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Benthic biofacies to interpret Holocene environmental changes and human impact in Alexandria's Eastern Harbour, Egypt

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Abstract: Holocene molluscan and foraminiferal faunas, sensitive ecological markers, are statistically treated to define their temporal and spatial distributions in radiocarbon-dated cores in Alexandria's Eastern Harbour. Up-core variations of these benthic biofacies record the evolution of depositional environments during the past 8000 years in this long-occupied Eastern Mediterranean port. The most important change occurred in the mid-Holocene between ~6300 and ~4300 yr ago, a time of lower sea level and minimal human activity. This faunal change, indicating a transition from a somewhat protected to a more open and higher-energy marine environment, resulted primarily from rise of sea level, lowering of the harbour floor and diminished shielding by Pleistocene coastal ridges and reefs near the bay mouth and within the harbour. Since that time, faunal assemblages have remained generally constant, except during the period from ~2100 to ~1800 yr ago when Greeks and Romans built the Heptastadion that connected Alexandria to Pharos Island; this construction effectively separated the Eastern from the Western Harbour. Absence of a well-marked faunal change during the past 18 centuries is unexpected, particularly in light of the much-increased population and associated human effects. The harbour's overall large size, rise in relative sea level and continued exchange of marine water between the open shelf and port have maintained an active circulation pattern. The strong current regime and reworking of bottom sediments have generally masked short-term human effects and altered the harbour's late-Holocene sediment stratigraphy. These factors help explain why benthic biofacies primarily record influences of natural processes that prevailed in this relatively unconfined, high-energy marine setting rather than those of a more constricted and anthropogenically impacted port.

Key words: Confinement factor, foraminifera, Holocene, human impact, molluscs, sediment cores, Alexandria, Egypt.

Introduction

Alexandria, Egypt's major coastal city, developed rapidly after Alexander the Great's passage in the fourth century BC. Its port became the most important one in the Eastern Mediterranean during the reign of the Greeks, Romans and Byzantines (Mahmoud-Bey, 1872; Fraser, 1972; Empereur, 1998; Goddio *et al*., 1998, 2006; Hirst and Silk, 2004). Alexandria experienced phases of decline and expansion following the Arab Conquest in the seventh century AD and at present, with more than 4 million inhabitants, it remains a major commercial harbour and the largest population centre in the southeast Mediterranean (Figure 1A, B).

The present investigation is one of several initiated to interpret environmental conditions that prevailed in the Eastern Harbour proper during the Holocene. A major objective of this survey is to refine the history of this embayment in which large human-emplaced structures such as temples and quays were built and now lie at depths of 2–7 m below present sea level (Figure 1C). Information on these ancient now-submerged sites, including three ancient ports, and details of the bay floor bathymetry were compiled by Goddio and others (1998). A set of seven vibracores were recovered in 2001 to provide a means to define the chrono- and lithostratigraphy (Jorstad and Stanley, 2006; Stanley and Bernasconi, 2006) and

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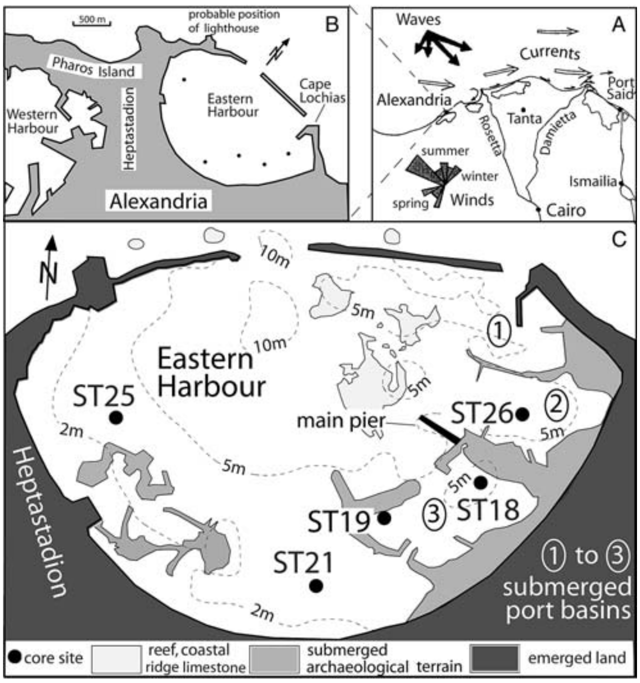

Figure 1 (A) Location map of the study area west of the Nile delta margin. (B) Alexandria's Eastern Harbour and associated features, including the Heptastadion. (C) Position of five core sites, submerged archaeological terrains (including ancient ports 1–3), shallow limestone (ramleh, kurkar) reefs and sea walls at the bay mouth (simplified topography after Goddio *et al.*, 1998)

petrology (Stanley and Landau, 2006) of Holocene sediment sections in this ancient harbour. These studies supplement findings made on Holocene and pre-modern sediments, microfossils and molluscs in two cores recovered in adjacent Alexandria south and southwest of the harbour (Goiran *et al.*, 2000). Synthesis of core stratigraphy shows that Holocene sections in the southern parts of the port are formed by five units (from base up, coded I–V; Figure 2); thicknesses of these units are variable in different parts of the harbour and along its adjacent land margin. Some units are locally absent because of topographic elevation differences and variations of depositional processes and oceanographic factors that have changed through time, such as mass circulation pattern and erosional intensity on the bay floor.

Herein, assemblages of molluscs and foraminifera are examined in the five stratigraphically most complete of the seven cores (Figure 1C) to obtain a more refined definition of harbour evolution and detect changes in depositional environments prior to, during and following submergence of ancient port structures. These two benthic groups have proven to be sensitive environmental markers in Mediterranean coastal settings (Pérès and Picard, 1964; Pérès, 1982; Albani and Serandrei Barbero, 1990; Murray, 1991; Sgarrella and Moncharmont Zei, 1993). Of particular interest are potential effects of natural depositional conditions, such as water circulation patterns and energy levels, and also those that record the impact of human activity. It is of archaeological importance to determine if the faunal record is sufficiently sensitive to measure the increased importance of anthropogenic influences associated with construction of early sites, including those that pre-date Ptolemaic time (eg, Jondet, 1916; Stanley and Landau, 2006). It would also be expected that biofacies changes would record effects of the much-increased volumes of urban, agricultural and industrial waste water discharged in recent time into the Eastern Harbour. Thus, we consider whether the benthic faunas in late-Holocene sections of the examined cores can detect human influence, especially during the past 2400 years.

Methodology

Molluscan and foraminiferal faunas were examined in 42 samples selected in the five Holocene cores recovered in the Eastern Harbour (Figure 1). From west to east, the selected cores are: ST25, positioned in the bay, just east of the Heptastadion; ST21, in the open southern sector of the harbour; and ST19, ST18 and ST26 in now-submerged ancient port basins of the SE bay. Core lengths range from 193 to 552 cm. Litho- and chronostratigraphic details of these Holocene core sections are reported in Stanley and Bernasconi (2006), Jorstad and Stanley (2006) and Stanley and Landau (2006). A type Holocene section, based on synthesis of earlier studies of the five cores, is presented in Figure 2; chrono-stratigraphy is determined from radiocarbon dates shown on logs in Figure 5 and listed in Jorstad and Stanley (2006). All ages in text and figures herein are given in uncalibrated radiocarbon years.

The faunas were recovered from 42 bulk samples (~ 100 cm^3) collected from the cores. Most sediment is sand-rich carbonate of biogenic origin. The number of samples ranges from 4 to 14 per core (recovered at intervals ranging from 20 to 100 cm), and depths below mean sea level (msl) are shown on the simplified logs of the five cores (see Figure 5). Grain-size of samples was determined using a Coulter Counter Laser Scattering LS2 unit at the Sedimentology Laboratory of the National Museum of Natural History (NMNH), Smithsonian Institution (Washington DC). Sediment grain size and compositional data are presented in Stanley and Landau (2006).

Molluscs and foraminifers were separated from the terrigenous fraction using a 0.5 mm sieve for molluscs and a 0.062 mm sieve for foraminifers. The faunas were identified, statistically

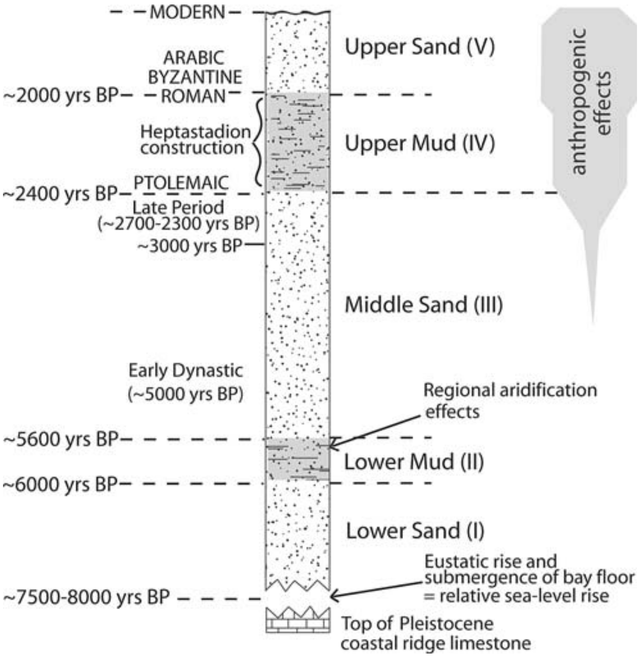

Figure 2 Stratigraphically complete Holocene type section, based on analysis and synthesis of Eastern Harbour cores, particularly borings ST18 and ST19; the section is subdivided into the five dated Holocene lithofacies (I–V) shown in Figure 5, as defined by Stanley and Bernasconi (2006) and Stanley and Landau (2006). Human activity in the vicinity of the port began at least 3000 years ago (discussion in text)

analysed and interpreted independently by M.P. Bernasconi (molluscs) and by R. Melis (foraminifers).

For the multivariate analysis, two separate data matrices were created using the abundance data pertaining to molluscs and foraminifers (two tables available from authors). Only molluscs identified at specific level and present in more than one sample were retained. Foraminifer species present in only one sample were omitted or gathered in major generic groups linked by similar ecological behaviour (such as *Bolivina* spp., *Massilina* spp., *Peneroplis* spp., *Textularia* spp.). Abundance data have been double-square root transformed (no standardization, no further species reduction) in order to limit the contribution of the most abundant ubiquitous species and simplify interpretation of the data structure (Field *et al.*, 1982). The cluster analyses (Figure 3) were based on Bray-Curtis similarity measure because, when coupled with double-square root transformation, the obtained similarity coefficient is invariant to a scale change (eg, the dimension of the sample; Field *et al.*, 1982). Similarity analyses have been performed in order to know the contribution of each species to the total similarity within a given group cluster (indicator species, eg, Field *et al.*, 1982). Moreover, in some instances, the breakdown of dissimilarity between different clusters has been considered in order to identify the discriminant species. The Shannon-Weaver index (H), a measure of diversity taking into account the number of specimens as well as the number of taxa, was calculated using logarithm to the base e, both for molluscs and foraminiferal assemblages (Figure 4). Statistical analysis was performed using the software PRIMER v5 (Plymouth Marine Laboratory; Clarke and Warwich, 2001).

