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Terrigenous-Carbonate Sediment Interface (Late Quaternary) Along the Northwestern Margin of the Nile Delta, Egypt

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ABSTRACT

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This petrological study characterizes the nature of various mixtures of terrigenous and carbonate sedimentary sequences of Late Pleistocene to Holocene age along the northwestern margin of the Nile delta in the Alexandria region, Egypt. Focus on the composition and proportions of sand-sized components serves to distinguish siliciclastic sediments of the River Nile to the east from carbonate sediments of the Arab's Gulf carbonate province to the west. Considered in this investigation are the petrologic attributes of (1) surface facies in shallow marine environments and prominent carbonate ridges, and also of (2) subsuface sediments recovered in radiocarbon-dated borings collected south and west of Abu Qir to Borg el Arab. Surface and subsurface sections can be correlated on the basis of compositional analysis.

Distribution in time and space of the mixed terrigenous-carbonate facies is delineated in the Alexandria-Lake Maryut region. Temporal and geographic shifts of this facies along the coast are induced by natural (eustatic sea level, subsidence, transport processes) and also man-induced factors. The latter include irrigation projects along the western delta margin, and development of coastal structures, particularly in the Agami to Abu Qir region. It is proposed that the terrigenous-carbonate sediment interface can be used as a gauge to detect changes in coastal depositional patterns along the northwest delta. Displacement of this interface would be induced by changes such as coastline configuration, erosion rates, and amount and nature of the sediment input from River Nile branches flowing to the Mediterranean.

ADDITIONAL INDEX WORDS: *Abu Qir headland, Alexandria coast, Arab's Gulf, Borg el Arab, carbonate petrology, carbonate ridges, coastal processes, Lake Maryut, Nile delta evolution.*

INTRODUCTION

Irrigation projects along the margins of the Nile delta have served to expand the cultivated surface of this vital food-producing region of Egypt. Desert dunes and evaporite pans are encroaching on some delta margin sectors, such as the northeastern delta which extends into northwestern Sinai east of the Suez Canal. The opposite is noted along the northwestern delta border west and south of Alexandria, Egypt's second largest city, where man has long exerted efforts to reclaim the desert area. Development of major canal and drainage systems, such as the Nubariya canal, has resulted in substantial western extension of a 'green belt' over an otherwise hostile desert terrain. The limit between delta and desert in the Alexandria region is well defined in field surveys, on aerial photographs and in satellite images (IWACO, 1989). The westerly expansion of this delta boundary has accelerated from the time of Greek and Roman occupation and now, with a rapidly expanding population, an understanding of the sedimentary evolution of this sector becomes a matter of even more vital importance.

Of particular interest in this study is the composition and distribution of the Late Quaternary sediment facies that have accumulated along the contact between the terrigenous River Nile province to the east of Alexandria, and the Arab's Gulf carbonate province to the west. Lithofacies along the delta boundary in this region would be expected to comprise variable mixtures of quartz- and carbonate-rich sediment. Among the surface facies considered in this investigation are terrigenous Nile deposits near Abu Qir, various lithologies forming the distinct carbonate ridges in the region between Abu Qir and Borg el Arab south of Arab's Bay (Figure 1), and littoral and surficial deposits on the inner Egyptian Shelf.

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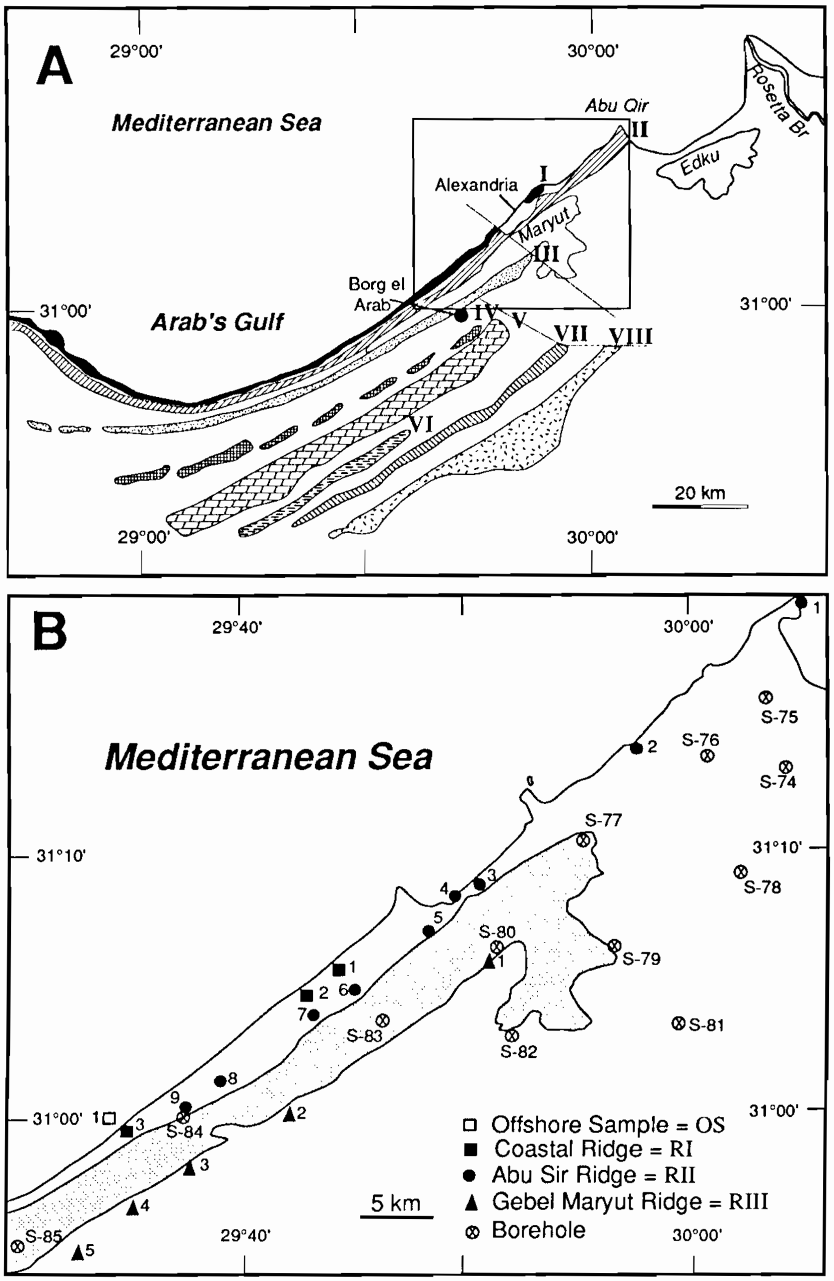

Figure 1. (A) Map showing 8 carbonate ridges parallel to the coast in the Alexandria region northwest of the Nile delta, Egypt (modified after BUTZER, 1960). (B) Position of offshore and carbonate ridge sample sites, and locations of Smithsonian boreholes S-74 to S-85. Shaded area denotes Lake Maryut and its western extension between ridges II and III.

Late Quaternary sections in the delta region east of Abu Qir, comprised largely of non-carbonate sands and silty muds, have been described at length in a series of earlier studies (ATTIA, 1954; UNDP/UNESCO, 1978; SESTINI, 1989; ARBOUILLE and STANLEY, 1991). In contrast, the region west of Alexandria has long been recognized as a carbonate province. Numerous studies have discussed the composition and distribution of carbonate deposits in coastal (HILMY, 1951) and offshore (SUMMERHAYES *et al.*, 1978; EL-WAKEEL and EL-SAYED, 1978; STOFFERS *et al.*, 1980; ANWAR *et al.*, 1981; EL-SAYED, 1988) environments. On land, the carbonate province is characterized primarily by a series of long (some > 100 km) carbonate-rich ridges, Pleistocene in age, that parallel the Mediterranean coast south of Arab's Gulf. The number of ridges southwest of Alexandria, as reported by various workers, varies from 8 (Figure 1) to 10. In the present study we focus on the three northern ridges, namely, from north to south, the Coastal Ridge, Abu Sir Ridge and Gebel Maryut Ridge. These Late Pleistocene ridges are herein coded respectively as ridges I, II and III. The northwestern limit of the Nile delta would almost certainly be related to, and affected by, these prominent features.

There is considerable controversy concerning the age, origin, and eastward extent of these ridges below Nile delta silts. Age assignments have been determined on the basis of relative elevation of each ridge with respect to present-day sea level, geographic position relative to the coast, elevation relative to the other ridges, and to faunal content. Some studies, for example, consider that the three northernmost ridges are of non-marine coastal dune origin (HUME, 1912; HUME and HUGHES, 1921; HUME and LITTLE, 1928; SANDFORD and ARKELL, 1939; PICARD, 1943; SCHWEGLER, 1948; HILMY, 1951; PAVER and PRETORIUS, 1954; SHATA, 1955; HASSOUBA, 1980). Other workers, however, interpret these ridges as shallow marine deposits such as offshore bars (FOURTAU, 1893; BLANCKENHORN, 1901, 1921; ZEUNER, 1952; SHUKRI *et al.*, 1956; SAID *et al.*, 1956; BUTZER, 1960; ISMAIL and SELIM, 1969; CHERIF *et al.*, 1988). The depositional origin of these ridges, the focus of a separate on-going investigation by us, is not discussed in any detail in the present study.

