Human-induced sedimentological changes in Manzala Lagoon, Nile Delta, Egypt

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Abstract The Manzala Lagoon in Egypt's Nile Delta has become a sediment sink of reduced area and depth, with increased contaminant levels. Loss of much-needed fresh to brackish water reserves and decreased fish catches have serious ramifications. Herein, maps of temporal and regional sediment distributions in Manzala incorporate petrological and statistical analyses of 200 surficial and short core samples. These provide baseline information needed to help implement protection measures for this vital wetland. Four periods are considered: 1920s, 1940s, ~1965, and 1990. Important depositional changes between 1940s and ~1965 resulted from anthropogenic effects on this quasi-closed lagoon system, including industrial buildup, wetland conversion to agricultural land, and irrigation waterway development. Further modification from ~1965 to 1990 is associated with closure of the Aswan High Dam, continued construction of waterways that discharge waste water into lagoon margins, and marine incursion into the northern lagoon. If current practices continue, the lagoon could be reduced to about one-third of its present area by 2050 AD.

Key words Delta lagoons · Fish resources · Manzala Lagoon · Nile Delta · Pollution · Waste water

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Introduction

Wetlands in the northern part of the Nile Delta have been significantly altered by anthropogenic activity during the past century. These serve as large, much-needed fresh to brackish water reservoirs and major fish resources for Egypt (George 1972). The marsh and lagoon systems, of which only four remain in the delta (Maryut, Idku, Burullus, Manzala), continue to be reduced in area and otherwise modified as a function of increased population pressures (Sestini 1989; Stanley and Warne 1993). Since the turn of the century, the margin configuration and hydrographic, floral, faunal, and other attributes of the delta wetlands, positioned near the Mediterranean coast (inset, Fig. 1), have been markedly altered. Numerous articles and unpublished reports (citations in Kerambrun 1986) summarize attributes of the lagoons and adjacent marshes, and call attention to recent changes as ever larger sectors of these vital wetlands continue to be converted for agriculture and aquaculture (Waterbury 1979). Most studies of the recent delta lagoons have emphasized chemical, physical, and biological attributes (Kerambrun 1986).

Population density (locally to >1000 persons per km^2) and industrialization have increased significantly since the Second World War, and in 1964 the High Dam began to function on the River Nile at Aswan. These factors have altered Nile flow and sediment and waste-water discharge and, in turn, induced alteration of the Manzala Lagoon morphology and deposits accumulating in this quasi-closed system. Little information however is presently available on these topics, even though depositional changes are affecting water quality and toxicity in Manzala, presently the single largest fish source for Egypt's growing population.

The present sedimentological study of Manzala, the largest of the delta lagoons, updates earlier surveys (El-Wakeel and Wahby 1970b; Saad 1980), and also complements those made of Idku, Burullus, and Maryut (Arbouille and Stanley 1991; Loizeau and Stanley 1993, 1994) as part of the Smithsonian's Deltas-Global Change Program to evaluate modern depositional attributes of Nile Delta wetlands. Herein, we focus on petrological change of Manzala deposits that have accumulated during an approximately 70-year period (~1920–1990) in this century. Changes of paleogeography and of sedimentary petrology that have occurred in recent time and space in the Man-

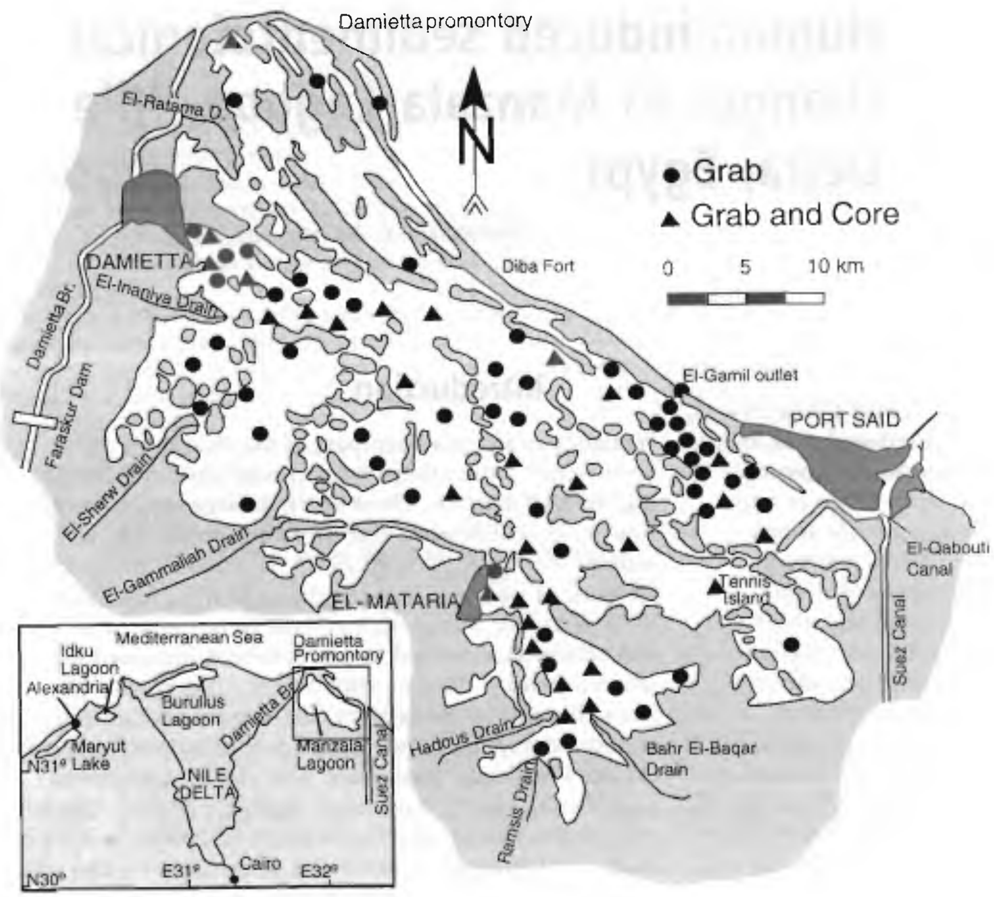

Fig. 1
Map of Manzala Lagoon study area in the NE Nile Delta, showing position of 83 grab and 30 core sites. Also shown are major drains and localities cited in text

zala wetland are recorded in this article. New sedimentological data presented supplement information that was documented earlier, including satellite imagery (Abdel-Kader 1982), geochemistry (Siegel and others 1994, 1995), hydrography (El-Sayed El-Hehyawi 1977; Shaheen and Yosef 1978) and paleobiology (Bernasconi and others 1991; Pugliese and Stanley 1991; Bernasconi and Stanley 1994). The updated data base is herein developed to help managers implement protection measures for this vital Nile Delta sector. Our record, documenting the altered depositional regime in this wetland system during this century, serves to measure the recent impact of anthropogenic activity associated with population expansion around Manzala.

Description of study area

Manzala Lagoon, situated in the northeastern Nile Delta, is a shallow, rhombohedral-shaped wetland (Fig. 1) formed in the actively subsiding delta plain (Stanley 1988, 1990). The lagoon is bound by sand ridges to the north (Fig. 2a) and marshes (Fig. 2b) along its three other margins; marshes are characterized by rooted plants, including *Phragmites sp.*, *Potamogeton sp.*, *Ceratophyllum sp.*, and *Najas sp.* (Shaheen and Yosef 1978). The longest axis (NW–SE) of the wetland, parallel to the Mediterranean coast, is ~50 km; the maximum width across the lagoon, trending NE to SW from the coast inland to the southern shore, is ~30 km. As of 1990, the surface area of the lagoon had been reduced to about 950 km^2. The lagoon is shallow (Fig. 2c–f): water depth greater than 100 cm accounts for 25% of the lagoon area; between 50 and 100 cm about 50% of area; and less than 50 cm in the remaining 25% of area (Shaheen and Yosef 1979). Water exchange between Manzala and the sea occurs primarily at the El-Gamil outlet (Fig. 2a), located ~4 km west of the city of Port Said.

At its northern margin, Manzala is separated from the Mediterranean by a series of broad (0.5–2 km), subparallel sand ridges that are typically 1 to 2 m in elevation. During winter, seawater is driven into the lagoon via the El-Gamil outlet and across the ridges, especially by southwest-directed storms. The eastern lagoon receives saltwater from the Suez Canal via the El-Qabouti canal (Fig. 1), positioned a few kilometers south of Port Said. Until the seventh century, the lagoon received freshwater from the now-defunct Pelusiac, Tanitic, and Mendesian branches of the Nile (Montasir 1937); after that time, freshwater was primarily derived from the Damietta branch. Now freshwater from the Damietta branch (between Faraskour Dam and Damietta) flows eastward to the lagoon via El-Ratama, El-Inaniya, and other canals (Fig. 1). By 1965, these canals had been modified and their discharge reduced salinity of western lagoon water (El-Wakeel and Wahby 1970a).

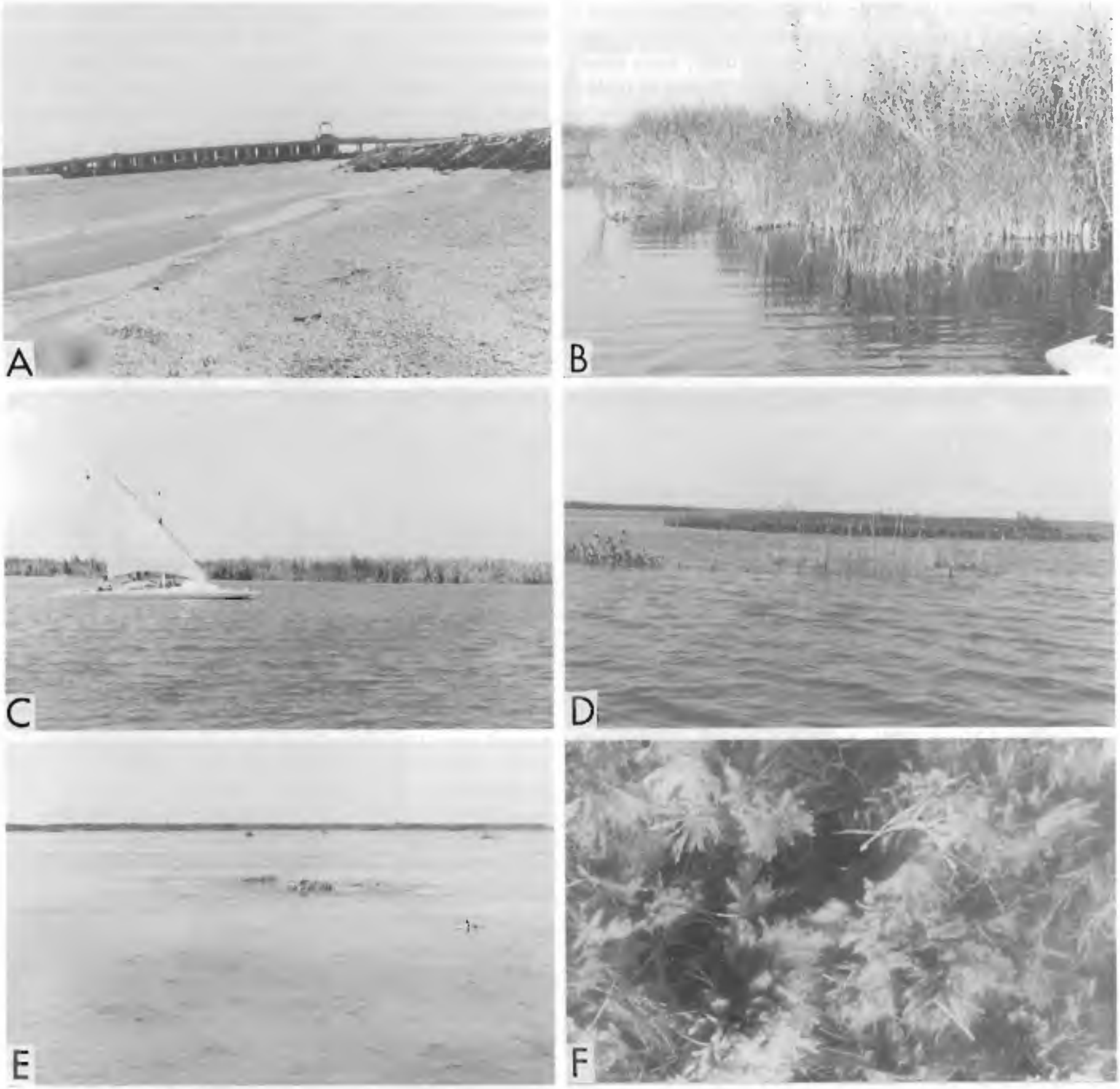

Fig. 2a–f
Photographs (1990) showing aspects of Manzala Lagoon discussed in text. **a** El-Gamil outlet and adjacent embankment west of Port Said, and shelly sandy sediments as viewed from Mediterranean coast; **b** marsh in western lagoon, south of Damietta; **c** shallow-draft felucca, typically used for fishing, in SE lagoon near El-Mataria; **d** floating island (water hyacinth) near Bahr El-Baqar drain, SE lagoon; **e** emergent vegetation in shallow lagoon, southeast of Damietta; **f** dense algal growth on shallow lagoon floor in SW lagoon

Prior to closure of the High Dam, seasonal floods carried a fine-grained sediment load ranging from 0.22 to 0.40 g/l, corresponding to annual solid transport of about 450000 tons (El-Wakeel and Wahby 1970b). Until 1964, the western part of the lagoon became saline from March to July as a result of evaporation and entry of sea water. After that time, however, with flood control measures in place at the High Dam and at other structures on the Nile, and water diversion in the delta west of the lagoon, there has been a consequent increase in freshwater flow into the lagoon, primarily from the south and west. Along the southern and southeastern sectors, the El-Sherw, El-Gammaliah, Hadous, Ramsis, and Bahr El-Baqar (Fig. 1) drains and other large waterways continued to carry wastewater into the lagoon from towns and agricultural land between Cairo at the southern delta apex and NE sectors of the delta plain.

