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Multivariate Statistical Analyses of Palynodebris from the Middle Miocene of the Niger Delta and Their Environmental Significance

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Fourteen types of palynodebris have been identified in Middle Miocene reservoir sediments from the Niger Delta. They include palynomorphs, cuticle, parenchyma, resins, black debris, woody fragments and degraded components. The palynodebris types were interpreted by Principal Components Analysis and Average Linkage Cluster Analysis. Four assemblages of samples emerged and they have been grouped into two palynofacies associations, A/C and B/D, because of their correlation with mudstone and muddy heterolithic lithofacies and sandstone lithofacies, respectively. The significant palynodebris components are black debris, parenchyma, resins and amorphous organic matter. The size, shape and texture of all the components were integrated with sedimentological features, palynomorph and foraminiferal assemblages to recognize seven, possibly eight, deltaic sub-environments of deposition in the reservoir. Mudstones and muddy heteroliths from low energy depositional environments are characterized by small-sized, lath-shaped woody debris, and high concentration of buoyant components such as palynomorphs, cuticles and degraded bundles. The sandstones contain larger and more equidimensional woody fragments. These sediments are also richer in black debris which are believed to be a function of exposure to oxidizing conditions for a longer period of time. Parenchyma and resins, though rare, are characteristic of distributary channel-fill sandstones.

INTRODUCTION

Since the discovery of hydrocarbons in the Niger Delta by the Shell Petroleum Development Company of Nigeria in 1956, large scale commercial exploration and exploitation have been going on in the West African basin. The major research focus in the region has been in the subject areas of geophysics, structural geology, organic geochemistry, sedimentology and stratigraphy (e.g., Allen, 1965, 1970; Stoneley, 1966; Short and Stäuble, 1967; Weber, 1971; Weber and Daukoru, 1975; Evamy et al., 1978; Ejedawe, 1981; Lambert-Aikhionbare, 1982; Bustin, 1988; Doust and Omatsola, 1990). Most of these studies have concentrated on the paralic sediments of the Agbada Formation which constitute hydrocarbon reservoirs, and it is one of the delta's three diachronous formations. Very few studies have been published on palynodebris or sedimentary organic matter in the delta. Nwachukwu and Chukwura (1986) and other authors grouped palynodebris into kerogen types I, II and III in relation to their source potential for oil and gas. So far only Bustin (1988) has attempted to relate palynodebris, in addition to hydrogen index and total organic carbon, to depositional environments.

The concept of palynofacies, which refers to suites of palynodebris, was introduced by Combaz (1964). It was applied by Batten (1973, 1980–1982) towards understanding the general origin of sediments and the association of palynodebris with hydrocarbon. Several workers, e.g., Fisher (1980), van der Zwan (1990) and Davies et al. (1991), have demonstrated its usefulness as a toll for environmental interpretation. These studies have resulted in a wide range of terminologies for classifying palynodebris, some of which can be found in Bujak et al. (1977), Habib (1979, 1982), Venkatachala (1981), Masran and Pocock (1981), Parry et al. (1981), Whitaker (1984), Boulter and Riddick (1986) and Lorente (1990).

The work presented here is on the palynodebris as seen by transmitted light microscope from 44 samples from the E2.0 Reservoir in the Kolo Creek field (Fig. 1). The 50-m long cores, from a depth interval of 3590–3655 m in Wells 27 and 29 (see Figs. 6 and 7 for stratigraphic columns), were provided by the Shell Petroleum Development Company of Nigeria and the Koninklijke/Shell Exploration and Production Laboratory in The Netherlands. The termi-

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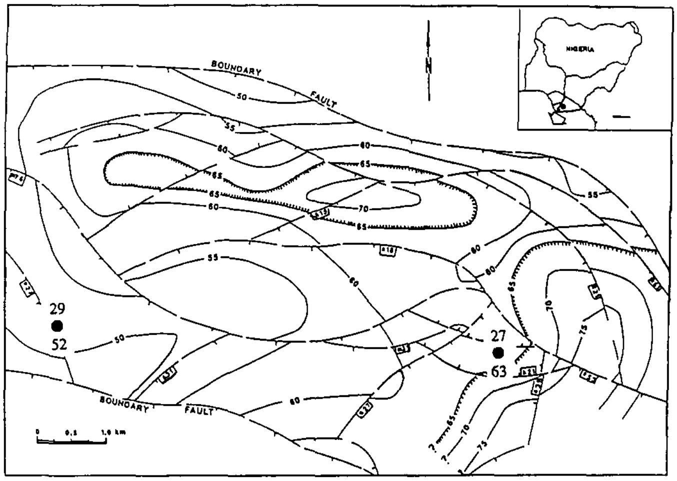


FIGURE 1—Isochore map of the E2.0 Reservoir showing the location of Wells 27 and 29 in the Kolo Creek field; contours in meters. Inset shows the location of the field in the Niger Delta, southern Nigeria; Scale Bar = 200 km.

nology of Boulter and Riddick (1986) has been adapted in recognizing an assemblage of 14 types of palynodebris. These are mainly terriginous. They were subjected to Principal Components Analysis and Average Linkage Cluster Analysis, and the four emergent palynofacies showed a good correlation with the lithofacies identified from gain size, textures, sedimentary structures and trace fossils (Table 1). Consequently, they have been grouped into two broad palynofacies associations A/C and B/D. Association A/C is dominated by mudstones and muddy heteroliths while B/D is essentially composed of sandstones. By integrating these palynofacies associations with gamma ray and resistivity logs, mineralogical composition, diagenetic imprints, palynomorph and foraminifera assemblages, seven, possibly eight, deltaic sub-environments were recognized in the reservoir (Oboh, 1990, 1991, 1992a). The reservoir has also been dated, using the palynomorph assemblage and foraminiferal data, as the earliest part of the Middle Miocene (Oboh, 1990).

TABLE 1—Summarized lithofacies and characteristics in the reservoir.

Facies	Characteristics	Color	Thickness (m)
S1	Pebbly sandstone; pebbles sideritic	Brownish	0.3
S2	Medium to coarse-grained sandstone with gray cm-scale cross-bedding; erosive bases ± root tubes and carbonaceous streaks	Brown-gray	0.2–6.0
S3	Fine sandstone; mm-scale horizontal, planar and ripple laminations; abundant burrows, few rootlets	Light gray	0.2–3.5
S4	Fine sandstone with clay drapes, flaser-bedding ± horizontal stratification; common burrows; few rootlets	Light gray	0.2–2.5
S5	Fine sandstone, heavily bioturbated	Gray	0.5–1.0
SM1	Wavy-bedded sandy heterolith; few to common burrows	Gray	0.3–1.0
SM2	Lenticular-bedded muddy heterolith; occasional burrows ± fluidization and load structures	Gray	0.1–2.0
SM3	Bioturbated heterolith; few sideritic nodules ± fluidization structures	Gray	0.2–1.3
M1	Mudstone with sideritic nodules/bands ± silty bands	Dark gray to brown	0.2–2.5
M2	Mudstone, homogeneous ± silty bands	Dark gray	0.2–0.5

METHODS

The samples used for analysis represent the ten lithofacies present in the reservoir (Table 1), varying from fine-grained homogeneous mudstones to coarse-grained sandstones. Since sedimentary organic matter is more abundant in mudstones, more samples from such lithologies were used. Maceration residues were obtained by digesting the sediments in 50% hydrochloric acid for 24 hours, followed by one to two weeks in cold 60% hydrofluoric acid. Excess fluorosilicates and fluorides which might have formed during the hydrofluoric acid treatment were removed by boiling the samples in 50% hydrochloric acid for ten minutes. Oxidation was omitted because the color of the palynodebris was one of the methods used for their interpretation. After heavy liquid separation with zinc bromide (specific gravity = 2.1), the residues were sieved to remove acid insoluble material below 10 μm in size and one slide was made for each sample. The samples were also centrifuged after each step outlined above.