Topographic maps show that the eastern surficial part of Coastal Ridge I disappears near Mex just west of Alexandria; Abu Sir Ridge II extends further east to Abu Qir, and Gebel Maryut Ridge III disappears near Ameriya at the southwest margin of Lake Maryut (Figure 1). Generally, all ridges show an eastward decrease in elevation, perhaps as a result of bending and burial under the load of Nile delta sediments (SANDFORD and ARKELL, 1939). The more southerly ridges disappear eastwardly along a distinct NW-SE trend (Figure 1), quite possibly along a fault trace (*cf.* SHUKRI *et al.*, 1956; BUTZER, 1960). On the basis of drilling, ATTIA (1954) indicated that limestone strata extend eastwardly beneath the deltaic deposits of the Nile, and HASSOUBA (1980) postulated that these carbonate deposits descend and interfinger with terrigenous Nile sediments. One example, a deep borehole drilled about 50 km east of Alexandria and 30 km south of the Rosetta mouth recovered a 24 m-thick layer of limestone, termed oolitic, at a depth of 104 m (ATTIA, 1954). HASSOUBA (1980) correlates this limestone unit with the third, or possibly older, ridge.

An integral part of this study of northwestern Nile delta margin sediments is the petrographic analysis of various Late Pleistocene to Holocene facies recovered in a series of 12 subsurface borehole sections. These sediment borings (lengths 10 to 45 m), most of them radiocarbon dated, were collected south and west of Abu Qir in 1990 as part of the Smithsonian Institution survey of the northern Nile delta. Microfacies investigation of these subsurface carbonate-rich facies takes into account the distribution of allochems, quartz and other terrigenous components, as well as the nature of cement in the consolidated samples. Correlation of subsurface with surface lithofacies would help determine the influence of carbonate ridges on western Nile delta sedimentation patterns during the Late Pleistocene to Holocene time. Also considered in this investigation are the factors, natural and man-induced, which caused shifts in time and space of the terrigenous/carbonate interface along the northwest delta margin.

METHODOLOGY

This survey includes field observations and sampling of three carbonate ridges between Abu Qir and Borg el Arab at 17 sites, and also detailed petrologic examination of 12 sediment borings in the same region. Particular emphasis here is placed on the petrographic analysis of 117 surface (49) and subsurface (68) samples, most of them carbonate-rich, collected by us in this sector. The database comprises 49 samples of surface carbonates, including one unconsolidated offshore sand and 48 poorly to well-cemented specimens from the three ridges (Figure 1). Samples include: 1 shallow nearshore bar off Abu Sir; 5 from the Coastal Ridge I (from east to west: Agami, Sidi Barakat, Km 36.4; sites 1 to 3 on Figure 1); 27

Table 1. *Petrographic data of sand-sized components from surficial offshore bar (OS), Coastal Ridge (RI), Abu Sir Ridge (RII) and Gebel Maryut Ridge (RIII). Percentages are averaged (from 40 samples) for the 18 sites.*

		Total Components		Total Carbonate (actual values)			Total Fossils (recalculated to 100%)			Ooids (actual values)	
Locality	Sample No.	Quartz + Litho-clastics	Total CO_3 Particles	Total Ooids	Fossils	Other Allochems	Algae	Forams	Others	True Ooids	Coated Grains
Offshore											
Abu Sir	OS-1	0.9	99.1	86.3	12.4	0.3	7.5	32.5	60.1	52.8	33.5
Ridge I											
Agami	RI-1b	0.7	99.3	80.9	18.0	0.4	51.8	4.8	43.5	34.6	46.3
Sidi Barakat	RI-2	1.3	98.7	86.3	12.4	—	40.4	2.4	57.4	21.1	65.2
Km 36.4	RI-3a, b	0.9	99.1	80.8	16.0	2.3	39.9	13.6	46.5	12.3	68.5
Ridge II											
Abu Qir	RII-1a, b, c	83.7	16.3	—	14.7	1.6	46.4	12.6	41.0	—	—
Hadra	RII-2a, b, c	35.7	64.3	0.3	64.0	—	38.3	6.1	55.6	—	0.3
Mex	RII-3	—	100.0	11.0	73.0	16.1	8.9	3.1	88.0	1.4	9.6
Dekheila	RII-4	10.3	89.7	2.2	82.5	4.9	15.0	3.9	81.1	—	2.2
Agami	RII-5a, b, c	0.6	99.4	67.5	25.5	6.5	10.6	5.2	84.3	6.4	61.1
Km 21	RII-6a, b	3.8	96.2	70.9	16.3	9.1	19.2	23.9	57.0	7.5	63.4
Sidi Barakat	RII-7b, c, f, g, h	4.2	95.8	35.4	58.6	1.8	35.6	19.8	44.7	2.0	33.4
Abu Zeira	RII-8	—	100.0	73.0	27.0	—	52.7	6.5	40.9	2.3	70.7
Manderet Abu Afesh	RII-9a, d	0.6	99.4	78.3	19.7	1.3	24.2	9.9	65.9	3.2	75.1
Ridge III											
Ameriya	RIII-1a, c, d	47.2	52.8	—	50.7	2.1	36.3	39.7	24.0	—	—
Sidi Medewird	RIII-2a, b, c	25.9	74.1	1.8	71.4	0.9	41.5	36.8	21.7	—	1.8
10 Km east Borg el Arab	RIII-3	7.7	92.3	16.3	67.9	8.0	29.1	35.0	35.9	—	16.3
Bahig Drain Cut	RIII-4a, b, c, d, f	12.8	87.2	6.9	78.1	2.2	36.7	32.2	31.1	—	6.9
Borg el Arab	RIII-5a, b	11.3	88.7	3.0	84.9	0.8	27.4	37.8	34.9	—	3.0

from Abu Sir Ridge II (from east to west: Abu Qir, Hadra, Mex, Dekheila, Agami, Km 21, Sidi Barakat, Abu Zeira, Manderet Abu Afesh; sites 1 to 9 on Figure 1); and 16 from Gebel Maryut Ridge III (from east to west: Ameriya, Sidi Medewird, 10 km east of Borg el Arab, Bahig Drain Cut, Borg el Arab; sites 1 to 5 on Figure 1). In addition, unconsolidated (47 samples of sand washings) and well-cemented carbonates (21 samples) were selected from the 12 sediment borings shown in Figure 1. Many of the subsurface sections have been radiocarbon dated (MEDIBA, 1991).

Polarizing and binocular microscope examination was used to identify and count both carbonate and non-carbonate sand-sized constituents in thin section (a total of 93 sections were studied). More than 300 grains were identified in each section, and percentages of the following were determined: terrigenous components (quartz, lithoclastics); inorganic carbonate components (true ooids, coated grains, pellets, aggregate lumps, intraclasts); and biogenic carbonate components (algae, large and small foraminifera, gastropods, echinoids, ostracods, shell fragments). These data are listed in Tables 1 to 3. Photomicrographs (Figures 2 and 3) and were made of selected carbonate-rich samples. The amount of insoluble residue (coded I.R.) was determined for 48 surface samples (weight percent determined by HCl dissolution). The size distribution (made in thin section) of most of the surface carbonate ridge samples was calculated. Chemical composition was also determined for 21 representative samples from the three ridges (MEDIBA, 1991). The classification and terminology used here are those of DUNHAM (1962).

CARBONATE STRANDLINE AND RIDGE DEPOSITS

Special attention is paid to lithofacies variations among nearshore and coastal deposits and among the three northernmost ridges which, together, comprise the representative carbonate-rich deposits in the study area. A database emphasizing the salient petrographic attributes of this carbonate province in the Alexandria region is needed to help delineate the western extent of the River Nile terrigenous sediment input. The more obvious field and petrographic characteristics of the sand-sized fraction are summarized below; averaged compositional data are listed in Table 1.

Surficial Nearshore and Coastal Facies

Surficial sediments on the inner to mid-continental shelf off the Nile delta are largely biodetrital carbonate sands and muds (UNDP/UNESCO, 1978; SUMMERHAYES *et al.*, 1978). Some of these carbonates, particularly sands, are distributed locally along submarine bars that, in some way, are comparable to the subaerial ridges exposed along the coast (SESTINI, 1989). Among the characteristic sand-sized carbonate components of Arab's Gulf are fossil shell fragments and ooids, including true ooids and coated grains (ANWAR *et al.*, 1981) and pellets (STOFFERS *et al.*, 1980). The proportion of the total carbonate content in surficial sediments in Arab's Gulf decreases in a northeastwardly direction rapidly from a maximum > 80% to < 20%, particularly toward the north and east of Alexandria and the Abu Qir headland (EL-WAKEEL and EL-SAYED, 1978). Many workers have noted that modern coastal sediments west of Dekheila (site 4 in Ridge II, Figure 1) are largely carbonates of the type described above; these strandline deposits to the west include almost no siliciclastic minerals derived from the River Nile (HILMY, 1951).

For this comparative study, a representative sample from Arab's Gulf was collected on an offshore bar just north of Abu Sir at a water depth of about 2 m (sample OS-1). Sand at this locality is composed largely of uncemented true ooids and coated grains (Figure 2A), along with diverse fossil allochems (echinoid spines, miliolid foraminifera, calcareous algae and molluscan shell fragments). The ooids and coated grains have an aragonite cortex composed of a concentric lamellar structure while the nucleus may comprise micritic carbonate material, echinoid spines, small foraminifera, algal fragments, or quartz grains (very rare). The ooids and fossil allochems constitute a moderately well sorted sand.

Coastal Ridge I Carbonates

Coastal Ridge I parallels the shore from Alexandria westward to about 30 km east of the Libyan border (SHUKRI *et al.*, 1956). This characteristically snow-white ridge ranges to 10 m above sea level in the western part of the study area, and decreases markedly in elevation and disappears just east of Agami (site 1 in Figure 1). Along Arab's Gulf, the upper surface of the ridge is typically covered by coastal dune plants, and is fronted by beaches of variable widths composed of white carbonate sand. Locally, the ridge is composed of loose, well-sorted, well-rounded carbonate sand, which displays cross-lamination. It is difficult to map the ridge in the Agami region because it is now almost completely covered by houses and buildings along the increasingly populated coastal plain. A Late Monasterian age has been attributed to these ridge deposits (SHUKRI *et al.*, 1956; CHERIF *et al.*, 1988).

