

# Plant-Rich Holocene Sequences in the Northern Nile Delta Plain, Egypt: Petrology, Distribution and Depositional Environments

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## ABSTRACT



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Petrological analyses of 70 borings recovered across the northern Nile delta, including counts of floral debris in 2200 core samples, serve to distinguish 4 different Holocene sediment types containing vegetal matter. These types constitute three major plant-rich lithostratigraphic sequences which are concentrated in two distinct areas: northeastern delta (south of Manzala lagoon) and north-central delta (from central Burullus lagoon to Idku lagoon). Petrological attributes of core sections containing vegetal debris indicate that these accumulated preferentially in back-barrier marshes, lagoon margins and interdistributary lows. The development of peat and related organic-rich facies was influenced by dilution effects, a function of seasonal detrital influx during flooding of River Nile distributary channels and sediment transport from the sea. Regional differences in lithofacies, aerial configuration and age of vegetal-rich sequences on the lower delta plain are interpreted in light of various controlling factors: submergence (tectonic subsidence, eustatic sea level rise), paleoclimatic change (affecting River Nile headwater flux and distributary channel migration and flooding), coastal processes and evolving configuration of depositional environments behind coastal sand ridges in a wave-dominated regime. Although the Nile delta has formed under generally arid conditions, thicknesses and accumulation rates of mid- to upper Holocene plant-rich layers locally are comparable to those in some deltas formed in temperate and tropical regions.

**ADDITIONAL INDEX WORDS:** *Dilution, Marsh-lagoonal environments, Nile delta paleogeography, Peat, Plant-rich layers, Submergence, Vegetal matter.*

## INTRODUCTION

This investigation focuses on plant-rich deposits, including peat and associated organic-rich facies, in Holocene subsurface sections from the northern Nile delta plain of Egypt. In general, deposition of vegetal matter is related to plant growth and preservation and, at least in part, to climatic conditions. The accumulation of peat and other plant-rich deposits is usually not favored in arid settings. It is of interest, therefore, that stratigraphic and sedimentological surveys of late Quaternary deposits in the Nile delta of Egypt have recorded the presence of dark organic-rich layers in some sediment borings (FOURTAU, 1915; ATTIA, 1954; UNDP/UNESCO, 1976; RIZZINI *et al.*, 1978; SESTINI, 1989). Dark organic-rich strata of Quaternary

age also have been mapped in subsurface sections on the Egyptian slope and Nile Cone seaward of the Nile delta (MALDONADO and STANLEY, 1976; ROSSIGNOL-STRICK *et al.*, 1982; ANASTASAKIS and STANLEY, 1984, 1986). To date, however, there has been no systematic study of peat and other types of organic-rich layers that accumulated in the delta proper, the largest depocenter in the eastern Mediterranean. Herein, the term plant-rich deposit is applied in a very general and comprehensive manner to all vegetal-rich sequences. Nomenclature of the various vegetal-rich deposits as used in this investigation is discussed in a subsequent section.

This study evaluates the spatial and temporal distribution of Holocene plant-rich deposits across the northern Nile delta plain on the basis of a large set (85) of recently recovered sediment borings (Figure 1). These cores,

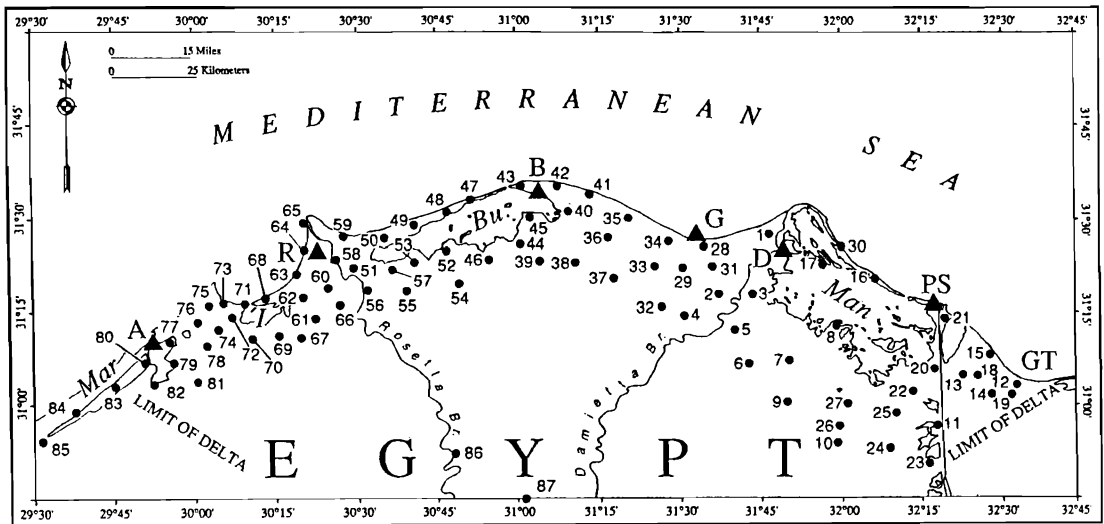


Figure 1. Map showing locations of 87 Smithsonian cores recovered across the northern Nile delta, Egypt. 2200 samples from borings S-1 to S-70 were examined in this study. A = Alexandria; B = Baltim; D = Damietta; G = Gamasa; GT = Gulf of Tineh; PS = Port Said; and R = Rosetta. Northern delta lagoons, from east to west, are: Manzala (Man); Burullus (Bu); Idku (I); and Maryut (Mar).

evenly distributed between the Gulf of Tineh on the east and the Alexandria region on the west (STANLEY, 1990), provide an extensive and unique data-base. Preliminary observations of radiocarbon-dated Holocene core sections have previously indicated that plant-rich layers are irregularly distributed in time and space (EL-ASKARY and FRIHY, 1986; SNEH *et al.*, 1986; COUTELLIER and STANLEY, 1987; WUNDERLICH, 1988a,b; ARBOUILLE and STANLEY, 1991). Sediments containing abundant vegetal debris in the Nile delta plain have been grouped as one general facies, termed organic-rich deposits (FRIHY and STANLEY, 1988), without differentiating various subtypes or interpreting specific depositional environments.

The present investigation distinguishes different types of strata with vegetal matter, largely on the basis of visual observation and X-radiography of split cores and of binocular microscope analysis of the sand-size fraction. The study distinguishes several petrological types and defines the major lithostratigraphic sequences comprising abundant vegetal matter. Mapping of the lateral distribution and age of such facies serves to better interpret the origin of some specific deltaic environments.

Herein, we focus more specifically on marshes and associated environments such as lagoons and interdistributary depressions which would have favored the accumulation of vegetal matter. This analysis, in turn, should help refine interpretations that bear on the paleogeographic evolution and neotectonics of the northern Nile delta plain during the Holocene.

## METHODOLOGY

Eighty-five borings were recovered in the northern Nile delta plain with trailer-mounted Acker II combination rotary-percussion machines during five Smithsonian Institution drilling surveys: 1985 (cores S-1 to -17), 1987 (S-18 to -30), 1988 (S-31 to -46), 1989 (S-47 to -65), and 1990 (S-66 to -85). These core sites are fairly evenly distributed over a 270 km long arcuate area about 20 to 45 km wide, and which extends parallel to the Mediterranean coast from Alexandria in the west to the Gulf of Tineh in the east (Figure 1).

Almost all cores, ranging in length from 15 to 60 m, have been radiocarbon dated. Continuous Holocene sections have been recovered at all sites, and late Pleistocene strata have been

cored at many locations as well. The lithofacies used here are defined and illustrated in COUPELLIER and STANLEY (1987, their Figure 3) and ARBOUILLE and STANLEY (1991, their Figure 3). These include: late Pleistocene marine and fluvial sands and overbank and interdistributary (stiff mud) deposits; late Pleistocene to lower Holocene basal transgressive sands; and Holocene marine prodelta and delta-front units, coastal sand, lagoonal and marsh deposits.

The sedimentary structures in split cores (diameter of 75 mm) were examined by X-radiography and samples were collected at an interval of about 1 m or less. These samples were analyzed for textural and petrological composition (methods in COUPELLIER and STANLEY, 1987; ARBOUILLE and STANLEY, 1990).

For each of 2200 core samples from 70 of the cores (S-1 to S-70), proportions of clay ( $< 2 \mu\text{m}$ ), silt ( $2\text{--}63 \mu\text{m}$ ), and sand ( $> 63 \mu\text{m}$ ) were calculated. The relative percentages of 16 major components were determined in the sand-size fraction on the basis of counts of  $> 300$  grains per core sample (method according to FRIHY and STANLEY, 1988). Components include: mineralogical [light and heavy mineral, mica, glauconite/verdine (*cf.* PIMMEL and STANLEY, 1989), pyrite, gypsum, lithic fragment, aggregate]; faunal (foraminifera, ostracode, gastropod, pelecypod, sponge spicule); and floral (diatom, plant fragment and fiber, seed). All the above information is available as tabular data-base listings and core logs at the Smithsonian Institution's National Museum of Natural History in Washington, D.C. (MEDIBA, 1990).