The lagoon floor typically comprises terrigenous mud, sandy mud, muddy sand, and sand with abundant molluscan (commonly *Cardium*) shells and fragments.

Hundreds of islands in Manzala are of variable size and shape, formed of mud and sand, and surrounded by vegetation (Montasir 1937). Three island groups, some inhabited by fishermen, are distinguished according to textural and geomorphologic characteristics and geographic position (El-Askary and Lofty 1980): islands in the northern lagoon sector, parallel to the coast between Damietta and Diba Fort, are large, sand-rich, flat, slightly curved with irregular and indefinite shorelines; smaller islands in the central and eastern sectors are mud-rich and more commonly oriented in a N–S or NW–SE direction; and islands in the southern sector, also mud-rich, are somewhat smaller. Archaeological sites on some islands, such as Tennis southwest of Port Said, indicate that this region has long been inhabited. There is a probable relation between the northern islands and former NW–SE trending coastal sand ridges: these islands record former northward-prograding ridges (Sestini 1976). Formation of the central and southern islands, less elongated and some trending south-to-north, have been attributed to deposition along former branches of the Nile in this region (Abdel-Kader 1982).

Dominant winds blow from the NW quadrant, some with maximum intensities in July and August (Quelennec 1977). Average minimal air temperatures are recorded in December and January (12°–15 C), and average maximum ones in July and August (27°–28 C). Lagoon water temperature varies seasonally and parallels air temperature largely as a function of stirring of shallow (< 1 m) water (Shaheen and Yosef 1978). Available records also indicate seasonally altered water salinity, ranging from high in the summer to low in the winter. Prior to the 1960s, from April to October (period of high evaporation), seawater was drawn into the lagoon, while from November to March the excess, less saline lagoon water flow was generally directed seaward. Mixing of fresh, brackish, and marine waters continues to be partially influenced by wind: those from NW and NE quadrants drive water toward the southern lagoon margin; wind from SE and SW quadrants pushes less saline lagoon water toward the northern sand ridges and sea (Shaheen and Yosef 1980). On the basis of water salinity, Wahby and others (1972) subdivided the pre-1970s lagoon into three areas: northern sector, with values ranging from 2.9 g/l in October to 10.1 g/l in July and, locally, in more direct contact with open seawater; southeastern sector, with values from 0.68 g/l in December to 2.0 g/l in July, with strong influence of freshwater flowing into the wetland from canals; and western sector, with values between 1.21 g/l in December and 3.12 g/l in August, influenced by Faraskur dam on the Damietta branch of the Nile and by diverse canals discharging into the west, southwest, and south lagoon margins.

The distribution of organic material in bottom sediments is highest along lagoon margins (Fig. 3b), with high values of 4.7 and 7.3% organic matter recorded at the mouths of El-Qabouti and Bahr El-Baqar canals (El-Wakeel and Wahby 1970a). Organic matter (from plant decomposition and diverse anthropogenic sources discharged into the locally eutrophic wetland) tends to diminish towards the lagoon center. High carbonate content recorded in more open Manzala, on the other hand, is primarily related to preservation of high proportions of debris from molluscs and other organisms such as serpulid worms (*Mercierella enigmata*).

Methodology

Field studies were undertaken in September 1990 using shallow-draft outboard motor boats to recover samples throughout Manzala, and also to survey recent morphologic changes along Manzala Lagoon margins. The geographic position of topographic features, such as coastal promontories along the southern and western margins, were noted using a Global Positioning System (GPS) Magellan NAV 1000 PRO© system. Changes in topography were recorded by comparing features depicted in U.S. Defense Mapping Agency charts compiled in the 1970s with those surveyed in 1990.

A series of 83 surface grab samples (5-l Van Veen grab, with sampling surface of 325 cm^2; Fig. 3a) were recovered, described and photographed (Fig. 3b, c); sample site position for each was determined by GPS. Water depth at each sample site was recorded. At 30 of the grab sample sites, short percussion cores (PVC tubes) driven to the bottom were also collected (Fig. 3d, e). Core lengths ranged from 18 to 98 cm, and core diameter was 8 cm.

In the laboratory, X-radiographs were obtained along two perpendicular core section axes while sediment was still in uncut PVC liners. After splitting the cores (Fig. 3f), one of the halves was again X-rayed and then photographed, macroscopic sedimentary features logged and then sampled. Lithological parameters were recorded on the basis of visual and x-radiographic examination, and recorded on logs (Randazzo 1992) according to methods previously used in the Nile Delta survey (Stanley and others 1992; Loizeau and Stanley 1993, 1994; Stanley and others 1996). Recorded were color, sediment hardness, stratal boundaries, sedimentary and biogenic structures, root and other plant traces (Howa and Stanley 1991), and amount and position of shell material, primarily molluscs. Seven major lithologic types (coded A–G) were identified on the basis of the preceding criteria, these are defined in Appendix A.

Samples for petrologic examination were taken in each core wherever a change in grain-size and/or color was noted. A total of 117 samples were taken from the 30 cores, i.e., from 2 to 6 in each core depending on core length and lithologic variation. Detailed core logs indicating position of sampled sections are shown in Randazzo (1992).

A statistical petrological determination of 200 (83 grab plus 117 core) sediment samples was made on the basis of analyses of both the texture and composition. This procedure provides a systematic method for identifying the specific microfacies (statistically determined "hand

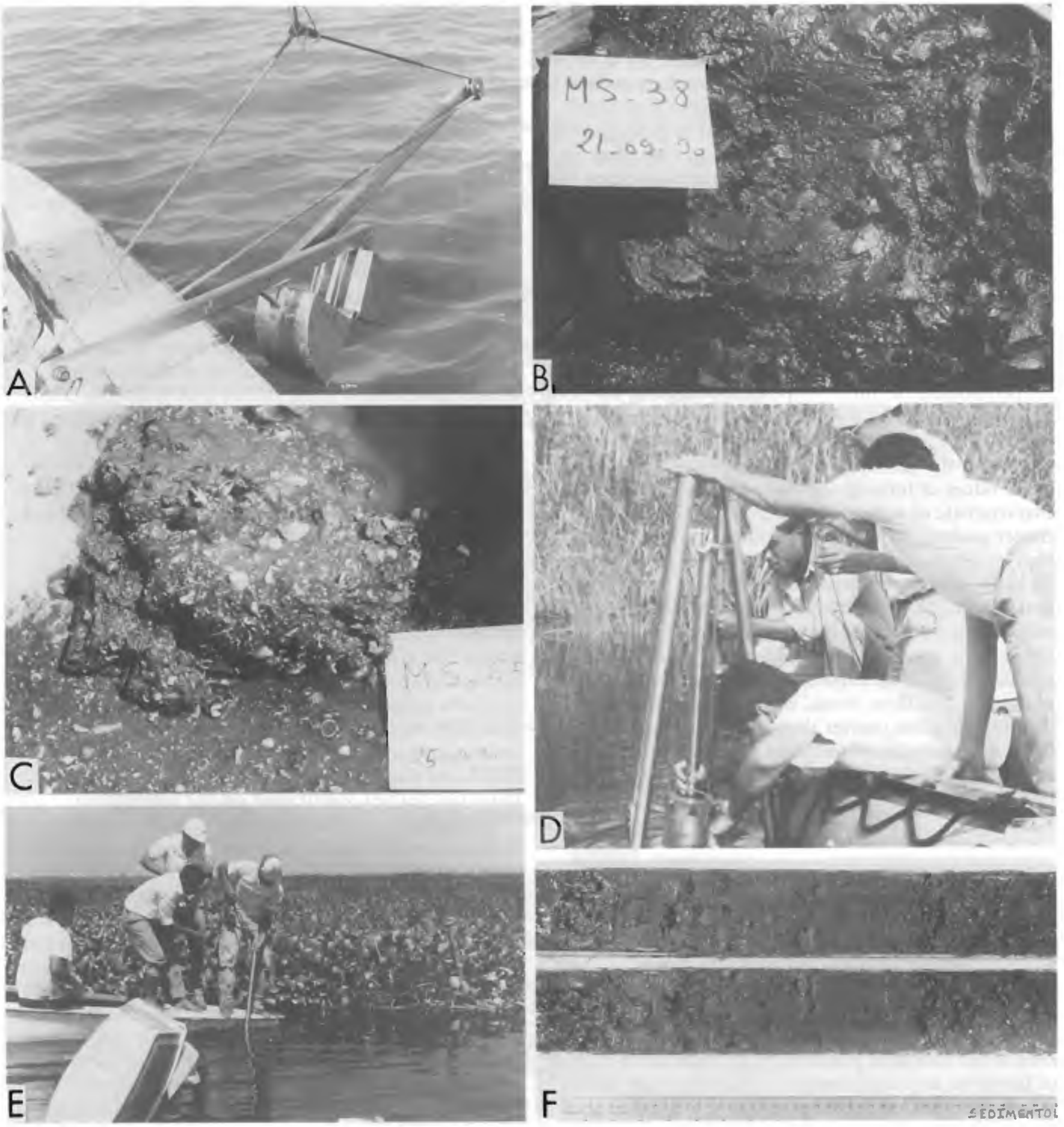

Fig. 3a–f
Photographs taken in Manzala Lagoon in 1990. a 5-l grab used to recover 83 surficial samples; b organic-rich olive-black mud collected in northern lagoon, south of Diba Fort; c muddy shell-rich sand in northern lagoon, south of coastal sand ridge; d coring from small boat in W lagoon, near Damietta; e short core recovery in water hyacinth-choked environment off mouth of Bahr El-Baqar drain, SE lagoon; f split core (~55 cm; core top to left), with a sandy mud-mud-shelly (some marine) sand section, collected in N lagoon near the El-Gamil outlet

sample" petrology) characterizing the samples. The method incorporates (1) the percentages of four major textural components in each sample: granule (>2000 μm), sand (63–2000 μm), silt (2–63 μm) and clay (<2 μm). Statistical treatment also includes (2) data on composition of 300 grains randomly selected from the sand fraction in each sample. Percentages of the following 14 compositional components were determined: (1) eight *terrigenous components* = light and heavy minerals, mica, glauconite/verdine (Pimmel and Stanley 1989), pyrite, gypsum, lithologic fragments and aggregates; and (2) six *biogenic* *components* = foraminifera, ostracod, undefined shell fragment, diatom, plant fragment, and "others".

Two cluster analyses (SAS 1986) were made: (1) to define statistically the dominant petrologic microfacies of the 1990 surficial lagoon floor sediments, and (2) to define subsurface (below core top) microfacies of deposits which accumulated during this century prior to 1990. Both statistical treatments used the extensive petrologic data base that included 15 variables, i.e., four textural and 11 of the 14 sand-size compositional components (the three excluded parameters were lithologic fragments, aggregates, and "others"). The first analysis used the 15 variables determined in the 83 surface (1990 lagoon floor) samples, and the second used the same 15 variables measured in the 117 subsurface core samples (i.e., all core samples except core tops, deposited prior to 1990).

All petrological (texture, composition) data and statistical information used for the present study are listed in Randazzo (1992), and these data are also available in tabular form from the first author. The minimal, maximum, and mean values of textural and compositional components characteristic of each of five microfacies (results of the cluster analysis; defined in Appendix B) are listed in Table 1.

To better distinguish depositional changes in time and space, distributions of lithologic types and of petrologic microfacies are discussed separately. In addition to the foregoing, a separate determination was made of the mollusc fraction, an important component of lagoon deposits (Fig. 3c); these forms, where present, were identified in the fraction coarser than 2000 μm. Molluscan biofacies were interpreted using the classification of Di Geronimo and Robba (1976) and Bernasconi and others (1991).

Distribution of surficial deposits

General lithology and molluscan faunas

Four lithologic types A–D (based on large-scale features defined in Appendix A) form most of the sediment on the modern lagoon floor. Deposits in the NW lagoon area, at the Damietta promontory and east and northeast of Damietta, are characterized primarily by light olive-grey terrigenous sand, with a moderate amount of shell (most similar to lithologic type A). Surficial sediment in the northern lagoon, forming a NW–SE belt positioned south of the linear coastal ridges, comprises largely olive-grey silty sand and sandy silt with variable amounts of shell (Fig. 3c), similar to types A and B. In the central and NE sectors, surficial deposits are olive-grey, sandy clayey silt and clayey silty sand with variable amounts of shell, similar to types B and C. In the southeastern lagoon, east and southeast of El-Mataria, surficial sediments consist of olive-grey and dark yellow-brown silt, clayey silt, and sandy silt with appreciable plant material and highly variable amounts of shell, similar to type D.

