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DISTRIBUTION AND PROVENANCE OF PALYNOMORPHS IN NORTHEAST ATLANTIC AEROSOLS AND BOTTOM SEDIMENTS

presented by

Michael Brendan Melia

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PhD degree in Geology

ander J. Cross

Major professor

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# DISTRIBUTION AND PROVENANCE OF PALYNOMORPHS IN NORTHEAST ATLANTIC AEROSOLS AND BOTTOM SEDIMENTS

By

Michael Brendan Melia

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#### ABSTRACT

# DISTRIBUTION AND PROVENANCE OF PALYNOMORPHS IN NORTHEAST ATLANTIC AEROSOLS AND BOTTOM SEDIMENTS

By

Michael Brendan Melia

Eolian dust and bottom sediment samples from the Northeastern Atlantic, off the coast of Northwest Africa were studied palynologically. Standard chemical and physical laboratory techniques were used to isolate the palynomorphs. Samples were examined primarily for their terrestrial plant detritus (pollen, spores, opal phytoliths and freshwater diatoms) but observations about marine entities were also made.

The spatial distributions of various palynomorphs were mapped and this facilitated detection of three distinct geographic palynofloras. A northern palynoflora consisted of pollen derived primarily from the Mediterranean basin, a central or Saharan palynoflora was characterized by pollen derived from desert plants (especially grasses) and a southern Tropical-Equatorial palynoflora was not only composed of pollen derived from tropical plants but also included up to 50% allochthonous pollen from the drier interior of West Africa.

Palynomorph distributions are related closely to both source vegetation and to atmospheric and oceanic transport mechanisms.

The quantity of pollen and spores per gram of bottom sediment ranges from greater than 2000 off the Saharan coast in Mauritania to less than 50 in deep ocean basins. Pollen and spores in Mediterranean aerosols may exceed 40 per cubic meter of air during the summer and range between 4 to 6 for tropical aerosols during the winter. Tropical aerosols and bottom sediments contained the greatest abundance of fungal spores.

The abundance of dinoflagellates and microforaminifera in bottom sediments is directly related to the area of upwelling off the West African coast.

The distribution of opal phytoliths and freshwater diatoms in both aerosols and bottom sediments indicates that dust storms are the major transporting agents for these entities from the interior of West Africa to the Gulf of Guinea. These storms are also an important agent for the transport of pollen to the tropical atmosphere.

Distances of transport for Mediterranean pollen may exceed 5000 km and distances on the order of 6000-7000 km are indicated for freshwater diatoms in eolian dust over the Atlantic Ocean, having originated in Chad or Niger.

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### INTRODUCTION

### Materials and Methods

Northwest African aerosols collected above the eastern Atlantic Ocean were examined for presence of pollen, spores and other palynomorphs in conjunction with similar studies of ocean bottom sediments and West African surface samples. Forty dust samples collected on filters by high volume (hi-vol) air samplers aboard R/V "Atlantis II" (Woods Hole Oceanographic Institution) during the period January 25-October 13, 1973, along a series of transects off the coast of Northwest Africa (Figure 1), were made available for study by Dr. Fred K. Lepple. Dr. Lepple also supplied an additional forty aerosol and soil samples from landbased stations on the continent of West Africa (see Figure 1 for locations and explanations of samples). In addition to the above dust samples, thirteen additional filter samples from the "Atlantis II" cruise (February to May 1966) had been obtained from Dr. Noshkin at Woods Hole prior to the study. These were also collected above the Atlantic Ocean (see Figure 2).

A total of seventy-one bottom sediment samples (core tops) were selected and made available from Lamont-Doherty Geological Observatory (see Figure 3 and Table 1 for







Table 1. Surface Location of Core Samples in Atlantic Ocean

Maceratic Numbers	on Core Name	Latitude	Longitude	Depth (m)
MS1958, 20 MS1959, 20 MS1960, 20 MS1961, 20 MS1962, 20 MS1964, 20 MS1965, 20 MS1966, 20 MS1966, 20 MS1966, 20 MS1966, 20 MS1966, 20 MS1966, 20 MS1966, 20 MS1967, 20 MS1967, 20 MS1977, 20	Name $058$ $V17-157$ $059$ $V17-158$ $060$ $V19-295$ $061$ $V19-295$ $062$ $V19-296$ $063$ $V19-296$ $063$ $V19-298$ $065$ $V19-300$ $066$ $V19-302$ $066$ $V19-303$ $067$ $V19-304$ $069$ $V20-235$ $070$ $V20-236$ $071$ $V20-236$ $072$ $V20-236$ $073$ $V20-236$ $074$ $V22-188$ $075$ $V22-188$ $077$ $V22-209$ $078$ $V22-198$ $077$ $V22-167$ $078$ $V27-167$ $081$ $V27-167$ $084$ $V27-177$ $085$ $V30-38$ $087$ $V32-37$ $084$ $V32-05$ $085$ $V30-38$ $087$ $V32-37$ $088$ $V30-48$ $089$ $V32-05$ $090$ $V32-37$ $091$ $V32-37$ $092$ $V32-37$ $093$ $V32-37$ $094$ $V12-81$ $083$ $V10-81$ $084$ $V12-5$ $083$ $V12-81$ $084$ $V12-81$ $085$ $V12-81$ $084$ $V12-81$ $085$ $V12-81$ </td <td>9 21 N 12 23 N 1 26 N 2 57 N 1 25 N 2 39 99 N 2 50 30 N 2 50 50 N 2 50 N 2 50 N 2 50 N 2 50 N 2 50 N 2</td> <td>18° 38'W 18° 55'W 2'''W 5''W 12° 5'W 15° 22'W 19° 22'W 3''W 2''W 3''W 2''W 3'W 3''W 3''W 3''W 3''W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3</td> <td>4082 4082 4082 4082 4092 4099 4009 4000 4000 4000 4000 4000</td>	9 21 N 12 23 N 1 26 N 2 57 N 1 25 N 2 39 99 N 2 50 30 N 2 50 50 N 2 50 N 2 50 N 2 50 N 2 50 N 2 50 N 2	18° 38'W 18° 55'W 2'''W 5''W 12° 5'W 15° 22'W 19° 22'W 3''W 2''W 3''W 2''W 3'W 3''W 3''W 3''W 3''W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3'W 3	4082 4082 4082 4082 4092 4099 4009 4000 4000 4000 4000 4000
MS2141, 21	188 V23-97	24° 07 ' N	17° 26' W	1928

Table 1 (cont'd.)

Macerat Number	tion rs	Core Name	Latitude	Longitude	Depth (m)
MS2142, MS2143, MS2143, MS2144, MS2145, MS2146, MS2146, MS2147, MS2148, MS2150, MS2150, MS2151, MS2152, MS2153, MS2154, MS2156, MS2158, MS2159, MS2160,	2189 2190 2191 2192 2193 2194 2195 2194 2195 2196 2197 2198 2199 2200 2201 2202 2203 2204 2204	V23-108 V26-34 V26-54 V27-162 V27-170 V27-235 V27-253 V27-253 V27-260 V27-260 V27-260 V27-260 V27-262 V29-164 V29-166 V30-53 V30-62 V30-72 V30-73 V30-93	17 24 N 19 51 2 N 5 28 2 S 34 11 9 N 24 25 8 N 2 27 4 N 8 08 7 N 27 46 1 N 25 55 8 N 31 44 N 4 15 N 6 16 4 N 8 09 N 14 58 5 N 22 02 N 25 49 5 N 34 08 N 35 40 5 N	43° 14' W 36° 54° 5' W 11° 55° 9' W 16° 51° 5' W 34° 02° 2' W 0° 14° 9' W 17° 34° 4' W 36° 43° 9' W 36° 43° 9' W 36° 08' W 2° 40' E 12° 36° 4' W 14° 19' W 20° 56° 9' W 18° 04' W 16° 55' W 22° 19' W 24° 13' W 38° 37° 2' W	4367 5601 2906 4281 6224 4854 4726 5590 4082 3768 51590 4082 53268 5150 2160 9421 5325
MS2161,	2206	V30-197	32° 38'N	10 11.8 W	2996
MS2162		V32-54	20° 7° 27'N	20 20 52 W	3834
MS2163,	2207	V32 <b>-</b> 55	17 <sup>•</sup> 58 • 34 <sup>•</sup> N	17 <sup>-</sup> 46.19'W	2780
MS2164,	2208	V32 <b>-</b> 62	16 <sup>•</sup> 06 • 29 <sup>•</sup> N	18 <sup>-</sup> 09.12'W	2965

geographic locations and depths of sampling).

Most samples were studied both qualitatively and quantitatively where possible, each being examined for its terrestrial plant detritus i.e., pollen, spores (including fungal spores), opal phytoliths and freshwater diatoms. The African soil and land-based aerosols, however, were not studied quantitatively since their prime use was for the determination of the provenance of various palynomorphs in the marine aerosols and bottom sediments. Nevertheless, relative percentages of major taxa were determined from the continent-based samples. Comparison was made between bottom sediment palynofloras and airborne palynofloras. <u>Objectives of the Study</u>

The objectives of the study included the following:

1) the identification of palynomorphs to lowest taxonomic rank feasible;

2) the determination of their spatial distribution in the atmosphere and bottom sediments;

3) the determination of their relationship to African and Mediterranean vegetation zones (hence determination of provenance);

4) the identification of relationship of palynological distribution to tropospheric and oceanic circulation and hence to the importance of eolian (dust storm), fluvial or oceanic transport mechanisms; and

5) determination of the significance of numbers of pollen, spores, freshwater diatoms and opal phytoliths

per gram of surface sediment or gram of eolian dust, as an indication of the distance from shoreline, proximity to deltas or stream mouths and distance down-wind from their respective source areas.

#### Background to the Nature of the Problem

Northwest Africa is one of the world's major sources of eolian dust. Sediment from this region can be transported in dust storms as far as the mid-Atlantic and has been known to produce haze as far away as the Caribbean (Prospero and Carlson, 1970). Evidence that this eolian dust is incorporated into nearshore sediments is present in the area of upwelling along the northwest coast of Africa and its presence in some deep-sea sediments is also evident. The organic fraction of this terrestrially derived detritus contains various palynomorphs including pollen, spores, bacteria, fungi, opal phytoliths, fresh water diatoms and other plant material (Delany, <u>et al</u>., 1967; Folger, <u>et al</u>., 1967; Folger, 1970; and Parkin, <u>et al</u>., 1972).

Periodic dust storms and haze banks extend off the coast of Northwest Africa with a dust pulse frequency of 3 to 4 days (Lepple, 1975). Although dust storm frequency varies during the year, storms are more common in the winter months (January and February) and less frequent in November (Lepple, 1975). Delany <u>et al.</u>, (1967) state that in summer, dust most probably originates in Morocco but as winter progresses, material from south of Dakar, Senegal,

may be included in the storms. Plant detritus in aerosols should therefore reflect this seasonal variation in provenance.

Rapp (1974), illustrates two areas of major dust storm activity off the coast of Northwest Africa. A northern summer dust front extends from the vicinity of Dakar, Senegal, northward to about Cap Rhir in Morocco and extends westward to approximately 25 W. A larger winter dust front to the south extends from Cap Blanc, Mauritania, in the north to as far south as the equator, eastward to the Niger delta and westward over the Atlantic to about 35 W.

The annual dust flux in the North Atlantic ranges from 25-37 million tons in and around Barbados (Prospero and Carlson, 1972) to nearly half a billion tons near the northwest African coast during periods of drought (Lepple, 1975). During a 6-hour dust storm in March, 1974, Lepple estimated that 400,000 metric tons of dust were transported offshore along 100 km of West African coastline. Analysis of this dust showed an average carbon content of 2.6%, which is equivalent to 10,000 tons of organic carbon or 20,000 tons of actual organic material. The majority of these organics are of botanical origin.

Lepple and Brine (1976), examined the chemistry of several north Atlantic dust samples and analyzed some north African wind-erodible surface sediments in an attempt to determine whether the Sahara was the source of the

airborne dust. They found a greater organic content in the eolian dusts than in the North African soils which indicated a "more biologically active area than desert regions" for dust provenance. Again, the present study was expected to shed more light on this problem of dust provenance.

Maynard (1976) reported that fresh water diatoms and opal phytoliths in surface bottom sediments from the Atlantic were especially abundant in the vicinity of Northwest Africa. Although Maynard did not study other palynomorphs in the sediments, such a study of these entities is of the utmost importance to determining the ultimate disposition of continentally derived materials such as pollen and spores. Therefore, a study to compare distribution patterns of palynomorphs in ocean bottom sediments to similar data obtained from marine aerosols above those bottom sediments was undertaken.

Any correspondance between the two sets of data should provide further insight into the determination of the provenance for the eolian fraction in the deep-sea sediments. Since information about wind and ocean currents and submarine geology is fairly well understood for the Atlantic off Northwest Africa, it was considered that deciphering transport mechanisms for terrigenous particulates in this area would be possible. Also, a study of this type (i.e., distributional), under known atmospheric and physical oceanic conditions, might serve as a model for understanding similar situations in the geologic past where atmospheric winds and marine conditions, e.g., proximity to shoreline etc., could only be estimated from a study of the distribution patterns of various palynomorphs. Geological studies of this kind would then become more meaningful if they could be related to similar known physical conditions in the present study.

### PREVIOUS WORK

### Palynology

Ocean Bottom Sediments: The source and distribution of pollen and spores in surface sediments have been studied in relatively small bodies of water such as bays, gulfs, estuaries and lakes but have not been studied extensively in the open ocean itself. The classic study by Muller (1959), on the distribution of pollen and spores in the recent Orinoco delta and associated shelf sediments more or less paved the way for later studies involving similar problems, although Koreneva (1957), had reported on studies of surface sediments from the Sea of Okhotsk prior to Muller's 1959 report. Another palynological study by Koreneva (1964), involved the examination of both surface sediments and core material over a large area in the southern Pacific Ocean.

Cross <u>et al.</u>, (1966) reported on studies of the sediments of the southern part of the Gulf of California; Bronskiy (1975), studied the distribution of pollen and spores in the surface sediments of the Persian Gulf; Rossignol (1961 and 1973), Vronskiy and Panov (1963) and Koreneva (1971), have worked on recent sediments of the Mediterranean. Rossignol (1969), has also studied recent

palynological sedimentation in the Dead Sea, and the bottom sediments of the Baltic Sea have been palynologically studied by Lubliner-Mianowska (1962).

Shelf and nearshore sediments in various locations have been studied by Groot (1971a and 1971b), Groot <u>et al.</u>, (1967), Traverse and Ginsburg (1966 and 1967) and Habib <u>et al.</u>, (1971). Shelf sediments off southwestern Africa, much closer to the present study area, have been studied by Davey (1970), and Davey and Rogers, (1975) and off western Africa by Koreneva (1975) and Rossignol-Strick and Duzer (1979).

Several workers are presently investigating the distribution of terrestrial palynomorphs in surface sediments from the open ocean, especially the eastern Pacific (Heusser and Florer, 1973, and Heusser and Balsam, 1977) and the western Atlantic (Heusser, 1977). However, none of these studies integrate both palynological data from bottom sediments and that from air samples above those sediments.

Overviews on the study of pollen and spores in marine sediments have also been published. For these the reader is referred to the works of Cross <u>et al.</u>, (1966), and Heusser (1978), for additional discussion. It should be mentioned however, that the major concern with oceanic palynologists has been restricted to the study of the subsurface, particularly pre-Pleistocene rocks and sediments.

The distribution of dinoflagellates in oceans and

bottom sediments has been studied more extensively than purely terrestrial entities such as pollen and spores. The literature on this subject, however, will not be reviewed since the major concern here is with purely terrestrial palynomorphs.

Organic Matter in Eolian Dust: The palynologic investigation of the atmosphere over many parts of the globe has been extensively studied for a number of years and it should be sufficient to mention only those works of relevance to the present study.

Ehrenberg (1845), presented the first detailed description of freshwater diatoms and opal phytoliths blown out over the Atlantic from Africa. Later studies on airborne, continentally-derived organic debris in the north Atlantic include those of Meier and Lindberg (1935), Erdtman (1938), the study of airborne fungi by Pady and Kapica (1955) and the study of freshwater diatoms by Kolbe (1957). More recent literature on the subject includes Bowden <u>et al.</u>, (1971), Folger (1970 and 1974), Folger <u>et al.</u>, (1967), Gregory (1973) and Stix (1975). Probably the only palynological study concerned with dust storm provenance has been that of Horowitz <u>et al.</u>, (1975), which involved the eastern Mediterranean area.

Organic matter in eolian dust has been studied by Crozat <u>et al.</u>, (1973), along the Ivory Coast, and by Lepple (1975), Lepple and Brine (1976), Simoneit (1977), and Simoneit <u>et al.</u>, (1977), over the Atlantic Ocean. Ketseridis <u>et al.</u>, (1976) have also discussed the organic constituents of atmospheric particulates and Handa (1977) discussed land sources of organic matter found in the marine environment. However, most of the latter studies cited were concerned primarily with the chemistry of the particulates rather than the palynology.

<u>West Africa</u>: Palynological studies made on the West African continent and concerned with the existing vegetation and modern pollen rain include the following: Van Campo (1957, 1958 and 1974), Van Campo and Hallé (1959a and 1959b), Van Campo <u>et al.</u>, (1960 and 1965a), Panelatti (1960), Bronckers (1967), Lobreau <u>et al.</u>, (1969), Guers (1970), Guers <u>et al.</u>, (1971), Maley (1970 and 1972), and Cour <u>et al.</u>, (1973).

