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The Saharan–Sahelian boundary during the Brunhes chron

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SUMMARY

Atmospheric circulation patterns over NW Africa are recognized in isopoll maps of offshore bottom sediments. Assuming that the atmospheric circulation model of the last glacial–interglacial transition, based on snapshots of three time-slices, holds for the entire Brunhes chron, the 0·7 My-long pollen record of ODP Site 658 has been interpreted. Fluctuating percentages and influx rates of pollen of Chenopodiaceae–Amaranthaceae, Poaceae, Cyperaceae, and savanna elements record a repeatedly shifting Saharan–Sahelian boundary between *c.* 14° and 23°N during the Brunhes chron. Most of the humid interglacials occured before 280 ka, and extreme glacial conditions are only found during the last 480 ka. Assumptions and possible conclusions are argued. A coherency between the pollen signal of Poaceae and that of Cyperaceae is demonstrated by cross-correlation and a distinct 42 ka periodicity suggests forcing by obliquity.

Key-words: Africa, marine palynology, paleoclimatology, Pleistocene, Sahel, savanna.

INTRODUCTION

Several authors have shown that in the offshore marine sediments of NW Africa much pollen from the adjacent NW African and SW European continents is preserved (e.g. Caratini *et al.* 1979; Rossignol-Strick & Duzer, 1979; Agwu & Beug, 1982; Bonnefille *et al.* 1982; Melia, 1984; Hooghiemstra & Agwu, 1986; Hooghiemstra *et al.* 1986). The NW African vegetation is characterized by a number of latitudinal zones (White, 1983) (Fig. 1) due to the distinct climatic gradient ranging from the Mediterranean to the Gulf of Guinea. Each of these vegetation zones is characterized by a number of plant taxa traceable by pollen analysis (e.g. listed in Rossignol-Strick & Duzer, 1979; Agwu & Beug, 1982; Lezine, 1987). By relating the pollen spectrum found in recent marine sediments to their present source area, information is obtained about their indicator value.

The workers mentioned above arrived at the conclusion that eolian pollen transport to the Atlantic accounts for a major proportion of the pollen found in marine sediments off NW Africa. The distribution of many pollen types in the modern marine surface sediments reflects the average course of trajectory of the major wind belts (Fig. 1), namely the African

This paper is dedicated to Professor Dr T. van der Hammen on the occasion of his 65th birthday.
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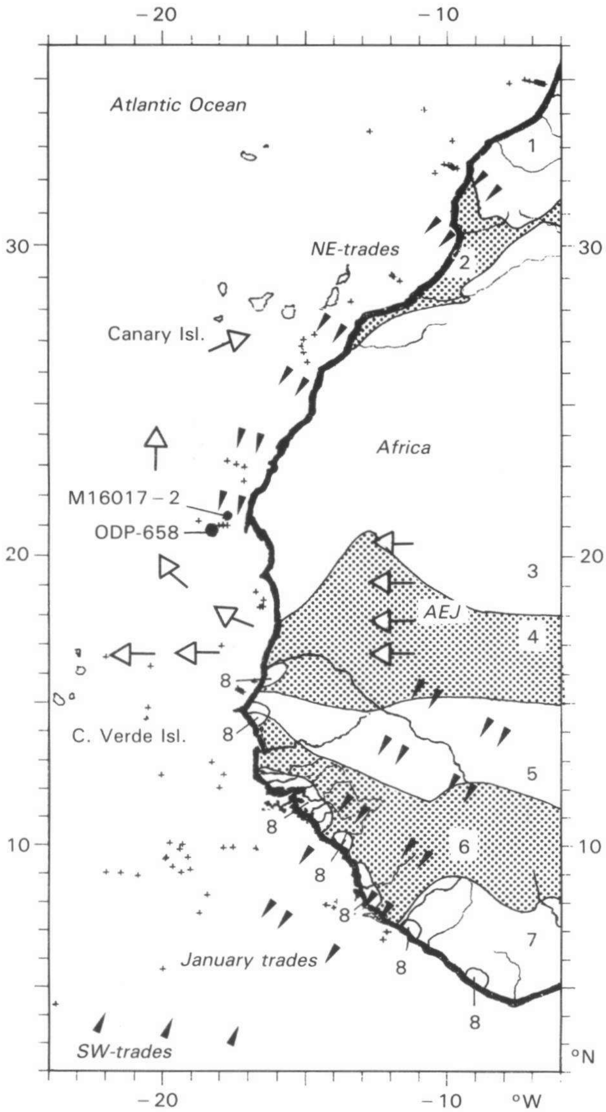