Three hundred counts per slide were made and, in order to minimize slide-making bias, care was taken to macerate 25 g of sediments and standardize the concentrations of residues mounted on the slide. At the commencement of counting one slide was point counted twice to determine the consistency of the observed values and they were found to vary by $<5\%$. Multivariate statistical programs written by Kovach (1986) for the IBM-PC were used for Principal Components Analysis and Average Linkage Cluster Analysis. Log transformed percentage values of palynodebris were analyzed by Principal Components Analysis using a centered covariance matrix because log transformation reduced the skewness of the data. The unweighted pair average clustering method was carried out on a matrix generated by the Spearman rank-order correlation coefficient for palynodebris and samples. The Spearman coefficient is a non-metric, quantitative similarity measure in which correlations are based on the rank-order rather than on the actual abundances themselves.

PALYNODEBRIS TYPES

Pollen and Spores (Fig. 2A–D)

This group of particle types has been discussed extensively in the literature. Spore belonging to pteridophytes and pollen of angiosperms and few gymnosperms were recovered. The angiosperms dominate the assemblage, with high concentrations of the grass pollen *Graminidites* and two mangrove species, *Zonocostites ramonae* Germeraad, Hopping and Muller and *Verrutricolporites rotundiporus* van der Hammen and Wymstra. The presence of *Spirosyncolpites bruni* Legoux and *Multiaeriolites formosus* Germeraad, Hopping and Muller, the relative abundance of *V. rotundiporus* and the absence of *Crassoretitriletes vanraadshooveni* Germeraad, Hopping and Muller and *Belskipollis elegans* Legoux, were incorporated with foraminiferal data to date the E2.0 Reservoir as the earliest part of the Middle Miocene (Oboh, 1990).

Some of the sporomorphs have corroded surfaces as a result of degradation during fluvial transport (Starling and Crowder, 1981) while a few of them are known to be reworked. Spore coloration work (Oboh, 1990, 1992b) indicates that the reservoir sediments are immature to marginally mature. Although sporomorphs are all terrestrially-derived, they are dispersed widely by water and wind into marine environments, especially when they have small sizes and are morphologically adapted. This has been demonstrated in modern and ancient sediments by Muller (1959), Traverse and Ginsburg (1966), Chaloner and Muir (1968) and Heusser (1988). Their sizes range from 12 μm to 102 μm in these sediments.

Fungal Spores (Fig. 2E, F)

Fungal spores and hyphae are very diverse and ubiquitous in the sediments. The abundance of *Exeisisporites, Inapertisporites, Fusiformisporites, Multicellaesporites* and *Tetraploa* and the presence of *Hypoxylonites* and *Foveodiporites* indicate warm, humid conditions in the Tertiary (Elsik, 1969; Kumar, 1990). Many of the fungal spores are characteristically deep brown in color and are usually better preserved than other palynomorphs. Their abundance can be attributed to high production and their being more resistant to geothermal alteration and oxidation (Ediger, 1981; Sheffey and Dilcher, 1981; Traverse, 1988). Fungal spores are generally more abundant in Well 29 than 27 and the well is characterized by more degraded sporomorphs and amorphous organic matter (Oboh, 1990). Like pollen and spores they can be dispersed easily by water. Their dimensions vary from 6 μm to more than 100 μm.

Marine Microfossils (Fig. 2G)

Microforaminiferal test linings are the only forms recorded in this category. These are the inner chitinous linings of foraminiferal tests which survived acid digestion during sample preparation and they have been shown by Muller (1959) to be abundant in modern marine sediments. The test linings range in size from 30–90 μm, with very few exceeding 60 μm.

Algae (Fig. 2H, I)

Cysts attributable to algae and specimens of a green algal mass (?Chlorophyceae) are present in some of the mudstones. They are rarely abundant and are of unknown origin. The specimens range in size from 20 μm to 70 μm.

Cuticle (Fig. 3A)

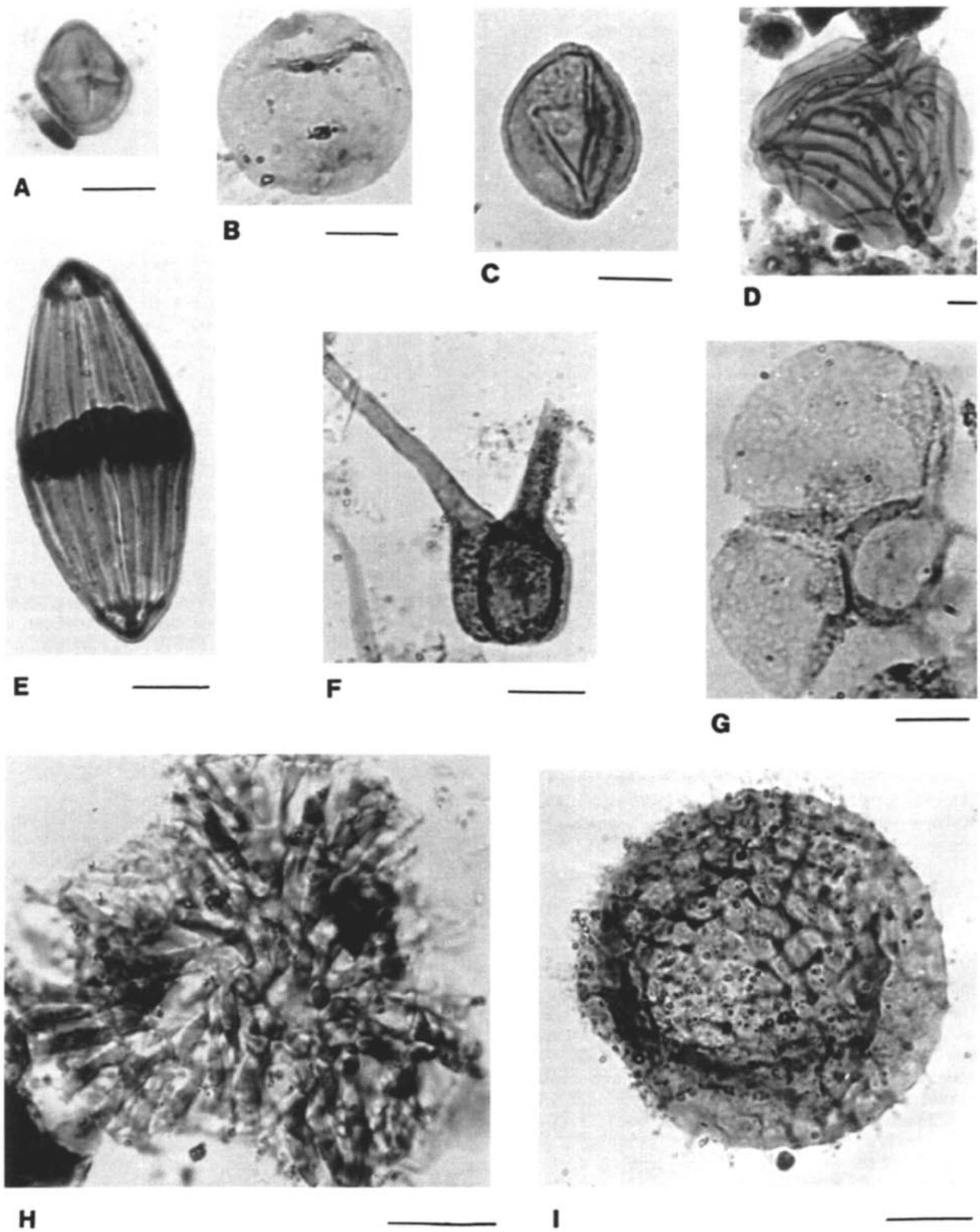
Cuticles are thin, platy epidermal fragments from non-woody plant organs such as leaves and roots. They are usually well-preserved and show clear structure of epidermal cell outlines; occasionally it is possible to distinguish the upper and lower epidermis. Although degradation is evident in several particles, cuticles have ben shown to have a high fossilization potential (Thomas and Spicer, 1986; Kerp, 1990). The colors of the cuticle fragments in these sediments vary from pale yellow to light brown and the specimens range in size from 40 μm to over 250 μm. Their buoyant nature ensures easy dispersal by water and they can be deposited either in low energy conditions by settling out of suspension (Parry et al., 1981) or pushed under heavier particles of sand in high energy conditions (Boulter and Riddick, 1986). In this study sandstones contain fewer cuticle fragments than mudstones.

