Human impact on sediment mass movement and submergence of ancient sites in the two harbours of Alexandria, Egypt

Jean-Daniel Stanley, Thomas F. Jorstad & Franck Goddio

Historic records indicate that structures built in and around the two harbours of Alexandria, Egypt, were periodically damaged by powerful events such as earthquakes and tsunamis. This geoarchaeological study reveals that human activity in nearshore and port settings has also triggered sediment deformation and construction failure. Analysis of radiocarbon-dated Holocene cores and submerged archaeological excavations record a significant incidence of sediment destabilization and mass movement in the ports since human occupation in the 1st millennium B.C. Anthropogenic substrate failure is documented from about the time of the city's founding by the Greeks in the 4th century B.C. to the present. Construction on unconsolidated sediment substrates was a factor of sediment destabilization, at times in conjunction with earthquakes, storm waves and tsunamis. Engineer reports on port construction during the past century, however, show substrate failure can also occur by building and other human activity, independently of high-energy natural events. Some recent failure and associated mass flows in the harbours were triggered by loading effects associated with emplacement of large structures on weak, water-saturated substrates. Slumps, debris flows and mudflows, initiated by substrate destabilization, caused lateral displacement of sediment and construction debris for tens of meters away from construction sites. Human-induced processes that triggered sediment failure in the ports from Greek to recent time are not likely to be unique to this sector, and findings here may help explain how some sites in coastal settings elsewhere were submerged.

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Introduction

Historic records indicate that natural events such as earthquakes and tsunamis have long been destructive to human settlements positioned along the world's low-lying coastlines. Loss of life and damage to structures caused by such episodic events in nearshore environments (Carroll 2005) are attributed to sudden physical failure of depositional strata that, in some instances, also included mass sediment flows. Among the more common triggers of sediment failure are earthquake tremors of both high and low magnitude, excess loading by large storm waves, hurricane and tsunami surges, and sudden weighting by increased water and sediment discharge during and following high flood stages of rivers flowing towards the coast.

Only a few archaeological investigations have focused on submerged sites in offshore coastal settings affected by human-influenced geohazards involving sediment destabilization and remobilization. Some settlements have been impacted by simple progressive sea-level rise and/or damaged by sudden and powerful natural events. Recent observations have shown that sediment failure in low-lying coastal settings can also be directly influenced by human activity, especially where sites are positioned on weak vulnerable substrates. Some still-emergent historic locations such as Venice have been locally subject to partial submergence by progressive sea-level rise and lowering of land surface (Carbognin & Marabini 1995). Other sites, now offshore and at depths of 5 to 15 m beneath the waves, were lowered more abruptly by intense processes such as faults and tsunamis. Among these are: the town of Port Royal (failed in 1692 A.D.) that suddenly subsided off SE Jamaica (Clark 1995); the Mahabalipuram temple area (lowered after 1000 A.D.) off the SE coast of India (Sundaresh Gaur et al. 2004); and several ancient Dynastic to Byzantine sites now off Egypt's and Israel's Mediterranean coast (Goddio et al. 1998; Stanley et al. 2004; Boyce et al. 2004).