Fig. 1. Vegetation zones of NW Africa (after White 1983). From north to south: (1) Mediterranean vegetation zone, (2) steppes of the western Atlas region, (3) deserts and semi-deserts of the Sahara, (4) Sahel zone, (5) Sudanian woodland (savannas), (6) Guinea zone, (7) rain forest, and (8) mangrove vegetation (*Rhizophora*). (+) Indicate the surface sediment sample stations, (●) indicate the location of the marine sediment cores referred to in this study. (▲) Surface winds (NE trades, January trades, and southerly trades), (⇡) zonal African Easterly Jet at higher altitudes.

Easterly Jet (being the summer maximum of the Saharan Air Layer or mid-tropospheric easterly jet) and the NE trade winds (Hooghiemstra & Agwu, 1986; Hooghiemstra *et al.* 1986, 1987).

Although the Canary Current is potentially important for pollen transport and its average flow pattern matches the trajectory of the NE trade winds, the pollen records hardly suggest transportation by water currents (Hooghiemstra *et al.* 1987; Hooghiemstra, 1989; Melia, 1984). Additional evidence for an eolian pollen displacement was provided by Melia (1984) who showed that the isopoll maps of the area off NW Africa of several taxa (such as Chenopodiaceae–Amaranthaceae, *Pinus, Betula*, and *Quercus*), based on aerosol and bottom sediment samples, correspond to a significant degree. This means that during passage of the pollen grains through the water column the distribution pattern does not seem to be substantially changed. This observation is consistent with the model of vertical particulate matter flux through the water column: the rapid lumping of dust particles (pollen and spores included) by both inorganic and organic aggregation (the latter through ingestion by organisms and subsequent excretion) results in relatively high settling velocities, and thus limiting horizontal displacements in the water column (see relevant references in Hooghiemstra, 1989). In the area under study, isopoll maps may therefore be interpreted in terms of atmospheric circulation.

This paper uses the results of the time-slice studies of the present (Melia, 1984; Hooghiemstra *et al.* 1986), of 9 ka (Hooghiemstra, 1988a), and of 18 ka (Hooghiemstra *et al.* 1987) as a basis for interpreting older intervals of Ocean Drilling Program (ODP) Site 658. The objective of this paper is to unravel the history of the NW African savannas and the southern border of the Sahara during the Brunhes chron.

SNAPSHOTS OF THE PAST ATMOSPHERIC CIRCULATION

In order to trace changes in (eolian) pollen transport during the last glacial-interglacial transition, the mechanism of recent pollen transport, as deduced from the analysis of surface sediment samples, was verified for two selected time-slices of the past. The isopoll maps of 9 ka represent the phase of the maximum northward expansion of the vegetation zones south of the Sahara, and the isopoll maps of 18 ka represent the situation during the last glacial maximum. The last glacial–interglacial transition subsequently serves as a model for the interpretation of the long-range ODP record which includes some 18 glacial–interglacial stages. In the next section the major characteristics of the atmospheric circulation during the last 18 ka and the main plant taxa are briefly reviewed.

The halophytic shrubs and herbs of the Chenopodiaceae–Amaranthaceae group have a wide distribution in NW Africa in the saline littoral and the extensive saline evaporation areas in the Sahara. The anemophilous flowers produce great quantities of pollen which make these taxa very favourable objects for tracing wind trajectories. At the northern fringe of the Sahara the period of main pollen release is from November to April, but from June to September at the southern fringe. In these periods of the year the trade winds and the African Easterly Jet, respectively, are the major wind systems in those areas. Furthermore, in these areas river systems are hardly present or totally absent. This explains why the distribution pattern of Chenopodiaceae–Amaranthaceae pollen in the recent marine sediments matches the average wind flow pattern of those wind belts. The isopoll maps of 9 and 18 ka show a latitudinally stationary area with a distinct pollen supply from the east by the African Easterly Jet, thus indicating that the belt with African Easterly Jet-transport did not shift latitudinally during the last glacial–interglacial transition and remained stationary at *c.* 17–22°N. On the basis of quartz accumulation rates from several ODP sites northwest of Africa, Tiedemann & Sarnthein (1989) concluded that the African Easterly Jet did not shift in latitude over the past 4 My, irrespective of major climatic change. This wind belt thus forms a latitudinally stable and sensitive recorder of north–south shifting vegetation zones. The dominant pollen type in the marine sediments between 17° and 22°N (chenopodiaceous or poaceous) is related to the major floral composition between these latitudes on the adjacent continent: desert vegetation, or savanna, respectively (Hooghiemstra, 1988a).