Parenchyma (Fig. 3B)

Parenchyma fragments are rare and are made up of spherical to polygonal cells which are sometimes thick-walled. The fragments are believed to be derived from root remains (Cross et al., 1966; Boulter and Riddick, 1986). In this study the fragments are common in sandstones which have remains of rootlets preserved. Parenchyma tissues of angiosperms are not easily preserved in sediments like those of gymnosperms (C. O. C. Agwu, University of Nigeria, pers. comm., 1989) and this may account for their rarity. The size and shape of the particles show a considerable variation.

Well-Preserved Wood (Fig. 3C)

The specimens assigned to this category show well-preserved conducting vessels and occasionally pits and annular thickenings. They are pale yellow to medium brown, mainly lath-shaped but sometimes nearly equidimensional. They also vary in size from 50 μm to over 450 μm. Well-preserved wood is present in both sandstones and mudstones with little or no variation in distribution.



Brown Wood (Fig. 3D)

These specimens show some cellular structure but are dark brown in color and appear dense. Some are black for most parts but contain paler edges which show some cell structures. The fragments are mainly lath-shaped but sometimes more equidimensional. Although they show a considerable variation in size, they appear to be in the same size range with well-preserved wood.

Black Debris (Fig. 3E)

These fragments are opaque with sharp angular outlines and are usually lath-shaped, or equidimensional fragments, although there is a very slight rounding of some fragments in two sandstone samples. The category is called black wood, charcoal or inertinite by several workers. Many of the fragments appear similar to wood but their opaque nature makes it difficult to determine with certainty what tissues they are derived from. The fragments are common in many samples and tend to be more abundant in sandstones; this may be a taphonomic effect. They show a considerable variation in size from 20 μm to over 300 μm.

Degraded Bundles (Fig. 3F)

Degraded bundles are pale colored, flat and sheet-like fragments showing very badly preserved cell-like structures. Some of them can be related to wood and epidermal tissues. Since the category is a function of the degradation and possibly reworking which the sediments have undergone, fragments of well-preserved wood and cuticle may well have been reduced in numbers because of their transformation into degraded bundles. They are common in all the sediments and their sizes vary from 20 μm upwards.

Resins (Fig. 3G)

Resins are normally derived from stem tissues and are mainly associated with gymnosperms. They are rare in the sediments where they occur as unstructured amber-colored fragments. The fragments appear to be more common in sandstones than mudrocks and their rarity may be related to the dominance of angiosperms in the vegetation. Their sizes vary from 50 μm upward.

Black Specks (see Fig. 3A)

These particles are 1–20 μm in diameter, spherical to framboidal in outline and occasionally cubic. They are either disseminated within slides or associated with amorphous organic matter and large fragments. Their appearance, x-ray diffraction data, whole rock scanning electron microscopy and the drastic reduction in their numbers in oxidized palynological residues suggest that they are mainly pyrite crystals, although another mineral or even organic debris, e.g., coprolites, can not be ruled out. Black specks are present in minor amounts in all of the sediments.

Degraded Debris (Fig. 3H)

These are yellow to brown colored, sometimes nearly black fragments with irregular outlines. They do not show any cell structure. Their distribution in all the samples does not appear to be significant and may be a function of the amount of degradation the sediments have undergone. The fragments show considerable variation in size and thickness.

Amorphous Organic Matter (Fig. 3I)

This palynodebris type occurs as irregularly shaped, yellowish-amber to brown masses with no cellular details. They are gel-like and exhibit a "clotted" appearance (Tyson, 1984), and are believed to be alteration products rather than primary material (Staplin, 1969; Rogers, 1979). Rogers (1979) showed that bacterial and thermal degradation can produce amorphous material from other palynodebris. Since these sediments are immature to marginally mature at burial temperatures of 107°–110° C (Oboh, 1990, 1992b), this palynodebris type is most likely due to bacterial and possibly fungal degradation. The yellowish-amber color suggests derivation from terrestrial material as opposed to the gray-colored marine variety (Masran and Pocock, 1981; Venkatachala, 1981). Amorphous organic material is present in high amounts (>10%) in several samples.

MULTIVARIATE STATISTICAL ANALYSES

The use of multivariate analytical methods in palynological and paleobotanical studies has become more widespread in the last twenty years (Clapham, 1972; Spicer and Hill, 1979; Boulter and Riddick, 1986; Kovach, 1988, 1989; van Waveren, 1989). The choice of methods depends on the type of data and the specific problems being solved (Kovach, 1989). Principal Components Analysis and Average Linkage Cluster Analysis were chosen for this study in order to identify groups of palynodebris types and samples which are associations of the variables contained within the data available.