Of the 2200 samples, 1614 are of Holocene, and 586 are of late Pleistocene age. None of the late Pleistocene samples contained more than 1% of vegetal remains, and these are not considered here. Almost half of the Holocene samples (817) contain trace to abundant (99%) vegetal remains in the sand-size fraction. The vegetal matter, examined with the binocular microscope, comprises plant fragments, fibers, seeds, pollen and undifferentiated vegetal remains. Each individual floral component of sand size was counted as one grain (*cf.* method in STANLEY, 1966; FRIHY and STANLEY, 1988). We have taken note of two important attributes in the case of each sample: the relative percentage of the sand fraction of the total sediment, and the percentage of floral components in the sand-size fraction. Using these two val-

ues, it is possible to calculate the approximate percentage of vegetal matter for the total sediment in each sample.

Attention in this study is paid to all core layers containing vegetal matter. Special consideration is given to the specific stratigraphic position and petrological nature of the richer plant-rich strata. The position of such layers relative to lithofacies with little or no vegetal matter lying directly below and above them is noted. Observations also were made of the number and thickness of these layers relative to the entire Holocene section in which they occur. Finally, attention is paid to the specific geographic and age distributions of these plant-rich strata in core sections.

### CONSIDERATIONS OF NOMENCLATURE

A review of the literature on modern deltas in various regions of the world reveals that there are problems of nomenclature with regards to various types of vegetal- and organic-rich layers (ANDREJKO *et al.*, 1983; KEARNS and DAVISON, 1983; MEADOWS, 1988; KOSTERS, 1989). Moreover, systematic study of such deposits in deltas and other settings has been carried out in various ways (*cf.* COHEN, 1972; POTTER *et al.*, 1980; GORE, 1983).

For the purpose of this sedimentological investigation of the Nile delta, our emphasis is on determining the amount of microscopically recognizable vegetal matter of sand-size, the texture and structures of the associated organic-rich layer, and its detailed lithostratigraphy. The focus, then, in this preliminary study is on sedimentary petrology rather than on micropetrography, organic chemistry and/or botanical analysis. Herein an attempt is made to categorize various plant-rich sediment types in a straight-forward and descriptive manner emphasizing volume rather than weight in a way which can be duplicated by others. We also recognize the need to minimize semantic complications.

Reference herein is made to terms such as peat and muck as very generally defined in most studies of deltas (FISK, 1960; RAINWATER, 1966; BROUSSARD, 1975; REINECK and SINGH, 1980; COLEMAN, 1982; GALLOWAY and HOBDAV, 1983). For example, we apply the term peat to "an unconsolidated deposit of semicarbonized vegetal remains of a watersaturated environ-

ment" (GRAY *et al.*, 1972, p. 521). Muck is also used as commonly defined, *i.e.* as a "dark, finely divided, well decomposed, organic material intermixed with a high percentage of mineral matter, usually silt, which forms surface deposits in some poorly drained areas" (GRAY *et al.*, 1972, p. 467).

## PETROLOGY

In a statistical factorial analysis performed to discriminate the different Holocene deposits in the eastern Nile delta, vegetal-rich samples were considered as one distinct facies (FRIHY and STANLEY, 1988). That study was based on three textural and sixteen compositional variables, including relative percentages of vegetal matter, considered for each sample. Discrimination of the various organic-rich subtypes, however, was not made in that earlier study. In the present petrological analysis, the first consideration was a determination of the relative percentage of vegetal components of sand size in a large (2200) sample population selected from cores recovered across the entire northern delta. The approach emphasizes volume rather than weight. On this basis, the 817 plant-bearing samples can be readily subdivided into two groups (Figure 2) by plotting the percentage of vegetal debris in the total sediment against the percentage of vegetal debris in the sand-size (> 63  $\mu\text{m}$ ) fraction.

The first group, with < 15% vegetal debris in the total sediment (D in Figure 3), comprises the largest number of samples (*i.e.* 772 samples, or 94.5% of the population of 817 samples containing vegetal debris). In this group, 25 samples (or 3.2%) are primarily sand with < 1% vegetal matter in the total sediment, 214 samples (or 27.7%) are muddy sand to sandy mud with < 5% vegetal matter, and 533 samples (or 69%) are mud with up to 15% vegetal matter.

Samples of the second, but much smaller group (45 samples, or 5.5% of the population of 817 samples) contain from 18 to nearly 100% vegetal debris in the total sediment, and always more than 60% in the sand-size fraction (Figure 2). Samples in this plant-rich group can be subdivided into three distinct types defined by the amount of vegetal matter (A, B, C in Figure 3).

Thus, four types of sediment containing vegetal matter are distinguished on the basis of percentage (rounded to the nearest 5%) of vegetal

debris in the total sediment. The actual percentages calculated are given below in parentheses. The four types are herein named in order of decreasing vegetal matter content, respectively: **peat**, **mucky peat**, **muck** and **mucky mud** (respectively A to D). These names take into consideration various nomenclatures used in North America to describe mixed (vegetal and inorganic matter) sediment (*cf.* ANDREJKO *et al.*, 1983), including the field classification proposed by KEARNS and DAVISON (1983). For the purposes of this study, the four sediment types, distinguished on the basis of decreasing amount (volume rather than % weight) of vegetal matter in the total sediment, are coded from A to D as follows:

- Type A (*peat*) = 65 to 100% (= 67 to 95%), 12 samples in 11 cores
- Type B (*mucky peat*) = 45 to 65% (= 47 to 61%), 12 samples in 10 cores
- Type C (*muck*) = 15 to 45% (= 18 to at least 39%), 21 samples in 13 cores
- Type D (*mucky mud*) = 0 to 15% (= trace to 15%), 772 samples in 65 cores

Several of the above types may occur in one core section. Sediments containing vegetal matter are present in most of the cores drilled in the northern Nile delta plain. They are usually grey to dark grey and fine-grained, and their petrology indicates deposition under reducing conditions. Dark grey to black plant-rich layers that contain more than 15% vegetal matter (types A, B, C) have been found at only 24 of the 70 sites examined.

Discrimination of the four types on the basis of vegetal matter is further confirmed when the non-floral composition of the sand-size fraction is taken into account (Figure 4). A general trend becomes apparent as the percentage of vegetal debris decreases. Light minerals, rare to present in type A, increase progressively to 30% in type C, and can be abundant (to about 60%) in type D. Mica, glauconite/verdine, pyrite and heavy minerals, always in low percentages (< 5%) in types A, B, and C, increase gradually and each component can reach 10 to 20% (and even more than 30% in some samples) in type D. Evaporite, with percentages as high as 19% in some samples of type A, decreases and becomes rare or absent in the other types. Biogenic components like sponge spicules and diatoms are found in every type; a relatively high percentage of sponge spicules can occur in type

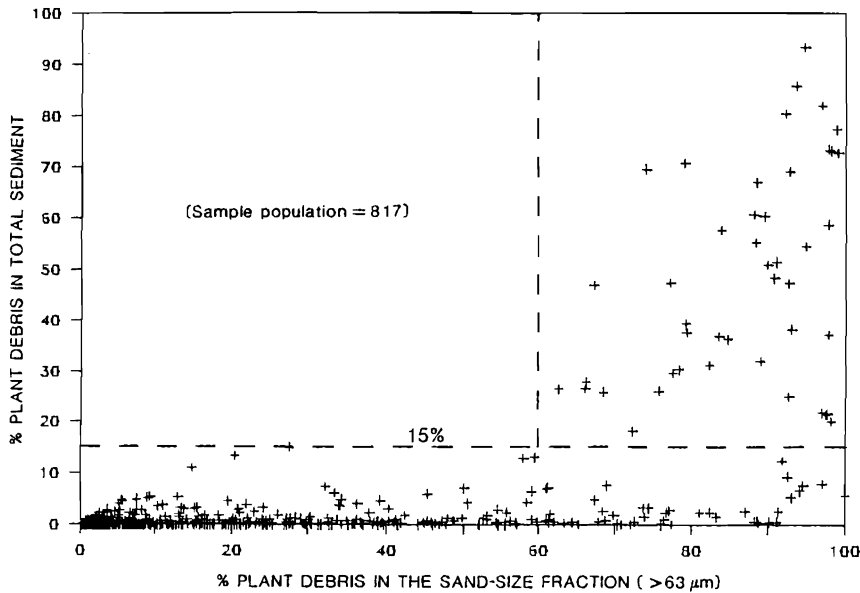


Figure 2. Nile delta core samples with vegetal matter (total of 817), of Holocene age, plotted on diagram showing % of plant debris in the sand-size fraction versus % of vegetal debris in total sediment. Most samples (772) contain < 15% plant debris in total sediment; only a relatively small population (45 samples) is characterized both by > 15% vegetal debris in total sediment and by > 60% vegetal debris in the sand-size fraction.

C (to 24%). Foraminifera and ostracodes are rare in type C and present in type D; echinoderm spicules are present only in type D.