Large parts of the Mediterranean–Saharan transition zone are covered with tussock grasslands. Grass pollen is mainly released from November to April and transported by the trade winds. South of the Sahara grasses are most abundant in the savanna zone between 19° and 12°N (Fig. 1, zones 4 and 5). Grasses also occur in the Sahara itself but this source area with a sparse vegetation cover is of less importance. South of the Sahara pollen is produced from March to December. Maximal pollen release occurs from June to September and is coeval with the period of maximal African Easterly Jet transport. This explains the distribution pattern of Poaeceae pollen in recent marine surface sediments (Fig. 2a). It matches the average flow of the trade winds in the northern sector, and in the southern area accounts for a high representation of African Easterly Jet-transported grass pollen at *c*. 16–19°N. Between 10° and 16°N, river transport, in addition to winter trade transport, accounts for high Poaceae percentages. The 18 ka isopoll map shows a latitudinal southward shift of 2–3°, as compared with the recent situation, of the area with a maximum representation of grass pollen. This indicates a southward shift of the savanna zone. The 9 ka isopoll map shows a northward extension of the savannas of about 3° of latitude as compared to the present-day situation.

The Cyperaceae are ambiguous ecologically. Some taxa are characteristic of moist and wet environments (the swampy litteral), but others are characteristic of the xerophytic environments of the Sahara (White, 1983). Cyperaceae are also abundant at the Saharan–Sahelian boundary (Cour & Duzer, 1976; Schulz, 1987). The main period of pollen production in the southern sector is estimated at April to September and the distribution pattern in the marine sediments between 18° and 22°N (fig. 2b) may display an African Easterly Jet transport in addition to trade-wind transport and transport associated with the Senegal River. From our model it can be deduced that transport of pollen of Cyperaceae by the African Easterly Jet will increase when the Saharan–Sahelian boundary shifts northward during more humid periods. The isopoll map for the 9 ka time-slice shows a northward displacement of the 10% isopoll of 2–3° of latitude, thus indicating a more northern position of the Saharan–Sahelian boundary. In the 18 ka map only values below 10% could be recorded, which indicates arid conditions and a southern latitudinal position of the savannas.

Accepting a stationary African Easterly Jet belt during the Brunhes chron, and expecting an increase of the pollen signal of (anemophilous) taxa which shift into the belt with African Easterly Jet transport when responding to climatic changes, one can establish a correlation between the pollen signal of Poaceae and Cyperaceae. A cross-correlation performed on data from ODP Site 658 for the period from 80 to 680 ka does indeed show a high degree of coherency between the two spectra (Fig. 3). Moreover, both spectra show a strong and significant 42 ka periodicity indicating a forcing by obliquity (Dupont *et al.* 1989).

Generalizing, it can be stated that from the central Sahara towards the tropical forest area the pollen produced by Chenopodiaceae–Amaranthaceae, Poaceae, and Cyperaceae is dominating successively. Latitudinal shifts of the southern Saharan vegetation zone, and the Sahelian and Sudanian savannas seems to be registered by marine pollen records located in the African Easterly Jet belt by successive maxima of these groups of pollen. This assumption was substantiated by core M 16017-2 at 21°N representing the interval 20–5 ka (Hooghiemstra, 1988b) which provides a basis to interpret the long-range pollen record of ODP Site 658 (Dupont *et al.* 1989).