Molluscan biofacies

Approach

Species were identified, and their abundances were determined following the method of Di Geronimo and Robba (1976) and also Stanley and Bernasconi (1998). A listing of the species determined is available from the authors. All mollusc species recorded have been previously identified in modern marine and lagoonal settings of the Mediterranean Sea. Literature concerning modern and Quaternary molluscs in the Eastern Mediterranean includes several contributions (Barash and Danin, 1982a,b, 1992). More specific consideration of these faunas on the Nile Delta shelf includes those by Pallary (1911), Steuer (1939), Bernasconi and Stanley (1997) and Stanley and Bernasconi (1998), and in Nile Delta lagoons by Bernasconi *et al.* (1991), Bernasconi and Stanley (1994), and Bernasconi *et al.* (2006).

The ecological meaning of the determined taxa has been derived mostly from contributions published by French bionomists (Pérès and Picard, 1964; Picard, 1965, 1971; Pérès, 1967, 1982; Massé, 1970–1972; Guelorget and Perthuisot, 1983). Terms and letter codes applied in the text for ecological meaning of species are those introduced by the above-cited authors, and presently used in studies on Mediterranean ecology and palaeoecology (Colella and Di Geronimo, 1987; Bernasconi and Robba, 1993; Basso and Corselli, 2002). Newly proposed terms and letter codes referring to the biofacies interpreted in the present study (MS, R, MC, MV, MI) are shown in Figure 5.

Indicator species

A total of 162 species were identified, and these include 48 bivalves, 103 gastropods and 1 scaphopod; 16 taxa are reported in open nomenclature (data available from authors). The state of preservation of the shelled material is generally good except for tests recovered from the three lowermost samples of core ST18.

The better represented species, in terms of number of taxa and specimens, are those requiring a vegetated bottom: *Bittium reticulatum*, *Cerithium vulgatum*, *Tricolia pullus pullus*, and the *Pusillina* spp. In addition, the Rissoids, as well as the above species, are epifaunal, herbivores and characterize the *Posidonia* Meadows (HP) and Photophilous Algae (AP) biocoenoses. Infauna is represented by taxa characteristic of biocoenoses

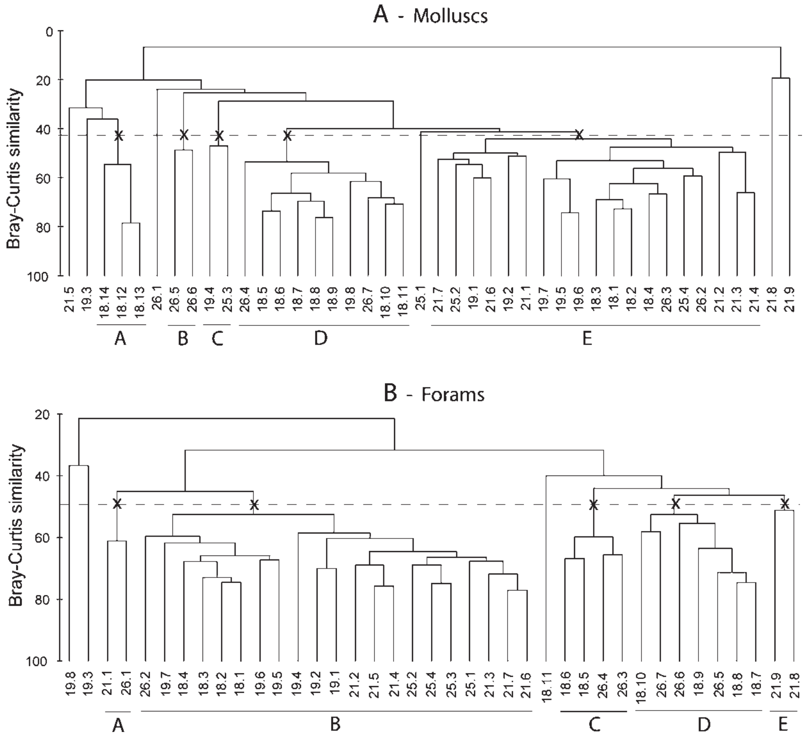

Figure 3 Dendrograms resulting by hierarchical agglomerative clustering of 42 samples, based on Bray-Curtis similarity, double square-root transformation. (A) Five clusters for molluscs; (B) five clusters for foraminifers

that merge with the HP and AP biocoenoses, such as the Fine Well Sorted Sands biocoenosis (SFBC) (*Chamelea gallina*, *Tellina nitida*, *Neverita josephinia*) and the Superficial Muddy Sands in Sheltered Areas biocoenosis (SVMC) (*Loripes lucinalis* and *Paphia aurea*).

Corbula gibba is also present. This is an opportunistic species that is widespread on shelves and recorded in different biocoenoses; it is usually considered as a characteristic species of Heterogeneous Communities (PE) and an indicator of environmental instability (Di Geronimo and Robba, 1989). Guelorget and Perthuisot (1983) indicate the presence of *C. gibba*, associated with *P. aurea*, *L. lucinalis* and *Gastrana fragilis,* in paralic (coastal, lagoonal) environments as well. Associated with *C. gibba* in some samples is *Parvicardium exiguum*, a characteristic species of Invertebrates in Very Polluted Waters biocoenosis (IETP) that also occurs where waters are renewed with difficulty.

Most of the 42 molluscan assemblages analysed are well diversified, with a Shannon-Weaver index (H) ranging between 1.82 (ST21-3) and 2.98 (ST21-7). Exceptions in the core samples include those at the base of ST18 and ST21, and sample ST25-3 (Figure 4A).

Cluster analysis and interpretation

The data matrix (available from authors), consisting of 42 variables (samples) and 108 observations (species), provided the basis for cluster analysis. At the 44% of B-C similarity, five clusters (A to E) are distinguished (Figure 3A). Six samples (ST21-5, ST19-3, ST26-1, ST25-1, ST21-8, ST21-9) are not grouped; this may be explained by their poor diversity and/or by the presence of only a few species, different from those included in the five clusters. Dominant traits of the five clusters are listed below, and an ecological interpretation is provided for each group.

Cluster A groups the three basal samples of core ST18 (12, 13, 14), each characterized by the lowest diversity values within the same core (Figure 4A). The average similarity of the cluster is 64.01% (Table 1). The indicator species (eg, those responsible for the observed similarity within cluster A), in order of contribution, are *Bittium reticulatum*, *Partulida spiralis* and *Obtusella macilenta*; they belong to the vagile epifauna, related to vegetated bottoms on which they feed. The diagnostic characteristic of this cluster is poor preservation of all shell material: the specimens are strongly abraded, with smoothed surfaces, and are interpreted here as indicators of a high-energy

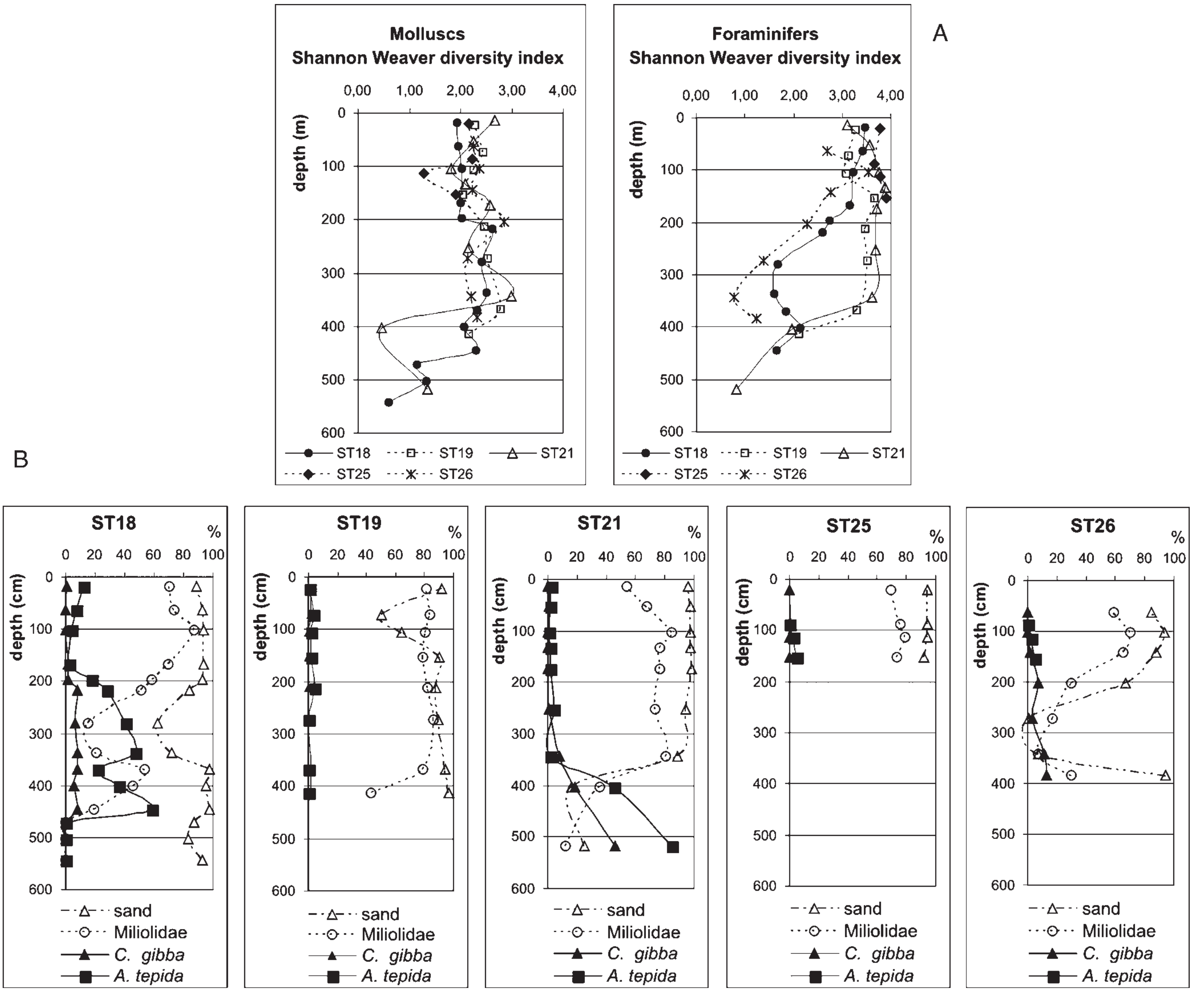

Figure 4 (A) Variations of Shannon-Weaver diversity index with depth in the five cores. (B) Variations of *Corbula gibba* (mollusc), *Ammonia tepida* and Miliolids (foraminifers) in the five cores as related to core depth and sand percentage (explanation in text)