Saharan palynological studies of surficial deposits primarily concerned with Quaternary vegetation and climatic change include the following: Pons and Quézel (1956 and 1957), Quézel and Martinez (1958, 1960 and 1962), Quézel and Pons (1958), Quézel and Thébault (1959), Quézel (1960), Van Campo and Coque (1960), Van Campo <u>et al</u>., (1964a, 1964b, 1965b, 1966 and 1967), Beucher (1963, 1967, 1971 and 1975), Beucher and Conrad (1963), Van Campo (1964a, 1964b, 1967 and 1975), Maley (1973 and 1977) and Cour and Duzer (1976).

### Aerosols and Dust Storms

Much useful information has been obtained from studies concerned with the geochemistry and mineralogy of bottom

sediments and the inorganic fraction of eolian dust, especially with that produced in the Sahara and transported out into the Atlantic. Some of the more recent contributions to Atlantic eolian chemistry and mineralogy are the studies of Delany <u>et al.</u>, (1967), Prospero (1968), Prospero <u>et al.</u>, (1970), Parkin <u>et al.</u>, (1970 and 1972), Chester and Johnson (1971a, 1971b and 1971c), Chester <u>et al.</u>, (1971 and 1972), Carlson and Prospero (1972), Chester (1972), Aston <u>et al.</u>, (1973) and Lepple (1975).

Biscaye (1965) and Biscaye and Eittreim (1977) have studied bottom sediments in light of the continental contribution of eolian debris and Biscaye <u>et al.</u>, (1974), have made isotopic studies of aerosols for the purpose of using the information to determine continental dust provenance. Information on the eolian sediment budget of the world's oceans has also been extensively reported on by Windom (1969, 1970, 1975 and 1976) and Windom and Chamberlain (1978).

Lepple (p. 5-19, 1975), has reviewed the most important contributions to the study of eolian dust and dust storm phenomena on land and above the ocean, and has also reviewed most of the previous work done on eolian transport in the North Atlantic. Prior to Lepple's study the total knowledge about eolian dust over the ocean off the African coast was based on less than 100 air samples, and no nearsource sampling had taken place until his study.

### THE WEST AFRICAN CONTINENT

### Geography

The study area extends from about 10° E to 50° W and from 5° S to 40° N (see Figure 1). The continental portion includes everything between the Gulf of Guinea and the Mediterranean and as far east as the eastern border of Algeria in the north and coastal Gabon in the south. Elevations are between 200 and 1000 m with areas of greater relief in the Atlas mountains in the north and the Guinea Highlands and Fouta Djallon to the south (see Figure 6). In the central Sahara elevations exceed 1000 m in the Aïr and Hoggar Highlands. Off the coast of Spanish Sahara and Morocco elevations on the volcanic Canary and Madeira Islands also exceed 1000 m.

Major rivers are absent north of 16 N and in southern Spanish Sahara coastal sand dunes evidently block some streams from entering the ocean (Summerhayes <u>et al.</u>, 1976). South of 16 N latitude important perennial streams emptying into the Atlantic are the Senegal and the Gambia, both with headwaters in the Fouta Djallon. Southeast of these are less important streams draining the Guinea Highlands with mouths along the Grain Coast in Sierra Leone and Liberia.

The Sassandra, Bandama and Comoé Rivers drain northsouth through the Ivory Coast. These, with the major Ghanan stream, the Volta, all empty into the Gulf of Guinea. The Niger River which heads in the Guinea Highlands is the longest and most important perennial stream in West Africa and its delta in coastal Nigeria is one of the most conspicuous features of the Gulf of Guinea. The annual discharge of the Niger into its delta is approximately 200 x 10<sup>9</sup> m<sup>3</sup> of fresh water and the supply of sediment is about 18 x 10<sup>6</sup> m<sup>3</sup> (NEDECO, 1959 and 1961, <u>in</u> Hospers, 1971).

Most of the area north of 16°N is characterized by systems of internal drainage, except for short drainageways in Morocco and Northern Algeria which empty into the Atlantic or Mediterranean. Consequently, large areas of the desert are covered by playas, most of which are found north of 20°N. They are especially numerous in Spanish Sahara and the area bordering that country in Mauritania. The largest (some being greater than 1000 km<sup>2</sup> in area) and most important playas both geologically and economically are found in northern Algeria and Tunisia (Lefond, 1969). Chott Djerid however, in Tunisia exceeds 5000 km<sup>2</sup>. Many of the smaller ephemeral lakes are coastal lagoons ("aftouts") and extend intermittently along the coast from Mauritania to Morocco but are especially common in Spanish Sahara. These coastal playas may be important sources of sediments derived by deflation. Some of these sediments may contain

palynomorphs (especially diatoms) that may be transported out over and into the Atlantic during the summer by the Northeast Trades.

Coastal swamps and lagoons extend from the Ivory Coast to Nigeria. From Sierra Leone to Senegal coastal stream valleys are characteristically drowned or ria-like. Geology

Northwest Africa is largely composed of Precambrian shield rocks which are structurally aligned more or less northeast-southwest. These rocks cover approximately two-thirds of the area south of 12°N and much of the Sahara is underlain by either Precambrian or lower Paleozoic rocks, especially in southern and western Mauritania. Western Guinea also has extensive areas of lower Paleozoic rocks (see Figure 4).

Of importance to the present study are those areas with deposits of Cretaceous, Tertiary and Quaternary rocks through which the Niger River drains in Mali, Niger and Nigeria. Tertiary rocks and sediments, especially in the Niger delta, could also become reworked and be reincorporated into the sediments being deposited on the bottom of the Gulf of Guinea. The Senegal and Gambia Rivers also drain extensive areas of Upper Cretaceous and Tertiary strata in Senegal. Palynomorphs contained within these rocks could potentially be reworked.

Cenozoic rocks are at the surface in coastal Spanish Sahara and in western Mauritania, with extensive dune sands



Figure 4. Geologic Sketch Map of Northwest Africa (modified from Grove, 1970)

of Quaternary age overlying lower Paleozoic strata. Much of the Sahara (eastern Mauritania, Mali and southern Algeria) is covered by Quaternary dunes overlying rocks of varying ages from Precambrian to Tertiary. The Hoggar Highlands and Air ou Azbine are mainly Precambrian although Quaternary volcanics are also present.

The Atlas mountains are composed of both Mesozoic and Cenozoic rocks (Triassic to Tertiary with Quaternary deposits especially in the playas) but the rocks are increasingly older to the southwest in Morocco where lower Paleozoics are found. The east-west structural fabric of the Atlas Range was produced during the Alpine orogeny in the late Cenozoic, (Trümpy, 1960), although earlier Hercynian deformation is evident. An excellent account on the geology of West Africa, and Africa in general, is given by Furon, (1963).

### Climate

Although there are numerous systems for classifying African climates those of northwest Africa are primarily latitudinal (Figure 5). Following this, most of the area north of 18°N has an arid (Saharan) climate except for the extreme north, i.e., in Morocco, northern Algeria and Coastal Tunisia, where the climate is dry subtropical or Mediterranean. The Atlas Mountains however, exercise orographic control, and therefore altitudinal zonation is present, with montane and sub-alpine climates generally above 2000 m.


Figure 5. General Climatic Zonation of Northwest Africa (modified from Church, 1968; Grove, 1970 and Hance, 1975)

Between 18°N and 8°N the climate can be characterized as Tropical-Sudanese with the Sahel occupying the area between 14°N and 18°N and the true Savanna climate between 14°N and 8°N, depending somewhat on altitude. Along the southwestern coast however, in Liberia, Sierra Leone and Guinea, the Savanna is replaced by a true coastal Monsoon climate. The area south of 8°N can be considered truly Equatorial, although in the northern part of this zone the climate becomes more seasonal or 'Semi-equatorial' (Church, 1968).

An important aspect in the climatology of northwest Africa is the seasonal movement of two air masses. The largest of these masses is the Tropical Continental mass (warm and dry) which extends from northern Algeria south to about 5° N of the equator in winter but only as far south as 18° N in the summer. This seasonal alternation is produced by the northward and inland extension of the smaller mass of Equatorial Maritime air (warm and humid) from the south during the summer months (Church, 1968). Associated with the northern dryer air mass are the Northeast Trades (see Figure 6) and with the southern air mass are associated the wet south-westerly or westerly winds (Church, 1968).

Associated with the Northeast Trades is the especially warm and dry Harmattan (Figure 6) which blows during the dry season (winter) from the south side of the Sahara and into the Gulf of Guinea. Most plant growth in West Africa



has ceased at this time, and much organic matter is eroded from various surfaces by this wind and is incorporated into the lower troposphere forming a haze with other dust particles. The present study includes the investigation of such a haze off the coast of Ghana in the Gulf of Guinea.

In the north an equivalent hot dry easterly wind blows out from the Sahara during the dry months across Spanish Sahara and Morocco and also carries much dust out into the Atlantic. Over most of the northern fringe of Africa cooler northern westerly air masses prevail for most of the winter months and bring rain to the Mediterranean. During summer months, however, drought prevails as the moist westerly masses move northward. During most of the year the coastal Sahara experiences a more moderate climate than the interior region because the cool Canary Current produces lower air temperatures above the ocean. Major wind patterns for the Northwest African continent and adjoining ocean areas are shown in Figure 6.

The average annual precipitation in the Saharan climatic zone is less than 250 mm and over much of this area is less than 100 mm. The greatest precipitation occurs in the coastal Monsoon zone where it averages more than 2000 mm. The Equatorial zone receives between 1000 and 1500 mm of rain per annum generally decreasing northward from the coast, except for the dry zone around Accra in coastal Ghana where rainfall may be as low as 500 mm. The Savanna zone receives between 500 and 1000 mm of rain

per annum and the Sahel usually less than 500 mm but more than 100 mm. However, in the latter zone during the recent Sahelian drought (1968 to 1973) precipitation values were even lower than 100 mm and consequently this greatly accelerated deflation.

### Vegetation

<u>Background</u>: West African vegetation zones are primarily determined by the latitudinal relationship or control of precipitation and relative humidity (Church, 1968). Therefore, vegetation zones are more or less parallel to the climatic zones. This latitudinal zonation of vegetation is generally the rule except in areas with orographic control or anthropogenic interference (see Figure 7, modified from Church (1968), Eyre (1968) and Grove (1970)).

Coastal mangrove forest predominates on the Niger delta and along much of the southern coast of West Africa and westward to as far north as the Senegal River except for the drier coastal scrub and grassland section of Ghana and Togo. It is best developed in the south-western monsoonal climatic region. Tropical rain forest on the other hand extends northward from the coast of the Gulf of Guinea to about 8° or 10° N in Liberia, Ivory Coast and Nigeria. North of this forest to about 15° N extends the Sudanese vegetation with broad-leaved tree savanna in the southern part of the zone and thorn tree-tall grass vegetation in the northern part (Eyre, 1968).

From Dakar, Senegal, eastward to Lake Chad and north



Figure 7. Major Vegetation Zones of Northwest Africa (modified from Church, 1968; Eyre, 1968 and Grove, 1970)

of 15°N to approximately 17.5°N this area is occupied by Sahel vegetation which is characteristically thorn treedesert grass savanna. This zone also extends north along a thin coastal strip of Senegal and Mauritania to just north of Nouakchott. Desert and semi-desert scrub vegetation extends north of the Sahelian zone to the Atlas Mountains except where orographic rainfall (notably in the Hoggar) is sufficient to produce maquis and garrigue vegetation, i.e., 'Mediterranean' vegetation characterized by evergreen bushes, maquis being denser and taller than garrigue.

On the lower elevations of the southern flank of the Atlas Mountains the dominant vegetation is a combination of garrigue and desert grass, with more characteristically Mediterranean maquis on the northern coastal side of the Atlas (Eyre, 1968). On the higher central Atlas, generally above 1000 m, the North African coniferous forests are found and above 2000 m a montane scrub or shrub zone is found, and above 2500 m a sub-alpine zone.

The Fouta Djallon is dominated by a plateau type of vegetation (Church, 1968) whereas the vegetation of the Guinea Highlands is more montane in character. However, vegetational characterization or distinction between either of these two areas and their adjacent lowlands is somewhat difficult.

Mention should also be made of the vegetational zonation on the Canary Islands. Here the vegetation from

sea level to about 500 m is semi-desert scrub becoming more Mediterranean in character up to about 2000 m. Zones are generally wetter on the northern sides of the islands and consequently a wetter Mediterranean type of vegetation is found there. A wet forest zone with broad-leaved Mediterranean types is found up to about 1300 m (depending upon aspect) with a dryer, needle-leaved (pine savanna) forest up to 2000 m (Bramwell and Bramwell, 1974). Above 2000 m, as in the Atlas mountains, the vegetation becomes montane to sub-alpine in character.

<u>Detail</u>: The literature on the flora and vegetation of Northwest Africa is very extensive and detailed. However, the present summary should be sufficient to introduce the reader to those plants and vegetational environments of importance to this study.

The mangrove forest mainly occurs in the low-lying coastal swamp land associated with muddy rivers, lagoons and deltas (Church, 1968). Its most extensive development is in the Niger delta and consists of the same species of mangroves as are found along the eastern coast of America (Church, 1968). The commonest species is <u>Rhizophora</u> <u>racemosa</u> (red mangrove), with <u>R. harrisonii</u> and <u>R. mangle</u> being of lesser importance. <u>Avicennia africana</u> (white mangrove) is also important and can be found as far north as Cape Timiris in Mauritania (de Naurois and Roux, 1965). Other mangroves do occur but tend to reflect local edaphic, moisture or salinity conditions. The seaward margin of the mangrove swamp may have a rather varied flora which includes species in the Amaranthaceae, Malvaceae, Convolvulaceae and Papilionaceae (Nielsen, 1965).

On the Niger delta (north of the mangroves) a freshwater swamp forest occurs but it may also be found in freshwater streams and lagoons along much of the West African coast. On the outer periphery of this forest is a zone of floating grass dominated by <u>Vossia cuspidata</u> or floating sedge (<u>Cyperus papyrus</u>). Further inland and on dry stream banks, communities of <u>Pandanus candelabrum</u> (Screw Pine), climbing palms (rattans) and <u>Raphia</u> sp. (Palmae) may be found (Church, 1968). Common arboreal vegetation usually fringing the swamps includes members of the following families: Apocynaceae, Annonaceae, Moraceae, Passifloraceae, Rubiaceae, Euphorbiaceae and Myrtaceae (Nielsen, 1965).

The tropical rain forest although having been reduced to nearly one half of its total original area is still an important zone for timbering. Mahoganies (<u>Khaya</u> sp.) are important in this respect and occur as part of the upper story in the wettest parts of the rain forest. Other upper story species are found in the following families: Rhizophoraceae, Bombacaceae, Meliaceae, Caesalpiniaceae, Ochnaceae, Sapotaceae, Rubiaceae and Sterculiaceae. In the drier areas members of the Bignoniaceae, Bombacaceae, Combretaceae, Euphorbiaceae, Meliaceae, Mimosaceae, Moraceae, Sterculiaceae and Ulmaceae

are well represented (Nielsen, 1965). Lower story species of the rain forest include members of the above families as well as members of the Annonaceae, Apocynaceae, Ebenaceae, Flacourtiaceae, Rutaceae and Sapindaceae. Nielsen (1965) also includes the following families that are found in the shrub layer but generally not in the arboreal strata, i.e., the Compositae, Menispermaceae, Polygalaceae, Solanaceae, Verbenaceae and the Violaceae. The lianes and climbing shrubs are included in a wide number of families most of which have already been mentioned. The tropical rain forest is also the zone for widespread cultivation of the oil palm, <u>Elaeis guineensis</u>, although it is indigenous to the swampy parts of West Africa.

In the southern part of the Sudanese zone the broadleaved tree savanna consists of both deciduous trees and tall grasses. The grasses include <u>Andropogon</u> sp., <u>Imperata</u> sp., <u>Hyparrhenia</u> sp. and <u>Pennisetum</u> sp. The arboreal vegetation is mostly fire-tolerant and has thick corky bark with the following families well represented: Caesalpiniaceae, Euphorbiaceae, Mimosaceae, Ochnaceae, Rubiaceae, Sapotaceae and Verbenaceae. In addition to these families, shrubs are represented by members of the Annonaceae, Celastraceae, Combretaceae and Loganiaceae (Nielsen, 1965). Common herbaceous families excluding grasses and sedges include: Araceae, Compositae, Iridaceae, Liliaceae, Malvaceae, Orchidaceae and Zingiberaceae.

The thorn tree-tall grass savanna (northern Sudanese)

is dominated by various arboreal species of <u>Acacia</u> (Mimosaceae), several species in the Caesalpiniaceae and species in the Anacardiaceae, Combretaceae, Dipterocarpaceae, Ebenaceae, Euphorbiaceae, Myrtaceae, Sapotaceae, Sterculiaceae and Verbenaceae. The shrub species are similar to those in the broad-leaved tree savanna except that <u>Protea elliottii</u> (Proteaceae) is also found (Nielsen, 1965). The grasses are also similar.

The Sahel vegetation zone can best be described as acacia-desert grass savanna. Arboreal vegetation is short (3 to 6 m) and widely spaced. Many species of acacia (both trees and shrubs) predominate as well as other thorny shrubs such as the African myrrh (<u>Commiphora africana</u>), and shrubs in the family Asclepiadaceae are also very well represented. Other shrubs in the following families are present: Papilionaceae, Caesalpiniaceae (especially the genus <u>Cassia</u>), Tiliaceae, Capparidaceae, Euphorbiaceae and Boraginaceae. The most common herbs are members of the Amaranthaceae but short tussock grasses and sedges tend to dominate the surface. The date palm <u>Phoenix dactylifera</u> is commonly planted in this zone too.