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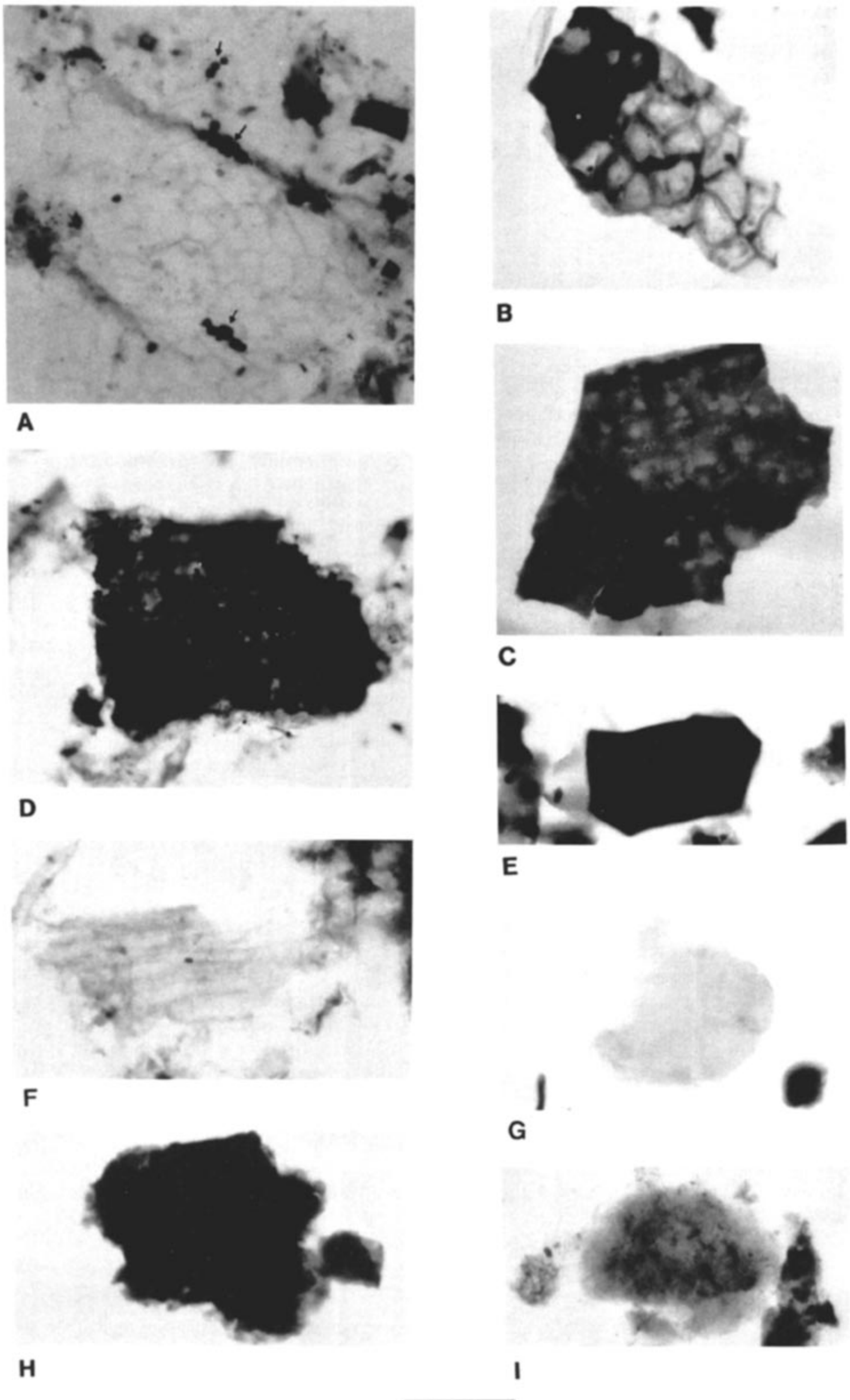
FIGURE 2—Palynomorph-type palynodebris. **A)** Mangrove pollen *Zonocostites ramonae* Germeraad, Hopping and Muller. Scale Bar = 10 μm. **B)** Mangrove pollen *Verrutricolporites rotundiporus* van der Hammen and Wymstra. Scale Bar = 10 μm. **C)** Grass pollen *Graminidites* sp. Scale Bar = 10 μm. **D)** Fern spore *Magnastriatites howardi* Germeraad, Hopping and Muller. Scale Bar = 10 μm. **E)** Fungal spore *Fusiformisporites* sp. Scale Bar = 10 μm. **F)** Fungal spore *Tetraploa* sp. Scale Bar = 10 μm. **G)** Microforaminiferal test lining. Scale Bar = 10 μm. **H)** Green "algal" mass. Scale Bar = 10 μm. **I)** ?Algal cyst. Scale Bar = 10 μm.


A
B
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Principal Components Analysis

Table 2 shows that four principal components account for more than 75% of the total variance of a centered covariance matrix based on log transformed palynodebris data. When the palynodebris with high component loadings (absolute values greater than 0.20) within each component are identified, four associations are defined. In Principal Component 1, pollen and spores, fungal spores, cuticles and degraded bundles have high positive loadings while black debris has a high negative loading. Principal Component 2 is characterized by high positive loading for amorphous organic matter and degraded bundles and high negative loadings for pollen and spores, fungal spores, well-preserved wood and black specks. In Principal Component 3 fungal spores, amorphous organic matter, black specks and black debris have high positive loadings while well-preserved wood and brown wood have high negative loadings. Principal Component 4 is characterized by high positive loadings for pollen and spores, fungal spores, black debris and degraded debris and a high negative loading for black specks.

Principal Component 1 is the strongest association that is confirmed by the cluster analysis of palynodebris (see Fig. 4). It shows that light textured and buoyant debris, i.e., pollen and spores, fungal spores, cuticles and degraded bundles are commonly associated with one another and not with black debris. Thus, they are more abundant in mudstones. Although the high negative loadings of well-preserved wood and brown wood in Principal Component 3 are confirmed, the two types of woody debris are abundant in almost all the samples. The ordination by Principal Components Analysis is most affected by palynodebris occurring in high abundances and those with low abundances are not distinguished. Since some of the low abundance types might be environmentally significant, this method does not give a very satisfactory result.

Average Linkage Cluster Analysis

The unweighted pair group Average Linkage Cluster Analysis on a matrix generated by the Spearman rank-order correlation coefficient was found to be more suitable for this study. The lengths of the branches of the dendrograms presented in Figure 4 depend on the average similarity of each group as they are fused. Since the clusters in the samples and those of the palynodebris were derived from separate analyses, they are not mathematically related. With the data matrix displayed between the two dendrograms, the structure of the original data can be seen along with the dendrograms. Four groups or assemblages of samples can be characterized in the left-hand dendrogram by the presence of certain dominant palynodebris and two groups of dominant palynodebris are also identified in the other dendrogram. Degraded bundles, amorphous organic matter, well-preserved wood and brown wood occur in high frequencies throughout the wells. Generally, rare palynodebris have little effect on the formation of the main groups, particularly where they occur in low abundances in samples with abundant types. Nevertheless, sample assemblages B to D are characterized by frequent but low abundances of parenchyma and resins while assemblage B does not record microforaminiferal test linings.

