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Bottom Sediment Patterns Evolving in Polluted Mariut Lake, Nile Delta, Egypt

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ABSTRACT

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Bottom sediments in surficial and short-core samples collected in different parts of highly polluted Mariut Lake, Nile Delta, Egypt, record the increased anthropogenic influence during the past century. The study is based on identification of lithofacies in short-core sections integrated with petrographic analyses of grain size and composition of the sand-size fraction in both core and surficial samples. Most Mariut lacustrine subfacies that date back to the last century are similar to those in modern Nile Delta lagoons (Idku, Burullus, Manzala), and also to older lagoon deposits examined in Holocene core sections. During this century, the lake has become artificially separated into three distinct regions, each with different petrologic attributes. These differences are a function of both natural and man-influenced factors in the three settings: sabkha-desert conditions prevail in the topographically most isolated western sector southwest of Alexandria; totally enclosed artificial salt ponds in the central sector, south of Alexandria's industrial complex, into which waters are pumped from the sea; and much lower salinity sub-basins in eastern Mariut which receive larger amounts of fresh water, much of it polluted, through a series of canals, sewage outfalls and drains. With time, there have been lake-wide changes such as decreased proportions of benthic fauna, including molluscs. Marked variations related to specific sub-basins include the formation of very dark, distinctly layered sediment subfacies in central Mariut, and deposits rich in bio-precipitate carbonate and plant debris in the eastern part of the lake. These latter water plant-related carbonate crusts are herein interpreted as indicators of increased pollution and eutrophication. The much increased domestic, industrial and agricultural wastes discharged into Mariut, particularly in eastern sub-basins, have serious potential consequences for the large, rapidly growing population of the Alexandria region. Closely integrated sedimentological and geochemical study of bottom sediments should be carried out to carefully monitor anthropogenic-related changes.

ADDITIONAL INDEX WORDS: *Alexandria, bottom sediments, carbonate crusts, eutrophication, grain size analysis, lagoons, Mariut Lake, Nile Delta, pollution.*

INTRODUCTION

Mariut Lake is one of four shallow water bodies in the northern Nile Delta of Egypt. This lake is shallow, of variable salinity and positioned adjacent to the coast, and is similar in a number of respects to Idku, Burullus and Manzala lagoons to the east (Figure 1). Mariut is essentially enclosed while these lagoons are connected to the Mediterranean Sea by outlets. Positioned in the highly populated and industrialized Alexandria region, Mariut is the most polluted of the four water bodies (SAAD *et al.*, 1984; EL-SOKKARY, 1992).

During this century, the Alexandria region has experienced a marked increase in population, which now exceeds 3.5 million, and this growth has induced severe problems of domestic pollution in the region (MITWALLY, 1982; SAAD, 1983b; SAAD *et al.*, 1984). Heavy industry has also increased markedly during the last half century, and these plants release large volumes of untreated wastes along the Alexandria coast and in Mariut Lake (SAAD *et al.*, 1985; EL-SOKKARY, 1992). Moreover, an ever-larger loading of agricultural runoff is introduced into the lake via canals and drains (WAHBY and EL-MONEIM, 1979; SAAD *et al.*, 1984). This is, in large part, a response to the emplacement in 1964 of the High Dam at Aswan which caused the cessation of seasonal Nile flooding, cut off the vital source of natural nutrients formerly carried onto the Nile Delta plain, and in consequence now requires the use of artificial fertilizer.

Since Mariut has long been affected by man and is now being altered dramatically at an even

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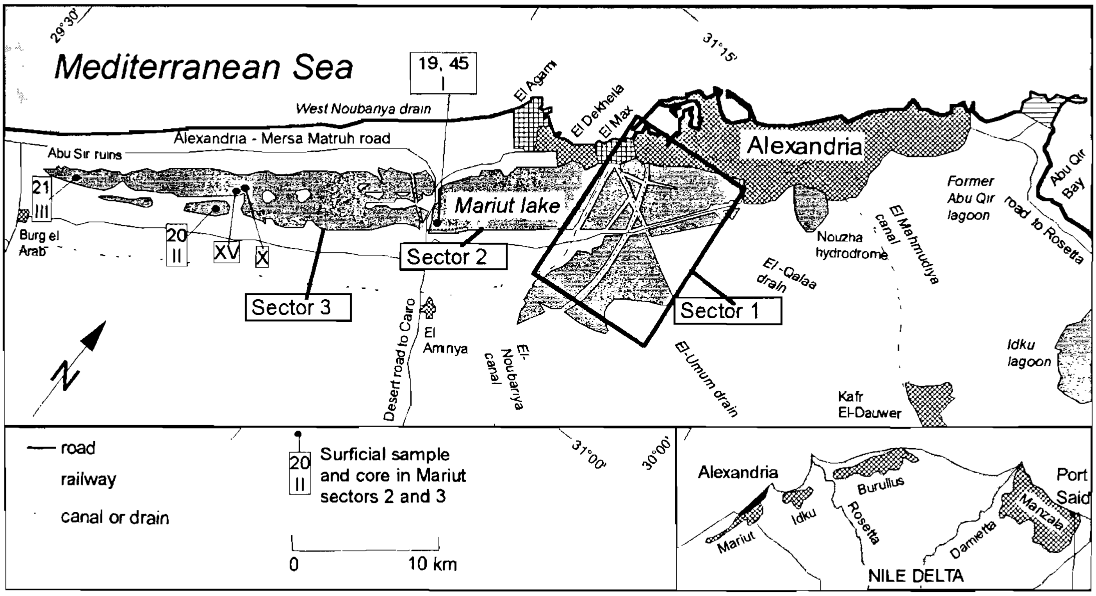

Figure 1. Map of Mariut Lake region showing prominent geographic features. The three main parts of the lake are designated in this study as sectors 1, 2 and 3. Positions of surficial samples and cores (identified by roman numerals) in sector 2 and 3 are indicated. Locations of surficial samples and cores in sector 1 are depicted in Figure 2. Inset map shows location of the three Nile Delta lagoons east of Mariut.

more accelerated rate, it is of importance to record and intercept regional and temporal distributions of sediment before further transformations of the lake occur. The primary purpose of this investigation is the description of surficial and sub-recent (past century) bottom sediments and lacustrine depositional patterns in the different Mariut sub-basins for base-line inventories. Our petrologic analyses, integrating lithofacies with more detailed analyses of composition and grain size, complement earlier studies of Mariut which examined texture and chemistry of bottom sediments, particularly in the eastern lake sub-basins (EL-WAKEEL, 1964; EL-WAKEEL and WAHBY, 1970; SAAD, 1974a, 1978; SAAD *et al.*, 1985). This study aims to identify changing sedimentary patterns in the Mariut sub-basins and to distinguish those related to natural factors from those that are evolving in response to anthropogenic activity.

GENERAL SETTING AND BACKGROUND

Mariut, with an area of about 90 km^2, is the smallest of the four coastal water bodies in the northern Nile Delta. Unlike the three delta lagoons to the east, Mariut has no natural outlet or opening with the sea and, therefore, is referred to as a lake. The major part of this shallow water body is situated south of Alexandria and is completely separated from the sea by a high (to ~20 m), rather well lithified carbonate ridge of late Pleistocene age (Abu Sir Ridge or Bar, *cf.* BUTZER, 1960; ALI and WEST, 1983). The long, narrow extension of the lake southwest of Alexandria (to beyond the ruins at Abu Sir) occupies the lowest part of the depression between two carbonate ridges (Abu Sir and Gebel Mariut ridges). This lake extension parallels the coastline (Figure 1) and is separated from the sea to the north by two carbonate ridges, one (Abu Sir Ridge) which rises to 30 m above sea level (ALI and WEST, 1983; WARNE and STANLEY, 1993).

Mariut Lake is presently only a small remnant of its precursor, Lake Mareotis, which covered a large area south of Alexandria during the middle and late Holocene. WARNE and STANLEY (1993) showed that Mareotis had developed by at least 6,100 years BP. At that time, it covered approximately 700 km^2 extending more than 40 km south and southeast of Alexandria and 70 km southwest along the coast (WARNE and STANLEY, 1993, their

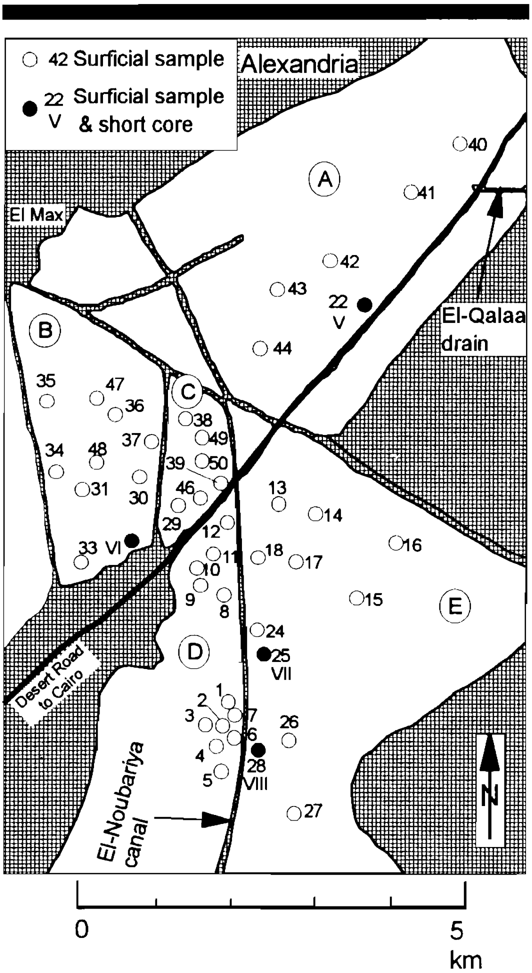

Figure 2. Index map of five eastern Mariut Lake sub-basins (A–E) in sector 1, showing position of surficial samples and cores.

Figure 15). During most of its existence, Lake Mareotis was isolated from the Mediterranean (De Cosson, 1935). There have been phases, however, when this water body had a connection with the sea. For example, it became a lagoon with an exchange of seawater at Abu Qir Bay during the fourth century as a result of minor earthquakes in this region (De Cosson, 1935; Shafei, 1952). Analysis of historic records suggests that all canals linking Lake Mareotis to the Canopic and Rosetta branches silted up by the twelfth century. In consequence, lake level fell and the region was transformed into a series of salt lakes and sabkhas. Lake level remained low until 1801 when the dike between Mariut depression and former Abu Qir lagoon was breached several times for tactical military purposes (De Cosson, 1935). In 1808, the barrier separating Mariut and Abu Qir lagoon and Abu Qir Bay to the east was restored (presently the leveed El-Mahmudiya canal) and much of the lake again became dry until 1892. At that time the irrigation system of the northwestern Nile Delta was modernized. The Mariut depression then served as a drainage basin for the adjacent cultivated land, and various canals and drains (Figures 1, 2) were designed to flow into it (Aleem and Samaan, 1969). Recently, large portions of this lake have been reclaimed and converted to land for agriculture (Abdel-Kader, 1982; Saad *et al.*, 1982, their Figure 1).

Mariut Lake is now artificially divided into many sub-basins. Previous investigators recognized four in the eastern lake (Aleem and Samaan, 1969; El-Wakeel and Wahby, 1970; Wahby *et al.*, 1978), whereas at least nine sub-basins are described in a more recent study (Warne and Stanley, 1993). The lake continues to be further divided and extensively altered by new causeways and canals. The part of the lake south of El Dekheila and El Agami is now almost completely separated for use as a pond to pre-concentrate brines for salt production. Another example is the Nouzha hydrodrome (Figure 1), once part of easternmost Mariut Lake, which was separated from the lake in the late 1930's to create a seaplane airport (Saad *et al.*, 1985) and is now used as a fish farm. This isolated sub-basin (not sampled in this investigation) receives water from the El-Mahmudiya canal.

In the present study, the different lake sub-basins are geographically grouped into three regions. These, termed sectors herein, are of roughly similar dimension but are characterized by markedly different environmental attributes.