This geoarchaeological investigation focuses on examples of anthropogenically-triggered sediment failure and subsidence of ancient structures in the two harbours of Alexandria, Egypt (Fig. 1). To explore influences and causes of their submergence, the study determines whether human-triggered mechanisms, perhaps in concert with natural ones, led to episodic sediment deformation and displacement off Alexandria. This
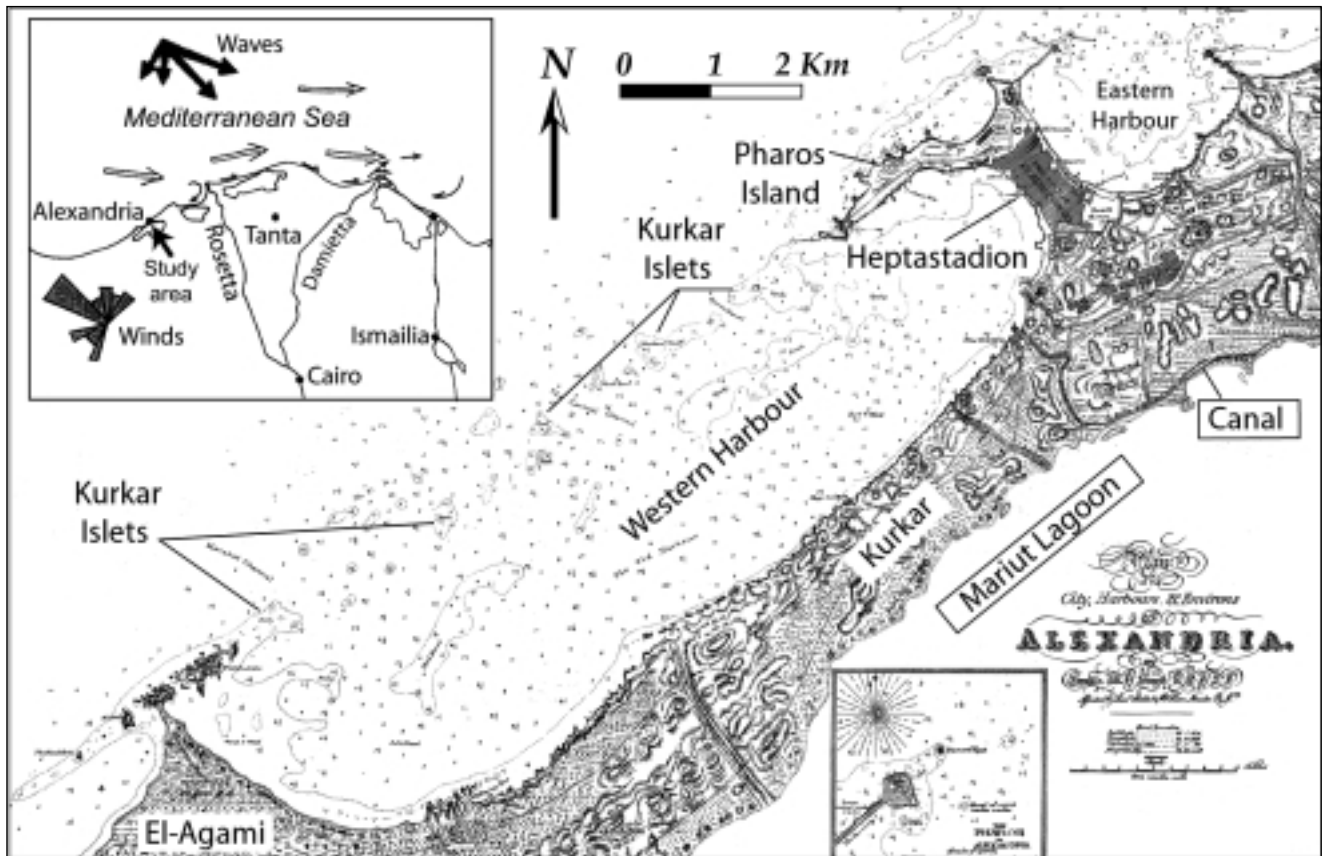
Fig. 1: Historic map of the Alexandria region of Egypt showing the Western and Eastern harbours (W.H., E.H.) and other features discussed in text (chart base by Captain W.H. Smyth, published in London in 1833, and reproduced in Jondet 1921). In inset, dominant directions of winds, waves and coastal currents.

survey takes into account available historical records pertaining to the two Mediterranean ports, and examines the nature and age of destabilized sections by means of sediment borings and underwater archaeological excavation. Stratigraphic and petrological analyses of cores are made in both Western and Eastern harbours of Alexandria (abbreviated herein as W.H. and E.H., respectively).

The methodology in this study is largely determined by applying the principle proposed by Charles Lyell, that is, "the present is the key to the past." We emphasize herein that understanding of past sediment failure in Alexandria's W.H. and E.H. is improved by evaluating causes of such destabilization in the study area in recent time. We (a) describe and date examples of archaeologically ancient offset and failed substrate sections in both ports, including those now buried beneath submerged vestiges of Greek, Roman and Byzantine structures (Jondet 1916; Empereur 1998; Goddio et al. 1998; Bernand & Goddio 2002). We then (b) interpret these older examples of failure and associated features in the two harbours in light of stratigraphic, petrologic and civil engineering concepts learned from modern collapsed sediment and structures in these same settings.

Brief historical review

For many centuries, Alexandria was the major port city in the Eastern Mediterranean. It was established by Alexander the Great in 332 B.C. and developed by his successors, the Ptolemies, who reigned until 30 B.C. (Mahmoud-Bey 1872; Fraser 1972; Empereur 1998). Historians recognize that this coastal region was known to mariners sailing the waters of the SE Mediterranean prior to the 1st millennium B.C. Of note in this respect was the small coast-parallel island known as Pharos located about 1 km north of present Alexandria. Its leeward side provided shelter for mariners seeking refuge from storms and rough seas. Minoan, Phoenician, Philistine and perhaps Egyptians during New Kingdom and later Dynastic periods were likely familiar with Pharos Island as early as one thousand years before Alexander reached the area (Jondet 1916; Marazzi et al. 1986). Pharos Island is cited in literary sources such as Homer's *Odyssey*, indicating that the island had been reached by the early Greeks. This epic poem, orally transmitted after the fall of Troy (~1230 B.C.), was probably transcribed after the 7th century B.C. (Garraty & Gay 1981).