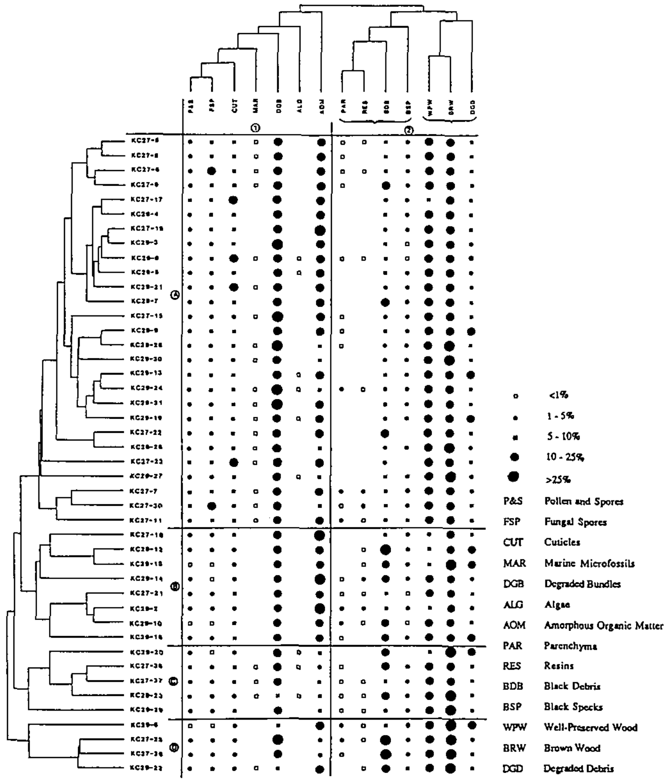

FIGURE 4—Dendrograms for the unweighted pair group average cluster analysis for samples (left-hand) and palynodebris types (top). The data matrix is displayed between the dendrograms.

The dendrogram for palynodebris components shows two broad associations, one of which has two sub-clusters. The first association has a strong linkage of pollen and spores and fungal spores and hyphae occurring with cuticles, marine indicators, degraded bundles, algae and amorphous organic matter (Fig. 4). This was less obvious from work with the microscope. The linkage of palynomorphs and degraded bundles seems to be of hydrodynamic importance since they can be expected to behave in the same way when suspended in water and during deposition because of their light texture. Amorphous organic matter shows the weakest linkage in this cluster and

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FIGURE 3—Nonpalynomorph-type palynodebris; Scale Bar for all figures = 50 μm. **A)** Fragment of cuticle with black specks (arrowed). **B)** Parenchyma. **C)** Well-preserved wood. **D)** Brown wood. **E)** Black debris. **F)** Degraded bundles. **G)** Unstructured amber-colored resin. **H)** Degraded debris. **I)** Amorphous organic matter.

TABLE 2—Principal component loadings in which the asterisk indicates absolute values greater than 0.20; Eigenvalue 1 = 0.189 (42% of total variance); 2 = 0.073 (16.27%); 3 = 0.054 (12.08%); 4 = 0.033 (7.40%).

Palynodebris	Eigenvectors (component loadings)			
	PC 1	PC 2	PC 3	PC 4
Pollen and spores	0.35*	−0.31*	0.09	0.40*
Fungal spores	0.48*	−0.23*	0.46*	0.30*
Cuticles	0.30*	0.03	−0.11	0.07
Parenchyma	−0.05	−0.15	0.18	0.07
Well-preserved wood	0.03	−0.20*	−0.32*	−0.02
Brown wood	−0.14	−0.10	−0.22*	−0.05
Black debris	−0.59*	0.02	0.39*	0.35*
Degraded bundles	0.40*	0.37*	−0.14	−0.17
Resins	−0.06	−0.06	0.15	−0.08
Black specks	0.01	−0.54*	0.33*	−0.58*
Amorphous organic matter	0.13	0.54*	0.53*	−0.18
Degraded debris	−0.03	0.05	−0.10	0.45*
Algae	0.01	0.00	−0.05	0.06
Marine microfossils	0.07	−0.13	0.00	0.01

appears to be more of a post-depositional (diagenetic) feature.

The first sub-cluster of the second association contains parenchyma, resins, black debris and black specks, with the first two being closely linked. Angiosperm parenchyma is not usually preserved but in the sediments fragments of parenchyma seem to be more frequent in sandstone lithofacies which have rootlet remains. Their association with resins may be more environmentally related, as Parry et al. (1981) interpreted the latter as being characteristic of oxidizing environments, mainly distributary channels. Black debris is also more prominent in sandstone samples whereas the distribution of the black specks appears to be insignificant. If the black specks are mainly pyrite as earlier speculated, they are most likely redeposited from older sediments or of early diagenetic origin.

Well-preserved wood and brown wood are closely linked (Fig. 4) and they show a weak linkage with degraded debris to form the second sub-cluster. The first two have the same shape and similar size range, which makes their association sedimentologically and hydrodynamically significant. Their linkage with degraded debris may be related to composition, in which case the latter is most likely to be of woody origin. The occurrence of well-preserved wood, degraded bundles and cuticles as recorded in this study is at variance with their co-occurrence in the North Sea basin as "palynowafers" (thin, sheet-like fragments) associated with high energy marine depositional environments such as prograding lobes (Boulter and Riddick, 1986).

PALYNOFACIES ASSOCIATIONS

The four assemblages in the sample dendrogram in Figure 4 can be treated as indicators of palynofacies because they also confirm most of the observations made from work with the microscope. Although they vary in their occurrence in the two wells, the assemblages are related to lithofacies types which give an indication of the hydrodynamic conditions during deposition. Consequently, they have been grouped into two associations.

Palynofacies Association A/C (Fig. 5A, B)

This palynofacies association is dominated by four palynodebris types: well-preserved wood, brown wood, degraded bundles and amorphous organic matter. Each of them is usually more than 10% in the samples. In assemblage A (Fig. 5A) black debris is subordinate and constitutes less than 8% of the assemblage in most sediments. The degraded bundles and woody material are fine to medium-sized and generally not larger than 200 μm. Assemblage A also records the highest values (5–14%) for cuticles in the wells. Terrestrial palynomorphs show a considerable variation from 1% to just over 10% and are most prominent in this assemblage. Microforaminiferal test linings, algae, parenchyma and resins show scanty, low occurrences. Black specks and degraded debris do not show any significant trend in their distribution in this or in the other assemblages.

Assemblage C (Fig. 5B) differs from A in being richer in brown wood and poorer in amorphous organic matter. There is also a slight reduction in the amount of degraded bundles present in the sediments. The difference between the two assemblages appears to be related to preservational and diagenetic effects and, with the exception of lithofacies S4 (Table 1) occurring in C, both assemblages are characteristics of sediments from the muddy heterolithic and mudstone lithofacies.

Palynofacies Association B/D (Fig. 5C, D)

Assemblage B (Fig. 5C) is diagnostic in having high occurrence of black debris, some of which are very slightly rounded in two samples. Degraded bundles and brown wood occur as in Palynofacies Association A/C but the sediments have more amorphous organic matter and fewer well-preserved wood fragments. All these main components are fine to medium-sized. Parenchyma and resins are more frequent than in the other associations and sometimes record up to the highest value of 2%. Neither microforaminiferal test linings nor algae have been recovered in these sediments. Terrestrial palynomorphs and cuticles are present in low frequencies.