Lake Sector 1

All sub-basins in the eastern region directly south of Alexandria (Figure 2) are fed year round by water from canals and drains, and thus remain permanent, brackish coastal water bodies. Water depth generally ranges from 0.9 to 1.5 m, and salinity from 2 to 4.7 g/l (Kerambrun, 1986). Due to shallow depths, lake water is vertically well mixed and is not stratified. Water temperature parallels that of the air; in 1980, for example, water ranged from 14 °C in January to 29.5 °C in July (Saad, 1983a). Evaporation in this region is

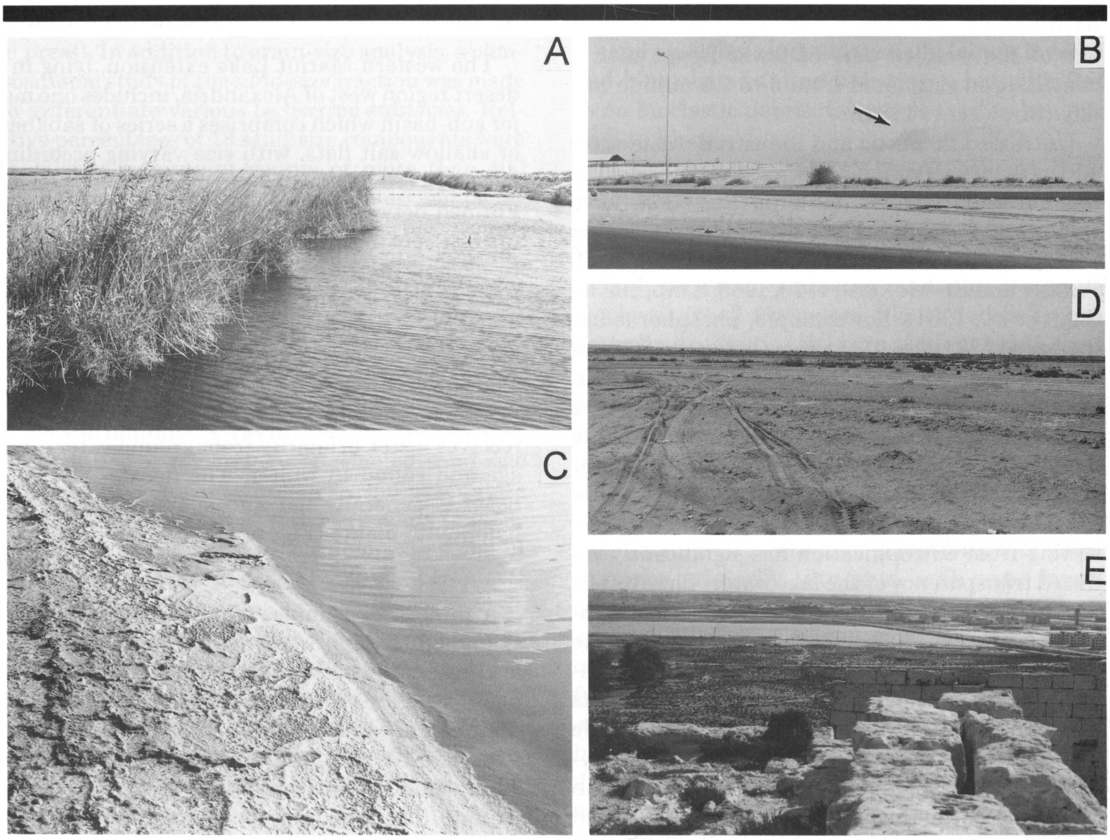

Figure 3. Selected photographs of the three Mariut Lake sectors. (A) Vegetation (*Phragmites* in foreground) along Noubariya canal (view toward north) in southern part of sector 1 (sub-basin D), eastern Mariut. (B) Salt ponds in central sub-basin in sector 2, as observed from the El Amiriya-to-Agami causeway (view toward northeast); smoke in background (arrow) is from industrial complex near El Dekheila, west of Alexandria. (C) Salt crust along western margin of sector 2. (D) Dry, recently reclaimed portion of western Mariut Lake extension, sector 3, as observed from the El Amiriya-to-Agami causeway (view toward west). (E) Western Mariut Lake extension, sector 3; View, toward south, taken from Abu Sir ruins on carbonate ridge. Burg el Arab in background.

fairly high, with an average value of 5.3 mm/day (SESTINI, 1992). The water level is artificially maintained at 2.6 to 3.1 m below mean sea level (EL-WAKEEL and WAHBY, 1970) by a pumping station located at El-Max (Figure 1). The lake thus presently occupies only 13% of the size it would be if the water surface was allowed to rise to sea level. The southern sub-basins (Figure 3A) and the western part of the northern sub-basin are densely covered by plants (including *Potamogeton* sp., *Phragmites communis* and *Typha latifolia;* WAHBY and EL-MONEIM, 1979).

The water supply feeding the lake is derived mainly from El-Qalaa drain which carries industrial and domestic wastes and agricultural runoff and discharges on the eastern side of the lake. To the south, El-Umum drain extends across the lake to El-Max, where water, also polluted with raw domestic wastewater and agricultural runoff, is pumped to the Mediterranean. Water from this drain enters into the lake through several breaks in the embankments separating the main course of the drain from the lake (SAAD *et al.,* 1984). Large amounts (about 200,000 m^3/day) of untreated industrial and domestic wastewater with their trace metal loading are released directly into the lake via sewage pipes from the southern part of the city (SAAD *et al.,* 1981; EL-SOKKARY, 1992). Alexandria, with its population of about 3.5 million, is the second largest city in the Middle East, and about 40% of Egyptian industries are located here (MITWALLY, 1982; SESTINI, 1992). These sub-basins also receive water from agricultural drainage of the western part of lower Egypt with a contribution estimated from 6 to 7.5 million m^3/day (MITWALLY, 1982).

Untreated domestic and industrial wastewater and agricultural runoff have greatly increased the organic and nutrient contents and thus have transformed this sector of Mariut into a highly eutrophic lake (SAAD, 1974b; WAHBY *et al.*, 1978; WAHBY and EL-MONEIM, 1979, 1983; SAAD, 1983b; SAAD *et al.*, 1984). For example, phosphorus has increased 128 times in 15 years (between 1963 and 1978) (WAHBY and EL-MONEIM, 1979), particularly in sub-basins adjacent to Alexandria where values as high as 25 μg P/l of dissolved phosphate have been recorded (SAAD *et al.*, 1984). Water plant growth has much increased in the lake proper. The high phytoplanktonic productivity resulting from eutrophication has significantly reduced transparency of the lake water. The average Secchi disk value is as low as 41 cm, with a minimum of 31 cm on the northern side of the lake (SAAD, 1983a). Other notable effects of eutrophication on water chemistry are increased contents of organic matter, ammonia, hydrogen sulphide and depletion of dissolved oxygen. Locally, oxygen is totally depleted (WAHBY *et al.*, 1978; SAAD *et al.*, 1984). In addition to contaminants carried through canals and drains, Mariut region suffers from atmospheric fallout (Figure 3B) which accounts for a major source of trace elements, including noxious heavy metals such as mercury (EL-SOKKARY, 1989). Five of the sub-basins in sector 1 have been sampled, and these are coded A to E (Figure 2) in the present study.

Lake Sector 2

The central part of Mariut Lake southwest of El-Max is the sub-basin most altered by man. It comprises a major pre-concentration complex and a series of drying pans for salt production (Figure 3B and C). In contrast to sector 1, no major drains carrying fresh water enter this part of the lake which, for the most part, is shallower than 1 m. Water color tends to be pink to light red from algal cysts and microscopic shrimp. Salinities of 92 g/l are maintained in the main body of this sub-basin by pumping water from the sea into the lake through underground pipes. At its northern edge, 15 pans concentrate salt water before its processing at the El-Max salt factory (Mr. H.Z. HANAFI, El Salines Co., *personal communication*, 1992).

Lake Sector 3

The western Mariut Lake extension, lying in a desert region west of Alexandria, includes one major sub-basin which comprises a series of sabkhas, or shallow salt flats, with size varying according to season (HASSOUBA, 1980; ALI and WEST, 1983). Formed between two long carbonate ridges (Figure 3E), it extends from the West Noubariya drain to beyond the ruins at Abu Sir and the town of Burg el Arab (Figure 1). Large sectors of this sub-basin are dry during much of the year (Figure 3D), with evaporation prevailing during summer. The sub-basin, now essentially cut off from lake sectors by the El Amiriya to El Agami causeway, receives water primarily from groundwater seepage and runoff in winter. The floor of this sub-basin is generally flat and sparsely covered by halophytic plants (Figure 3D).

METHODOLOGY

A total of 82 samples from Mariut Lake were examined in the present study. These include 48 of the 50 surficial samples (upper 5 cm; coded 1 to 50 in Figures 1, 2) collected with a 5-liter grab sampler during two Smithsonian field expeditions (1990 and 1992). Of these, 44 were recovered from lake sector 1, two from sector 2, and two from sector 3. The remaining 34 samples were selected from nine short Mariut (Mt) cores (identified by Roman numerals in Figures 1, 2, 6 and 9) taken during the 1992 field survey. Samples in short cores were taken along sections at every marked lithological change. The short borings were recovered with a hand-percussion corer and range in length from 46 to 69 cm. Four borings are from sector 1, one from sector 2, and four from sector 3. Surficial sample and core locations were determined by satellite positioning, with a precision of about 50 m, using a Magellan GPS NAV 1000 PRO©.

Visual and X-radiographic examination was made of all split cores to record general lithology, stratal boundaries, faunal and floral remains, sedimentary and biogenic structures, color and other macroscopic features.

The processing and analyses performed on both surficial and core samples were the same as described by LOIZEAU and STANLEY (1993). For all 82 samples, the fractions finer and coarser than 500 μm were separated by wet sieving, and the weight percentage of both fractions was determined. A complete grain-size analysis was made of the $<$ 500 μm fraction with a Coulter laser diffraction grain-size analyzer (*cf.* LOIZEAU *et al.*, in press). In addition to grain-size analysis, a compositional study of the sand-size fraction was made to differentiate various lacustrine subfacies. Relative percentages of 18 sand-size components were calculated from point counts of more than 400 grains for each sample. These components include: nine mineralogical (light and heavy minerals, mica, glauconite/verdine, pyrite, gypsum, lithic fragment, aggregate, and biogenically-induced precipitate carbonate encrustation); six faunal (ostracod, foraminifera, gastropod, pelecypod, indeterminate shell fragment, and other); and three floral (plant fragment, charophyte oogonia and diatom). X-ray diffractometry was used to identify the mineralogy of selected sand-size particles that are interpreted as bio-precipitate carbonate. Thin sections also were made to identify the light minerals which dominate some of the samples, and primarily to distinguish quartz from carbonate grains.

Statistical cluster analysis is used here to group samples using both textural data and composition of the sand-size fraction (*cf.* LOIZEAU and STANLEY, 1993). A K-means cluster (Q-mode) analysis (HARTIGAN, 1975) was performed on an IBM-compatible personal computer using NCSS 5.X software©.

A set of 21 maps showing the geographic distribution of each specific textural and compositional constituent was used to help interpret the various depositional environments. These are available from the authors, as well as a table listing raw data of relative percentage of compositional constituents and of grain-size parameters for all 82 samples examined in this study (MEDIBA, 1994).

DISTINGUISHING MARIUT SUBFACIES

It is readily apparent that the lithology of sediments in short borings, examined visually in split cores and with X-radiographs, is quite different in the three lake sectors. We distinguish five distinct lacustrine sediment types, and these Mariut subfacies are coded I to V. In sector 1 (eastern sub-basins), most sediments are greenish grey (5GY 6/1) to dark greenish grey (5G 4/1) and comprise three different subfacies (see core Mt V, Figure 4); I = unstratified coquina-like sediment, comprising mostly concentrates of unbroken shell and shell fragments in a sparse mud matrix; II = bioturbated mud, generally faintly layered and locally rich in sand fraction and bioclastic debris, including shell fragments and plant roots; and III = sand and silty sand, also usually faintly layered and bioturbated (often indistinct), but with few to no bioclastic debris. Core tops tend to be dark grey to black.

In sector 2 (central sub-basin), characteristic sediment observed in the middle to upper parts of a short core constitutes a fourth subfacies (core Mt I, Figure 4): IV = greyish black to black (N4 to N1), very well-laminated mud with few to no bioclastic (shell fragments, plant) debris. In one partially dry part of the core section, a thin light laminae of gypsum needles is noted (arrow in core Mt I, Figure 4). Also observed at the base of the core is a thick layer (14 cm) of concentrated shells in a mud matrix; this lithology resembles the unstratified shell-rich subfacies (I) observed in sector 1.