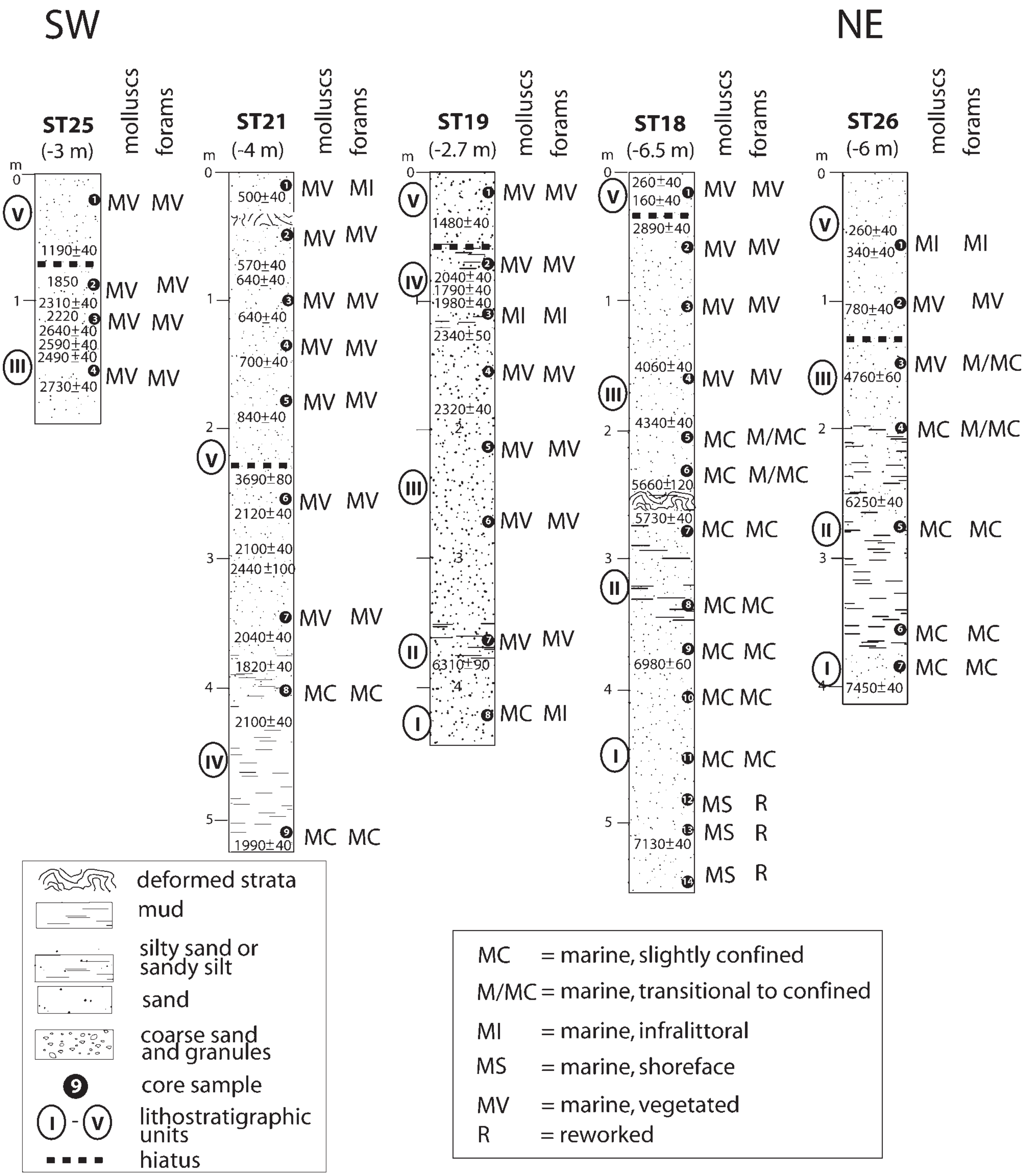

Figure 5 Simplified lithologic logs showing core sample positions, radiocarbon (uncalibrated) dates, positions of five lithostratigraphic units (I–V) and environmental interpretations based on molluscan and foraminiferal biofacies. Present water depth of core site in metres indicated under the core number. Hiatus (dashed line) in upper core sections associated with tsunami erosion, after Stanley and Jorstad (2005) and Stanley and Bernasconi (2006)

shoreface environment, where shells are continuously reworked by wave action.

Cluster B groups two samples (5, 6) of the mid-basal portion of core ST26; they show the lowest diversity values within the core (Figure 4A). The average similarity is 37.78% (Table 1). Seven species account for 90% of the similarity; they are, in order of contribution, *B. reticulatum*, *Pusillina lineolata, Retusa truncatula*, *Parvicardium exiguum*, *Hemilepton nitidum*, *Loripes lucinalis* and *Corbula gibba*. The listed taxa are comparable with those of cluster D; the difference between clusters B and D is the relatively smaller number of species and specimens in B. From an ecological point of view, cluster B represents an impoverished example of cluster D, which is described below.

Cluster C groups two samples, one in the mid-basal sector of core ST25 (3) and the other in the mid-portion of core ST19 (4). Both samples show the lowest diversity values within their respective cores (Figure 4A). The average similarity of cluster C is 60.87%, and 90% of this similarity is explained by three taxa that require a vegetated bottom: *B. reticulatum, Tricolia pullus* and *Conus mediterraneus* (Table 1). The ecological interpretation of this cluster corresponds to that of cluster E, of which it represents an impoverished (fewer representative species and specimens) example.

Cluster D groups ten samples, and seven of these are from the mid-basal portion of core ST18 (5-11), two from core ST26 (4,7) and one from the base of core ST19 (8). The diversity value is >2 in all samples (Figure 4A). The cluster average similarity is 49.68%, and more than 75% of the similarity is explained by six species, in order of contribution: *B. reticulatum, Retusa truncatula, P. exiguum, C. gibba, Pusillina marginata* and *Hemilepton nitidum* (Table 1). The dissimilarity between clusters D and E is the presence of two more taxa considered among the discriminant ones, ie, *Paphia aurea* and *L. lucinalis* that are better represented in cluster D. On the basis of the presence of *C. gibba, P. exiguum, P. aurea* and *L. lucinalis*, this cluster is interpreted as an example of a slightly confined environment (Zone III) as defined by Guelorget and Perthuisot (1983).

Cluster E groups 19 samples that are distributed in the mid- and upper part of core ST21 (1–4, 6–7), in the mid-lower and upper portions of core ST19 (1–2, 5–7), in the upper sector of cores ST18 (1–4) and ST26 (2–3), and in the middle and lower portions of core ST25 (2, 4). The average similarity of the cluster is 48.06% (Table 1). Four species explain more than 75% of the similarity, in order of contribution: *B. reticulatum, T. pullus, P. marginata* and *Pusillina radiata.* All these species are vagile epifauna, living on leaves of fanerogams and/or algae on which they feed. The environment indicated by these taxa point toward a marine infralittoral vegetated bottom.

The cluster analysis indicates that six samples (ST21-5, ST19-3, ST26-1, ST25-1, ST21-8, ST21-9) are not grouped. Nevertheless, it is possible to assign them to palaeoenvironmental settings ranging from open to slightly confined settings, on the basis of better represented species in these samples. The occurrence of *B. reticulatum* alone (ST21-5) or associated to other epiphyte taxa such as *Gibbula varia* and *P. marginata*, suggests a marine vegetated bottom for samples ST25-1 and ST21-5. A shallow infralittoral setting is suggested for samples ST19-3 and ST26-1 on the basis of the occurrence of *Nassarius mutabilis* and *Smaragdia viridis, Macoma cumana*, ie, characteristic species of the Fine Well Sorted Sands biocoenosis (SFBC) and of *P. aurea* and *L. lucinalis* that, in absence of *C. gibba,* are considered indicative of the Superficial Muddy Sands in Sheltered Areas biocoenosis (SVMC). Samples ST21-8 and ST21-9 are indicative of a slightly confined environment on the basis of occurrence of *Cerastoderma glaucum*, species characteristic exclusive of Euryhaline and Euritherm Lagoons biocoenosis (LEE) accompanied by *C. gibba*.

Table 1 Breakdown of average similarity within each cluster identified in dendrogram of Figure 3A. Molluscan species are listed in order of contribution, up to 90% of similarity in clusters A, B and C, and to 75% in clusters D and E

Species	Av. abund.	% S	% S cum
Cluster A (average similarity 64.01)			
Bittium reticulatum	14.7	78.40	78.40
Partulida spiralis	2.0	9 35	87.75
Obtusella macilenta	2.0	5.79	93.54
Cluster B (average similarity 37.78)			
Bittium reticulatum	7.0	41.18	41.18
Retusa truncatula	5.5	23.53	64.71
Pusillina lineolata	1.0	5.88	70.59
Parvicardium exiguum	2.5	5.88	76.47
Hemilepton nitidum	10.5	5.88	82.35
Loripes lucinalis	1.0	5.88	83.24
Corbula gibba	4.0	5.88	94.12
Cluster C (average similarity 60.87)			
Bittium reticulatum	37.0	83.33	83.33
Tricolia pullus	4.0	4.76	88.10
Conus mediterraneus	3.5	4 76	92.86
Cluster D (average similarity 49.68)			
Bittium reticulatum	208.6	42.08	42.08
Retusa truncatula	55.9	11.91	53.99
Parvicardium exiguum	26.8	7.36	61.35
Corbula gibba	33.5	7.35	68.70
Pusillina marginata	14.8	4.39	73.09
Hemilepton nitidum	17.4	3.93	77.02
Cluster E (average similarity 48.08)			
Bittium reliculatum	145.7	58.54	58.54
Tricolia pullus	34.3	12.57	71.11
Pusillina marginata	16.7	3.70	74.81
Pusillina radiata	5.7	2.11	76.92

Foraminiferal biofacies

Approach

Quantitative data were obtained from study of the 42 core samples, examining approximately 300 tests in each. In samples where foraminifers were numerous, they were subdivided using a dry splitter until an aliquot containing approximately 300 specimens was obtained. In the case of very low density of specimens (usually in sandy sediment), a flotation method using carbon tetrachloride (CCl_4) was used to concentrate the tests. After initial qualitative analysis, species counts were performed and recorded as number of specimens of each taxon; successively, these data have been reported as frequency percentages.

Identification of foraminifer species follows the Mediterranean systematic proposed by Le Calvez and Le Calvez (1958), Parker (1958), Jorissen (1987), Cimerman and Langer (1991), Levy *et al.* (1992), Hottinger *et al.* (1993) and Sgarrella and Moncharmont Zei (1993). The Ellis and Messina online catalogue of foraminifera (http://www.micropress.org/, last accessed September 2006) was used for consultation of original taxa description.