Twenty-four cores comprise sections with plant-rich types A, B and C. Forty-two of the 70 cores examined comprise only type D (< 15% vegetal matter). Only 5 cores contain no samples with vegetal matter.

#### ORGANIC-RICH LITHOSTRATIGRAPHIC SEQUENCES

The above four petrological types A to D are not randomly distributed in the 24 Holocene cores where they occur, but form a number of distinct depositional assemblages. These are termed lithostratigraphic sequences. Three major sequences are recognized here (Figure 5). These take into account the vertical succession of types and also the nature of the lithofacies just below and above the plant-rich layers.

**Sequence I**, formed of A, B and C, has a maximum thickness of about 5 m and occurs in 18 cores. It comprises at its base a thick dark grey

to black peaty layer (type A), ranging from 0.2 to 4 m, which lies unconformably above Holocene coastal sands or older sections including Pleistocene overbank muds or latest Pleistocene to early Holocene basal transgressive sands. Fresh water gastropods (M.P. BERNASCONI, 1990, *personal communication*) sometimes occur in this peaty sequence. Vegetal debris becomes progressively less abundant in grey sediment above the organic-rich type A peat layer. This sediment, usually mud (0.2 to 2 m), is of type B and then evolves to C toward the top of the sequence. The clastic sand-sized components abound in light minerals (20 to 35%) and mica (10 to 20%) throughout the entire sequence; sponge spicules are the only faunal component present. No obvious sedimentary structures are noted. The top of the sequence is bound by a sharp lithologic contact and is overlain by soft grey mud poor in vegetal matter (type D) or by sandy mud deposit. At one site (core S-8), this sequence comprises only a thin (0.2 m) peat layer (type A) which rests unconformably on a basal transgressive sand.

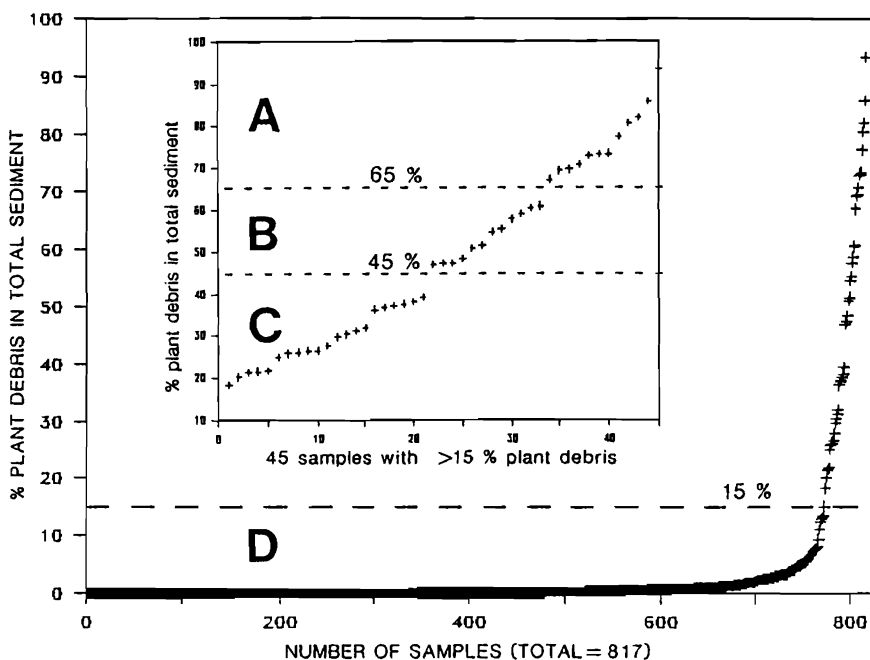


Figure 3. The population of 817 Nile delta core samples with vegetal matter is subdivided in 4 groups (A–D) based on % of plant debris in total sediment: A, peat; B, mucky peat; C, muck; and D, mucky mud. The expanded inset diagram details the attributes of 45 samples (types A, B and C) with > 15% plant debris in total sediment.

In this core, the top of the type A peat is truncated and overlain by a marine prodelta mud unit.

**Sequence II**, formed of types D, and (possibly C) B and A, has a maximum thickness of about 4 m and occurs in 4 cores. It fines upward from a grey sandy mud to dark grey or black type A peat layer, and is underlain by sand. The succession, from bottom to top, is constituted by a grey sandy mud unit with thin (< 1 cm) layers of sand that show cross-lamination, and then a grey homogenous silty mud or mud with vegetal remains (type D) and, commonly, traces of burrows and roots; light minerals (about 20%) and mica (to 25%) are the dominant clastic sand-sized components. This lower portion (1–3 m thick) is topped by a thin, dark grey transitional layer of peaty muck (type B, and possibly C) which, in turn, is covered by a peaty type A unit ranging in thickness from 0.5 to 1 m. This sequence is separated from an overlying soft grey mud unit of type D (usually shelly) by a sharp contact, sometimes erosional. A mollus-

can shell layer usually lies directly above the contact.

**Sequence III**, formed by types D and C, has a maximum thickness of about 4 m and occurs in 11 cores. It occurs, without sharp facies boundaries at its base and top, in sections of soft grey mud that contain only few scattered vegetal remains. Sequence III is typically represented by several (2 to 9) thin layers of dark grey muck (type C) alternating with grey mucky mud (type D). Variable numbers of thin layers of fine muddy sand are commonly interbedded in type D units. The thickness of these layers in the sequence ranges from 1 to 12 cm. The dominant clastic sand-sized components include light minerals (40 to 60%), glauconite/verdine (10 to 25%) and pyrite (4 to 11%). The faunal components in the sand-size fraction are more abundant and diverse than in sequences I and II. There are significant proportions of shell fragments, foraminifera, ostracodes and echinoderms. It is of note that fine horizontal laminae are well preserved; this

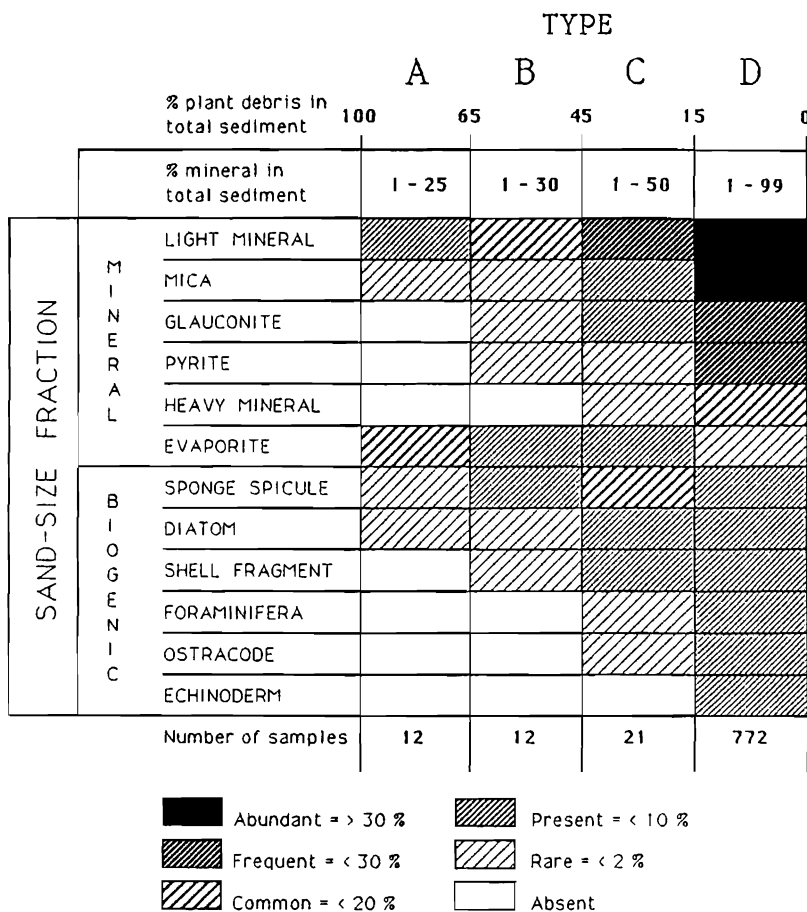


Figure 4. Diagram serves to distinguish the 4 types (A–D) of Nile core samples on the basis of abundance of vegetal matter and associated mineral and biogenic components of sand size.

well-laminated section is disrupted by long vertical root structures which penetrate the entire sequence.

A total of 39 of these I, II and III sequences are identified in various parts of the Holocene section in 24 cores. These cores may display one or several superposed sequences.

**DISTRIBUTION OF ORGANIC-RICH SEDIMENTS IN SPACE AND TIME**

This study demonstrates that plant-rich deposits are unevenly distributed in space and time in the northern Nile delta. When all 70 borings are considered from west to east, we find that the 817 samples of types A, B, C, and

D are concentrated primarily in cores of two widely-separated regions (Figure 6). The first, herein termed western sector, extends from the eastern part of Idku lagoon toward the central Burullus lagoon region. The second, termed eastern sector, extends from southwest of Damietta toward the southern Manzala lagoon region. In these two regions, an average of more than 5% vegetal debris per core is recorded.