Molluscs, collected in granule (>2000 μm) and coarser fractions (Figs. 3c, 4 a), were identified (Fig. 4b), and three groups distinguished on the basis of salinity tolerance.

marine: *Nassarius arcularius*, *Donax trunculus*, *Donax semistriatus*, *Mactra corallina*, *Ostrea sp.*, *Chamelea gallina*, and *Barnea candida*;

euryhaline (brackish): *Pirenella conica*, *Hydrobia spp.*, *Cerithium scabridum*, *Cerastoderma edule*, and *Abra ovata*; and

freshwater: *Melanoides tuberculata*, *Theodoxux sp.*, *Viviparus unicolor*, *Bithynia sp.*, *Phisa acuta*, *Bulinus truncatus*, *Valvata piscinalis*, *Planorbis planorbis*, *Corbicula sp.*, and *Unio sp.*

One marine sample was recovered at the El-Gamil outlet; assemblages near Port Said and the El-Gamil outlet include various mixes of euryhaline and freshwater forms. Euryhaline organisms prevail in most of the northern lagoon (60–70% of the fauna); variable proportions of mixed assemblages of freshwater and euryhaline faunas occur in central and western sectors. Even larger proportions of freshwater forms are identified in southern and southeastern sectors (Fig. 4b).

Major textural and compositional components

Textural attributes of grab samples collected in 1990 record marked regional differences in surficial lagoon deposits. The granule fraction (>2000 μm) comprises primarily shell fragments, with percentages from 10% in the northern sector to 20–30% in the southern and central areas (Fig. 4a). Sand (63–2000 μm) prevails in the northwestern and central sectors (respectively 50–70% and >75%), as shown in Fig. 5a. Silt (2–63 μm) is the most important textural component on the lagoon floor (Fig. 5b), with percentages usually ranging from 25 to 50%; high silt values (50 to >70%) occur in the eastern sector, while low values (<25%) occur in small patchy areas in different lagoon areas. The clay fraction (<2 μm) accounts for <10% in the northern and eastern sectors (Fig. 5c), while higher proportions occur near El-Mataria (10–25%) and south and southeast of Damietta (25–50%) where vegetation favors clay accumulation. Textural data in this study (listed in Table 1) are generally comparable to observations of El-Wakeel and Wahby (1970b), i.e., a prevalence of sand in the NW sector and silt and sand throughout the remainder of lagoon.

Compositional components in the sand-size fraction also record variable distribution patterns [data are listed in Randazzo (1992), and available from the authors]. The terrigenous fraction (Fig. 6a) comprises important proportions of light minerals (primarily quartz): >75% in the NW sector and near El-Gamil outlet; from 50 to 70% south of the NW sector, near El-Qabouti canal in the east, and near drains south of Damietta in the west; and from 10 to 25% and 25 to 50%, respectively, in central and southern sectors. Heavy minerals are relatively important (to 19%) in the NW sector, while smaller values (<5%) are recorded in central and southern areas. Mica content ranges from <3% near the El-Gamil outlet to 5%

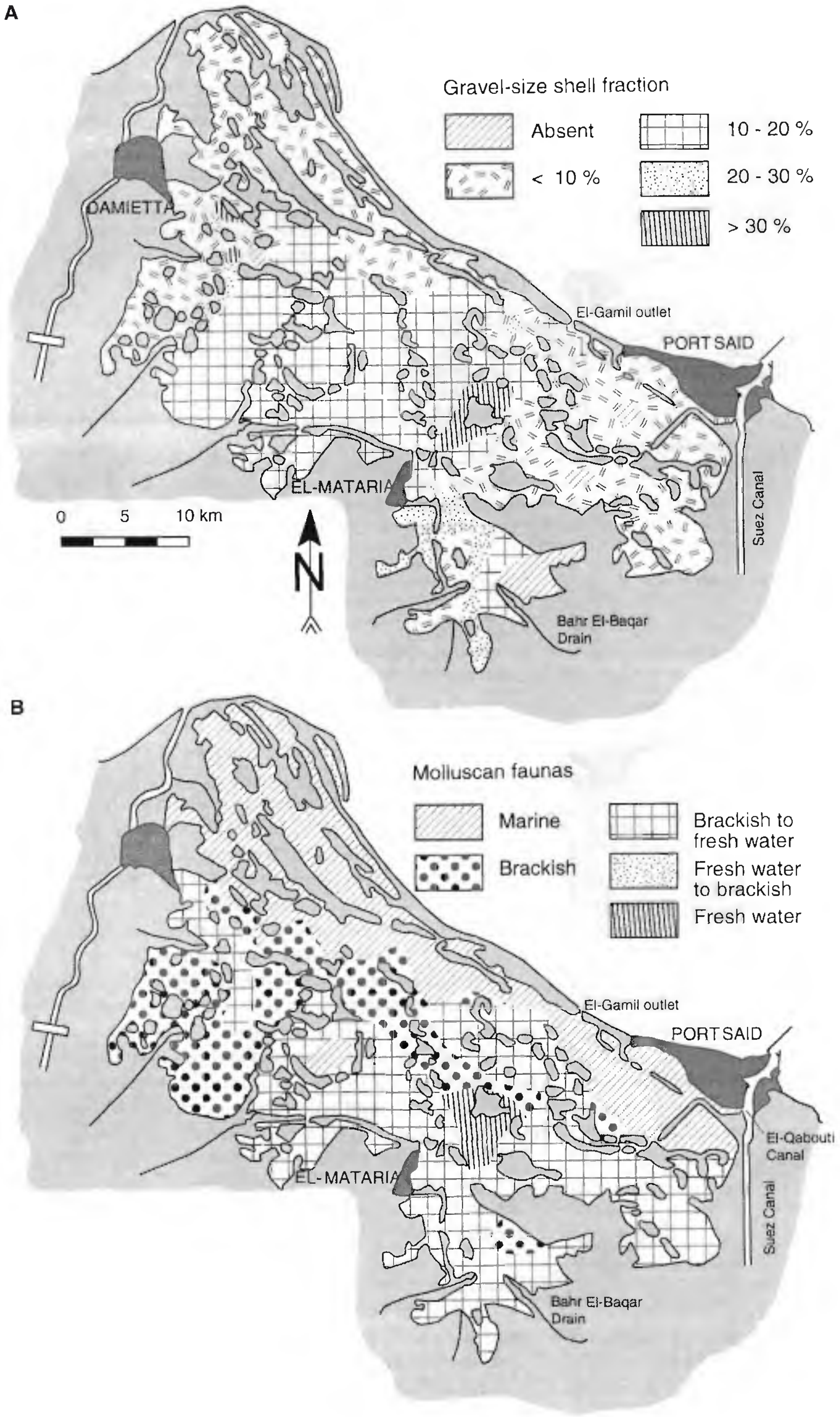

Fig. 4a,b
Maps showing distributions of **a** gravel-size shell fraction and **b** molluscan faunas in surficial Manzala deposits

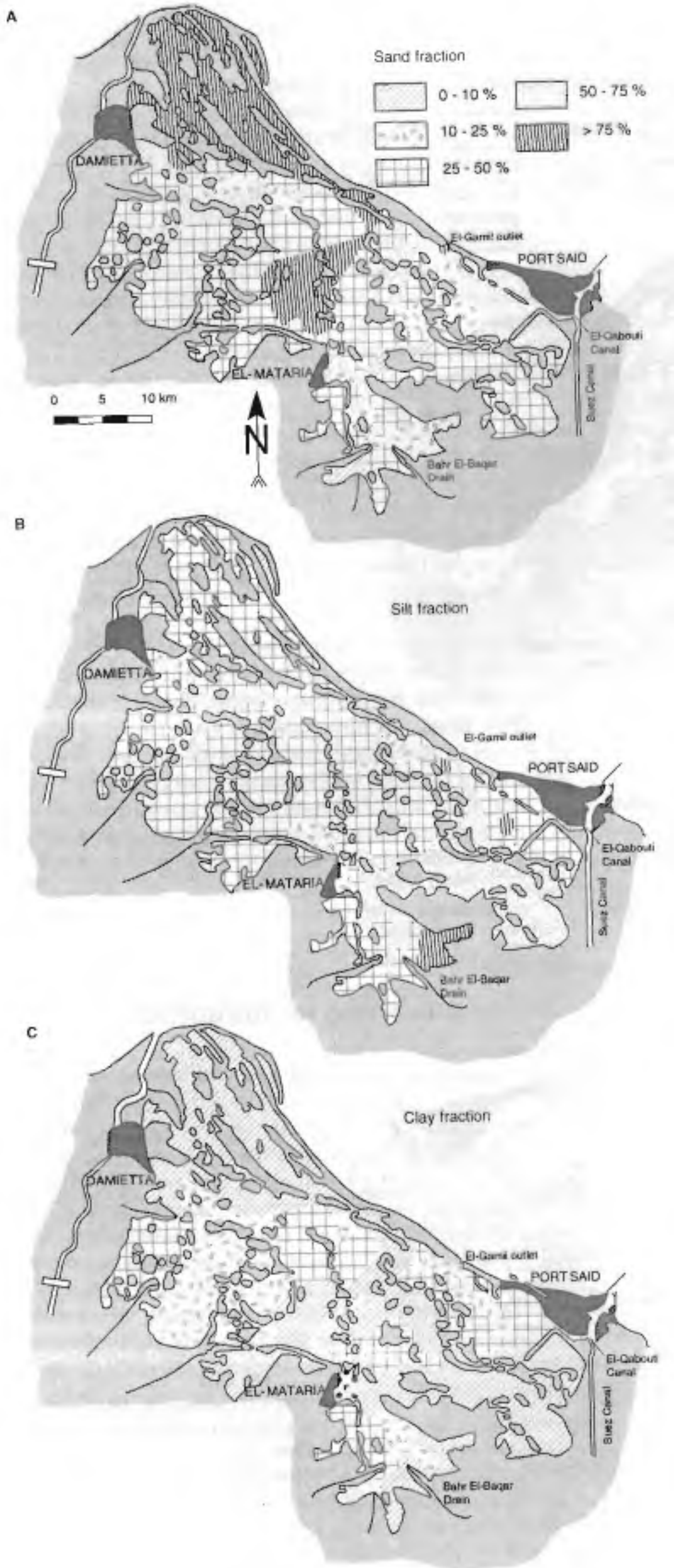

Fig. 5a–c
Maps showing distributions of **a** sand, **b** silt, and **c** clay fractions in surficial Manzala deposits

Table 1
Petrological attributes of five microfacies in Manzala lagoon, including proportions of four textural and eleven compositional (six terrigenous and five biogenic) components

	MICROFACIES I			MICROFACIES II			MICROFACIES III/1			MICROFACIES III/2			MICROFACIES III/3			MICROFACIES IV			MICROFACIES V		
	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean	min	max	mean
GRANULE	0.8	6.4	2.8	0	2.54	1.21	0	34.06	13.87	10.74	26.94	19.85	0	26.4	10.02	0	19.36	7.06	0	37.71	4.51
SAND	90.8	99.35	94.64	0.59	21.58	12.6	0	67.89	28.67	44.19	77.06	58.52	31.84	85.46	49.94	5.45	85.49	24.31	1.39	39.71	12.22
SILT	0.64	9.82	5.49	31.12	77.25	53.04	2.68	66.18	39.75	14.93	31.73	22.8	6.46	63.97	33.94	13.2	85.96	51.84	3.24	71.05	42.85
CLAY	0	0	0	17.69	49.45	31.86	1.5	45.06	29.62	6.17	28.34	18.81	0	33.14	15.99	0	63.52	17.45	18.23	69.47	45.27
L. MIN.	76.1	88.89	82.69	46.11	68.17	55.01	12.58	42.74	24.16	17.76	58.22	35.81	27.44	73.48	52.26	4.58	43.82	22.99	6.34	77.05	30.46
H. MIN.	5.88	19.81	11.69	1.85	10.03	6.97	0	7.81	2.67	0	6.58	2.89	1.3	12.26	5.17	0	4.97	1.68	0	6.82	1.52
MICA	0	3.91	1.11	0.93	15.48	7.25	0	6.88	2.47	0	5.14	1.73	0	13.55	4.11	0	4.68	1.56	0	5.82	1.2
GLAUC.	0	1.24	0.41	0	1.58	0.24	0	0.6	0.08	0	0.33	0.03	0	0.65	0.1	0	0.88	0.07	0	0.89	0.07
PYRITE	0	0	0	0	0.99	0.24	0	0	0.02	0	0	0	0	0.33	0.06	0	0.29	0.02	0	0.28	0.01
GYPSUM	0	1.54	0.26	1	4.73	2.43	0	3.28	0.99	0	5.92	1.46	0	4.67	1.59	0	2.17	0.4	0	4.92	1.03
FORAM.	0	0	0	0.64	8.89	3.61	2.2	28.44	12.82	4.61	19.96	10.73	0.32	22.58	6.92	1.61	16.21	11.27	8.19	65.69	40.24
SHELL	0	1.64	0.43	0.95	28.83	9.95	1.26	43.89	16.44	13.79	58.19	26.73	2.27	25.75	14.25	4	42.35	16.99	4.52	26.95	11.72
OSTRAC.	0	1.96	0.8	0.96	9.79	6.44	11.55	52.04	32.3	0.53	23.17	13.61	2.84	35.78	10.93	6.13	87.67	29.23	0.66	34.14	11.52
PLANT	0	0.98	0.27	1.95	9.64	6.23	0	14.13	3.78	0	3.95	1.88	0	7.38	2.62	0	18.53	6.48	0	3.01	0.34
DIATOM	0	0	0	0	0.66	0.27	0	5.96	1.03	0	1.94	0.65	0	4.72	0.5	0	5.79	0.99	0	0	0
TOTAL TERRIGENOUS			96.16			72.23			30.39			41.92			63.29			26.72			34.29
TOTAL BIOGENIC			1.5			26.05			66.37			53.6			39.22			64.96			63.82