Most of the plants of significance to the present study in the Saharan zone are those of herbaceous character. The Chenopodiaceae are especially well represented as are the Compositae, but to a lesser extent; the former are found especially in saline areas (playas). Grasses include <u>Stipa tenacissima, Lygeum sp., Panicum turgidum, Aristida</u>

sp. and <u>Eragrostis</u> sp., (Walter, 1973). Shrubs found in wetter habitats include the genera <u>Tamarix</u>, <u>Nitraria</u> and <u>Ziziphus</u> and in the southern Sahara various acacias (and many other shrubs) are encountered, especially towards the Sahelian transition zone. The southern Saharan woody species tend to have tropical affinity whereas the herbs are mainly Mediterranean (Church, 1968). The coastal Sahara of Morocco has succulent members of the Euphorbiaceae especially <u>Euphorbia</u> sp., and most appear as dwarf shrubs (Walter, 1973).

In the Hoggar above 1800 m a garrigue vegetation with Mediterranean counterparts is encountered with important species being <u>Olea laperrini</u> (an endemic relic), <u>Myrtus</u> <u>nivellei</u>, <u>Pistacia atlantica</u> and <u>Verbascum dentifolium</u> (Quézel, 1965).

On the Mediterranean side of the Atlas Mountains the maquis vegetation is dominated by sclerophyllous shrubs such as <u>Olea europaea</u> (wild olive), <u>Ceratonia siliqua</u> (carob), <u>Pistacia lentiscus</u> (lentisk), <u>Quercus coccifera</u> (Kermes oak), <u>Cistus</u> sp. (cistus) and <u>Arbutus</u> sp. (arbutus) (Eyre, 1968). The so called 'High Maquis' may also have <u>Q. ilex</u> (Holm oak) and <u>Pinus halepensis</u> (Aleppo pine), both tall trees, as well as some larger shrubs such as <u>Myrtus commumis, Erica arborea</u> (tree heather), <u>Phillyrea</u> <u>media</u> and <u>Spartium junceum</u> (Polunin and Huxley, 1966) not all of which are sclerophyllous.

On the Saharan side of the Atlas the garrigue has

typical maquis species but most communities are characterized by non-sclerophyllous vegetation including members of the Labiatae and <u>Thymus</u> sp. Garrigue occurs extensively on the northern flank of the Atlas also.

Above the maquis and garrigue (evergreen forest) a deciduous forest zone may occur but it is more characteristically found on the northern shore of the Mediterranean and not on the southern Mediterranean or Atlas shore. This deciduous zone is effectively squeezed out here due to its altitudinal limit of 1000 m where, in the Atlas, the lowland evergreen forest only finally relinquishes its dominance to the coniferous forest above. Between 800 m and 1500 m in Algeria and Morocco the coniferous forests of <u>Pinus halepensis</u> and <u>Abies numidica</u> are present and above these extending up to 2000 m are the famous cedar forests of <u>Cedrus atlantica</u>.

In the Canary Islands the lower communities of semidesert scrub are dominated by members of the Compositae and species of <u>Euphorbia</u> and <u>Aeonium</u> (Crassulaceae). Generally between 400 and 600 m, this lower xerophytic zone merges into a forest scrub zone (Mediterranean in character) with <u>Juniperus phoenicea</u> and <u>Erica arborea</u> (Bramwell and Bramwell, 1974). This Juniper scrub zone is better developed on the southern slopes where a rain shadow is produced by the loftly volcanic mountains, especially on Tenerife where El Teide rises to 3707 m.

An evergreen forest zone with broad-leaved trees and

shrubby heaths occurs above the Juniper scrub (generally on the wetter northern slopes) and is dominated by arboreal laurels including <u>Laurus azorica</u>, <u>Apollonias barbusana</u>, <u>Persea indica</u> and <u>Ocotea foetens</u>, all of which according to Bramwell and Bramwell (1974) are relicts of an extinct Tertiary Mediterranean flora which, from fossil evidence, occupied southern Europe and northern Africa between 15 to 40 million years B. P. <u>Arbutus canariensis</u>, <u>Salix</u> <u>canariensis</u> and half a dozen more trees including evergreen oaks are also important in laurel communities (see Bramwell and Bramwell, 1974, for a more complete list of trees, shrubs and herbs). The laurel zone may extend up to 1300 m.

The pine forest, with the endemic <u>Pinus canariensis</u> being the predominant species, is generally found above the more characteristically Mediterranean zones at 1200 m and may extend up to 2000 m. It is an open park-like forest except in areas that have been reforested.

The vegetation on the highest peaks of the Canaries, generally above 2000 m, consists of open montane scrub dominated by shrubs in the family Leguminosae (Bramwell and Bramwell, 1974). Many rare endemics are found in this zone.

Many of the characteristic species found in the Canary Islands are also found on the Madeiras and Azores. The vegetation found on the Cape Verde Islands is also similar to that of the Canaries but tends to be more xerophytic as it is geographically closer to the Saharan

climatic zone.

## THE NORTHEAST ATLANTIC OCEAN

### Oceanography

<u>Bathymetry</u>: The salient bathymetric features for the portion of the Atlantic related to this study consist of various basins and rises, the latter being associated with volcanic islands or the Mid-Atlantic Ridge (see Figure 8). The Mid-Atlantic Ridge extends more or less along the western border of the study area. The major physiographic feature of the Ridge is the Azores Plateau (the surface of which is generally no deeper than 2000 m) located around 30° N latitude and 30° W longitude.

The Cape Verde Terrace extends off the coast of Mauritania for some 1000 km and the ocean above it is generally shallower than 4000 m. The 4000 m submarine contour is closer to the continent around the southern and eastern coasts of West Africa and off Ghana is even as close as 120 km offshore. A line of sea mounts extends from the Azores to Gibraltar and forms the Azores-Gibraltar Ridge. The only other major 'high' is the Sierra Leone Rise which lies some 750 to 1000 km from the coasts of Guinea and Sierra Leone.

Major basins and abyssal plains (shown in Figure 8) are often deeper than 6000 m. The continental shelf in



general extends between 50 to 150 km offshore except off Guinea Bissau and Guinea where its width may reach 200 km. The narrowest section of the Shelf is found in the Bight of Benin off the coast of Ghana where it only extends 20 km offshore.

Ocean Currents: The most important surface current in the study area is the cold Canary Current which flows generally southwest from the Iberian Peninsula and then bifurcates at the Cape Verde Islands where part of it unites with the westward moving North Equatorial Current. The other part of the Canary Current flows south and east around the coast of West Africa and forms the Guinea Current east of Liberia (see Figure 9). The Guinea Current moves eastward parallel to the coast and then is deflected south against the coasts of Cameroon and Gabon; it then joins the South Equatorial Current below the equator flowing west to the Brazilian coast. The Equatorial Counter Current originates over the Guiana Basin and moves eastward until it joins the Guinea Current in the vicinity of the Sierra Leone Rise. Recently, McGrail (1977), identified a Canary Counter Current along the shelf edge of Guinea Bissau, Guinea and Sierra Leone which he considers to be an agent of north-westward sediment transport beneath the southeasterly flowing Canary Current.

The currents and general oceanography for the Gulf of Guinea have been reviewed by Longhurst (1962 and 1964). In the same area Lemasson and Rebert (1973a and 1973b),





have reported on a coastal Ivorian undercurrent which originates in the Bight of Benin near Lagos (Nigeria) and flows westward beneath the Guinea Current.

Upwelling: The zone of upwelling off the southwest coast of Africa is well known. It produces high biologic productivity in the waters of the outer and middle shelf (Koblentz-Mishke et al., 1970 and Milliman, 1977). Consequently large concentrations of organic detritus are found both in the shelf and slope water (Emery et al., 1973) and bottom sediments (Calvert and Price, 1971). In contrast to the southwestern upwelling zone that along the northwestern coast of Africa (and especially off Spanish Sahara and Mauritania) has not been studied in as much detail. The upwelling occurs on a rather shallow shelf. the sedimentary regime of which is less well known (Milliman. 1977). However, McMaster and LaChance (1969). McMaster et al., (1970) and Summerhayes et al., (1972 and 1976) have studied the shelf sediments and Emery et al., (1974) have reported on the distribution of suspended matter in the surface waters where upwelling occurs.

According to Milliman (1977), the middle and outer shelf off southern Spanish Sahara has a lower organic content than the corresponding shelf area off southwestern Africa. The reason he gives for this discrepancy is in the contrasting degrees of oxidation found within the two bottom environments. On the southwest African shelf the oxygen minimum is found deeper on the shelf than its

counterpart on the northwest African shelf; therefore, organic-rich material is retained in the former but tends to be recycled in the latter. Also, vertical turbulence is evidently greater off Spanish Sahara, the consequences of which are slower settling rates and more nutrient recycling within the water column (Milliman, 1977). The overall effect of this is that less organic detritus reaches the bottom environment (Milliman, 1977). Upwelling off the northwest African coast may be related to an undetermined northward flowing counter current, since upwelling along the Ivory Coast seems to be related to the Ivorian Undercurrent by conversion of the latter into vertical flow against the continental shelf (LeMasson and Rebert, 1973b).

<u>Sediments</u>: The physical properties of the various sedimentary provinces in the North Atlantic have been summarized by Horn <u>et al.</u>, (1974). Most of the topographic highs off the coast of northwest Africa are dominated by bottom sediments of carbonate ooze, especially along the trend of the Mid-Atlantic Ridge, on the Sierra Leone Rise, on the Cape Verde Terrace and around the Canary Islands. The bottom sediments on the continental shelf and slope to a depth of about 4000 m are predominantly terrigenous hemipelagites. Turbidites are found in a zone around the Cape Verde Islands extending to about 30° W and between 10° N and 20° N. A northeast-southwest turbidite trend extends from 35° N to 20° N in the Canary Basin and a similar zone is found in the Guinea Basin between 10°W and 5°E. A major zone of "Red Clay" extends from 5°N to 30°N, as far west as 40°W and extends east encircling the Cape Verde "Carbonate ooze" and "Turbidite" zones to about 20°W (Horn <u>et al.</u>, figure 5, p. 426, 1974).

Diester-Haass (1976), has studied the accumulation rates of sediments off the coast of Northwest Africa and reports that Holocene rates decrease with depth down the continental slope. In 600 m of water rates are about 8 cm/1000 yr and in 3000 m about 2.5 cm/1000 yr (Diester-Haass, 1976). Rates off Senegal tend to be higher than those off Spanish Sahara because of added river sediment. Rothe (1973), estimated rates of 2-3 cm/1000 yr adjacent to the Canaries and Cape Verde Islands. However, rates for the North Atlantic as reported by Ku <u>et al.</u>, (1968), seem to be somewhat lower in general and vary between 0.2-1 cm/1000 yr.

Fluvial sedimentary contribution to the ocean bottom sediments of West Africa is primarily confined to the continental shelf and since most bottom sediments in the study were collected from abbysal or near abbysal depths, the influence of fluvial transportation and deposition on palynomorph distribution may not be great.

Finally, Delany <u>et al.</u>, (1967), calculated the sedimentation rates in the North Atlantic from eolian sources to be about 0.6 mm/1000 yr, which agrees with figures estimated by Goldberg and Griffin (1964), for equatorial and southern regions of the Atlantic.

### DATA COLLECTION

## Types of Samples

Three types of samples were used in this study. These included Atlantic bottom sediments (core tops), air-filter samples and West African wind-erodible surface sediments collected on land. The sources of these samples have already been mentioned (p. 1). Locations for the above samples are shown on Figures 1 and 2 and Table 1 of this report. Since some of the sample localities on the West African continent involved serial collection at various times of the year or during different seasons information on sampling dates is given in Table 2. Those air-filter samples collected aboard the R/V "Atlantis II"-1973 cruise and used in the present study are tabulated with information on the meteorology at the time of collection, length of filter exposure and various filter measurements of importance to the study (see Table 3). This information is taken from Lepple (Appendix A, 1975). Similar information on air filter samples collected on the "Atlantis II"-1966 cruise is presented in Table 4.

# Methods of Collection

Most of the bottom sediment samples were obtained from trigger weight cores whilst others were obtained from

Table 2.	Collection Data	a for	Land-based Ae	rosols
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MS2118, 21	177	NA	6	3/13/74-3/13/74
MS2031		NA	16	3/19/74-3/20/74
MS2032		NA	24	$\frac{1}{4}/3/74 - \frac{1}{3}/74$
MS2119, 21	178	NΔ	<b>69-7</b> 0	5/29/74-5/30/74
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MS2105		20	029	
MSZU JO		20	070	
M52166		SC	071	7/15/74-7/14/74
MS2037		SC	890	August 1974
MS2167		SC	919	10/5/74-10/5/74

Table 3. Collection Data for "Atlantis II"-1973 Aerosols

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piston cores. Approximately 1-2 grams of sediment was sampled from the core tops. Maynard (1976), could find no statistically significant differences between data obtained from trigger weight as opposed to piston cores and so no undue apprehension about the comparison of data from these two types of cores was experienced by the present author.

Some of the dust samples supplied by Dr. Lepple were collected by foreign contacts and are not well documented as to the method of sampling, length of sampling, etc., and so data gathered from these samples are viewed with some reservation.

Lepple (p. 29-36, 1975) has discussed at length his method of sample collection aboard the R/V "Atlantis II" and so only those features of collection pertinent to the present study will be discussed here. Standard National Air Surveillance Network (U.S.EPA) high volume (hi-vol) air samplers were used by Dr. Lepple to collect the samples. These samplers draw air through a 20 x 25 cm filter at the rate of between 1.0 to 1.8 m<sup>3</sup>/min and according to Pate and Tabor (1962) effectively remove virtually 100% of the particulates 0.3  $\mu$ m or greater in diameter. Most palynomorphs are therefore effectively removed by using this type of sampler although those above 90  $\mu$ m may be excluded. Some bisaccate pollen lårger than 90  $\mu$ m and other very large grains might then be excluded by using this sampling method.

Dr. Lepple collected the airborne detritus on pre-

weighed glass fiber (Gelman GF-A) or cellulose acetate (Whatman #41) filters. Those air-filter samples studied in the present report were collected with a standard hi-vol (GMWL-2000) sampler. However, some of the other samples supplied by Dr. Lepple had been collected by an Andersen cascade impactor (Model 65-000) which aerodynamically separates airborne particulates into 5 size fractions. For the collection of marine aerosols samplers were located well forward of the ship's stack and approximately 10 m above the sea surface. Dr. Lepple's other hi-vol samplers were located on the coast of Africa in Mauritania, one at Tour Bleu (9 m above sea level and actually 5 m above ground) and another at Nouadhibou Airport (10 m above ground). The airport sampler was oriented north-northeast being that this was the predominant wind direction and the sampler at Tour Bleu was oriented towards north (Lepple, 1975).

Samples from R/V "Atlantis II"-1966 cruise were collected on 20 cm diameter Delbag-Microsorban Dry Lager Air Filter Medium 99/97 Microsorban.

### Sample Treatment

Introduction: Owing to the variety of different sample types in the study any uniform treatment between types was precluded. However, all samples of one particular type or series were treated uniformly except where samples had been collected on different filters. Since filters of three different compositions were used in sampling the

aerosols three different maceration schedules were necessary. None of the samples in the study were indurated sediments, consequently no preliminary crushing or sizing was necessary.

Bottom Sediments: Since both acid insoluble plant microfossils (pollen, spores and dinoflagellates) and acid soluble plant microfossils (diatoms and opal phytoliths) were to be studied in this project two separate processes for concentrating these entities were employed.

Schedule 1: Concentration of pollen and spores

(a) Place about 0.5 to 3 grams of dry sample (weighed to four decimal places on a mettler balance) in a beaker and cover with HCl (10%); wash three times with distilled water after reaction ceases. (All samples disaggregated at this stage).

(b) Cover sample with HF (50%) and allow to stand for 48 hours with frequent stirring; wash while heating one to three times with HCl (10%) to remove silicofluorides; wash three times with distilled water.

(c) Separate clays from sample with heavy liquid (ZnCl<sub>2</sub> of specific gravity 1.95).

(d) Transfer sample to 15 ml glass centrifuge tube and dehydrate with glacial acetic acid.

(e) Acetolize the sample (acetolysis mixture consists of 1 part concentrated  $H_2 SO_4$  (95%), added slowly to 9 parts acetic anhydride) in a fume hood heating to a temperature of 70-80°C. (Maximum time involved-5 minutes) (f) Reduce the specific gravity with glacial acetic acid and wash once with the same; wash three times with distilled water.

(g) Transfer to small vial and cover with H.E.C. (Hydroxyethyl Cellulose WP-09, Union Carbide Corp.).

(h) Mix residue thoroughly and transfer one drop to a coverslip (average drop equals 1/200th of total mixed residue) using a Pasteur pipette and effecting as even a distribution as possible. Allow residue to dry on the hot plate and then mount on a microscope slide with one to two drops of H.S.R. (Harleco Synthetic Resin). Allow slides to dry and set in an oven at 35°C for 24 hours. Generally 3 slides were mounted for each sample processed.

Schedule 2: Concentration of diatoms and opal phytoliths

(a) Place about 0.01 to 0.5 grams of dry sample (weighed to four decimal places on a mettler balance) in a glass beaker and cover with HCl (10%); wash three times with distilled water after reaction ceases.