Literature discussing modern and Quaternary foraminifers from coastal settings in the Eastern Mediterranean includes several investigations on Nile delta sectors (El-Wakeel *et al.*, 1970; Kulyk, 1987; Abdou *et al.*, 1991; Samir, 2000; Goiran *et al.*, 2000; Samir and El Din, 2001; Bernasconi *et al.*, 2006). Studies on foraminifers of the Pleistocene coastal ridges of the Alexandria area are presented by Cherif *et al.* (1988) and Cherif and El-Halaby (1996); results from the Holocene in cores on land at Alexandria are discussed by Goiran *et al.* (2000). Distribution of modern foraminifers in the Western Alexandria Harbour and contiguous areas are reported by Samir *et al.* (2003).

Interpretation of the Holocene evolution of foraminiferal assemblages examined in the present study is established by comparison with the ecological significance of various associations from several Mediterranean coastal areas. Particularly useful are the following: Tyrrhenian Sea (D'Onofrio *et al.*, 1976; Vismara Schilling and Ferretti, 1987; Sgarrella and Moncharmont Zei, 1993; Bellotti *et al.*, 1994); Adriatic Sea (Albani and Serandrei Barbero, 1990; Albani *et al.*, 1991; Donnici and Serandrei Barbero, 2002); and the late Quaternary of the Po Plain near Ravenna (Fiorini and Vaiani, 2001; Amorosi *et al.*, 2004).

Indicator species

Foraminifers in the 42 core samples include 136 species, pertaining to 49 genera (data available from authors); among these, six taxa are reported in open nomenclature. In addition, some species of *Discorbis*, *Glabratella*, *Polymorphina* and *Trochammina* are collectively grouped as *specie plurimae* (spp.), since they were not readily distinguished. A group of very small tests of porcellaneous species are reported simply as Miliolidae.

It is noted that some samples at the base of cores ST18 and ST21 contain reworked older foraminifers mixed with autochthonous forms; the reworked foraminifers mainly pertain to *Cibicides*, *Elphidium*, *Rosalina* genera and to Quinqueloculinae family. Generally, their occurrence corresponds to an abundance of carbonate sand fragments on the bay floor, as reported by Stanley and Bernasconi (2006) and Stanley and Landau (2006), and probably also record some contribution of sediment derived from the Pleistocene limestone coastal ridges (ramleh or kurkar) that surround the Alexandria region. Furthermore, basal samples of core ST18 are formed by well-sorted yellow sands, in which foraminifer tests are rare and poorly preserved (abraded and rounded). These forms, including *Ammonia*, *Elphidium* and *Quinqueloculina* genera, are generally associated with proximal high-energy transport conditions in nearshore environments. These three sampled horizons were not considered for the statistical analysis.

With regards to autochthonous well-preserved species, most taxa are well known in modern Mediterranean coastal (brackish, infralittoral, circalittoral environments) settings. Some species, such as *Spiroloculina antillarum*, *Planogypsina acervalis* and *Planogypsina squamaformis* are described in the Gulf of Aqaba and the Red Sea (Hottinger *et al.*, 1993). The observed foraminiferal assemblage in the study area is generally rich and diverse, comprising mainly porcellaneous and hyaline taxa and, very subordinately, agglutinated ones. Species of *Ammonia*, *Bolivina*, *Elphidium* and *Rosalina* among the hyaline taxa, and *Adelosina*, *Cycloforina*, *Quinqueloculina*, *Sinuloculina* and *Triloculina* among the porcellaneous ones, are the most frequent foraminifers. Among them, *Ammonia tepida*, *Cycloforina schlumbergeri*, *Quinqueloculina laevigata* and *Triloculina schereiberiana* are distributed in almost all core sections.

Ammonia tepida ranges from a minimum of 1.3% (ST19-4) to a maximum of 84.5% (ST21-9) of the total assemblage. This species is more frequent at the base of cores ST18, ST21 and ST26, in somewhat finer-grained sediment, while it is scarce throughout cores ST19 and ST25, which are characterized by sandy sediment (Figure 4B). *Cycloforina schlumbergeri* ranges from 0.9% (ST18-11) to 23.0% (ST26-3) and generally increases in younger sections. *Quinqueloculinae laevigata* is homogenously distributed, with limited frequency (maximum of 5.1%, ST18-6). *Triloculina schreiberiana* occurrence ranges from a minimum of 1.0% (ST18-5) to a maximum of 41.3% (ST18-9); it is particularly abundant at the base of core ST18, and in some sample horizons of ST26. With regards to other species, only *Adelosina carinata-striata*, *Ammonia parkinsoniana*, *Peneroplis pertusus* and *Peneroplis planatus*, *Quinqueloculina disparilis* and *Sigmoilina costata* are commonly distributed with an abundance $>10\%$ of the total assemblage, while the remaining taxa are less abundant and irregularly distributed.

The Shannon-Weaver index (H) varies from a minimum of 0.76 (ST26-6) to a maximum of 3.90 (ST25-4) (Figure 4A). Lowest values (<2.0) are recorded at the base of cores ST18, ST19 and ST26, while values >2.0 characterize the remaining samples. All samples in cores ST19 and ST25 show high diversity values.

Cluster analysis and interpretation

The data matrix (table available from authors), consisting of 39 variables (samples) and 100 observations (species), provided the basis for cluster analysis. Three basal samples of core ST18 (12–14) were not included in the cluster analysis inasmuch as foraminifers were scarce and, based on their poor state of preservation, appear reworked. These probably record a shoreface environment.

Q-mode cluster analysis classified the studied samples into five groups (A–E), each one characterized by a different benthic foraminiferal composition (Figure 3B). These groups are regarded as biofacies and are used to interpret the different paleoecological settings of core sections.

Cluster A includes two samples (ST21-1 and ST26-1), comprising rich and diversified assemblages. The sediment is characterized by a high sand content ($>80\%$). The average similarity of the cluster is 60.94%, and 79.8% of this similarity is explained by the following taxa, in order of decreasing contribution: *Bolivina* spp., Miliolidae, *Cycloforina schlumbergeri*, *Quinqueloculina trigonula*, *Ammonia tepida*, *Elphidium gerthi*, *Elphidium jenseni*, *Quinqueloculina lata* and *Triloculina schreiberiana* (Table 2). This assemblage represents a typical marine infralittoral setting; the occurrence of numerous small tests of porcellaneous taxa together with Bolivinidae may perhaps represent sediment transported by current flow from a more protected area. It has been shown elsewhere that Bolivinidae are generally abundant in fine sediments, with lower oxygen content (Bernhard, 1986; Barmawidjaja *et al.*, 1992).

Cluster B includes 21 samples distributed throughout all the cores; it comprises sediment with a high sand content (usually $>90\%$, except for ST19-2), in which the foraminiferal assemblage is well diversified ($H>3.0$) (Figure 4A). The average similarity of the cluster is 46.13% (Table 2). This biofacies is characterized by the following species, in decreasing order of importance: *C. schlumbergeri*, *Peneroplis* spp., *Triloculina marioni*, *T. schreiberiana*, *Q. trigonula*, *Massilina* spp., *A. tepida*, *Adelosina longirostra*, *Quinqueloculina berthelotiana*, *Spiroloculina* spp., *E. gerthi, Bolivina* spp., *Sorites variabilis*, *Quinqueloculina disparilis*, *Rosalina* spp., *E. jenseni* and *Triloculina trigonula*. These species normally occur in shallow vegetated marine environments. The noteworthy occurrence of phytophylous species, such as *Peneroplis* spp. and *Sorites orbiculus*, characterize the major part of studied samples and indicate that the bay floor was probably well lighted and populated by algae and marine fanerogams, such as *Posidonia oceanica*. Higher values of the diversity index, with respect to other studied samples, indicate stability of palaeoenvironmental conditions.

Cluster C includes four samples (ST18-6, ST18-5, ST26-4, ST26-3) characterized by a variable amount of sand content (from 66.8 to 92.5%). The average similarity of the cluster is 58.43% (Table 2). The following species that form this cluster are, in decreasing order of importance: *A. tepida*, *C. schlumbergeri*, *Ammonia carinata-striata*, *Sigmoilina costata*, *A. longirostra*, *Adelosina* cf. *ferussacii*, *Elphidium granosum*, *T. schreiberiana* and *Quinqueloculina laevigata*. The decreased values of diversity ($2.29<H>2.76$), in comparison to cluster B, may indicate increased unstable (highly variable) conditions of the palaeoenvironment. On the basis of occurrence of *A. tepida* and *E. granosum*, it appears that this cluster indicates either a brackish environment, such as lagoon, or a slightly confined infralittoral environment.

Cluster D includes seven samples located at the base of cores ST18 and ST26. The average similarity of the cluster is 59.11% (Table 2). Sediment in these samples is characterized

Table 2 Breakdown of average similarity within each cluster identified dendrogram of Figure 3B. Foraminiferal species are listed in order of contribution, up to variable percentage of similarity in the five clusters

Species	Av. abund.	% S	% S cum
Cluster A (average similarity 60.94)			
Bolivina spp.	57.0	25.53	25.53
Milliolidae	45.0	22.34	47.87
Cycloforina schlumbergeri	23.5	9.04	56.91
Quinqueloculina trigonula	9.0	4.79	61.70
Ammonia tepida	15.0	4.79	66.49
Elphidium gerthi	15.0	4.26	70.74
Elphidium jenseni	7.5	3.72	74.47
Quinqueloculina lata	6.0	3.19	77.66
Cluster B (average similarity 46.13)			
Cycloforina schlumbergeri	24.7	8.90	8.90
Peneroplis spp.	29.1	8.08	16.98
Triloculina marioni	12.1	5.49	22.47
Triloculina schreiberiana	12.6	4.91	27.39
Quinqueloculina trigonula	13.9	4.79	32.18
Massilina spp.	9.9	3.20	35.38
Ammonia tepida	10.3	3.12	38.50
Adelosina longirostra	9.9	3.02	41.52
Quinqueloculina berthelotiana	7.1	2.83	44.35
Spiroloculina spp.	7.1	2.63	46.97
Elphidium gerthi	7.4	2.39	49.36
Bolivina spp.	8.1	2.34	51.70
Sorites variabilis	7.6	2.23	53.93
Quinqueloculina disparilis	9.9	2.21	56.14
Rosalina spp.	6.1	2.10	58.25
Elphidium jenseni	7.2	2.10	60.34
Triloculina trigonula	6.0	2.06	62.40
Cluster C (average similarity 58.43)			
Ammonia tepida	75.5	33.03	33.03
Cycloforina schlumbergeri	51.8	22.35	55.38
Adelosina carinato-striata	15.3	6.45	61.83
Sigmollinita costata	15.0	5.26	67.09
Adelosina longirostra	11.0	4.78	71.87
Adelosina cf. *ferussacli*	12.5	4.76	76.63
Elphidium granosum	20.5	3.07	79.70
Triloculina schreiberiana	9.8	2.32	82.03
Quinqueloculina laevigata	7.8	2.15	84.17
Cluster D (average similarity 59.11)			
Ammonia tepida	158.1	62.81	62.81
Triloculina schreiberiana	50.9	15.05	77.86
Aubignyna perlucida	51.1	10.49	88.38
Cycloforina schlumbergeri	14.6	5.36	93.71
Cluster E (average similarity 36.15)			
Ammonia tepida	259.0	65.08	65.08
Cycloforina schlumbergeri	23.5	15.87	80.95
Triloculina schreiberiana	8.0	5.56	86.51
Bolivina spp.	9.0	5.56	92.08

by high variability of sand content (from 0.7 to 97.4%) and by diversity values of foraminifer assemblages, normally <2.0, except for ST18.10 ($H=2.12$). This cluster is defined by a larger proportion of *A. tepida*, together with *T. schreiberiana*, *Aubignyna perlucida* and *C. schlumbergeri*, and this presence explains the 93.7% of similarity. The high increase of *A. tepida* in this cluster is associated with a decreased percentage of miliolids (Figure 4B). This assemblage, characterized by a decreased diversity (H), indicates stressed environmental conditions and represents a relatively poorly confined environment.