Note: this table summarizes data from 200 samples: listings for microfacies I–IV are derived from analyses of 83 surficial grab samples; data for microfacies V are from 22 of the 117 core samples. Shown are minimal, maximum, and mean values of the 15 components, and mean total values of terrigenous and biogenic components in each microfacies

in the central lagoon; it is also present southwest of Port Said and northwest of El-Mataria. Gypsum is present in low quantities but more often absent; it is of importance (~6%) only in the NW sector, near Damietta. Pyrite and glauconite/verdine are present in low amounts or absent. Distribution of the biogenic components of sand size is also variable (Fig. 6b). Foraminifera account for <5% in the northern sector, and increase southward, with very high values (to 20%) recorded in the extreme SE sector. The assemblage is dominated by forms (primarily *Ammonia*), tolerant to wide ranges of salinity and temperature (Phleger 1960; Pugliese and Stanley 1991). Bivalve and gastropod shell fragments account for <10% in the northern sector, and increase toward the SE (10–20%) and central (10–25%) lagoon. Ostracods account for <10% in the NW sector, and proportions increase toward the south; locally, large amounts (to >40%) occur in protected areas, within bays and near islands. Plant fragments usually account for <5% of the sand-size fraction; small patchy areas comprising higher values (10–20%) are recorded in central and SE sectors. Diatoms are present primarily in the central lagoon, where this component locally comprises >5% of the sand-size fraction. Four depositional sectors are distinguished on the basis of the preceding findings of our 1990 surficial samples:

NW sector, characterized primarily by sandy sediment, light and heavy minerals, and euryhaline molluscs;

NE sector, characterized by clayey silt with high proportions of light and heavy minerals (but less than in the NW sector), variable amounts of euryhaline molluscs, and other shell fragments;

central sector, characterized by silty sediment, light minerals, bivalve fragments, and both freshwater and euryhaline molluscs;

southern sector, characterized by silty and sandy sediments, with mica, foraminifera, shell fragments, ostracods, and large proportions of freshwater molluscs.

Microfacies

Four petrologic microfacies (coded I–IV, defined in Appendix B), identified in modern lagoon floor sediment (Fig. 7a), are determined statistically on the basis of cluster analysis from data obtained from the 83 surficial samples (Table 1). These microfacies incorporate four textural variables (granule, sand, silt, clay) and eleven sand compositional variables (six terrigenous plus five biogenic), as identified earlier in the methodology section. Their distribution is as follows:

I: *Terrigenous well-sorted sand*, prevails in the NW sector of the lagoon in and east of Damietta promontory and along the southern margin of coastal sand ridges.

II: *Micaceous muddy sand*, is distributed in a narrow linear zone along the landward margin of facies 1, i.e., immediately south of the linear NW–SE trending islands.

III: *Shelly silty mud*, covers the largest surface area of Manzala, and is dominant in the central sector and also along the NW, S, and SE margins. Three subfacies of III (also defined in Appendix B) are located as follows: III/1, south of the city of Damietta; III/2, in the central part of the lagoon and covering the largest area; and III/3, primarily east and southeast of the town of El-Mataria in the SE lagoon.

IV: *Plant-rich silty clayey mud*, with its irregular distribution pattern, is located primarily along the southern lagoon margin near the El-Gammaliah drain and near Hadus and Ramsis drains.

It is of note that microfacies V (*Mica-*, *foraminifera-*, and *plant-rich silty mud*) was restricted to the El-Gamil outlet in our 1990 survey.

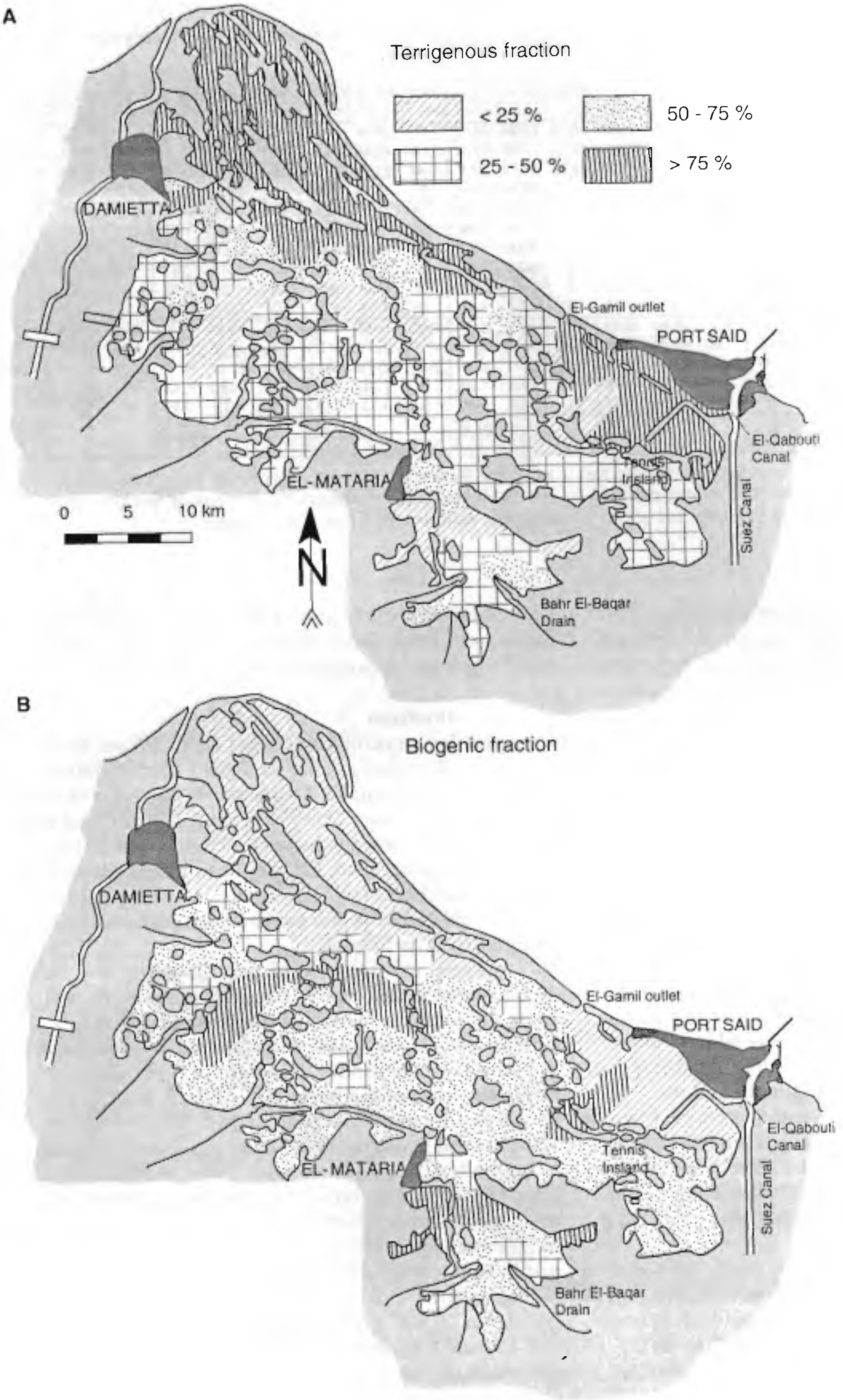

Fig. 6a,b
Maps showing distributions of **a** sand-size terrigenous and **b** biogenic fractions in surficial sediment of Manzala Lagoon

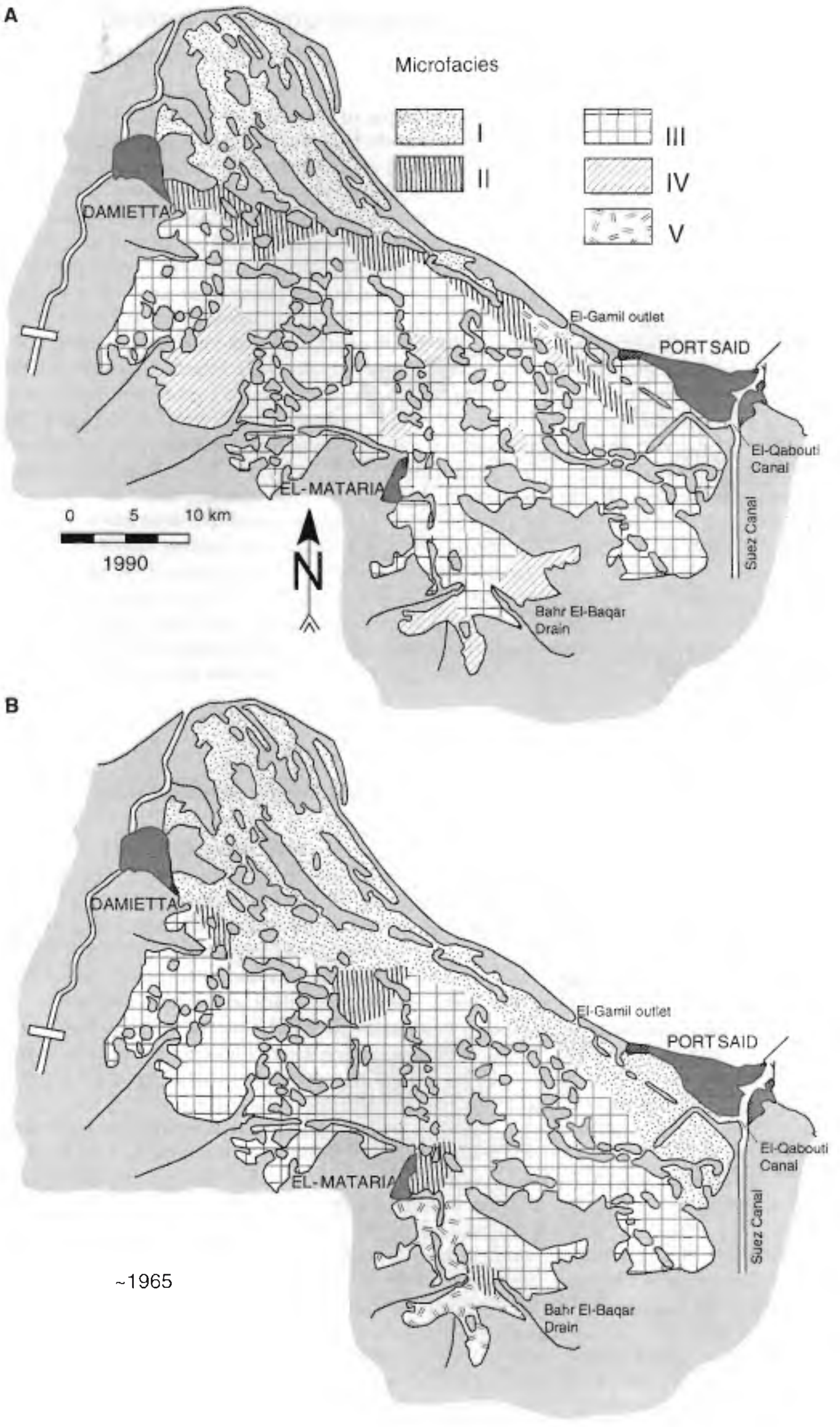

Fig. 7a–d
Maps showing distributions of five microfacies (I–V; defined in text and Appendix B) in Manzala Lagoon through time: **a** 1990, **b** ~1965, **c** 1940s, and **d** 1920s