The per-core values plotted in Figure 6 have been calculated by averaging the percentage of vegetal debris of samples with A to D types in each core. The number of such plant-rich samples per core is variable. Only 5 cores do not display any trace of vegetal debris (sites are shown by arrows in Figure 7A). Although not every A

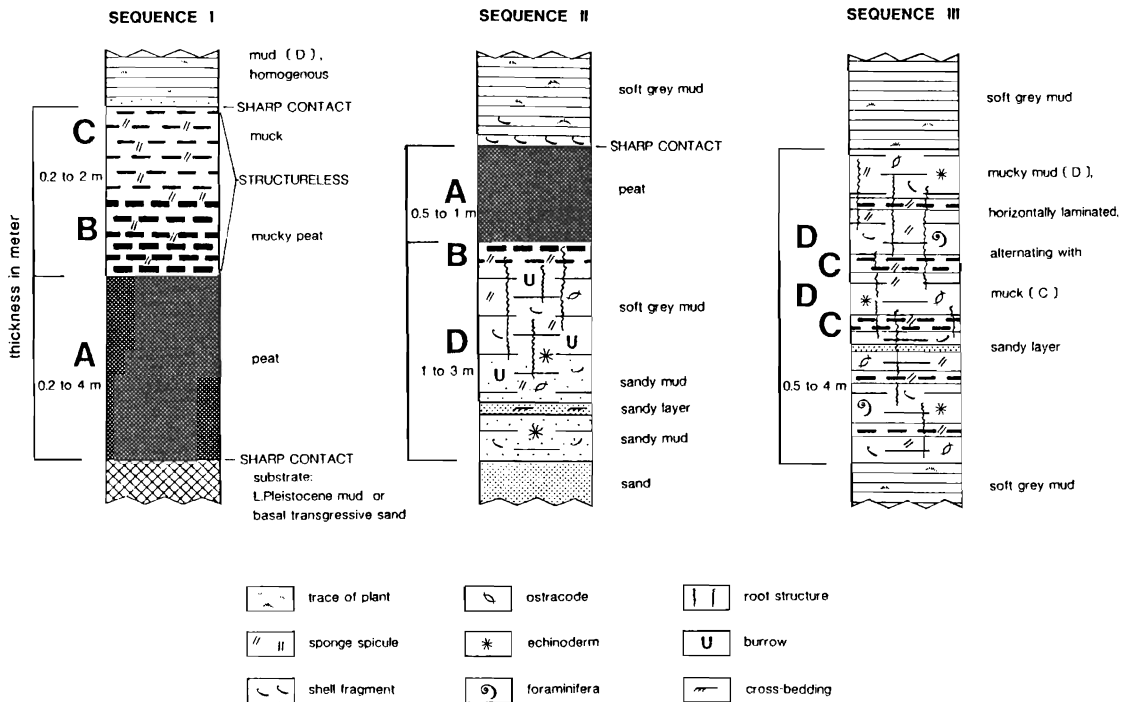


Figure 5. Simplified lithologic logs depicting the 3 major plant-rich sequences I, II and III of Holocene age which have been identified in 24 Nile delta cores (see Fig. 7A). A, B, C and D pertain to plant-rich types as defined in Figure 3.

to D layer has been sampled across the study area, there has been ample and consistent sampling of all 70 cores (total of 2200 samples) so as to provide a representative population of plant-rich facies for each of the cores considered. Thus, the data plotted in Figure 6 present a reliable indication of regional west-to-east variations in vegetal debris content.

Plant-rich samples of the western sector occur in 17 cores, and those of the eastern in 7 cores (Figure 7A). The southern limit of these deposits in the western sector lies about 30 km from the present coast; this is determined with Smithsonian cores from this study and also with borings described by ATTIA (1954) and WUNDERLICH (1988b). The southern extension in the eastern sector lies about 40 km from the present coast. The 17 cores of the western sector occupy an area of about 45 km long by 20 km wide. In contrast, the 7 cores with plant-rich samples in the eastern sector are distributed along a narrow arcuate belt approximately 65 km long.

Focusing on the lateral distribution of type A peat layers, we find a total of 93 strata in the two regions (Figure 7B). Most cores in the western sector contain more peat layers (average of about 5) than those in the eastern. The total thickness of peat layers (based on one or more layers/core) has been measured for each of the 24 cores (Figure 7C). The western sector comprises a higher average total thickness of peat (1.52 m) than the eastern (0.56 m). It is of note that, of the 24 borings containing plant-rich facies, core S-61 southeast of Idku lagoon comprises the greatest thickness (4.1 m). The percentage of total peat thickness per total thickness of Holocene section in each core has also been calculated (Figure 7D): cores in the western sector contain a higher average percentage of total peat thickness (11.2%) than in the eastern (4.2%). In both sectors, there is a marked south-to-north diminution in the percentage of type A peat thickness per total thickness of Holocene section (Figure 7D).

The lateral distribution of all plant-rich types

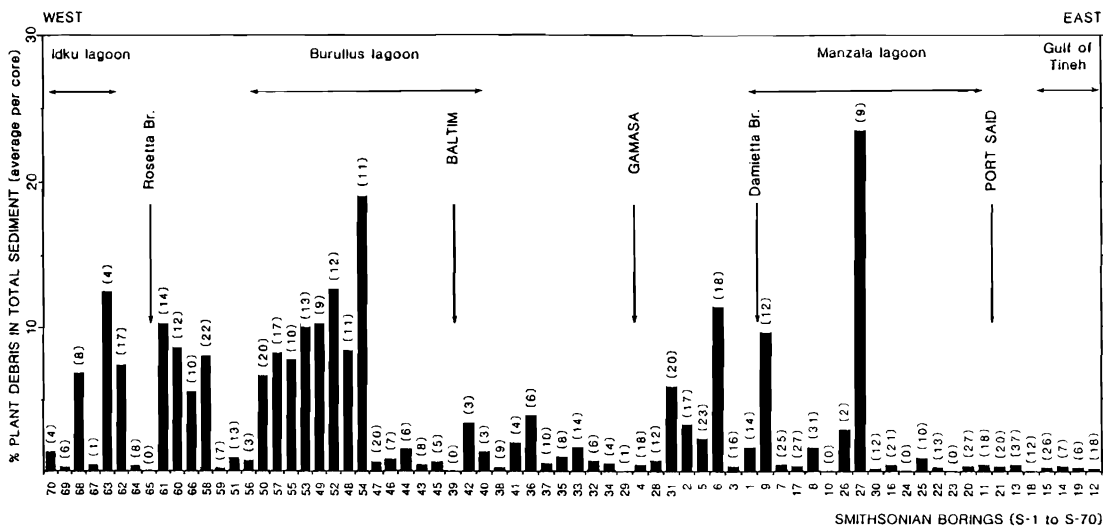


Figure 6. Bar graph showing the regional distribution, from west to east, of vegetative matter across the northern Nile delta plain. Each bar depicts average % vegetative matter in total sediment per core based on analysis of the 817 samples (number in parenthesis) which contained identifiable sand-size vegetative matter in 70 Smithsonian borings (S-1 to S-70).

(B,C,D), as well as peats (type A), has been determined. This is most readily shown by depicting the distribution of 39 plant-rich lithostratigraphic sequences I, II and III in the 24 cores (Figure 7E). Most of the 17 cores in the western sector comprise two or more sequences, while 6 of the 7 cores in the eastern sector include only one. Sequences in the east are, for the most part, of type I; those in the western sector include I, II and III. There is no systematic lateral distribution of sequence types within the western sector.

Ten cores in the west and one in the east display two or more superposed sequences (Figure 7E). It is of note that the lower sequence in most cores is a type I, regardless of geographic distribution.

Consideration is also made of the non-vegetal (mineral and biogenic) components in the sand-size fraction of the 39 sequences in the two sectors. Mineral and biogenic components are distributed in comparable fashion in both sectors, with the exception of a general absence of echinoderm spicules in the eastern sector.

Most of the 39 plant-rich sequences in the 24 cores have been dated (Figure 7F) by the radiocarbon method (using total organic carbon) and by interpolated ages (5 dates). A total of 33 radiocarbon dates are available for 31 of the 39

sequences (MEDIBA, 1990), a fairly even distribution throughout the study area. The 5 interpolated dates are derived from data in MEDIBA (1990). Three sequences have not been dated. Figure 8A shows that most of the 25 radiocarbon dates of sequences in the western sector range from about 7500 to 1700 years before present (B.P.). Sequences in two cores in this sector (toward the eastern portion of Burullus lagoon) show younger (about 1700 years B.P.) ages (Figure 7F). In contrast, 8 dated sequences in the eastern sector range from about 4000 to 2500 years BP (Figure 8B). An unusually old and probably questionable date of about 9000 years BP was recorded by a type A peat sample collected at the very base of core S-8 on the southern margin of Manzala lagoon. This peat layer lies directly on an underlying much older sand of late Pleistocene age.