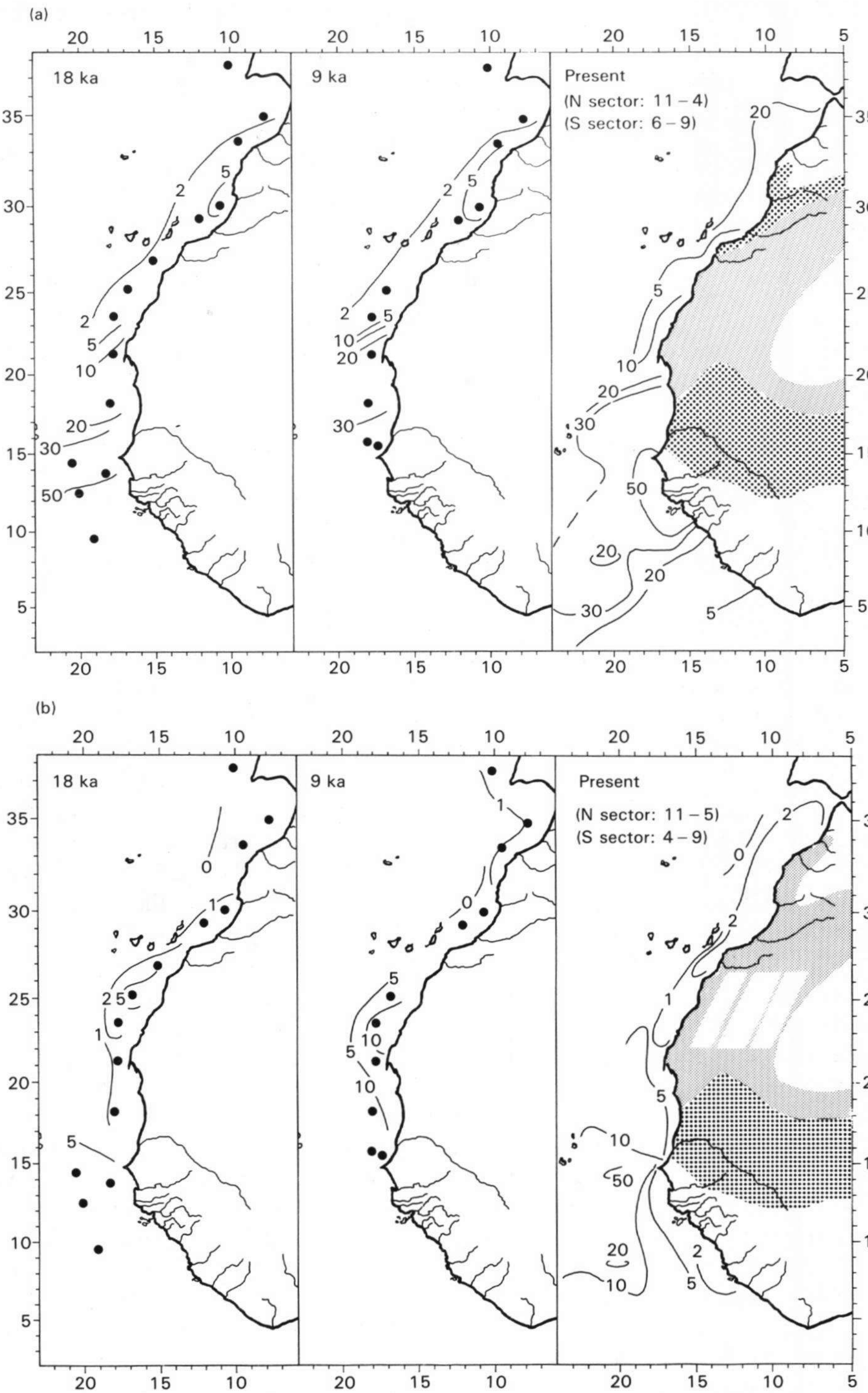

Fig. 2. Isopoll maps of the Poaceae (a) and Cyperaceae (b) of the Atlantic off NW Africa for the present, 9 ka, and 18 ka. Maps of the modern situation are based on 109 surface-sediment samples (locations indicated by + in Fig. 1); maps for 9 and 18 ka are based on 11 and 14 deep-sea core intervals, respectively. (▦) Main pollen source area, (▢) pollen source area of secondary importance, (●) location of deep-sea cores with the pertaining time-slice. Months of main pollen release (1–12: January–December) are shown for N and S sectors. Changes in the river systems and coastline of northwest Africa are not considered in the paleo–isopoll maps.