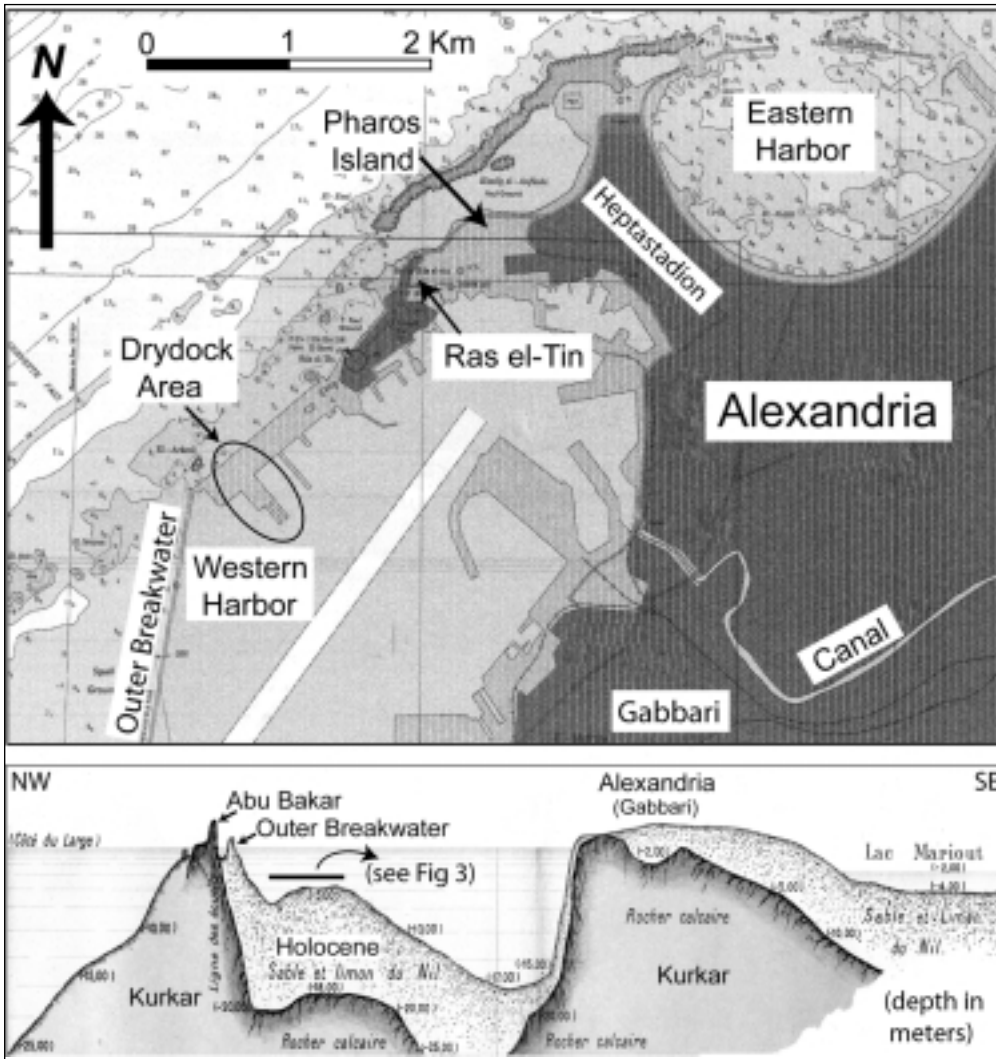A settlement named Rhakotis was located in the Ale-

Fig. 2: Upper, cored dry-dock facility in the eastern part of the W.H., denoted on chart 56103 (NIMA 1999); for detail of cored area in oval, see Fig. 3. Lower, NW-SE cross-section in the W.H. extending from the dry-dock area (see Fig. 3) to Alexandria mainland and Mariut lagoon, showing the Holocene sediment cover and underlying Pleistocene kurkar limestone (modified after Jondet 1916).

xandria area prior to Ptolomaic occupation, but there is surprisingly little information as to its exact location or origin of the inhabitants (Baines 2003; McKenzie 2003; Ashton 2004). Recent exploration undertaken in the E.H. since the mid-1990s has recovered some useful findings relative to early maritime activity. Wood pilings and plankings, some radiocarbon-dated at about 400 B.C., were mapped in failed structures now submerged in the southeastern E.H. (Bernand & Goddio 2002). Even older finds (between the 10th and 7th centuries B.C.) are potsherds, of probable local production, identified in core sections collected in this port (Stanley & Landau 2006).

