Palynological Records from Northwest African Marine Sediments: A General Outline of the Interpretation of the Pollen Signal [and Discussion]

H. Hooghiemstra, Judith Maizels, H. Hooghiemstra and R. G. W. Ward

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Palynological records from northwest African marine sediments: a general outline of the interpretation of the pollen signal

By H. Hooghiemstra†

Institute of Palynology and Quaternary Sciences, University of Göttingen, Wilhelm-Weber-Strasse 2,
D-3400 *Göttingen, F.R.G.*

Pollen analysis of over 100 modern surface-sediment samples from the Atlantic off northwest Africa (between 35° and 4° N) has improved the understanding of the relation between modern pollen source areas, modern pollen transport and the modern distribution patterns of the pollen concerned in the marine sediments. Aeolian pollen transport is dominant in this region and the distribution patterns reflect the modern average atmospheric circulation.

Palaeoisopollen maps of the time slices of 9 ka BP and 18 ka BP monitor the atmospheric circulation during the last glacial–interglacial transition, providing evidence for the latitudinal position of the northeast trade winds and the African Easterly Jet, and the average northernmost and southernmost position of the intertropical convergence zone. In this way the number of major variables in time-series (continuous pollen records) was reduced to one; this has made it possible to interpret these records in terms of vegetational change, climatic humidity and changes in the intensity of the northeast trade winds.

1. Introduction

Pollen and pteridophyte spores are essentially products of the land vegetation and are therefore indicators of continental environmental conditions. The way in which pollen and spores are transported to the marine sediments may be complex. For a long time river and ocean current transport was considered as being generally dominant (see, for example, Muller (1959), Orinoco delta; Traverse & Ginsburg (1966), Great Bahama Bank; Cross *et al.* (1966), Gulf of California; Koreneva (1971), Mediterranean Sea). This may certainly be so in many areas, but it is not appropriate to generalize about methods of transport. Mudie (1982) and Melia (1984) showed that, in eastern Canada and northwest Africa, respectively, the aeolian factor may be important in the transport of pollen to the marine sediments.

A palynological study of modern marine surface-sediments off northwest Africa (between about 35° and 4° N) has provided distribution patterns (displayed as isopollen maps) of the most important northwest African and south European pollen producers. By relating these modern distribution patterns to the modern position of the source areas concerned, the transport mechanisms can be deduced. In this respect it is important to establish, for each pollen-producer, the period of main pollen release and to take into account the average atmospheric circulation over northwest Africa, which changes from month to month. In this way a model of modern pollen transport in the northwest African area can be established (Hooghiemstra & Agwu 1986; Hooghiemstra *et al.* 1986). This model of modern pollen

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† Present address: University of Amsterdam, Dept. of Palynology and Palaeo/Actuo-Ecology, Hugo de Vries Laboratory, Kruislaan 318, 1098 SM, Amsterdam, The Netherlands.

transport was verified for selected time-slices of the past, namely, for 9 ka BP (this paper) and for 18 ka BP (Hooghiemstra *et al.* 1987). The model was then applied to studies of continuous pollen records (time-series) of deep-sea cores from the southern sector (*ca.* 9° N) (Hooghiemstra & Agwu 1988), from the central part of the area under study (*ca.* 21° N) (Hooghiemstra 1988*a*) and from the northern sector (*ca.* 29–37° N) (Hooghiemstra 1988*b*). The time intervals represented by these marine pollen records are 140–70 ka BP (southern sector), 20–5 ka BP (central part of the area under study) and (250) 140–3 ka BP (northern sector), including several glacial phases, interglacial phases and terminations.

The objective of this paper is to integrate the results of these studies, to present a general outline of the interpretation of pollen records of deep-sea cores from the northwest African area, and to emphasize the potential of marine palynology in palaeoclimatological and palaeoecological studies.

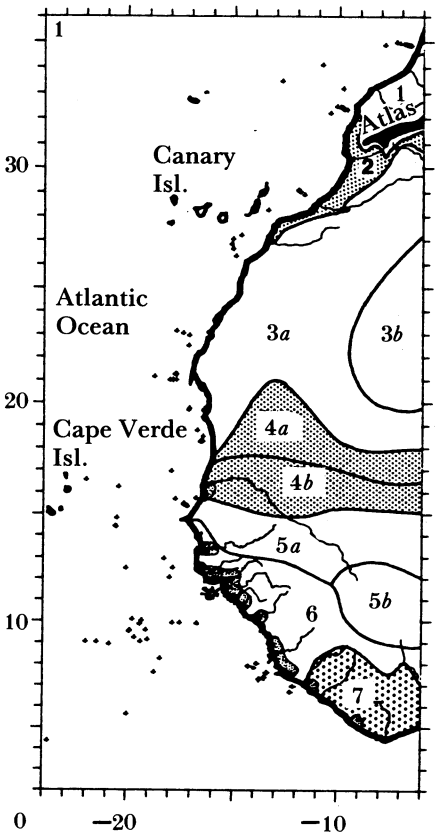
2. SETTING OF PRESENT VEGETATION AND ATMOSPHERIC CIRCULATION

The distinct climatic gradient between the arid Sahara and the humid climate in equatorial Africa is clearly reflected in a number of latitudinal vegetation zones (White 1983) (figure 1). These vegetation zones are characterized by the presence of certain taxa, which are palynologically mostly identified to the generic or family level.

Northwest Africa is further characterized by a pronounced atmospheric circulation system (figure 2) with surface winds (northeast trade winds, January trades, southerly trades) and a zonal wind belt at higher altitudes (African Easterly Jet or Saharan Air Layer).

The northeast trade winds reach as far south as *ca.* 23° N in July and August, and to *ca.* 4–6° N in January (January trades), depending on the main position of the intertropical convergence zone (ITCZ) in the course of the year (Leroux 1983). Although the January trades are most frequent in January and February, the associated sandstorms and dry hazes can also occur with high frequency as early as October and may persist until May (Maley 1982). The northeast trade winds today contribute only a limited amount of dust (including pollen), originating from the northwestern fringe of the Sahara and carried only a limited distance offshore. The trade winds obtain their maximum strength during late spring and blow basically parallel to the shoreline, and south of 18° N even slightly onshore towards the SSE (Sarnthein *et al.* 1982; Leroux 1983). From April to November the southwesterly trades account for a northeastward transport at the surface in the southern sector of the area under study.

The Saharan Air Layer (figure 2) is a zonal wind, which originates in the southern Sahara (corresponding today mainly to the source area of the Chenopodiaceae–Amaranthaceae pollen) and moves west above the trade-wind inversion between 8° and 23° N. A maximum concentration of transported dust (including pollen) is found at an altitude of *ca.* 3000 m between about 17° and 21° N. It passes around the upper-air high-pressure system found over the western Sahara, and finally forms a sickle-shaped course of trajectory over the eastern Atlantic (Tetzlaff & Wolter 1980; Sarnthein *et al.* 1982). Favourable transport conditions occur in the summer season between May and September, but most of the Saharan dust arrives at the Atlantic during July and August, when the Saharan Air Layer functions as a real jet wind between 17° and 21° N (African Easterly Jet).



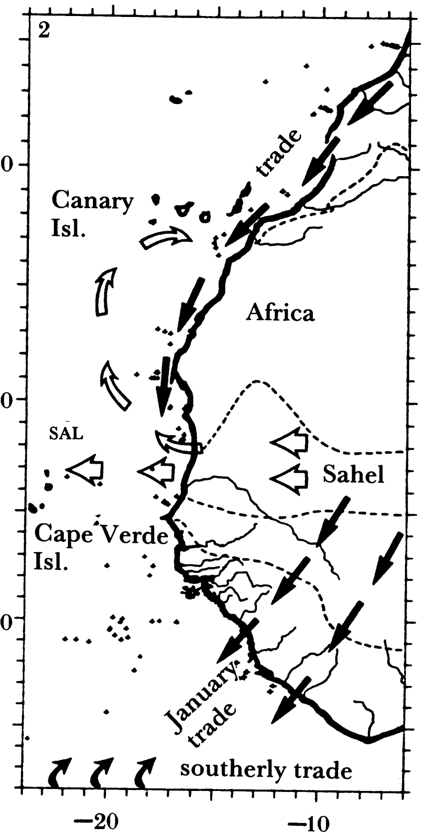


Figure 1. Vegetation of northwest Africa (after White 1983). From north to south, the numbers indicate: 1, Mediterranean vegetation zone; 2, steppes (semi-desert grassland and shrubs) of the western Atlas region; 3*a*, deserts and semi-deserts (regs, wadis, hamadas) of the Sahara; 3*b*, desert dunes without perennial vegetation, and absolute deserts; 4*a*, northern Sahel zone: semi-desert grassland and shrubs (dry thorn savannas); 4*b*, southern Sahel zone: *Acacia* wooded grassland and deciduous bush; 5*a*, Sudanian undifferentiated woodland (dry savannas); 5*b*, Sudanian woodland with abundant *Isoberlinia*; 6, Guinea savanna zone: mosaic of lowland rainforest and secondary grassland; 7, rainforest. The small stippled areas along the coast between 16° and 5° N indicate areas with mangroves (*Rhizophora*). As well as the climatic gradient, local orographic and edaphic factors determine the vegetational distribution and complicate the general pattern presented here. Crosses indicate the sample stations.

Figure 2. Major wind belts of northwest Africa. Solid arrows indicate surface winds (northeast trades, January trades, southerly trades); open arrows indicate zonal winds at higher altitudes (African Easterly Jet or Saharan Air Layer). Broken lines indicate the boundaries of the major vegetation belts; crosses, positions of sample stations.