(b) Cover sample with concentrated HNO, (70%) and allow to stand for a few hours; wash three times with distilled water.

(c) Pass sample through a 15 µm sieve retaining both fractions. Coarse fraction contains mainly marine diatoms and radiolarians. Fine fraction contains most of the freshwater diatoms and opal phytoliths.

(d) Proceed with (g) and (h) in Schedule 1, for both

fractions. Mount coarse and fine fractions separately.

<u>Air Filter Samples</u>: Samples on glass filters were not examined for diatoms or opal phytoliths. Most of these filters were exposed west of 30° W or north of 25° N where concentrations of these entities are usually low in comparison to areas east or south of these coordinates.

Schedule 3: Glass filters (Gelman GF-A)

(a) Saturate ‡ of filter (125 cm²) with distilled
water (enough to cover) then cover with concentrated HF
(50%). Reaction is instantaneous and the filter is
destroyed immediately. Wash three times with distilled
water.

(b) Proceed with Schedule 1, sections (d) through(h).

Schedule 4: Cellulose filters (Whatman #41)

(a) Place  $\frac{1}{2}$  of filter (125 cm<sup>2</sup>) in a 90 ml glass centrifuge tube and cover with cold concentrated H<sub>2</sub>SO<sub>4</sub> for twenty minutes. The filter is destroyed during this time but pollen and spores are not appreciably degraded.

(b) Centrifuge for ten minutes at 1200 RPM. Separate sink fraction from float fraction retaining both. Sink fraction contains mineral particles and siliceous microfossils, some heavy fungal spores and very little pollen. Float contains pollen and spores and very little siliceous material.

(c) To sink fraction proceed with section (f) in Schedule 1.

(d) Clear sink fraction of sample with KOH (5%) and wash 3 times with distilled water.

(e) Proceed with sections (g) and (h) in Schedule 1.

(f) To the float fraction successively reduce its specific gravity with glacial acetic acid and then distilled water.

(g) Clear with KOH (5%) and wash with distilled water three times and then continue with sections (g) and (h) of Schedule 1. Mount sink and float fractions separately.

Schedule 5: Microsorban filters

(a) Place a measured section of filter into a 90 ml glass centrifuge tube. Cover filter with carbon tetrachloride (CCl<sub>4</sub>). Filter dissolves within a few minutes.

(b) Reduce specific gravity slightly, with acetone (adding too much acetone causes the filter to reprecipitate) and centrifuge, retaining both sink and float fractions.

(c) Continue to reduce specific gravity of both fractions until solutions are effectively 100% acetone and water miscible.

(d) Wash three times with distilled water and recombine both fractions.

(e) Proceed with sections (d) through (h) of Schedule 1.

<u>West African Land-based Samples and Wind-erodible</u> <u>Soils</u>: The schedule used for those samples not studied for siliceous entities was identical to that used for glass filters (Schedule 3). Samples studied for opal phytoliths and freshwater diatoms were processed only through sections (g) and (h) of Schedule 1.

## Microscopy

Not all the samples processed were productive in regard to containing large numbers of palynomorphs. However, all the samples were examined since those that proved to be barren were critical to the study in so far as their geographic distributions were concerned. Therefore, no suitable minimum number of palynomorphs to be counted per sample could be determined. Some of the bottom sediment sample preparations when counted (even at only 100X magnification) provided zero palynomorphs per traverse while some of the aerosol preparations (viewed at 500X magnification) contained over 50 palynomorphs per traverse.

Quantitative Examination: Slides studied for pollen, spores and dinoflagellates were counted at 500X magnification on a Leitz Ortholux microscope (Michigan State University No. GG 2667) in vertical traverses covering the total area of the cover slip. Rather unproductive slides with small numbers of palynomorphs were first scanned at 100X magnification in order to reduce the time involved in viewing nonessential organic and mineral debris. Those samples prepared for the study of freshwater diatoms and opal phytoliths were in general counted at 1000X or 500X magnification on a Zeiss phase contrast microscope (Michigan State University No. GG 2702) over a number of random vertical traverses until 200 entities had been counted. The number of traverses in most instances did not exceed ten since some contained over 100 palynomorphs each.

In the above procedures every effort was made to identify the palynomorphs to generic and specific taxonomic level. When this was not possible they were identified to familial level or placed in some useful morphological group. The only exception to this was in counting marine dinoflagellates which were all considered as a single discrete category.

In order to determine the "absolute" number of some particular taxon or group of palynomorphs in one gram of original sample the following equation was employed: the total number of a particular palynomorph on the number of counted slides x the reciprocal of the aliquot used from the vial of residue x the reciprocal of whatever fraction of one gram was used in processing = total number of that particular taxon in one gram.

In order to obtain "absolute" numbers from macerated filter samples the area of filter used had to be related to the total volume of air passed through the filter or the total weight in grams of sediment retained on the filter before the above equation could be used.

<u>Qualitative Examination</u>: In general, the only samples studied qualitatively were those collected as wind-erodible soil or as aerosols above the African continent. They were primarily examined to determine the relative percent-

ages and geographic occurrence of particular palynomorph taxa in order to determine the possible provenance and relative importance of the same taxa found in bottom sediments or marine aerosols. Relative abundance was determined by counting up to 200 palynomorphs per sample (generally on three slides) under either the total cover slip surface or a number of random vertical traverses. Some of the less productive samples, however, were rather limited as to the type of data they could provide and could only be studied in relation to the presence or absence of certain taxa, this limitation being generally a function of either sample lithology or collection site geography.

# Photography

The majority of the photomicrographs (Plates 1-22) were taken with a Leitz Orthomat microscope camera mounted on a Leitz Ortholux microscope using Kodak Panatomic-X film. Photographs were printed on medium weight Kodak polycontrast rapid RC paper.

# African Reference Samples

Reference samples of African pollen and spores from thirty-five individual families in the Michigan State University pollen herbarium were studied and photographed as an aid to identifying some of the palynomorphs in the present study. Other herbarium material was also utilized for determining various taxonomic affinities and at least familial rank for some of the unknown palynomorphs in the
study.

## African Palynological Literature

Most of the useful palynological reports with reference to the existing tropical and northern African vegetation have been mentioned in the section on previous work (p. 12 this report). However, the major Ethiopian studies of Bonnefille (1969, 1971a and 1971b) were also extensively used, as was that of Sowunmi (1973), for palynomorphs produced by Nigerian woody plants. Literature on Specific Vegetation Arrays in Northwestern

## Africa Used in the Study

A number of papers were consulted during the study for information about specific vegetation associations in North West Africa in order to facilitate the connection of palynological data with possible source vegetation. The following papers were important for determining vegetation arrays in Senegal (especially in the vicinity of Dakar where some of the samples in the present study were collected): Trochain (1940), Roberty (1952), Adam (1955, 1956, 1957, 1958, 1961a, 1961b, 1962a, 1962b, 1962c, 1962d, 1963, 1964a, 1964b and 1965), and Berhaut (1967).

Adam (1966), also studied the vegetation of the Mauritanian aftouts and this type of information on the coastal vegetation of areas where both air and surface samples were collected (in Mauritania and Spanish Sahara) was of the utmost importance to the present study. Other studies obtained for information on vegetation groups in Mauritania include: Naegelé (1958a, 1958b, 1959 and 1960), Monod (1952 and 1954) for the western Saharan section, and Gauthier-Pilters (1975) for the Zemmour area. Major works consulted for information on the vegetation of the Sahara included: Ozenda (1958) and Quézel (1965). Lapie and Maige (1914), was consulted for information on the forest flora of Algeria, Tunisia and Morocco, as were the more up-to-date Quézel and Santa (1962 and 1963) for the Algerian flora, and Nègre (1961 and 1962) for that of western Morocco.

Literature pertinent to the montane or altitudinal vegetation communities in Sierra Leone included Cole (1967 and 1968) and Jaeger (1965) and a comparative study on the forests of Sierra Leone and Liberia by Adam (1969). Liberian coastal vegetation has been studied by Adam (1970). Contributions to the study of Guinean vegetation associations and flora include: Devois (1948), Jaeger and Schnell (1958), Adam (1968), and in the Fouta Djallon, Killian (1951). All of these papers were consulted during the study.

Various papers on Ivory Coast pteridophytes used during the study include reports by Des Abbayes <u>et al.</u>, (1951 and 1953), Adams (1956), Des Abbayes and Tardieu-Blot (1956) and Hall and Bigger (1974). Adams and Alston (1955) also studied pteridophytes in Ghana.

Literature of a more general nature on the West African vegetation consulted during the study includes

the following: Schnell (1945 and 1950), Roberty (1953, 1954a, 1954b, 1954c, 1954d and 1955), Nielsen (1965), Church (1968), Eyre (1971), and Hutchinson and Dalziel (1972).

## PRESENTATION OF DATA

## Introduction

A series of maps was prepared showing the geographic distribution, abundance or relative frequency for particular taxa of palynomorphs in both aerosol and bottom sediment samples (Figures 10 to 48). Certain interesting distribution patterns emerged on the maps and will be discussed in due course.

In analyzing the aerosol data, temporal considerations necessitated somewhat disjointed contouring, because samples were collected during different seasons. Those samples collected during the winter were mainly from the Gulf of Guinea and so data from here are contoured as a separate geographic entity. The majority of samples north of the Azores were collected during late spring and early summer and so again are treated as a separate contourable entity. Consequently, absolute numbers of palynomorphs in these two main areas bear no relationship to each other.

In the southern (winter aerosols) area (Gulf of Guinea) generally south of 10°N the number of palynomorphs tends to be an order of magnitude smaller than that in the northern area where aerosols were collected during spring and early summer. This is especially true for pollen and



















































































Figure 41. Distribution of Palmae Pollen in Northeast Atlantic Aerosols (winter 1973)




Figure 43. Distribution of Mangrove Pollen in Northeast Atlantic Bottom Sediments







Figure 45. Distribution of <u>Melosira granulata</u> in Northeast Atlantic Bottom Sediments











spores (see Figure 10).

West of 30° W, 1500 km from the West African coast, so few data points exist that aerosol data generally cannot be related numerically to either the northern or southern areas. The single sample locality south of the Azores should also be regarded separately since it was collected nearly two months after the other northern samples used in the study.

Since the top centimeters of bottom sediment in core tops were probably deposited during a similar time period i.e., 500 to 1000 years (see p. 43 for discussion of sedimentation rates) one datum was used for contouring. This is of course assuming that no appreciable change in palynomorph sedimentation rates has occurred during the past millenium.

# ANALYSIS OF DATA

#### Introduction

Discussion of aerosol distributions will be followed by a discussion and comparison of bottom sediment distributions for the same geographic area.

In both aerosol and bottom sediment samples three specific palynofloral zones were detected. A southern, equatorial-tropical zone south of 10°N, a northern Mediterranean zone above 25°N and a Saharan zone between 10°N and 25°N. The Mediterranean zone however, is extended to 10°N in the bottom sediments due probably to southwestern transport of palynomorphs by ocean and air currents.

# Palynomorph Distributions

# Terrestrially Derived Entities:

POLLEN AND SPORES: The discrepancy between numbers of pollen and spores per gram of dust (spores generally comprising less than 0.25% of the total) found in Gulf of Guinea aerosols to that of Mediterranean aerosols may be due to time of sampling. The major flowering season in the Mediterranean is between mid-April to mid-June with the peak for Mediterranean perennials coming at the end of April (Polunin and Huxley, 1966). This coincided with time of air sampling in the north above the ocean during

1973 although land-based aerosol sampling in 1974 took place later in the season from middle July to early October. Aerosol sampling in the Gulf of Guinea took place during the winter (or dormant season in the tropics) and so the majority of land-derived plant entities were introduced into the atmosphere via dust storm activity and not from actual pollen production at that time.

The greatest abundance of pollen and spores was found above the ocean 100 km off the coasts of Spanish Sahara and Morocco (see Figure 10). Here aerosols contained up to 5 million pollen grains per gram of eolian dust during late June or 40 grains per cubic meter of air. Furthermore, air extending out to 30° W or 2000 km from the north African coast, still contained up to 2 grains per cubic meter of air.

The highest numbers of pollen and spores in aerosols south of 10° N occurred along the coasts of Gabon and Ghana. These high abundances are related to high dust concentrations at the time of sampling which were in excess of  $60 \ \mu g/m^3$  (Lepple, figure 8, p. 50, 1975). Numbers of pollen grains per cubic meter of air sampled during this dust storm averaged between 4 and 6 although when compared to the number of freshwater diatoms (1300 per cubic meter of air) this does seem somewhat paltry. The numbers of pollen and spores per gram of bottom sediment (Figure 11) shows a distribution similar to that of the aerosols. The greatest abundance is found east of 30° W and although this

is also true of the aerosols it must be pointed out that only three air samples west of this meridian were used in the study. Numbers of pollen and spores in bottom sediments dropped sharply beyond this point.

Air samples in the vicinity of the Cape Verde Islands contained low numbers of all categories of palynomorphs yet the highest abundances in bottom sediments are found on the Cape Verde Terrace. It seems that a plausible explanation for this contradictory situation could be the southwesterly transport of palynomorphs from the Mediterranean via the Canary Current.

The high concentration of pollen and spores in sediments off the coast of Mauritania north of the Senegal River to about Cap Mirik may be explained by the direct transport of pollen out of the Sahara via the Northeast Trades since relatively little pollen appears to be of Mediterranean character. Stream transport does not seem probable since the zone is at least 50 km north of the Senegal River. However, if northward flowing coastal countercurrents are present, a fluvial source for these palynomorphs is still possible.

The high abundance zone in sediments off Sierra Leone may be explained more readily by fluvial transport since many short streams enter the Atlantic along the coasts of Guinea and Sierra Leone. Coastal swamps in this vicinity introduce mangrove pollen into the water and this becomes incorporated into bottom sediments fairly readily.

A plume of high pollen and spore concentration in the bottom sediments extending south from the coast of Liberia may be related to dust storm activity during winter since a similar pattern is produced in aerosols (Figure 10).

Although it can be seen in Figure 11 that pollen and spore abundance increases towards the Nigerian coast the bottom sediment samples were probably too far from the Niger delta itself to show any major contribution of palynomorphs by the river.

The northeast-southwest elongation of isopleths (Figure 11) north of Madeira and south to about 30° N may be a reflection of palynomorph transportation by the Northeast Trades but another possibility is that it reflects the outward spread of heavy saline Mediterranean waters into the Atlantic. These heavy waters may therefore be charged with a considerable particulate load.

The high abundance of pollen and spores north of 30° N and west of 30° W is hard to explain unless westerly transport from North America is involved in the concentration of terrestrial detritus on the western flank of the Mid-Atlantic Ridge. Although this seems unlikely, organic matter contained in eastward moving North American dust storms might be concentrated in this manner.

Low abundances of pollen and spores were found associated with deep basins in the Atlantic (cf. Figures 8 and 11). This may be due to slower terrestrial sedimentation rates in deep basins as a consequence of their being far

distant from the West African continent.

FUNGAL SPORES: Disjunction of isopleths is again evident in Figure 12 due to collection time variation for aerosols.

The greatest concentration of fungal spores in the air was present some 800 km directly off the Liberian coast. Here greater than 5 million fungal spores per gram of eolian dust or 600 spores per cubic meter of air were present. Other areas with greater than one million per gram of dust were found down-wind from the Azores and around the Canaries. The Ghanan dust storm during the first half of March, 1973, also contained greater than one million fungal spores per gram of dust.

Stix (1975) also found high concentrations of fungal spores around the Azores (nearly 2000/m<sup>3</sup> of air) during October, 1972, although these numbers are two orders of magnitude greater than were found in the present study during August, 1973. Stix also observed that in late autumn spore content increased with distance from the European continent. Figure 12 also demonstrates an increase in numbers of fungal spores down-wind from southern Europe and the Azores.

Major distribution patterns of fungal spores in bottom sediments are indicated in Figure 13 (marine and terrestrial spores were not differentiated). Distributions reflect proximity to major streams and areas of high marine productivity with the greatest abundance towards the Niger delta, even though the sample involved was 200 km from the actual delta.

The north-south trending zone of upwelling off the Saharan coast is well defined by fungal spore abundance. however. further to the south from Senegal to Liberia fungal spores are up to ten times as abundant as in the actual zone of upwelling. This is held to be a function of proximity to the many streams along this section of coast. Probably most of the fungal spores in bottom sediments are marine and a good parallel is found when comparison is made between fungal spore distribution and that of dinoflagellate distribution (cf. Figures 13 and 20). Cross et al., (1966), also found a high incidence of fungal spores and dinoflagellates related to winter upwelling in the Gulf of California. In the present study this parallelism between fungal spores and dinoflagellates in bottom sediments is not restricted only to areas of upwelling. The broad plateau of fungal spore abundances south of the Cape Verde Islands and west of the Gulf of Guinea may be related to the eolian transport of spores southwest of West Africa by the Northeast Trades, rather than to purely high marine spore abundances.

OPAL PHYTOLITHS: Since only winter aerosols were processed for opal phytoliths, distribution patterns only show two areas of concentration (Figure 14), (1) an area associated with the March, 1973, dust storm off Ghana and (2) an area south of Senegal probably derived from the

southern Sahara and Sahel. The Ghanan area seems to have no counterpart in the bottom sediments (see Figure 15) and indeed opal phytoliths seem to be absent from the Gulf of Guinea sediments. This may be due to the transitory nature of the winter Harmattan (the major transporting agent for this area) transporting opal phytoliths from the Sahel in Niger and Mali to the Gulf of Guinea, whereas the Northeast Trades transport large quantities of opal phytoliths to the Atlantic Ocean most of the year.