It is suggested that Alexandria's population rapidly expanded to hundreds of thousands during the city's early Hellenistic history under Greek rule. Although positioned on a desert margin, the developing city was able to sustain a large manpower base by means of essential fresh water provided by canals (Toussoun 1922) and increased supplies of food and goods from expanded trade. During this period, the E.H., known

as port of the Ptolemies or Portus Magnus, was separated from the much longer western Alexandria embayment (Hesse 1998; Goiran et al. 2000). A causeway-aqueduct complex, the Heptastadion, was constructed between the Alexandria coast and Pharos Island (Fig. 1). This structure was built from about 2200 to 1800 years ago on a pre-existing shallow marine topographic high, and then further expanded and modified in Roman and Byzantine time. The major canal that brought fresh water from the Nile Delta to Alexandria flowed to and around the city's southern wall. The mouth of this channel, positioned just west of the Heptastadion, discharged water into the eastern sector of the W.H. (Figs. 1, 2; Mahmoud-Bey 1872; Jondet 1921). During this early period, several important port facilities were constructed in the eastern and western sectors of the E.H. (Goddio et al. 1998; Bernard & Goddio 2002). By Roman time, the coastline bordering the E.H. had been considerably reshaped by large warehouse and dock structures built to absorb trade that previously had been directed to Athens and other Eastern Mediterranean cities.
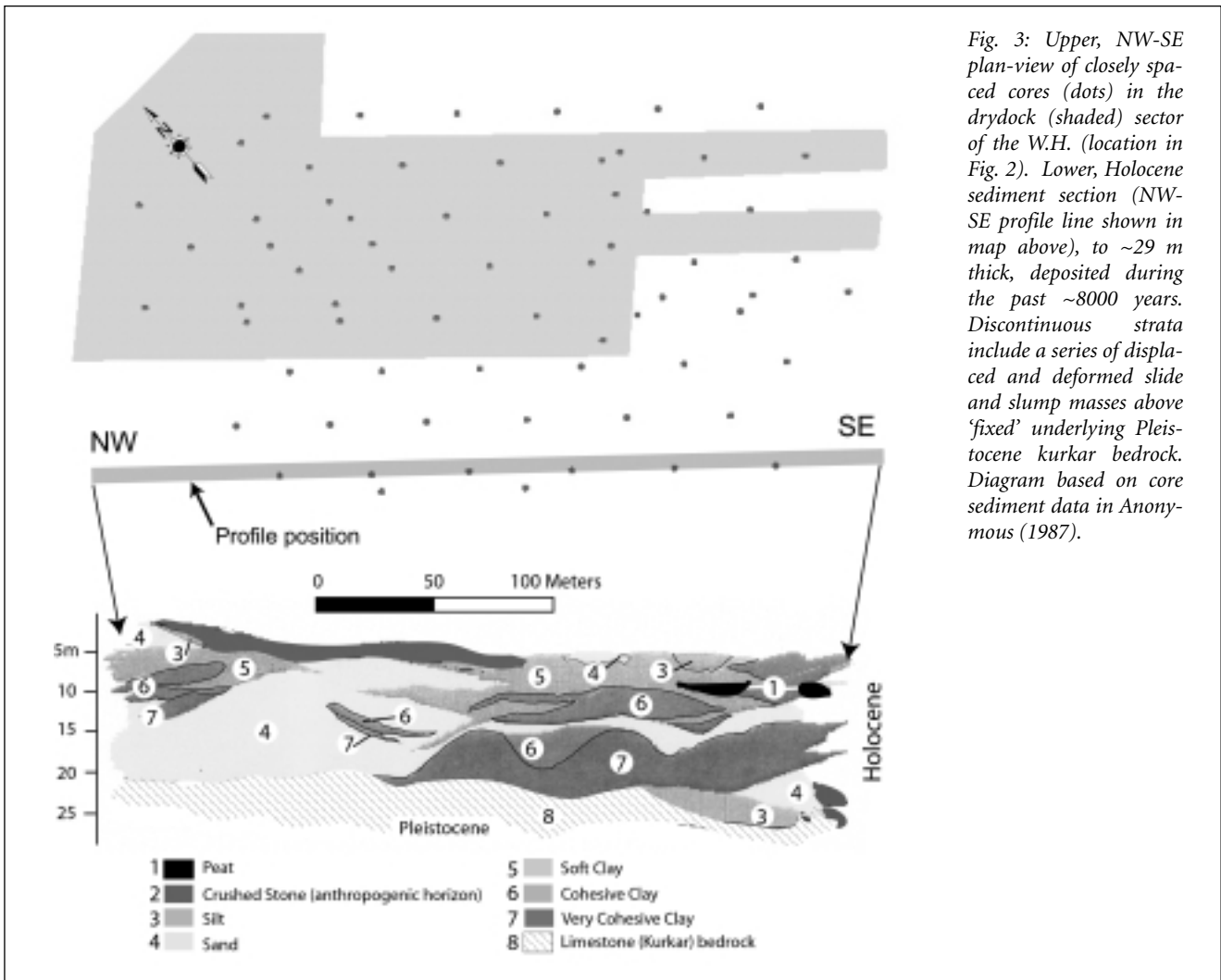
Fig. 3: Upper, NW-SE plan-view of closely spaced cores (dots) in the drydock (shaded) sector of the W.H. (location in Fig. 2). Lower, Holocene sediment section (NW-SE profile line shown in map above), to ~29 m thick, deposited during the past ~8000 years. Discontinuous strata include a series of displaced and deformed slide and slump masses above 'fixed' underlying Pleistocene kurkar bedrock. Diagram based on core sediment data in Anonymous (1987).