3. Pollen records and methodology

3.1. *Pollen records*

Intervals of different lengths from about 30 deep-sea cores from the Atlantic off northwest Africa have been palynologically analysed by several authors. A survey is presented by Hooghiemstra (1987). In most of the cores, time control is provided by oxygen-isotope chronology. The cores are located between about 37° and 9° N and mainly represent the time interval of 150–5 ka BP.

3.2. *Methods of clustering*

The source area of the pollen found in the modern marine surface sediments off northwest Africa can often be delineated with accuracy, owing to the characteristic composition of the northwest African vegetation zones. In our studies, we recognized five groups of pollen, representing distinct vegetation zones (after Agwu & Beug (1982); main representatives are indicated in brackets):

(i) pollen of forest trees and shrubs of west and south Europe and north Africa (*Pinus*, *Corylus*, *Betula*);

(ii) Mediterranean trees and shrubs, including deciduous oaks (*Quercus*, *Erica*, Oleaceae, *Rhus*);

(iii) plants of steppe and desert communities (*Ephedra*, *Calligonum*, *Maerua*, *Balanites*, *Heliotropium*, *Salvadora*);

(iv) taxa with many representatives in steppe and desert regions (pollen-analytically only identifiable to the family or generic level; Chenopodiaceae–Amaranthaceae, Gramineae, *Artemisia*);

(v) taxa with a centre of distribution in tropical forests and savannas, including the Sahel zone (*Acacia*, *Alchornea*, Bombacaceae, *Butyrospermum*, *Cassia*, Combretaceae, *Elaeis*, Meliaceae, *Rhizophora*).

Two other groups of pollen include taxa often characteristic of moist or wet localities (*Isoëtes*, *Typha–Sparganium* type, Cyperaceae), and a group of taxa which are not characteristic of the above mentioned vegetation zones and have a wide distribution. This way of grouping pollen types appeared to be efficient in the reconstruction of the vegetational shifts and climatic history of northwest Africa. Several authors, however, have grouped pollen taxa from northwest Africa (mostly land-based studies) in a more-or-less different way; see, for example, Bonnefille (1982), Caratine *et al.* (1979), Caratini & Cour (1980), Cour *et al.* (1973), Cour & Duzer (1976), Lezine (1987), Maley (1983), Rossignol-Strick & Duzer (1979) and Van Campo (1975). The most favourable way of grouping the northwest African pollen taxa depends heavily on the objective of the study concerned. The type of grouping given above is effective in monitoring large-scale latitudinal shifts of the northwest African vegetation zones. However, a different method of clustering has been used to monitor changes in the intensity of the northeast trade winds (see, for example, Hooghiemstra 1988*a*).

3.3. *Time-slices and time-series*

When studying changes of the northwest African vegetational and climatic conditions by means of pollen analysis of deep-sea cores we are dealing with two major variables. Firstly, the latitudinal position of the northwest African vegetation zones has changed and, as a consequence, the pollen source areas have changed positions. Secondly, the transporting mechanisms of the pollen concerned may have changed. In order to deal with these two variables we have studied three time-slices, namely, the modern situation, the time-slice of 18 ka BP (representing the situation during the last glacial maximum), and the time-slice of 9 ka BP (representing the phase of maximum northward expansion of the vegetation zones south of the Sahara).

The modern relation between the latitudinal position of the pollen source areas, the transporting mechanisms (wind, water currents) and the resulting distribution patterns of the pollen concerned in the marine surface-sediments can be investigated in detail, as the grid of surface-sediment samples is relatively dense. Comparing the modern situation with the 'snapshots' of the situation at *ca.* 9 ka BP and 18 ka BP (on the basis of a series of well-dated deep-sea cores), relevant changes in the transport of pollen during the last glacial–interglacial transition can be inferred. In this way the second variable mentioned above may be eliminated, this makes an interpretation possible of the time–series (continuous pollen records) into terms of changes in the northwest African vegetation.

4. TIME-SLICES

4.1. *Modern situation*

The modern distribution of pollen and fern spores, originating from the northwest African vegetation, in the marine surface-sediments is based on pollen analysis of 109 sample stations, located between 35° and 4° N. (Full data and detailed discussion of the results are given by Hooghiemstra *et al.* (1986); concise results have been published by Hooghiemstra (1986) and Hooghiemstra & Agwu (1986).) The distribution of the mapped taxa (displayed as isopollen maps, figures 3–12) corresponds to the modern pattern of atmospheric circulation. Evidence for transport by water-currents is poor; this is not surprising in an area mainly characterized by climatic aridity. Most of the isopollen maps display a close relation between the geographical location of the source area and the distribution of the associated pollen and spores in the marine surface-sediments, taking into account for each taxon the main period of pollen release and the atmospheric circulation pattern characteristic of that part of the year. Thus the isopollen maps have the potential to record seasonal wind patterns. The above-mentioned close relation is most evident for *Quercus*, *Olea*, *Artemisia*, Chenopodiaceae–Amaranthaceae, Gramineae, Combretaceae, *Rhizophora*, *Alchornea*, *Elaeis* and the fern spores.

Studies on transportation and sedimentation of sediment fractions (Sarnthein *et al.* 1982) and microorganisms (Honjo 1976) demonstrated a process of lumping of dust particles into 'faecal pellets' in the water column near the sea surface, causing an accelerated sinking and preventing marked horizontal transport by ocean currents. Rapid sinking of pollen and spores to the ocean floor, after pollen and spores have passed the air–water boundary, can also be inferred from the clear-cut, not smeared, distribution patterns in the marine surface-sediments.

4.2. *Isopollen maps of* 9 *ka* BP *and* 18 *ka* BP

Palaeoisopollen maps of the time-slice of 18 ka BP are based on pollen analysis of core intervals of 14 well-dated deep-sea cores, located between 37° and 9° N (full data and detailed discussion of the results in Hooghiemstra *et al.* (1987). Eleven deep-sea cores, located between 37° and 15° N, were available with the time-slice of 9 ka BP and form the data set of the 9 ka BP palaeoisopollen maps (tables 1 and 2). The isopollen maps of 10 taxa and groups of taxa at these three time-slices are presented (figures 3–12).

The isopollen maps of the elements with a source area north of the Sahara (e.g. *Pinus*, Mediterranean elements, *Artemisia*) indicate that during all time-slices trade winds transported pollen from the Iberian Peninsula and the northern fringe of the Sahara in southern and southwestern directions. It may be concluded, therefore, that the belt with trade winds did not shift latitudinally during the last glacial–interglacial transition. This evidence is not compatible with the hypothesis assuming a zone of surface westerlies in the northern part of northwest

TABLE 1. MARINE POLLEN RECORDS OFF NORTHWEST AFRICA REPRESENTING THE TIME-SLICE 9 ka BP

core number	position		water depth	core interval (representing conditions at 9 ka BP)	dating method[a]	reference[b]
	lat.	long.	m	cm		
8057 B	37° 41′	10° 05′	2811	101–130	R_p/R_b index	3
M 15669-1	34° 53′	07° 49′	2030	6–17.5	$\delta^{18}O$	3
M80-17B	33° 37′	09° 25′	3016	50–80	^{14}C	1
M 16004-1	29° 59′	10° 39′	1512	9–25	$\delta^{18}O$	5, 3
M 15627-3	29° 10′	12° 05′	1024	0–14	$\delta^{18}O$	3
M123-92-1	25° 10′	16° 51′	2575	10–25	$\delta^{18}O$	1
M123-10-4	23° 30′	17° 43′	3080	10–35	$\delta^{18}O$	1
M 16017-2	21° 15′	17° 48′	800	50–72	$\delta^{18}O$, ^{14}C	2
M 13289-2	18° 05′	18° 01′	2490	35–65.5	^{14}C	5
M12347-2	15° 50′	17° 51′	2576	90	foram.	4
M12345-5	15° 29′	17° 22′	945	90–145	foram., $\delta^{18}O$	4

[a] R_p/R_b index: planktic/benthic foraminifera index.

[b] References: 1, Agwu & Beug (1982); 2, Hooghiemstra (1988*a*); 3, Hooghiemstra *et al.* (1988); 4, Rossignol-Strick & Duzer (1979); 5, this paper.

Africa (Rognon 1976; Rognon & Williams 1977; Nicholson & Flohn 1980). Changes in the intensity of the northeast trade winds during the last glacial–interglacial transition are amply demonstrated in the literature and can also clearly be inferred from our pollen data. The isopollen maps of 18 ka BP also suggest that, in the northern sector (around 30° N), the glacial trade winds had a stronger eastern component; this is in agreement with the sedimentological studies of Sarnthein & Walger (1974).

When the 18 ka BP and 9 ka BP isopollen maps are compared with the map of the modern situation it is evident that the latitudinal position of the Chenopodiaceae–Amaranthaceae maximum in the marine sediments is exactly at the same place (figure 8). The zone between *ca.* 19–22° N has apparently been continuously characterized by an abundant pollen supply from the east. It may be inferred, therefore, that the zonal belt with African Easterly Jet transport was stationary during the last glacial–interglacial transition and was continuously situated around 17–21° N. As the latitudinal position of the African Easterly Jet is related to the northernmost position of the ITCZ, it may be concluded that the latter was also stationary.

The stationary position of the belt with African Easterly Jet transport during the last glacial–interglacial transition is an important fact in the reconstruction of latitudinal shifts of the northwest African vegetation zones: Which pollen type is mainly transported by the African Easterly Jet to the Atlantic depends on the type of vegetation present between *ca.* 16 and 22° N.