In sector 3 (western lake extension), four cores comprise primarily silty mud, with some layers containing few shells and/or plant debris. There are also thin interbedded sand layers. A thick coquina-like concentration of shells and shell fragments in a mud matrix is recorded at the base of one core. Color of the mud is highly variable, but usually lighter than in cores in sectors 1 and 2, and often mottled (Core Mt II, Figure 4). Prevailing colors are: dark yellowish brown (10YR 6/2), dark yellowish orange (10YR 6/6), light olive grey (5Y 5/2) and olive grey (5Y 4/1). The light colored brown and orange sediments in sector 3, identified as a fifth subfacies (V), suggest accumulation in less reducing and, in some cases, oxidized depositional environments. This subfacies is thus quite different than sediment types in sectors 1 and 2, with their darker color indicative of reducing conditions.

The above observations indicate that it is possible to distinguish, at least in a general way, a different suite of lithologies in the three geographic sectors of Mariut Lake. While vertical lithological changes are noted at most core sites in the three sectors (Figure 4), these up-core variations tend to be irregular and cannot be correlated from core to core.

Three (I–III) of the five subfacies forming sediment in Mariut short cores have counterparts in modern Idku (LOIZEAU and STANLEY, 1993) and Manzala lagoons (RANDAZZO, 1992) in the Nile Delta. In contrast, subfacies IV in sector 2 with its very distinct lamination, dark color and layered gypsum (core Mt I in Figure 4, upper to middle section) is markedly different from those

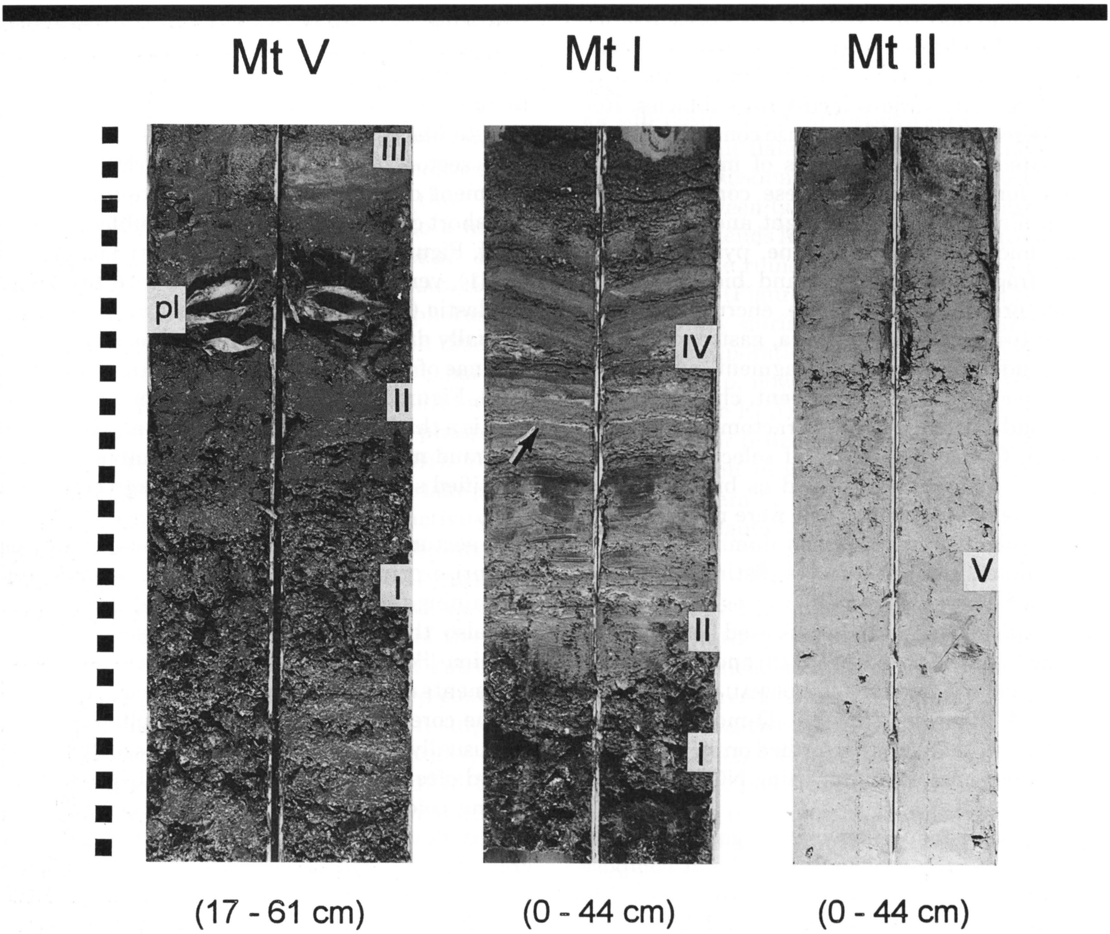

Figure 4. Photographs of selected split-core sections from the three different Mariut Lake sectors. Core Mt V (from sector 1) comprises subfacies I, II and III, and large plant debris (pl). Core Mt I (from sector 2) shows subfacies I, II and IV; arrow points to thin gypsum laminae. Core Mt II (from sector 3) comprises primarily subfacies V. Subfacies are described in text. Bar scale = 44 cm.

in Mariut sectors 1 and 3 and from those of modern lagoons. Moreover, a large portion of core sections identified as subfacies V in Mariut sector 3 is characterized by variable textural types of light color, and commonly mottled, with small proportions of shell fragments and plant debris, and an absence of coquina-like layers of shell concentrations. These sections formed by subfacies V are readily distinguished from the darker, more shell- and plant-rich lithologies widely observed in Mariut sector 1 and also in modern Nile Delta lagoons (RANDAZZO, 1992; LOIZEAU and STANLEY, 1993).

This lithofacies analysis indicates that it is the lacustrine subfacies of Mariut sector 1 which are most closely comparable to, although somewhat less diverse than, those in the two modern delta lagoons and also in deeper and much older Holocene lagoon sequences underlying Mariut (core logs in CHEN *et al.*, 1992, and WARNE and STANLEY, 1993). Moreover, some subfacies are notably absent in Mariut, such as the type characterized by dispersed shells in bioturbated mud and sandy mud; this subfacies is commonly recorded in Idku (LOIZEAU and STANLEY, 1993) and Manzala (RANDAZZO, 1992) lagoons, and is also present in many coastal water bodies in other parts of the world (KATUAN and INGRAM, 1974; HARBRIDGE *et al.*, 1976; THORNTON *et al.*, 1980; THORBJARNARSON *et al.*, 1985). We recognize that the above observations may be biased by the small

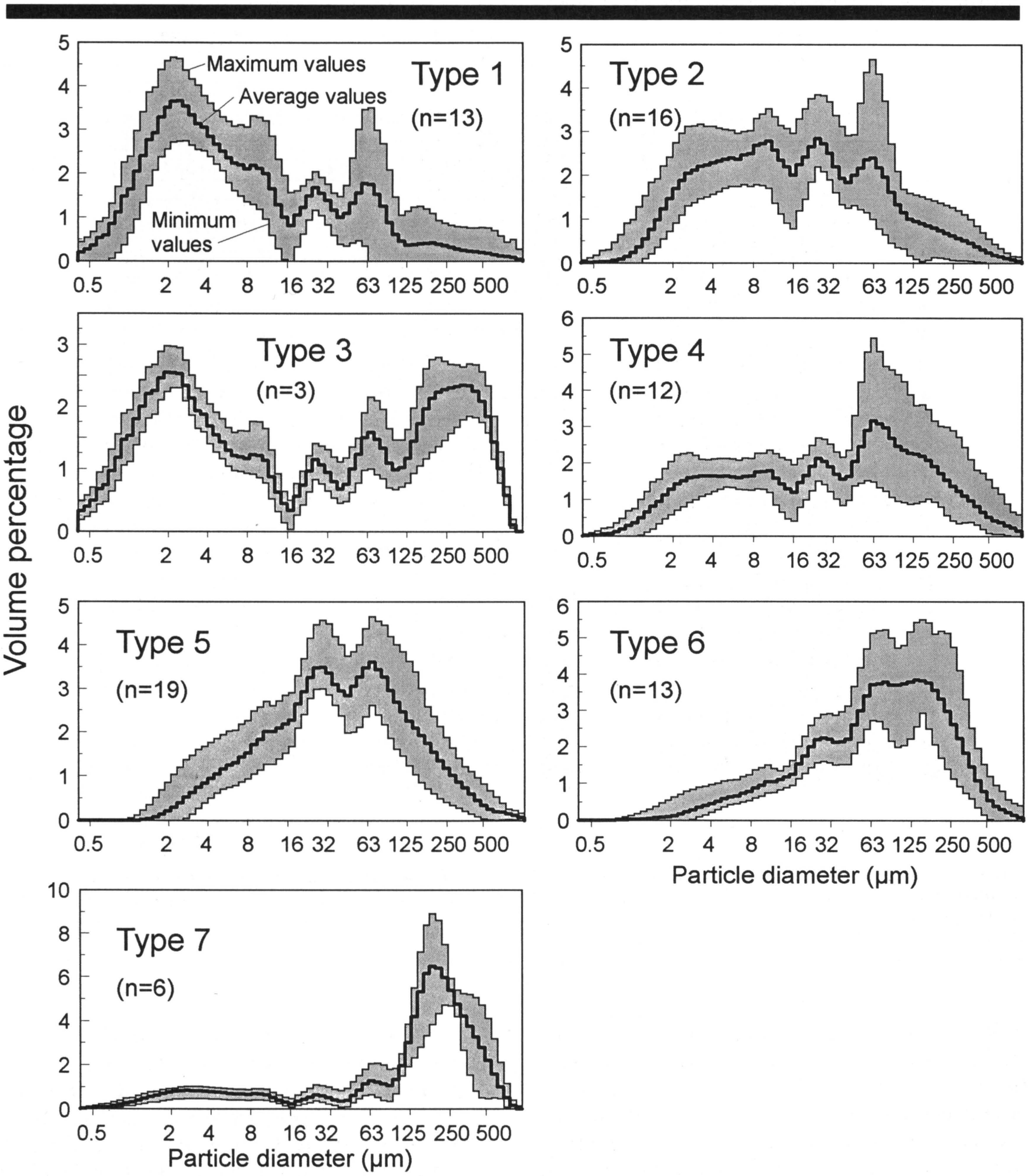

Figure 5. Seven histograms depicting grain-size types (1 to 7) defined in text (data base comprises 82 Mariut surficial and subsurface samples). Maximum, average and minimum values are shown on each histogram. Additional textural data are listed in Table 1.

number of available cores examined, and also by the fact that cores in sector 1 were, for the most part, sampled along margins (and not the center) of various sub-basins.

TEXTURE AND COMPOSITION

The above observations reveal some apparent similarities among lithologies of bottom sediments in the three sectors of Mariut Lake and

Table 1. *Statistical moments for grain-size types 1 to 7 (< 500 µm fraction) based on analysis of 82 surficial and subsurface Mariut Lake sediment samples. The size frequency distribution of each grain-size type is depicted in Figure 5.*

Type	n	Mean Grain Size		Standard deviation		Skewness		Kurtosis	
		Average (µm)	Range (µm)	Average	Range	Average	Range	Average	Range
1	13	6.9	3.7-11.6	1.56	1.10-1.79	0.67	0.18-1.03	-0.31	-1.27-0.54
2	16	16.4	9.9-26.6	1.44	1.17-1.61	0.23	-0.05-0.49	-0.67	-1.30-0.14
3	3	19.5	11.5-29.9	2.23	2.16-2.25	0.05	-0.06-0.47	-1.49	-1.47-(-1.16)
4	12	27.8	19.2-45.6	1.66	1.46-1.82	-0.21	-0.45-0.27	-0.97	-1.20-(-0.86)
5	19	36.0	21.6-50.1	1.22	1.03-1.37	-0.14	-0.53-0.12	-0.43	-0.72-(-0.05)
6	13	66.9	53.5-87.3	1.20	0.95-1.55	-0.66	-0.95-(-0.37)	0.08	-0.64-0.55
7	6	91.8	72.5-150.0	1.69	1.42-1.78	-1.34	-1.93-(-0.92)	0.61	-0.39-3.12

those in Idku and Manzala lagoons. Better discrimination among subfacies in the three sectors of Mariut Lake requires integration of detailed analyses of texture and composition. Such analyses also could be used to distinguish Mariut Lake lithologies from those of the two modern Nile Delta lagoons.