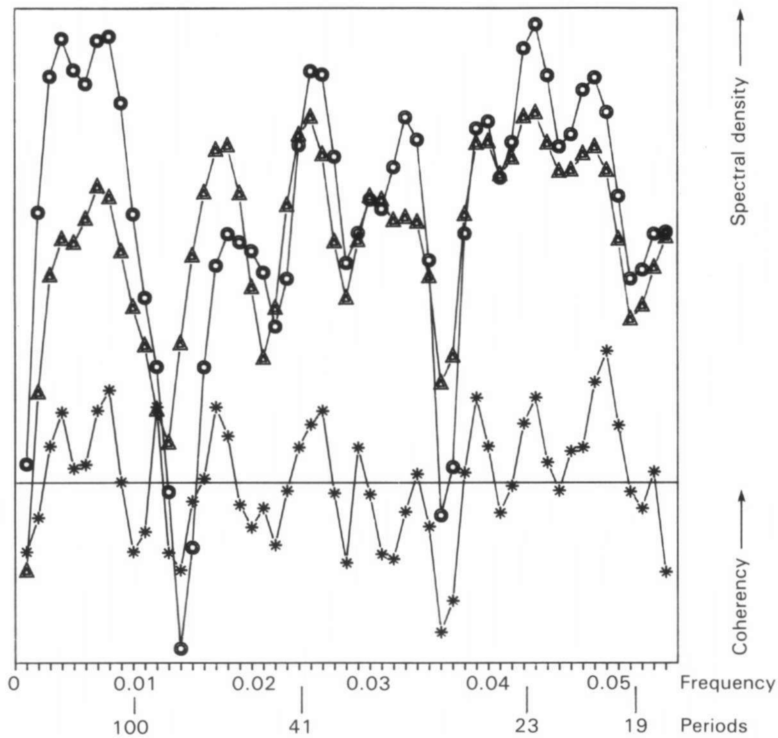

Fig. 3. Frequency spectrum (upper part) and coherency spectrum (lower part, ★) of influx values of Poaceae (○) and Cyperaceae (△) in marine sediments of ODP Site 658 at 21°N. Spectral analysis has been carried out with the Fortran programs CROSPEC and SPECTDF on a microcomputer. From the pollen data set, 111 data points were interpolated linearly at 5 ka for the interval of 75–625 ka. From all curves mean and linear trends were removed and a pre-whitening constant of 0·5 was set. Frequencies were scanned from 0·001 to 0·055 cycles/ka with steps of 0·001 using a bandwidth of 80 lags. Coherency is plotted on an arctangent hyperbolicus scale. The horizontal line represents the 80% confidence level for coherency. Power is plotted on a relative log scale. Frequencies are plotted linearly. The bandwidth variance is 0·0332 (frequency scale). Periodicities belonging to 'eccentricity' (100), obliquity (41), and precesion (23, 19) are labelled in ka.

MIGRATIONS OF THE SAHARAN–SAHELIAN BOUNDARY DURING THE BRUNHES CHRON

The diagram of selected pollen types of ODP Site 658 (Fig. 4) shows large fluctuations which are mainly related to the prevailing wind vigour and pollen production. The latitudinal position of the Saharan–Sahelian boundary can be deduced from the absolute and relative values of the chenopodiaceous–amaranthaceious, poaceous, and cyperaceous pollen, and the pollen total originating from the Guinean and Sudanean forests. On the basis of both the pollen and the oxygen-isotope signal (both measured in the same core), 34 zones could be distinguished (Dupont *et al.* 1989; Dupont, 1989). They could be classified into seven types, representing four types of glacial phases (G1-G4) and three types of interglacial phases (I1-I3). Types G1, G2, G3, G4, I3, I2, and I1 successively range from extremely arid to extremely humid.