Around 18 ka BP, when the Sahara had expanded maximally into northern and southern directions, this area was occupied by a chenopod-rich desert vegetation. This is reflected by high values (*ca.* 65%) of chenopod pollen in the marine sediments around 21° N. At about 9 ka BP the vegetation zones south of the Sahara had shifted to their northernmost position. It was estimated that the graminaceous-rich Sudanian and Sahelian vegetation zones extended at that time between about 16–17° and 23–24° N (Hooghiemstra 1988*a*; Lezine 1987). Thus

Table 2. Pollen percentages of selected taxa for 9 ka bp deep-sea core intervals

(Mean values are given in the second column of each taxon.)

deep sea core	depth/cm	*Pinus*		Mediterranean elements		*Ephedra*		*Artemisia*		Chenopodiaceae–Amaranthaceae		Gramineae		tropical elements		Compositae Tub. + Lig.		fern spores		trade-wind indicators	
8057 B	101–110	60.0	61.4	14.3	18.2	0.2	0.1	0.2	0.3	1.6	1.1	1.2	1.9	0	0	2.1	2.0	1.7	1.2	62.6	63.8
	111–120	61.6	—	21.4	—	0.1	—	0.3	—	0.4	—	2.2	—	0	—	1.4	—	1.1	—	63.4	—
	121–130	62.5	—	19.0	—	0.1	—	0.4	—	1.2	—	2.2	—	0	—	2.4	—	0.9	—	65.4	—
M 15669-1	6–7.5	17.8	22.1	13.3	14.6	2.2	3.8	—	2.7	0	0	2.2	1.1	0	2.7	8.9	9.7	15.6	10.5	28.9	38.2
	16.0–17.5	26.3	—	15.8	—	5.3	—	5.3	—	0	—	0	—	5.3	—	10.5	—	5.3	—	47.4	—
M80-17B	50–60	18.4	20.4	34.6	32.0	4.7	5.4	2.1	3.4	14.3	15.7	6.1	4.7	0	0	0.9	1.7	0	0	26.1	31.0
	60–70	15.4	—	22.9	—	7.9	—	4.8	—	21.1	—	4.7	—	0	—	2.5	—	0	—	30.6	—
	70–80	27.3	—	38.5	—	3.7	—	3.4	—	11.8	—	3.4	—	0	—	1.7	—	0	—	36.2	—
M 16004-1	9–10	17.9	26.3	2.6	7.1	5.1	6.4	5.1	2.6	7.7	7.7	7.7	7.7	0	0	48.7	34.0	5.1	14.1	76.9	69.2
	24–25	34.6	—	11.5	—	7.7	—	—	—	7.7	—	7.7	—	0	—	19.2	—	23.1	—	61.5	—
M 15627-3	0–4	17.9	14.4	7.5	7.8	—	4.9	9.0	10.2	13.4	22.4	6.0	4.5	0	0	10.4	11.2	0	0.6	37.3	40.7
	10–14	10.9	—	8.0	—	9.7	—	11.4	—	31.4	—	2.9	—	0	—	12.0	—	1.1	—	44.0	—
M 123-92-1	10–15	57.1	58.0	3.4	3.0	2.6	2.9	2.2	2.7	18.4	17.5	2.2	2.1	0	0	3.0	2.7	0	0	64.9	66.2
	20–25	58.9	—	2.5	—	3.1	—	3.1	—	16.6	—	1.9	—	0	—	2.3	—	0	—	67.4	—
M 123-10-4	10–15	34.9	20.5	4.8	5.9	0.8	1.3	1.3	2.9	16.7	18.9	5.4	4.0	0.8	1.3	2.4	3.9	0	0	39.5	28.5
	30–35	6.1	—	7.0	—	1.8	—	4.4	—	21.1	—	2.6	—	1.8	—	5.3	—	0	—	17.5	—
M 16017-2	50–52	0.8	0.7	1.4	1.4	1.2	1.8	2.3	2.6	38.5	44.0	26.7	22.9	5.5	3.7	6.1	5.8	0.2	0.3	10.3	10.8
	60–62	0.5	—	1.8	—	1.8	—	2.3	—	55.2	—	13.3	—	3.1	—	5.1	—	0.3	—	9.7	—
	70–72	0.8	—	1.1	—	2.3	—	3.2	—	38.2	—	28.7	—	2.5	—	6.1	—	0.3	—	12.4	—
M 13289-2	35–36	5.8	3.1	1.4	0.6	5.8	4.7	1.4	1.0	14.5	12.7	24.6	24.8	20.3	25.0	2.9	4.0	2.9	2.7	15.9	12.8
	56–57	2.6	—	0.5	—	2.6	—	1.0	—	11.5	—	21.4	—	28.1	—	4.7	—	3.6	—	10.9	—
	64.5–65.5	1.0	—	0	—	5.6	—	0.7	—	12.2	—	28.4	—	26.7	—	4.3	—	1.7	—	11.6	—
M 12347-2	90	0	0	0	0	0	0	0	0	2.0	2.0	37.2	37.2	36.1	36.1	2.0	2.0	0.2	0.2	2.0	2.0
M 12345-5	90	0	0.1	0	0	0	0.2	0	0	2.1	2.8	37.3	35.1	35.5	40.9	0.3	0.4	0.5	0.3	0.3	0.6
	145	0.1	—	0	—	0.4	—	0	—	3.5	—	32.9	—	46.2	—	0.4	—	0	—	0.8	—

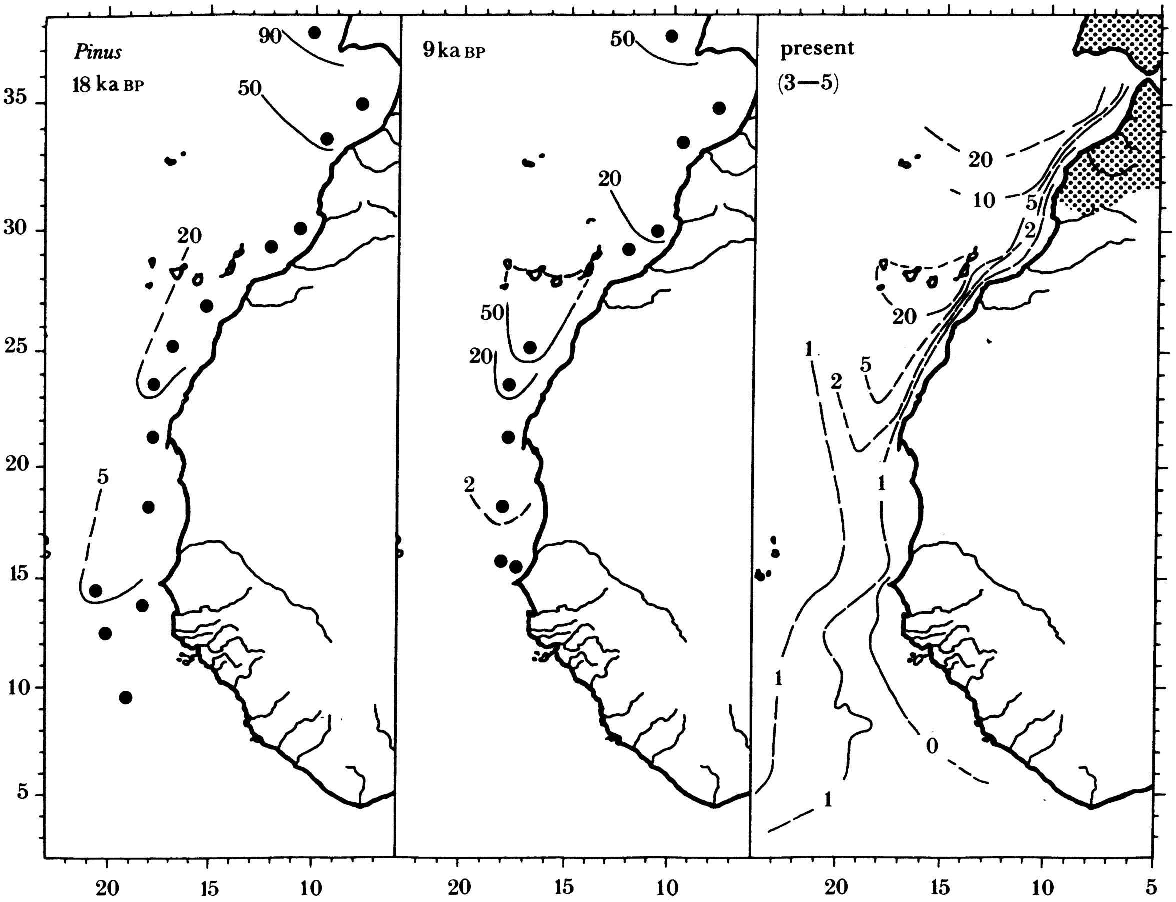


FIGURE 3. For legend see p. 443.