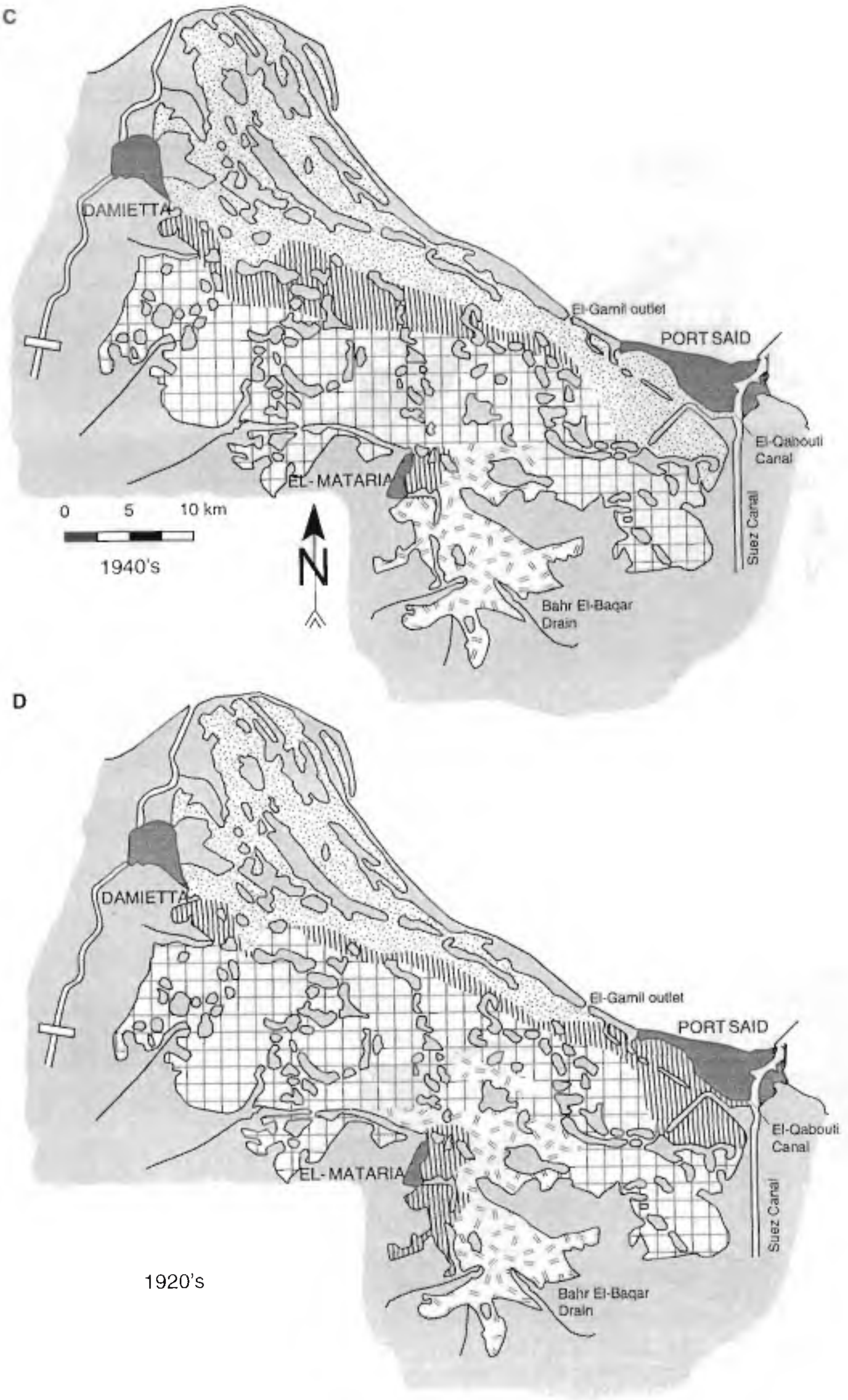
C
DAMIETTA
El-Gamil outlet
PORT SAID
El-Qabouti Canal
EL-MATARIA
0 5 10 km
1940's
N
Suez Canal
Bahr El-Baqar Drain
D
DAMIETTA
El-Gamil outlet
PORT SAID
El-Qabouti Canal
EL-MATARIA
Suez Canal
1920's
Bahr El-Baqar Drain

Fig. 7c–d

Determining approximate depositional rate

To convert sediment depth in core to approximate date of deposition in this century, we used chronostratigraphic information, based on ^{210}Pb and fission-product radionuclides and determined from detailed study of a core recovered in central Manzala lagoon (Benninger and others 1998). The rate of modern sediment accumulation is ~1.2 cm/year. This value is markedly higher (nearly double) than the long-term mean rate of accumulation (ranging from 0.5 to 0.7 cm/year) calculated for the past 7500 years in long core sections (Stanley and Warne 1993; Stanley and Goodfriend 1997). Accumulation until recently has been less than 1 cm/year, when taking into account sediment compaction of core sections.

On the basis of the foregoing, an extrapolated sediment rate for this century of ~1.2 cm/year is used for Manzala, and the following four approximate ages to four respective short core depths are assigned: 1920s, at the base of the 55–80-cm section below core top; 1940s, at the base of the 30–55-cm section; ~1965, at the base of the 0–30-cm section; and 1990 (our survey date), for surficial sediment at the core top. Sediment characteristics at these intervals are determined in each core to evaluate change in the lagoon over the course of this century.

Subsurface sediment distribution

General lithologic types

The 30 cores in this survey were recovered primarily in the Damietta-NW sector ($n=10$), El-Gamil-north central sector ($n=9$), and El-Mataria-SE sector ($n=11$) of the lagoon. Seven lithologic types (A–G, defined in Appendix A) are identified in cores on the basis of visual and X-radiographic attributes, including texture, color, megafauna and sedimentary and biogenic features (Fig. 3f). Types A to D are generally more widespread, and E to G tend to be more locally restricted.

Lithologic type A is regionally well distributed east and northwest of Damietta, and is also present in small patches east of El-Mataria, south of Port Said, and in the central lagoon. Type B is the most broadly recorded, especially in the eastern lagoon between Port Said and El-Mataria. Type C is distributed in the El-Mataria region, and also locally in the central lagoon, southeast of Damietta, and south of Port Said. Type D is commonly present at the base of cores, and distributed primarily between Port Said and El-Mataria region, and also southeast of Damietta. Type E is locally present in the north-central lagoon and southeast of Damietta. Type F occurs in more restricted areas southeast of Damietta and west of Bahr El-Baqar. Type G, the least common, was recorded at the base of one core positioned southeast of Damietta.

Examination of lithologic types reveals that four predominate (A–D) and that these record important regional variations through time (Fig. 8). In the 1920s, C and D lithologic types prevailed widely from Port Said to the El-Mataria region in E and SE lagoon sectors, and in the northern lagoon east of Damietta (near some coastal ridges and linear belt of islands). By the 1940s, type B had become important in the central lagoon and east of Damietta, while the area covered by type C became more restricted to the eastern lagoon between Port Said and El-Mataria. By ~1965, type B prevailed throughout the lagoon, and type A in the north-central sector; C lithology at that time had become restricted to small areas at the mouth of Bahr El-Baqar, near the El-Gamil outlet, and southeast of Damietta. In 1990, type B remained the major type, particularly in the eastern part of Manzala, and type A had become somewhat more concentrated along N and NW lagoon margins. Our observations indicate depositional changes from the 1920s to the 1940s, but an even greater modification occurred from the 1940s to ~1965, including change from type C to B throughout most of the eastern lagoon.

Microfacies

Petrologic data from 117 core samples taken below core tops were treated separately, but statistically in the same fashion as surficial grab samples (Table 1). The second cluster analysis identifies three of the same microfacies (I, II, III) that were distinguished in surficial samples, plus one (V) not identified in the grab samples (Fig. 7b–d). Microfacies V (*Mica-*, *foraminifera-*, and plant-rich silty mud) is associated primarily with core lithologies C, and, to a lesser extent, B. Microfacies IV, identified in surficial samples, is not recorded in subsurface core sections.

Temporal and regional changes in microfacies are also identified during this 70-year period (Fig. 7). Microfacies I extended from Damietta and Damietta promontory to the southeast (to south of El-Gamil and Port Said) from the 1920s to 1940s, and its area continued to broaden somewhat farther to the south by ~1965. There was a marked reduction in the lagoon region covered by I between ~1965 and 1990, time of our survey; by then, this sandy microfacies became restricted primarily to the area of the Damietta promontory (east and north of Damietta), and to a small sector adjacent to El-Gamil outlet.

Microfacies II, in the 1920s, occupied a narrow linear belt trending NW-SE from Damietta to south of Port Said, and along the southern margin of the lagoon east of El-Mataria. By the 1940s, the area covered by II had widened and extended southeast of Damietta, was substantially reduced east of El-Mataria, and absent from the region south of Port Said. By ~1965, only several small patchy areas remained southeast of Damietta and east of El-Mataria region. By 1990, this facies had disappeared in the El-Mataria sector, but once again formed a narrow, near-continuous belt between Damietta and Port Said.

Microfacies III has been the dominant one in Manzala Lagoon, occupying most of the southern half of the wet-

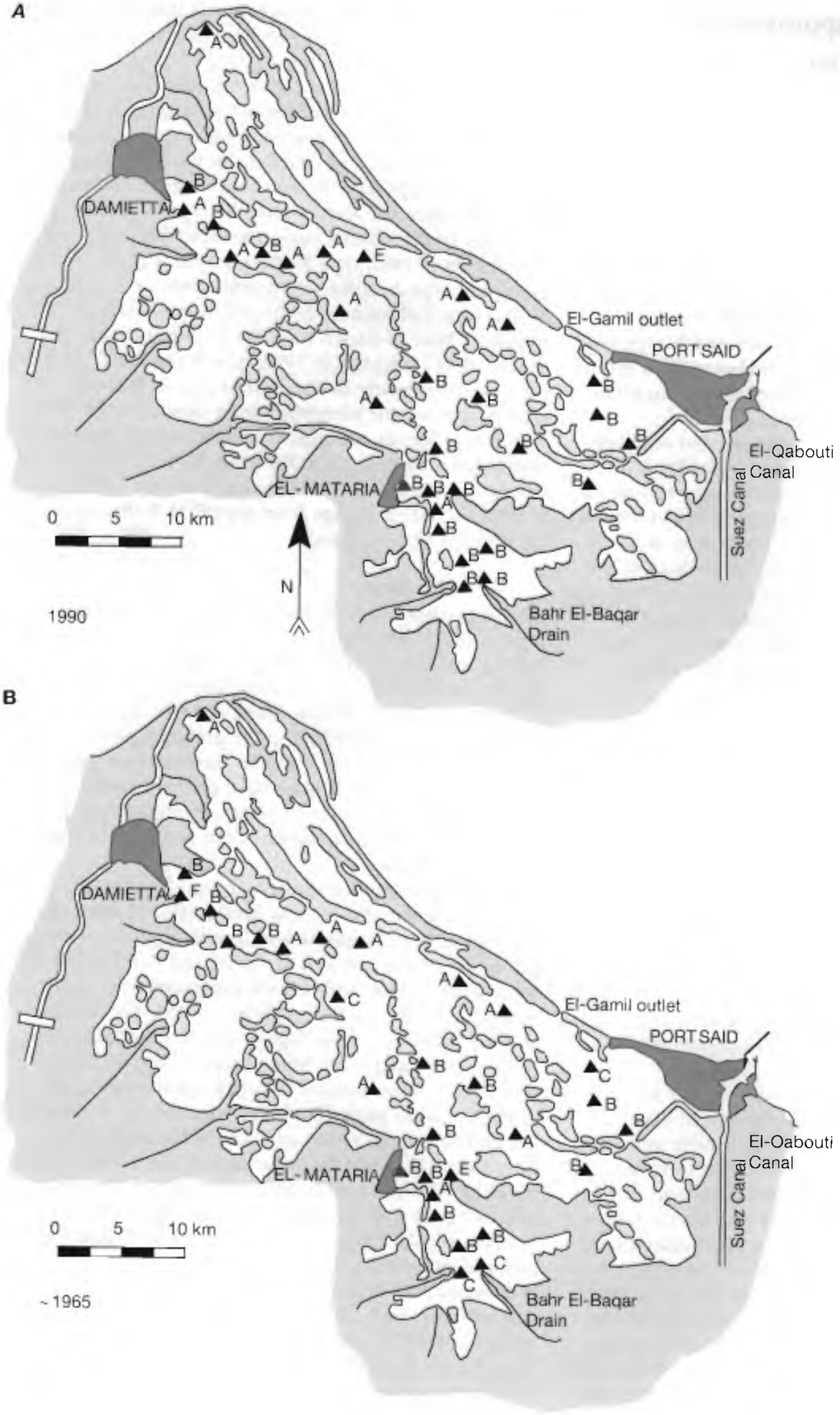

Fig. 8a–d
Maps showing distributions of seven lithologic types (A–G; defined in text and Appendix A) in Manzala Lagoon through time: **a** 1990, **b** ~1965, **c** 1940s, and **d** 1920s