Large concentrations of opal phytoliths were found in bottom sediments as far west as 40° W (2500 km from Africa) although due to sampling inadequacy this is not reflected in aerosols collected during 1973. However, those aerosols collected during the 1966 cruise of R/V "Atlantis II" show appreciable concentrations of opal phytoliths and other palynomorphs with African provenance (see Table 5) as far west as 50° W (3000 km from Africa). Here opal phytolith concentration exceeded 200/m<sup>3</sup> of air.

Major opal phytolith concentration in bottom sediments is found south of 20°N. Concentrations decrease from 2.5 million/gram of sediment at 500 km from the African coast to less than 100,000/gram at 1000 km.

FRESHWATER DIATOMS: Winter aerosols in the Gulf of Guinea showed the greatest concentration of freshwater diatoms associated with dust storm activity off the coasts of Ghana, Liberia and Ivory Coast. Here concentrations exceed 25 million whole diatoms per gram of dust (Figure 16)

Table 5:	Numbers "Atlanti	of Major s II"-19	Types of Pa 66 Cruise.*	lynomorphs Po	er Cubic Met	er of Air Sam	pled During
Sample Name	Pollen and Spores	Fungal Spores	Freshwater Diatoms	Freshwater Diatom Fragments	Opal Phytoliths	Average Distance From Large Continent (k	Average Distance From Africa (km) m)
AF37 AF37 AF38 AF40 AF43 AF443 AF443 AF443 AF443 AF443 AF49 AF49 AF50 AF50	ed) 794,000 4.1 794,000 4.4 70,000 4.4	000000040 50- 400 000	5385 7310 7445 7445 782 782 782 782 782 782 782 782 782 782	6, 204 49, 562 6, 443 6, 941 6, 941 00 00	00 00 00 10 00 00 00 00 00 00 00 00 00 0	72 000 000 000 000 000 000 000 000 000 0	5700 4700 3700 3700 33300 2800 2800 5700 5700
Ldom ocom							

\*See Table 4 p. 48 for dates of collection

and one billion diatom fragments per gram of dust (Figure 17). Greater concentrations offshore (in Figure 16) may be associated with the greater numbers of smaller diatoms compared to larger individuals (in particular of <u>Melosira</u> <u>granulata</u>) over 500 km from the coast.

Fragmentation of these freshwater diatoms is probably mainly the result of impact and abrasion during aerosol residence. However, some may become broken as a result of alternately wetting and drying at the site of growth (Cross, 1979, pers. commun.), or as a result of water transport before becoming incorporated into the aerosol.

Bottom sediments contain appreciable numbers of freshwater diatoms in two areas of the Northeast Atlantic (see Figures 18 and 19). These two areas include a northern zone above 25°N and a more important southern zone south of 20°N. The northern zone is the least important and contains generally less than 0.5 million freshwater diatoms per gram of sediment. Parts of the southern zone contain over 10 million freshwater diatoms per gram of bottom sediment especially towards the Niger delta, off the coasts of Sierra Leone and Liberia and on the Cape Verde terrace west of Dakar, Senegal, 500 km offshore. Although stream transport may be responsible for contributing freshwater diatoms to bottom sediments off Liberia and in the Gulf of Guinea these two areas also coincide with major areas of dust storm activity (at least during 1973) and so a major contribution to

bottom sediments may indeed be from eolian sources (cf. Figures 17 and 18).

The area of the Atlantic with a high abundance of freshwater diatoms in bottom sediments off Senegal seems to be directly of eolian origin since influence from the Senegal River is not considered to be of importance 500 km offshore. However, concentration by ocean current action should be entertained as a mechanism for producing the pattern observed. The westward bulge of diatom isopleths off the coast of Mauritania and the smaller triangular wedge off Spanish Sahara must be directly related to eolian transport. The former due to the proximity of the Sahel and dry lakes in Mauritania and the latter to the many large coastal sebkas in Spanish Sahara and inland dry lakes along the Mauritania-Spanish Sahara border.

Since no large streams can possibly discharge freshwater diatoms into the Atlantic north of 17°N an estimate of both eolian and fluvial input can be made. It seems possible that up to 1 million diatoms/gram of sediment could be directly related to an eolian source (especially when a concentration of this size is found between 30°W and 40°W and north of 10°N) but when abundances exceed 1 million/gram much of the remainder could be of fluvial origin, (possibly up to 9 million/gram). This is probably an over simplified estimate and underestimates the eolian contribution to bottom sediments which the author considers should be more, especially when diatom concentrations in

aerosols south of 10°N may be five times as high as those north of that parallel.

#### Marine Entities:

DINOFLAGELLATES: The salient feature in Figure 20 is the north-south linear along the western coast of West Africa. This zone of elevated numbers of marine dinoflagellates per gram of bottom sediment coincides directly with the upwelling zone along the same coast. The Cape Verde terrace can also be delineated by high dinoflagellate abundance as can other physiographic features of the Northeastern Atlantic such as the Canary Basin which is characterized by low abundance of dinoflagellates. However, the Azores Plateau shows low values whereas the Cape Verde Basin shows high absolute values, both contrary to expected results. Another anomally is that observed in the extreme northwest of the study area where high numbers of dinoflagellates are found in bottom sediments west of the Mid-Atlantic Ridge. This area is on the edge of the Sargasso Sea (an area of low productivity) where high numbers of organisms would not be expected in bottom sediments.

Another area with low annual net production occurs off the coasts of Guinea and Sierra Leone (Steemann-Nielsen and Jensen, 1957), however, bottom sediments in this area do contain low numbers of dinoflagellates as should be expected.

The map showing the ratio of dinoflagellates to

pollen and spores per gram of sediment (Figure 21) in general simplifies the data on the previous figure (Figure 20).

MICROFORAMINIFERA: Chitinous inner membranes from microforams in bottom sediments (Figure 22) are concentrated along the area of upwelling with a maximum of 800/gm of dry sediment off the southern coast of Spanish Sahara and a much higher but isolated maximum directly west of Freetown, Sierra Leone. However, this latter maximum is based on a single sample which was collected in shallower water than the other samples on Figure 22. In general, a decrease in numbers of foram linings can be positively correlated with increasing water depth.

### Palynofloral Zonation

<u>Mediterranean Palynoflora</u>: A characteristically northern palynoflora was encountered in both aerosols and bottom sediments north of 25° N. This flora was characterized by the following taxa: <u>Olea, Quercus, Betula, Alnus,</u> <u>Ulmus</u>, and <u>Plantago</u>, bisaccates including <u>Pinus</u> and <u>Abies</u> and members of the Myrtaceae, Umbelliferae, Compositae, Chenopodiaceae-Amaranthaceae, Cruciferae, Gramineae, Cyperaceae and Cupressaceae.

During summer (June, 1973) a plume of bisaccate (mainly <u>Pinus</u>) pollen in aerosols extended with a triangular pattern south from the Azores to the Cape Verde Islands (Figure 23). A general north to south decrease in the relative frequency from 5% to less than 2% was observed but 5% of the atmospheric pollen load for <u>Pinus</u> seems to be too low. However, since aerosols were collected after the main period of pine anthesis (April-May, with <u>Pinus halepensis</u> being March to May) this may account for the seemingly low amounts in the atmosphere.

A somewhat different picture is shown in the relative frequencies of bisaccate pollen in the bottom sediments (Figure 24). The greatest frequency is found west of Madeira and the Canary Islands (up to 60%) and the triangular distribution pattern opens out to the northwest and southwest. Part of the northwestern abundance of bisaccate pollen north of 30°N and west of 40°W may be due to North American influence whereas it seems clear that the northeast-southwest elongation of the main part of the distribution pattern is produced by pollen having a southern European and North African provenance (western Mediterranean), being predominantly dispersed by the prevailing Northeast Trades. The close spacing of isopleths (Figure 24) west of the Canary Islands may indicate that pollen is transferred from the atmosphere to the ocean somewhere in this vicinity since a rapid drop in frequency is observed and further southwesterly extension of bisaccate frequencies could be accomplished by ocean current transport. The combined effects of the Northeast Trades and Canary surface current can probably outweigh any northeasterly transport of palynomorphs by Canary bottom currents.

The distribution pattern for bisaccate pollen in

bottom sediments (Figure 24) can best be explained after recognition that the pattern is based on relative frequencies. The greatest frequency (mentioned above) is some 1000 km due west of the North African coast. The reason for this must be in the fact that bisaccate pollen is both aerodynamically and hydrodynamically best suited for optimum transport when compared to non-saccate pollen grains. Since it travels further away from the African coast than other types of pollen its relative numbers must increase at distance also, even though the absolute numbers of bisaccates may be much greater nearer to the African coast.

Quercus pollen in 1973 aerosols (Figure 25) appears to have a southern European provenance since frequencies increase northwards from the Canary Islands to Madeira. However, distribution patterns in bottom sediments (Figure 26) reflect a Moroccan source for <u>Quercus</u> in addition to that of the Mediterranean area in general. The southern limit for <u>Quercus</u> in bottom sediments seems to be at the 10° N parallel and a clear relationship between prevailing southwestern atmosphere and ocean surface current transport is seen. "Quercoid" pollen of unknown affinity found south of 10° N and east of 20° W is somewhat problematical but is nevertheless plotted on Figure 26.

Pollen from <u>Betula</u> shows a southern European or Moroccan provenance in aerosols (Figure 27) and amounts to over 10% of the atmospheric pollen count east of Madeira.

The same source area is suggested from the relative frequencies found in bottom sediments (Figure 28) and <u>Betula</u> can be traced as far south as the equator. The major percentages of <u>Betula</u> are found north and east of Madeira but downwind from the Canary Islands percentages do increase locally. The anomalously high percentage of <u>Betula</u> off the coast of Senegal seems inexplicable. It is quite possible that there is another plant with <u>Betula</u>like pollen which is not being recognized here (Cross, 1979, pers. commun.).

No <u>Betula</u> pollen was encountered in sediments near the coast south from Dakar, Senegal, around the whole coast of West Africa and into the Gulf of Guinea. However, there is a significant distribution of <u>Betula</u> further offshore in part of this area (see Figure 28). It is interesting to note that the eastward bulge in the <u>Betula</u> frequency north of the equator and south of 5° N (Figure 28) coincides with the location of the Equatorial Counter Current. A direct relationship between the two is hard to substantiate however, especially since the current is surficial in character.

The transport of <u>Betula</u> pollen through the atmosphere for at least 2000 km (to  $30^{\circ}$  W) from southern Europe (Figure 27) and 1000 km from the nearest island appears to be demonstrated. It is found as far west as  $40^{\circ}$  W in bottom sediments and as far south as the equator (Figure 28).

Two other taxa have Moroccan or Spanish Saharan

sources, these being <u>Olea europaea</u> (Oleaceae) and some members of the Umbelliferae (see Figures 29 and 30). <u>Olea</u> appears not to be transported as far as many other palynomorphs originating in Morocco and local sources in the Canary Islands may be responsible for its high incidence in aerosols off Morocco and Spanish Sahara. <u>Olea europaea</u> is cultivated on the Canaries and during aerosol sampling must have been in flower (flowering months being May-June). Pollen from some Umbelliferae was found in aerosols as far south as the Canaries but was not encountered in any of the bottom sediments. Surprisingly, <u>Olea</u> pollen was not encountered in any bottom sediments either. Koreneva (1971), however, has encountered <u>Olea</u> pollen in western Mediterranean bottom sediments.

<u>Olea europaea</u> has been observed to demonstrate cyclic variation in pollen production (Pinto da Silva, 1960). Evidently odd numbered years have been those of greatest abundance and so it is not surprising that 50% of the pollen in some aerosols collected during early summer 1973 was of this species.

Pollen from the Cupressaceae (Figure 31) has a southern European provenance but <u>Alnus</u> (Figure 32) appears to have a more northern European source. Characterization of relative frequencies for these two taxa in bottom sediments could not be attempted because of discontinuous occurrence.

Pollen from various grasses was found in north Atlantic

aerosols with highest incidence being due north of the Canary Islands (see Figure 33). However, no appreciable amounts of monoporate pollen were found in Northeast Atlantic bottom sediments east of the Azores or north of the Tropic of Cancer (Figure 38).

Although pollen from the Myrtaceae is found in both Mediterranean and tropical aerosols (in neither of the bottom sediments), that in the Mediterranean is characteristically larger in size. This is because of the presence of pollen from various species of Eucalyptus. Eucalyptus has been planted all over the Mediterranean and its pollen may comprise an appreciable percentage of the pollen rain throughout that area. Horowitz <u>et al.</u>, (1975), found as much as 9% in a January, 1968, storm and in May, 1973, 1% of the pollen rain at the eastern end of the Mediterranean was Eucalyptus. In Morocco, Panelatti (1960), also found Eucalyptus pollen present in the atmosphere in the Rabat area.

A North American provenance is indicated for some palynomorphs by the occurrence of <u>Ulmus</u> pollen (Figure 34) in increasing percentages towards the west; transport via the westerlies north of 30° N being the probable mechanism of dispersal towards the east. <u>Ulmus</u> does occur in southern Europe but relative frequency patterns appear to oppose such a provenance for its pollen. Distribution limits for <u>Ulmus</u> pollen in bottom sediments (Figure 35) also tends to indicate a North American source area for this

palynomorph.

Transport of North American palynomorphs some 4000 to 6000 km is possible during major eastward moving dust storms or if vertical circulation elevates palynomorphs to an eastward moving jet stream. Vertical circulation can be associated with pre-frontal turbulence and convection or post-frontal turbulence associated with a rapidly moving cold front (Healey, 1970). Deposition out of the jet stream could then be produced at a tropopause break where vertical circulation is again associated. Healey (1970) offers the jet stream mechanism for dust transport from Australia to New Zealand and Reiter (1963) has reported on the transport of dust from the Sahara to the European Alps via a jet stream mechanism.

Saharan Palynoflora: Dominating both aerosols (Figure 36) and bottom sediments (Figure 37) is the pollen of the Chenopodiaceae-Amaranthaceae. Bottom sediments off Cap Blanc in Mauritania contained Cheno-Am pollen amounting to over half the total pollen and spore count, and aerosols in the same area between middle March to early April, 1974, (Nouadhibou airport) contained an average of over 30% Cheno-Am pollen out of the total count. During the middle of May, 1973, aerosols still contained 15% Cheno-Am pollen 400 km from the coast of Africa.

The distribution pattern for the pollen of grasses and sedges in bottom sediments off the West African

continent (Figure 38) indicates a close correspondance to the vegetation from which the pollen is derived. The highest frequencies of the above pollen (up to 50%) extend from Dakar, Senegal, in the south to the Tropic of Cancer in the north along the coast of Spanish Sahara. This zone extends through the northern savanna vegetation (thorn tree-tall grass), in Senegal, the Sahel along the coast of Mauritania, and the semi-desert scrub in northern Mauritania and Spanish Sahara (see Figure 7).

The 10% relative frequency for pollen of the above taxa off the coast of Ghana and Nigeria (Figure 38) could be related to the coastal dry Ghanan vegetation zone as far as a source of the pollen is concerned, being transported in winter dust storms via the Harmattan. Also, some of the pollen from sedges and grasses growing in the Niger delta area could be transported distances of a few hundred kilometers into the Gulf of Guinea. However, a more continental source for this pollen is indicated and will be discussed later. The much larger zone of such pollen southwest of the Azores may be linked to a North American source, but before this idea can be seriously entertained study should be made of aerosols collected over the western Atlantic during a major North American dust storm.

The Compositae are second only to the Cheno-Ams as far as abundance and importance are concerned in Saharan and near Saharan aerosols (Figure 39). Along much of the Saharan coast the relative frequency of Compositae pollen

is 15%, however, above the ocean south of the Cape Verde Islands the frequency exceeds 40% (middle February to the end of April, 1973). Comparison of bottom sediments in the Cape Verde vicinity produces fair correspondance to aerosol data with a 30%-40% frequency being the average (see Figure 40). Very low percentages of Compositae pollen are encountered off the coast of Dakar, Senegal, yet frequencies start to increase at about 1000 km from the African continent. It may be possible that the Cape Verde Islands are the major source for Compositae pollen found to the southwest of these islands in the bottom sediments. However, a better explanation for this increase in Compositae pollen out to sea is the fact that there is relatively little pollen in abyssal sediments to start with and just a few grains of Compositae pollen (ubiquitous as it is) would naturally overshadow the abundance of any other palynomorphs.

Van Campo (1975), reports that the ratio of echinulate to fenestrate Compositae decreases to the south in the Sahara. In the present study a similar observation from the Canary Islands to Dakar, Senegal, was realized, however, fenestrate composite pollen was absent from the Gulf of Guinea. Pollen from the Gramineae that represents a northern or Mediterranean flora is evidently ovoid whereas that from the tropics tends to be more spherical (Van Campo, 1975). This was not generally evident in the present study although monoporate pollen from Niger was almost totally spherical.

<u>Tropical-Equatorial Palynoflora</u>: Major components of this flora included pollen of Palmae (especially <u>Elaeis</u> <u>guineensis</u>), pollen from mangroves (primarily <u>Rhizophora</u> sp.) and that from the Euphorbiaceae, Combretaceae, Sterculiaceae, Celastraceae, various members of the Leguminosae, Gramineae and Cyperaceae. Although both Cheno-Am and Compositae pollen in combination accounted for up to 20% of the pollen in aerosols, bottom sediments contained less than 5%. This seems to imply that the winter aerosols contained much extra-equatorial material derived from the interior continent during dust storms, although grass and sedge and legume pollen could have had a local source in the dry coastal zone of Ghana.