Grain-Size Types

Textural analyses indicate that each of the 82 Mariut surficial and short core samples can be grouped in one of seven types. Each sample is assigned to one of the 7 specific types on the basis of attributes of size distribution curves, including number, position and relative percentage of modes, and general signature of size frequency histogram (< 500 µm fraction). In most cases, the > 500 µm fraction generally accounts for less than 10% of the total sediment and consists primarily of mollusc shells, shell fragments and plant debris. This coarse fraction is not considered in the textural classification for Mariut Lake.

The distribution curves of all samples forming each of the seven grain-size types (coded 1 to 7) have been averaged to produce a single representative curve for the type (Figure 5). Data listing the average of four statistical moments (mean grain-size, standard deviation or sorting, skewness, kurtosis) and their minimum and maximum values (or range) for each of these 7 grain-size types are listed in Table 1. Mean grain size increases from type 1 to type 7. Names of grain-size types (in parenthesis in following text) and sorting classification used here are those of FOLK (1961).

Grain-size types 1 (mud to sandy mud) and 2 (sandy mud to sandy silt) are primarily mixtures of clay and silt with a mean size of 6.9 and 16.4 µm, respectively. Type 3 (sandy mud) is composed, in large part, of fine silt and clay and also of fine to medium sand, with a mean size of 19.5 µm. The presence of two very distinct size fractions present in similar proportions in type 3 is recorded by poor sorting and an almost symmetrical grain-size distribution. Type 4 (sandy silt) has a mean size of 27.8 µm and is poorly sorted. Type 5 (sandy silt) is characterized by two modes, at 28 and 66 µm, and a mean size of 36.0 µm. Type 6 (silty sand) is identified by two or more modes (66 to 200 µm) in the sand size range and a mean size of 66.9 µm. Although it is moderately sorted, type 6 is the best sorted of all grain-size types. Type 7 (silty sand) has one mode in the sand-size range and a mean size of 91.8 µm. Clay and silt fractions are present, but in minor amounts; these fines are recorded by a very low skewness value.

Geographic and temporal distributions of these 7 grain-size types are depicted in Figure 6. In sector 1, surficial samples are characterized primarily by grain size type 5, and also types 2 and 6. In contrast, subsurface sediment in cores in this region commonly comprises types 4, 7 and 1 (in diminishing importance). In sector 3, surficial samples are characterized by type 2, while subsurface sediment in cores most commonly comprise type 1. Grain-size types of sediment in sector 2 (core Mt I) resemble those in sector 3.

This overview indicates that lacustrine sediments tend to be finer grained in central and western than in eastern sub-basins, both in surficial sediment and at depth. Moreover, surficial sediments in the eastern sub-basins tend to be slightly coarser than in subsurface.

Petrological Components of Sand-size Fraction

Components forming the sand-size fraction of Mariut Lake surficial and core samples can be grouped into one of three distinct petrological assemblages. These three groups, comprising 17 components, are: (1) siliciclastic and diagenetic (light and heavy minerals, mica, glauconite/verdine, pyrite, gypsum, lithic fragment, aggregate); (2) **bioclastic** (ostracod, foraminifera, pelecypod, gastropod, undetermined shell fragment, plant debris, charophyte oogonia, and diatom); and (3) **bio-precipitate carbonate**. Spatial and temporal variations in the proportion of different components are also summarized below (see Table 2).

The siliciclastic and diagenetic group is largely dominated by light minerals, primarily quartz grains. This is determined by point counts in thin section analyses. There are low proportions of **light minerals** with an average value of 6.2% in surficial sediments of sector 1. In marked contrast, subsurface sediments in cores in this region record higher values (average 50.3%). In sectors 2 and 3, high to moderate values are usually observed, both in surface and at depth (averages range from 38.3 to 48.9%). **Heavy minerals** are usually present, but in low proportions (ranging from 0 to 2.6%) in both surficial and core samples. One exception is surface sample #42 in the center of subbasin A in sector 1, which comprises 10.7% heavy minerals, mostly opaques. **Mica** content is extremely low in most sediment of the three sectors, with average values ranging from 0.1 to 0.2%. **Pyrite** and **glauconite/verdine** are virtually absent in Mariut sediments; some pyrite grains (0.3 to 0.7%) are recorded in a few surficial samples. Proportions of **lithic fragments** are usually null to very low (0.2%) in surficial samples in sector 1, and slightly higher (0.4%) in cores of this region. Surficial samples in sectors 2 and 3 contain higher proportions (3.7 and 3.3%, respectively), whereas those in core samples of these sectors are comparable to those of sector 1. **Aggregates**, sand grains formed of silt-size particles, are found mostly in surficial sediment (4.5%) of sector 1; they are much less common (1.2%) in cores of this sector, and are almost absent in sectors 2 and 3. **Gypsum** is relatively uncommon in surficial sediments (0.6%), but is present in modest amounts in most core samples (5.5%) in sector 1. The latter average value results from the presence in two layers of a high gypsum content of 30.2% and 39.6%, in core VII. In contrast, gypsum is locally abundant in sectors 2 and 3 with a content as high as 80.2% in core Mt I. Two gypsum types are observed: lenticular "milky" crystals (Figure 7A), and transparent needles (Figure 7B). The former is the most common type in Mariut sediments, whereas the latter is recorded primarily in sediments of core Mt I in sector 2. Formation of gypsum in

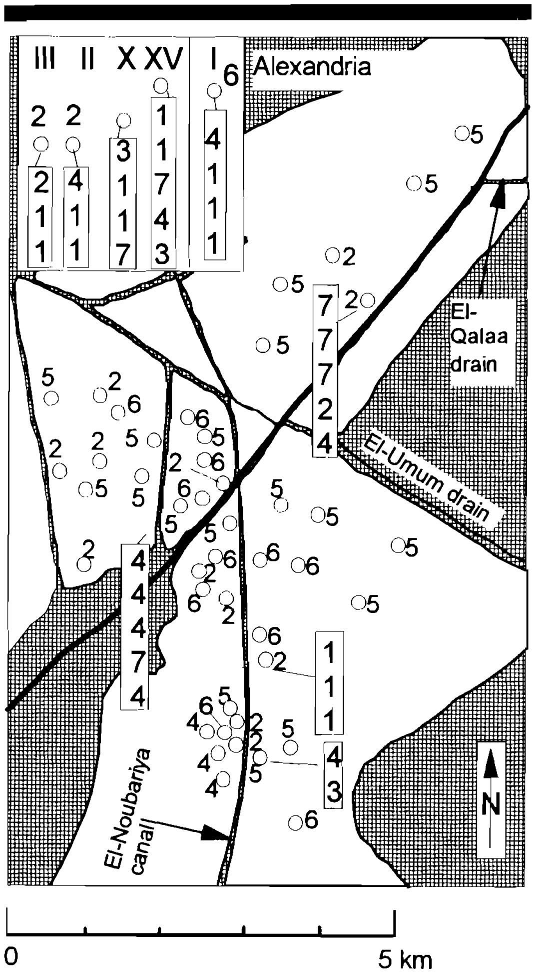

Figure 6. Geographic distribution of the 7 grain-size types (see Figure 5) identified in surficial and subsurface samples of Mariut Lake. Vertical sequences of textural types in short cores are shown in elongate boxes. Inset comprises data for surficial and subsurface samples in sectors 2 (1 core) and 3 (4 cores) to the west of sector 1. Roman numerals in inset refer to core number.

sabkhas of the western extension of Mariut has been investigated by West *et al.* (1979), Hassouba (1980) and Ali and West (1983). Lenticular crystals are believed to have formed within the sedimentary section during early diagenesis, whereas transparent needles may have been more recently developed as a result of evaporation of interstitial brine, in some cases possibly after core recovery (*cf.* Kinsman, 1969).

The bioclastic group is dominated by ostracods and plant debris. In sector 1, **ostracods** are usually more abundant in surface (15.9%) than at depth

Table 2. *Frequency data for 17 sand-size components (average value, given in percentage) in each of the three Mariut Lake sectors; data are listed separately for surficial and core samples.*

	SECTOR 1 (Eastern sub-basins)								SECTOR 2 (Central sub-basin)						
	Surficial samples (n= 43)				Core samples (n= 15)				Surficial s. (n= 2)			Core samples (n=4)			
	Mean	Std	Min	Max	Mean	Std	Min	Max	Mean	Min	Max	Mean	Std	Min	Max
Light mineral (%)	6.2	9.4	0.0	51.3	50.3	32.3	4.8	93.6	40.4	38.9	41.9	38.3	22.2	18.1	65.7
Heavy mineral (%)	0.7	1.6	0.0	10.7	1.4	1.0	0.0	3.2	0.6	0.6	0.6	1.2	1.2	0.0	2.6
Mica (%)	0.1	0.1	0.0	0.6	0.2	0.3	0.0	1.2	0.2	0.0	0.3	0.1	0.2	0.0	0.3
Glauconite/verdine (%)	0.0	0.0	0.0	0.3	0.0	0.1	0.0	0.3	0.0	0.0	0.0	0.1	0.2	0.0	0.3
Pyrite (%)	0.1	0.2	0.0	0.7	0.1	0.2	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum, evaporite (%)	0.6	1.4	0.0	7.5	5.5	12.2	0.0	39.6	17.9	12.9	22.9	28.4	36.7	0.3	80.2
Lithic fragment (%)	0.2	0.4	0.0	2.0	0.4	0.5	0.0	1.7	3.7	3.5	3.8	0.5	0.5	0.0	1.2
Aggregate (%)	4.5	6.4	0.0	26.3	1.2	2.1	0.0	6.8	0.0	0.0	0.0	0.2	0.2	0.0	0.5
Bio-precipitate carbonate (%)	45.9	32.9	0.6	90.3	5.1	10.0	0.3	40.4	3.4	0.0	6.8	1.4	2.0	0.0	4.2
Ostracod (%)	15.9	13.2	0.5	52.2	6.8	7.7	0.0	21.1	2.1	0.3	3.9	12.8	22.7	0.9	46.8
Foraminirera (%)	2.3	3.1	0.0	14.7	3.1	3.7	0.0	12.6	1.1	0.6	1.6	4.1	7.4	0.0	15.2
Gastropod (%)	1.3	1.7	0.0	6.6	1.1	1.2	0.0	3.8	0.0	0.0	0.0	0.3	0.4	0.0	0.8
Pelecypod (%)	0.7	1.9	0.0	8.4	9.2	13.4	0.0	44.5	0.2	0.0	0.4	2.0	2.7	0.0	5.9
Unidentified shell (%)	7.7	9.5	0.3	39.3	11.6	7.8	0.0	24.7	29.8	28.4	31.2	10.2	8.7	0.0	18.4
Plant (undiff.) (%)	13.0	14.4	0.1	61.4	3.7	4.7	0.0	16.7	0.3	0.0	0.6	0.3	0.1	0.1	0.4
Charophyte oogonia (%)	0.1	0.2	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diatom & other (%)	0.2	0.5	0.0	2.2	0.1	0.1	0.0	0.3	0.2	0.0	0.3	0.1	0.1	0.0	0.3