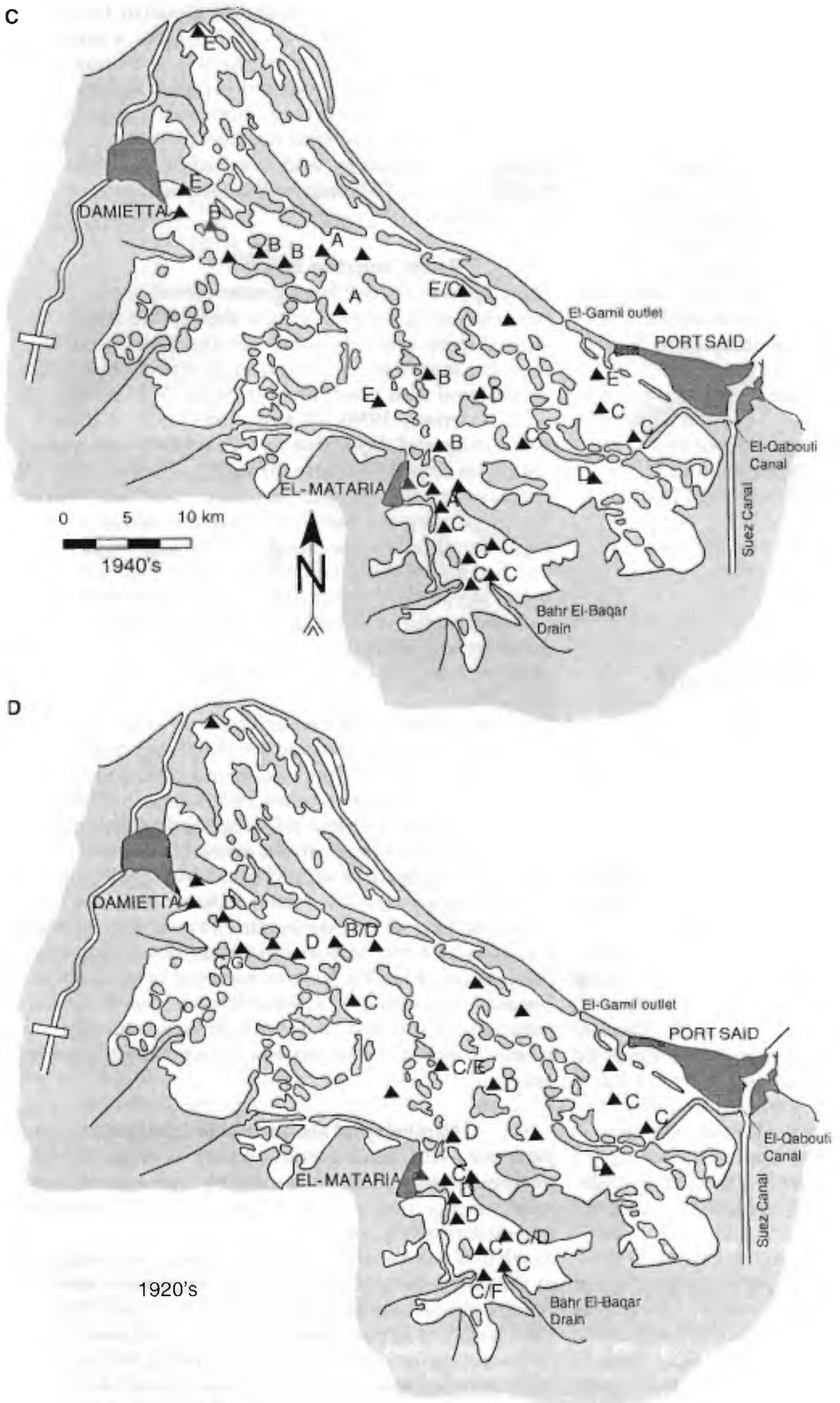
C
DAMIETTA
El-Gamil outlet
PORT SAID
El-Qabouti Canal
Suez Canal
EL-MATARIA
Bahr El-Baqar Drain
0 5 10 km
1940's
N
A
B
C
D
E
E/C
D
1920's
B/D
C/E
C/D
C/F
C/G

Fig. 8c–d

land during the time-span considered. Most obvious changes are with regards to the northern limit of its extent: this boundary migrated southward and reached its maximum southern limit from the 1920s to 1940s, then shifted markedly northward to ~1965 and still occupied this general position in 1990.

Microfacies IV did not appear as a surficial facies until or after ~1965, and occurs primarily along margins of the lagoon, including north of El-Gammaliah and close to Hadus and Ramsis drains southeast of El-Mataria.

Microfacies V prevailed in the southern lagoon sector, east and southeast of El-Mataria until after the 1940s. Its area, however, became markedly reduced from the 1940s to ~1965. Some of the area formerly occupied by V was replaced subsequently by microfacies IV.

Summarizing temporal variations, we find that major microfacies changes during this century occurred from the 1940s to ~1965: enlargement of area covered by III, and a marked reduction of areas occupied by II and V. Important modifications, nevertheless, continued to occur from ~1965 to 1990: first appearance of IV, increase in area covered by II and its displacement northward, and reduction of area formed by I.

Integrating morphologic and sedimentologic changes

Earlier evolution

There is evidence of almost continuous anthropogenic modification of the NE Nile Delta since prehistoric times, initially as a result of canal development for irrigation (Butzer 1976). The general configuration of the Manzala Lagoon evolved between 1400 and 1000 years ago (Butzer 1976; Sestini 1976; Coutellier and Stanley 1987). The modern marsh-lagoon system we know today developed initially by merging of marshes and small wetlands; these then expanded laterally in response to changes in flow of former Nile distributaries and, most recently, the Damietta branch. A series of military maps prepared in Egypt by British expeditionary forces (Arrowsmith 1807) and Napoleon's savants (Du Bois-Aymé 1814; Cordier 1818) show the general configuration of the lagoon as it appeared at the beginning of the 19th century, including position of major canals and former branches of the Nile which, at that time, still flowed into the southern part of Manzala. Also of note on these early charts is the presence of at least two outlets connecting the lagoon to the Mediterranean, and a somewhat different configuration of some islands in the wetland.

The major modification of Manzala in recent times occurred between the mid-1800s and 1869 when the Suez Canal was opened; this large waterway and adjacent levees in effect separated the NE corner of the original lagoon from the wetland. By the end of the 19th century, only one major outlet with the sea (El-Gamil) remained, and continued municipal expansion altered coastal sand ridge development west of Port Said (Fourtau 1915). Moreover, from the mid-1800s to mid-1900s, a series of barrages was constructed along the Nile, including the Delta barrage north of Cairo and Faraskur barrage dam on the Nile's Damietta branch, immediately west of the lagoon. These water-control structures and conversion of wetlands to agricultural lands resulted in substantial transformation of Manzala well before the beginning of this century.

Recent reduction in area

There appears to have been greater overall change at Manzala during the past century than earlier historic times (Fig. 9). Most obvious is continued reduction in area, due mostly to (1) conversion to agricultural and aquacultural (fish pond) areas (George 1972; Worthington 1972; Waterbury 1979), (2) alteration of lagoon margin morphology and deposition as a direct function of discharge via large canals into the lagoon (Stanley 1996), (3) emplacement of water-control protection structures, (4) rapidly growing population in numerous villages and towns surrounding this region, and (5) control of water flow by closure of the Low Dam and the High Dam in Upper Egypt. To interpret the recent depositional evolution, it is useful to correlate the relation between general petrology and microfacies changes identified from the 1920s to 1990, and recent morphological modifications of the lagoon.

Changes in area, based on our survey of selected lagoon margin sectors, are measured for the period from 1973 to 1990. Configuration of the lagoon and adjacent regions dating to the 1970s is recorded on a base comprising detailed maps (U.S. Defense Mapping Agency Hydrographic/Topographic Center charts, series P773; scale 1:50,000). Comparison of 1973 maps with 1987 satellite Landsat imagery (IWACO 1989) reveals a reduction in area of at least 90 km^2 during that 14-year period, which translates to a rate of loss of ~6.5 km^2/year. Moreover, comparison of lagoon margins surveyed by us during summer 1990 with 1987 Landsat images records further reduction of at least 53 km^2. This denotes a marked increase in rate of annual wetland reduction to 17.6 km^2/year.

Morphological and sedimentological modifications

Since the 1920s, there appears to have been greater morphologic change of Manzala margins than of its more open water sectors. A brief clockwise overview highlights this evolution (Fig. 7).

North and northwest sector: sand and mud accumulated in the northern third of the lagoon, along some elongate islands east of Damietta and south of Port Said. These emergent terrains are associated with recent modification of the coastal sand ridge system separating the lagoon from the sea. Physiographic and depositional changes primarily record effects of increased erosion of this ridge system as a result of a two-stage reduction in sediment dispersed at the mouth of the Damietta branch: first at the turn of the century, following construction of the

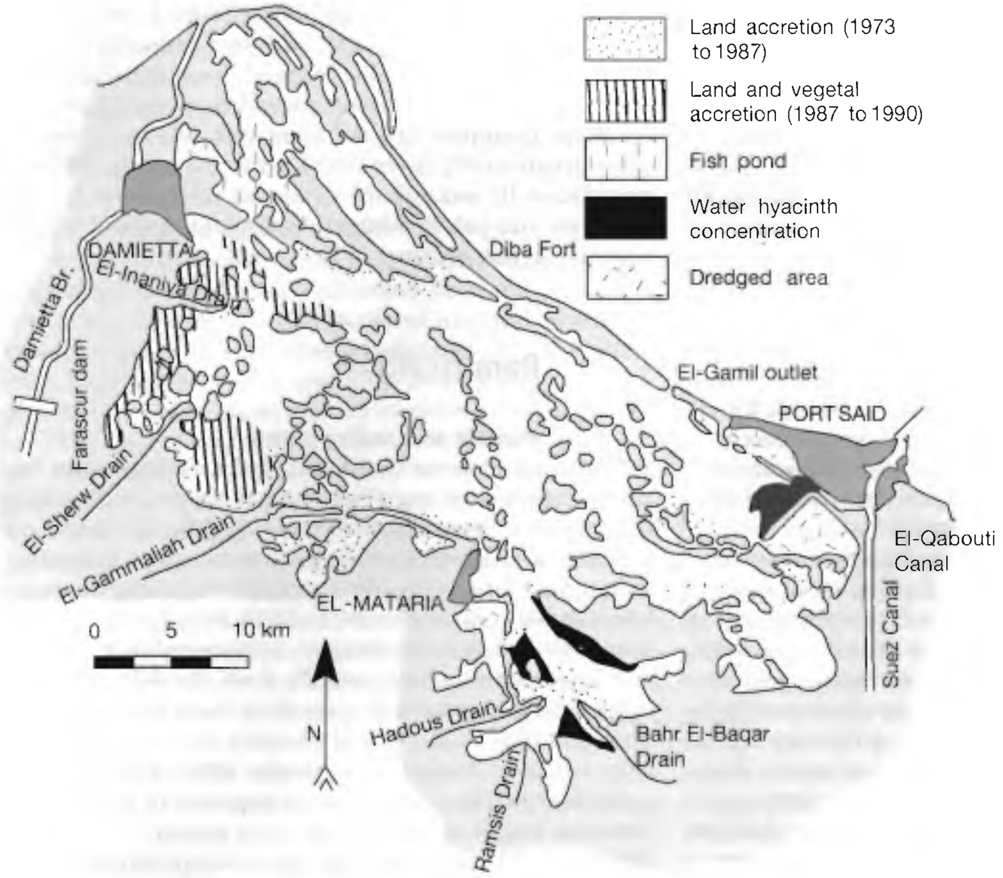

Fig. 9
Map showing recent (post-1973) modification of Manzala Lagoon, including land and vegetal accretion, dense growth of water hyacinth, fish pond development, and dredging

Lower Dam at Aswan (1902), and then after closure of the High Dam (1964). Coastal current activity has cut back the Damietta promontory (Kassas 1972; Frihy 1988, 1992; Inman and others 1992) at rates up to 30–40 m per year. Easterly dispersal of sand along this coast is recorded by spits recently formed east of the promontory (Fig. 1), and by ongoing sediment accretion that alternates with shoreline erosion east of Damietta (Smith and Abdel-Kader 1988; Inman and others 1992). As the Damietta promontory has been cut back and Manzala coastal ridge system narrowed by erosion, more sand is driven along the shoreline and into the lagoon, primarily by strong winds and high seas (wave amplitude to 2 m) during winter storms. Destruction of the main highway connecting the cities of Port Said and Damietta is one of the more obvious effects of accelerated erosion in this region (Stanley and others 1992).

As a consequence of accelerated coastal erosion, lithologic types in Manzala changed from primarily D (soft micaceous mud) in 1920s to B (silt and sandy silt) and some A (medium- and fine-grained sand and silty sand) in 1940s, and then to A and B from ~1965 to 1990. This upward coarsening is accompanied by a change in microfacies: an increase in area covered by I (terrigenous well-sorted sand) from 1920s to 1940s, and then a reduction in area and northward shift of I from ~1965 to 1990. These sedimentary changes through time record agradation of the NE Nile Delta and active deposition north and east of Damietta until ~1965. The marked modification after that time likely records sand and finer sediment cutoff at the mouth of the Damietta branch of the Nile, following closure of the High Dam and increased flow control between the Aswan and Faraskur Dam on the Damietta branch.

Also noted in this region is alteration of marshes and lagoons to numerous fish ponds, especially in shallow depressions between ridges and islands north and east of Damietta. This aquacultural activity has subdivided the lagoon floor into small artificial depressions, completely altering the natural depositional regime by favoring selective entrapment of fine-grained sediment.

Northeast sector: changes in the region south of El-Gamil and Port Said include modification of the outlet between lagoon and the sea, numerous construction projects at Port Said, and dredging to the south and southwest of the city for municipal extension and maintenance of channel passages for fishing and ferry transport to El-Mataria and other towns. Lithologic types C (shelly soft muddy silt), D (soft micaceous mud) and E (medium-grained sand), dominant in the 1920s and 1940s, had changed to B (silt and sandy silt) and A (sand and silty sand) by ~1965, and then primarily to B by 1990. Microfacies II (micaceous muddy sand) and III (shelly silty mud) in the 1920s changed to I (terrigenous well-sorted sand) and III by 1940s. This pattern remained fairly constant until ~1965; after that time the area became characterized primarily by III and, locally, II and IV (plant-rich silty clayey mud).