The most abundant pollen grain in Ghanan aerosols was that from <u>Hymenocardia acida</u> (Euphorbiaceae) (up to 26%). This arboreal species grows particularly in the southern Guinean or broad-leaved tree savanna zone. During early to middle March, 1973, palm pollen amounted to 10-15% of the count in aerosols in the Gulf of Guinea (Figure 41), although in bottom sediments it amounted to as much as 30% of the count (see Figure 42). Mangrove pollen between 5-15% of the total in bottom sediments (Figure 43) was not found in the aerosols. No bisaccate pollen was found in Gulf of Guinea aerosols but in bottom sediments west of Ghana up to 30% of the pollen counted was bladdered (see Figure 24). Two possible reasons for

finding bisaccates south of 10° N are: (1) the pollen had been transported by the Southwesterlies from South Africa or (2) it had been transported via the Guinea Current around the coast of Liberia and as far west as Ghana. The second mechanism of transport is probably the most likely even though neither mechanism offers a very satisfactory explanation.

The Tropical-Equatorial Palynoflora seems to be quite impoverished as far as diversity is concerned but this is very probably the result of having only a few bottom sediment samples in the Gulf of Guinea and sampling aerosols during the winter.

Freshwater Diatom Flora: The most abundant freshwater diatoms encountered in both aerosols and bottom sediments were species of the genera Melosira and Cyclotella. The most abundant diatom altogether was Melosira granulata with three other species Cyclotella ocellata, C. stelligera and Stephanodiscus astraea following in frequency of occurrence. In general M. granulata was observed to increase in frequency offshore in aerosols (Figure 44) and bottom sediments (Figure 45) but a decrease in bottom sediments offshore was noted in the Gulf of Guinea. Coastal Ghana may be an important source for the diatom M. granulata since both aerosols and bottom sediments in this vicinity contain the highest frequencies, and the dry coastal Ghanan climate facilitates the erosion of dessicated algal mats on the Coastal and Lagoonal Lowlands

(Lower Volta Plain) when the Harmattan prevails. However, a provenance in Niger is indicated as the major source for most freshwater diatoms in aerosols and will be discussed later.

Some of the freshwater diatoms that become incorporated into bottom sediments off the Ghanan coast may also have had their origin in the waters of the Volta River. Since the formation of Lake Volta however, the numbers of diatoms transported to the Gulf will probably have been reduced. The high frequency of <u>M. granulata</u> in bottom sediments off the coast of Liberia is again due to dust storm activity.

North of 20° N the numbers of freshwater diatoms in bottom sediments decrease but the high frequencies of <u>M</u>. <u>granulata</u> are due to its cosmopolitanism. It is probably the most abundant freshwater diatom in oceanic sediments anywhere in the world. No data were collected for the abundance of freshwater diatoms in aerosols north of 20° N although these entities are to a minor extent present (Stix, 1975).

Figures 46 and 47 show the relative frequencies of the freshwater diatom <u>Cyclotella</u> in both aerosols and bottom sediments. This diatom genus is relatively rare off Ghana where <u>M. granulata</u> greatly overshadows it in importance. This is probably because most of the species of <u>Cyclotella</u> become easily fragmented during atmospheric transport.

<u>Cyclotella</u> appears to increase in frequency away from the African continent especially in the Gulf of Guinea and this is probably a result of the larger diatoms dropping out of dust storms closer to the coast. A similar situation is illustrated (Figure 48) by the decrease in size of <u>M. granulata</u> seaward from the West African coast.

# DISCUSSION

#### Palynomorph Provenance

Three palynofloras were recognized in the study which represent in gross form the major climatic-vegetational zones of Northwest Africa. The northern Mediterranean palynoflora was the most complete in so far as representing the major families of plants in the Mediterranean and was the most readily recognizable both in aerosols and bottom sediments. Since both air and oceanic transport systems trend northeast to southwest the similar trend in bottom sediment palynomorph distributions proved to be fortunate. Two general source areas for the Mediterranean palynoflora were recognized i.e., (1) Morocco and (2) Southern Europe. Since both of these areas have a similar flora, local meterological conditions probably determined where in the western Mediterranean the pollen in the aerosols originated. The overall picture of source is better provided by bottom sediment distributions although both aerosol and bottom sediment distributions for many taxa are complementary.

Certain palynomorphs in the Mediterranean palynoflora appeared to have a more northern provenance e.g., <u>Alnus</u> (perhaps northern Europe) whilst others e.g., <u>Olea</u> may

have had a more restricted origin (possibly the Canary Islands). Furthermore, a North American provenance is not discounted for a variety of palynomorphs including <u>Ulmus</u>.

The Saharan palynoflora could be directly correlated with its source vegetation in Mauritania, Mali, and Senegal since the major components i.e., pollen from the Gramineae, Cyperaceae and Chenopodiaceae-Amaranthaceae, were derived from the grasslands of the savanna and sahel and the desert scrub areas directly east. Pollen from the Leguminosae was sparse to non-existent in both aerosols and bottom sediments west of the savanna vegetation zone, although in the southern part of the palynofloristic zone in the vicinity of Dakar. Senegal, minor amounts were present. In soil samples from Niger however, the Leguminosae were well represented palynologically. The reason for soil samples containing large amounts of legume pollen when aerosols contain very little is probably a function of the large size of legume pollen. It is therefore transported only short distances through the atmosphere, mostly by insects and thence by gravity to the soil. Pollen in the Caesalpinioideae and Papilionoideae for instance may reach over 70 µm (cf. <u>Baikiaea</u> robynsii, 140 µm) and that in the Mimosoideae over 100 µm in polyads.

Surface pollen spectra from desert areas south of the Tropic of Cancer tend to be dominated by pollen of the Gramineae and Cyperaceae (Van Campo, 1975). In this respect Van Campo cites Assemien (1971), as reporting

that in the Sebkha de Chinchane in Mauritania (450 km east of Cap Blanc) pollen is exclusively from the Gramineae and Cyperaceae, as it is in the Sebkha of Taoudenni in Mali (1300 km east of the Cape). In the present study then, it is somewhat surprising that aerosols did not contain appreciable quantities of grass and sedge pollen, although bottom sediment samples off the Saharan coast contained up to 50% of the pollen count in the form of Gramineae and Cyperaceae (cf. Figures 33 and 38).

The tropical-equatorial palynoflora was low in diversity even though pollen from both savanna or sahel and rain forest vegetation was present. Major reasons for this are: (1) that trees of tropical and equatorial regions are predominantly entomophilous and release little pollen into the air (Whitehead, 1969; Proctor and Yeo, 1972; and Van Campo, 1975), (2) aerosols were collected during the winter dormant season in the Gulf of Guinea, and (3) the prevailing winds are from the southwest and blow onshore except when the winter Harmattan is present. Under the influence of the Harmattan appreciable numbers of pollen grains are injected into the atmosphere (in dust storms).

It appears that pollen grains of a semi-desert scrub character (mainly grasses) may be derived from the alluvial plain of Bilma in Niger ( $18^{\circ}$  N,  $12^{\circ}$  E) and off the southern and western flank of the Tibesti massif in the vicinity of Faya Largeau in Chad ( $18^{\circ}$  N,  $19^{\circ}$  E) since this is the source area for dust in the Harmattan (Wilson, 1971, and Kalu,

1979). Surface sediments studied palynologically from Niger (southwest of Bilma) show a profile dominated by pollen from grasses and sedges (up to 60%) and so the provenance for grass pollen is probably Niger and Chad rather than coastal Ghana as was mentioned in the previous section. Nevertheless, the latter should not be overlooked as a possible source for such pollen.

As the Harmattan blows across Nigeria it incorporates pollen from savanna vegetation into its particulate load and this is probably the reason for high frequencies (26%) of the euphorb <u>Hymenocardia acida</u> in Gulf of Guinea aerosols. Sowunmi (1976), also finds up to 10% of this pollen grain in honey from the southern savanna zone (broadleaved tree savanna). Most of the pollen in the Gulf of Guinea aerosols derived from rain forest vegetation is primarily that from canopy species such as <u>Cola cordifolia</u> (Sterculiaceae) and members of the Combretaceae.

Since the Harmattan traverses many of the West African vegetation zones the palynology of dust storms necessarily reflects this, and elements from desert, savanna and tropical floras are therefore present in the tropical-equatorial palynoflora. Overlap of palynofloral elements is also found in the desert palynoflora. Here some typically Mediterranean or northern forms e.g., <u>Corylus avellana</u> are found. According to Van Campo (1975), desert palynology north of the tropics is influenced appreciably by the pollen produced in the Mediterranean basin.
The diatom flora in Gulf of Guinea aerosols indicates that its provenance is probably the same as that of the pollen. All the important species of freshwater diatoms in aerosols are found in the Ennedi highlands area of Chad (see Compère, 1970) on the western flank of the Tibesti and in Lake Chad itself, in the common corner of Chad, Niger, Nigeria and Cameroon.

#### Seasonal Provenance and Transport

Seasonal changes in both dust transport and provenance are evident and have been reported by a number of workers. The winter provenance in the vicinity of Bilma has been previously discussed (p. 128) and the summer source for dust that is transported out into the Atlantic over Mauritania and Morocco is evidently in the Tamanrasset area to the west of the Hoggar Massif in Algeria (Kalu, 1979).

Winter aerosols have plant detritus characteristic of a sahelian or savanna vegetation, and are loaded with diatoms and opal phytoliths. A change in dust provenance during summer should not necessarily change the type of palynological material within the dust since source areas have similar vegetation types. However, pollen and spores from the Mediterranean vegetation are a major component of summer aerosols. Smaller concentrations of freshwater diatoms and opal phytoliths are characteristic of summer dust.

During winter, dust is transported by the north-

easterlies to the Gulf of Guinea north of the Intertropical Discontinuity (ITD). During summer however, the ITD moves north of the Gulf and hence the major dust trajectory also moves north and west across the desert to affect Mauritania, Morocco and Spanish Sahara.

#### Temporal Considerations in Aerosol Sampling

In studying aerosols palynologically it is of the utmost importance to know the time of flowering of angiosperms near to sampling. Exemplification of this can be seen in the present study with the distribution of pollen in the atmosphere from <u>Olea europaea</u> (Figure 29) and which is not found anywhere in bottom sediments. Due to the cyclic nature of pollen production by the olive, that which was collected during middle to late June of 1973 at the end of the flowering season probably represents an appreciable percentage of the total <u>Olea</u> pollen produced in Morocco or the Canaries every two years. Therefore, one would expect <u>Olea</u> pollen to be found in bottom sediments in this general area even though it is apparently not.

One would have expected pollen from <u>Pinus</u> to have been more abundant in aerosols than was found in the study, except that these samples were collected after the major pine pollen season. Therefore, as far as relative abundance is concerned for a particular taxon, aerosols and bottom sediment distribution patterns may have little correspondance.

A particularly good example of the importance of the time of collection in the analysis of data is demonstrated in Table 5, p. 109. Aerosols were collected from early February to early May, 1966, from Woods Hole, U.S.A., to Freetown, Sierra Leone, and back. Samples collected off the east coast of North America and in the Caribbean (AF 37 and 38) in early February contrast with those collected in similar geographic positions (AF 49 and 50) in early May (see Figure 2, p. 3). No pollen and spores were found in early February compared to nearly 6 per cubic meter of air sampled in early May (Table 5), off the North American coast. Similarly, in the Caribbean, 0.3 pollen and spores per cubic meter of air (9-12 February) contrasts sharply with 3.7 grains per cubic meter of air collected between 29 April and 2 May. Seasonal influence is also apparently demonstrated with the doubling in quantity of palynomorphs in the atmosphere, when comparing aerosols AF 39 (12-14 February) and AF 48 (26-29 April).

#### Distance of Transport with Relation to Size of Palynomorph

Opalescent particulates associated with the Harmattan, in general range between 1.3 to 2  $\mu$ m in size (El-Fandy, 1953). Most of the organic particulates found in Gulf of Guinea aerosols in the present study (characterized as diatom fragments) were also ca. 2  $\mu$ m in size. If these particulates have a Bilma provenance then in transport to the Gulf of Guinea a distance of 2500 km is involved.

Freshwater diatoms 10 µm in diameter in appreciable

quantities (more than 500 per cubic meter of air) from "Atlantis II"-1966 cruise aerosols were found 3000 to 4000 km from the African continent. If their source was the Bilma alluvial plain or Chad then a total distance of transport greater than 6000 km is possible. Tertiary diatomites on the western flank of the Tibesti Massif may also have served as a source for some of these airborne diatoms.

In most instances the size of a pollen grain cannot be accurately related to distance of air transport since under one set of meteorological conditions a large grain may be transported further than a small grain under another set of conditions. The problem of aggregation may also limit the distance to which small grains may be dispersed. In the present study aggregation of small grains especially Cheno-Ams in desert aerosols and Artemisia in Mediterranean aerosols, was common (see figure 4 in Plate 8). Since most aggregation involved mineral particulates and palynomorphs, this effectively increased the specific gravity of the palynomorph and probably caused premature sedimentation. Lepple (1978, pers. commun.), indicated that the aggregation of organic particulates with more dense inorganic aerosol components might strongly affect fallout patterns at the sea/air as well as the water/ sediment interfaces. Hence in discussing palynomorph transport, the minimum distance of dispersal is probably the most reasonable estimate that one can make.

# <u>Relationship of Palynomorph Distribution Patterns to</u> Transport Mechanisms

<u>Surface Ocean Currents</u>: The salient oceanic transporting agent in the study area is the Canary Current. A clear definition of this agent is demonstrated by the northeast-southwest elongation for the distribution of <u>Quercus</u> pollen in bottom sediments (Figure 26). Although the relative frequency of bisaccate pollen in bottom sediments shows a similar distribution (Figure 24) it appears that it is more related to air transport than <u>Quercus</u> since bisaccate pollen shows its greatest frequency over 1000 km west of Morocco whereas <u>Quercus</u> only 100 km offshore.

Deep Ocean Currents: The plume of both pollen and fungal spore concentrations directly west of Gibraltar may reflect the spreading of the dense saline Mediterranean waters out into the Atlantic, especially since these palynomorphs are lower in concentration closer to the Iberian and Moroccan coasts. Fungal spores however can be better related to the abundance of dinoflagellates north of Madeira.

The distribution of <u>Quercus</u> pollen in bottom sediments (Figure 26) may also reflect the spreading of saline Mediterranean waters out into the Atlantic, even though its distribution was discussed above in relation to surface ocean currents. The influence of this Mediterranean water is evidently felt as far south as the equator and as far

west as the Azores (Kuenen, 1950).

Fluvial Transport: No clear mechanism involving the fluvial transport of palynomorphs can be demonstrated by the present study. However, certain inordinately high concentrations of pollen and spores south of 15°N (see Figure 11) off the coast of Sierra Leone may be related to fluvial transport and very high concentrations of fungal spores in the Bight of Benin off the Nigerian coast (see Figure 13) may reflect proximity to the Niger delta and transport of fungal spores from its vast hinterland out into the Gulf of Guinea. The low abundance of opal phytoliths in the Gulf of Guinea bottom sediments east of 10°W opposed to highly abundant freshwater diatoms in the same area probably indicates fluvial transport of diatoms associated with the delta swamps and the whole Niger drainage system.

Eolian Transport and Storms: The clearest evidence for palynomorph transport by the wind is demonstrated in most of the previous distribution figures concerned with aerosols (cf. Figures 10, 17, 23, 27, 29 and 34). Distribution patterns for palynomorphs in aerosols show clearly that north of 15°N summer aerosols are dependent upon the Northeast Trades for mobility and that during the winter, south of 10°N the Harmattan is the predominant transport agent for palynomorphs (mostly freshwater diatoms). The importance of the winter Harmattan system as a transport mechanism for pollen from Niger and Chad has been emphasized

previously.

That storms are significant in affecting the distribution patterns of palynomorphs in both aerosols and bottom sediments seems unquestionable. The distributions of freshwater diatoms and opal phytoliths off the coasts of Ghana and Liberia attest to this significance, especially in the atmospheric samples but also in the bottom sediments. South of 20° N or 25° N distributions of the above entities in bottom sediments can be related to major dust storm activity and to the distribution of haze frequency shown by Folger <u>et al.</u>, (1967), and Turekian (1968). Mechanisms for Incorporation of Palynomorphs into the

Atmosphere and Subsequent Transport

Kalu (1979), discusses dust propagation in light of there being three phases to the process; i.e., the instantaneous, the spreading, and the equilibrium phases. In the instantaneous phase dust particles are injected into the atmosphere due to surface wind and vertical turbulence. According to Kalu (1979), in this phase no horizontal motion is involved. After the dust reaches a particular elevation the wind velocity becomes strong enough to transport it horizontally; this is the second phase in the system of dust propagation. The final or equilibrium stage in the propagation system is supposedly controlled by the prevailing winds and evidently starts some hundreds of kilometers downwind of the previous stages (Kalu, 1979). The prevailing wind is the most important meteorological

factor controlling dust transport (Kalu, 1979) and in this respect the upper winds are those primarily responsible for its transport, with the 900 mb pressure level being on the average the height of maximum dust transport. At this level wind velocities are around 56 km/hr. Since the threshold value for raising dust off the ground is about 22 km/hr (Morales, 1979) once the dust and pollen gets up above the 900 mb zone (often 1 km above the ground) it should then travel without settling for considerable distances. The dust evidently travels with an anvil-like leading front above a lower less dusty atmosphere.