	SECTOR 3 (Western sub-basin)						
	Surficial s. (n=2)			Core samples (n=14)			
	Mean	Min	Max	Mean	Std	Min	Max
Light mineral (%)	48.5	35.0	62.0	48.9	26.9	6.9	88.3
Heavy mineral (%)	0.8	0.6	1.0	0.6	0.7	0.0	2.1
Mica (%)	0.1	0.0	0.3	0.2	0.3	0.0	1.0
Glauconite/verdine (%)	0.0	0.0	0.0	0.1	0.1	0.0	0.3
Pyrite (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gypsum, evaporite (%)	21.3	1.9	40.7	8.6	20.3	0.0	78.2
Lithic fragment (%)	3.3	0.9	5.7	0.3	0.4	0.0	1.5
Aggregate (%)	0.3	0.0	0.6	0.1	0.2	0.0	0.6
Bio-precipitate carbonate (%)	4.5	0.6	8.4	8.1	13.6	0.0	55.0
Ostracod (%)	2.4	2.2	2.6	7.7	6.9	0.3	22.5
Foraminirera (%)	0.9	0.6	1.1	1.1	1.2	0.0	3.4
Gastropod (%)	0.0	0.0	0.1	0.5	1.0	0.0	3.9
Pelecypod (%)	0.0	0.0	0.0	0.6	0.8	0.0	3.1
Unidentified shell (%)	13.7	5.2	22.2	21.5	13.3	5.2	51.4
Plant (undiff.) (%)	3.6	3.0	4.2	1.7	5.4	0.0	21.4
Charophyte oogonia (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diatom & other (%)	0.3	0.3	0.3	0.0	0.1	0.0	0.3

(6.8%). Some samples are ostracod rich with proportions reaching to 52.2%; these include in the same samples adult and juvenile carapaces and valves of *Cyprideis torosa* (N. PUGLIESE, *written communication,* 1993). In sector 2, ostracods are generally much less common, with values ranging from 0.3 to 3.9% (except at the base of core Mt I, where a value of 46.8% is recorded). In sector 3, surficial sediments generally comprise lower values (2.4%) than those recorded in cores (7.7%). **Foraminifera** are somewhat more common (3.1%) in cores than in surficial samples (2.3%) in sector 1. In sectors 2 and 3, the values in cores and surficial samples are 0.9% and 1.1%, respectively; an exception is found at the base of core Mt I in sector 2 where foraminifera account for 15.2%. **Gastropod** content (faunal lists in BERNASCONI and STANLEY, 1994) in sector 1 is about the same at the surface (1.3%) and in subsurface (1.1%). There are no gastropods in surficial samples of sectors 2 and 3, but a few in subsurface (0.3 and 0.5%, respectively). **Pelecypod** (faunal lists and abundances in BERNASCONI and STANLEY, 1994) values are very low to absent in surficial samples of sectors 1, 2 and 3; in contrast, they account for high values in subsurface shell-rich layers in sector 1 (to 44.5%), and low to modest proportions in sectors 2 and 3 (to 5.9%). **Unindentified broken shell** material in sector 1 is less common in surficial samples (7.7%) than in cores (11.6%). A comparable surface (13.7%) versus subsurface (21.5%) content is noted in sector 3. In contrast, shell fragments in sector 2 are more common in surficial sediments (29.8%) than in cores (10.2%). **Char-**

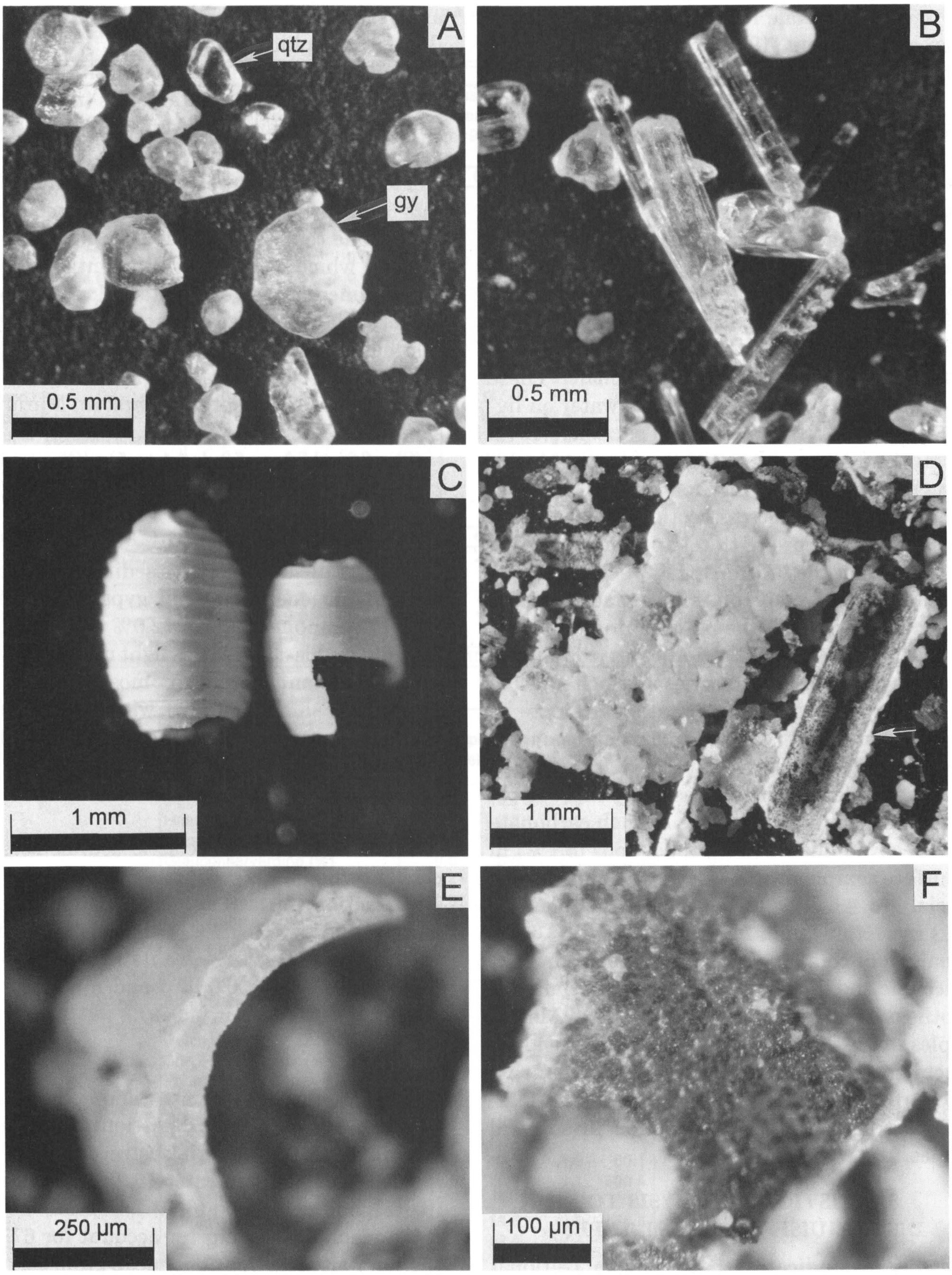

Figure 7. Photo-micrographs of selected components in sand-size fraction of Mariut sediment. (A) Lenticular "milky" gypsum crystal (gy) and transparent quartz (qtz) grain (core I, 24–26 cm). (B) Needle-shaped crystals of gypsum (core I, 0–2 cm). (C) Charophyte oogonia (surficial sample #47). (D) Two grains of bio-precipitate carbonate (surficial sample #49). Large grain on left shows irregular external surface of the carbonate crust; elongate grain on right reveals outer white carbonate rim (arrow) and internal plant structure (enlarged in F). (E) Transversal section across a carbonate crust recording rounded shape of plant on which the crust formed (surficial sample #49). (F) Enlarged view showing detail of plant structure on the internal side of elongate carbonate grain in D (surficial sample #49).

ophyte oogonia (Figure 7C), calcification of charophyte (algae) female reproductive structure (*cf.* WOOD and IMAKORI, 1965), are observed only in surficial sediments (to 0.6%) in sector 1. **Undifferentiated plant debris** in sector 1 is more abundant in surficial samples (13.0%) than in subsurface (3.7%). A parallel observation is made in sector 3, with 3.6% at the surface and 1.7% in subsurface. There is very little (0.3%) plant debris in either surficial or subsurface samples of sector 2. **Diatoms** are rare (0.1 to 0.2%) in sand-size fractions of all Mariut samples examined.

Biogenically-induced calcite precipitation which forms encrustations on hydrophytes are herein abbreviated to **bio-precipitate carbonate**. These carbonate crusts, which form in the water on living plants (*cf.* WETZEL, 1960; TERLECKY, 1974; MURPHY and WILKINSON, 1980), occur in Mariut sediment as medium to very coarse sand-size fragments (Figure 7D). In cross-section, their rounded form provide a record of the shape and size of the plant on which they formed (Figure 7D,E). Also, commonly preserved on one side of such grains is the surface imprint of the plant material (Figure 7F). X-ray diffractometry indicates that these grains are primarily low-magnesian calcite (5–7% $MgCO_3$) crystals. Bio-precipitate carbonate is generally abundant (45.9%) in surficial samples of sector 1; highest values (to 90.3%) are recorded in southern plant-rich sub-basins of this region. In marked contrast, fragments of such carbonate crusts occur in much lower proportions (5.1%) in subsurface samples of this sector and also in both surficial (to 4.5%) and subsurface samples (to 8.1%) in sectors 2 and 3.

Analysis of component distributions show that siliciclastic and diagenetic particles are dominant in both core and surficial sediments in all Mariut samples, with the exception of surficial deposits in sector 1. In that region, bioclastic components and bio-precipitate carbonate constitute the dominant part of the sand-size fraction in surficial samples.

STATISTICAL ANALYSIS TO DISTINGUISH SEDIMENT TYPES

Our survey indicates that (1) compositional components have distinct spatial and temporal distribution patterns in Mariut, and (2) only a few components dominate sediment at each sample site of the lake. To synthesize all textural and compositional observations (Tables 1, 2), a statistical cluster analysis is performed using the data for the 82 Mariut surficial and core samples. This analysis groups lake samples having the most similar petrographic attributes.

Proportions of the 17 compositional components and 4 grain-size parameters (mean size and percent of sand, silt and clay) are used as the base matrix to perform this analysis. Since K-mean cluster analysis requires that the number of clusters be set prior to computation, several attempts were made to determine the optimum number of clusters which would best differentiate the various sediment types. Both statistical and geological criteria were used to choose the appropriate number (total of 5) of clusters. The statistics of component percentages and grain-size data of the 5 clusters from surficial and subrecent Mariut Lake samples are listed in Table 3.

The five clusters (coded **1** to **5**) obtained by the statistical analysis are summarized as follows:

Cluster 1

(Fine-grained siliciclastic sediment). Siliciclastic and diagenetic (mainly gypsum, average of 14.5%) components form 72.0% of the sand-size fraction in this cluster with light minerals (55.3%) as the dominant component, mostly quartz. Mean grain size is small (16.0 μm), with a sand-size fraction accounting for only 21.0% of the total sediment.

Cluster 2

(Coarse-grained siliciclastic sediment). Siliciclastic components comprise 67.1% of the sand-size fraction, formed largely by light minerals, mostly quartz (60.3%). This cluster is distinguished from cluster 1 by its markedly coarser mean grain size (106.0 μm) and much lower average gypsum content (4.0%).

Cluster 3

(Bioclastic-rich sediment). Samples forming this cluster comprise large proportions of broken and unbroken skeletal material: ostracod (27.3%), unidentified shell fragments (16.9%), foraminifera (6.6%), and pelecypod (6.3%). Overall, bioclastic components in this cluster account for 67.3% of the sand-size fraction. The mean grain size is 42.7 μm.