Cluster E includes two samples at the base of core ST21 (8, 9), where a relatively low sand content ($<20\%$) and low diversity value (<2.0) are recorded. The average similarity of this cluster is 36.15% (Table 2). This assemblage, like clusters C and D, indicates a relatively poorly confined environment, especially on the basis of *A. tepida* occurrence.

The cluster analysis indicates that three samples (ST19-3, ST19-8 and ST18-11) were not grouped. On the basis of high proportions of *A. tepida*, sample ST18-11 may represent a relatively poorly confined environment, while the other two samples of core ST19 perhaps indicate infralittoral settings on the basis of larger proportions of *Ammonia beccarii*, which commonly are associated with high energy nearshore conditions.

Discussion

Absence of distinct brackish water facies

One of the objectives of this study is to determine if, when and to what extent Holocene deposits accumulated in brackish, normal marine and/or hypersaline water settings, and whether such variations were due to natural process, anthropogenic effects, or both. The Eastern and Western harbours of Alexandria initially formed a subaerially exposed elongate embayment positioned between two linear coast-parallel calcareous ridges (also termed ramleh or kurkar) of Pleistocene age (Butzer, 1960; Stanley and Hamza, 1992). Shallow water accumulated in this embayment at times of lower sea-level stands, during the late Pleistocene to the early to mid Holocene; the embayment was more directly enclosed by the coastal ridge relief features than at present. As sea level continued to rise, the relief of the coastal margin became less accentuated. The bay floor also continued to be lowered by compaction of underlying sediment and isostatic depression (Warne and Stanley, 1993; Stanley and Warne, 1998). The linear embayment began to fill with sea water that entered across breaches in the emergent outer coastal ridge limestone positioned about 1.3 km north of the ridge on which Alexandria would eventually be built.

The configuration of the Alexandria embayment was coast-parallel and more lagoon-like during its early submergence history, with considerably more restricted communication with the Egyptian shelf than at present. However, our faunal data do not record evidence of low salinity conditions, even during the early Holocene depositional phase at ~8000 yr BP. Sea level at that time was still well below its present stand (roughly 25 m), and marine water from the shelf was only beginning to enter the depression; the shoreline progressively retreated landward, toward the south, as sea level continued to rise (Stanley and Warne, 1998, after Fairbanks, 1989; Stanley and Bernasconi, 2006). Even during this initial early Holocene water entry phase, the shallow depression does not appear to have received sufficient amounts of rain and/or low-salinity groundwater infill to sustain a distinct brackish water fauna. At ~7500 yr BP, the molluscan and foraminiferal faunas already record fully marine conditions, such as shoreface and infralittoral settings at core sites ST18 and ST26, respectively. Thus, all faunal assemblages in sediment sections that accumulated shortly after early submergence of the embayment and before its full drowning by the rising waters from the Egyptian shelf were already marine.

Some mollusc and foraminifer species we identified in the defined Eastern Harbour core biofacies (Figure 4B) commonly occur in modern brackish Nile Delta lagoons such as Mariut, Idku, Burullus and Manzala (Bernasconi and Stanley, 1994); some of the same species also have been recovered in older Holocene lagoon deposits of the delta's subsurface (Bernasconi *et al.*, 2006). These include the mollusc *Cerastoderma glaucum* and foraminifera taxa such as *A. tepida*, *A. perlucida* and

E. granosum. However, the presence of diversified marine assemblages associated with very few specimens of *C. glaucum* and absence of other specific lagoonal molluscan species (Bernasconi and Stanley, 1994) indicate a marine setting. Foraminifer assemblages with *A. tepida*, even if less abundant in respect to the studied cores, are reported in modern sediments of Alexandria's Western Harbour where lower water energy characterizes this somewhat more sheltered, semi-closed marine environment (Samir *et al*., 2003).

Both molluscan and foraminiferal species in the 42 core samples define assemblages associated with several distinct marine environments (Tables 1 and 2). Our faunal biofacies and environmental determinations differ from those of workers who have indicated episodic development of a lagoonal brackish fauna. Some ostracod and foraminiferal assemblages have been interpreted as brackish faunas in cores at Alexandria in more landward and confined environments protected by Pharos Island (Goiran *et al*., 2000).The apparent absence of distinct brackish water conditions at the Eastern Harbour also differs from findings in several other ancient Mediterranean ports where brackish water conditions are believed to have prevailed, at least periodically (cf. at Caesarea Maritima in Israel, Reinhardt *et al*., 1994; Reinhardt and Raban, 1999; at Kition in Cyprus, Morhange *et al*., 2000; and at other harbour sites, Morhange, 2000).

Benthic faunas in the bay remained fully saline, even after large canals were built to transfer fresh water from Nile branches in the delta to Alexandria during the past 2400 years (Toussoun, 1922), and began to discharge an important volume of low salinity water into the harbour. More surprising is the absence of any marked change in the faunal assemblages indicative of salinity decreases in recent time, a period during which there has been a remarkable increase of waste-water discharge directly into the port from municipal sources in Alexandria. This large city presently includes 4 million inhabitants in summer, and a growing number of industries located on the adjacent coast. Noteworthy in this respect are findings from systematic water sampling at ten oceanographic stations occupied monthly during a 10-yr period (1985–2004) near waste-water outlets in this polluted harbour (Professor M.A. Said, personal communication, 2004). It is of note that surface water salinity values have ranged from 31.6‰ to 39.4‰, and bottom salinities from 35.5‰ to 39.6‰. These values do not indicate substantially lowered salinities as might be expected from the much-increased human activity and large quantities of waste water discharged into the port in recent years.

Biofacies and environmental changes through time

The Lower, Middle and Upper Sand (I, III, V) units can not readily be distinguished from each other by means of detailed mineralogical compositional and textural analyses made on the same sediment samples in the five cores that were selected for faunal studies (Stanley and Landau, 2006). Although of distinctly different age, the sand fraction of these three bioclastic facies are petrologically so similar that it has not been possible to clearly differentiate their different processes and depositional environments. However, definition of their benthic biological components, evaluated in a stratigraphically defined framework, now provides a means to distinguish environmental conditions for the three Holocene sand (I, III, V) and also for the two mud-rich (II, IV) units.

Molluscan and foraminiferal assemblages examined in the same sediment sample for the most part record a similar marine environmental setting (Figure 5). Synthesis of the biofacies show that the two dominant assemblages in the 42 core samples, present in both Holocene sand (units I, III, V) and mud (II, IV) lithologies, are those typically indicative of a marine vegetated seafloor (MV, indicated by 23 samples of molluscs and 21 of foraminifers), and of a somewhat more protected marine environment (MC, by 14 samples of molluscs and 10 of foraminifera). These findings show that both faunas were comparably sensitive to environmental conditions in which they lived. A general persistence of biofacies upwards in the five cores is recorded by the Shannon-Weaver diversity index (H). The values range from 2 to 3 for most molluscan faunas in the samples, and from 3 to 4 for foraminifers in mid- and upper core sections (Figure 4A).

There is no strong relation between specific biofacies and sample sediment type (sand, silty sand, sandy silt, mud), nor is there a good correlation between biofacies and the five radiocarbon-dated lithostratigraphic (I–V) units forming the cores (Figure 5). These five units comprise more than one biofacies. The older unit I (Lower Sand) in different cores includes marine, slightly confined (MC), marine shoreface (MS) and reworked (R) assemblages. Unit II (Lower Mud) comprises MC and MV assemblages. Unit III (Middle Sand) includes primarily the MV and some open marine transitional to somewhat more protected environment (M/MC) assemblages. Unit IV (Upper Mud) is characterized by MC, MV, and a minor amount of marine infralittoral, non-vegetated (MI) assemblages. The youngest unit V (Upper Sand) comprises primarily MV and some MI biofacies.

Although correlation between faunas and the five lithofacies is weak to non-existent, there are nevertheless some notable similarities of up-core faunal assemblage trends through time. An example of this is apparent in core ST18 (Figure 5). Here, an important concentration of marine shoreface (MS) molluscs and reworked (R) foraminifers in the lower part of unit I are dated at somewhat older than ~7000 yr BP. The generally poorly preserved aspect of faunas in this unit indicates that tests were subject to considerable wear most likely in a shallow current- or swash-influenced marine environment such as beach shoreface. This high-energy erosive environment was not suitable for settlement by living faunas. This is substantiated by very low values of Shannon-Weaver diversity index plotted on a graph for molluscs in the lower three samples of the core (Figure 4A). Progressively upward in the core, from the mid-portion of unit I to the mid-portion of unit III (~7000 to ~4300 yr BP), the prevailing assemblages indicate a somewhat protected marine (MC) setting and one transitional to a more open (M/MC) environment. In upper core sections, from about 4300 yr BP to the present, both molluscs and foraminifers primarily show a more open marine vegetated (MV) sea floor. In sum, this vertical sequence of faunas in core ST18 records marine environments at this site that have evolved from (a) very high-energy nearshore coastal setting (in the early Holocene) to (b) one indicating a more protected lower energy conditions (mid Holocene), and then (c) to more open and less protected ones (late Holocene to present).

The vertical biofacies sequence in the core at site ST26 (base with an age older than 7450 yr BP) shows a biostratigraphic time-sequence evolution that is remarkably similar to that of site ST18 (base to ~7130 yr BP). These two core sites are both positioned at a present water depth of ~6 m, one in now-submerged ancient port basin 3, and the other in port basin 2 (Figure 1). In contrast, the timing of biofacies change in core ST19 (base to >6400 yr BP), positioned in ancient port basin 3, differs markedly from that of ST18 and ST26. Here, the transition from a somewhat more protected marine to a more open vegetated (MV) environment occurred much earlier, at ~6300 yr BP rather than at 4300 yr BP. Although ST19 is now located in a relatively protected setting at about the same distance from shore as the other two cores, it was recovered at a substantially shallower water depth (presently 2.7 m) in a site that was once more exposed.