Assemblage D (Fig. 5D) is similar to B in composition but differs from the latter in having more brown wood, less amorphous organic matter and fewer fragments of cuticles. Furthermore the components are coarser. There is also considerable variation in the amount of degraded bundles present. Microforaminiferal test linings are rare to absent and no algae has been recovered. Whereas assemblage B is composed of sediments from lithofacies S1, S3, S4, S5 and the sandy heterolithic lithofacies, D is restricted to sediments belonging to lithofacies S2 and S3 (Table 1).

ENVIRONMENTAL SIGNIFICANCE OF THE PALYNODEBRIS

An integration of palynofacies with lithofacies, mineralogical composition, diagenetic imprints, palynomorphs and foraminifera resulted in the recognition of seven, possibly eight, sub-environments within a deltaic offlap sequence (Oboh, 1990, 1992a; Figs. 6, 7). These depositional settings are the distributary channel-fill, ?tidal channel-fill, lagoon/tidal flat, lagoonal delta, flood-tidal delta in the lower delta plain, the coastal barrier, and the delta fringe and prodelta in the outer delta (Table 3). In addition to specific types of palynodebris found in certain environments, the important characteristics used for interpretation are their sizes, shapes and textures.

The deposition of sandstones in high energy environments (Palynofacies Association B/D) is reflected in the shape of the woody debris recovered from such sediments. These fragments which are denser than other palynodebris, e.g., palynomorphs, are usually larger and more equidimensional than those of mudstones from lower energy environments, such as lagoon/tidal flat and prodelta (Palynofacies Association A/C), which are mainly lath-shaped. The lath shape suggests their flotation in water for a longer period before deposition (Parry et al., 1981) while the more equidimensional fragments were most likely deposited in the same manner as sand particles. Black debris, which may be oxidized wood fragments (as indicated by cluster analysis), are usually dominant in channel sands (Boulter and Riddick, 1986). The existence of some very slightly rounded black debris in two coastal barrier samples is

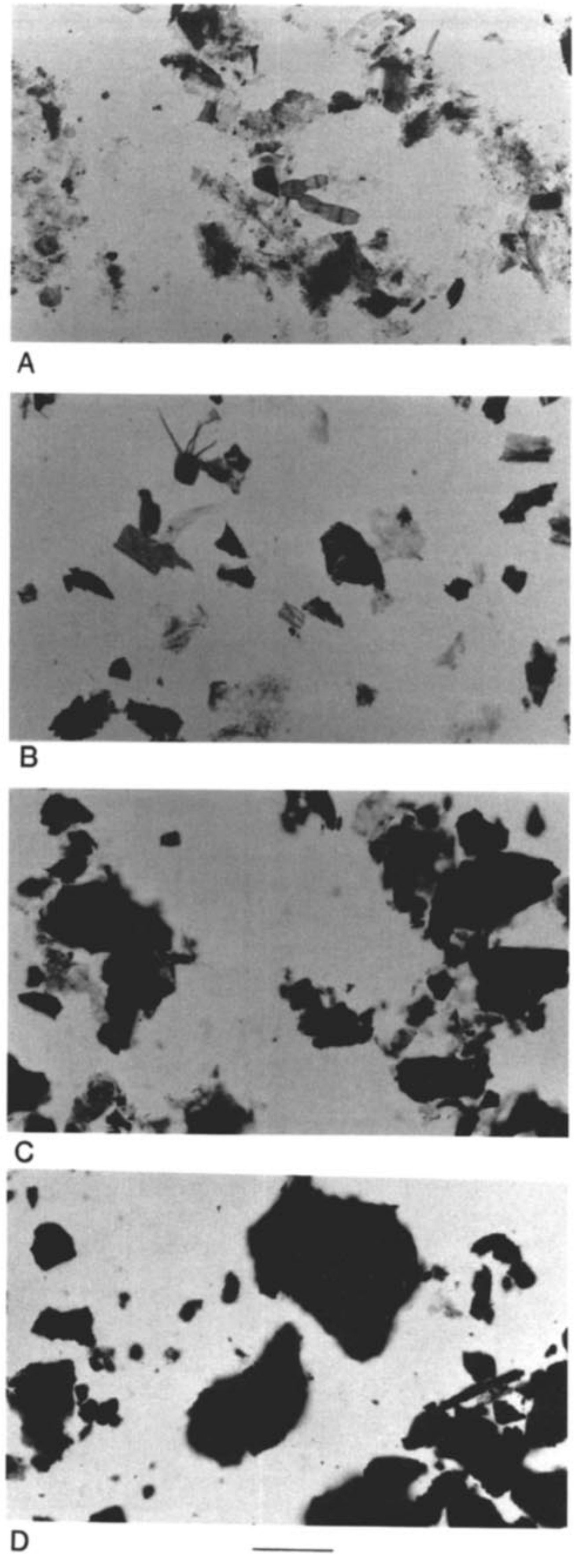

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FIGURE 5—Palynofacies assemblages which make up Palynofacies Associations A/C and B/D. Scale Bar for all figures = 100 μm. **A)** Assemblage A. **B)** Assemblage C. **C)** Assemblage B. **D)** Assemblage D.