Cluster 4

(Bio-precipitate carbonate and plant debris-rich sediment). This cluster is usually characterized by high proportions of bio-precipitate carbonate

Table 3. *Statistics of compositional component percentages and grain-size data for clusters 1 to 5 for all (n = 82) surficial and subsurface Mariut Lake samples; values characteristic for each cluster are highlighted in boxes. Geographic and temporal distribution of clusters is shown in Figure 9.*

	Cluster 1 Fine-grained siliciclastics (n=20)				Cluster 2 Coarse-grained siliciclastics (n=9)				Cluster 3 Bioclastics (without plant debris) (n=19)			
	avg	std	min	max	avg	std	min	max	avg	std	min	max
Light mineral (%)	55.3	24.9	6.9	90.4	60.3	25.1	22.4	93.6	10.4	9.2	1.2	29.2
Heavy mineral (%)	0.9	0.7	0.0	2.6	1.6	0.8	0.0	2.6	0.5	0.7	0.0	2.4
Mica (%)	0.1	0.3	0.0	1.0	0.1	0.1	0.0	0.3	0.1	0.1	0.0	0.3
Glauconite/verdine (%)	0.0	0.1	0.0	0.3	0.1	0.1	0.0	0.3	0.0	0.1	0.0	0.3
Pyrite (%)	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.5	0.0	0.1	0.0	0.4
Gypsum, evaporite (%)	14.5	24.5	0.0	80.2	4.0	9.4	0.0	28.7	4.4	11.0	0.0	39.6
Lithic fragment (%)	0.9	1.6	0.0	5.7	0.4	0.5	0.0	1.5	0.4	0.6	0.0	2.0
Aggregate (%)	0.3	0.7	0.0	3.2	0.6	1.5	0.0	4.7	6.9	8.2	0.0	26.3
Bio-precipitate carbonate (%)	3.2	3.1	0.0	10.3	3.4	2.9	0.3	7.6	9.8	15.9	0.0	62.9
Ostracod (%)	5.0	6.4	0.3	21.1	2.9	3.7	0.0	10.2	27.3	12.9	5.5	52.2
Foraminirera (%)	1.2	1.8	0.0	6.2	1.0	0.8	0.2	2.8	6.6	3.9	2.0	15.2
Gastropod (%)	0.1	0.2	0.0	0.6	0.7	1.0	0.0	2.4	2.5	1.8	0.3	6.6
Pelecypod (%)	0.5	1.5	0.0	6.6	6.0	14.5	0.0	44.5	6.3	8.3	0.0	31.1
Shell, other, unknown (%)	16.9	11.4	0.0	38.5	17.6	15.1	0.0	51.4	16.9	10.6	2.9	39.3
Plant (undiff.) (%)	0.8	1.2	0.0	4.2	1.0	1.4	0.0	4.6	7.6	6.7	0.0	19.4
Charophyte oogonia (%)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.6
Diatom & other (%)	0.1	0.1	0.0	0.3	0.1	0.2	0.0	0.3	0.1	0.2	0.0	0.6
Siliciclastic components (%)	72.0	16.9	37.3	98.8	67.1	24.6	27.7	95.9	22.8	13.9	5.3	62.5
Bioclastic components (%)	24.8	15.3	1.2	52.5	29.3	23.9	1.4	69.6	67.3	15.8	31.8	87.7
Sand (%)	21.0	15.8	0.1	54.3	72.0	9.8	56.8	87.9	40.8	14.5	15.8	70.4
Silt (%)	44.8	9.6	26.2	66.5	18.2	9.5	7.8	33.8	44.8	13.0	18.3	65.2
Clay (%)	34.2	16.1	7.3	59.9	9.8	5.5	1.1	21.0	14.4	10.9	0.9	38.1
Mean (μm)	16.0	13.7	3.7	59.6	106.0	43.6	59.3	205.6	42.7	24.5	12.8	91.6

	Cluster 4 Bio-precipitate carbonate + plant debris (n=33)				Cluster 5 Heavy minerals (n=1)
	avg	std	min	max	
Light mineral (%)	6.8	10.7	0.0	47.4	19.9
Heavy mineral (%)	0.5	0.6	0.0	3.2	10.7
Mica (%)	0.1	0.2	0.0	1.2	0.0
Glauconite/verdine (%)	0.0	0.0	0.0	0.0	0.0
Pyrite (%)	0.4	1.9	0.0	10.9	0.0
Gypsum, evaporite (%)	0.5	1.3	0.0	6.4	0.3
Lithic fragment (%)	0.2	0.3	0.0	0.9	0.9
Aggregate (%)	2.3	3.6	0.0	13.1	1.6
Bio-precipitate carbonate (%)	59.1	26.4	2.8	90.3	7.7
Ostracod (%)	9.2	7.3	0.5	27.4	28.8
Foraminirera (%)	0.8	1.1	0.0	5.4	1.5
Gastropod (%)	0.7	1.1	0.0	5.1	0.4
Pelecypod (%)	0.1	0.3	0.0	1.1	0.0
Shell, other, unknown (%)	4.1	5.0	0.3	23.2	10.1
Plant (undiff.) (%)	14.4	16.0	0.9	61.4	17.7
Charophyte oogonia (%)	0.1	0.1	0.0	0.5	0.0
Diatom & other (%)	0.2	0.5	0.0	2.2	0.3
Siliciclastic components (%)	10.9	12.5	1.0	50.1	33.5
Bioclastic components (%)	29.8	20.7	6.1	80.5	58.5
Sand (%)	41.4	14.0	19.1	75.8	21.1
Silt (%)	51.6	12.8	17.3	74.4	65.0
Clay (%)	7.0	7.0	0.4	27.0	13.8
Mean (μm)	47.0	25.0	13.5	145.3	19.99

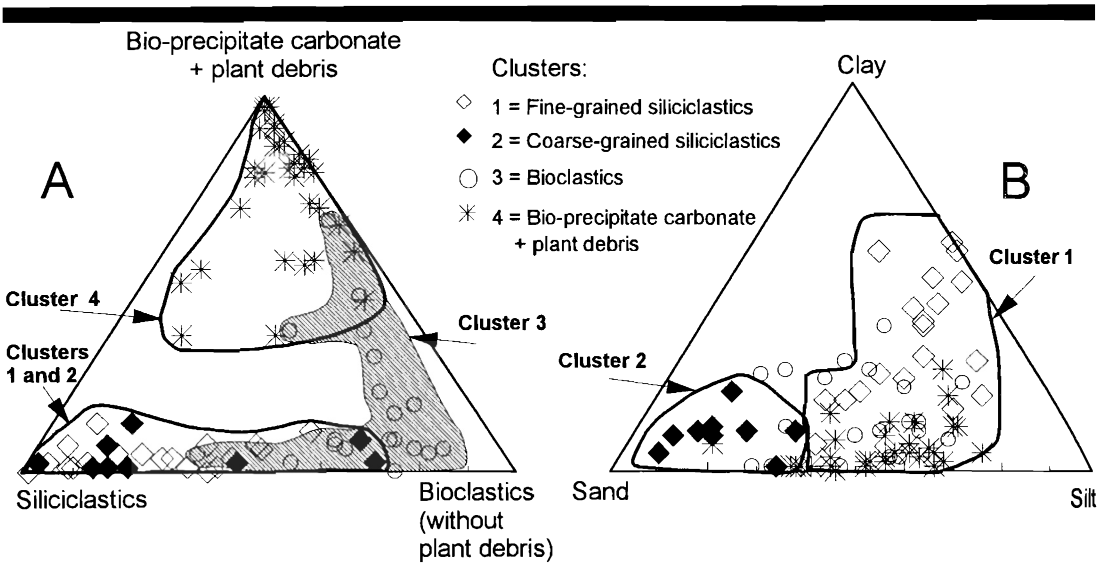

Figure 8. Ternary diagrams in which are plotted in 82 Mariut surficial and subsurface samples petrographically examined and statistically analysed in this study. (A) End-members on triangle are key compositional components which serve to distinguish clusters 1 and 2 from cluster 4. (B) Triangle, with textural components as end-members, used to distinguish cluster 1 from cluster 2. Explanation in text.

(average 59.1%) and/or high content of plant debris (to 61.4%). Mean grain size diameter is 47.0 μm.

Cluster 5

(Heavy mineral-rich sediment). This cluster comprises only one sample, characterized by a high proportion (10.7%) of heavy minerals. Other major components are ostracod (28.8%), light minerals (19.9%), and plant debris (17.7%).

The significant compositional components (from the listing in Table 3) which have the highest weight to define clusters are shown in the ternary diagram in Figure 8A. Key end-members are siliciclastics, bioclastics (excluding plant debris), and bio-precipitate carbonate plus plant debris. This diagram reveals the relative importance of each of these components for all 82 Mariut surficial and core samples examined. Data plots show that many samples forming clusters 1 and 2 lie at or near the siliciclastics end-member, cluster 3 near the bioclastic end-member, and cluster 4 near the bio-precipitate carbonate plus plant debris end-member.

The ternary diagram (Figure 8A) indicates that samples forming clusters 1 and 2 are clearly distinguished from those of cluster 4. In contrast, there is overlap of areas occupied by samples forming cluster 3 and 4, and also by those forming clusters 1, 2, and 3. Most samples forming clusters 1 and 2 plot within the same area and cannot be distinguished in the compositional triangle. Samples forming these two clusters, however, are clearly differentiated on the basis of grain size as noted in a ternary diagram with textural end-members (Figure 8B).

SEDIMENT DISTRIBUTION IN SPACE AND TIME

Temporal and geographic variations of bottom sediments in Mariut are, in some instances, more clearly identified by detailed petrographic analysis than by examination of the general lithology of the five subfacies (I to V) earlier described in this study. A map showing the distribution of clusters reveals that some regional patterns are associated with the three geographic sectors of the lake, and also with temporal (up-core) variations (Figure 9). Samples forming cluster 1 occur mainly in sectors 2 and 3 (central and western sub-basins), both at the surface and in cores. In sector 1 (eastern sub-basins), only four samples forming this cluster are noted, a surficial sample and three samples in two cores. Samples forming cluster 2 are distributed irregularly in the three Mariut sectors, but in all cases are restricted to subsurface core sediments. Samples forming cluster 3 occur mainly in sector 1, both at the surface and at depth. In sectors 2 and 3, samples attributed to this cluster occur only at the base of two cores (Mt I and Mt XV). Most samples forming cluster 4 are surficial sediment in sector 1; this is a much more important cluster in sector 1 than is cluster 3. Two samples of this cluster are also observed at the top of two cores (Mt II, Mt X) in sector 3. The surficial sample forming cluster 5 is positioned in center of sub-basin A in sector 1.

In Mariut Lake, as in Idku lagoon (LOIZEAU and STANLEY, 1993), cluster analysis of texture and composition of the sand-size fraction is a valuable tool to refine subfacies definitions and their distribution patterns in space and time. With regards to regional patterns, cluster 1 occurs primarily in sectors 2 and 3, while 3 and 4 are concentrated in sector 1. With respect to temporal changes, cluster 2 occurs primarily in subsurface sediments, while 4 is concentrated mainly in surficial sediments, especially in sector 1.

It is not possible in every case to differentiate the distribution of sediment facies only by statistical analysis of composition and texture. For example, sediment types in sectors 2 and 3 are characterized by comparable clusters both at surface and at depth. In these regions, other petrologic attributes of subfacies are needed to distinguish temporal and geographic variations of bottom sediments: dark, distinctly laminated sediment with layered gypsum (subfacies IV) prevails in sector 2, while light colored, brown to orange sediment types (subfacies V) are most common in sector 3 (Figure 4).

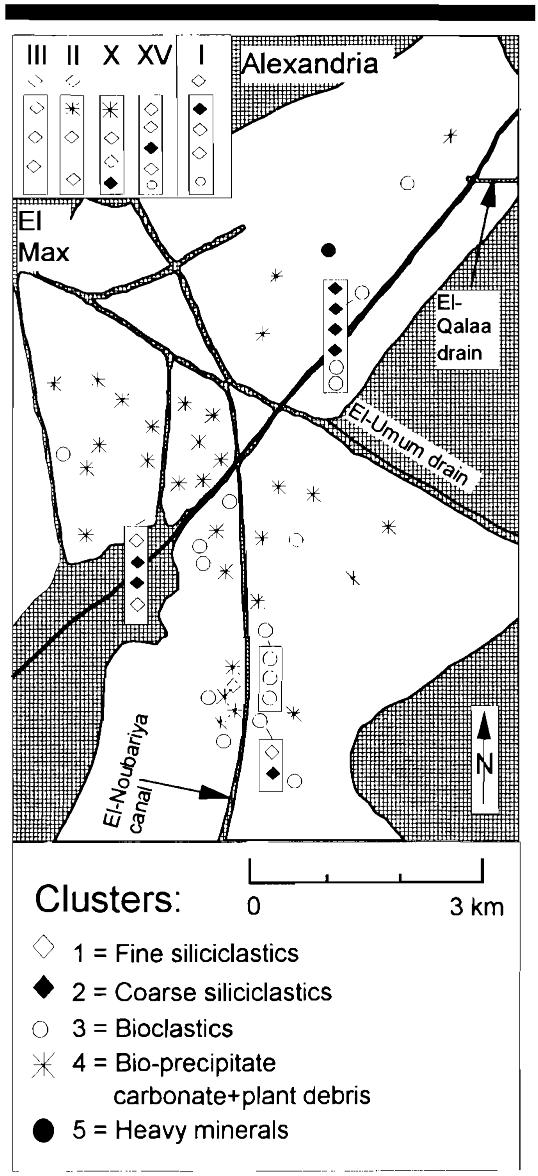

Figure 9. Map showing temporal and spatial distributions of the 5 clusters in Mariut Lake. Vertical sequences of clusters in short cores are shown in elongate boxes. Inset comprises data for surficial and subsurface samples in sectors 2 and 3.