The approximate rate of accumulation for plant-rich sequences, without taking into account compaction, has been calculated for four sequences. This is done by using two radiocarbon ages per sequence (MEDIBA, 1990). Two sequences are in the western sector (in cores S-54 and S-55) and 2 in the eastern (in cores S-9 and S-27). Average accumulation rates for type I sequences in cores S-9, S-54 and S-55 are, respectively, 0.18, 0.14 and 0.17 cm/yr. It is of

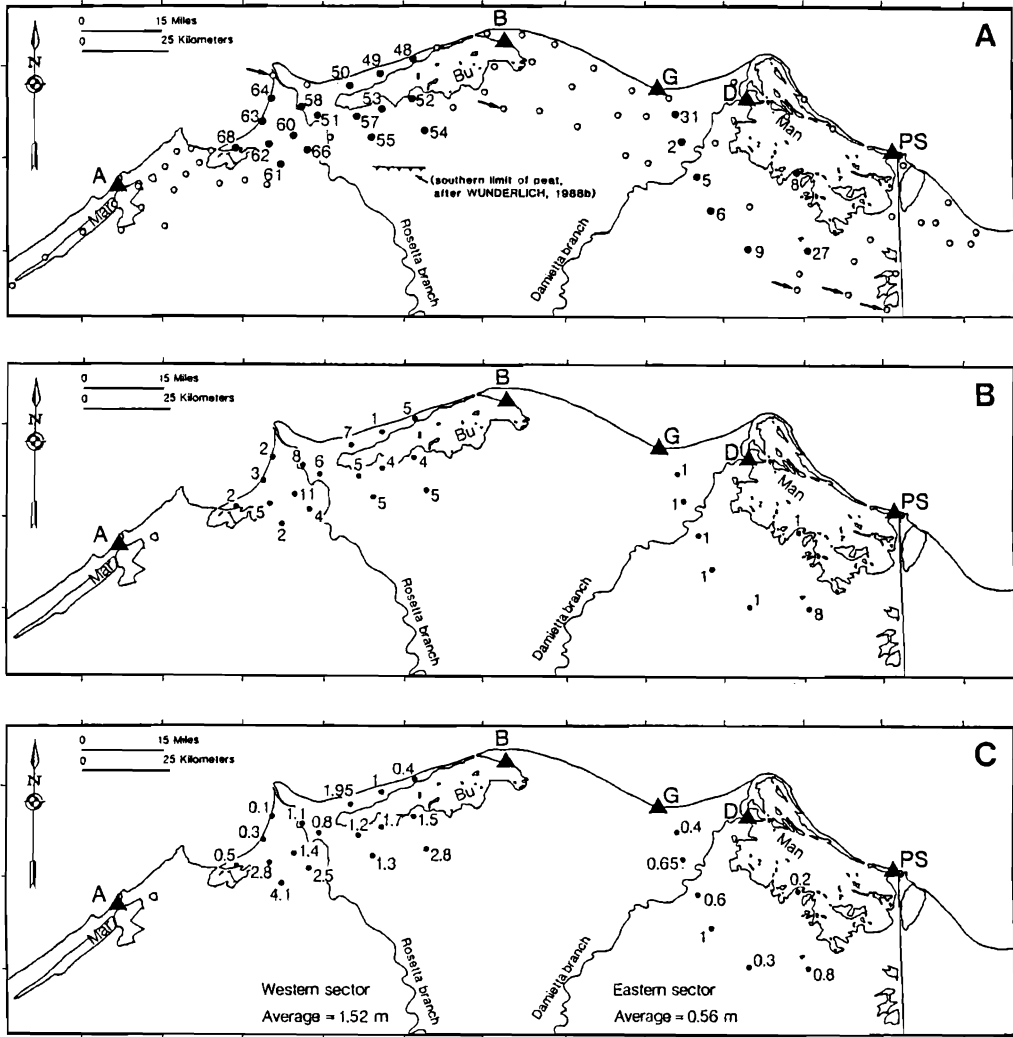


Figure 7. Series of maps showing spatial and temporal distribution of plant-rich deposits in the northern Nile delta. A, location of 24 cores (solid dots) with plant-rich types A, B, and C (17 borings in western sector, and 7 in eastern sector); also shown are 5 borings without any vegetative matter (arrows), and the southern limit of peat (after Wunderlich, 1988b). B, number of type A peat layers in each core. C, total thickness, in meters, of peat in each Holocene section, showing a higher average total thickness in the western sector (1.52 m) than in the eastern (0.56 m).

note that this rate for a type III sequence (in core S-27) is somewhat higher, *i.e.* 0.20 cm/yr.

**PLANT-RICH LAYERS, MARSH-LAGOONAL SETTINGS AND DILUTION EFFECTS**

The four sediment types containing vegetal remains (A to D) defined in the present study

are the basic framework units which constitute the major plant-rich lithostratigraphic sequences of Holocene age in the Nile delta. With the exception of studies of pollen and spores (SAAD and SAMI, 1967; and several others), and diatoms (SNEH *et al.*, 1986), there have been no systematic analyses and compilations of specific vegetal remains in subsurface core sections. It is recognized by most workers that peat and

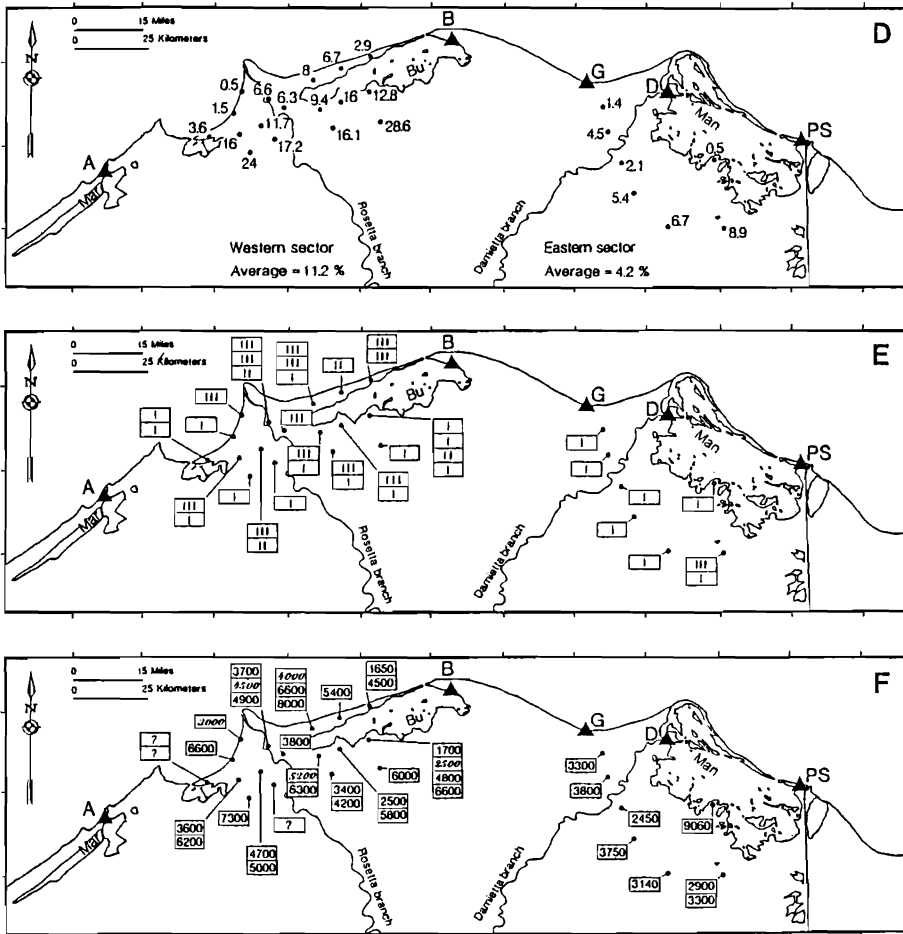


Figure 7 Continued. D, relative % of peat thickness per total Holocene section for each core, showing a higher average % in the western sector (11.2%) than in the eastern (4.2%). E, distribution of 39 plant-rich sequences I to III in the 24 cores; their superposition is shown where several sequences occur in a same core. F, ages in years BP of plant-rich sequences, based on radiocarbon dating method or interpolation (in italics).

other identified dark grey to black plant-rich types (A, B, C) are deposits which require water-saturated and generally reducing conditions.

Our sedimentological and petrological analyses of Nile delta core sections support the hypothesis that vegetal matter accumulated in wetlands on the former lower delta plain. We suggest that the most likely settings favoring plant growth and its preservation are marshes which would have developed in proximity to lagoon margins and seasonally-inundated interdistributary channel depressions. Pre-

vious studies, in fact, have suggested that marshes and lagoons covered large areas of the northern Nile delta at various times during the mid- and upper Holocene to the present (COUTELLIER and STANLEY, 1987, their Figure 7; ARBOUILLE and STANLEY, 1991, their Figure 11).