Characteristic petrographic attributes of Coastal Ridge I are summarized as follows:

(1) The carbonate content of studied samples exceeds 98.5% (Table 1); the very small amount of insoluble residue (I.R. < 1.5%) at the three examined sites is composed of angular, occasionally polycrystalline, quartz and rare angular feldspar grains.
(2) True ooids and coated grains are the major (to 80%) allochem constituents.
(3) Among the fossil allochems, only the miliolids decrease from east to west; proportions of other fossils appear to remain constant along the ridge.
(4) Cement occurs as an extremely thin rim of aragonite around the allochems.

Coastal Ridge I is composed almost entirely of pure carbonate, and can be classified as an ooid grainstone along its entire extent (Figure 2B). The term coated grains (syn. superficial ooids, CAROZZI, 1960) is applied here to particles which have few laminae in their cortex and have a cortex/nucleus (C/N) ratio of < 0.1. The nucleus of coated grains is usually composed of either quartz or bioclastic particles. In contrast, true ooids comprise a cortex formed by well-developed concentric layers (Figure 2B), and the characteristic cross-bar figure is observed under cross nicols. The cortex thickness ranges from 12.5 to 287 μm. The nuclei range in size from 87.5 to 612 μm, and the cortex/nucleus (C/N) ratio ranges from 0.1 to 1.53. The nucleus is usually composed of a bioclastic grain, such as algae, mollusc, or foraminifer, or of micritic carbonate material.

Other allochems include pellets and fossils, such

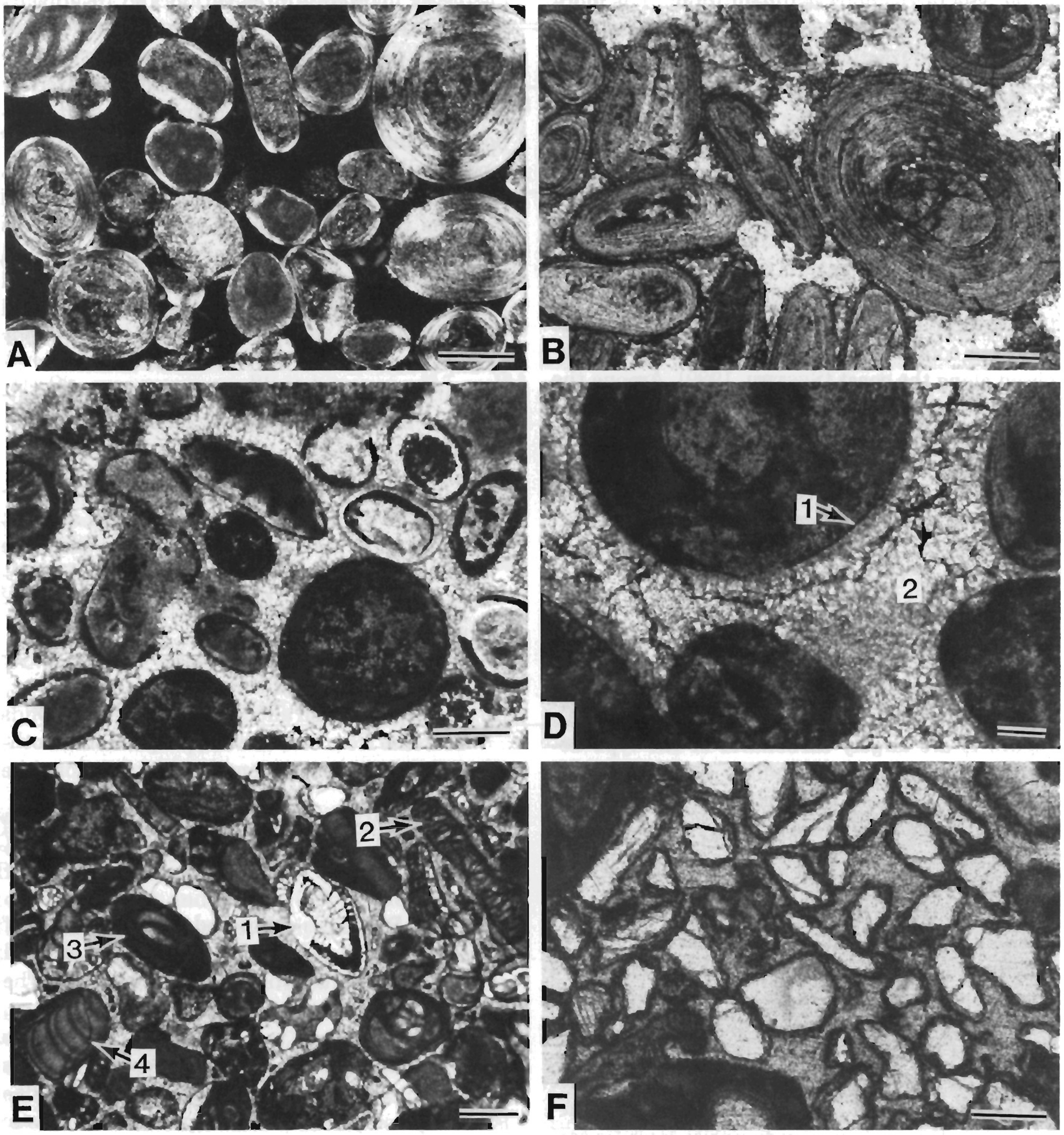

Figure 2. Photomicrographs of selected Holocene offshore (A) and Pleistocene carbonate ridge (B–F) samples; (A) under cross-nicols, and (B–F) ordinary light. (A) modern offshore bar sample OS-1, from off Abu Sir (water depth 2 m). Uncemented true ooids, with well developed aragonite cortex showing cross-bar; nucleus composed of carbonate material or fossil shell fragments (upper left corner). (Bar = 200 μm). (B) Coastal Ridge I, site 3, sample RI-3b, showing poorly cemented true ooids; cortex displays well developed concentric radial fabric. (Bar = 200 μm). (C) Abu Sir Ridge II, site 8, sample RII-8, showing partially cemented coated grains with very thin coats of calcite. (Bar = 200 μm). (D) Abu Sir Ridge II, site 9, sample RII-9b, showing two cement types: an early stage, isopachous calcite that rims allochems (arrow 1); and blocky calcite filling intergranular voids (2). (Bar = 50 μm). (E) Gebel Maryut Ridge III, site 4, sample RIII-4a, showing typically high diversity of fossil allochems: 1 = *Amphistegina* sp.; 2 = *Sorites* sp.; 3 = miliolid; 4 = calcareous algae. (Bar = 400 μm). (F) Gebel Maryut Ridge III, site 1, sample RIII-1c, showing large proportion of angular to subangular, poorly sorted quartz grains recording dominant terrigenous input from River Nile. (Bar = 200 μm).

as algae, small gastropods, foramaminifera, and echinoids. CHERIF *et al.* (1988) has noted the difficulty of accurately determining the proportions of different foraminiferal faunas in the coastal ridge since some of their tests serve as nuclei of ooids and thus are difficult to identify.

Some east to west changes are noted along ridge I. Texturally, there is a slight difference in the amount of medium to fine material (< 0.6 mm) between samples collected from sites 1 and 2, and samples from site 3 in the western part of the study area. Fines decrease from 82.5% at Agami to 73.4% at site 3, resulting in somewhat improved textural sorting westward. Toward site 3, the coarse sand-size fraction is represented mainly by true ooids (up to 1 mm diameter), and, to a lesser extent, by diverse allochems including coated grains.

In addition to the above, a marked lateral change in heavy mineral content in ridge I was recorded by SHUKRI and PHILIP (1956): heavy minerals and quartz constitute as much as 21% of the deposits east of Dekheila and the western approaches to Alexandria; siliciclastics account for only 2% west of Dekheila. Also, as noted by SHUKRI *et al.* (1956), the fossil content east of Dekheila (1.5%) is lower than to the west (2%). Our analyses of samples from the three studied localities reveal that the proportion of fossils (16–18%) exceeds the above-cited values and, moreover, the fossil content is almost constant in sand-sized fractions along the ridge.

At site 1, where only a ~ 1.5 m section is exposed, the ridge is composed of coarse, poorly consolidated oolitic limestone. The actual thickness at site 2 is about 5 m, and here small gastropod shells are present in the ooid-rich sediment. Further west, at site 3, the exposed section attains 6.0 m and is composed of alternating coarse and fine ooid-rich layers that display small-scale, low angle cross-stratification.

Chemical analysis indicates the presence of minor amounts of SiO_2, Al_2O_3, and Fe_2O_3, all of which decrease slightly westward. This may perhaps record a decreased clay content and/or influence from the River Nile terrigenous sources to the western sites. Ridge I ooid-rich carbonates likely accumulated in a shallow, high energy marine environment receiving a very low terrigenous influx (*cf.* FLUGEL, 1982). It has been suggested that it accumulated under conditions similar to those prevailing currently along the coast north and west of Alexandria (CHERIF *et al.*, 1988).

Abu Sir Ridge II Carbonates

Abu Sir Ridge II, almost parallel and landward of Coastal Ridge I, extends from Abu Qir to the town of Sallum, near the western border of Egypt. It is this ridge on which Alexandria has been built (Figure 1). The elevation of this cream-colored limestone ridge averages about 25 m and decreases eastward toward Abu Qir (6 m). It is quarried along the coastal plain, from site 3 to the west of the study area, for building and industrial use. Some previous studies assigned a "Main Monasterian" age for this ridge (*cf.* BLANCKENHORN, 1921; SHUKRI *et al.*, 1956; CHERIF *et al.*, 1988).