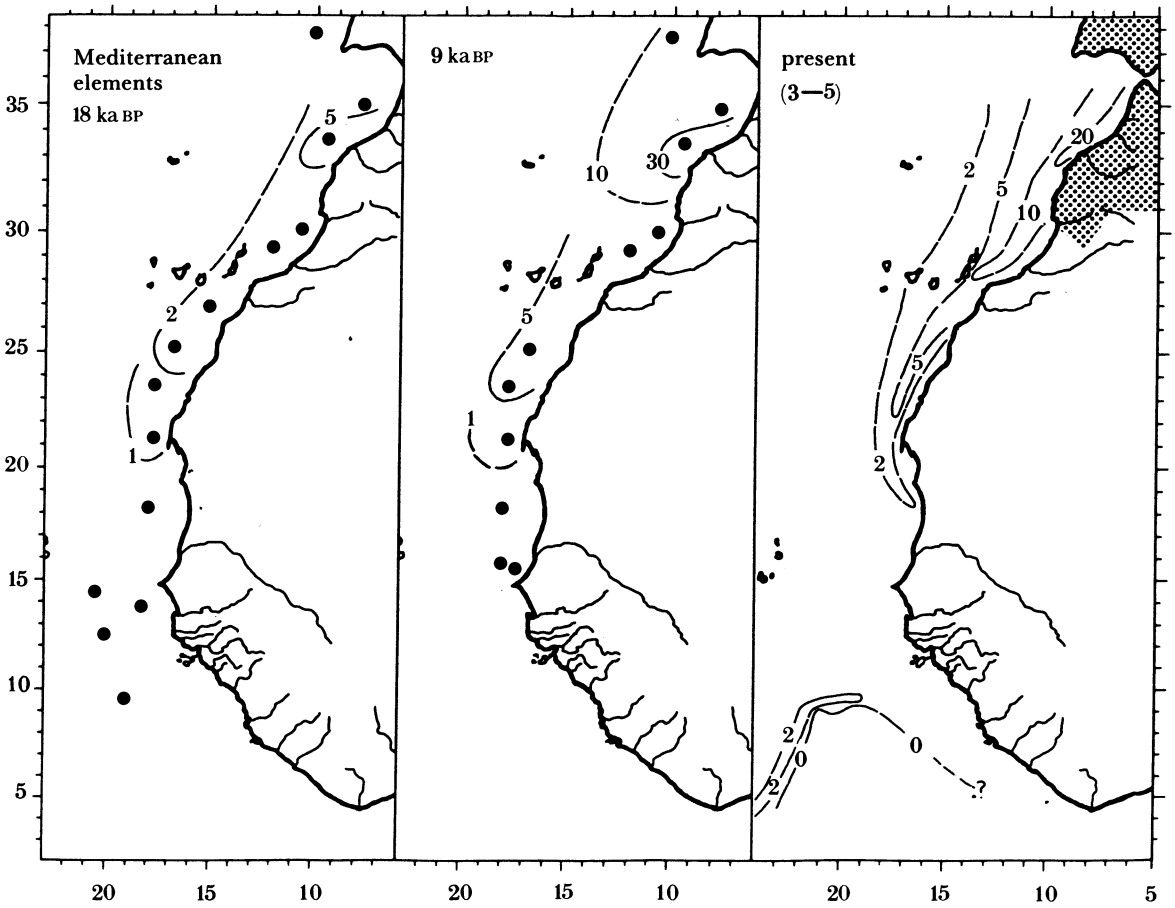
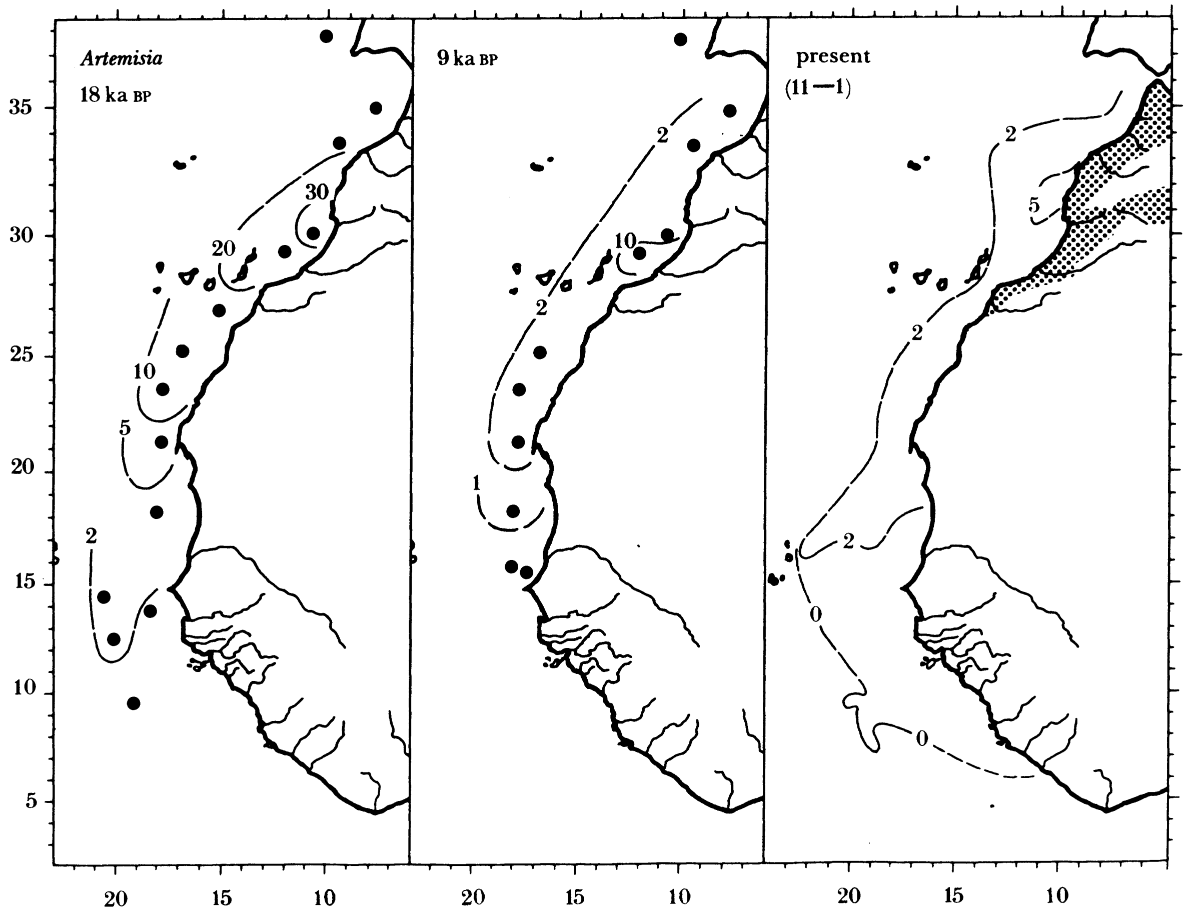


FIGURE 4. For legend see p. 443.



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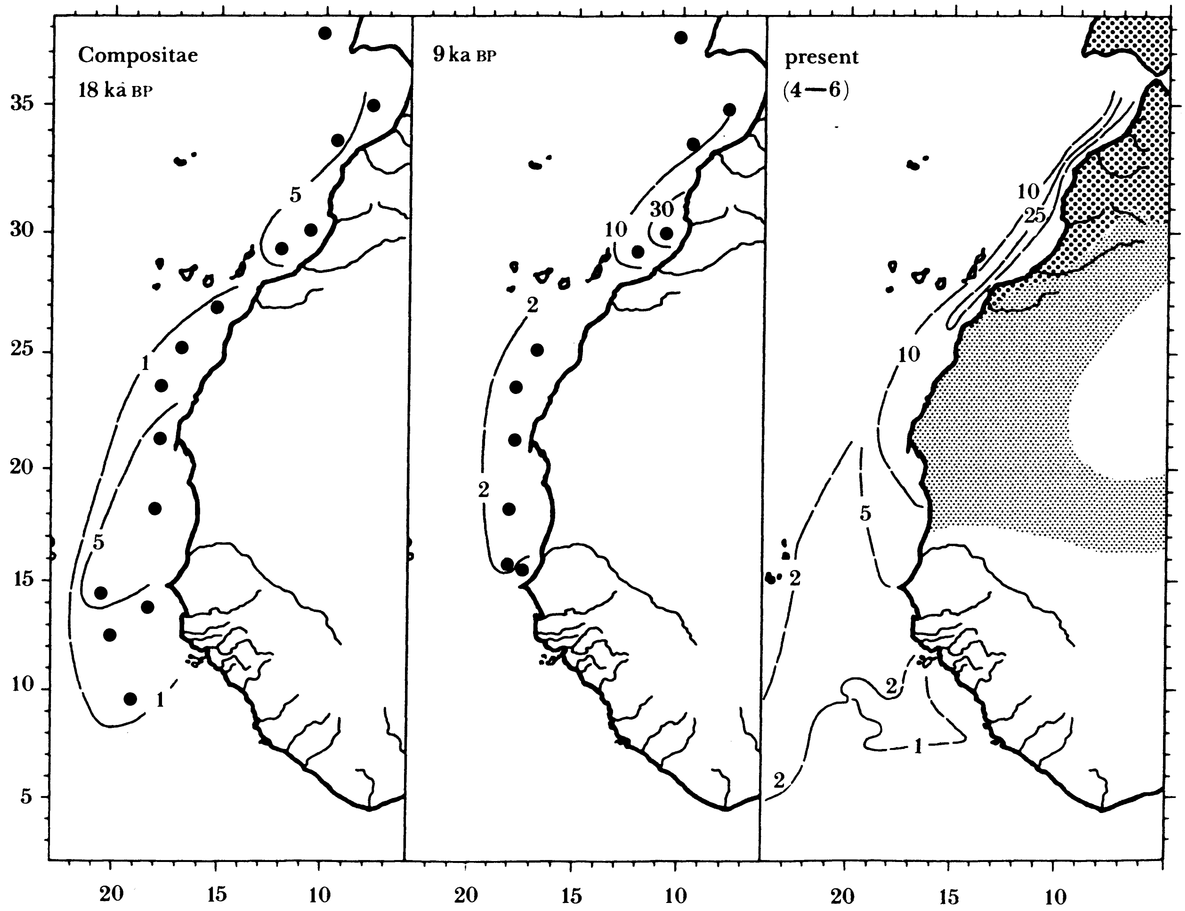