Modern Nile delta environments, such as marshes and lagoon margins where floral development is extensive (*cf.* MONTASIR, 1937; IWACO, 1989), can serve as examples to interpret some of the subsurface Holocene deposits considered in this investigation. On the present northern

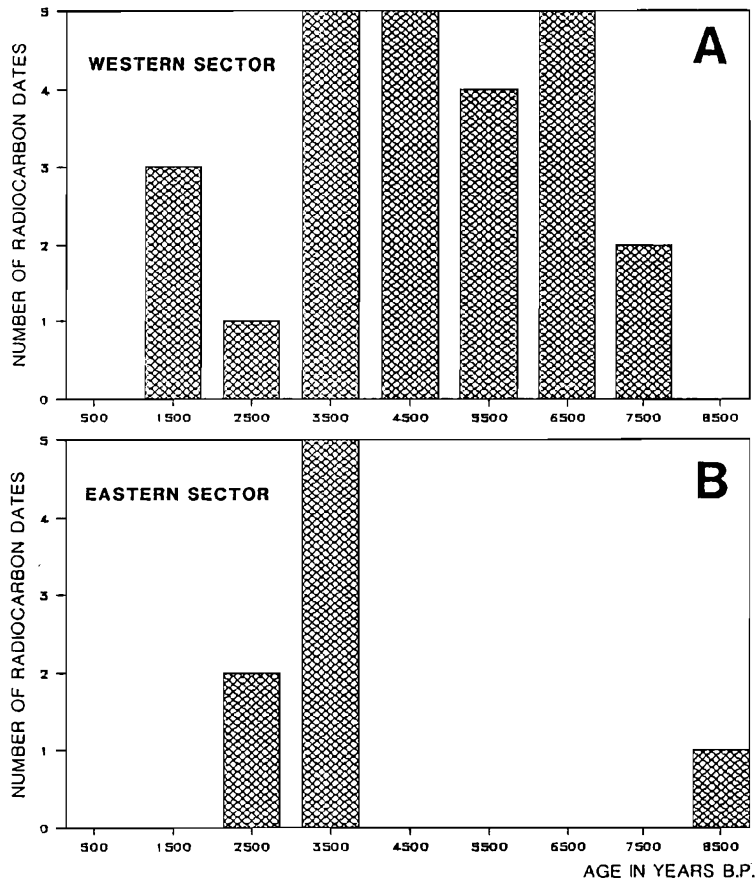


Figure 8. Diagrams showing the range of ages, in years BP, of plant-rich sequences in the western (A) and eastern (B) sectors of the northern Nile delta. Depicted are 33 radiocarbon dates for 31 of 39 sequences (see Fig. 7F).

delta plain, there are four shallow lagoons (EL-WAKEEL and WAHBY, 1970; KERAMBRUN, 1986) with associated fresh water to brackish and saline marshes (UNDP/UNESCO, 1976). These inundated areas of the delta which support extensive, primarily non-woody, plant growth, are marshes rather than swamps as defined by COLEMAN (1982) and other workers. It would appear that most Holocene subsurface sections with thick and laterally extensive peaty and/or associated deposits rich in vegetal matter formed in comparable environments. The former lagoons on the northern delta plain mapped by ARBOUILLE and STANLEY (1991) appear to have been sites where clayey silt, sandy mud and fine sand accumulated. These lagoon depos-

its comprise silt and clay which have relatively low amounts of vegetal debris (type D, but not A or B).

The four of the five cores in the study area where no vegetal matter was recorded (arrows in Figure 7A) almost certainly occupied sites just south of major marsh-lagoonal settings. There is additional evidence indicating that marshes and lagoons during the Holocene were restricted to the northern delta plain. A strong argument for this is that most borings recovered south of our core study area (FOURTAU, 1915; ATTIA, 1954) tend to be poor in vegetal debris. Moreover, this diminished abundance of vegetal matter in cores has been used to map the southern limit of peat (type A) devel-

opment south of the present Burullus lagoon (in Figure 7A, after WUNDERLICH, 1988b).

Vegetal components in the sand-size fraction that were counted in this study include fibers, undifferentiated vegetal matter and seeds of the remains of dominant autochthonous forms such as *Phragmites* and reeds, sedges and grasses similar to present Nile delta marsh and lagoonal flora. In addition to flora that evolved locally, we would also expect allochthonous components, *i.e.* seeds, spores and plant fragments derived from the distal River Nile headwaters in the Ethiopian and Central African plateaus (*cf.* MONTASIR, 1937; SNEH *et al.*, 1986). This allochthonous fraction was, in fact, noted in a study of the flora in a core recovered south of Rosetta (near Berenbal, SAAD and SADI, 1967), close to our core S-51. Specific floral components are to be identified and numerically evaluated in subsequent investigations.

The surface distribution of modern marsh-lagoon systems on the northern Nile delta is irregular and discontinuous, perhaps not unlike those existing in the past. These environments tend to be elongate and lie behind coastal sand ridges (SAID, 1958; SESTINI, 1989); such settings are ideal for the development of back-barrier marshes (*cf.* GALLOWAY and HOB-DAY, 1983). Their position relative to the coast and their pronounced shore-parallel trend are largely a function of the Nile's delta being wave-dominated. As at the present, coastal ridges developed in response to easterly-driven currents prevailing along the coast (INMAN and JENKINS, 1984).

The evolution of associated lagoons and marshes during the past 7500 years of the delta's progradational history can be linked (as they are now) to the formation of (a) promontories at the mouth of major distributaries and (b) coastal sand ridges (SAID, 1958; EL-ASKARY and FRIHY, 1986). The configuration of such back-barrier marshes would have been modified not only by coastal processes affecting beach ridges but also by migration and switching of River Nile distributary channels and by man. This latter anthropogenic impact has been in play during much of the delta's history (BUTZER, 1976), but has increased markedly in recent years due to damming, irrigation, land reclamation and aquacultural projects (WATERBURY, 1979).

The four sediment types with vegetal matter,

even the most plant-rich (type A, with 65% or more of floral remains of sand size and coarser fractions), include variable amounts of mineral and biogenic components (Figure 4). This compositional mix would indicate that some layers, such as type A which probably formed *in situ*, were affected by dilution effect (*cf.* COLEMAN and SMITH, 1964; KOSTERS, 1989; KRONENFELD, 1989). Dilution, in pre-Aswan High Dam time, most likely resulted from seasonal flooding of the delta plain via overbank deposition along River Nile distributaries (*cf.* BUTZER, 1976). Detrital input from flooding would consist largely of siliciclastic, and not biogenic, components associated with vegetal matter of variable size. Overbank flow and crevasse-splay processes would have resulted in siliciclastic deposition localized along channels (*cf.* ELLIOTT, 1974). More widespread depositional events in the delta are attributed to distributary channel migration and switching (COUTELLIER and STANLEY, 1987; ARBOUILLE and STANLEY, 1991). Even larger-scale phenomena were influential in changes of fluvial input and associated dilution effects during the Holocene. These include major paleoclimatic oscillations which affected large areas of the East Africa drainage basin (*cf.* ADAMSON *et al.*, 1980; PAULISSEN and VERMEERSCH, 1989). Such changes in fluvial input from Blue and White Nile headwaters, as determined by mineralogical fluctuation in delta core sections (FOUCAULT and STANLEY, 1989), would explain the irregular input with time of allochthonous flora (SAAD and SAMI, 1967; SNEH *et al.*, 1986).

The dilution effects in some plant-rich deposits, as recorded by clastic components, are from marine rather than fluvial influx effects. Petrological data provide evidence for some transport of sediment to marsh-lagoonal settings from adjacent nearshore sectors. This is recorded by increased proportions, with the vegetal matter, of marine micro- and macrofossil remains and also grains of glauconite/verdine derived from the delta-front (PIMMEL and STANLEY, 1989). As in the case of many low-lying coastal regions seasonally affected by storms, we find evidence for sediment displacement by washover along the northern Nile delta. Core analysis indicates that non-floral components were displaced by winter floods passing over coastal sand ridges which separate nearshore marine settings from the marsh-

lagoon systems behind them (ARBOUILLE and STANLEY, 1991). Dilution by marine components can occur in other ways, such as by influx of shallow marine sediments landward into a lagoon via a coastal inlet cut across the coastal ridge system (*cf.* EL-WAKEEL and WAHBY, 1970).

It is with the specific assemblages of non-floral sand-sized components associated with the vegetal matter that we can distinguish, in a very general way, two marsh-lagoonal end-members: those that are proximal to and primarily influenced by the sea; and those that are primarily influenced by fluvial input. In some instances, these latter marshes can be positioned close to the coast, but are shielded from the direct influence of inland sediment transport from the sea.