Characteristic petrographic attributes of Abu Sir Ridge are summarized as follows:

(1) The content of quartz and other components that constitute the insoluble residue is very high at sites 1 and 2 (I.R. = 76.6%), and decreases markedly west of site 3.
(2) The ridge to the west of site 2 is composed of ooidal-coated grain-bioclastic grainstone.
(3) In fully cemented samples, there are two cement types: an isopachous rim around particles and intergranular equant calcite; the amount of cement decreases downward in the sequence at each site and also westward along the ridge.
(4) Allochems, dominated by coated grains and algae, also include considerable amounts of shell fragments, large benthic foraminifera, and few planktonic foramaminifera.
(5) Thin calcrete crusts (a few to 15 cm in thickness, hard, light to dark brown, and thinly laminated) occur irregularly throughout the ridge sequence; these suggest intermittent subaerial exposure of ridge deposits and resulting fresh water (meteoric) diagenesis (*cf.* EL-SHAHAT *et al.*, 1987).

Moreover, there is a change westward in the nature and proportion of allochems in Abu Sir Ridge II. Allochems are more diverse and abundant west of site 4. Generally, calcareous algae are the major components among the biogenic allochems, reaching to 52.7% of the fossil content (Table 1). Foraminifera (represented by soratiids, rotalids, miliolids, and a few planktonics) are not as abundant as algae, and account for 23.9% of the fossil content. Other biogenic allochems include echinoid spines and molluscan shell fragments. Abundant fish bone fragments and teeth are also recorded in some sample horizons at sites 5 and 7.

True ooids and coated grains are not nearly as abundant in ridge II as in Coastal Ridge I. They are absent at the two eastern sites, but are present at site 3; their cortex are better developed further to the west of this site. Generally, coated grains far exceed true ooids (Figure 2C). The true ooid cortex is altered to calcite, and rarely reaches one half of the ooid diameter. The nucleus of both coated grains and true ooids is composed of shell fragments, micritic carbonate material, and (rarely) quartz grains.

An east to west site-by-site summary follows. The studied section at the Abu Qir headland (site 1) is exposed directly along the shore. The lower 1 m of section is composed largely of sandy algal limestone. This horizon is overlain by 3.5 m of poorly-cemented, normally sorted, quartz sandstone (I.R. = 67.7%); it is almost devoid of fossils and yields only are miliolid tests. The upper 2.5 m of section consists of partially cemented, sandy bioclastic grainstone; it is composed almost entirely of well-rounded, obliterated, calcareous algal debris with few delicate molluscan shell fragments.

At site 2, the exposed part of this ridge is 8.5 m thick and is divided into two parts. The lower 3 m comprise light yellow to dark brown, soft, massive, fine to medium-grained, quartzose sandstone (I.R. = 83.6%); it is rich in small gastropods. The upper 5.5 m of section are composed of light yellow, relatively harder, cross-bedded, bioturbated skeletal grainstone (I.R. = 6.1%). The top of the section yields large naticoid gastropod shells. The exposed part of Abu Sir Ridge at site 3 attains about 6 m. It is composed of light yellow to yellowish-grey, soft, thinly-bedded, low angle cross-stratified, fine-grained oolitic grainstone (I.R. = 0.9%). At site 4, the ridge is only partially exposed (3–4 m) along the coast due to an expanding housing development. It is composed of light yellowish-pink, fine-grained, bioturbated, cross laminated grainstone (I.R. = 3.3%). In fully-cemented samples, at sites 3 and 4, the cement is composed of two types: an isopachous calcite rim around the particles, and coarse equant calcite that fills intergranular spaces (Figure 2D). In the area between sites 4 and 5, the exposed part of ridge II (I.R. = 1.2%) is about 12 m thick. The lower half is a massive bioclastic grainstone. The upper 6 m are extensively bioturbated and display trough cross-stratification.

Westward, from sites 6 to 9, the Abu Sir Ridge has a fairly consistent thickness (about 22 m) and lithology, *i.e.* an almost pure grainstone. The carbonate content is almost always higher than 95% (I.R. < 5%), and displays large scale low angle cross-bedding. Locally, as at site 7, there are several paleosol (hamra) horizons which are characterized by a dark brownish color, high terrigenous content (I.R. = 67.1%) and abundant terrestrial gastropod shells. The hamra is almost entirely composed of poorly sorted quartz with minor amounts of feldspar; grains range in size from 80–600 μm, subrounded, and intergranular space is entirely filled with calcite cement. Chemical analysis of representative samples shows that this paleosol horizon yields the highest content of Al_2O_3, Fe_2O_3, and $MgCO_3$ among all analyzed samples in this ridge. At site 9, the exposed section is composed entirely of bioclastic grainstone, and the I.R. is < 2%.

Chemical analysis of 12 representative samples of this ridge reveals a generally consistent composition among all studied samples. One exceptional interval, at site 7, yields a relatively high content of Al_2O_3 (7.2%) and Fe_2O_3 (3.7%) which suggests subaerial exposure with subsequent soil (hamra) formation. The petrographic attributes, however, indicate that this ridge was, for the most part, originally deposited under shallow marine conditions and, as denoted by calcrete crusts, intermittently exposed (*cf.* FLUGEL, 1982).

Gebel Maryut Ridge III Carbonates

Ridge III lies south of, and parallel to, Abu Sir Ridge II. In the study area, ridges II and III are separated by a depression occupied by the western linear extension of Lake Maryut (Figure 1). The elevation of ridge III ranges from 20 to 30 m above the lake floor. Some previous studies have assigned a Late Tyrrhenian age to this grayish-yellow to light brown limestone ridge (SANDFORD and ARKELL, 1939; SHUKRI *et al.*, 1956; CHERIF *et al.*, 1988).

Characteristic petrographic attributes of Gebel Maryut Ridge III are summarized as follows:

(1) Of the three ridges, ridge III has the highest terrigenous content which extends further west than in the other two ridges.

(2) Of the three ridges, ridge III has the largest and the most diversified fossil content. Calcareous algae and foraminifera are the major fossil allochems along the studied part of the ridge (Figure 2E); amphistegins are the most characteristic foraminifera.

(3) The amount of cement is low along the entire eastern ridge sequence, and in the lower part of the ridge in the west.
(4) True ooids are totally absent, while coated grains (to 16.3%) are recorded in the upper part of the ridge in the western part of the study area.
(5) As in Abu Sir Ridge II, ridge III is characterized by repeated occurrence of paleosols and calcrete horizons characterized by a high concentration of carbonate silt and fine quartz sand.

Field and petrographic (Table 1) study reveals that the Gebel Maryut Ridge III gradually changes from a terrigenous-dominated facies in the east to a carbonate-dominated facies in the west. An interfingering of these two end-members is observed at the Bahig Drain Cut (site 4).

In the east, at sites 1 and 2, quartz grains are angular, poorly sorted and are of medium to fine sand size (Figure 2F). The I.R. values reach 52.1% in the east, and are as low as 4.1% in the west at the top of the sequence.

Algae is the major fossil component, accounting to 41.5% of fossil allochems. Forams are almost as abundant as algae and constitute to 37.9% of total fossils. Characteristic foraminiferal constituents are amphistegins and sorites; amphistegins are rarely observed in Abu Sir Ridge II, and never found in Coastal Ridge I. CHERIF *et al.* (1988) have reported that this foraminiferal assemblage is similar to those in modern Red Sea littoral environments, indicating a warmer climate during deposition of this ridge. Echinoids (spines and plates) are also important (to 6.3%) among ridge III fossil allochems.

At site 1, the exposed section is 15 m thick and is formed almost entirely by carbonate-cemented quartz-rich sandstone and siltstone (I.R. = 47.2%). There is a markedly bioturbated interval (1 m thick) at about 9.5 m above base of section. At site 2, the section is about 17 m thick. It is more calcareous (I.R. = 25.9%) than at site 1, and the bioturbated interval is thicker. The topmost 3 m of the section consist of hard, yellowish-grey bioclastic grainstone.

The stratigraphic section at site 4 is about 32 m thick. The basal part (9 m) of the section consists of yellowish-grey, soft, bioclastic grainstone. This is overlain by a 1.2 m interval of light brown calcareous siltstone with small gastropods and reworked lithoclasts composed of almost the same material as the underlying interval. The overlying interval (8.0 m) consists of grey, thinly bedded (50–80 cm) bioclastic grainstone. This unit is followed upward by 2 m of dark yellow to light brown, soft, calcareous, fine-grained quartz sandstone with *Helix* sp. (I.R. = 21.5%). The high carbonate content of this sandstone results from the abundance of these gastropod shells. The upper part of the section (11.7 m) is composed of hard, light pink bioclastic grainstone with a brownish, very hard calcrete horizon at the top.

At site 5, only the upper part (12 m) of the ridge is exposed, and it is composed of bioturbated, light yellow, cross-bedded bioclastic grainstone (I.R. = 11.3%).

Chemical analysis of 6 samples (from site 4) reveals an important content of $MgCO_3$ (to 8.7%), Al_2O_3 (to 2.0%), and Fe_2O_3 (to 1.2%), possibly recording the influence of Nile sediment transport as far west as site 4.

On the basis of facies criteria proposed by FLUGEL (1982, his table 50, p. 484), we suggest ridge III formed in a shallow subtidal zone. It is noted that soil horizons and calcrete crusts within the sequence record periodic emergence.