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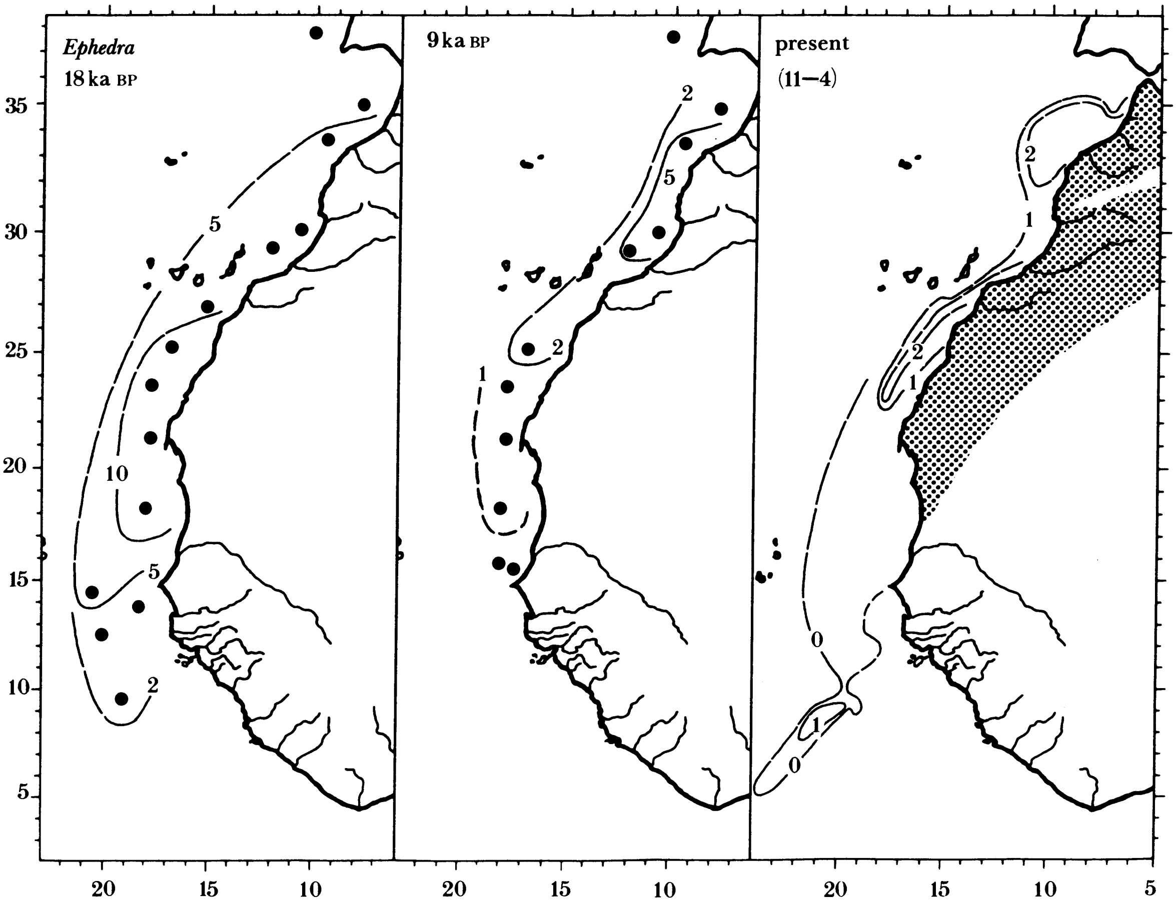

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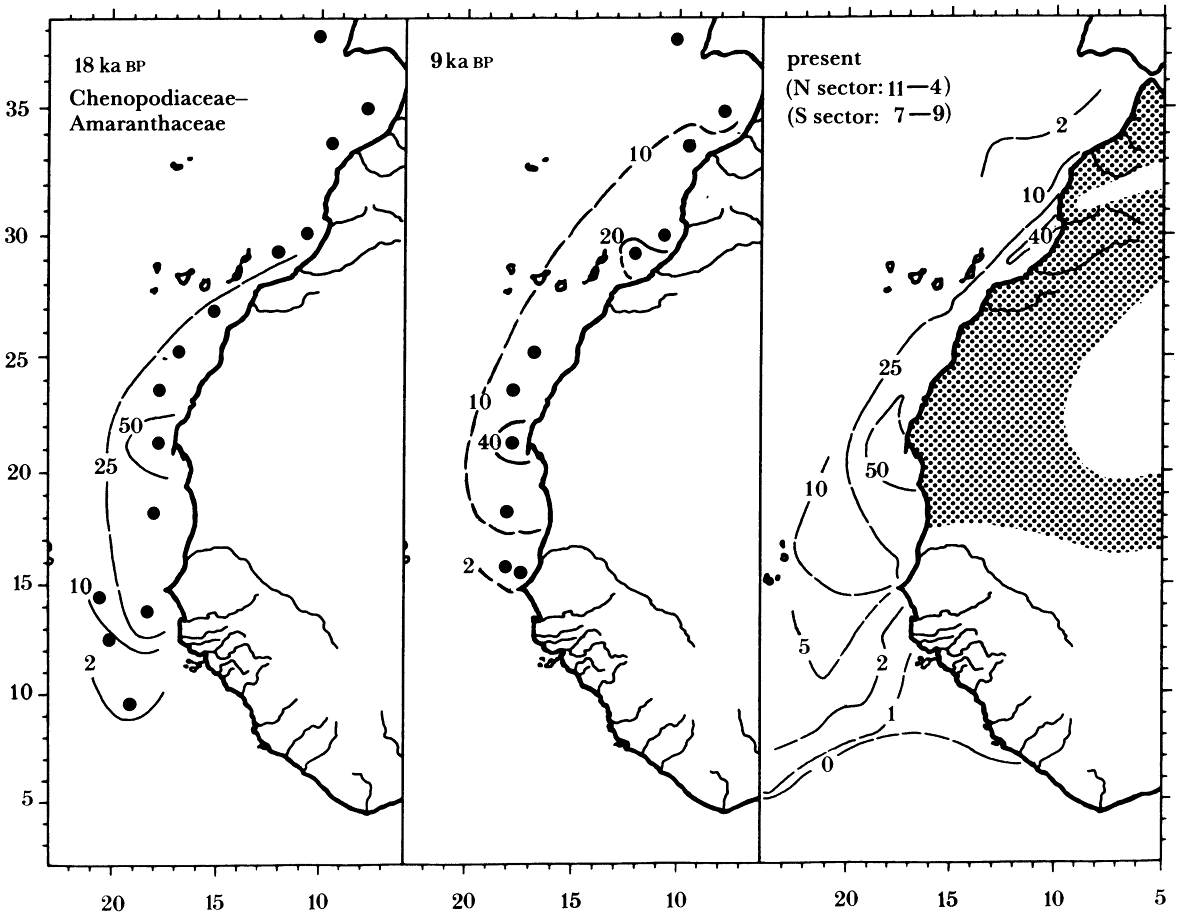

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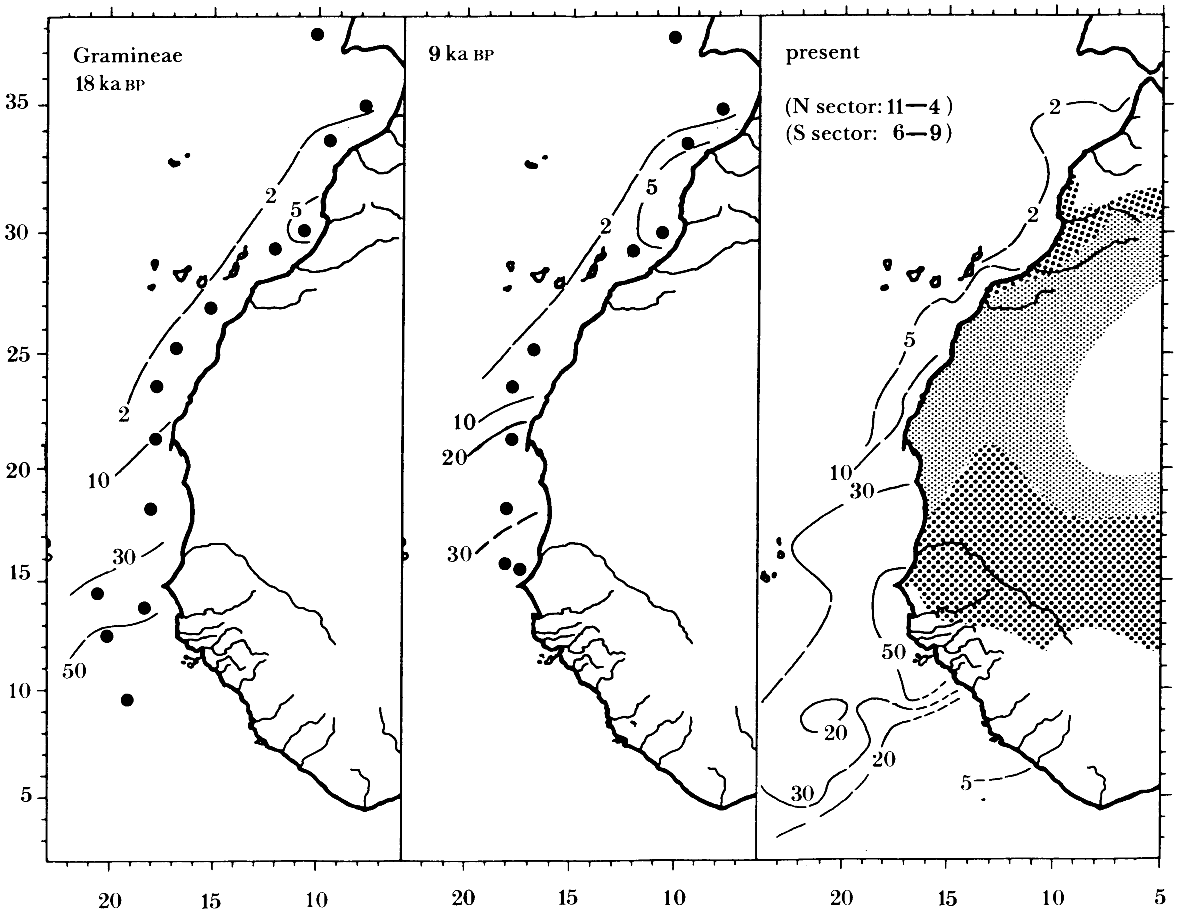