Where it is well developed in cores ST18 and ST26, the Lower Mud unit (II), dated from ~6000 to ~5600 yr BP, is characterized by an MC biofacies (Figure 5). This assemblage, associated with muddy sands (Figure 2), may have resulted from the regionally important mid-Holocene climate changes that affected the Nile basin after ~7000 yr BP (Adamson *et al*., 1980; Williams and Faure, 1980). The altered conditions, including aridification, are believed to have impacted current and wave flow patterns along Egypt's coastal margin (Stanley and Galili, 1996). These may have induced proportionally increased displacement landward of finer-grained sediment from the Egyptian shelf into the more protected Alexandria embayment (Stanley and Landau, 2006).

The finer-grained Upper Mud unit (IV) of late Holocene age, dating from approximately 2100 to 1800 yr BP, is particularly well developed in the expanded late-Holocene section of core ST21. The presence therein of an MC environment recorded by the faunas, instead of MV as in ST19, indicates that this depositional phase was induced by substantially altered oceanographic conditions at this site. The Upper Mud unit is interpreted as the result of modified wave current circulation patterns and much increased accumulations of fine-grained sediment and turbidity within the harbour. These changes most likely are associated with construction during Ptolemaic and Roman time of the Heptastadion on a shallow strip of land, built to connect the city of Alexandria with the island of Pharos lying offshore (Figure 1). This finding is consistent with archaeological (Hesse, 1998) and petrological (Goiran *et al*., 2000, 2005; Stanley and Bernasconi, 2006) investigations. These indicate that emplacement of the large and progressively broadened aquaduct and byway structure effectively subdivided the original elongate Alexandria embayment into two completely separate ports. It is not surprising that this large artificial feature would have radically altered current and depositional patterns in the newly separated and now much smaller Eastern Harbour.

Confinement and defining subenvironments

Among the dominant attributes of the Eastern Harbour are its semi-enclosed configuration, shallow depths and relatively broad openings to the sea that allow ample exchange of embayed marine waters with those of the Egyptian shelf. Additional information on the depositional evolution, in time and space, of recorded Holocene marine biofacies distributions can be derived by evaluating benthic assemblages in light of the confinement factor defined by Guelorget and Perthuisot (1983). This approach has been applied elsewhere in the Mediterranean for interpreting ecological conditions in coastal margin re-entry environments, such as lagoons (usually shallow enclosed settings with narrow entrances to the sea) and bays (characterized by wide, curving, open indentations of the sea into land, and commonly positioned between capes or headlands). Subtle environmental differences within such settings can be distinguished by means of the specific faunal and floral assemblages therein; these provide a record of 'the time of renewal with marine originated elements in each given point' (Guelorget and Perthuisot, 1983: 8). Thus, unlike faunas and floras in a fully open littoral setting bordering the inner shelf, those at each geographic site in a partially enclosed coastal re-entry (lagoon, bay or gulf) such as the Eastern Harbour record their sensitivity to and requirements for specific water mass attributes that include factors such as nutrients, energy levels, turbidity, oxygen and salinity.

As originally conceived, a coastal re-entry setting can be subdivided biologically into a series of sectors (zones coded I to VI) that define increasing gradients of confinement (Figure 6A). For example, Zone I refers to the most marine-influenced subenvironment, usually at or close to an entry of the sea; this it is usually characterized by a shallow open marine faunal assemblage commonly associated with sandy sediment (MI biofacies in the present study). In contrast, Zone VI (the most confined gradient, usually positioned at the greatest distance from point of seawater entry) usually refers to a setting that may be either hypersaline or hyposaline, and where faunas tend to be diminished; bottom sediment lithologies are variable here, and commonly are characterized by extensive algal mats formed by cyanobacteria.

The more confined molluscan and foraminiferal biofacies (MC) were concentrated in the lower half of the core sections, prior to ~4300 in ST18 and 26 (both sites occupied in the SE sector of the Eastern Harbour). These assemblages settled in what must have been a considerably shallower water environment than that of today because of lower stands of sea level; nevertheless, they appear to record a more protected, lower energy environment. At that time, bay floor sectors at the two core sites were likely more protected by natural topographic high features formed by limestone coastal ridge exposures, which were then emerged (Figure 6B); these features, now referred to as shallow 'reefs', still preserve erosional wave-cut surfaces produced during the earlier lower sea-level stands (cf. Goddio *et al*., 1998). The calcareous highs, and especially the largest reef in the east-central bay, shielded the depressed bay floor landward behind them from intense wave erosion, and thus enabled finer-grained sediment to accumulate, especially at site ST26. The geographic settings of the cored sites at that time of deposition correspond most closely to Zone III (Figure 6A) of Guelorget and Perthuisot (1983).

Although site ST19 lies in the same sector as sites ST26 and ST18, it occupied a shallower position on the bay floor. Exposure to higher-energy conditions resulted in much earlier cessation (~6300 yr BP) of protected bay floor conditions and development of a more open marine vegetated bottom (MV) (Figure 6C). At the two other core sites (ST18, 26), this transition to the MV less confined biofacies occurred more recently, at ~4300 yr BP (Figure 6D), and continued until the near-present (Figure 6E). These high-energy harbour settings correspond to zones II and I (Figure 6A) of Guelorget and Perthuisot (1983).

Human impact on biofacies evolution

There is evidence that human activity on adjacent land and, possibly, in the port proper began prior to Ptolemaic time and development of Alexandria (Jondet, 1916; Goiran *et al*., 2000; Stanley and Landau, 2006). For example, radiocarbon-dated core ST19 includes potsherds, allochthonous lithoclasts and other components (marked increase of organic matter, heavy minerals) that had begun to accumulate by 3000 yr BP, ie, well before occupation by the Ptolomies and deposition of the Upper Mud unit (IV) (Figure 2). Following 2300 yr BP, large structures were constructed in the port (temples, quays and others; Goddio *et al.*, 1998; Goddio and Bernand, 2004), particularly in its SE sector where some of our cores were recovered. Thus, it could expected that benthic biofacies during, and, especially after, the time of Alexander the Great might record effects of human activity in what became the major port in the Eastern Mediterranean. A striking record of such anthropogenic impact is the transition from MC to MV

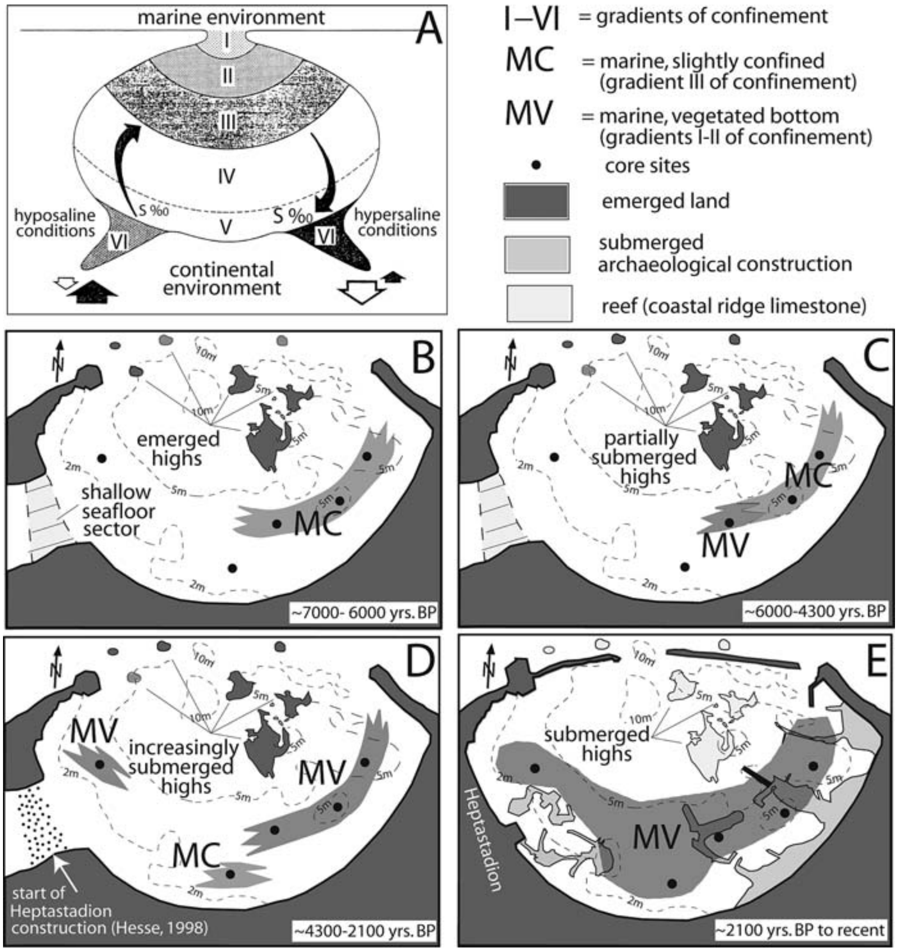

Figure 6 (A) Schema modified from Guelorget and Perthuisot (1983) depicting the six biofacies–environmental confinement zones (I–VI), from open marine (I) to most terrestrial influenced (VI). (B–E) Distribution in time and space of molluscan and foraminiferal biofacies in the Eastern Harbour. Faunal evolution is related to changes of bay morphology, physical oceanographic parameters, depositional patterns and human impact (discussion in text)

biofacies at about 2000 yr BP in core ST21 collected in the south-central sector of the bay (Figure 5). Faunal changes at this time in this locality may well be a response to markedly increased human impact. It is recalled that major construction efforts associated with building of the Heptastadion on top of what had been a former shallow sea-floor sector lying near sea level effectively separated the Alexandria embayment into the Eastern and Western harbours and precluded water exchange between them (Hesse, 1998; Goiran *et al.*, 2005) Major changes in water circulation patterns, in turn, altered the water column–bay floor conditions as recorded by the substantial faunal change.

Following the construction of the Heptastadion, however, it appears that biofacies trends have remained generally consistent until recently, without recording any obvious changes of assemblages resulting from the increased impact of human activity. Possible detection of faunal changes during the ~1800 yr period following construction of the Heptastadion is made by evaluating distributions of several key species and groups deemed sensitive to environmental change. For example, *C. gibba* and *A. tepida* in core ST19 record low proportions during most of the past ~6300 yr, in ST18 during the past ~4300 yr, in ST25 ~3000 yr, and in ST26 at least during the past millennium (Figure 4B). The expanded late-Holocene section in core ST21 does not show major temporal fluctuations, but fairly constant low proportions of these species during this time span. Distributions of the two species indicate a close inverse relationship with proportion of sand in the core samples, ie, higher the percent of sand, lower the proportions of these two species (Figrue 4B, core ST21). The Miliolids generally show a more pronounced and direct relation with sand content. The decreased percentages of Miliolids near core tops (ST18, ST21, ST25, ST26) may record a recent transport regime change that affected displacement of these tests.