DISTINGUISHING SURFICIAL CARBONATE FACIES

Field observations and petrographic analysis of sand-sized components provide a reliable means to discriminate among the dominant surficial nearshore and ridge carbonate lithofacies encountered in the study area west of the River Nile terrigenous province. In this respect, we consider the proportions of the various particle types listed in Table 1. It is particularly helpful to focus on the average percentages of four of the dominant sand-sized components (true ooids, coated grains, foraminifera, and quartz). Relationships among the four components can be summarized as follows:

(1) Surficial offshore sediments can be differentiated from ridge carbonates primarily on the basis of proportions of true ooids: these are generally more abundant in surficial littoral and nearshore deposits than in any of the ridges, including Coastal Ridge I (Figure 4A).
(2) True ooids are much more abundant in Coastal Ridge I than in Abu Sir Ridge II, and true ooids are absent in Gebel Maryut Ridge III (Figure 4A).

Table 2. *Petrographic data of sand-sized components from subsurface samples recovered in 9 boreholes (S-77 to S-85): listing includes percentage counts from 32 unconsolidated sand washings (W), and from 11 consolidated samples (from cores in boreholes S-84 and S-85).*

Borehole No.	Wash No.	Quartz	Litho-clastics	Ooids	Coated Grains	Pellets	Lumps	Intra-clasts	Algae	Large Forams	Small Forams	Miliolids	Gastro-pods	Echi-noids	Ostra-cods	Shell Frag-ments
S-77	W_1	48.4	—	3.6	7.4	1.4	—	—	12.8	2.9	0.9	0.7	0.5	0.2	0.2	21.2
	W_2	92.4	—	—	0.9	—	—	—	2.1	0.2	0.7	—	0.2	—	—	3.5
	W_5	85.9	—	0.8	1.4	—	—	—	3.1	—	—	0.2	—	—	—	8.6
	W_8	95.5	—	—	0.2	0.4	—	—	0.9	—	0.4	—	—	—	—	2.6
	W_{19}	86.6	—	1.4	1.6	0.2	—	—	2.4	—	0.8	—	—	—	—	6.9
S-78	W_1	43.1	—	2.9	0.4	—	—	—	—	—	10.8	—	—	—	—	42.7
	W_3	96.9	—	—	—	—	—	—	0.6	—	—	—	—	—	—	2.5
	W_4	93.0	—	0.6	—	1.0	—	—	1.3	—	1.6	—	—	—	—	2.6
	W_8	95.8	—	—	—	1.2	0.3	—	1.2	—	—	—	—	—	—	1.5
S-79	W_{12}	87.0	2.2	—	—	—	—	—	2.0	—	1.0	—	—	0.2	—	7.6
S-80	W_2	82.9	0.2	—	0.2	0.2	0.2	—	5.8	1.5	3.3	—	—	0.2	—	5.4
	W_4	89.6	—	—	—	—	—	—	3.1	1.0	1.4	—	—	0.5	—	4.5
	W_7	71.3	0.7	—	0.4	0.4	—	—	9.8	4.7	1.4	—	—	0.2	—	11.9
	W_{10}	93.6	—	0.2	—	—	—	—	3.0	0.7	0.7	—	—	—	—	1.7
S-81	W_6	85.8	1.5	—	—	—	—	—	4.0	—	1.5	—	—	—	—	7.3
	W_8	80.6	4.6	—	—	—	—	—	4.0	—	2.4	—	—	0.8	—	7.5
S-82	W_2	91.1	7.5	—	—	—	—	—	—	—	0.6	—	—	—	—	0.9
	W_4	85.8	0.6	—	—	—	—	—	9.2	0.6	1.1	—	—	—	—	2.8
	W_{12}	80.5	0.9	—	—	0.7	—	—	12.2	0.5	3.6	—	0.2	—	—	1.4
	W_{18}	84.6	0.6	—	—	—	—	—	10.4	0.3	1.1	—	—	0.3	—	2.8
S-83	W_7	67.9	1.4	—	—	—	—	—	4.5	8.7	1.8	—	0.2	1.6	—	13.8
	W_{10}	73.7	3.8	—	—	—	—	—	1.6	5.4	6.0	—	—	0.5	—	9.2
	W_{16}	83.8	6.2	—	—	—	—	—	1.1	0.3	1.9	—	—	—	—	6.7
	W_{19}	82.5	4.3	—	—	—	—	—	1.8	4.1	2.8	—	—	0.4	—	4.1
S-84	W_1	11.4	16.4	1.4	2.5	—	—	—	15.3	8.6	1.1	—	3.1	4.7	—	35.6
	W_2	28.8	4.5	—	2.8	—	—	—	23.7	23.0	1.7	—	0.6	2.1	—	12.8
	W_3	5.9	2.0	1.1	0.6	2.5	1.1	—	35.0	22.9	4.0	—	0.9	4.0	—	20.1
	W_5	5.5	—	1.8	2.5	1.5	—	—	37.9	19.3	2.1	—	—	2.1	—	27.2
	W_{10}	21.9	—	—	1.9	0.8	—	—	28.8	15.6	5.0	—	—	2.9	—	23.2
	W_{13}	8.6	0.4	—	1.1	0.9	0.4	—	25.7	24.3	4.0	—	1.1	2.2	—	31.2
S-85	W_3	26.1	1.1	0.5	3.0	1.1	—	—	39.8	12.4	2.2	—	—	1.6	—	11.8
	W_6	33.8	1.5	—	1.5	2.1	0.6	—	25.0	16.8	3.4	—	0.6	3.1	—	11.6
S-84 core III	III-25 4 cm	5.4	0.9	0.4	2.6	0.9	—	—	40.2	23.9	3.7	—	1.1	2.4	—	18.7
	III-29 81 cm	2.9	5.4	1.6	5.6	—	—	—	38.9	22.0	1.8	—	2.5	2.5	—	16.9

Table 2. *Continued.*

Borehole No.	Wash No.	Quartz	Litho-clastics	Ooids	Coated Grains	Pellets	Lumps	Intra-clasts	Algae	Large Forams	Small Forams	Miliolids	Gastro-pods	Echi-noids	Ostra-cods	Shell Frag-ments
S-85 core I	I-11	2.6	6.4	0.5	28.9	—	1.5	—	6.9	31.2	0.8	1.0	1.5	3.3	—	15.4
	I-13	2.7	14.9	—	0.6	23.7	—	—	17.0	22.3	0.8	—	1.7	3.2	—	13.0
	I-14	8.5	3.2	0.2	0.2	0.2	—	3.9	35.3	31.2	—	—	2.3	5.7	—	9.2
	I-16	1.6	1.6	2.6	40.6	—	—	—	10.0	25.7	—	—	1.8	1.8	—	14.4
	I-18	0.5	1.7	—	21.8	—	—	—	20.5	36.7	0.7	—	1.7	3.9	1.7	10.8
	I-20	—	4.6	—	3.7	—	—	—	34.1	41.0	—	—	0.9	2.0	—	13.8
S-85 core II	II-21	1.5	13.2	0.3	2.2	—	—	—	15.3	36.8	3.7	1.5	2.8	8.3	1.5	12.9
	II-23	3.6	3.3	0.3	1.2	—	—	—	53.5	16.3	2.4	—	3.3	3.3	—	12.7
	II-26	1.3	8.2	0.6	22.3	7.9	—	—	23.6	13.2	0.9	—	1.3	1.6	—	19.2

(3) The offshore and Coastal Ridge I carbonates, with their low quartz and very high total ooid (true ooid + coated grain) percentages, are distinguished from sediments of ridges II and III (Figure 4B).

(4) Quartz content alone does not serve to reliably distinguish among samples from ridges II and III (Figure 4B). More diagnostic are the higher proportions of coated grains (Figure 4A) and lower percentages of foraminifera (Figure 4C) in Abu Sir Ridge II than in Gebel Maryut Ridge III.

(5) Although ridge II and III lithofacies are sometimes difficult to differentiate, higher proportions of foraminifera (particularly amphistegins) serve to distinguish Gebel Maryut Ridge III (Figure 4C, D).

CORRELATING SUBSURFACE WITH SURFACE FACIES

Sedimentary sections recovered in borings enable us to define the western Nile delta boundary and to delineate the mixed terrigenous-carbonate facies of Late Pleistocene to Holocene age along the northwestern sector of the River Nile system in the Alexandria region. Of the 12 borings examined (S-74 to S-85), only the two westernmost recovered consolidated carbonate intervals (Figure 1): S-84 (in core III, from 4.5 to 6.0 m; total depth = 23 m), drilled at the base of the southern flank of Abu Sir Ridge II near site 9; and S-85 (from 6.0 m to the base of the core at 10 m), drilled in the western Lake Maryut depression between Abu Sir Ridge II and Gebel Maryut Ridge III (the drill site was positioned closer to ridge III). Detailed logs and petrologic data pertinent to the borings are available in MEDIBA (1991). Radiocarbon dating indicates that the lithified carbonate units in both boreholes are older than 40,000 years before present (BP). In addition to these consolidated horizons, we also examined unconsolidated samples selected from all 12 borings (Table 2).