The population had diminished substantially by the time of Arab occupation in the 7th century A.D., and subsequently the number of inhabitants fluctuated but remained generally low until about the 1840's, the period of Muhammad 'Ali. The W.H. became the city's major commercial port in the latter part of the 19th century, with extensive seawall and dock construction that considerably altered the harbour (Figs. 2,3; Jondet 1916). In the early 20th century the famous Corniche that parallels the E.H. coast was modified, and two seawalls were emplaced at that port's seaward edge (Fig. 4). These numerous structures transformed Alexandria's originally more open coastal embayments into two partially-closed, better protected ports (Malaval & Jondet 1912). Currently, Alexandria's population increases to 4 million during the summer season. Associated with this growth are large volumes of municipal wastewater that are directly discharged into the E.H. from the city proper and surrounding suburbs. Presently, important anthropogenic effects in the W.H. record nearshore and port construction, dispersal of polluted wastewater from Egypt's industrial complex west of the city, and discharge of agricultural wastewater and dredging.

Geological and geographic setting

The study area is positioned on a relatively tectonically stable margin of northeast Africa. Periodic instability affecting this region results from readjustment to downwarping (sediment compaction, faulting, isostatic lowering) of the thick underlying sedimentary sequence (locally exceeding 4000 m). Beneath the thin Holocene cover of unconsolidated deposits lie Quaternary and Tertiary sequences of Nile Delta origin that, in turn, are superposed on Mesozoic sedimentary units (Said 1981; Schlumberger 1984). This sector is periodically affected by earthquake tremors (Kebeasy 1990), growth faulting (Stanley 2005b) and tsunamis (Guidoboni et al. 1994).

The Egyptian margin west of the Nile Delta is defined by a straight SW to NE-oriented coastline that is >100 km in length. The only suitable sites for building protected ports between Arabs Gulf to the west and the Nile Delta east of Alexandria were the two bay-like re-entries adjacent to Pharos Island. The city was constructed on the
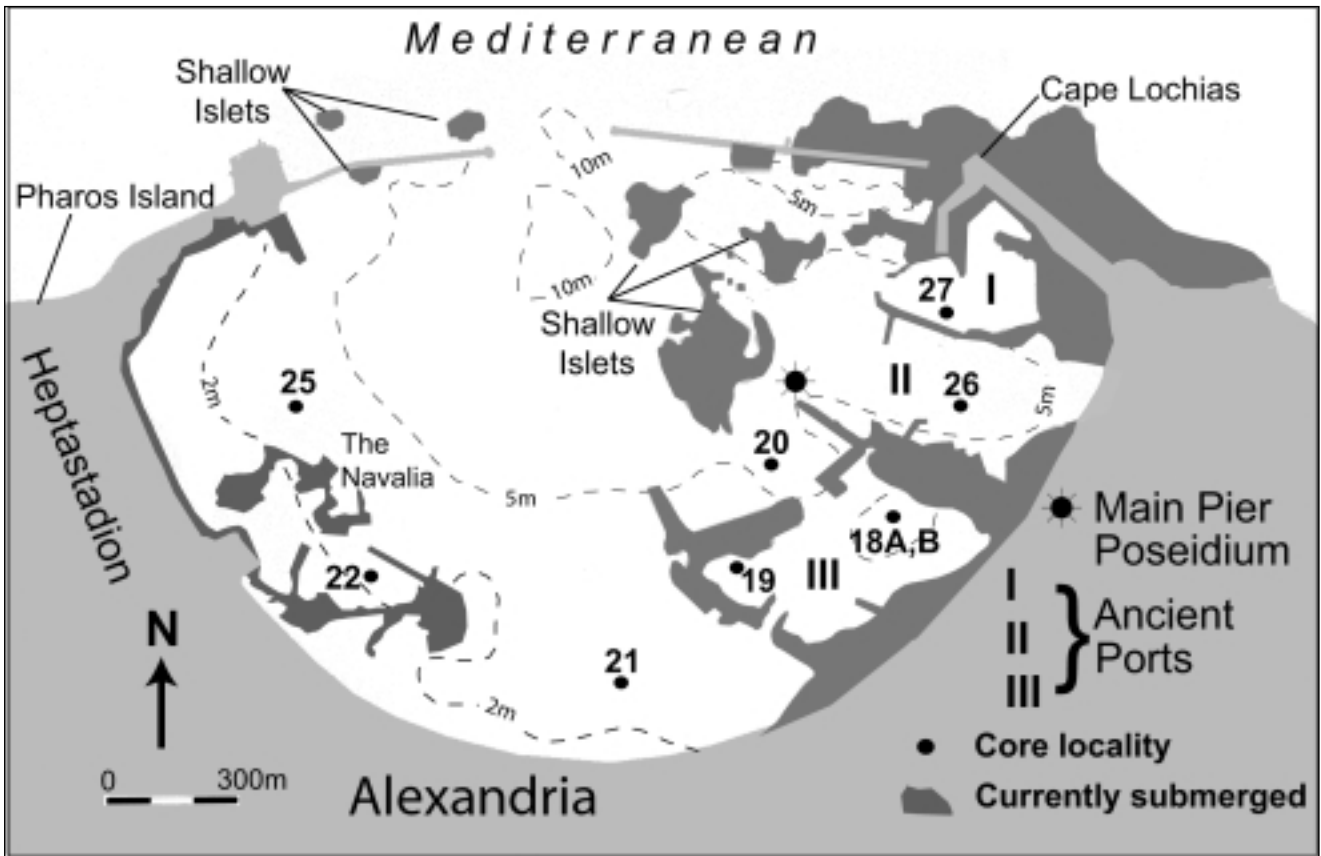
Fig. 4: Map of the E.H. showing vibracore locations, port configuration, bathymetry, and other features discussed in text (base modified after Goddio et al. 1998).