#### PLANT-RICH SEQUENCES AND EFFECTS OF SUBMERGENCE

There are other factors, in addition to dilution, which control the rate of peat formation. Among the more significant is rate of submergence of the substrate on which vegetal debris accumulate (COLEMAN and SMITH, 1964; KOLB and VAN LOPIK, 1966; KOSTERS *et al.*, 1987; KRONENFELD, 1989). Development of thick peat over a broad area (blanket peat) implies plant growth which keeps up with a slow rise of the water table, and also biological and chemical conditions favorable for preservation of the floral mass after accumulation. Submergence may be due to subsidence of land relative to the sea, or to eustatic rise in sea level, or to both. A reduction of vegetal accumulation or a truncated peat layer as we note in some cores results from the inability of plant growth to keep pace with rising water level, and/or increased influx of detritus and the effect of dilution (FISK, 1960; GALLOWAY and HOBDA, 1983). In some parts of deltas, peat development can also be retarded by an emerging substrate: in such cases, decrease in water saturation arrests the development of plant growth and/or accumulation.

The three plant-rich lithostratigraphic sequences (I,II,III) recognized in the northern Nile delta cores provide a record of some of the above-cited depositional conditions during the Holocene. Sequence I, with A, B and C types from base to top, is the most common unit in both western and eastern sectors of the delta

plain. Several attributes are of note: (1) the basal type A peat layer lies unconformably above older deposits; and (2) a progressive decrease in the amount of vegetal matter and associated increase in siliclastic components toward the upper part and top of the sequence. These attributes suggest that peat (type A) formed on a submerging substrate. COLEMAN and SMITH (1964) refer to such layers as transgressive peats. In time, types B and C accumulated at the site as water depth and/or detrital influx increased. Similar sequences have been described in the lower Mississippi delta plain in settings such as abandoned delta lobes (KOSTERS *et al.*, 1987). In Holocene sections of the Nile delta, sequence I occurs above coastal sand or lagoonal mud, and is topped by lagoonal sandy mud and mud. The stratigraphic position of such sequences in core sections suggests accumulation in water-saturated depressions near the outer delta plain, usually in association with a shore-parallel coastal ridge system such as depicted by GALLOWAY and HOBDA (1983, their Figure 12.6). At some sites in both the western and eastern sector, type I sequences occur at the base of the Holocene section directly above either sands or muds of late Pleistocene age. A somewhat comparable stratigraphic situation is described in coastal sections of North Carolina (KRONENFELD, 1989) and in Florida Bay (DAVIES and COHEN, 1989).

Sequence II, with types D to A from base to top, is the least frequently encountered, and occurs only in three cores of the western sector. Here, the most plant-rich type (A) is at the top of the section rather than at the base, and is sharply truncated by an overlying mud (sometimes shelly) of lagoonal origin. The sequence indicates that conditions for peat development improved with time, perhaps as a result of a shallowing of the water table and/or progressive decrease in lagoon water depths. The sequences resemble sections in deltaic environments described by other workers, *i.e.* those that comprise thin cross-bedded sand layers and muds topped by peat and organic-rich layers (*cf.* ELLIOTT, 1974, his Figure 1). Somewhat similar peat-topped facies attributed to basin fill have been noted in the lower plain of the Mississippi delta (Barataria Bay) by KOSTERS (1989) and the Elbro delta by MALDONADO (1975). As in these deltas, the base of sequence II in Nile delta cores indicates accumulation in

an area of active sedimentation. The increasing amount of plant debris upward and other petrological attributes (such as root structures), identify depositional settings that experienced accretion; a consequent shallowing of the water body fostered increased plant growth. Such conditions on the lower Nile delta plain may have resulted, for example, by migration, by-passing or switching of a distributary channel away from the site. Displacement of a depocenter, away from a core site for example, would result in less clastic input and diminished dilution effects. The presence of sequence II may indicate filling of an interdistributary depression or a build-up of a lagoon margin, *i.e.* conditions favoring local floral growth and vegetal matter accumulation.

Sequence III, comprises numerous alternating layers of plant-rich types C and D, but without notable type A peat development. These occur, without sharp stratal boundaries, in core sections of lagoonal muds. Sequence III is more widely distributed than sequence II (Figure 7E). The presence of some marine biogenic components and of glauconite/verdine grains derived from the delta-front setting (PIMMEL and STANLEY, 1989) suggests that these sequences accumulated in brackish to salt marshes influenced by the sea. Root structures indicate that plant debris was not displaced but accumulated *in situ* and that the marsh settings were protected from the open sea. Some brackish to salt marshes in open and restricted bays of the Mississippi delta, described by FRAZIER and OSANIK (1969), may serve as examples. In the Nile delta, alternations of many thin organic-rich types in sequence III indicate that the marsh-lagoon sites were subject to fluctuations of clastic input (dilution effect) as well as to changing configuration with time.

### PALEOGEOGRAPHIC CONSIDERATIONS AND CONCLUSIONS

Depositional environment is a more significant factor than climate in controlling regional variations of plant-rich facies. This is borne out by the presence of plant-rich sediments in most cores recovered in the northern Nile delta (Figure 6), a depocenter which developed in an arid region. We recall that Holocene facies of marsh and/or lagoonal affinity have recently been mapped across much of the northern Nile delta

plain (COUTELLIER and STANLEY, 1987; ARBOUILLE and STANLEY, 1991). The present study, however, reveals that Holocene plant-rich sequences, including peat, are not ubiquitously distributed but, rather, are restricted to two separate and distinct sectors. Core sites in the western sector usually comprise several superposed plant-rich sequences, whereas most of those in the eastern sector are characterized by only one sequence. Moreover, the age of the sequences differs in the two regions: type A peat and associated facies accumulated during a much longer duration in the western sector (about 7500 to 1700 years BP) than in the eastern sector (about 4000 to 2500 years BP). This discontinuous stratigraphic configuration of plant-rich sequences can be related with the paleogeographic evolution of the lower Nile delta plain margin during the Holocene. The regional variations are highlighted by four lithologic cross-sections of the western sector and one of the eastern sector (Figure 9).

In the western sector, the thickest and most extensive type A peat layers are concentrated in the southwestern area. Blanket peats in this sector are also the oldest of such Holocene units on the Nile delta plain. These layers (always part of sequence I) thin toward the east (section 2) and also toward the north (sections 1, 3, 4). Peat layers accumulated on either late Pleistocene sand or mud substrates. Sequence I, always the lower of superposed sequences, records early phases of submergence of this delta plain surface during the Holocene. This submergence was progressive and of sufficient duration to allow vegetal matter to accumulate as a thick mass (to > 4 m compacted thickness in core S-61). It appears that marshes occupying the southwest area received less detrital influx from the sea and from flooding via distributary channels (at core site S-52), than marshes toward the north and east. Basal sequence I was covered by lagoonal deposits, usually mud and sandy mud. This stratigraphic configuration records the eventual encroachment by the sea onto coastal marshes, many of which lay behind a coastal ridge system.

During much of the Holocene, sea level has risen relative to the northern delta plain due to eustatic sea level rise and tectonic subsidence (STANLEY, 1990). Nevertheless, the restricted occurrence of sequence II facies in this marsh-

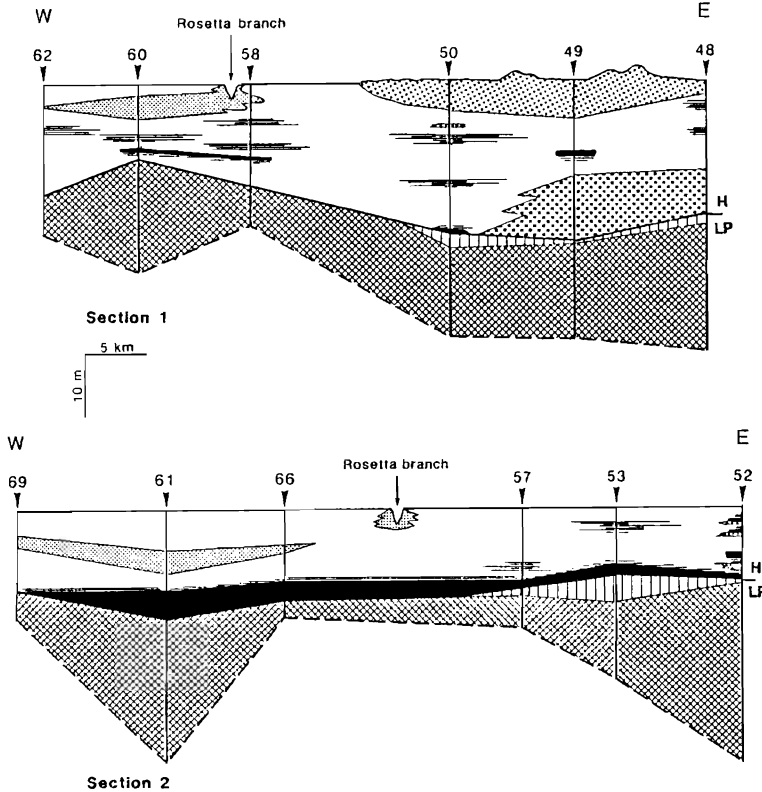
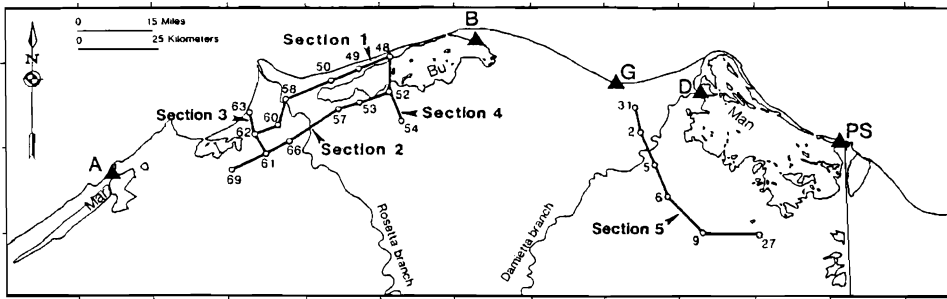


Figure 9. Stratigraphic cross-sections for the western (sections 1–4) and eastern (section 5) sectors comprising plant-rich sections in the northern Nile delta, based on petrologic analyses of sediment borings. The lateral distribution of sequences I, II and III, which likely accumulated in back-barrier marshes, is shown relative to late Pleistocene (LP) and Holocene (H) sections.

lagoonal setting of the western sector records very localized phases of emergence or near-emergence. These surfaces on which plants grew likely resulted from sediment input and accretion from the evolving River Nile distributary channel system.