The subsurface petrographic data was derived from thin-section analyses of 11 (of a total of 21) consolidated and of 32 unconsolidated (sand washing) samples from 9 borings (S-77 to S-85) in the study area (Table 2). Data averaged per core are listed in Table 3. It is noted that thin sections of these samples were treated in the same manner as those of surface samples for correlation and regional comparisons. In addition, compositional counts of 15 washings from an additional

Table 3. *Averaged percentages of major compositional components derived from counts of subsurface washing (W) and core (C) samples (boreholes S-77 to S-85) listed in Table 2. Data at bottom of table lists averaged percentage values for sand washings from additional boreholes S-74 to S-76 (original data in MEDIBA, 1991).*

		Total Components		Total Carbonate (actual percentages)			Total Fossils (recalculated to 100%)		
Borehole	Sample No.	Quartz + Lithoclastics	Total CO_3 Particles	Total Ooids	Fossils	Other Allochems	Algae	Forams	Others
S-77	$W_{1,2,5,8,19}$	81.7	18.3	3.5	14.4	0.4	29.6	9.5	60.9
S-78	$W_{1,3,4,8}$	82.2	17.8	1.0	16.2	0.6	4.8	19.2	76.0
S-79	W_{12}	89.2	10.8	—	10.8	—	18.2	9.1	72.7
S-80	$W_{2,4,7,10}$	84.6	15.4	0.2	15.0	0.2	36.1	24.5	39.4
S-81	$W_{6,8}$	86.2	13.8	—	13.8	—	29.1	14.2	56.7
S-82	$W_{2,4,12,18}$	87.9	12.1	—	12.0	0.2	66.5	16.1	17.4
S-83	$W_{7,10,16,19}$	80.9	19.1	—	19.1	—	11.6	40.6	47.8
S-84	$W_{1,2}$	30.5	69.5	3.3	66.2	—	29.4	26.0	44.5
	CIII-25, 29	7.3	92.7	5.1	87.2	0.4	45.4	29.5	25.2
	$W_{3,5,10,13}$	11.1	88.9	2.2	84.9	1.8	37.5	28.6	33.9
S-85	$W_{3,6}$	31.5	68.5	2.5	64.1	1.9	50.1	27.1	22.4
	CI-11, 13, 14, 16, 18, 20	8.0	92.0	16.5	70.4	5.0	29.3	45.2	25.5
	CII-21, 23, 26	10.3	89.6	9.0	78.0	2.6	39.5	32.0	28.5

Borehole	Washing No.	Insoluble Residue	Carbonate	Depositional Environment	
S-74	$W_{2,4,5,6,7}$	97.8	3.3	Lagoonal facies ($CaCO_3$ are shell fragments)	
S-75	$W_{5,7,8,10,11}$	96.6	3.6	Transgressive sand	(No ooids)
S-76	$W_{1,4,5,6,7}$	70.3	29.7	Lagoonal facies ($CaCO_3$ are shell fragments)	

3 borings (S-74, S-75 and S-76) were made using a binocular microscope (Table 3).

Consolidated Subsurface Carbonates

Examination of samples from the lithified carbonate horizon in boring S-84 reveals only trace amounts of true ooids, low to modest quantities of coated grains and quartz, and moderate amounts of foraminifera (Figure 5). The proportions of the four components in S-84 are closely similar to those of samples from Abu Sir Ridge II (*cf.* Figure 4). However, (1) important proportions of calcareous algae and (2) the presence of coarse, subrounded reworked fragments enclosing fossil debris of large foraminifera (Figure 3B, arrow 1) and algae (Figure 3B, arrow 2), together, record some similarity with carbonates in Gebel Maryut Ridge III (see also Figure 5). Thus, this analysis indicates that sediment in S-84 forming the basal part of the southern flank of Abu Sir Ridge II may have been, at least in part, derived from erosion and reworking of carbonates from ridge III.

Lithified carbonate samples in S-85 reveal trace to low amounts of true ooids, modest amounts of quartz, large proportions of foraminifera, and a very broad range of coated grains (from trace to > 40%). It is of note that proportions of those four components in some S-85 samples (for example, 85-I-20 and 85-II-21; Table 2 and Figure 5) are directly comparable to carbonates in Gebel Maryut Ridge III. Moreover, sample 85-I-20 displays cement amount and attributes (Figure 3E) characteristic of ridge III. Other S-85 samples, on the other hand, have proportions of foraminifera, coated grains and other attributes suggesting a composition intermediate between those of ridges II and III (Figure 5). For example, sample 85-I-15 (Figure 3C) displays vadose diagenetic alteration (calcrete) commonly noted in carbonates of both ridges II and III. Overall, however, the high proportion of calcareous algae (Figure 3A) and presence of characteristic amphistegin foraminifera (Figure 3D) indicate that most carbonate samples in boring S-85 are of ridge III origin.

Unconsolidated Subsurface Facies

Samples recovered as unconsolidated sand washings were selected from all 12 cores. Washings from below the indurated carbonate unit in boring S-84 are probably as old as Abu Sir Ridge

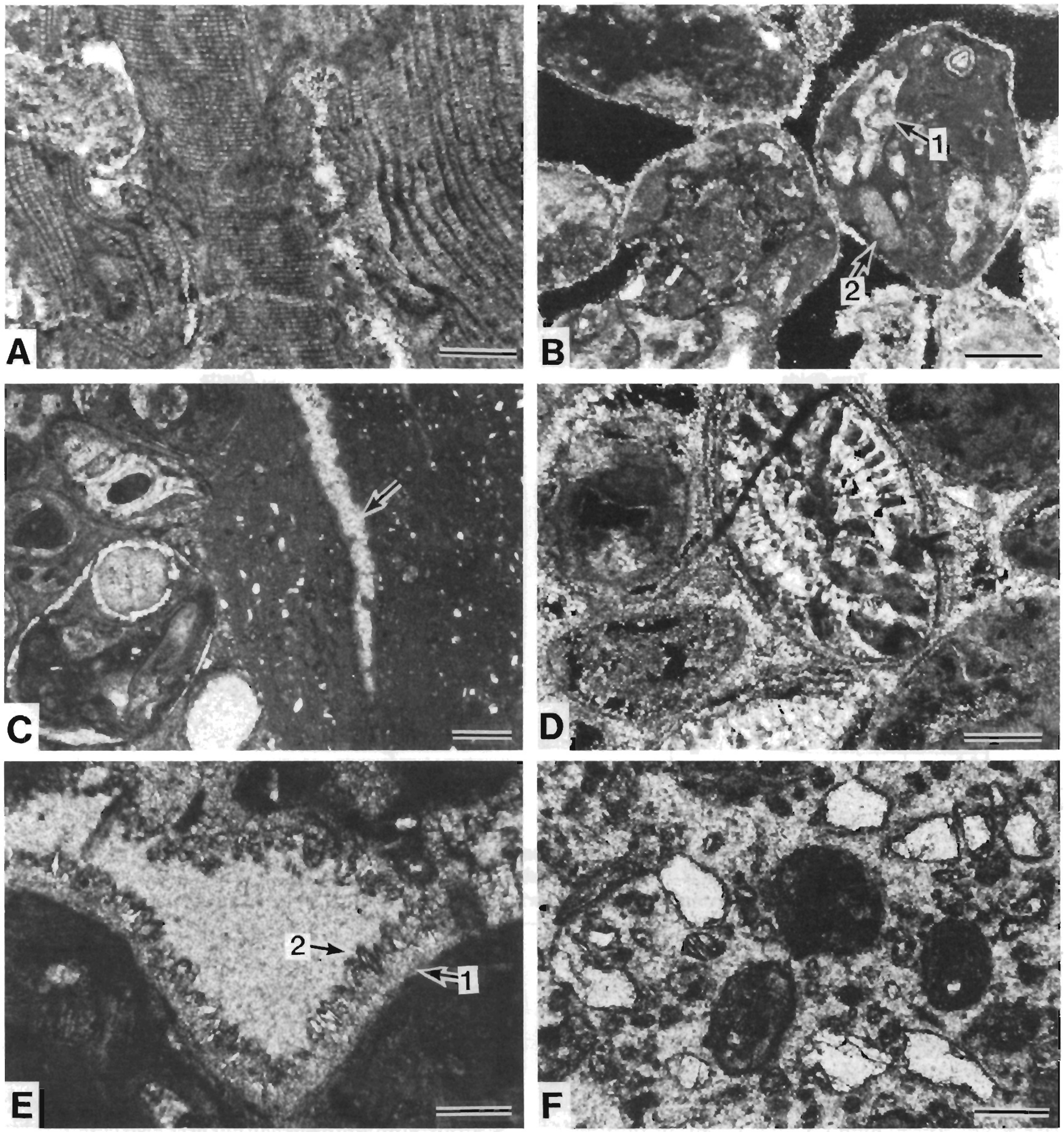

Figure 3. Photomicrographs of selected subsurface samples of Late Pleistocene age from sediment borings; (B) and (D) under cross-nicols, and (A, C, E, F) ordinary light. (A) Borehole S-85, sample CIII-31, showing algal bindstone (growth position is to the left of photograph), indicative of shallow subtidal to intertidal environment. (Bar = 200 μm). (B) Borehole S-84, sample CIII-27, showing subrounded rock fragments enclosing fossil debris (arrow 1 = fragment of foraminiferal test, arrow 2 = algal fragment) indicative of probable reworking of carbonates from Gebel Maryut Ridge III. (Bar = 200 μm). (C) Borehole S-85, sample CI-15, showing evidence of meteoric diagenesis in a consolidated bioclastic grainstone: concentration of vadose carbonate with terrigenous silt (in dark area on right part of photo), with a calcite vein (arrow). (Bar = 400 μm). (D) Borehole S-85, sample CI-18, showing bioclastic grainstone rich in amphistegin foraminifera, and almost devoid of quartz. (Bar = 200 μm). (E) Borehole S-85, sample CI-20, showing two generations of cement: early microcrystalline calcite rimming allochems (1), and initial phase of pore-filling cement (2). (Bar = 200 μm). (F) Borehole S-85, unconsolidated (washing) sand sample W3, rich in angular quartz grains. (Bar = 200 μm).