Biofacies in the Eastern Harbour differ from those of some other ancient Mediterranean ports that indicate more ‘confined port assemblages’ (Morhange *et al.*, 2000). This may be due to the overall larger size of the partially closed bay (2.5 km^2) and its broader connection to the open Egyptian shelf that have allowed more sustained exchange with open marine water. Strong wind-driven action (wave heights to >1 m in winter) induces active water circulation throughout the port, causing the bay floor to be actively stirred and almost continuously reworked by the swash. Entry of open shelf waters into the port has remained important although a number of protection structures have been emplaced over time, including two long breakwaters at the bay mouth to the north (built about a century ago). This mass exchange factor has probably become progressively more significant through time with relative sea-level rise allowing waves to overtop limestone high-relief barriers. The effects of strong, almost persistent water motion, resulting from powerful winds, winter storm wave surges and occasional tsunamis (Guidoboni *et al.*, 1994), are recorded in core samples by the variable presence of allochthonous biogenic components. These include corals and red algal fragments that normally live in settings outside of the harbour, and are periodically introduced into the bay (Stanley and Bernasconi, 2006). The presence locally of these components and removal by erosion of unit IV in core ST25 and upper Holocene sections in other cores probably record, at least in part, effects of the historic tsunami in AD 365 (Guidoboni *et al.*, 1994; Stanley and Jorstad, 2005).

Recent diver observations (Empereur, 1998; Goddio *et al.*, 1998) indicate that the coarse sandy (bioclastic) floor is actively reworked by wave and swash action in many port sectors. Local absence of large or well-developed floral growth on the bay floor (indicated by the MI biofacies in cores ST21 and ST26) may result from strong bottom agitation, perhaps in conjunction with much increased pollution levels of harbour water. This is in marked contrast to findings of sea grass fragments, including *Posidonia* (Goiran *et al.*, 2000), which were more widespread in the past (MV).

Human activity in the city of Alexandria, as well as in the harbour proper, increased substantially during and following the reign of the Ptolemies and Romans (Figure 2). There can be little doubt that this very rapid construction development, building of the Heptastadion, maintenance of port basins in the bay and dredging activity, in addition to intensive alteration of the harbour's coastal margin, would have markedly modified current circulation and sedimentation patterns. Such anthropogenic influences would have locally modified the natural erosional–depositional sequence, inducing modification of the stratigraphic record (hiatuses, artificially increased thicknesses, repetition of strata) and causing some up-core reversals of radiocarbon dates (Figure 5). Intensification of human activity, however, does not appear to have substantially induced short-term changes in up-core faunal assemblages, at least none that are readily apparent on the basis of our core sampling and methodology. It is postulated that almost continuous reworking of the harbour floor by generally high-energy sea-floor current activity during most of this setting's Holocene evolution has masked some human effects. The present study indicates that benthic faunas, in addition to petrologic attributes as emphasized in a first analysis (Stanley and Bernasconi, 2006), record the major environmental changes that occurred through time as would be expected in a large marine embayment that remained open to water of the Egyptian shelf. More specific identification of human influences in the Eastern Harbour during the past several millennia will be better distinguished by geochemical analyses in a third phase of core study.

Conclusions

This investigation records distinct changes in lithofacies and assemblages of molluscs and foraminifera since the early Holocene in the Eastern Harbour. An important lithofacies transition from coarser- to finer-grained sedimentation recorded in the early Holocene at ~6000 yr BP likely resulted from altered water mass circulation patterns linked to effects of the regionally important climate change (altered Mediterranean circulation and Nile Basin aridification patterns) at that time. Most apparent with regards to fauna, however, is the natural transition from a somewhat protected marine to more open, higher energy marine environment between 6300 and 4300 yr ago, prior to important human activity affecting this geographic setting. This mid-Holocene evolution is best explained by changes resulting from rising sea level and entry of shelf water coupled with diminished shielding effects produced by coastal ridges at and near the bay mouth and within the harbour proper.

One of the more obvious changes in biofacies is attributed to effects induced by human activity in Greek to Roman time (~2100–1800 yr ago), most likely resulting from construction of the Heptastadion that separated the Eastern from the Western Harbour. These marine settings, serving as major ports for over two millennia, would have inevitably been affected by larger populations at Alexandria. The absence of marked benthic faunal changes resulting from anthropogenic activity, particularly during the past several centuries, is thus an unexpected finding in this study. The generally constant nature of marine faunal assemblages indicates that they have been most closely influenced by geographic attributes of the bay and associated prevailing physical and oceanographic parameters. Even core samples collected in two of the three smaller artificial ports constructed within the SE sector of the harbour do not reveal what could be termed a 'harbour assemblage' of the type identified in some other, usually smaller and better confined, ancient Mediterranean ports.

The large size of the Eastern Harbour and continued water exchange between the Egyptian shelf and bay have enabled this port to maintain marine benthic faunas associated with relatively unconfined high-energy marine coastal conditions. Moreover, progressive rise of sea level and decreased dampening effects of high coastal ridges features during the late Holocene have enabled water masses to be actively circulated throughout the harbour. These conditions have generally masked short-term anthropogenic effects, and sustained open marine biofacies until present, despite the increased number of artificial protective structures, including the large sea walls emplaced at the bay mouth. It is expected that ongoing geochemical analyses of core sediment, including shell material from benthic faunal assemblages, will provide a more direct means to detect some of the more specific effects of human impact in upper core sections of the Eastern Harbour.

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References

Abdou, H.F., **Samir, A.M.** and **Frihy, O.E.** 1991: Distribution of benthic foraminifera on the continental shelf off the Nile Delta. *Neues Jahrbuch für Geologie und Paläontologie*, *Monatshefte* 1, 1–11.

Adamson, D., **Gasse, F.**, **Street, F.** and **Williams, M.** 1980: Late Quaternary history of the Nile. *Nature* 288, 50–55.

Albani, A.D. and **Serandrei Barbero, R.** 1990: I foraminiferi della Laguna e del Golfo di Venezia. *Memorie di Scienze Geologiche* XLII, 271–341.

Albani, A.D., **Favero, V.** and **Serandrei Barbero, R.** 1991: The distribution and ecological significance of recent Foraminifera in the lagoon south of Venice (Italy). *Revista Española de Micropaleontologia* 23, 29–45.

Amorosi, A., Colalongo, M.L., Fiornini, F., Fusco, F., Pasini, G., Vaiani, S.C. and **Sarti, G.** 2004: Palaeogeographic and palaeoclimatic evolution of the Po Plain from 150-ky core records. *Global and Planetary Change* 40, 55–78.

Barash, Al. and **Danin, Z.** 1982a: Mediterranean Mollusca of Israel and Sinai: composition and distribution. *Israel Journal of Zoology* 31, 86–118.

—— 1982b: Contribution to the knowledge of Mollusca in the Bardawill lagoon. *Bollettino Malacologico* 18, 107–28.

—— 1992: *Annotated list of Mediterranean mollusks of Israel and Sinai*. Keterpress Enterprises.

Barmawidjaja, D.M., Jorissen, F.J., Puskaric, S. and **Van Der Zwaan, G.J.** 1992: Microhabitat selection by benthic Foraminifera in the Northern Adriatic Sea. *Journal of Foraminiferal Research* 22, 297–317.

Basso, D. and **Corselli, C.** 2002: Community versus biocoenosis in multivariate analysis of benthic molluscan thanatocoenoses. *Rivista Italiana di Paleontologia e Stratigrafia* 108, 153–72.

Bellotti, P., Carboni, M.G., Di Bella, L., Palagi, I. and **Valeri, P.** 1994: Benthic foraminiferal assemblages in the depositional sequence of the Tiber Delta. *Bollettino della Società Paleontologica Italiana, Special vol.* 2, 29–40.

Bernasconi, M.P. and **Robba, E.** 1993: Molluscan palaeoecology and sedimentological features: an integrated approach from the Miocene Meduna section, northern Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology* 100, 267–90.

Bernasconi, M.P. and **Stanley, D.J.** 1994: Molluscan biofacies and their environmental implications, Nile Delta lagoons, Egypt. *Journal of Coastal Research* 10, 440–65.

—— 1997: Molluscan biofacies, their distributions and current erosion on the Nile Delta shelf. *Journal of Coastal Research* 13, 1201–12.

Bernasconi, M.P., Stanley, D.J. and **Di Geronimo, I.** 1991: Molluscan faunas and paleobathymetry of Holocene sequences in the northeastern Nile Delta, Egypt. *Marine Geology* 99, 29–43.

Bernasconi, M.P., Melis, R., Pugliese, N. and **Stanley, D.J.** 2006: Faunal analyses to interpret submergence of substrates beneath Herakleion and Eastern Canopus, ancient cities in Egypt's Abu Qir Bay. In Stanley, J.D., editor, *Abu Qir I*. University of Oxford.

Bernhard, J.M. 1986: Characteristic assemblages and morphologies of benthic foraminifera from anoxic, organic-rich deposits: Jurassic through Holocene. *Journal of Foraminiferal Research* 16, 207–15.

Butzer, K.W. 1960: On the Pleistocene shorelines of Arab's Gulf, Egypt. *Journal of Geology* 68, 626–37.

Cherif, O.H. and **El-Halaby, O.M.** 1996: Comparative studies on the distribution of some Recent and Pleistocene foraminiferal assemblages of Egypt and Greece. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte* 10, 605–21.

Cherif, O.H., El-Sheikh, H. and **Labib, F.** 1988: The foraminifera of the Pleistocene coastal ridges of the area to the west of Alexandria, Egypt. *Revue de Paléobiologie*, *Special volume* 2 Benthos 86, 735–40.

Cimerman, F. and **Langer, M.R.** 1991: Mediterranean foraminifera. *Slovenska Akademija Znanosti in Umetnosti. Opera Academia Scientiarium et Artium Slovenica.*, Classis 4, Historia Naturalis 30, 1–118.

Clarke, K.R. and **Warwich, R.M.** 2001: *Change in marine communities: an approach to statistical analysis and interpretation* (2nd edition, in 2 volumes). PRIMER-E ltd.

Colella, A. and **Di Geronimo, I.** 1987: Surface sediments and macrofaunas of the Crati submarine fan (Ionian Sea, Italy). *Sedimentary Geology* 51, 257–77.

Di Geronimo, I. and **Robba, E.** 1976: Metodologie qualitative e quantitative per lo studio delle biocenosi e delle paleocomunità bentoniche marine. *C.N.R. Gruppo Paleobenthos, Rapporto di Lavoro* 1, 1–35.

—— 1989: The structure of benthic communities in relation to basin stability. In Boriani, A., Bonafede, M. and Vai, G.B., editors, *The lithosphere in Italy. Advances in earth science research.* Accademia Nazionale dei Lincei, Atti Convegno Lincei 80, 341–52.