I1-type zones differ from other I-types having much larger influx values for most pollen taxa. This high pollen influx can be attributed to a high pollen production, produced by a denser vegetation cover, rather than to an increased pollen transport. High

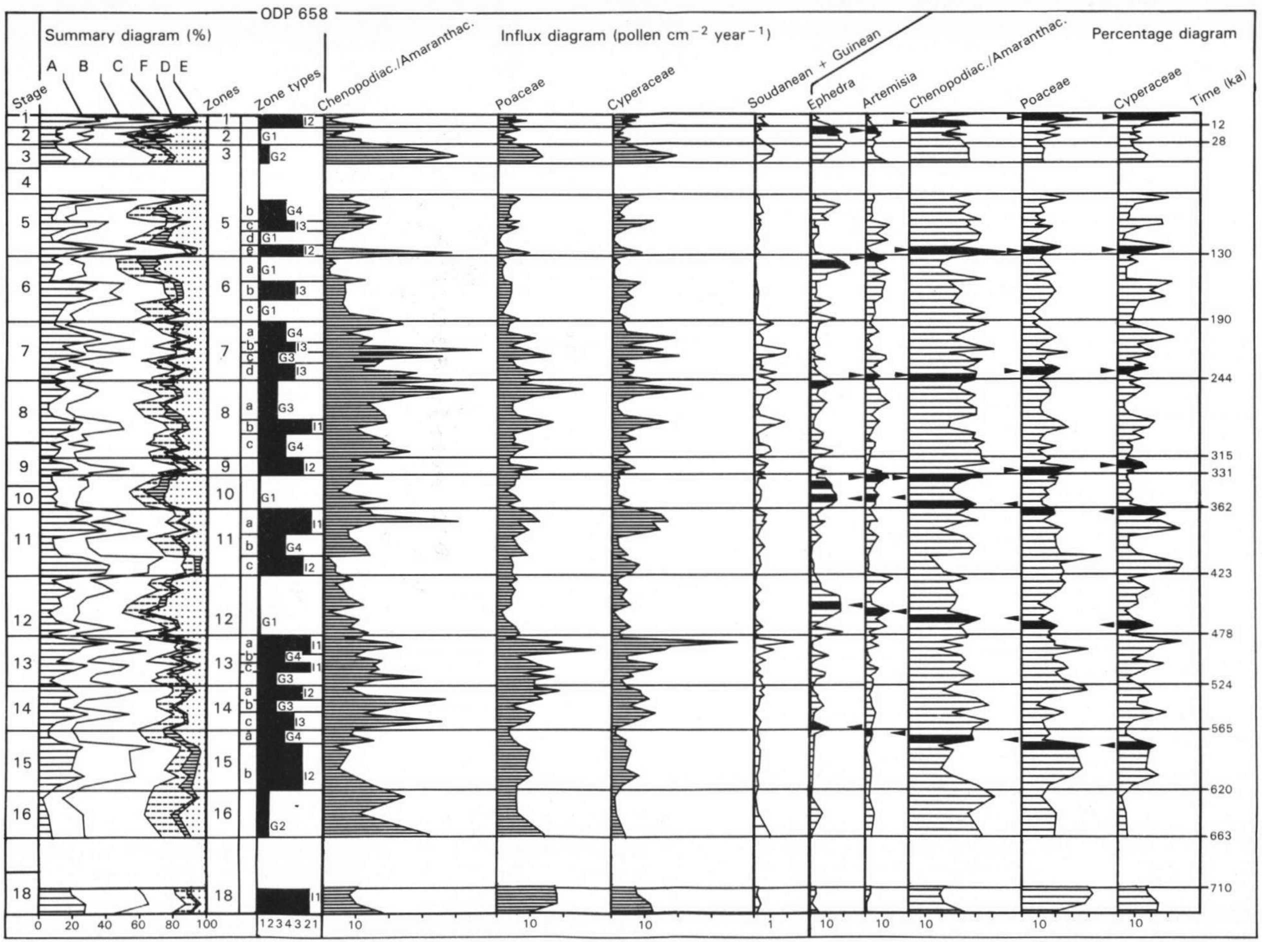

Fig. 4. Pollen diagram of ODP Site 658. From left to right: oxygen isotope stages 1–18, summary diagram (%) of pollen groups (A–F), zones 1–18, zone types (G1, G2, G3, G4, I3, I1, I1), influx curves (pollen cm^{-2} year^{-1}) and percentage curves (%) of the total of pollen) of selected pollen taxa, arranged from left to right according to their dry to wet indication value (bars and arrows are explained in the text), and age of the zone boundaries (ka). In the summary diagram pollen taxa were assigned to the following groups (see also Dupont *et al.* 1989): (A) elements from the Guinean forests and the Sudanean woodland, Cyperaceae, and elements from swamps and wet localities (incl. *Rhizophora* and *Typha*); (B) Poaceae; (C) desert and steppe elements from Sahara and Sahel (incl. Chenopodiaceae–Amaranthaceae; (D) European and mediterranean elements; (E) dry elements from the southern Mediterranean and northern Sahara (*Ephedra* and Asteraceae, incl. *Artemisia*); and (F) other taxa. These groups are arranged according to their indicator value of arid conditions from negative (A) to positive (E). Pollen zones are grouped into seven zone types, ranging from extremely arid (left, glacial G1 type) to extremely humid (right, interglacial I1 type). The influx values are given for a selection of taxa. Oxygen-isotope stages and time scale (in ka) after Sarnthein & Tiedemann (1989).

influx values of Poaceae and Cyperaceae pollen, and high percentages of Cyperaceae pollen of the I1-type zones, indicate a very northern position of the Saharan-Sahelian boundary, probably to the north of 23°N. Arid glacial periods (type G1) showed a very low pollen influx, apparently attributable to a low pollen production by a sparse vegetation cover in large parts of NW Africa. In G1 zones the percentages of *Ephedra* and *Artemisia* are high. During these periods the Saharan–Sahelian boundary apparently attained its southernmost position at about 14°N, corresponding to the situation at 18 ka (compare M 16017-2 in Hooghiemstra, 1988b). Between these extremes five types of zones (I2, I3, G4, G3, G2) can be recognized, successively corresponding to a gradual increase in aridity. Zones of type I2 have low influx values for Chenopodiaceae–Amaranthaceae pollen, moderate influx values for Cyperaceae pollen, and maximal percentages for