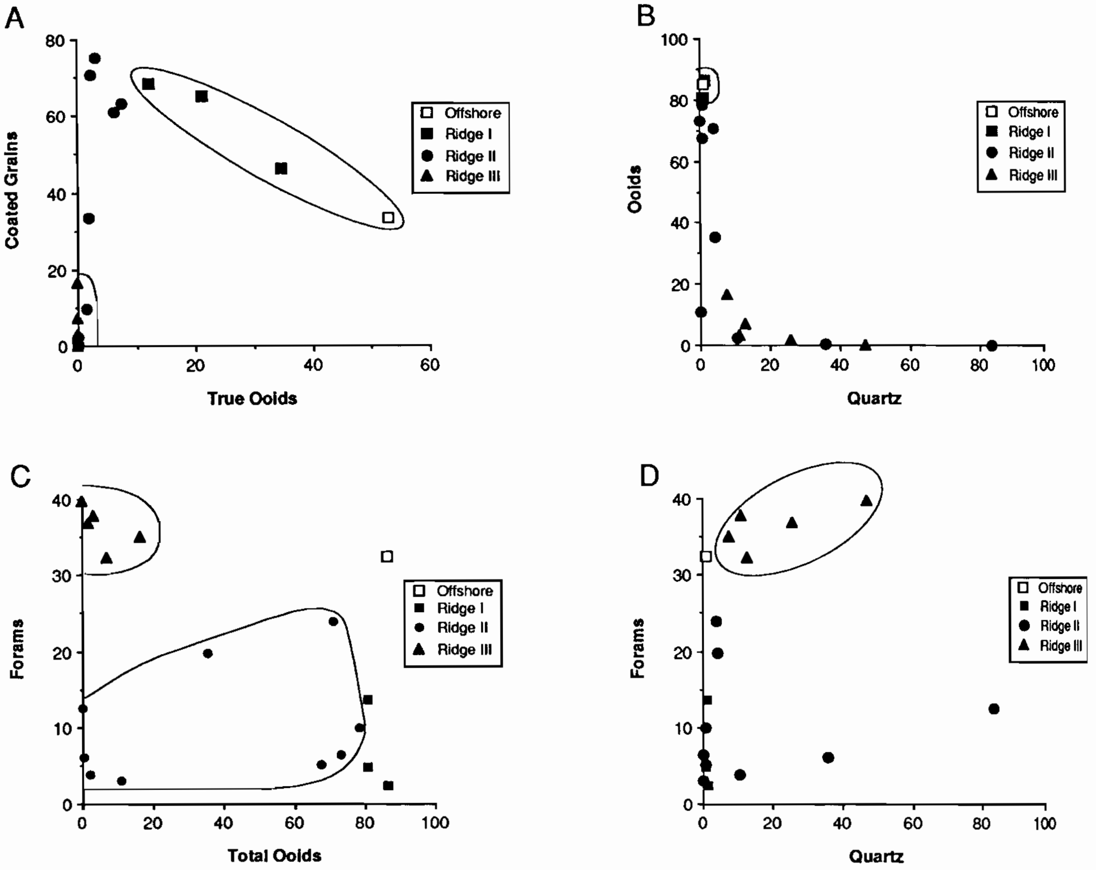

Figure 4. Binary plots depicting the proportions of four dominant sand-sized components (true ooids, coated grains, foraminifera, quartz) to differentiate offshore and ridge I, II and III samples (data from Table 1). Discussion in text.

II, while most other washings examined are of younger Late Pleistocene (< 40,000 years BP) to Holocene age. These samples generally contain very low proportions of true ooids and coated grains, moderate amounts of foraminifera, and (with the exception of washings in borings S-84 and S-85) a very high (> 70%) content of quartz (Figure 5). Moreover, moderate amounts of calcareous algae are present (Tables 2 and 3). Thus, most washings are mixtures of terrigenous and carbonate elements. It is of note that, on the basis of proportions of dominant components, subsurface sands are compositionally most similar to cemented deposits forming the easternmost sectors of ridges II and III (compare Figures 2F and 3F).

The most notable compositional change occurs between borings S-83 and S-84, that is, west of Lake Maryut proper and toward the central part of the Lake Maryut extension. In unconsolidated subsurface samples west of this region, proportions of quartz decrease and fossil allochems increase markedly (Table 2). The composition of washings in the upper parts of borings S-84 and S-85 are similar to each other and also comparable to sediments in easternmost ridges II and III (Table 1). In contrast, washings below the cemented carbonate unit in S-84 are more similar to these cemented Pleistocene carbonates in that core and to the western parts of ridges II and III (Table 3).

DISCUSSION AND CONCLUSIONS

Delineation of the northwestern extent of the terrigenous River Nile influence in the Alexandria region during the Late Pleistocene to Holocene is

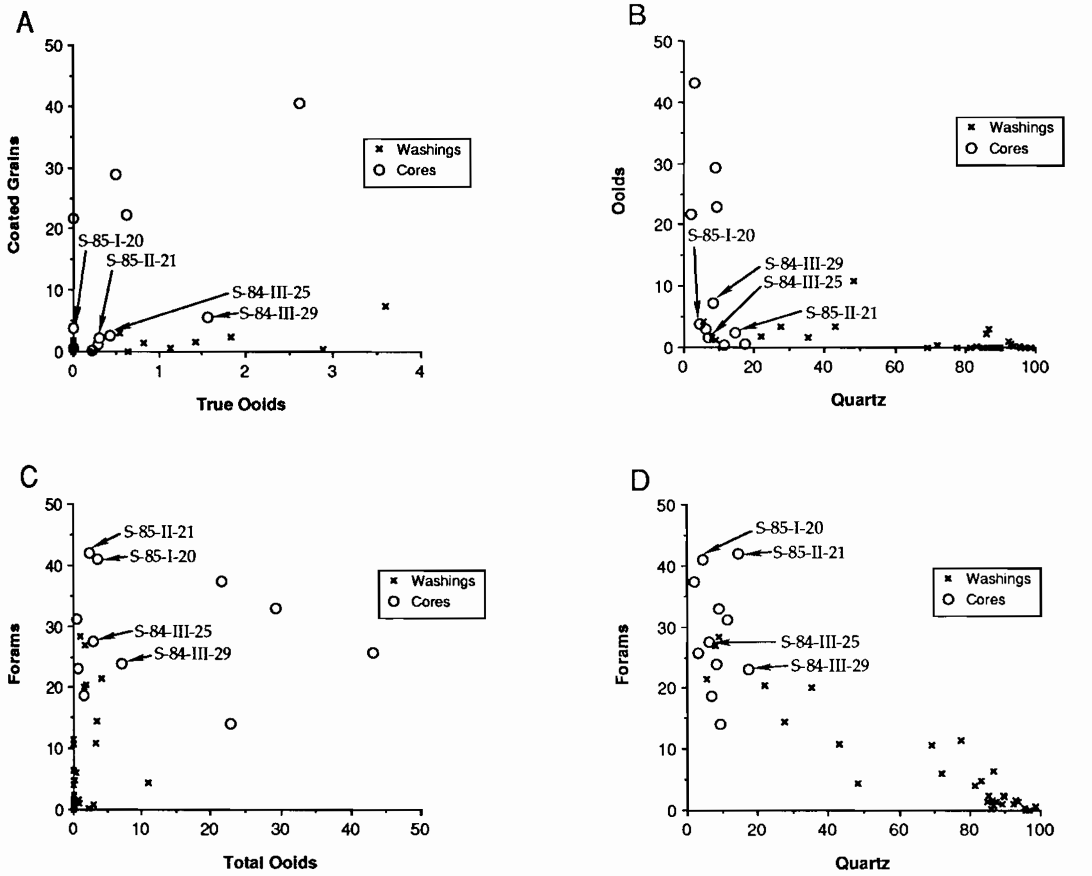

Figure 5. Binary plots depicting the proportions of four dominant sand-sized components (true ooids, coated grains, foraminifera, quartz) in subsurface samples from 12 boreholes. Data for consolidated (cores from boreholes S-84 and S-85) and unconsolidated sand samples (washings from boreholes S-77 to S-85) are listed Table 2. Discussion in text.

based on several considerations. Transport of significant amounts of quartz, heavy minerals and other insoluble residues (feldspars, lithic fragments, *etc.*) from the north and west of Alexandria is precluded: these offshore and littoral sectors are essentially carbonate-dominated. Provenance of sand-sized material from the south is also minimized: most quartz particles transported by wind from the desert west of the Nile delta northward across some of the ridges toward Alexandria is very fined-grained (*cf.* VENKATARATHNAM and RYAN, 1971). In fact, thin-section study indicates that quartz grains in both surficial offshore sediments and in surface ridges (Figure 2F) are commonly medium to coarse grade and angular, that is, of a size and shape not likely to have been transported by wind from the south.

It is probable, therefore, that most sand-sized terrigenous components that occur mixed with carbonate allochems have been derived from the region to the east of Alexandria. This siliciclastic fraction was transported northwestward by River Nile distributaries. The dispersal from sources to the east of Maryut Lake is indicated, albeit indirectly, by the distribution of the heavy mineral fraction in the Alexandria-Abu Qir headland region (SHUKRI, 1950; SHUKRI and PHILIP, 1956; STANLEY, 1989).