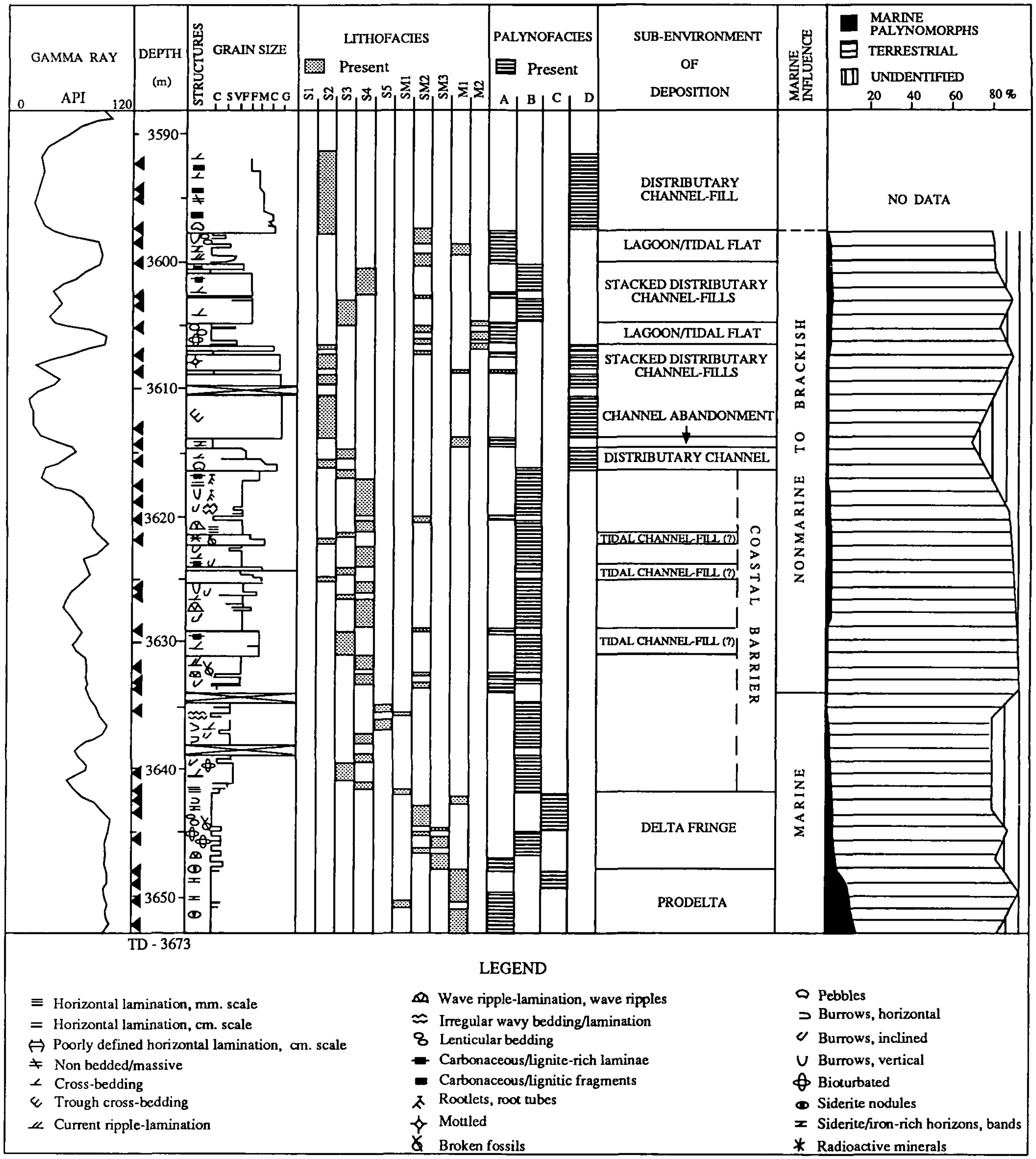

FIGURE 6—Integrated paleoenvironmental interpretation of the E2.0 Reservoir in Well 27. Arrows indicate sample positions (from Oboh, 1992a).

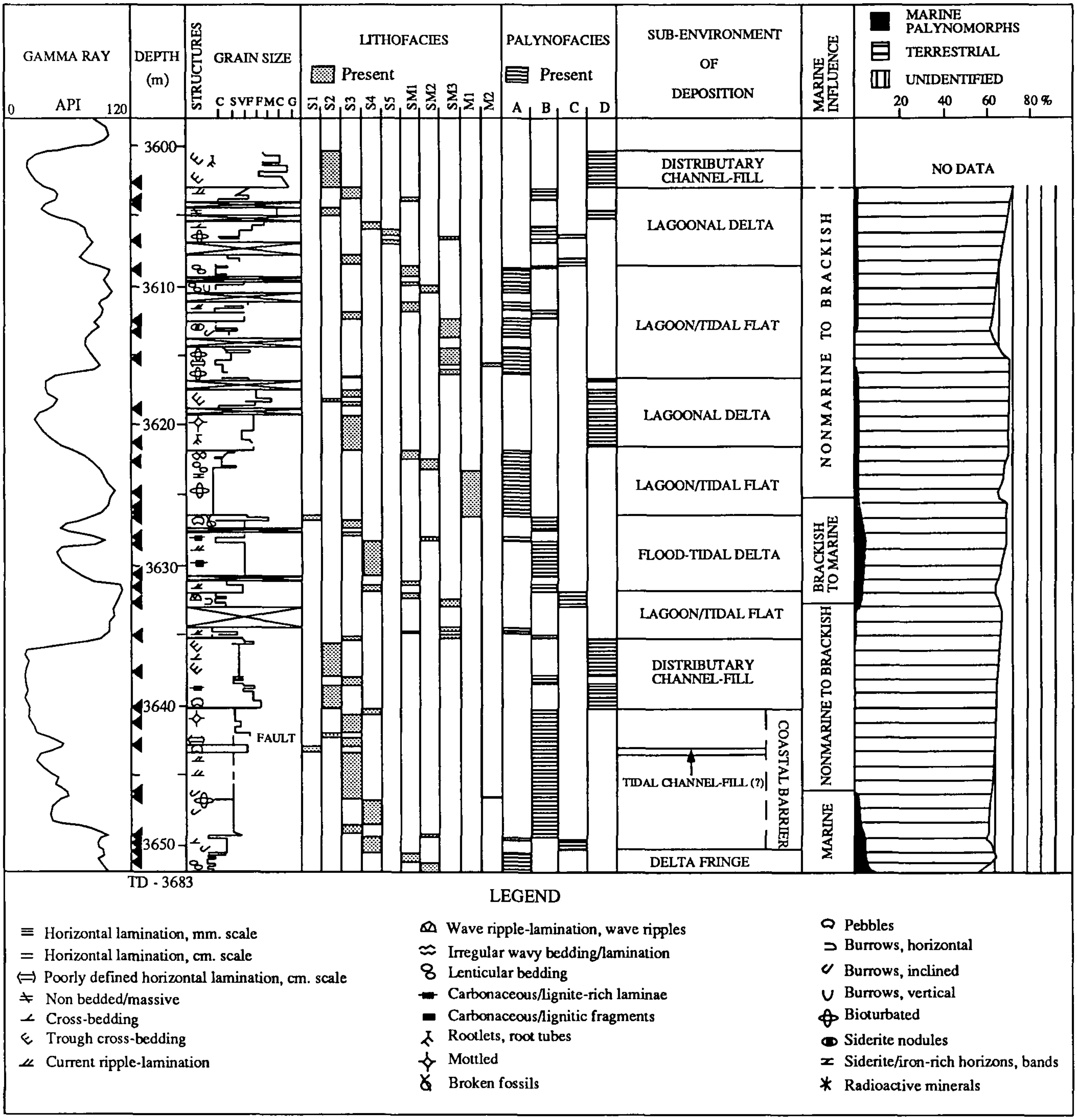

FIGURE 7—Integrated paleonenvironmental interpretation of the E2.0 Reservoir in Well 29. Arrows indicate sample positions (from Oboh, 1992a).

unclear because rounding of opaque debris by attrition has not been proven.

Parenchyma and resins, though rare, occur mainly in distributary channel sandstones (Palynofacies Association B/D). Gymnosperm parenchyma has a higher preservation potential than angiosperm parenchyma possibly because of the latter's susceptibility to degradation and fungal attack, particularly in warm, humid conditions. Since parenchyma is commonly preserved in roots, its distribution can be linked to the traces of rootlets and root tubes pre-

TABLE 3—Summary of deltaic sub-environments of deposition in the E2.0 Reservoir (from Oboh, 1990).