One of the most important factors controlling atmospheric dust transport and hence deposition is the moisture content of the atmosphere (Kalu, 1979). The particulates act as condensation nuclei and if the dust storm passes through a humid parcel of air, haze or fog may be produced and then precipitation of the particulate load ensues.

The importance of grassland fire as a mechanism for introducing palynomorphs into the atmosphere when compared to dust storms is minimal. Charred plant detritus in aerosols west of the Sahel and the Savanna was sparse. Since temperatures during brush fires may reach 560°C at 50 cm above the ground and 375°C at 1.5 m (Pitot and Masson, 1951) it is unlikely that much grass or sedge pollen could survive this type of treatment. Pollen within the top 1 cm of soil however, would not be appre-

ciably affected by these temperatures and along with the soil would be subjected to deflation after the fire. Temperatures at ground level during fires rarely exceeds 100°C to 140°C although aberrant temperatures of up to 350°C have been recorded by Pitot and Masson (1951). Even though fire may not be the mechanism of injection of pollen and spores into the atmosphere it may prepare the soil surface for deflation and hence injection afterwards.

Opal phytoliths should not be appreciably affected by the above temperatures and injection into the atmosphere from plant tissues is probable during major fires. This could not be substantiated however, in the present study. <u>The Use of Deep-Sea Palynology for Determining Terrestrial</u>

# Vegetation Zones in the Geologic Record

Probably the best indication of an arid or desert vegetation type is the association of pollen from the Gramineae, Cyperaceae, Chenopodiaceae-Amaranthaceae and Compositae. A totally herbaceous character could be expected up to 1000 km seaward of the desert coast. However, much caution would have to be exercised in the interpretation of such a palynoflora in the geologic record since wind directions and ocean currents may transport other types of pollen into the area. In the present study it is fortunate that the Canary Current turns westward north of the Cape Verde Islands and transports many northern pollen types away from the desert coast.

The characterization of a Mediterranean vegetation

type from bottom sediments should be much more difficult in the fossil record, especially since cool-temperate types of palynomorphs may also become incorporated into those sediments along with palynomorphs from the Mediterranean. In addition, the producing plants may grow in both vegetation zones. A further problem is that palynomorphs characteristic of a Mediterranean vegetation (such as <u>Olea</u>) may not be incorporated into the bottom sediments. Pollen from <u>Quercus</u> and <u>Pinus</u> dominating deep-sea sediments as in the present study, indicate a temperate climate and vegetation just as well as a Mediterranean type of climate and vegetation.

A tropical flora can probably not be reliably determined from bottom sediments unless indicator palynomorphs such as the Palmae or possibly mangroves are present. The tropical palynoflora in the present study contains at least 50% sahelien or savanna type palynomorphs and therefore only 50% can be considered truly tropical-equatorial in character. The added problem of low pollen production in the tropics makes it necessary to study those palynomorphs of low frequency in bottom sediments more carefully. In the geologic record a tropical palynoflora might just as easily be considered semi-arid when high percentages of pollen from dry climatic zones are present.

### CONCLUSIONS

1) Three palynofloras with specific geographic extent off Northwest Africa were detected in both aerosols and bottom sediments of the Atlantic Ocean. These three palynofloras are here identified as the Mediterranean, the Saharan and the Tropical-Equatorial.

The Mediterranean palynoflora is the most diverse (in terms of number of taxa present), the Saharan the most discrete (in terms of ease of characterization) and the Tropical-Equatorial the most complex (in terms of demonstrating the greatest amount of overlap in provenance).
The freshwater diatom flora of the sediment samples and aerosols is characterized by low diversity with three taxa dominating.

4) Vegetation in southern Europe and Morocco serves as the source for the Mediterranean palynoflora; desert playas (sebkas) in Mauritania and Mali west of the Hoggar Highlands are probably the sources for palynomorphs in the Saharan palynoflora; and in the Tropical-Equatorial palynoflora pollen and spores are derived from two sources: (i) the grasslands and desert scrub in Niger and Chad (distal source) and (ii) the tropical rain forest (canopy stratum) and Mangrove swamps along the coast of the Gulf of Guinea

(proximal source).

The distribution of palynomorphs in aerosols demon-5) strates preferred orientation to the prevailing wind direction. This same orientation is found in bottom sediments but becomes even more pronounced where ocean currents and prevailing wind directions are complementary, as with the case of the Northeast Trades and Canary Current. 6) Freshwater diatoms in bottom sediments are distributed in two major geographic zones. These coincide with the northern (summer) dust storm area north of 25°N and a southern (winter) dust storm area south of 20° N. 7) The upwelling zone off the coast of West Africa is well defined in bottom sediments by a pronounced northsouth linear of dinoflagellate concentrations. Both fungal spore and microforam abundances in general parallel the dinoflagellate trend.

8) The abundance of pollen and spores in general decreases offshore from the African continent, although an anomalous area in bottom sediments southwest of the Azores suggests a North American influence on palynomorph sedimentation in the deep-sea, at least as far east as the Mid-Atlantic Ridge. Some American palynomorphs such as <u>Ulmus</u> may even be transported as far east as the Moroccan coast by the Westerlies.

9) Normally, tropical aerosols contain few palynomorphs. Therefore, it is apparent that dust storms are the major transporting agents for pollen and spores (as well as

freshwater diatoms and opal phytoliths) from the West African interior to the Gulf of Guinea.

10) The greatest concentrations of pollen and spores in the atmosphere were found to occur in Mediterranean and Moroccan aerosols (collected during the early summer) and in general were an order of magnitude higher than those found in tropical aerosols, although the latter were collected during winter. However, in bottom sediments, those off the Saharan coast contained the greatest concentration of these entities. Fungal spores were the most abundant acid insoluble palynomorphs in both tropical aerosols and bottom sediments.

11) Appreciable quantities of pollen may be transported over the Atlantic by the Northeast Trades over 5000 km downwind from its source in the Mediterranean. Even greater distances of transport are attained by freshwater diatoms and opal phytoliths from interior West Africa (Chad and Niger) when an overland transport of 2500 km is included in the figure. Some of these entities are transported a further 3500 km from the coast of West Africa, although the majority are deposited within 500 km from the shore. 12) Taxa of pollen very abundant in aerosols are often apparently absent from bottom sediments.

13) To continue the study of a palynological problem as large in scope as that at present, it would be necessary to integrate some data from water column samples at various depths in the ocean wherever and whenever possible. Also,

continuous and simultaneous ocean aerosol sampling over the study area should be undertaken in order to be better able to relate palynological information quantitatively from one geographic area to another. BIBLIOGRAPHY

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# APPENDIX

Location of Palynomorphs Photographed (Plates 1-22) in Department of Geology Slide Collection, Michigan State University

# PLATE 1

Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 12 3 4 5 6 7 8 90 11 12 3 4 5 6 7 8 90 11 12 3 4 5 6 7 8 90 11 12 13 14 5 14 5 16 7 8 90 11 12 11 11	MS1983-1 MS2028-3 MS2028-3 MS2028-3 MS2101-3 MS2166-1 MS2037-1 MS2027-1 MS2025-3 MS1979-2 MS2025-3 MS1973-3 MS2025-3 MS2025-3 MS2167-2 MS2167-2 MS1974-3	$39.7 \times 115.3$ $41.7 \times 112.6$ $38.0 \times 115.4$ $41.7 \times 119.5$ $36.0 \times 121.8$ $27.8 \times 119.1$ $31.5 \times 120.0$ $33.8 \times 120.0$ $36.4 \times 119.3$ $40.6 \times 119.3$ $40.6 \times 119.3$ $34.0 \times 121.7$ $39.7 \times 116.9$ $38.5 \times 111.2$ $25.8 \times 122.0$ $40.5 \times 112.5$ $33.7 \times 117.5$ $28.7 \times 127.2$
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4	MS1983-1 MS1975-1 MS2167-2 MS2024-2 PLATE 3	29.7 x 113.5 29.1 x 124.3 37.5 x 115.6 32.7 x 114.6
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10	MS2028-3 MS2027-1 MS2028-3 MS2028-3 MS2028-2 MS2028-3 MS2107-1 MS2026-2 MS2022-3 MS2018-3	37.6 x 118.8 33.0 x 122.7 35.0 x 117.6 43.5 x 111.6 34.1 x 118.1 40.5 x 114.8 30.1 x 127.0 40.6 x 116.1 35.1 x 113.0 38.5 x 118.1

	PLATE 3	
Figure	M.S.U. Slide No.	Coordinates
11 12 13 14	MS2020-1 MS2167-1 MS2036-6 MS2205-1	34.0 x 124.3 31.8 x 117.3 28.0 x 122.0 29.7 x 119.0
	PLATE 4	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 0 11 2 3 4 5 6 7 8 9 0 11 2 3 4 5 6 7 8 9 0 11 2 3 4 5 6 7 8 9 0	MS2026-2 MS2036-5 MS2020-2 MS2026-2 MS2026-2 MS2024-1 MS1968-1 MS1968-1 MS2027-1 MS2027-1 MS2027-2 MS2024-3 MS2024-3 MS2024-3 MS2098-2 MS1970-2	$39.5 \times 115.9$ $35.9 \times 125.1$ $37.9 \times 125.1$ $33.8 \times 118.8$ $40.3 \times 119.1$ $31.5 \times 122.8$ $38.8 \times 120.4$ $31.6 \times 120.0$ $36.4 \times 115.5$ $30.7 \times 110.8$ $32.0 \times 117.4$ $37.7 \times 119.5$ $25.0 \times 115.0$ $39.5 \times 109.6$ $28.9 \times 119.0$
	PLATE 5	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10 11	MS2020-1 MS2027-2 MS2027-3 MS2028-2 MS1989-2 MS2024-1 MS2028-3 MS2027-2 MS2024-1 MS2024-1 MS2025-1	37.9 x 122.9 33.8 x 115.0 38.7 x 115.0 32.2 x 117.0 38.6 x 118.9 35.3 x 113.8 38.0 x 114.7 40.9 x 113.0 34.3 x 117.4 30.7 x 122.1 37.9 x 119.7
	PLATE 6	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4	MS2028-3 MS2166-1 MS1977-2 MS2028-1	42.7 x 115.5 37.0 x 116.8 32.8 x 119.6 37.3 x 125.3
	PLATE 6	
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Figure	M.S.U. Slide No.	Coordinates
5 6 7 8 9 10 11 12 13	MS2207-1 MS2167-2 MS2020-1 MS1975-3 MS2036-3 MS2028-3 MS1975-1 MS2028-3 MS1989-1	37.8 x 119.8 34.8 x 119.2 35.0 x 121.6 35.5 x 121.1 40.1 x 116.2 39.1 x 117.0 27.7 x 120.4 30.8 x 113.5 35.3 x 115.7
	PLATE 7	<b>a</b>
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10 11 12 13	MS2018-3 MS2026-1 MS2102-2 MS2025-1 MS2026-2 MS2020-1 MS1977-1 MS2028-3 MS2020-2 MS2192-1 MS1966-1 MS2101-2	$33.1 \times 117.8$ $34.3 \times 123.8$ $36.1 \times 121.0$ $35.8 \times 124.8$ $32.4 \times 122.9$ $44.6 \times 121.8$ $31.5 \times 123.5$ $30.3 \times 116.5$ $32.2 \times 117.1$ $38.8 \times 120.5$ $37.4 \times 117.3$ $32.6 \times 120.8$ $34.0 \times 120.7$
	PLATE 8	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16	MS2036-2 MS2166-1 MS2166-1 MS2025-2 MS2025-1 MS2025-1 MS2036-3 MS2184-2 MS2037-3 MS2037-3 MS2037-3 MS2036-5 MS2166-1 MS2166-2	$30.8 \times 121.6$ $35.9 \times 112.3$ $34.5 \times 121.0$ $35.8 \times 119.3$ $31.0 \times 120.0$ $31.6 \times 123.1$ $29.4 \times 123.4$ $33.2 \times 112.2$ $40.1 \times 116.7$ $42.2 \times 119.2$ $35.7 \times 124.7$ $31.7 \times 122.6$ $26.9 \times 115.5$ $37.0 \times 117.6$ $39.6 \times 121.6$ $34.5 \times 118.2$

Figure	M.S.U. Slide	No.	Coordinates
1 2 3 4 5 6 7 8 90 11 12 13 14	MS2027-1 MS2036-4 MS2026-1 MS2026-1 MS2026-1 MS2026-2 MS2026-2 MS2026-2 MS2026-2 MS2026-2 MS2026-2 MS2036-5 MS2036-4 MS2028-3	10	38.4 x 112.4 36.7 x 118.7 39.8 x 112.8 30.6 x 123.4 35.0 x 122.7 42.2 x 120.2 44.5 x 124.2 37.0 x 121.1 33.7 x 113.4 38.9 x 115.3 37.5 x 116.6 36.2 x 120.2 34.5 x 116.4 41.3 x 114.3
	PLATE	IU No	
Figure	M.S.U. Slide	NO •	Coordinates
1 2 3 4 5 6 7 8 90 11 12 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90 11 2 3 4 5 6 7 8 90	MS2027-2 MS2025-2 MS2036-6 MS2036-5 MS2037-1 MS2166-1 MS2166-2 MS2028-2 MS2027-2 MS2027-2 MS2027-1 MS2036-6 MS2025-2 MS2028-3 MS2167-2 MS2028-2 PLATE	11	32.7 x 119.0 35.5 x 119.2 30.7 x 115.8 39.7 x 124.7 40.0 x 119.6 30.9 x 114.0 27.0 x 121.1 37.2 x 114.0 37.2 x 115.4 34.3 x 113.0 33.5 x 118.0 30.2 x 115.0 37.5 x 114.5 41.6 x 113.6 43.2 x 117.4 33.4 x 117.8
Figure	M.S.U. Slide	No.	Coordinates
1 2 3 4 5 6 7 8 9	MS2042-1 MS2038-4 MS1968-3 MS2039-1 MS2039-2 MS2039-1 MS2039-1 MS2178-1 MS2178-1		34.6 x 118.6 37.4 x 121.0 27.7 x 115.6 35.3 x 120.0 37.1 x 121.9 34.2 x 121.4 33.6 x 118.2 30.3 x 117.3 32.5 x 115.4

	PLATE 11	
Figure	M.S.U. Slide No.	Coordinates
10 11 12 13 14	MS2178-1 MS2040-3 MS2207-2 MS2208-2 MS2208-1	30.7 x 114.2 32.4 x 117.4 44.8 x 125.0 37.6 x 111.1 35.0 x 113.0
	PLATE 12	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 90 10 11 12 13 14 5 16 17	MS2031-2 MS2178-2 MS2178-1 MS2172-2 MS2098-2 MS2174-1 MS2207-1 MS2178-2 MS2178-2 MS2178-2 MS2032-4 MS2032-4 MS2032-4 MS2032-1 MS2039-1 MS2032-3 MS2032-3 MS2172-1	29.3 x 117.6 41.7 x 113.0 37.7 x 117.7 40.6 x 120.7 43.9 x 117.4 28.1 x 112.7 37.8 x 119.8 33.0 x 121.8 28.7 x 115.6 31.4 x 117.6 42.3 x 114.3 36.6 x 120.2 31.2 x 118.2 40.6 x 117.6 37.2 x 116.2 38.8 x 113.6 38.7 x 110.7
	PLATE 13	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18	MS2097-1 MS2178-1 MS2098-3 MS2032-2 MS2042-3 MS2016-1 MS1967-1 MS1967-3 MS1988-1 MS1979-2 MS2178-2 MS2178-2 MS2178-1 MS1988-2 MS2040-2 MS2040-1 MS2100-1	$40.5 \times 126.8$ $37.7 \times 123.4$ $26.3 \times 113.0$ $34.3 \times 114.7$ $35.6 \times 114.3$ $40.4 \times 120.4$ $35.5 \times 119.2$ $39.4 \times 119.2$ $37.1 \times 118.5$ $40.6 \times 110.6$ $39.2 \times 116.2$ $37.5 \times 123.0$ $34.4 \times 116.0$ $43.3 \times 110.4$ $27.0 \times 116.4$ $30.3 \times 118.3$ $30.3 \times 118.2$ $35.5 \times 117.3$

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Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9	MS2174-2 MS2099-2 MS2039-1 MS2031-2 MS2177-2 MS2174-1 MS2168-1 MS2176-1 MS2172-1	34.0 x 117.7 35.7 x 116.3 38.6 x 119.7 33.7 x 117.1 34.0 x 119.2 25.0 x 122.1 32.9 x 119.4 32.3 x 115.4 37.3 x 112.7
	PLATE 15	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8	MS2039-2 MS2039-2 MS2039-2 MS2039-1 MS2039-1 MS1979-2 MS2175-1 MS2178-1 PLATE 16	39.7 x 113.0 39.7 x 116.8 36.7 x 115.3 37.0 x 118.3 35.5 x 123.8 34.2 x 119.8 34.2 x 116.1 39.5 x 123.3
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8	MS2099-1 MS2199-2 MS2013-3 MS2001L-3 MS2001L-3 MS1970-2 MS2002L-2 MS2008L-3 PLATE 17	38.8 x 114.3 25.6 x 113.4 41.0 x 122.9 38.9 x 119.5 31.7 x 121.5 38.1 x 121.6 35.1 x 115.1 34.8 x 116.6
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9	MS2043-3 MS2043-3 MS2043-4 MS2043-4 MS2005L-1 MS2099-1 MS2043-4 MS2043-3 MS2043-3	29.5 x 114.1 27.0 x 112.8 33.3 x 117.3 34.6 x 121.5 26.4 x 114.3 25.3 x 110.9 38.7 x 118.2 31.6 x 117.1 30.1 x 117.1