Studies of surficial offshore sediments confirm that carbonates prevail largely to the west of Alexandria (EL-WAKEEL and EL-SAYED, 1978; SUMMERHAYES *et al.*, 1978; ANWAR *et al.*, 1981). Dominant coastal currents and winds are presently oriented to the southeast (INMAN and

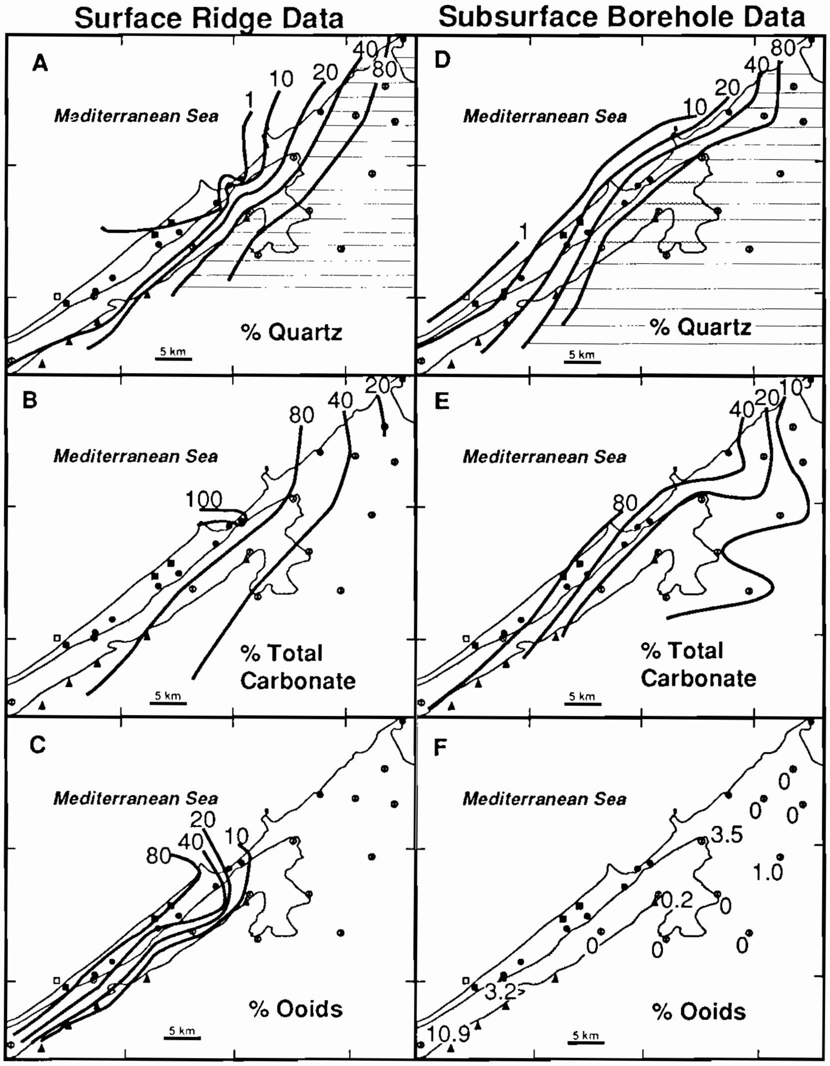

Figure 6. Contours on the northwestern margin of the Nile delta showing % quartz, total carbonate and total ooids (true ooids + coated grains) in surface (A–C) and subsurface (D–F) samples. Data are derived, respectively, from Tables 1 and 3. Hachured areas in maps A and D indicate the western extent of high proportions (at least 40% quartz) of terrigenous River Nile influx in the Late Pleistocene (A) and in the younger Late Pleistocene to Holocene (D).

JENKINS, 1984); this regime prevailed during most of the Holocene period during which the Nile delta, as we know it today, evolved. In consequence, carbonates have mixed with siliciclastic components in nearshore and coastal environments, as both particle types were transported eastward to and beyond the Abu Qir headland. Since such mixing of siliciclastic and carbonate components takes place primarily along the coast, any significant change in eustatic sea level would alter the position of the siliciclastic-carbonate transition. A shift in Nile distributary flow would also inevitably alter the geographic position of the terrigenous-carbonate interface.

Our study indicates that the distribution of the mixed siliciclastic-carbonate facies, as defined by high proportions of quartz (Figure 6A) and of total carbonate (Figure 6B), shifted eastward during the Late Pleistocene: the quartz-rich carbonates of Abu Sir Ridge II extend further to the northeast than those of the older Pleistocene Gebel Maryut Ridge III. More recent sediment with comparable quartz and total carbonate values are located even further to the east, that is, off Abu Qir Bay (EL-WAKEEL and EL-SAYED, 1978; SUMMERHAYES *et al.*, 1978).

It is estimated that much of the unconsolidated sand-sized sediment above lithified carbonates in boreholes S-84 and S-85 in the study area accumulated during the last complete eustatic cycle, that is, since ~ 35,000 years BP. Sediment west of the Abu Qir headland accumulated in various nearshore marine (during high stands) and subaerially exposed (alluvial and desert, during low stands) environments, depending upon sea level position and location of the coast during the various phases of this major eustatic cycle.

It is difficult to assess sediment dispersal patterns of the Nile system in the study area during the last eustatic low sea level stand (the maximum low stand occurred about 20,000–18,000 years BP). Recent surveys indicate that at some time during this low stand, the ancestral River Nile flowed primarily northward across the central Nile delta. Dominant flow at that time appears to have been positioned further to the east, *i.e.* north of the Burullus-Baltim region, well to the east of the presently active Rosetta distributary channel (ARBOUILLE and STANLEY, 1991; STANLEY *et al.*, 1992). During this period, it is probable that the terrigenous-carbonate limit had shifted toward the east. Moreover, isostatic subsidence of the northern delta plain and its structural tilt to the northeast (STANLEY, 1988, 1990) probably also played a role in the eastward displacement of the terrigenous-carbonate interface.

During the last rise in sea level and during the evolution of the modern Nile delta, since about 7500 years BP, a larger proportion of siliciclastic components were once again transported northwestwardly by Nile distributaries such as the Canopic and Alexandria branches (SAID, 1981). It is likely that during this phase quartz-bearing sediments were displaced westward as far as Sidi Medewird, about midway between Ameriya and Borg el Arab (Figure 6D). More recently, with the development of the Rosetta branch and increased transport of Nile sediments east of the Canopic 'branch (UNDP/UNESCO, 1978), the terrigenous-carbonate influence once again shifted eastward, that is, to the Alexandria-Abu Qir headland sector (Figure 6E). Ooids, which have a quite specific and geographically restricted origin west of Alexandria (Figure 6C), serve as useful tracers of the interface position: in latest Pleistocene to Holocene deposits, they can be traced only as far east as the eastern margin of Lake Maryut (Figure 6F).

The terrigenous-carbonate interface helps define the northwestern margin of the Nile delta, and can serve as a useful gauge to detect the changes presently taking place along the coast. Most notable among these changes are depositional patterns altered by the marked reduction in river flow and sediment deposited at the mouth of the Rosetta branch since closure of the High Dam at Aswan in 1964. An eastward shift of the terrigenous-carbonate interface is predicted if present conditions are maintained.

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□ RÉSUMÉ □

Cette étude pétrographique caractérise les mélanges de séquences terrigènes et carbonatées des marges NW du delta du Nil (région d'Alexandrie), depuis la fin du Pléostocène jusqu'à l'Holocène. Les composition et proportion des composantes des granulats permettent de distinguer les sédiments siliceux du Nil de l'Est des sédiments carbonatés de la province calcaire du Golfe d'Arabie à l'Est. On a considéré les attributs pétrologiques (1) du faciès de surface dans les milieux peu profonds et les sillons carbonatés, et (2) les sédiments de subsurface identifiés dans des sondages effectués au Sud et à l'Ouest de Abu Qir jusqu'à Borg el Arab, et datés au radiocarbone. Les sections de surface et de subsurface peuvent être correllées sur les base de l'analyse de leur composition. La distribution dans l'espace et le temps des faciès mixtes terrigènes et carbonatés sont limités à la région d'Alexandrie-Lac Mayrut. Des changements spatio-temporels de ce faciès le long de la côte sont induits par des facteurs naturels (niveau eustatique de la mer, subsidence, processus de transport littoral) et aussi humains. Ces derniers comprennent les projets d'irrigation des marges occidentales du delta et le développement de structures côtières tout spécialement entre Agami et la région d'Abu Qir. On propose que cet interface sédimentaire terrigène/carbonaté soit utilisé comme indicateur de la détection des modifications des dépôts littoraux le long du delta NW. Le déplacement de cet interface serait la conséquence de modifications de la configuration de la côte, des taux d'érosion et de la quantité et/ou de la nature des apports sédimentaires des branches du Nil en Méditerranée.—*Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

□ RESUMEN □

Este estudio petrológico, caracteriza la naturaleza de varias mezclas de secuencias sedimentarias terrígenas y carbonáticas de Pleistoceno Tardío hasta el Holoceno, a lo largo del margen noroeste del delta del Nilo en la región de Alejandría, Egipto. Atendiendo a la composición, proporciones y dimensiones de los componentes de la arena, éstas sirven para distinguir sedimentos silioccllásticos del Río Nilo hacia el este y sedimentos carbonáticos de la provincia de carbonatos del Golfo de Arabia hacia el oeste. En esta investigación se han considerado los atributos petrológicos de: 1) facies superficiales en ambientes marinos de baja profundidad y bancos de carbonatos notables, y 2) sedimentos subsuperficiales recuperados de muestras tomadas para dataciones con radiocarbono y colectadas al sud y al oeste de Abu Qir hasta Borg el Arab. Secciones superficiales y subsuperficiales han sido correlacionadas sobre la base de análisis composicional. En la región Alejandría-Lago Mayrut se han delineado las distribuciónes espacio-temporales de las facies mezcladas terrígeno-carbonática. Variaciones temporales y geográficas de estas facies a lo largo de la costa son inducidas por factores naturales (nivel del mar eustático, subsidencia, procesos de transporte) y antropogénicos. Estos últimos incluyen proyectos de riego a lo largo del margen oeste del delta, y desarrollos de estructuras costeras, particularmente en la region de Agami hasta Abu Qir. Se ha propuesto que las interfases de los sedimentos terrígenos-carbonáticos pueden usarse como un medidor para detectar cambios en los sistemas deposicionales costeros a lo largo del noroeste del delta. Desplazamientos de estas interfases pueden ser inducidos por cambios tales como la configuración de la costa, tasas de erosión y naturaleza, y cantidad de sedimentos que ingresan en las ramas del Río Nilo fluyendo hacia el Mediterráneo.—*Néstor W. Lanfredi, CIC-UNLP, La Plata, Argentina.*