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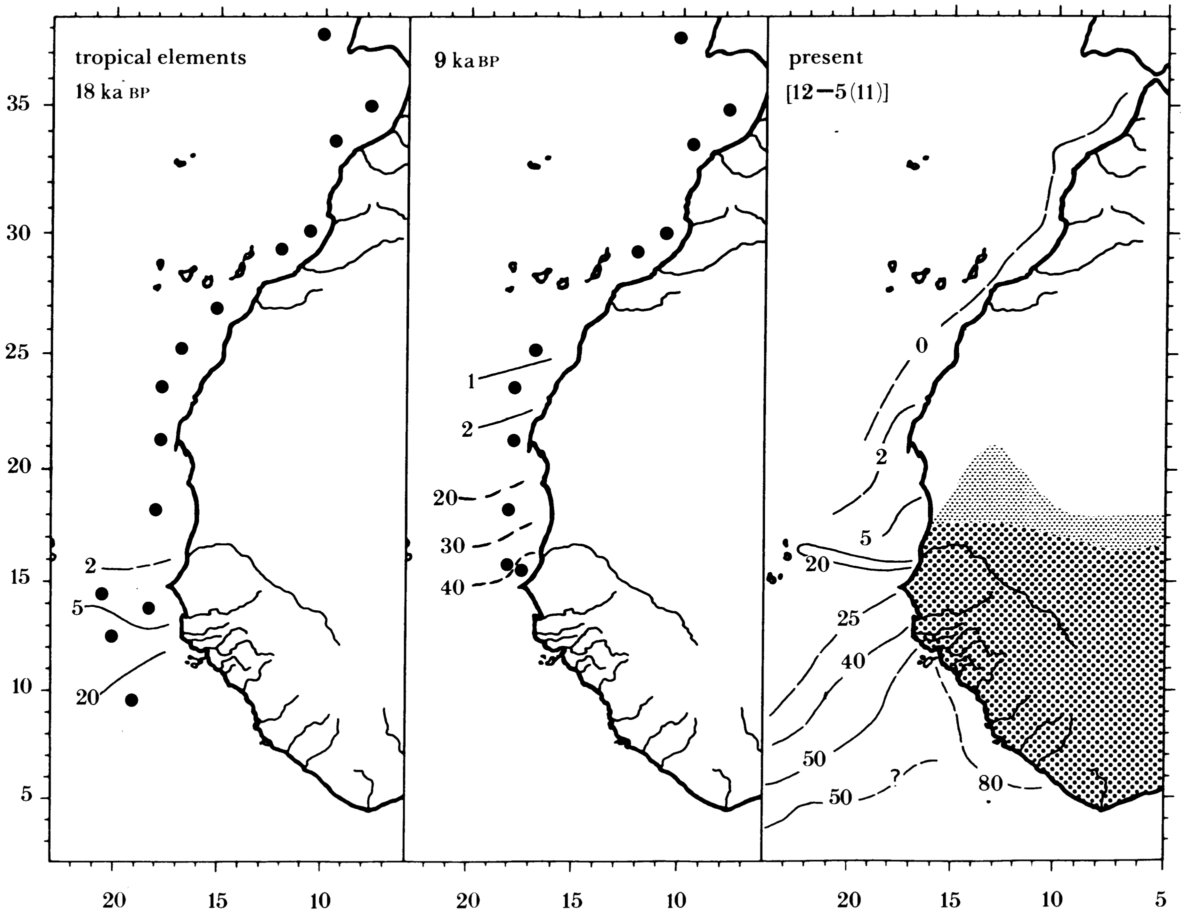

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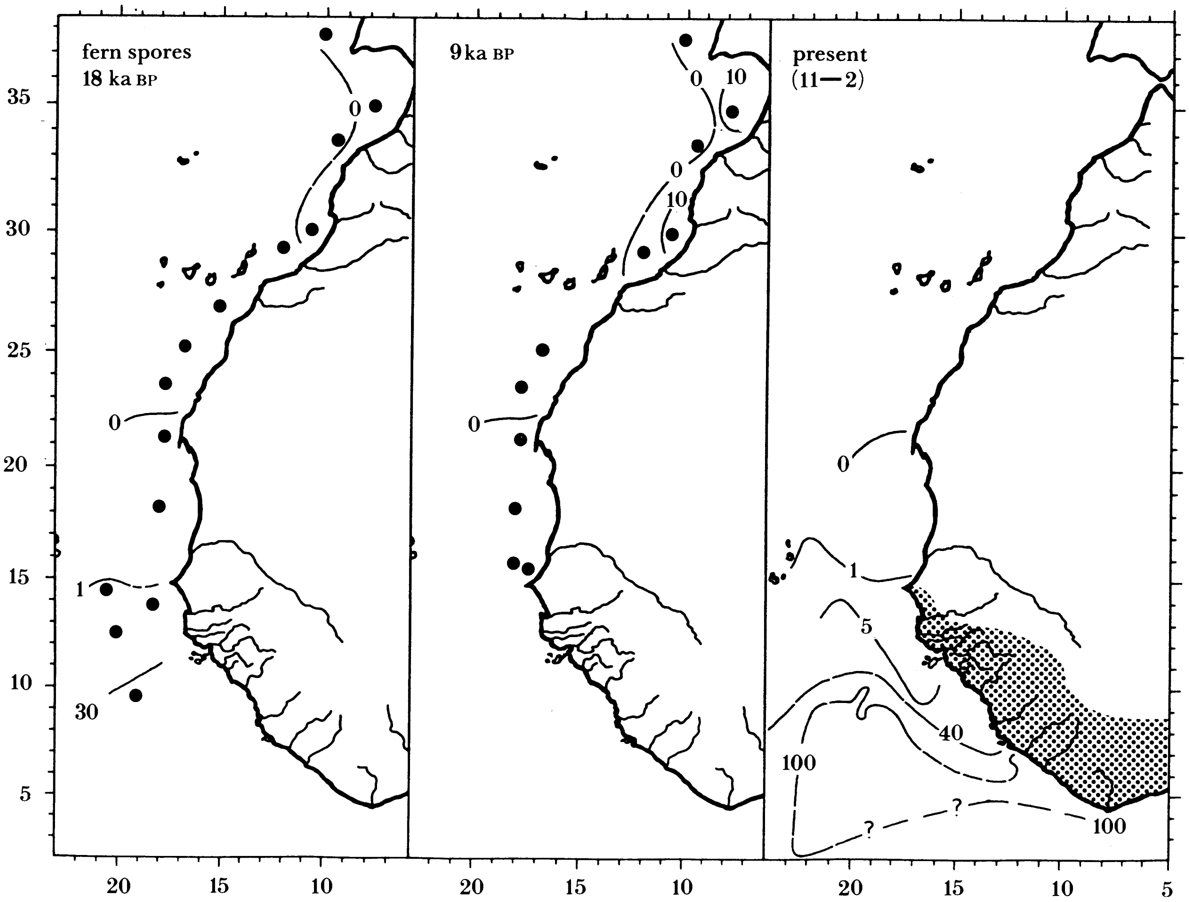

FIGURE 11. For legend see opposite.

