry" elements like A. Tubuliflorae with the isotope maximum (maximum deep-sea temperatures, minimum ice volume) is about 6 kyr, and the lag between the "wet" elements like Poaceae and tropical forest with the isotopes is about 10 kyr. Owing to large statistical errors, however, the difference is not significant.

Discussion

Without marking a prominent boundary, the beginning of a declining trend in the benthic oxygen isotopes of the eastern equatorial Pacific started around 3 myr, signaling colder deep-sea temperature minima and increased maxima of global ice volume (Shackleton et al., 1995; Shackleton, this vol.). The same result was found by Tiedemann (1991) for the eastern tropical Atlantic. However, because elements of a biocoenose respond only if certain thresholds are passed, parts will react sensitively to certain ranges while staying indifferent to others. These ranges are not necessarily congruent in all parts of the system, implying that one fixed starting point for global change may be an illusion and that a number of changes during a limited time range marked the onset of the Ice Age period.

The pollen record of ODP Site 658 shows comparably gradual change in sensitivity to possible forcing mechanisms. Long-term variation indicates a first step toward drier climate between 3.5 and 3.2 myr and a second, stronger one starting at about 2.6 myr. Before 3 myr, a correlation between "dry" pollen taxa and oxygen isotopes indicates a link between drought in northwestern Africa and low deep-sea temperatures. There is, however, no synchronization between insolation and the pollen record over that period.

This situation changes after 2.6 myr (de Menocal et al., 1993; deMenocal and Bloemendal, this vol.). The period of 2.2–1.7 myr records a lag of about 5 kyr be-


Poaceae
Rhizophora
tropical forest
Caryophyllaceae
Cheno/Ams
Ephedra
A.Tubuliflorae
A.Liguliflorae
oxygen isotopes
A
41 kyr
3.5-3.2 myr
Caryophyllaceae
Cheno/Ams
A.Liguliflorae
Ephedra
Insolation July 65° N
41 kyr
2.2-1.7 myr
Rhizophora
tropical forest
Poaceae
δ18O benthos
Ephedra
A.Tubuliflorae
Caryophyllaceae
Cheno/Ams
B
oxygen isotopes
Cheno/Ams
A.Tubuliflorae
tropical forest
Poaceae
100 kyr
2.2-1.7 myr
C

tween the maxima of the "wet" elements and the minima of the "dry" elements, with maximum insolation at 65°N. The Brunhes part of ODP Site 658 also shows correlation between pollen influx and ETP (the modeled curve of Eccentricity, Tilt, and Precession) and a lag of about 3 kyr between "wet" elements (Cyperaceae and Poaceae pollen) and insolation (Dupont et al., 1989 and unpublished data).

There are two possible nonexclusive explanations of forcing at the obliquity (41 kyr) band. One is a link between the climate of northwestern Africa and sea-surface temperatures of the North Atlantic advocated by de Menocal and Rind (1993) and deMenocal et al. (1993). The other is a correlation between the strength of the Hadley circulation, trade-wind vigor, and aridity in northwestern Africa. Model results reducing southern Asian orography show a reduction of the Hadley circulation through reduction of the high-pressure cell over the Himalayas. Trade winds, which are the surface component of the Hadley circulation, increase in periods with large ice volume, which is likewise attributable to an intensification of the high-pressure cell over the Himalayas (Kutzbach et al., 1989; Ruddiman et al., 1989; de Menocal and Rind, 1993). Trade winds are connected with sinking airflow and therefore contribute to aridity.

In conclusion, the short-term pulses of climatic cycles (less than 100 kyr) are already present well before 3 myr (and probably well before the Pliocene). Spectral analysis shows a positive correlation between low deep-sea temperatures and aridity in northwestern Africa. After 2.6 myr, when glaciations in the Northern Hemisphere increasingly mark global climate, our results strongly suggest forcing by obliquity of northwestern African climate. Trade winds in combination with North Atlantic sea surface temperatures then largely determine the climate of northwestern Africa.

Summary

Short-term fluctuations and long-term trends in the pollen record of ODP Site 658 reveal vegetation and climatic changes in northwestern Africa during the Upper Pliocene (3.7–1.7 myr). The pollen record correlates with oxygen isotopes indicating that aridity corresponds to low deep-sea temperatures and large global ice volume. Long-term variation involves decline in river discharge, southward retreat of mangrove swamps and tropical forest by at least 5°, development of desert vegetation in the western Sahara, and the onset of trade winds in three steps. Comparison of short-term fluctuations of periods before and after 2.5 myr shows that obliquity forcing of northwestern African climate started with the first large glaciations in the Northern Hemisphere.

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Fig. 20.6. A summary of phase relationships is given by phase wheels of the 41 kyr band for the periods 3.5–3.2 myr (A) and 2.2–1.7 myr (B) and of the 100 kyr band for the period 2.2–1.7 myr (C). Zero phase on wheels A and C is set for the oxygen isotope signal of *Cibicidoides wuellerstorfi* (minimum ice volume, maximum deep-sea temperature) and on wheel B for the maximum July insolation at 65°N. Vectors are used to represent the phase difference between pollen taxa and oxygen isotopes or between pollen taxa and insolation. Counterclockwise orientation represents a lead, clockwise represents a lag, and a phase of 180° represents a negative correlation. Phases are plotted if coherency is statistically significant at the 80-percent level (dashed circles). Hatched areas represent the phase error for each taxon. Power and coherency spectra of the influx values of nine different pollen taxa have been calculated after the Blackman-Tukey method (Jenkins and Watts, 1968). Pollen influx values have been interpolated to an equidistant step size of 3 kyr using a Gaussian filter of 9 kyr; the older sequence (3.5–3.2 myr) has an average sample distance of 3 kyr, and the younger one (2.2–1.7 myr) of 4 kyr. Gaps of more than two interpolated values between two measured ones are not closed but marked as missing values. All series are linearly detrended. The older series has a length of 100 and is analyzed using 60 lags, resulting in a bandwidth of 0.0074 kyr^{-1} and a level of nonzero coherency of 0.856. The younger series has a length of 176 and was analyzed using 100 lags resulting in a bandwidth of 0.0044 kyr^{-1} and a level of nonzero coherency of 0.835. The confidence interval is set at 80 percent. Poaceae = grasses, *Rhizophora* = mangrove tree, Cheno/Ams = Chenopodiaceae-Amaranthaceae, A. Tubuliflorae = Asteraceae Tubuliflorae, A. Liguliflorae = Asteraceae Liguliflorae, Asteraceae = Compositae.

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