Poaceae pollen. They represent warm and humid phases, but with a lower pollen production than in the I1 zones. The Saharan–Sahelian boundary would lie at a northern position (about 23°N) comparable to its position at 9 ka (compare M 16017-2 in Hooghiemstra, 1988b). The lower influx values indicate a less effective wind transport. Type I3 zones show higher influx values for Chenopodiaceae–Amaranthaceae and lower ones for Poaceae, indicating drier conditions and a more southern position of the Saharan–Sahelian boundary than of types I1 and I2, and they are comparable to the present-day situation. The Saharan–Sahelian boundary during type G4 (this type forms an intermediate between the I- and the G-type zones) is probably at about the same position as in type I3 (present-day situation) or lay a bit farther south. In type G3 the Saharan–Sahelian boundary is still at an intermediate latitude, thus showing low influx values and percentages of Cyperaceae and moderate to low Poaceae pollen percentages. High influx values for all pollen taxa indicate an effective wind transport and a high to moderate pollen production. The conditions were probably more arid than during I3, but not as arid as during the G2 zones. In type G2 the Saharan–Sahelian boundary lay farther to the south as indicated by the low influx of Poaceae pollen. The influx of Chenopodiaceae–Amaranthaceae pollen is still high; rather arid conditions prevailed during these periods.

From the zone types described above basic differences between the lower and the upper part of the pollen record of ODP Site 658 can be detected: (1) periods characterized by very humid conditions (I1 zones) occurred only before 280 ka, (2) the Poaceae pollen values (influx and percentages) show a decline from 680 ka to the present and maximum percentages exceed 40% only before 300 ka, and (3) extreme glacial conditions (during G1 zones) are only found during the last 480 ka. These characteristics of the pollen record lead to the conclusion that in glacial stages younger than 480 ka the aridity increased, and in interglacial stages younger than 280 ka the humidity decreased.

On the short range, successive maxima of pollen percentages of *Ephedra, Artemisia*, Chenopodiaceae–Amaranthaceae, Poaceae, and Cyperaceae also show a gradual change in climatic conditions. At least seven such sequences, with a duration of about 15 ky, can be recognized (bars and arrows in the right part of Fig. 4). They strongly suggest that the transitions between the various recognized zones must be interpreted in terms of a gradual latitudinal shift of vegetation zones south of the Sahara.