Sub-environment	Characteristics	Interpretation
Distributary channel-fill	Fining-upward, poorly sorted unit represented by lithofacies S2 (dominant), S3 and S4 with erosive bases, rootlets, root tubes and carbonaceous material; few palynomorphs and no marine indicators; Palynofacies Association B/D rich in angular equidimensional fragments of wood and black debris, also records highest numbers of resins and parenchyma	Deposited by high energy tractional currents without tidal influence; channel migration resulted in stacked sequences
?Tidal channel-fill	Fining-upward unit which has similar characteristics with distributary channel-fill sediments; in addition lithofacies S1, faunal remains, glauconite, and calcite cements present	Deposited by high energy tractional currents in tidal channels eroding coastal barriers
Lagoon/tidal flat	Unit comprised of the 2 mudstone and 3 heterolithic lithofacies, also contains thin intercalations of sandstones S3 and S4 with sharp bases and tops; rich in trace fossils preserved in various orientations, e.g., *Chondrites* and *Arenicolites*; abundant grass and mangrove pollen in a diverse assemblage of angiosperms and ferns, few marine indicators (<3%); Palynofacies Association A/C rich in amorphous organic matter, degraded bundles and small-sized, lath-shaped woody material	Deposited in low energy conditions in shallow lagoons with tidal and wave influence and/or in tidal flats; occasional single, non-prograding flood events took place
Lagoonal delta	Coarsening-upward, moderately to poorly sorted unit of sandstones S2, S3, S4 and S5 and heterolith SM3; contains rootlets and trace fossils, occasionally bioturbated; trace fossils and palynomorphs similar to those of lagoon/tidal flat; Palynofacies Association B/D characterized by angular equidimensional woody material and black debris	Deposition by medium–high energy currents as small crevasse deltas in shallow lagoons; low energy conditions permitted bioturbation
Flood-tidal delta	Coarsening-upward unit of sandstones S3 and S4 and heterolith SM2 which is capped by pebbly sandstone S1, contains minor reversals of cross-laminations; rich in grass pollen and shows slight increase in the numbers of marine indicators (>3%); rich in feldspars (20–25%) and faunal remains; sandstones Palynofacies Assemblage B which is richer in black debris than heterolith (Palynofacies A)	Tidally-influenced prograding deposition in shallow lagoon
Coastal barrier	Coarsening-upward, well sorted unit of sandstones S3, S4 and S5, few intercalations of heteroliths SM1 and SM2; well-preserved trace fossils, e.g., *Ophiomorpha* cf. *O. nodosa*, occasional bioturbation and slight increase in horizontal and inclined burrows with increasing depth; trace fossils in the *Skolithos* ichnofacies (Seilacher, 1967); rootlets and carbonaceous material in the upper part of the unit; faunal remains, glauconite and localized cements present, more compacted than channel-fill sandstones; Palynofacies Assemblage B with subrounded black debris and equidimensional woody debris, also rich in amorphous organic matter; heterolith Palynofacies A with lath-shaped woody debris, rich in grass and mangrove pollen, fern spores and contains a small number of coastal strand dwellers such as *Echiperiporites estelae* and *Racemonocolpites hians*.	Parallel to sub-parallel laminated sandstones with rootlets in the upper part of the unit deposited in high energy foreshore as barrier ridges; cross-bedded sandstones with more horizontal and inclined burrows possibly deposited in the shoreface
Delta fringe	Heterolithic unit with interbeds of ripple-laminated, fine-grained sands in the upper part; few faunal remains occur, commonly bioturbated; marine indicators >3%; Palynofacies Association A/C	Deposition influenced by low to moderate wave and current energy
Prodelta	Unit of siderite-bedded mudstone M1 which yields the largest numbers of marine indicators (11%) and the only suite of benthic foraminifera, including *Eggerella scabra*, *Textularia elegans* and *Ammoscalaria pseudospiralis*; very rich in neoformed pyrite and has the highest concentration of illite/smectite in the reservoir; this might be a function of increasing depth which enhanced smectite deposition in the sub-environment before diagenetic alteration	Deposited from suspension in low energy offshore and reducing conditions with occasional effects of storms

served in the sandstones. Resins occur in most delta plain sub-environments where wood is preserved in large quantities (Masran and Pocock, 1981) and they are diagnostic of oxidizing, high energy conditions as in distributary channels (Parry et al., 1981). Since they are commonly associated with gymnosperms, they are rare in these Niger Delta sediments because the vegetation is dominated by angiosperms. Therefore, the occurrence of parenchyma, resins and black debris in the same sub-cluster (Fig. 4) is environmentally significant.

Angiosperm pollen and pteridophyte spores are commonly preserved in the mudstones and muddy heteroliths from the lagoon/tidal flat, delta fringe and prodelta. Their linkage with fungal spores, cuticles, marine microfossils, degraded bundles and amorphous organic matter is of hydrodynamic and preservation interest. The buoyant textures of these palynodebris facilitates their deposition in low energy depositional environments. Fungal spores and hyphae must have played a role in the preservation potential of all the other categories. For example, the presence of poorly-preserved palynomorphs, unidentified grains and degraded bundles in Well 29 appears to correlate with the higher numbers of fungal spores recovered in the sediments (Oboh, 1990).

SUMMARY AND CONCLUSIONS

Palynodebris can be related to lithofacies, depositional environments and reservoir characteristics in the Middle Miocene E2.0 Reservoir in Wells 27 and 29 of the Kolo Creek field. Statistical analyses of the fourteen types of palynodebris identified resulted in two palynofacies associations (A/C and B/D) which agree with lithofacies analysis. Palynofacies Association A/C is made up of mudstones and muddy heteroliths while B/D is essentially sandstones. The significant palynodebris components are black debris, parenchyma, resins and amorphous organic matter. Assemblages A and B differ from C and D respectively in having more amorphous organic matter.

Palynodebris data enhanced the overall paleoenvironmental interpretation of the reservoir. By integrating the size, shape and texture of palynodebris with sedimentological characteristics, palynomorph assemblage and foraminiferal data, seven, possibly eight, deltaic sub-environments of deposition were recognized (Figs. 6, 7). Woody debris from mudstones in low energy depositional environments (e.g., lagoon/tidal flat, delta fringe, prodelta) are mainly small-sized and lath-shaped in contrast to larger and more equidimensional fragments in high energy environments (e.g., distributary channel-fill, coastal barrier, lagoonal delta). Similarly, more buoyant palynodebris such as palynomorphs, cuticles and degraded bundles are more abundant in mudstones. Black debris is an important component in channel-fill and coastal barrier sandstones where its prominence may be a function of exposure to oxidizing conditions for a longer period of time. Although parenchyma and resins are rare, they are commonly found in channel-fill sandstones which have well-preserved rootlets. Their rarity may be related to the dominance of angiosperms in the vegetation.

The types of palynodebris can also be related to reservoir characteristics, which are mainly due to post-depositional factors such as diagenesis and thermal maturity. Early diagenetic conditions can be inferred from sedimentological and mineralogical properties, e.g., high porosity, poor compaction in distributary channel-fill sandstones, types of cements, clay minerals and illite crystallinity (Oboh, 1990, 1992b). Furthermore, qualitative and quantitative spore color measurements indicate immature to marginally mature thermal conditions for the reservoir. The colors of the palynodebris would have been significantly altered to dark brown and black if the sediments had experienced late diagenetic and supermature thermal conditions, and this would have reduced the number of palynodebris components identified. The inferred burial temperatures of 107°–110° C (Oboh, 1990, 1992b) are in general agreement with the geothermal gradient of the Agbada Formation in the Niger Delta (Short and Stäuble, 1967; Evamy et al., 1978). This suggests that amorphous organic matter was most likely formed from bacterial and possibly fungal degradation of other palynodebris, which were almost all terrigenous. However, the occurrence of amorphous organic matter as a dominant component in palynofacies assemblages A and C is more prominent than Bustin (1988) reported for similar sediments in the Niger Delta.

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