DEPOSITIONAL CHANGES IN THE THREE LAKE SECTORS

General

This investigation differentiates bottom sediment types in the three sectors of Mariut Lake, and indicates that some important changes have occurred in very recent time. The age of the base of Mariut cores (to ~70 cm in length) is estimated to be at least as old as the mid-nineteenth century. This is based on sediment accumulation rates to 0.5 cm per year determined for the modern northern delta by SIEGEL *et al.* (1994).

In Mariut, spatial and temporal evolution of depositional patterns is a function of both natural factors and, increasingly, man's influence. To recognize time-related changes, it is useful to compare modern Mariut sedimentation patterns with those of underlying, much older (Holocene) dated sections. For this we have available data from lagoon deposits in deep drill borings at, or near, our modern Mariut sample sites collected by the Smithsonian Nile Delta Project (CHEN *et al.*, 1992; STANLEY and WARNE, 1993). Data on lithofacies, grain size and composition of the sand-size fraction of these older lagoon sequences are listed in MEDIBA (1994). Comparison of sediment patterns in short cores and surficial samples with those in older core sections helps to reveal very recent changes, including those recording the influence of anthropogenic activity.

Sedimentation patterns in the three lake sectors (Figure 1) are considered separately since Mariut sub-basins are now physically isolated by dikes and by road and rail causeways (Figure 1). In addition to evaluating depositional patterns in lake sub-basins from west to east, it is useful to compare recent Mariut sediments with those in less polluted, modern Idku and Manzala lagoons in the northern delta. In the case of each Mariut region, we consider on-going and future changes that may affect sedimentation in this rapidly evolving region.

Sector 3, Western Mariut Extension

This water body, located west of the Nile delta proper, lies entirely in a desert environment. The sub-basin is now separated from the central lake by the El Amiriya-to-Agami causeway (Figures 1 and 3E) so that there is no water exchange with that sub-basin (sector 2) to the east. Relatively small amounts of water flow to sector 3 *via* canals and drains, and most replenishment is derived from winter rains, surface drainage and groundwater.

Water level fluctuates more extensively and seasonally than in other Mariut sub-basins due to the limited volume of water supplied to this topographicaly restricted and evaporation-dominant setting. Surficial sediments in many parts of the western lake sector are thus periodically exposed subaerially (Figure 3D), with some deposits recording effects of oxidation. Although positioned between high carbonate ridges, and lying parallel to the carbonate-rich coast south of Arab's Gulf (BUTZER, 1960; STANLEY and HAMZA, 1992), the sand-size fraction of surficial and subsurface samples are quartz-rich. Prior to 1964, sedimentation was to some extent affected by Nile floods. It is envisioned that siliciclastic material now reaching this isolated depression is derived primarily from runoff and by wind transport from source areas to the south. Highly saline ground water feeding this depression and prevailing evaporative sabkha conditions result in higher proportions of gypsum and a much lower bioclastic (shell faunas, plant) content than in Mariut sub-basin sediments to the east and in modern Idku and Manzala lagoons. Modern depositional patterns in this western lake extension have few counterparts elsewhere in Mariut or in the lagoons to the east.

Modern subfacies are generally comparable to those of some much older Holocene lagoon margin muds underlying this sub-basin (*cf.* WARNE and STANLEY, 1993). Short core sections, however, indicate that there have been some changes during the past century. Of note is the upward decrease in macro- and microfauna and slight increase in floral debris. Moreover, the presence of a thick bioclastic-rich coquina shell layer at the base of one of the short core (Mt XV) records a phase when this sub-basin, having a more open connection and exchange of waters with Mariut basins to the east, was less saline. The presence of bioprecipitate carbonate at the top of two short cores records an even more recent change, perhaps related to effects of increased pollution (this matter is further considered in a following section on carbonate crust formation). Such pollution west of Alexandria is likely related to the rapidly increasing population on and along the carbonate ridges bounding the sub-basin, and in the Burg el Arab region.

Sector 2, Central Mariut Sub-Basin

The central part of Mariut has become completely separated from lake sub-basins to the east and west during this century. Lake level and configuration, and water chemistry are now completely controlled by man. Water is pumped from the Mediterranean and is used in this pre-concentration pond for salt production (Figure 3C), where salinities are more than double those of normal seawater. A fairly constant lake level is maintained here, unlike in sector 3. At present, only sparse to rare vegetation develops on most sub-basin margins (Figure 3B) and the lake floor.

The supply of fresh water and sediment, which earlier was derived primarily from the Nile delta sector to the southeast, has been essentially cut off. Our study indicates that bottom sediment composition and texture here is somewhat more similar to that observed in sector 3 than in sector 1: fine-grained siliciclastics are the dominant type, derived from wind transport and run-off from the southern flank of this depression. Most bottom sediment in this sub-basin, in contrast with that in sector 3, is permanently covered by water. Sediments are very dark in color, recording anoxic conditions at the lake floor. Formation of gypsum, sometimes concentrated as thin layers, is also indicative of deposition under highly saline conditions; in this respect, bottom sediment in sector 2 is more similar to that in sector 3 than in sector 1 to the east. Good preservation of fine laminae in core sections (Figure 4, core Mt I) is a function of low faunal content and minimal bioturbation. This is in contrast to abundant benthic faunas and intensive reworking of sediment in most Nile delta lagoon settings (*cf.* ARBOUILLE and STANLEY, 1991; PUGLIESE and STANLEY, 1991; CHEN *et al.*, 1992; BERNASCONI and STANLEY, 1994). Moreover, plant debris content in sector 2 is very low, in contrast with plant-rich lithologies in sub-basins of sector 1 and modern delta lagoons to the east (RANDAZZO, 1992; LOIZEAU and STANLEY, 1993), and also in underlying, much older (Holocene) marine- and fluvially-influenced lagoon muds (HOWA and STANLEY, 1991; WARNE and STANLEY, 1993).

The presence of shell fragments and of a freshwater influenced mollusc fauna in some surficial samples (BERNASCONI and STANLEY, 1994) is recorded. This is probably the result of anthropogenic reworking (dredging, causeway construction, salt pond development) of the lake floor which has exposed older sediments at the surface.

Recent subfacies in this completely altered and highly saline sub-basin do not presently have counterparts in older Holocene core sections (including former Lake Mareotis), or in eastern Mariut Lake and most parts of modern Nile Delta lagoons. Evolution of depositional patterns is recorded by vertical lithological changes. A 14 cm-thick, coquina-like shell layer at the base of core Mt I (Figure 4) accumulated before extensive modification of the sub-basin by man which induced reduction of benthic fauna. The shell layer in that core is covered by dark, moderately laminated mud; this in turn is overlain by very dark and progressively more distinctly laminated siliciclastic-rich sediment that includes thin layered gypsum. This latter subfacies, forming the upper 22 cm of core section, probably accumulated since the complete closure and transformation of this sub-basin. Sand-size composition and texture of surficial sediments in this region are generally comparable to that forming the top of core Mt I. Bio-precipitate carbonate, a dominant component in surficial samples in the eastern Mariut sub-basins, is absent in these samples.

The central lake region is essentially a highly polluted collecting pool. Geochemical analyses of short cores in this sector, positioned in close proximity to the high-density and rapidly growing population center and industrial complex of Alexandria's Dekheila-Agami region, would likely record increased quantities of pollutants. It is expected that industrial and domestic discharge will continue to accumulate in bottom sediments in view of complete closure of this sub-basin and its further subdivision into numerous shallow salt pans.

Sector 1, Eastern Mariut Sub-Basins

The eastern part of Mariut, positioned on the northwestern margin of the Nile Delta, became fully separated from lake sectors to the west during this century as a result of road and rail causeway construction. This part of the lake has continued to be further subdivided into numerous sub-basins by canals, drains and roads. Although water is lost as a result of high evaporation rates, sub-basins are replenished primarily by discharge from El-Qalaa and El-Umum drains (Figure 1) that flow during the entire year from the western delta. Salinities are much lower (2.0 to 4.7 g/l) than in sectors 2 and 3. A constant water level is maintained (at ~2.8 m below sea level) by pumping lake waters into the sea. Unlike sector 2, marshes and dense vegetation remain along some margins of the eastern sub-basin (Figure 3A), and many parts of the lake are floored by a dense water plant cover (WARNE and STANLEY, 1993).

Surficial sediment here comprises dark mud and sand, commonly with shell and plant debris, and frequently emitting a strong H_2S odor (SAAD *et al.*, 1984). Deposits (subfacies I–III) are markedly different from recent sediments in sectors 2 and 3 in that they are somewhat coarser, and comprise large proportions of bioclastics, plant debris and bio-precipitate carbonates. These components, for the most part, formed and accumulated in place. Terrigenous components, accounting for lesser amounts of the sand-size fraction, were derived by wind transport and also through drains and canals. A heavy mineral-rich, sandy mud deposit (cluster 5) was observed at one site. This latter type is a marker of active sedimentation, including reworking and concentration of denser grains as a result of bottom-stirring by waves, probably during winter.

Unlike western Mariut sub-basins, there is a significant difference between surficial and subsurface core deposits. Core sections are dark like

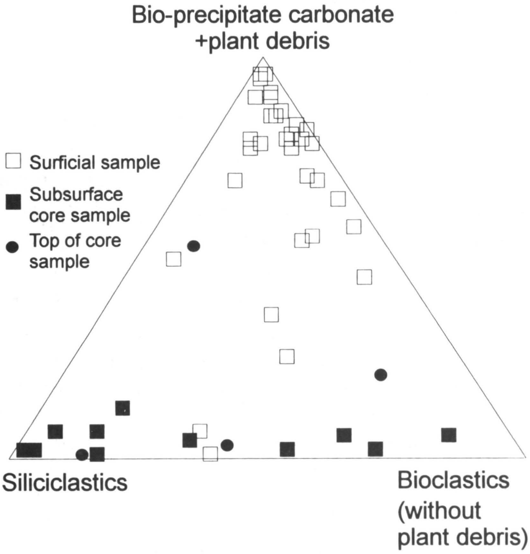

Figure 10. Ternary diagram, with major compositional components of Mariut samples in sector 1 as end-members, differentiates surficial from subsurface samples. Note that most surficial samples and one core top deposit have higher contents of bio-precipitate carbonate and plant debris than subsurface samples.

those in sector 2, but have a higher faunal content, particularly molluscs and ostracods, and are poorly stratified due to bioturbation. In this respect, they are more similar to the underlying, older Holocene marine- and fluvially-influenced lagoon muds (CHEN *et al.,* 1992; WARNE and STANLEY, 1993), and also to modern deposits in Idku (LOIZEAU and STANLEY, 1993) and Manzala (RANDAZZO, 1992) lagoons. However, benthic faunas in sector 1 are less abundant than in modern lagoons and interpreted as relict (*cf.* BERNASCONI and STANLEY, 1994), that is, remnants from stocks which originally entered Mariut when it was open to the Mediterranean via Abu Qir Bay at the beginning of the nineteenth century (WARNE and STANLEY, 1993). The more abundant ostracod faunas, comprising valves of adults and their juveniles, are autochthonous and closely resemble those in modern lagoons (N. PUGLIESE, *written communication,* 1993). Moreover, core sediments in sector 1 are richer in siliciclastics and, in some cases, faunal remains than most surficial deposits.

This difference between lake floor and subsurface deposits is revealed by a ternary diagram in which are plotted data for all surficial and core samples from this sector. End-members of the triangle are: siliciclastics, bioclastics (without plant debris), and bio-precipitate carbonate and plant debris (Figure 10). Data from most surficial samples plot at or near the bio-precipitate carbonate plus plant debris end-member, whereas all subsurface samples lie closer to siliciclastics and bioclastics end-members. This clear differentiation of surficial from subrecent sediments on the basis of sand-size fraction composition records a major depositional change in recent time.