Sequence III in younger core sections

throughout the western sector records a changing configuration of the marsh-lagoonal system. This is a function of fluctuations in sea level (due to both continued land subsidence and eustatic sea level rise) and in detrital influx (channel switching and displacement of lagoonal outlets). Sequence III, particularly at

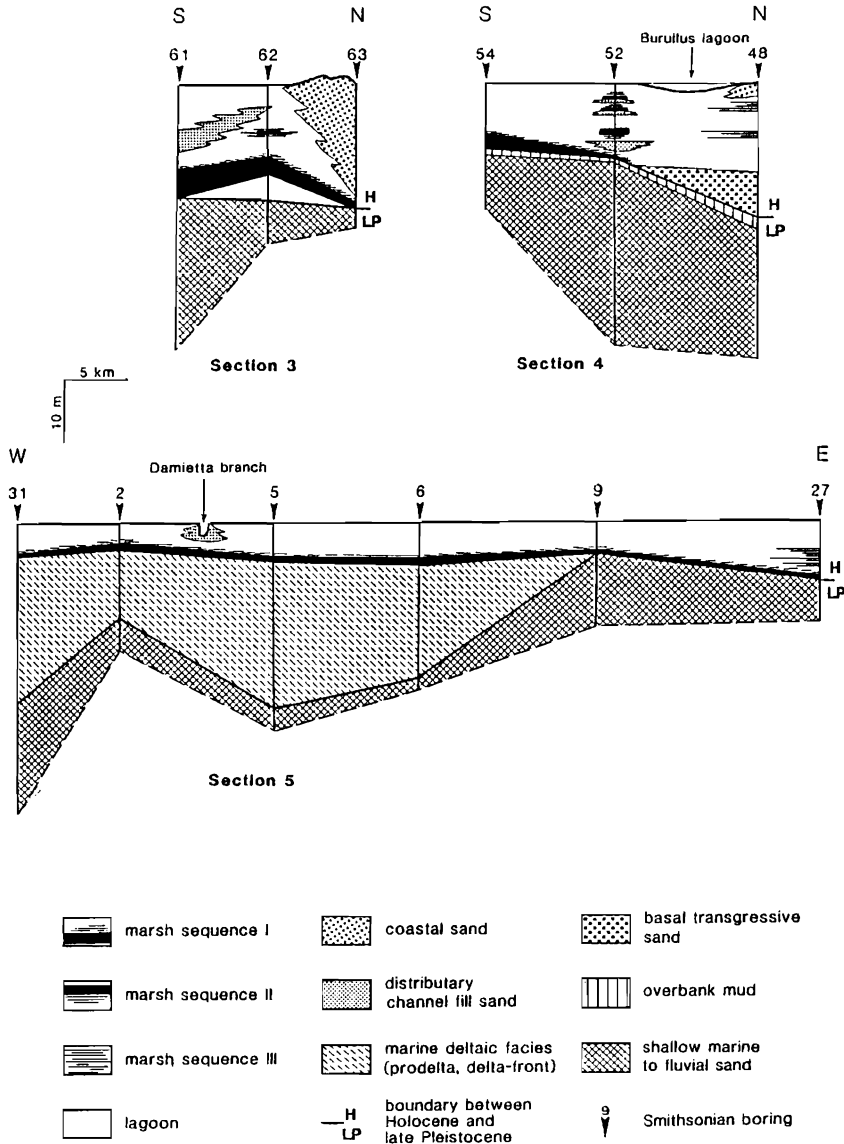


Figure 9. Continued.

core sites toward the north of the western sector, records increased clastic influx from the sea; these localities were likely positioned behind, or in proximity to, coastal sand ridges (sections 3, 4).

This study reveals that the large marsh-lagoon system which occupied the north-central delta plain region west of Baltim during most of the Holocene depositional history

(ARBOUILLE and STANLEY, 1991) extended, until recently, at least as far west as the present Idku lagoon (sections 1, 2). Total peat (layer A) thickness in some cores in parts of this area accounts for as much as 25% of the total Holocene section (Figure 7D). It is of note that such large proportions of peat thicknesses and high rates of accumulation measured locally in the Nile delta—a depocenter forming in an arid set-

ting—are comparable to those in some deltas in temperate and tropical climatic regions (*cf.* COLEMAN, 1982).

In contrast to the western sector, most sites in the eastern sector (south of Manzala lagoon), comprise only type I sequences (section 5). These sites are localized in a narrow belt that roughly parallels the present coast and lies further landward on the delta plain than plant-rich sites in the western sector. Peat accumulated during a more restricted time period, and is much younger, than the basal peat in the western sector (Figure 7F). Moreover, they usually lie above Holocene marine deltaic facies (delta-front or coastal sands), rather than on a late Pleistocene substrate. Sequence I organic-rich layers in this region are generally thinner indicating that vegetal matter had less time to accumulate on the substrate than those in the western sector. The presence of a sequence III in core S-27 is perhaps related to fluvial input from the Nile's Tanitic or Pelusiac Branch (SAID, 1981) which modified marsh development in this region. It appears that incursion by the sea (related to higher subsidence rates) have been particularly important in the northeastern Nile delta. This is indicated by (a) the much narrower and linear zone of plant-rich layer and peat development, (b) its more limited thickness, and (c) its lithostratigraphic configuration in the eastern sector. Regional geological studies, in fact, have shown that during the Holocene, the Manzala lagoon region was subject to remarkably rapid subsidence, particularly in the northeast (STANLEY, 1988). This is a result of tilting seaward of the lower delta plain toward the northeast (ABU-ZEID and STANLEY, 1990; STANLEY, 1990).

In both western and eastern sectors, peats accumulated landward of the area of direct marine influence. Of note, however, is the absence of plant-rich sequences (I to III) in three broad areas of the northern delta: (1) the northeasternmost delta (east of Manzala lagoon and south of the Gulf of Tineh); (2) the region between the central part of Burullus lagoon and Gamasa; and (3) the northwesternmost delta (west of Idku lagoon). Holocene sections cored in these regions comprise characteristic lagoonal deposits (MEDIBA, 1990), including type D layers. Moreover, rates of tectonic subsidence affecting the western plant-rich sector and contiguous areas to the east and west of it

without peat have been comparable during the Holocene. Thus this neotectonic factor alone does not explain the absence of plant-rich layers. One could, perhaps, invoke the role of markedly changing climatic conditions during the past 7500 years, from humid to dry at about 5000–4000 years BP (ADAMSON *et al.*, 1980; PAULISSEN and VERMEERSCH, 1989). However, peats (type A) and associated deposits (types B,C,D), dated from at least 7500 (humid phase) to about 1700 years BP (dry phase) in the western sector, indicate that paleoclimate has not been the dominant controlling factor. Rather, the absence of plant-rich types is more likely a function of limited marsh development in these regions. Those marshes and seasonally inundated depressions that were present are likely to have been locally restricted, small and short-lived.

The data presented in this study of the northern Nile delta emphasizes the close relationship among plant growth and preservation of vegetal material, submergence as related to eustatic sea level rise and neotectonics, and changing geographic configuration of the depositional environment in response to marine and fluvial transport processes. The evolution in time of coastal ridges, behind which back-barrier marshes and lagoons formed, and detrital influx from distributary channels have been significant factors in determining marsh configuration. Paleoclimatic oscillations affecting East Africa, including Egypt, during the past 7500 years inevitably influenced conditions leading to plant growth and accumulation in the northern Nile delta plain. This latter factor, however, does not appear to have been of primary importance in controlling the distribution patterns and accumulation rates of peat across the delta plain. Specific identification of the vegetal matter and associated fauna, plus systematic analysis of the organic carbon and trace element content of floral-rich core samples are projects initiated in conjunction with the present study. These will serve to further elucidate depositional conditions under which vegetal matter accumulated in the Nile delta during the Holocene.

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