DISCUSSION

From the pollen diagram of ODP site 658 we deduce that the Saharan–Sahelian boundary oscillated many times during the last 0·7 My between the latitudes of 14°N and over 23°N (Fig. 5). During the phases with extreme humid interglacial conditions the Saharan–

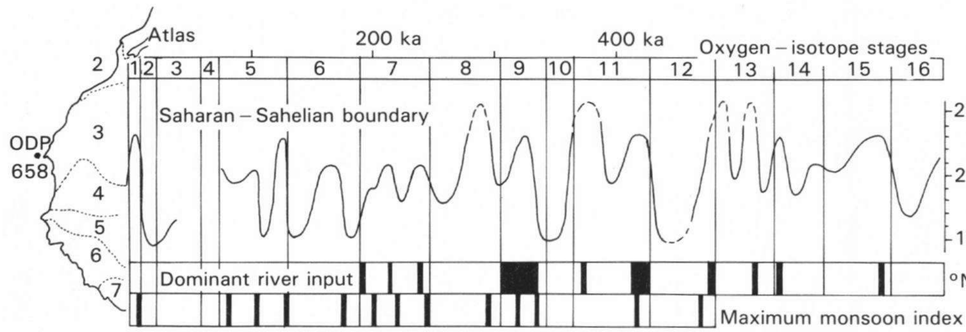

Fig. 5. Summary diagram on a linear time scale of the estimated latitudinal shifts of the Saharan–Sahelian boundary, based on pollen data of ODP Site 658, estimated periods of fluvial discharge from the Central Sahara recorded by a high clay content in ODP Site 658 (Tiedemann & Sarnthein, 1989) and periods, with a high monsoon index (Rossignol-Strick, 1983), giving rise to Mediterranean sapropels. The modern vegetational distribution is given at the left, (2) Mediterranean vegetation zone; (3) Sahara; (4) Sahel; (5) Sudanian woodland; (6) Guinean forests; and (7) rain forest (after White, 1983).

Sahelian boundary had probably a more northern position than was found for the early Holocene (9 ka). This suggests that the extreme arid vegetation types must have had a limited distribution during such times in NW Africa, depending on the location of the northern boundary of the Sahara. Such warm and humid phases have only been recorded for the older part of the Brunhes chron (zones 18, 13c, 13a, 11a, and 8b).

A high clay content in the ODP site 658 record during certain short periods of the Brunhes chron are apparently due to a fluvial discharge at 21°N probably from the Central Sahara (Tiedemann & Sarnthein, 1989). River discharge finally ceased in this region during oxygen-isotope Stage 7 (Fig. 5). Earlier river discharge took place during interglacial phases (the uneven stages) when the Saharan–Sahelian boundary was located at or north of 23°N. Exceptions are found during Stage 7, where fluvial transport has been noted during zones of type I3 and G4, namely phases with high values of Chenopodiaceae–Amaranthaceae pollen. This would imply a transitional period during which interglacials showed both an aridification of the Northern and Central Sahara and a fluvial supply.

Strong monsoons with high precipitation in tropical Africa caused the formation of sapropels in the Mediterranean through an increased freshwater discharge by the Nile. An exception occurred during Stage 9, when only one out of three phases with a high monsoon index (as computed from the insolation curves) produced Mediterranean sapropels (Rossignol-Strick, 1983). It seems as if the response of the NW African flora to the monsoon index increased during the Brunhes chron. During Stages 9–12 a high monsoon index tended to fall just after periods with a northern position of the Saharan–Sahelian boundary. During Stages 1–8, however, each high monsoon index value appears just before a period with a relatively northern position of the Saharan–Sahalian boundary (north of about 18°N), thus indicating a better response of the Sahel and Savanna vegetation cover on the intensity of the monsoon.

Distinct changes in the global paleoclimatic record at 0·4 or 0·3 Ma are reported by Schramm (1985), Jansen *et al.* (1986), Chuey *et al.* (1987) and Pisias & Rea (1988). A climatic deterioration (i.e. the incidence of more 'glacial' conditions) in the late Quaternary is reported for the northern hemisphere and an amelioration (with more 'interglacial' conditions) for the southern hemisphere and the equatorial regions (Jansen *et al.* 1986;

Chuey *et al.* 1987). The pollen data from ODP site 658, however, indicate a trend toward more extreme glacial stages and less pronounced interglacial stages during the younger part of the Quaternary.

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