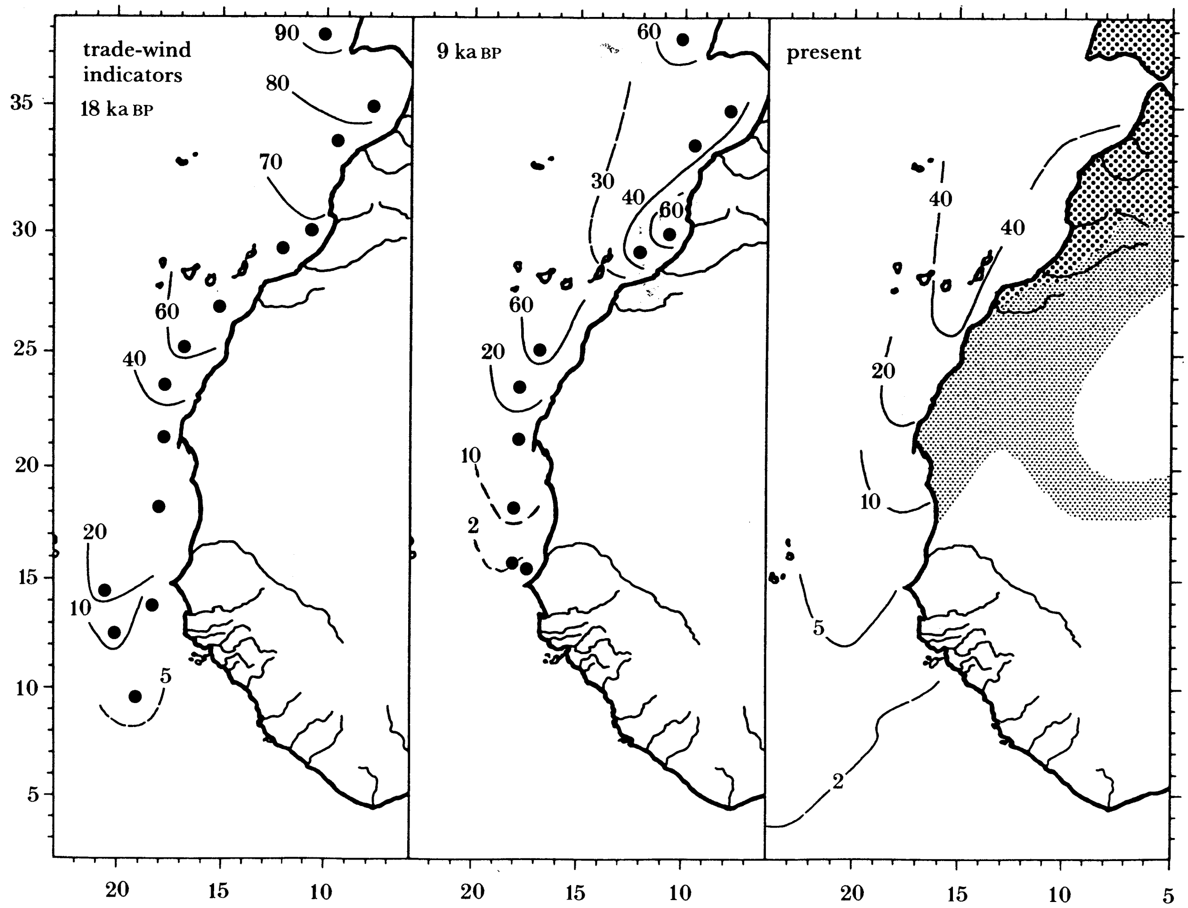

FIGURE 12. For legend see opposite.

GENERAL DESCRIPTION OF FIGURES 3–12

Isopollen maps of the Atlantic off northwest Africa, for various species at present and during the timeslices of 9 ka BP and 18 ka BP. Maps of the modern situation are based on 109 surface-sediment samples (locations indicated by crosses in figures 1 and 2); maps for 9 ka BP, based on 11 deep-sea core intervals (see tables 1 and 2); maps for 18 ka BP are based on 14 deep-sea core intervals. The modern isopollen maps and those of 18 ka BP were discussed in detail by Hooghiemstra *et al.* (1986 and 1987, respectively). Only a brief comment on the isopollen maps is provided in this paper.

Symbols: Bold stippled area, main source area; thin dotted area, source areas of secondary importance; dots, location of deep-sea cores with the concerning time-slice; figures in brackets, months of main pollen release (1–12, January–December). Changes in the river system and coastline of northwest Africa are not considered in the palaeoisopollen maps.

FIGURE 3. Isopollen maps of *Pinus*. Note: (1) pollen transport in southerly direction from the western Mediterranean area during all time-slices; (2) effective pollen transport far to the south *ca.* 18 ka BP, indicating strong trade winds; (3) the pine forests on the Canary Islands form a secondary source area for the trade winds.

FIGURE 4. Isopollen maps of the Mediterranean elements. Note: (1) A very poor representation *ca.* 18 ka BP, indicating the near-absence of the Mediterranean type of vegetation in the western Mediterranean area; the isopolls, however, reach far to the south, indicating strong trade winds. (2) around 9 ka BP this type of pollen is abundant, indicating a well-developed Mediterranean type of vegetation. The efficiency of pollen transport to the south has decreased markedly, indicating weak trade winds. (3) The modern isopollen map corresponds very well with the average flow pattern of the trade winds.

FIGURE 5. Isopollen maps of *Artemisia*. Note: (1) The very high representation *ca.* 18 ka BP, indicating abundant *Artemisia* vegetation at the northern fringe of the Sahara; (2) effective pollen transport to the south *ca.* 18 ka BP, indicating strong trade winds; (3) the source area of *Artemisia* is characteristic of the northern fringe of the Sahara during all time-slices.

FIGURE 6. Isopollen maps of the Compositae (subfamilies Tubuliflorae and Liguliflorae, *Artemisia* excluded). Note: (1) two main source areas *ca.* 18 ka BP at the northern and southern fringe of the Sahara; (2) a high representation *ca.* 9 ka BP and at present, indicating abundant Mediterranean vegetation in the western Mediterranean area; (3) the modern isopollen map corresponds very well with the average flow pattern of the trade winds; (4) the modern distribution of Compositae in northwest Africa is closely correlated with the distribution of the associated pollen in the marine sediments.

FIGURE 7. Isopollen maps of *Ephedra*. Note: (1) the high representation *ca.* 18 ka BP between 25° and 18° N, indicating extensive desert vegetation (expanded Sahara); (2) low efficiency of pollen transport to the south *ca.* 9 ka BP, indicating weak trade winds.

FIGURE 8. Isopollen maps of the Chenopodiaceae–Amaranthaceae. Note: (1) the latitudinally stationary area, with distinct pollen supply from the east by the African Easterly Jet, indicates that the African Easterly Jet did not shift latitudinally during the last glacial–interglacial transition. (2) The modern isopollen map corresponds between 35° and 5° N with the average flow pattern of the trade winds and between 17° and 22° N with the average course of trajectory of the African Easterly Jet. (3) In the modern isopollen map, the strong gradient in representation around 10° N reflects the southernmost position of the ITCZ; the accompanying rainbelt functions as a sharp cutoff for meridional aeolian pollen transport. (4) The northwards shift of the isopolls *ca.* 9 ka BP, in combination with a low representation, indicates a shrunken desert belt with a relatively northern geographical position.

FIGURE 9. Isopollen maps of the Gramineae. Note: (1) In the modern isopollen map, there is a close relation between the distribution of graminaceous-rich vegetation and the distribution of the associated pollen in the marine sediments. (2) In the modern isopollen map, there is a strong gradient in representation around 10° N, reflecting the southernmost position of the ITCZ; the accompanying rain belt functions as a sharp cutoff for meridional aeolian pollen transport. (3) A southwards shift of the isopolls *ca.* 18 ka BP, compared with the modern situation, indicates a southwards shift of the savanna zone. (4) The 9 ka BP isopollen map, especially, suffers from a shortage of core stations in the southern sector.

FIGURE 10. Isopollen maps of the tropical elements. Note: (1) The modern distribution of tropical forest is closely correlated with the distribution of the associated pollen in the marine sediments; (2) probable river-current transport of tropical forest pollen is evidenced by the Senegal river; (3) a southwards shift of the isopolls *ca.* 18 ka BP and a northwards shift of the isopolls *ca.* 9 ka BP (compared with the modern situation), indicates a shrunken and expanded area of tropical forest, respectively.

FIGURE 11. Isofrequency maps of fern spores. Note: (1) The modern isofrequency map shows a close correlation between the distribution of tropical forest and the distribution of fern spores in the marine sediments; (2) this potential for deducing the northernmost position of tropical forest could not be used for the timeslices of the past because of a lack of well-dated deep-sea cores in the southern sector; (3) an increase in the representation near the Mediterranean between 18 and 9 ka BP related to the development of the Mediterranean type of vegetation after about 10.5 ka BP; (4) in the modern surface-sediment samples of the northern sector, unfortunately, fern spores were not analysed: for this reason it is advisable not to use the map of the modern situation north of about 25° N.

FIGURE 12. Isopollen maps of the trade-wind indicators (*Pinus*, *Artemisia*, Compositae (Tubuliflorae + Liguliflorae, *Artemisia* excluded) and *Ephedra*). Note: (1) During all time-slices, pollen transport from the Mediterranean area to the south is demonstrated; this observation indicates a stationary belt with tradewind transport; (2) the position of the isopolls very far south *ca.* 18 ka BP indicates strong trade winds; (3) the main source areas *ca.* 9 ka BP are the Iberian Peninsula and the Canary Islands (contributing mainly *Pinus* pollen) and southern Morocco (contributing mainly *Artemisia* pollen); (4) low efficiency of southwards pollen transport *ca.* 9 ka BP indicates weak trade winds.

a great part of the Gramineae-rich vegetation zones was situated at that time in the belt with African Easterly Jet transport and, as a consequence, the offshore marine sediments contain chenopod pollen (*ca.* 44 %), as well as high percentages of graminaceous pollen (*ca.* 23–30 %, compared with about 10 % graminaceous pollen around 18 ka BP). It has to be noted that the offshore marine sediments between about 22 and 26° N receive African Easterly Jet-transported pollen, as well as trade-transported pollen. For this reason is cannot be expected that the representation of the Chenopodiaceae–Amaranthaceae decreased to a higher extend during that interval 18–9 ka BP. After the humid period of 9–7 ka BP climatic conditions turned more arid. The Sahara started to expand again in a southerly direction and the graminaceous-rich Sahelian and Sudanian vegetation zones shifted southwards and shrunk in north–south extension (see Hooghiemstra 1988*a*, figure 13). Thus the graminaceous-rich vegetation shifted out of the belt with African Easterly Jet transport, while the chenopod-rich desert vegetation became dominant again between 16 and 22° N. As a consequence, the representation of the Chenopodiaceae–Amaranthaceae in the marine sediments increased (to 50–60 % at present) and the representation of the Gramineae decreased (to 10–15 % at present).