long coast-parallel ridge of Pleistocene age that extends from southwest of Alexandria to Canopus (the modern town of Abu Qir) ~20 km northeast of the city. This narrow (1 to 2 km wide; Fig. 1) coastal ridge feature is formed of poorly to moderately cemented sandy carbonate called kurkar (Butzer 1960; Stanley & Hamza 1992; Hassouba 1995); the ridge reaches an elevation of ~30 m above msl. The ridge and city separate the shallow brackish Mariotis lagoon (now called Mariut; Loizeau & Stanley 1994), located to the south, from the ports and open marine shelf that lie to the north.

Coastal water in this region is microtidal (to ~30 cm) and characterized by temperate to warm sea-surface temperatures that range from 16.7 to 26°C, with a mean surface salinity of ~38.75 ‰. Coastal currents drive water masses eastward at an average velocity of 0.5 knots. Winds from the northwest and west prevail in summer, and from the southwest in winter (Fig. 1, inset). Wave height on the inner shelf north of the ports reaches 1.5 to 2 m, primarily in winter; water from the shelf is readily driven into the two port basins during most of the year, frequently with wave heights of 0.5 to 1.0 m. The resulting swash motion on harbour floors is sufficiently strong to actively scour bottom sediments, especially at shallow depths.

The two ports had a total combined length of almost 14 km when they were still connected, prior to construction of the Heptastadion. The outer (seaward) margins of both harbours are formed by linear, discontinuous series of emergent to shallow submerged islets and ridges formed of kurkar limestone (Fig. 1). Bathymetric profiles from land to sea record the depressed, basin-like configuration of the two harbours (Fig. 2, lower panel). Nautical charts show the detailed configuration and soundings (Malaval & Jondet 1912; Jondet 1921; NIMA 1999; Bernand & Goddio 2002).