Further evidence of this temporal change of sedimentation is provided by analysis of the composition of the sand-size fraction in core Mt VI samples and adjacent surficial sample #30 (Figure 11). Eleven core samples were examined, including 5 of the original suite of 82 samples treated statistically, plus 6 additional samples more recently analyzed. A remarkable up-core increase in both bio-precipitate carbonate and plant debris, relative to bioclastics and siliciclastics, occurs in the upper 25 to 30 cm of core section. This change is estimated to have begun about 50–60 years ago, based on the sediment accumulation rate of about 0.5 cm/year indicated earlier. The up-core compositional change would not be recognized by visual examination of the core section alone, and requires detailed petrographic analysis for detection. Our study shows that important temporal variations are widely recorded in this part of Mariut, and are almost certainly the result of amplified anthropogenic influence. Change in depositional patterns appear to correlate with increased industrialization in the Alexandria region during the following World War II.

There are ample indications that Mariut subbasins continue to receive ever larger amounts of domestic and industrial wastewater and agricultural runoff. Unless stringent measures are implemented, this part of the lake will become even more polluted with time. We expect that further consequent changes in bottom sediment patterns will occur at a greater rate in this sector than in the central and western Mariut sub-basins.

CARBONATE CRUST FORMATION AND EUTROPHICATION

To demonstrate that in Mariut there may be a relation between increased carbonate crust deposition and pollution, it is first necessary to firmly establish that bio-precipitate carbonate and vegetal production increase upward in short core sections of recent sediment.

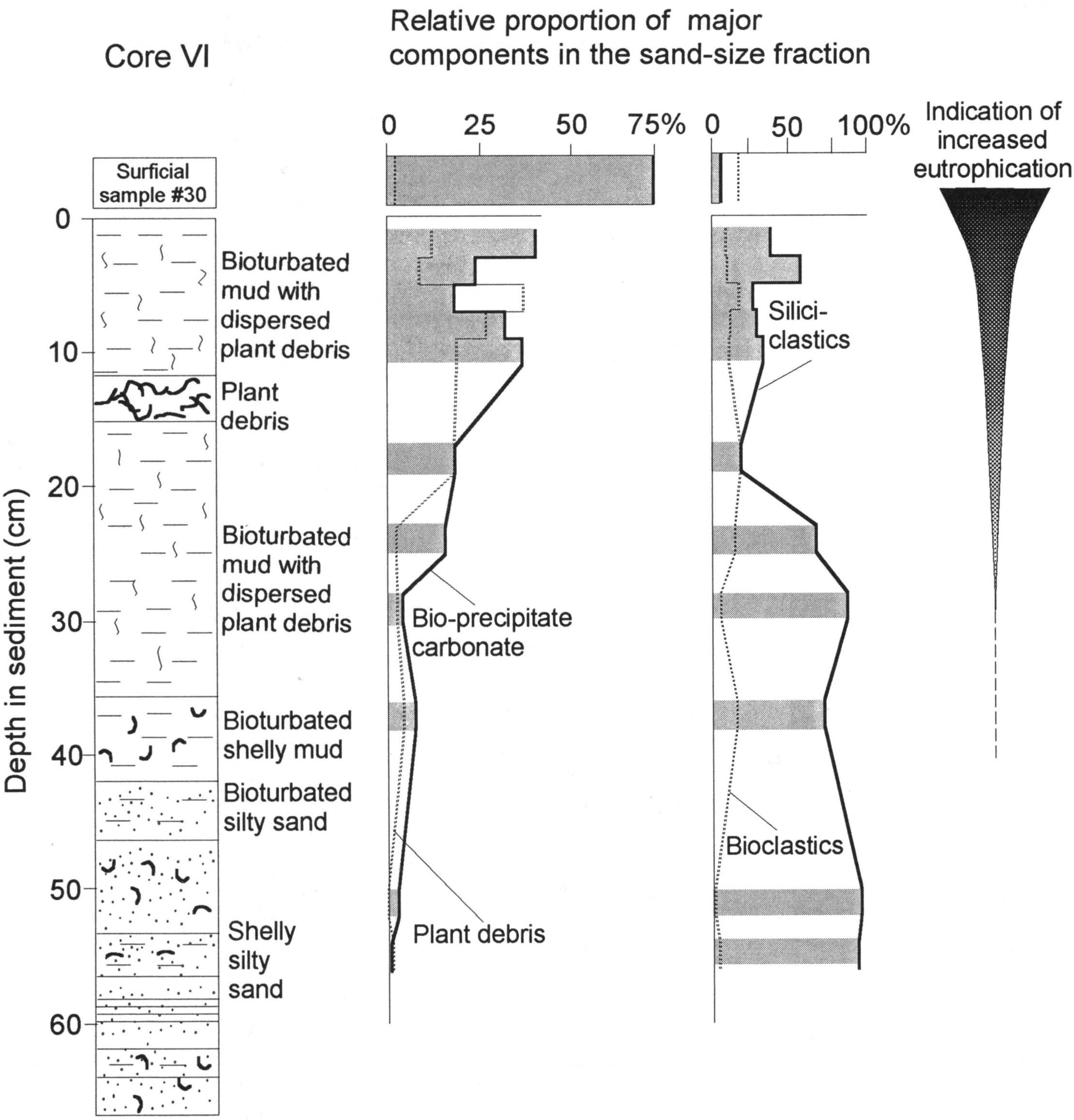

Figure 11. Simplified lithologic log of core Mt VI, recovered in eastern Mariut sector 1. Up-core changes of major compositional components of sand size are depicted, from near base of core to core-top and adjacent surficial sample #30. The marked up-core increase in bio-precipitate carbonate and plant debris is attributed to effects of increased eutrophication. This change, at a depth of about 25 to 30 cm, is not apparent from visual examination of split core section.

Although not observed in underlying subsurface deposits, we cannot exclude the possibility that carbonate crusts of sand and larger size (formed of calcite crystals of silt size; Figure 7D) similar to those we observe in surficial samples may originally have been present in older core sections. Since they are much less abundant below the top of short core sections, it may be possible that crusts disintegrated to silt size particles by attrition due to physical reworking shortly after their deposition. If so, small calcite crystals should be present in the silt size fraction of subsurface samples. No such crystals were observed. In core Mt VI, for example, calcite content as measured by geochemical analysis of the bulk fraction diminishes substantially down-core below a depth of 11 cm (F.R. SIEGEL, *written communication*, 1993). Another explanation for the down-core decrease in crusts is possible dissolution of carbonate during early diagenesis. In this case, carbonate crusts should display evidence for increased altered grain surfaces with depth. This is not observed.

We recognize that measurement of carbonate crust abundances by relative percentages has limitations. Inasmuch as amounts of sand-sized components are calculated as relative percentages, it follows that if one or several components decrease, then all others will increase. Calculation of ratios helps minimize this artifact. Our findings indicate that there are actual up-core increases in carbonate crusts and plant debris. As indicated in core Mt VI (Figure 11), the up-core content of bioclastics remains relatively constant relative to decreased proportions of siliciclastics, and a near-parallel up-core increase of both plant debris and bio-precipitate carbonate.

We note that earlier studies of bottom sediments in this part of Mariut Lake (EL-WAKEEL, 1964) do not report carbonate crusts, which are such a major and obvious component of the sand-size fraction. Was this authigenic component overlooked or have crusts become more important during the past 30 years, and if so, why ? Perhaps related to this is the fact that sector 1 sub-basins are characterized by a high organic matter and nutrient content, the presence of H_2S, and depletion of dissolved oxygen in the water column, and most workers agree that eastern Mariut has undergone eutrophication (WAHBY *et al.*, 1978; SAAD, 1983b; SAAD *et al.*, 1984).

This part of Mariut has recently experienced accelerated growth of water plants (ABDEL-KADER, 1982) on the lake floor (note, for example, the upward increase in plant debris in Figure 11) which entrained physico-chemical conditions that would foster formation of increased amounts of carbonate crusts. It is likely that carbonate formation in Mariut, as in many shallow, fresh water lakes and bogs, resulted from the process outlined is the one indicated by MURPHY and WILKINSON (1980, p. 124): "During photosynthesis, bicarbonate utilization produces a micro-environment of higher pH immediately surrounding the hydrophyte which in turn induces precipitation of calcium carbonate."

The numerous geochemical studies of Mariut lake waters and bottom sediments all record increased values of pollutants as part of the significant anthropogenic alteration of this water body. We propose that, in the case of Mariut Lake (primarily in sector 1), the presence of high amounts of carbonate crusts associated with plant debris also is an indicator of increased pollution. This interpretation is reinforced by our independent examination of 60 surficial samples collected throughout the different parts of Manzala lagoon. Several Manzala samples contained sand-size carbonate crusts, but only one comprised large amounts (~50%), along with plant debris of sand size in quantities comparable to those in Mariut surficial sediments. It is not coincidental that this sample was recovered in the most polluted portion of Manzala lagoon, *i.e.*, in the Ginka basin near the outlet of highly contaminated Bahr el Baqar drain (SIEGEL *et al.*, 1994).

CONCLUSIONS

This investigation reveals that lacustrine sediments in Mariut are comparable in many respects to those in modern Nile Delta lagoons, and in older Holocene lagoon sequences recovered by coring in this region. Petrologic analysis of Mariut short core sections that date back to the last century indicate that deposits in the different parts of the lake have close counterparts in modern Idku and Manzala lagoons. *A priori*, this might be surprising in that Mariut is completely separated from the sea, while the lagoons have outlets and an exchange of water with the Mediterranean. A number of factors, however, can explain this similarity, including the fact that Mariut was temporarily open to the sea as recently as the beginning of the nineteenth century. Moreover, the lake received an input of sediments and nutrients carried by former Nile channels from the delta regions to the south comparable to those transported to the lagoons. Mariut also has similar depth and water properties such as temperature and salinity, and in the past had important plant growth in and around the lake sub-basins. These natural factors gave rise to a suite of dark, organic- and faunal-rich, and bioturbated lacustrine subfacies many of which closely resemble older Holocene lagoon deposits that underlie this region.

Our investigation also reveals some differences between pre-modern Mariut lacustrine and the delta lagoon sediments, which can also be related to natural factors. These can best be detected by a method that integrates lithofacies attributes with detailed petrographic analysis of grain size and composition of the sand-size fraction. Mariut bottom sediments include a lower amount of sand-size material due to smaller flow discharge from former Nile branches and drains, and to a lack of input of coarse sediment from the Mediterranean coast. There is no outlet to the sea through which sand can be introduced, and the presence of a high carbonate coastal ridge system serves as a barrier that effectively cuts off Mariut from the strandline sediment supply. Also, increased amounts of gypsum in lake sediments result from greater influence of saline groundwaters flowing into the Mariut depression from the highly arid desert which borders the western margin of the Nile Delta.

The study further indicates that differences between Mariut sediment and those in lagoons have become more apparent in this century, and particularly during the past 50 or so years. One obvious change in all the lake sub-basins is the decrease with time in faunal content, such as molluscs. Even more apparent are the geographic changes across the lake from each to west, especially in central and eastern Mariut sub-basins: development of very dark and distinct lamination in sector 2, and increase in bio-precipitate carbonate and plant debris in sector 1. The formation of carbonate crusts in association with increased water plant growth is herein interpreted as a direct response to anthropogenic influences which have led to eutrophication of the lake. Recent changes in depositional patterns are considered to be a direct response to man's activity, which has completely separated Mariut into distinct sub-basins and modified lacustrine affected sedimentation patterns by the much increased discharge of domestic, industrial and agricultural wastes.

We expect that bottom sediments in the topographically isolated Mariut sub-basins will continue to be altered at an increasing rate. Population predictions for the Alexandria region approximate 5 million by the year 2020, with over 800 inhabitants per km^2 in the outlying countryside, and parallel increased (from 3 to 8% annually) and diversified industrial expansion (SESTINI, 1992). Clearly, anthropogenic activity has supplanted formerly important natural factors, is now the dominant control of sedimentation patterns, and in coming decades will increasingly control the nature of lake floor deposits. Mariut shell fishing is decimated, fish catch has declined, and marsh and lake margin wetlands are being dramatically reduced. Such changes are of concern, as are those relating to serious health ramifications of this highly polluted lake in close proximity to densely populated Alexandria. Systematic monitoring of bottom sediments in all parts of Mariut would be improved by more closely integrated sedimentological and geochemical study.

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