Southeast sector: Perhaps most evident along the SE margin and east of El-Mataria is a series of pronounced finger-like extensions at the mouths of Hadous and Bahr El-Baqar drains; these are interpreted as active small deltaic build-outs (subaerial and submerged) into the lagoon. Of note is the extensive change from lithological types C (shelly soft muddy silt) and D (soft micaceous mud) in the 1920s to primarily C in the 1940s; by ~1965, type B (silt and sandy silt) prevailed, along with some C. From that time to 1990, type B covered larger surface areas. In the case of microfacies, from the 1920s to 1940s V (Mica-, foraminifera-, and plant-rich silty mud) prevailed. By ~1965, the areal extent of microfacies V was reduced and replaced by III (shelly silty mud) and II (micaceous muddy sand), and by 1990 was largely characterized by III and IV (plant-rich silty clayey mud).

South-central sector: This part of the lagoon is topographically irregular, and includes spits, small bays, and islands bordered by marsh vegetation. Protected areas trap sediment carried to this sector by canals and some large drains (El-Gammaliah). Some reclaimed lagoon area is now being used for cultivation. The important port in this region, El-Mataria, serves the fishing industry (Fig. 2c) that prevails between the southern lagoon margin and Port Said to the northeast. While no cores are available from this region, surficial grab samples indicate that microfacies III (shelly silty mud) is dominant.

Southwest sector: Substantial modification of this sector has occurred during the period considered as a consequence of population increase south of Damietta and conversion of marsh and lagoon for rice and cotton cultivation. Vegetal blooms that cover extensive areas of the shallow lagoon are particularly in evidence in this sector (Abdel-Kader 1982); these, including algae (Fig. 2f), have increased entrapment of sediment carried by several large drains (El-Gammaliah, El-Sherw, El-Inaniya) into this region. Also noted south of Damietta are progradational, finger-like extensions into the lagoon at the mouth of several drains, including El-Gammaliah, El-Sherw, and El-Inaniya drains. Cores were not collected in this sector, but surficial samples indicate that microfacies III (shelly silty mud) now prevails and, over large areas, is being replaced by IV (plant-rich silty clayey mud).

Open lagoon sector: Among major changes within the lagoon proper since the turn of the century are an increasing number of dredged and shallow passageways for fishing and transport. Moreover, there has been a marked increase in water hyacinth (*Eichhornia crassipes* Salms) in open water areas (Figs. 2d, 3 e) as well as along its margins. These plants grow rapidly and now cover large sectors throughout Manzala, especially in the south and east. Also of note are extensive algal blooms (Fig. 2f) that, with hyacinth, choke off large areas of lagoon, particularly in the southwest. In the central lagoon, lithologic types C (shelly soft muddy silt) and D (soft micaceous mud) prevailed in the 1920s, and were then replaced by types A (medium- and fine-grained sand and silty sand), B (silt and sandy silt), and D by the 1940s. Types B and A floored the lagoon by ~1965, and then primarily by B in 1990. Microfacies have also changed: from the 1920s to ~1965, III (shelly silty mud) prevailed, while the area of V (Mica-, foraminifera-, and plant-rich silty mud) became progressively more restricted to the south. While microfacies III was still the dominant microfacies in 1990, moderate-size patchy areas of IV began to prevail locally near the lagoon center.

Ramifications

Manzala as a sediment sink

Depositional patterns in the Nile Delta lagoons, prior to closure of the Low and High dams at Aswan, were largely responses to three natural factors, i.e., Nile flooding events, seasonal variations in evaporation, and biogenic production. Since 1964, the most obvious change has been almost complete control of Nile flow by the High Dam. The volume of freshwater, bottom sediment load and suspensates carried annually from the delta into the lagoons have increased as a result of these large structures and flow in canals and pumping of waste-water into delta wetlands (Sestini 1989; Stanley 1996). Also, freshwater flow has increased as a consequence of diversion of Damietta branch water into the delta proper.

Evidence of the increased amount of water entering and retained in Manzala includes the recent change in biota and increased sediment accumulation rate. Of note is the higher proportion of freshwater molluscs relative to brackish and marine species, particularly in the southern half of Manzala (Fig. 4b). Changes in sediment petrology as recorded herein also record recent change in flow input in Manzala. For example, there has been modification of the texturally heterogeneous (clayey sand and sand-silt-clay) carbonate-rich sector (important shell fraction; Fig. 3c) within the lagoon proper since compilation of maps in the 1960s by El-Wakeel and Wahby (1970b). Our observations indicate a somewhat lower carbonate content throughout the central part of the lagoon than previous studies, but a wider distribution of carbonate-rich sediment now distributed in the lagoon. Increased amounts of carbonate are recorded in the western sector, likely influenced by El-Inaniya, El-Sherw, and El-Gammaliah drains that discharge a large amount of nutrients into Manzala.

Our findings indicate that surficial sediment is somewhat coarser than described by El-Wakeel and Wahby (1970b), perhaps as a result of altered shell species and size. These recent changes may have been influenced by modified discharge and chemical input. Differences between high carbonate percentages found by El-Wakeel and Wahby (1970b), and lower ones found by Saad (1972) and in the present study, may represent a masking effect, i.e., accelerated deposition of new sediment on pre-1960s deposits. This newly accumulated material is derived primarily from waterway input and, to a lesser extent, from marine sediment driven into the northern lagoon. Moreover, higher depositional rates are also attributed to increased sediment entrapment by vegetation in marshes (Fig. 2b) and in shallow protected sectors (Fig. 2e, f), including increased number of shallow fish ponds emplaced throughout this wetland.

Increased pollutant levels

It is not surprising that expanding population, agricultural development, and industrialization since the Second World War have resulted in increased amounts of waste-water discharge with associated pollutants (Abdel-Kader 1982; Siegel 1995). Higher pollution levels in Manzala are recorded by heavy metal content in cores (Siegel and others 1994), a response of more waste water being diverted and discharged into a smaller area. For example, study of Bahr El-Baqar drain, which discharges more than 2 million m^3 of waste daily into the SE sector of Manzala (Siegel 1995), indicates substantially higher amounts of heavy metal (Hg, Pb, Zn, Cu, Cr, Sn, Ag) accumulation in recent years (Siegel and others 1994). There is firm evidence of bioaccumulation in the food chain and in the principal fish (*Tilapia* sp.) recovered; this phenomenon poses an increasing health risk (Saad and others 1981).

Altered fish catches

Fishing in Manzala is of vital economic importance: in recent years the lagoon has provided the largest proportion (35%) of Egypt's total fish catch (World Bank 1984). The annual catch in the lagoon increased to $\sim$20–27 thousand tons per year after closure of the Aswan High Dam and consequent cessation of seasonal flooding (Shaheen and Yosef 1979). This represents an increase of 92% between 1908–1935 and 1963–1973, a period during which the area available for fishing decreased from 170000 to 117000 hectares. The large discharge of water into the lagoon by drains and canals helps account for markedly increased amounts of fertilizer and organic nutrients, i.e., from 1.2×10^9 m^3 (1908–1935) to 5.2–6.3 $\times 10^9$ m^3 (1963–1973). This contributed to much increased lagoon fertility, extensive algal blooms and vegetal growth (Fig. 2), and consequent increased eutrophication (Shaheen and Yosef 1978).

More recent documentation, however, reveals that overfishing in Manzala since the early 1980s now results in smaller total catches. It also appears that a reduction in size of fish caught may be attributed to altered chemical (including increased accumulation of pollutants) and physical conditions (Ichthyopathology Centre, El-Gamil, Egypt, general communication 1990). Increased floral growth in the lagoon traps sediment, associated chemicals and organic matter, and this has likely contributed to reduced catches. Measures that favor selective plant growth and vegetal bioremediation to absorb selected contaminants are needed (Siegel 1995).

Comparison with other delta wetlands

Sediment type distributions are generally comparable in the four Nile Delta wetlands (Fig. 1), i.e., muddy and shell-rich at southern and southeastern margins, and sandy mixed with silty material at the northern and northwestern margins. All four water bodies comprise high amounts of calcareous shell (Fig. 3) and shell fragment (especially molluscs and serpulid worm tubes): Manzala, Burullus, and Idku have 40 to 50% calcareous material in dry mud, while Maryut has average values >60% (Saad 1974). However, depositional patterns in the four delta wetlands have each been subjected to different anthropogenic modification during this century. For example, Manzala sedimentation patterns are most similar to those of Burullus lagoon (NNW delta), probably the least altered of the four water bodies (Saad 1976a; Smithsonian study in progress). Manzala and Burullus have generally comparable (1) population densities along their margins, (2) large waste-water and sediment discharge from drains along their southern margins, and (3) sand input entering their northern sectors from coastal ridges.

Differences are more pronounced between Manzala and Idku and Maryut (both in the NW delta). These latter two water bodies have been subject to considerably greater change than Manzala during this century: Idku has been greatly reduced in size, as a consequence of wetland drainage for agricultural use. Extensive municipal and industrial growth at Alexandria has resulted in rapid, almost complete, anthropogenic transformation of Maryut into a series of isolated ponds (Saad and others 1981; Warne and Stanley 1993; Loizeau and Stanley 1994). It is thus useful to evaluate anthropogenically altered changes in Manzala by considering Burullus (least modified) and Maryut (most modified) as end-members, and Manzala and Idku as intermediate altered wetland types. There are differences between lithologic distribution patterns in Manzala and Idku (Loizeau and Stanley 1993) lagoons. Sediment types in Manzala are generally coarser and distributed over a larger area, a function of the larger number of major drains that discharge significant sediment loads into Manzala. In Idku, a northern sediment province is defined by terrigenous and coarse-grain sediment types; these result from landward displacement of coarser sediment by wind and waves and from stirring of the lagoon floor. The northern Idku province (Saad 1976b) is similar to microfacies I (terrigenous well-sorted sand) and II (micaceous muddy sand) as defined in this study. In Manzala, however, coaser-grained microfacies cover a proportionally larger area along the northern ridge because of recent accelerated erosion of Damietta promontory and deposition of sand in the northern sector. Southern Idku sediment province, characterized by finer-grained material with high biogenic and aggregate content, is located along the S and SE margins of that lagoon. Similarities between that part of Idku and southern Manzala are probably a function of dispersal of fines from drains and their entrapment by vegetation concentrated along those margins of both lagoons.

Comparison of depositional changes through time in Idku and Manzala Lagoons are also of note. Microfacies III (shelly silty mud), well diffused at the surface and in cores in eastern Manzala, occurs in a more restricted manner in the uppermost part of cores in eastern Idku. On the other hand, the sandy silt and silty sand lithofacies mapped in the westernmost corner of Idku lagoon is most comparable with more widely diffused microfacies I (terrigenous well-sorted sand) in Manzala (Loizeau and Stanley 1993).

It is not surprising that there are more differences than similarities between sediment distributions in Manzala and highly modified Maryut lake (Saad and others 1981; Loizeau and Stanley 1994). For example, sand-size carbonate crusts and frustules (commonly associated with polluted conditions) that form on vegetation are recorded in both Maryut and Manzala; in Manzala, however, the distribution and amount of these crusts are generally less important than in Maryut. However, large amounts of such crusts occur locally, especially in the Bahr El-Baqar drain sector, the most polluted part of Manzala Lagoon (Siegel and others 1994).

This comparison of Nile Delta wetlands suggests that Manzala could eventually be transformed to a shrunken, segmented, highly polluted wetland not unlike Maryut if present conditions continue unabated.

Conclusions

Manzala, a tectonically subsiding basin, is receiving increased waste-water discharge from the south and seawater driven across the eroded coastal ridge system in the north. However, instead of becoming deeper, the lagoon is becoming shallower due to increasing sedimentation rates into a decreasing lagoon area. The present "settling basin" effect has serious implications, including loss of much-needed reserves of fresh to brackish water and decreased fish catches, at a time when both are much needed by Egypt.

This investigation summarizes important depositional changes during the period from ~1920 to 1990. The study reveals that major sedimentological modifications occurred from 1940 to ~1965, and records the impacts on Manzala's quasi-closed system by industrial build-up, wetland conversion to agricultural land, and irrigation waterway development during and following World War II. Further important changes in Manzala deposition, recorded from ~1965 to 1990, are related to closure of the High Dam at Aswan, continued construction of waterways that discharge waste water directly into the lagoon margins, and increased marine incursion into northern lagoon sectors.