Now separated, the W.H. (with an area of ~26 km²) has a long rectangular shape nearly 10.7 km in length between the SW margin (at El-Agami) and the Heptastadion coast to the east. This port has a coast-to-seaward width that locally reaches 2.5 km (Fig. 1), and depths that for the most part exceed 10 m. The eastern sector of the W.H. is now partially subdivided from the western area by a 3.5 km long seawall, the Outer Breakwater. The W.H. floor is asymmetric, deepening gently from the outer kurkar islet margin toward the SE, and then shallowing rapidly from ~15 to 20 m toward the Alexandria shoreline (Fig. 2, lower panel). Depth-wise, the port can be subdivided into 3 coast-parallel bands (NIMA 1999): a wide northern (seaward) one, with
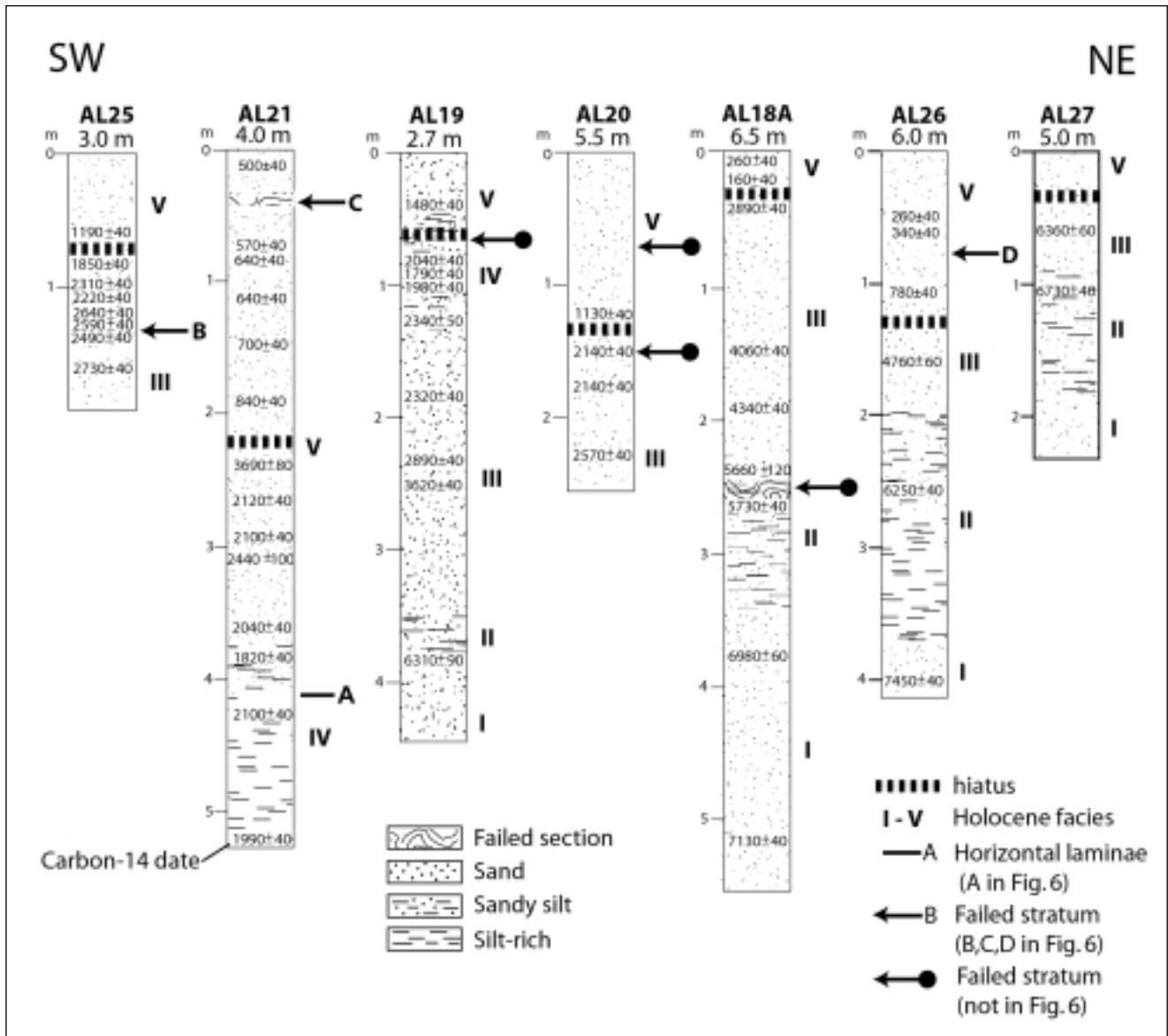
Fig. 5: Lithologic logs with radiocarbon dates (in conventional yrs. B.P.), showing disturbed stratification horizons (arrows). Depths noted at top of cores refer to harbour water depth (in m) below m.s.l. I-V, major stratigraphic horizons; heavy-line denotes erosional hiatus resulting from high-energy events, including the tsunami in 365 A.D.

shallow to intermediate depths from 1 to 10 m; a deep middle sector with depths ranging from 10 to >20 m; and a very narrow, steeply-inclined southern band along the coast with intermediate depths generally <10 m. The deepest depression (to 25 m) lies in the harbour's western sector. Three major ship paths to and within the W.H. with depths to ~20 m (El-Dikheilah Pass, Great Pass, El-Bogaz Pass), and other actively used navigational sectors, are maintained by dredging.

The E.H. is shallower and much smaller (area ~2.5 km²) than the W.H. (Fig. 1). This port is a partially-enclosed elliptical basin with a maximum distance of 2.5 km measured between the present eastern margin of the Heptastadion and Cape Lochias to the east (Fig. 4; NIMA 1999, chart 56103). A distance of ~1.5 km sepa-

rates the southern arcuate E.H. coastline, bordered by Alexandria's Corniche highway, from the harbour outlets to the north. Nearly half of the port lies at depths of <5 m; the north-central sector of the embayment is of greater depth, and reaches 11 m at the main harbour outlet. An irregular distribution of small shallow kurkar islets forms the northern margin of the E.H., and several larger (to >500 m wide) submerged kurkar highs are distributed in the east-central sector of the port (Fig. 4; detailed charts in Goddio et al. 1998).

Holocene sediment record

Recent surficial sediments of the Alexandria coast and

shelf have been described by El-Wakeel & El-Sayed (1978) and Summerhayes et al. (1978), and for the E.H. by Stanley & Landau (2006). Core sections recovered in the two harbours serve to detail the petrology and stratigraphy of the Holocene deposits that accumulated directly upon the Pleistocene kurkar limestone that forms the basin floor and margin framework of the two ports (Fig. 2). In the W.H., one important set includes 65 closely-spaced drill cores in the eastern part of the port (recovered in July 1985 and October 1986; Fig. 3). Other borings in this port have also been described by Jondet (1916) and Attia (1954). In the E.H., eight vibracores were collected in May 2001 (Fig. 4).