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Figure	M.S.U. Slide No.	Coordinates
10 11 12 13 14 15	MS1975-1 MS2099-1 MS2043-2 MS2043-2 MS2001L-1 MS2008L-2	23.8 x 122.0 36.4 x 111.2 33.5 x 121.8 36.9 x 117.0 32.1 x 118.8 37.3 x 119.0
	PLATE 18	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 90 11 12 3 4 5 11 12 3 4 5 6 7 8 90 11 12 3 4 5 6 7 8 90	MS2043-4 MS1974-3 MS2008L-3 MS2043-4 MS2043-4 MS2043-4 MS2043-4 MS2099-1 MS2043-4 MS2010L-1 MS2010L-1 MS2008L-3 MS1986-2 MS2043-4 MS2005L-2	$33.2 \times 119.4$ $30.2 \times 114.8$ $38.3 \times 116.2$ $44.0 \times 113.4$ $37.7 \times 121.7$ $35.2 \times 123.0$ $42.1 \times 116.4$ $31.2 \times 117.7$ $32.1 \times 119.7$ $38.5 \times 121.8$ $36.0 \times 117.3$ $33.0 \times 117.0$ $34.9 \times 110.5$ $36.8 \times 122.3$ $27.6 \times 118.5$
Figure	PLATE 19 M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18	MS2001L-3 MS2043-4 MS2043-3 MS2043-3 MS2199-2 MS2201-2 MS2098-1 MS2098-1 MS2099-1 MS2099-1 MS2043-4 MS2043-4 MS2043-4 MS2043-4 MS2043-4 MS2008L-1 MS1974-3 MS1974-3 MS1974-3 MS1974-3 MS1974-3	$42.4 \times 115.6$ $35.3 \times 123.1$ $29.3 \times 116.7$ $30.0 \times 110.9$ $35.0 \times 118.2$ $22.2 \times 118.3$ $33.2 \times 112.4$ $25.0 \times 119.3$ $39.0 \times 119.1$ $46.6 \times 125.8$ $35.1 \times 121.1$ $38.5 \times 122.2$ $38.0 \times 115.2$ $33.6 \times 118.5$ $34.5 \times 121.3$ $32.3 \times 114.3$ $26.8 \times 113.2$

Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 90 10 11 12 13 14	MS2005L-3 MS2043-4 MS2002L-2 MS2006L-2 MS2006L-1 MS2006L-1 MS2001L-3 MS2010L-2 MS1974-3 MS1974-3 MS1958-3 MS2004L-3 MS2004L-1 MS2043-4 MS2043-4	$31.0 \times 122.5$ $37.2 \times 119.7$ $40.9 \times 122.8$ $36.8 \times 118.4$ $34.5 \times 126.9$ $27.2 \times 124.2$ $37.4 \times 121.4$ $36.5 \times 125.8$ $35.5 \times 117.5$ $30.0 \times 113.2$ $31.5 \times 120.1$ $37.8 \times 117.5$ $36.2 \times 118.0$ $37.4 \times 121.8$
	PLATE 21	
Figure	M.S.U. Slide No.	Coordinates
1 2 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 3 4 5 6 7 8 9 0 11 12 2 3 4 5 6 7 8 9 0 11 12 2 3 4 5 1 12 2 3 4 5 1 2 2 3 4 5 1 2 2 3 4 5 2 3 4 5 2 3 4 5 1 2 2 3 4 5 2 3 4 5 2 3 4 5 2 3 4 5 2 3 4 5 2 3 4 5 11 12 2 3 4 5 2 2 3 4 5 2 2 3 4 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2 2 3 2	MS2002H-2 MS2047-1 MS2047-1 MS2047-1 MS2002H-2 MS2002H-2 MS2003H-1 MS2003H-1 MS2003H-1 MS2002H-2 MS2047-1 MS2047-1 MS2047-1 MS2047-1 MS2047-1 MS2047-1 MS2007H-1 MS2007H-1 MS2007H-1 MS2007L-1	$39.7 \times 106.7$ $38.0 \times 105.2$ $39.9 \times 103.2$ $39.9 \times 103.8$ $40.3 \times 106.3$ $40.3 \times 107.1$ $34.7 \times 98.6$ $50.8 \times 106.4$ $35.8 \times 96.6$ $34.5 \times 104.6$ $40.5 \times 103.2$ $38.1 \times 103.0$ $38.5 \times 104.9$ $38.1 \times 102.9$ $41.1 \times 97.0$ $40.2 \times 106.1$ $39.0 \times 96.9$ $38.1 \times 102.3$ $37.7 \times 105.7$ $38.9 \times 98.0$ $40.0 \times 101.4$ $39.9 \times 98.0$ $41.5 \times 96.2$ $48.4 \times 97.8$ $48.3 \times 102.5$

Figure	M.S.U. Slide No.	Coordinates
1	MS2047-1	38.0 x 105.0
2	MS2047-2	41.2 x 97.0
3	MS2005H-1	45.5 x 100.0
4	MS2005H-1	35.8 x 102.0
5	MS2098-1	34.7 x 119.8
6	MS2048-1	34.4 x 99.1
7	MS2075	39.6 x 99.8
8	MS2092	40.2 x 98.2
9	MS2005H-1	35.9 x 102.0
10	MS2000H-1	40.1 x 98.0
11	MS2000H-1	46.5 x 98.2
12	MS2075	43.8 x 99.7
13	MS2048-1	35.4 x 101.1
14	MS2000H-1	40.0 x 98.1
15	MS2009H-1	42.2 x 99.3
16	MS2099-2	44.1 x 100.8
17	MS2054-2	42.2 x 100.4
18	MS2145-1	47.4 x 101.1

#### EXPLANATION OF PLATES

	Plate
Mediterranean Palynoflora	1-10
Saharan Palynoflora	11-15
Tropical-Equatorial Palynoflora	16 <b>-</b> 20
Freshwater Diatoms	21
Opal Phytoliths	22

#### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

- 1 Monolete spore (unknown)
- 2, 3 Trilete spores (Pteridophyta)
- 4, 9, 10 Juniperus communis (Cupressaceae)
- 5-8 Juniperus sp. cf. J. occidentalis (Cupressaceae)
- 11-15 Cupressaceae
  - 16 <u>Abies</u> sp.; X500 (Pinaceae)
  - 17 <u>Picea</u> sp. (Pinaceae)

PLATE 1



### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

- 1 <u>Pinus</u> sp. cf. <u>P. nigra</u> (Pinaceae)
- 2-3 <u>Pinus canariensis</u> (Pinaceae)
- 4 <u>Pinus</u> sp. (Pinaceae)

PLATE 2



#### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

- 1-2 <u>Tricholaena teneriffae</u> (Gramineae)
- <u>3</u> <u>Tricholaena teneriffae</u> ? (Gramineae)
- 4 <u>Phleum pratense</u> ? (Gramineae)
- 5, 11 <u>Avena</u> sp. ? (Gramineae)
  - 6 <u>Zea mays;</u> X500 (Gramineae)
- 7, 9, 10 Gramineae
  - 8 <u>Dactylis</u> sp. (Gramineae)
- 12-13 Cyperaceae
  - 14 <u>Typha</u> sp. (Typhaceae)



### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

1-2	<u>Alnus</u> sp. (Corylaceae)
3 <del>-</del> 5	<u>Alnus</u> sp. cf. <u>A</u> . <u>glutinosa</u> (Corylaceae)
7	<u>Betula</u> sp. cf. <u>B</u> . <u>verrucosa</u> (Betulaceae)
6 <b>,</b> 8 <b>-</b> 11	<u>Betula</u> sp. (Betulaceae)
12	<u>Corylus</u> sp. cf. <u>C</u> . <u>avellana</u> (Corylaceae)
13-14	Triporates
15	<u>Carya</u> sp. (Juglandaceae)



# Mediterranean Palynoflora

# (All figures X1000 unless otherwise stated)

#### <u>Figure</u>

1, 2, 7	<u>Ulmus</u> <u>rubra</u> (Ulmaceae)
3	<u>Ulmus</u> glabra (Ulmaceae)
4 <b>-</b> 6	<u>Ulmus</u> sp. (Ulmaceae)
8	Tetraporate (unknown)
9-11	Tetraporate ( <u>Planera</u> -like)

PLATE 5



#### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

1	<u>Chenopodium</u> sp. (Chenopodiaceae)
2	<u>Salsola</u> sp. (Chenopodiaceae)
3	Atriplex sp. (Chenopodiaceae)
4	<u>Suaeda</u> sp. cf. <u>S</u> . <u>monoïca</u> (Chenopodiaceae)
5	<u>Amaranthus</u> sp. or <u>Bosia</u> sp. (Amaranthaceae)
6	<u>Gymnocarpos</u> <u>decander</u> (Caryophyllaceae)
7-8	<u>Juglans</u> sp. (Juglandaceae)
9-11	<u>Plantago</u> <u>lanceolata</u> (Plantaginaceae)
12 <b>-</b> 13	<u>Plantago</u> <u>major</u> (Plantaginaceae)

PLATE 6



# Mediterranean Palynoflora

### (All figures X1000 unless otherwise stated)

1-4	Quercus	<u>coccifera</u>	(Fagaceae)

- 5 <u>Quercus</u> <u>ilex</u> (Fagaceae)
- 6-10 <u>Quercus</u> <u>suber</u> (Fagaceae)
- 11-13 <u>Quercus</u> sp. (Fagaceae)

PLATE 7



#### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

- 1-4 <u>Artemesia</u> sp. cf. <u>A. canariensis</u> (Compositae)
- 5-6 <u>Ambrosia artemisiifolia</u> (Compositae)
- 7 Compositae-Tubuliflorae cf. <u>Senecio</u> sp.
- 8 <u>Prenanthes</u> sp. cf. <u>P. pendula</u> (Compositae)
- 9-10 Compositae-Liguliflorae
- 11 <u>Vernonia</u> sp. (Compositae)
- 12-16 Cruciferae
  - 12 <u>Lepidium</u> draba?
  - 14 <u>Cardaria</u> sp. ?



# Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

### Figure

1-6	<u>Olea europaea</u> (Oleaceae)
7	<u>Caucalis</u> sp. (Umbelliferae)
8-9	<u>Daucus</u> <u>aureus</u> (Umbelliferae)
10	<u>Daucus</u> <u>carota</u> (Umbelliferae)
11	<u>Magydaris</u> <u>panacifolia</u> (Umbelliferae)
12	<u>Oenanthe</u> <u>crocata</u> (Umbelliferae)

13-14 Umbelliferae

PLATE 9



#### Mediterranean Palynoflora

(All figures X1000 unless otherwise stated)

- 1-4 <u>Eucalyptus</u> sp. (Myrtaceae)
- 5 <u>Myrtus communis</u> (Myrtaceae)
- 6 <u>Thymus</u> sp. (Labiatae)
- 7-8 <u>Erica arborea</u> (Ericaceae)
- 9-10 <u>Tamarix</u> sp. (Tamaricaceae)
- 11-12 Unknown tricol(por)ates
- 13-14 Ranunculaceae cf. <u>Clematis</u> vitalba
- 15-16 Unknown





#### Saharan Palynoflora

# (All figures X1000 unless otherwise stated)

1	Lycopodium sp. (Lycopodiaceae)
2	Unknown spore
3	Gramineae
4	<u>Vossia cuspidata</u> (Gramineae)
5	Cereal (Gramineae)
6 <b>-</b> 7	<u>Sorghum</u> sp. cf. <u>S</u> . <u>arundinaceum</u> (Gramineae)
8-9	Gramineae
10	Aristida pungens (Gramineae)
11	<u>Triticale</u> sp <b>. ? (</b> Gramineae)
12	<u>Phragmites</u> sp. (Gramineae)
13	<u>Cyperus</u> <u>conglomeratus</u> (Cyperaceae)
14	<u>Cyperus</u> <u>laevigatus</u> (Cyperaceae)





#### Saharan Palynoflora

(All figures X1000 unless otherwise stated)

#### <u>Figure</u>

1	<u>Typha</u> sp. (Typhaceae)
2	Corylaceae
3	<u>Corylus</u> <u>avellana</u> (Corylaceae)
4	Corylaceae
5	<u>Urtica</u> sp. (Urticaceae)
6	<u>Amaranthus viridis</u> (Amaranthaceae)
7	<u>Amaranthus</u> sp. ? (Amaranthaceae)
8	<u>Celosia</u> sp. (Amaranthaceae)
9 <b>-</b> 10	<u>Salsola foetida</u> (Chenopodiaceae)
11	<u>Suaeda monoïca</u> (Chenopodiaceae)
12	<u>Atriplex</u> sp. ? (Chenopodiaceae)
13-16	Cheno-Am

17 <u>Tribulus</u> sp. cf. <u>T. terrestris</u> (Zygophyllaceae)



### Saharan Palynoflora

(All figures X1000 unless otherwise stated)

1	<u>Heliotropium bacciferum</u> (Boraginaceae)
2	<u>Commiphora</u> <u>africana</u> (Burseraceae)
3-6	<u>Capparis</u> sp. (Capparaceae)
7	<u>Gymnosporia senegalensis</u> (Celastraceae)
8-10	Compositae-Tubuliflorae
11	<u>Ambrosia</u> sp. (Compositae)
12-14	Compositae-Liguliflorae
1 <b>5-</b> 18	Leguminosae-(Caesalpinioideae)



#### Saharan Palynoflora

# (All figures X1000 unless otherwise stated)

### Figure

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1-2	<u>Cassia</u> sp. (Caesalpinioideae)
3	<u>Prosopis</u> sp. (Mimosoideae)
4	<u>Indigofera</u> sp. (Papilionoideae)
5	Papilionoideae ?
6	<u>Astragalus vogelii</u> (Leguminosae)
7-9	Leguminosae ?
PLATE 14



# Saharan Palynoflora

# (All figures X1000 unless otherwise stated)

### Figure

- 1-2 <u>Prosopis</u> sp. ? (Leguminosae)
- 3-4 Rosaceae ?
- 5-8 Unknown

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# Tropical-Equatorial Palynoflora

(All figures X1000 unless otherwise stated)

1	Unknown trilete spore		
2	Trilete spore cf. <u>Pteris</u> sp. (Pteridaceae)		
3	Unknown trilete spore		
4 <del>-</del> 5	Cupressaceae		
6,8	Unknown bisaccates; X500		
7	Unknown bisaccate		

PLATE 16



Tropical-Equatorial Palynoflora

(All figures X1000 unless otherwise stated)

- 1-9 <u>Elaeis guineensis</u> (Palmae)
- 10-11 Unknown monosulcate (Liliaceae ?)
- 12-13 <u>Cyperus conglomeratus</u> (Cyperaceae)
- 14-15 <u>Cyperus</u> sp. (Cyperaceae)



Tropical-Equatorial Palynoflora

(All figures X1000 unless otherwise stated)

Figure

1 <u>Panicum</u> sp.	cf. <u>F</u>	. turgidum	(Gramineae)
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2 Gramineae

3 <u>Hymenocardia</u> sp. (Euphorbiaceae)

4-7 <u>Hymenocardia</u> <u>acida</u> (Euphorbiaceae)

8-9 Unknown triporates

- 10 Amaranthaceae
- 11 Unknown polyporate
- 12 Cheno-Am
- 13-15 Unknown striates (probably Leguminosae)



15ь

Tropical-Equatorial Palynoflora

(All figures X1000 unless otherwise stated)

1	<u>Combretum</u> grandiflorum (Combretaceae)
2	<u>Mallotus</u> <u>subulatus</u> (Euphorbiaceae)
3	<u>Spondianthus</u> sp. ? (Euphorbiaceae)
4	<u>Rhizophora harrisonii</u> (Rhizophoraceae)
5	<u>Rhizophora mangle</u> (Rhizophoraceae)
6-9	<u>Cola cordifolia</u> (Sterculiaceae)
10-11	Unknown tricolpates
12-13	Unknown tricolporates
14-18	Quercoid grains (unknown affinity)



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### Tropical-Equatorial Palynoflora

### (All figures X1000 unless otherwise stated)

#### Figure

1-2 <u>Gymnosporia</u> <u>crenulata</u> (Celastraceae)

- 4-5 <u>Salix ledermannii</u> (Salicaceae)
- 6-10 Unknown reticulate tricol(por)ates
- 11-12 <u>Terminalia</u> sp. cf. <u>T. macroptera</u> (Combretaceae)
- 13-14 <u>Syzygium guineense</u> (Myrtaceae)

PLATE 20



#### Freshwater Diatoms

#### (All figures X1000 unless otherwise stated)

- 1-10 <u>Melosira granulata</u>
- 11-12 <u>Stephanodiscus</u> astraea; 12, X500
- 13-14 Cyclotella sp. cf. <u>C. stelligera</u>; 13, X500
- 15-18 <u>Cyclotella ocellata</u>
  - 19 <u>Cosinodiscus</u> sp.
  - 20 <u>Diploneis</u> <u>subovalis</u>
  - 21 <u>Eunotia</u> sp.
- 22-23 <u>Navicula</u> sp.
- 24-25 <u>Pinnularia</u> sp.



# Opal Phytoliths

# (All figures X1000 unless otherwise stated)

# <u>Figure</u>

- 1-9 Dumbbell types
- 10-11 Barrel morphologic types
- 12-18 Rods of various sizes