5. CONCLUSIONS: INTERPRETATING THE POLLEN SIGNAL IN MARINE SEDIMENTS OFF NORTHWEST AFRICA

On the basis of the modern isopollen maps and the palaeoisopollen maps of 18 ka BP and 9 ka BP the following conclusions may be drawn.

(i) In the marine sediments off northwest Africa, pollen is abundant in a relatively narrow offshore range. The method of grouping the pollen and pteridophyte spore taxa depends on the objective of the study.

(ii) The modern isopollen maps correspond to the modern flow pattern of atmospheric circulation, the northeast trade winds, the January trades and the African Easterly Jet being the major wind systems. Some water-current transport is indicated, but plays an unimportant part in the total pollen transport, owing to arid climatological conditions in a great part of northwest Africa and a pronounced atmospheric circulation.

(iii) The atmospheric circulation is driven by the intertropical convergence zone (ITCZ), which shifts over the continent between *ca.* 22° N (position during July and August) and *ca.* 4° N (position during December and January) in the course of the year. As many pollen-producers have a characteristic period of main pollen release, seasonal wind patterns can be recognized.

(iv) Washout of pollen from the atmosphere by the ITCZ-accompanying rainbelt functions as a sharp cutoff of meridional pollen transport. Pollen transport by long-distance transport (as in *Pinus*) shows, at the ITCZ, a slight increase in representation, whereas pollen from nearer source areas (e.g. Chenopodiaceae–Amaranthaceae, Gramineae) shows an abrupt decline in representation. The average southernmost position of the ITCZ can be inferred from these distribution patterns in the marine sediments.

(v) The modern isopollen maps show a close relation between the distribution of taxa in northwest Africa and the distribution of the associated pollen in the offshore marine surface-sediments. The average flow pattern of the major wind systems forms the link between both distribution patterns.

(vi) In studying the vegetational and climatic history of northwest Africa by means of pollen records of continuous deep-sea cores (time-series), we are dealing with two major variables: changing positions of the pollen source areas (i.e. vegetation zones) and changing transport systems. Palaeoisopollen maps ('snapshots' of the pollen distribution during time-slices of the past) of selected time-slices, on the basis of a number of well-dated deep-sea cores, provided qualitative evidence of changes in the atmospheric circulation during the last glacial–interglacial transition. In this way one major variable can be eliminated, making an interpretation of marine pollen records off northwest Africa possible in terms of vegetational changes.

(vii) Comparing the modern isopollen maps with those of 9 ka BP and 18 ka BP, we conclude that the trade winds did not shift latitudinally, but fluctuated only in intensity. Very effective pollen transport in the northern sector suggests that the last glacial trade winds intensified especially between about 36 and 24° N. The belt with maximum African Easterly Jet transport was situated, during the three time-slices, around 19–22° N; this indicates a stationary position of the African Easterly Jet during the last glacial–interglacial transition. This also implies a stationary northernmost position of the ITCZ.

(viii) The latitudinally stationary position of the belt with maximum zonal African Easterly Jet transport is an important datum for the reconstruction of latitudinal shifts of the northwest African vegetation zones: which pollen type is mainly transported by the African Easterly Jet to the Atlantic depends on the type of vegetation between about 16° and 22° N.

(ix) Climatic aridity may be the cause of a sparse vegetation cover and, as a consequence, a low pollen production in the area concerned. Relevant changes in the pollen production, displayed by pollen concentration and the pollen influx diagrams, may influence the quantitative record of the wind intensity. The quantitative pollen signal (pollen flux) in the marine sediments of an area with a very low pollen production probably has only a low correlation with the wind intensity (transport capacity).

(x) In the offshore sediments of northwest Africa, trade-transported pollen has source areas on the Iberian Peninsula, in Morocco and the northern fringe of the Sahara. In our studies we have used the taxa *Pinus*, Compositae (Tubuliflorae + Liguliflorae), *Artemisia* and *Ephedra* as trade-wind indicators.

(xi) The pollen influx record is the best proxy for evaluating changes in the trade-wind intensity. The pollen concentration record may be influenced by nonlinear accumulation processes. Knowledge of the regional vegetational history is necessary for a correct interpretation of the quantitative records.

(xii) A relative proxy for evaluating changes in the trade-wind intensity is the 'trade index', defined as the percentage of trade-transported pollen in the marine sediments. However, changes in the vegetational composition (e.g. leads and legs of the vegetational response to climatic change) may influence this relative signal to a considerable extent.

(xiii) Depending on the latitudinal position of the deep-sea cores studied, the pollen record has a different potential.

Marine pollen records from the northern sector (*ca.* 37–28° N) register mainly changes of the vegetation in the western Mediterranean area and the northern fringe of the Sahara. The trade wind record is influenced by vegetational changes to a considerable degree, as this area coincides with the source area of the trade-wind-indicating pollen.

Marine pollen records located in the area between *ca.* 22 and 16° N register changes of the vegetation from the western Mediterranean area to as far south as the Guinea zone, changes of fluvial runoff south of the Sahara (indicating climatic humidity) on the basis of the mangrove pollen record, changes in the intensity of the northeast trade winds, and African Easterly Jet transport.

Marine pollen records from the southern sector (*ca.* 16–7° N) record changes of the vegetation south of the Sahara, changes of the fluvial runoff south of the Sahara (indicating climatic humidity) on the basis of the mangrove record, seasonality in climatic humidity in the tropical forest area (climatic humidity all the year round is a prerequisite for tropical forest), and changes in the intensity of the northeast trade winds.

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Discussion

JUDITH MAIZELS (*Department of Geography, University of Aberdeen, U.K.*). Dr Hooghiemstra has mentioned that evidence from the Senegal River suggested that a dramatic increase in discharge occurred around 11 ka BP. This statement raises two important points that may have some bearing on Dr Hooghiemstra's interpretation of the distribution pattern of pollen off the coast of northwest Africa. Firstly, it would be helpful if Dr Hooghiemstra would summarize the type of evidence available for estimating this change in river discharge. Is this estimate based on changes in sediment volume at the river mouth, or on changes in particular sediment and/or channel-form characteristics? In the former case, an increase in sediment volume may reflect an increase in aridity rather than increased humidity, as Dr Hooghiemstra suggests. Increased aridity could act to reduce the vegetation cover, thereby exposing greater volumes of sediment to erosion and fluvial transport during infrequent flood events. Changes in sediment characteristics associated with changes in channel morphology, by contrast, would provide a more reliable indicator of climatic change.

My second point is that the many large rivers, such as the Senegal River, that issue into the North Atlantic along this coast, are likely to input large amounts of pollen, as well as sediment. Much of this pollen may include reworked pollen from older sediments. Fluvial currents might also extend for some distance offshore, acting to redistribute bottom pollen deposits and modifying the original aeolian pollen distribution. Would Dr Hooghiemstra comment on the significance of these fluvial processes in affecting the distribution of pollen in the bottom deposits off the coast of northwest Africa?

H. Hooghiemstra. The estimation of changes in fluvial run-off of the Senegal river was based on fluctuations of the pollen record of *Rhizophora* (mangrove). Mangroves occur abundantly in river deltas and in narrow ranges along the coast. High fluvial runoff may cause extensive delta areas with a high mangrove pollen production. In the modern day arid parts of the Senegal River delta, extensive Early-Holocene buried mangrove peats show these fluctuations in the stands of mangroves. A high representation and influx of mangrove pollen in the offshore marine sediments was assumed to indicate high fluvial runoff. This pollen evidence is corroborated by geomorphological evidence (Michel 1984). Some river current transport of pollen was evidenced by the modern isopollen maps of *Rhizophora* and Cyperaceae. Ocean floor topography may also apparently influence distribution patterns of pollen in marine sediments, as suggested by the modern isofrequency maps of *Elaeis* and the fern spores. There is no evidence for a relevent contribution of reworked pollen. In the Gulf of Guinea it is difficult to estimate the contribution of fluvial pollen transport, compared with aeolian pollen transport by the January trades. It is estimated as to be low. In general, in the literature, evidence for aeolian pollen transport in tropical forest areas is increasing.

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R. G. W. Ward. (*Environmental and Geographical Studies*, *Roehampton Institute*, *Southlands College*, *London*, *U.K.*) Dr Hooghiemstra showed us isopollen maps of the present day and 18 ka BP, and inferred from their similarity that the main elements of the atmospheric circulation (the position of the northeast trades, the easterly wind from the Sahel, and the location of the ITCZ) had remained largely unchanged throughout this period. However, the final determinant of where pollen comes to rest in sediments must be the oceanic circulation, particularly if pollen has a long residence time within the zone of moving waters. What we may be seeing, therefore, is stability within the pattern of ocean currents, rather than stability in the wind pattern. More recent studies about sedimentation processes in the ocean describe an aggregation of suspended material into larger particles (inorganic aggregation (flocculation), as well as organic aggregation, forming faecal pellets reaching several millimetres in diameter), which cause higher settling velocities. This mechanism may explain why horizontal transport of pollen by ocean currents is less relevant than expected. Water current transport of pollen in the northwest African area is not excluded and evidenced by the isopollen maps of *Rhizophora* and Cyperaceae. Aeolian pollen transport, however, is apparently dominant to a large extent; this observation is corroborated by the clear-cut, not smeared distribution patterns in the modern surface sediments.