Donnici, S. and **Serandrei Barbero, R.** 2002: The benthic foraminiferal communities of the northern Adriatic continental shelf. *Marine Micropaleontology* 44, 93–123.

D'Onofrio, S., Marabini, F. and **Vivalda, P.** 1976: Foraminiferi di alcune lagune del delta del Po. *Giornale di Geologia* 36, 283–334.

El-Wakeel, S.K., Abdou, H.F. and **Wahby, S.D.** 1970: Foraminifera from bottom sediments of lake Maryut and lake Manzalah, Egypt. *Bulletin Institute of Oceanography and Fisheries* 1, 429–48.

Empereur, J.-Y. 1998: *Alexandria rediscovered*. G. Braziller.

Fairbanks, R.G. 1989: A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* 342, 637–42.

Field, J.C., Clarke, K.R. and **Warwick, R.M.** 1982: A practical strategy for analysing multispecies distribution patterns. *Marine Ecology Progress Series* 8, 37–52.

Fiorini, F. and **Vaiani, S.C.** 2001: Benthic foraminifers and transgressive-regressive cycles in the Late Quaternary subsurface sediments of the Po Plain near Ravenna (Northern Italy). *Bollettino della Società Paleontologica Italiana* 40, 357–403.

Fraser, P.M. 1972: *Ptolemaic Alexandria*. Clarendon Press.

Goddio, F. 2006: *City and harbour, the archaeology of ancient Alexandria*. Oxford Centre for Marine Archaeology (in press).

Goddio, F. and **Bernand, A.** 2004: *Sunken Egypt – Alexandria*. Periplus Publishing Ltd.

Goddio, F., Bernand, A., Bernand, E., Darwish, I., Kiss, Z., and **Yoyotte, J.**, editors 1998: *Alexandria: the submerged royal quarters*. Periplus Publishing Ltd.

Goiran, J.-P., Morhange, C., Bourcier, M., Carbonel, P. and **Morigi, C.** 2000: Évolution des rivage d'Alexandrie à l'Holocène récent, marge occidentale du delta du Nil, Égypte. *Méditerranée* 1.2, 83–90.

Goiran, J.-P., Marriner, N., Morhange, C., Abd el-Maguib, M., Espic, K., Bourcier, M. and **Carbonel, P.** 2005: Évolution géomorphologique de la façade maritime d'Alexandrie (Égypte) au cours des six derniers millénaires. *Méditerranée* 104, 61–64.

Guelorget, O. and **Perthuisot, J.P.** 1983: Le domaine paralique. Expressions géologiques, biologiques et économiques du confinement. *Travaux du Laboratoire de Géologie, Ecole Normale Supérieure Paris* 16, 1–136.

Guidoboni, E., Comastri, A. and **Traina, A.G.** 1994: *Catalogue of ancient earthquakes in the Mediterranean area up to 10th century.* Istituto Nazionale di Geofisica.

Hesse, A. 1998: Arguments pour une nouvelle hypothèse de localisation de l'Heptastade d'Alexandrie. *Alexandrina* 1, 1–33.

Hirst, A. and **Silk, M.** 2004: *Alexandria, real and imagined.* Ashgate.

Hottinger, L., Halicz, E. and **Reiss, Z.** 1993: Recent foraminiferida from the gulf of Aqaba, Red Sea. *Slovenska Akademija Znanosti in Umetnosti. Opera Academia Scientiarium et Artium Slovenica*. Classis 4, Historia Naturalis 33, 1–179.

Jondet, M.G. 1916: *Les Ports Submergés de l'Ancienne île de Pharos.* Mémoires de l'Institut d'Egypte.

Jorissen, F.J. 1987: The distribution of benthic foraminifera in the Adriatic Sea. *Marine Micropalaeontology* 12, 21–48.

Jorstad, T.F. and **Stanley, J.-D.** 2006: Early human activity (pre-332 BC) in Alexandria's Eastern Harbour, Egypt. 2. The sediment cores. In Goddio, F. *et al.*, editors, *City and harbour, the archaeology of ancient Alexandria*. Oxford Centre for Marine Archaeology (in press).

Kulyk, V.A. 1987: Holocene foraminifera of the eastern Nile delta, Egypt. MSc Thesis, George Washington University, 1–104.

Le Calvez, J. and **Le Calvez, Y.** 1958: Répartition des Foraminifères dans la Baie de Villefranche. *Annales de l'Institut Océanographique* XXXV, 159–234.

Levy, A., Mathieu, R., Poignant, A. and **Rosset-Moulinier, M.** 1992: Foraminifers à arrangement quinqueloculin et triloculin (Miliolacea) de Méditerranée. *Revue de Paléobiologie* 11, 111–35.

Mahmoud-Bey, M. 1872: *Mémoires sur l'Antique Alexandrie, ses Faubourgs et Environs Découverts, par les Fouilles, Sondages, Nivellements et Autres Recherches.* Imprimerie de Bianco Luna.

Massé, H. 1970–1972: Contribution à l'étude de la macrofaune de peuplement des sables fins infralittoraux des côtes de Provence. *Téthys* 2, 783–820; II, *Téthys* 3, 113–58; III–IV, *Téthys* 3, 283–319; V, *Téthys* 3, 539–68; VI, *Téthys* 4, 63–84.

Morhange, C., editor 2000: Ports antiques et paléoenvironments. *Méditerranée* 94, 1–104.

Morhange, C., Goiran, J.-P., Bourcier, M., Carbonel, P., Le Campion, J., Rouchy, J.-M. and **Yon, M.** 2000: Recent Holocene paleo-environmental evolution and coastline changes of Kition, Larnaca, Cyprus, Mediterranean Sea. *Marine Geology* 170, 205–30.

Murray, J.W. 1991: Ecology and distribution of benthic foraminifera. In Lee, J. and Anderson, O.R., editors, *Biology of foraminifera*. Academic Press, 22–254.

Pallary, P. 1911: Catalogue des mollusques du littoral méditerranéen de l'Egypte. *Mémoires de l'Institut Egyptien* 7, 69–200.

Parker, F.L. 1958: Eastern Mediterranean foraminifera. *Swedish Deep-Sea Expedition* 8, 219–83.

Pérès, J.M. 1967: The Mediterranean benthos. *Oceanography and Marine Biology Annual Revue* 5, 449–534.

—— 1982: Major benthic assemblages. In Kinne, O., editor, *Marine ecology, V. 5, Part 1.* John Wiley & Sons Ltd, 373–522.

Pérès, J.M. and **Picard, J.** 1964: Nouveau manuel de bionomie benthique de la Mer Méditerranée. *Receuil des Traveaux de la Station Marine d'Endoume* 31, 1–137.

Picard, Ch. 1971: Les peuplements de vase au large du Golfe de Fos. *Téthys* 3, 569–618.

Picard, J. 1965: Recherches qualitatives sur les biocoenoses marines des substrats meubles dragables de la Région de Marseille. *Receuil des Traveaux de la Station Marine d'Endoume* 36, 1–160.

Reinhardt, E.G. and **Raban, A.** 1999: Destruction of Herod the Great's harbour at Caesarea Maritima, Israel – geoarchaeological evidence. *Geology* 27, 811–14.

Reinhardt, E.G., Patterson, R.T. and **Schröeder-Adams, C.J.** 1994: Geoarchaeology of the ancient harbour site of Caesarea Maritima, Israel: evidence from sedimentology and paleoecology of benthic foraminifera. *Journal of Foraminiferal Research* 24, 37–48.

Samir, A.M. 2000: The response of benthic foraminifera and ostracods to various pollution sources: a study from two lagoons in Egypt. *Journal of Foraminiferal Research* 30, 83–98.

Samir, A.M. and **El Din, A.B.** 2001: Benthic foraminiferal assemblages and morphological abnormalities as pollution proxies in two Egyptian bays. *Marine Micropaleontology* 41, 193–222.

Samir, A.M., Abdou, H.F., Zazou, S.M. and **El-Mehawey, W.H.** 2003: Cluster analysis of recent benthic foraminifera from the northwestern Mediterranean coast of Egypt. *Revue de Micropaléontologie* 46, 111–30.

Sgarrella, F. and **Moncharmont Zei, M.** 1993: Benthic foraminifera of the Gulf of Naples (Italy): systematics and autoecology. *Bollettino della Società Paleontologica Italiana* 32, 145–264.

Stanley, J.-D. and **Bernasconi, M.P.** 1998: Relict and palimpsest depositional patterns in the Nile shelf recorded by molluscan faunas. *Palaios* 13, 79–86.

—— 2006: Holocene depositional patterns and evolution in Alexandria's Eastern Harbor, Egypt. *Journal of Coastal Research* 22, 283–97.

Stanley, J.-D and **Galili, E.** 1996: Sediment dispersal along northern Israel coast during the early Holocene: geological and archaeological evidence. *Marine Geology* 130, 11–17.

Stanley, D.J. and **Hamza, F.H.** 1992: Terrigenous-carbonate sediment interface (late Quatenary) along the northwestern margin of the Nile Delta, Egypt. *Journal of Coastal Research* 8, 153–71.

Stanley, J.-D. and **Jorstad, T.F.** 2005: *The 365 A.D. tsunami destruction of Alexandria, Egypt: erosion, deformation of strata and introduction of allochthonous material*. Geological Society of America, Annual Meeting Salt Lake City, Program with Abstracts, p. 75.

Stanley, J.-D. and **Landau, E.A.** 2006: Early human activity (pre-332 BC) in Alexandria, Egypt. 1. New findings in Eastern harbour cores. In Goddio, F. *et al.*, editors, *City and harbour, the archaeology of ancient Alexandria*. Oxford Centre for Marine Archaeology (in press).

Stanley, J.-D. and **Warne, A.G.** 1998: Nile delta in its destruction phase. *Journal of Coastal Research* 14, 794–825.

Steuer, A. 1939: The fishery grounds near Alexandria – XIX Mollusca. *Notes & Mémoires Fouad I of Hydrobiology and Fisheries* 33, 1–152.

Toussoun, O. 1922: Mémoire sur les anciennes branches du Nil. *Mémoires de la Société Géographique d'Egypte* 4, 1–144.

Vismara Schilling, A. and **Ferretti, L.** 1987: Analisi semiquantitativa delle microfaune a foraminiferi e ostracodi nella laguna di S. Teodoro (Sardegna nord-orientale). Distribuzione delle associazioni in funzione del grado di confinamento. *Bollettino dell Accademia Gioenia di Scienze Naturali* 20, 45–92.

Warne, A.G. and **Stanley, D.J.** 1993: Late Quaternary evolution of the northwest Nile Delta and adjacent coast in the Alexandria region, Egypt. *Journal of Coastal Research* 9, 26–64.

Williams, M.A.J. and **Faure, H.** 1980: *The Sahara and the Nile: Quaternary environments and prehistoric occupation in northern Africa*. Balkema.