A scheme highlighting processes that are currently modifying deposition in Manzala is shown in Fig. 10. If 6 km^2 of wetland is lost annually (a conservative estimate), and if present conditions continue (Fig. 9), Manzala will retain only about one-third of its present area by the year 2050 (Fig. 10). Since sediment is no longer being discharged at the mouth of Damietta in the NW sector, wave erosion is cutting back unprotected parts of Damietta promontory, and eroded sand displaced by coastal currents is accreting as ridges and spits to the east. Sand is also filling shallow northern lagoon areas north and east of Damietta. Moreover, SE displacement of sand and coarse silt along the coast further modifies El-Gamil outlet and will require additional dredging to maintain the opening between lagoon and sea. In the northeastern sector, expansion of Port Said will inevitably require additional coastal protection and more extensive dredging. In the SW and S sectors, nutrient-rich water discharged from drains is continuing to favor plant growth which, in turn, increases sediment entrapment. Directly related to this phenomenon is the large amount of untreated waste-water discharged along SW, S, and SE margins of Manzala, with a consequent decrease in lagoon area and depth and concomitant increase in contaminants accumulating with sediment. Heavy metals are disseminating through the food chain and increasingly affect one of Egypt's most important fish source. The area of high bioaccumulation, already important in shallow southeastern sectors near El-Mataria, is likely to expand to other parts of the lagoon.

As anthropogenic alteration of Manzala continues, this wetland will appear increasingly similar to the more modified wetlands, first like Idku and then Maryut. It is not expected that Manzala will reach the extreme situation of Abu Quir lagoon, once positioned southeast of Alexandria and then completely drained before the end of the last century (Warne and Stanley 1993). It is recalled that Egypt already uses almost 98% of its Nile water source, and it is evident that progressive elimination of Manzala as a natural reservoir has serious ramifications. Such wetland loss would negatively impact upon a major, much-needed aquacultural food source, and also would have deleterious environmental and ecological consequences. One, for example, would be loss of the remaining major flyway for birds that migrate between southern Europe and eastern North Africa.

Sedimentological and associated morphological changes measured and documented herein through time serve as baseline criteria needed by environmental and coastal managers active in preserving this vital wetland. Sedimentological research should be integrated with that of geochemists, biologists, ecologists, and civil planners. In view of its obvious importance to Egypt, measures are needed to sustain Manzala as a properly functioning wetland system. There is some question as to whether present conditions could be reversed. It is recommended, at the very least, that stations be established along lagoon margins to systematically sample waste-water and sediment discharge from canals and drains, and to monitor depositional conditions in the open lagoon. Focus should be on preserving this, the largest wetland in eastern North Africa, and on improving physical and chemical conditions and thereby reduce existing health risks.

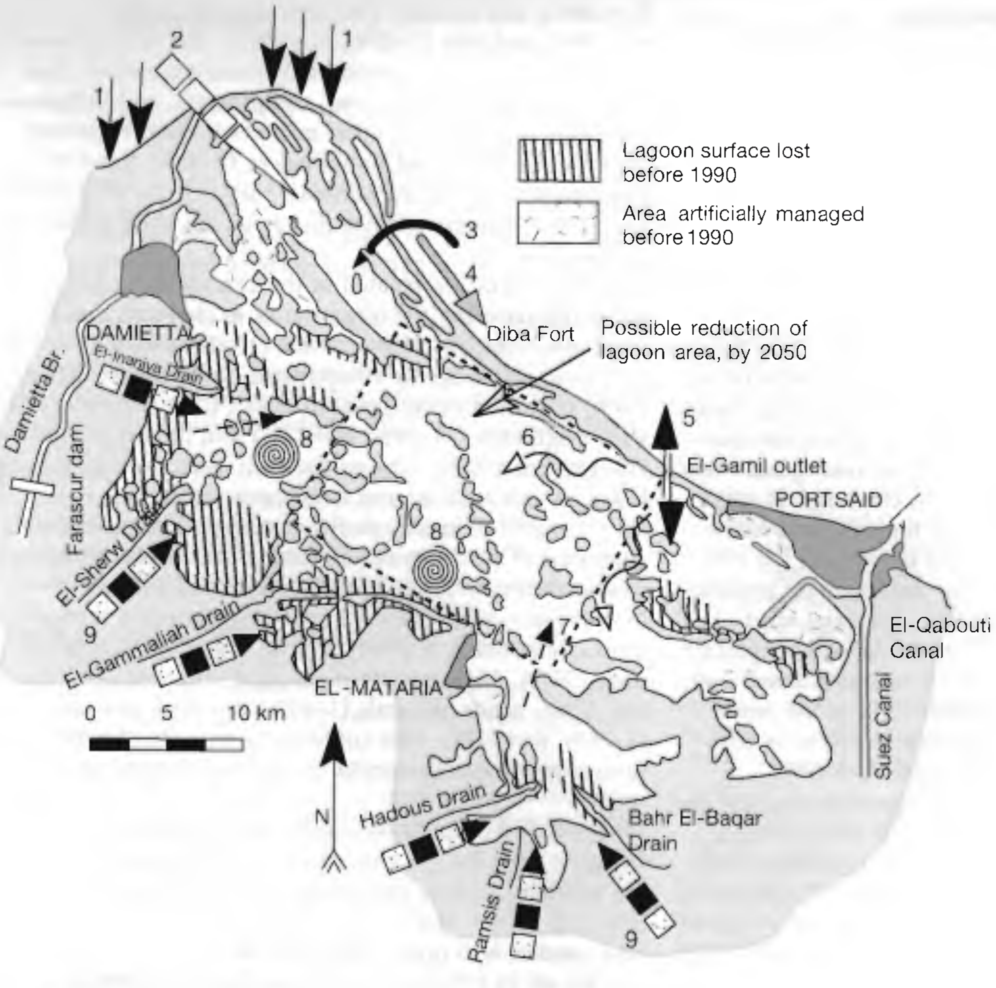

Fig. 10
Map of Manzala schematically depicting areas of lagoon lost and artificially managed prior to 1990. *Dashed rectangle* (~1/3 of present lagoon surface) is a conservative estimate of area that could remain by 2050 AD (not necessarily at position shown) if present conditions remain unaltered. Among factors affecting the wetland are: (1) erosion and retreat of coast at Damietta promontory; (2) sand and silt driven landward from Damietta promontory into NW lagoon by wind and waves; (3) bypassing of water and sediment from inner shelf to northern lagoon during storms; (4) coastal current transport of sand to southeast; (5) in- and outflow through El-Gamil outlet; (6) wind and current-driven circulation in lagoon (some water directed inland) in spring and summer; (7) wind and current-driven circulation in lagoon (some water directed seaward) in fall and winter; (8) increased sediment entrapped by plants in southern and central lagoon; and (9) discharge of waste water, sediment, and nutrients from drains and irrigation channels

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Appendix A. Description of major lithologic types in Manzala Lagoon cores

A. Light olive-grey (5Y 5/2) to olive-grey (5Y 3/2) medium- and fine-grained sand and/or silty sand is generally present in upper parts of cores. The lower part of this lithology usually comprises finer sediment. Abundant mollusc shells, broken and unbroken, are diffused along the whole section, as are root structures. Laminae are present in the lower part where shells are less common.
B. Light olive-grey (5Y 5/2) to dark yellow-brown (10Y 4/2) silt or sandy silt, is generally present in the upper parts of cores. Bivalve fragments and gastropods are concentrated as layers.
C. Light olive-grey (5Y 5/2) to dark brown (5YR 2/4) shelly soft muddy silt is always present in the middle to bottom part of cores. Shells are either diffused or concentrated in layers.
D. Light olive-grey (5Y 5/2) to dark brown (10YR 4/2) and to grey-black (N4) soft micaceous mud, with common root structures. Organic matter is preserved in pockets and as layers.
E. Olive-brown (5Y 5/6) to greenish-grey (5GY 6/1) medium-grained sand, with few mollusc shells.

F. Light brown (5Y 4/4) compact clay.
G. Layers of gypsum crystals enclosed in a light brown (5Y 4/4) silt matrix.

Appendix B. Description of petrologic microfacies in Manzala Lagoon

Petrologic microfacies (coded I–V) are mapped on the modern Manzala Lagoon floor (I–IV) and in subsurface (I–III, V). These are determined statistically on the basis of cluster analysis from data obtained from 83 surficial and 117 subsurface samples. Microfacies incorporate four textural variables (granule, sand, silt, clay) and 11 sand compositional (six terrigenous, five biogenic) variables.
I: *terrigenous well-sorted sand.* This prevails in the NW sector of the lagoon in and east of the Damietta promontory and along the southern margin of coastal sand ridges. The facies comprises by far the largest proportion of terrigenous components (96%); faunal and floral components, together, account for only ~2% of the sand-sized fraction. The large sand fraction (to 99%) is composed of high proportions of both light (76–89%; $\overline{m}=83\%$) and heavy (6–20%; $\overline{m}=12\%$) minerals, and low glauconite/verdine (~1%) content. This microfacies is also characterized by high proportions of polished, well-sorted grains (primarily quartz). Mollusc shell fragments are generally absent to rare in much of the NW sector of the lagoon. This microfacies, near the El-Gamil outlet, is generally comparable to that in the northwest, but includes somewhat higher amounts of mollusc shell material (to ~6% in the granule size fraction).
II: *micaceous muddy sand.* This is distributed as a narrow linear zone along the landward margin of facies I, i.e., immediately south of the linear NW–SE trending islands. It is characterized by large silt (31–77%; $\overline{m}=53\%$) and moderate sand (1–22%; $\overline{m}=13\%$) fractions, and an assemblage including relatively high proportions of light minerals (46–68%; $\overline{m}=55\%$), mica (1–15%; $\overline{m}=7\%$) and plant fragments (2–10%; $\overline{m}=6\%$) in the sand fraction. The proportion of shell (mostly mollusc) fragments in this facies is intermediate (1–29%; $\overline{m}=10\%$) between that of facies I and III.
III: *shelly silty mud.* This covers the largest surface area of Manzala, and is dominant in the central sector and also along the NW, S, and SE margins. Texture is highly variable, generally characterized by greater proportions of silt (3–66%) than clay (2–45%) or sand (0–85%). The sand-size fraction is dominated by biogenic components, including foraminifera (0–28%) and ostracod (0–52%). In addition, the amount of shell (mollusc) fragments (0–58%) is usually more important than in facies I, II, and IV. Three subfacies of III are recognized on the basis of sand-sized compositional components:
III/1: located south of the town of Damietta, this subfacies is characterized by a prevalence of silt (3–66%; $\overline{m}=40\%$), and variable amounts of sand (0–68%; $\overline{m}=29\%$) and clay (1–45%; $\overline{m}=30\%$). The proportion of biogenic (to 66%) is considerably more important than that of the terrigenous (30%) components, and includes abundant ostracod (12–52%; $m=32\%$), shell fragments (1–44%; $\overline{m}=16\%$) and foraminifera (2–28%; $\overline{m}=13\%$). The proportion of light minerals ranges from 13 to 43% ($\overline{m}=24\%$). Associated with this subfacies are freshwater molluscs.
III/2: this subfacies, located in the central part of the lagoon and covering the largest area, is characterized by sand (44–77%; $\overline{m}=59\%$) and silt (15–32%; $\overline{m}=23\%$). The proportion of biogenic components is somewhat higher (54%) than that of terrigenous ones (42%). Important are shell fragments (14–58%; $\overline{m}=27\%$) and light minerals (18–58%; $\overline{m}=36\%$). The subfacies is associated with both brackish (euryhaline) and freshwater molluscs.
III/3: Located primarily in the southeast lagoon, east and southeast of the town of El-Mataria, this subfacies is characterized by sand (32–85%; $m=50\%$) and silt (6–64%; $m=34\%$). However, the proportion of terrigenous components is greater (63%) than that of biogenic ones (39%). Also important are light minerals (27–73%; $\overline{m}=52\%$), heavy minerals (1–12%; $\overline{m}=5\%$), and ostracod (3–36%; $\overline{m}=11\%$). This subfacies is associated with molluscs typical of both euryhaline and freshwater environments.
IV: *plant-rich silty clayey mud.* This microfacies, with an irregular distribution pattern, is located primarily along the southern lagoon margin near the El-Gammalia drain and near Hadus and Ramsis drains; smaller, more localized patches also occur within the lagoon. It is characterized by silt (13–86%; $\overline{m}=52\%$) and variable amounts of clay (0–64%; $\overline{m}=17\%$) and sand (5–85%; $\overline{m}=24\%$). Proportions of ostracod are variable but generally high (6–88%; $\overline{m}=29\%$), and those of plant fragment (0–19%; $\overline{m}=6\%$) and diatom (0–6%; $m=1\%$) are also relatively important. Shell (molluscan) fragments range from 4 to 42% ($\overline{m}=17\%$). Of the four microfacies, IV comprises the lowest proportion of light minerals (5–44%; $\overline{m}=23\%$).
V: Microfacies V, not observed on the modern (1990) lagoon floor, is termed *Mica-*, *foraminifera-*, and *plant-rich silty mud.* It is characterized by dominant clay (18–69%; $\overline{m}=45\%$) and silt (3–71%; $\overline{m}=43\%$) fractions, a variable sand fraction (1–40%; $\overline{m}=12\%$). Also present is an important sand-size assemblage of mica (0–6%; $\overline{m}=1.2\%$), foraminifera (8–66%; $\overline{m}=40\%$), ostracod (1–34%; $\overline{m}=12\%$), and plant fragments (0–3%; $\overline{m}=0.3\%$).
Three of the 83 surficial samples, recovered in three different parts of the lagoon, cannot be grouped with any of the four above microfacies; they are coarser (30–78% granule) than most of the 80 other samples, and largely terrigenous (32–94%).

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