Core sections comprise largely bioclastic (shelly) and muddy carbonate sand strata interbedded with finer-grained sandy silt, silty mud and dark organic-rich layers (Fig. 5); logs are further detailed in Jorstad & Stanley (2006); Stanley & Bernasconi (2006) and Stanley & Landau (2006). Minor amounts of wind-blown quartz silt are also present (cf. Yaalon & Ganor 1979). Radiocarbon-dated marine strata near the base of borings indicate that the two coastal re-entries were subaerially exposed until ~8000 years ago, and then progressively filled as sea-level rose and land forming the margin subsided (Warne & Stanley 1993).

A pertinent data-set for this study are the numerous long and closely-spaced (<40 m apart) borings in the W.H. (Fig. 3). They were collected for civil engineering purposes, primarily construction of marine lift and drydock facilities west of Pharos Island and detailed in Anonymous (1987). The cores were recovered in a small, NW-SE oriented rectangular sector ~350 m by 150 m (~0.5 km^2) positioned about 1.6 km southwest of Ras el-Tin. This location is just landward of the Outer Breakwater and near the emerged kurkar islet of Abu Bakar (Fig. 2; Jondet 1916). The Alexandria mainland (Gabbari district) lies across the harbour, about 2 km southeast from the drydock sector. Recovered core lengths range from 18 to 35 m, with most cores reaching the Pleistocene kurkar limestone basement. Harbour water depths in the core area range to about 10 m, and then generally increase to ~15 m in a SE direction toward the central part of the basin. The cores in this eastern part of the port recovered Holocene thicknesses to ~22 m, with sections comprising variable proportions of bioclastic sand, silty sand and carbonate mud lithologies.

The eight vibracores (including two, A and B at core site 18) distributed in the smaller E.H. were collected at water depths from 2.7 to 6.5 m (Fig. 4), and their recovered lengths range from 1.9 to 5.2 m (Fig. 5). Holocene sediment sections, dated with 52 radiocarbon dates (most AMS; tabulated data in Jorstad & Stanley 2006) are generally much thinner (<12 m; Stanley & Bernasconi 2006) than in the W.H. Although none

recovered the underlying Pleistocene carbonate kurkar, the bases of several cores were as old as ~7500 conventional radiocarbon years B.P., that is, within 500 years of initiation of Holocene marine bay deposition. Bioclastic sand is the prevailing lithology. The longer, more complete core sections comprise five distinct dated stratigraphic units. From base upward, these radiocarbon-dated units are: (I) Lower sand (older than 6000 yrs B.P.), (II) Lower muddy sand (~6000-5600 yrs B.P.), (III) Middle sand (~5600-2300 yrs B.P.), (IV) Upper sandy and silty mud (2300-2000 yrs B.P.), and (V) Uppermost sand (less than 2000 yrs B.P.). Mineral components and benthic faunas (molluscs, foraminifera) in these cores have been used to identify biofacies and environmental changes as sea level rose during the past 8000 years (Bernasconi et al. 2006).

Evidence of human activity is recorded in upper core sequences (top of III, IV, V) by the presence of artifacts and diverse petrological components (Jorstad and Stanley 2006; Stanley & Landau 2006). The petrology, faunal content and cultural artifacts in drill cores collected on the coastal land margin adjacent to the E.H. have also been described in other studies (Chen et al. 1992; Warne & Stanley 1993; Goiran et al. 2000).

Petrology and age of failed sections

Two data-sets are needed to determine whether human activity had any effect on the destabilization of late Holocene deposits in Alexandria's two harbours. The first requires firm evidence of deformed sediment in dated upper stratigraphic sections, and the second needs to demonstrate that sediment failure actually took place during the period of human occupation in and around the ports. Together, this information would record whether failure occurred at either regular or irregular intervals during the past 8000 years of Holocene deposition. Moreover, the data would serve to determine the relative frequency of post-depositional deformation before, as well as after, occupation of historic Alexandria. The 332 B.C. date that signals the beginning of Alexandria's rapid development is proposed as a practical chronological reference level. The suites of sediment cores in the two ports, cited in the previous section, help determine the timing of failure.

Evidence of stratal disruption in 10-cm wide split-core sections from the E.H. was observed by visual inspection of borings and X-radiographs (Fig. 6). In contrast to horizontally stratified and well-laminated sections (Fig. 6A), failed sediments comprise poorly-defined mixes of disorganized particles (sand, granules and coarser grains) set in a silty mud matrix typical of slumps and debris flows (Fig. 6B-D). Disturbed layers display a fairly consistent thickness, ranging from 0.20
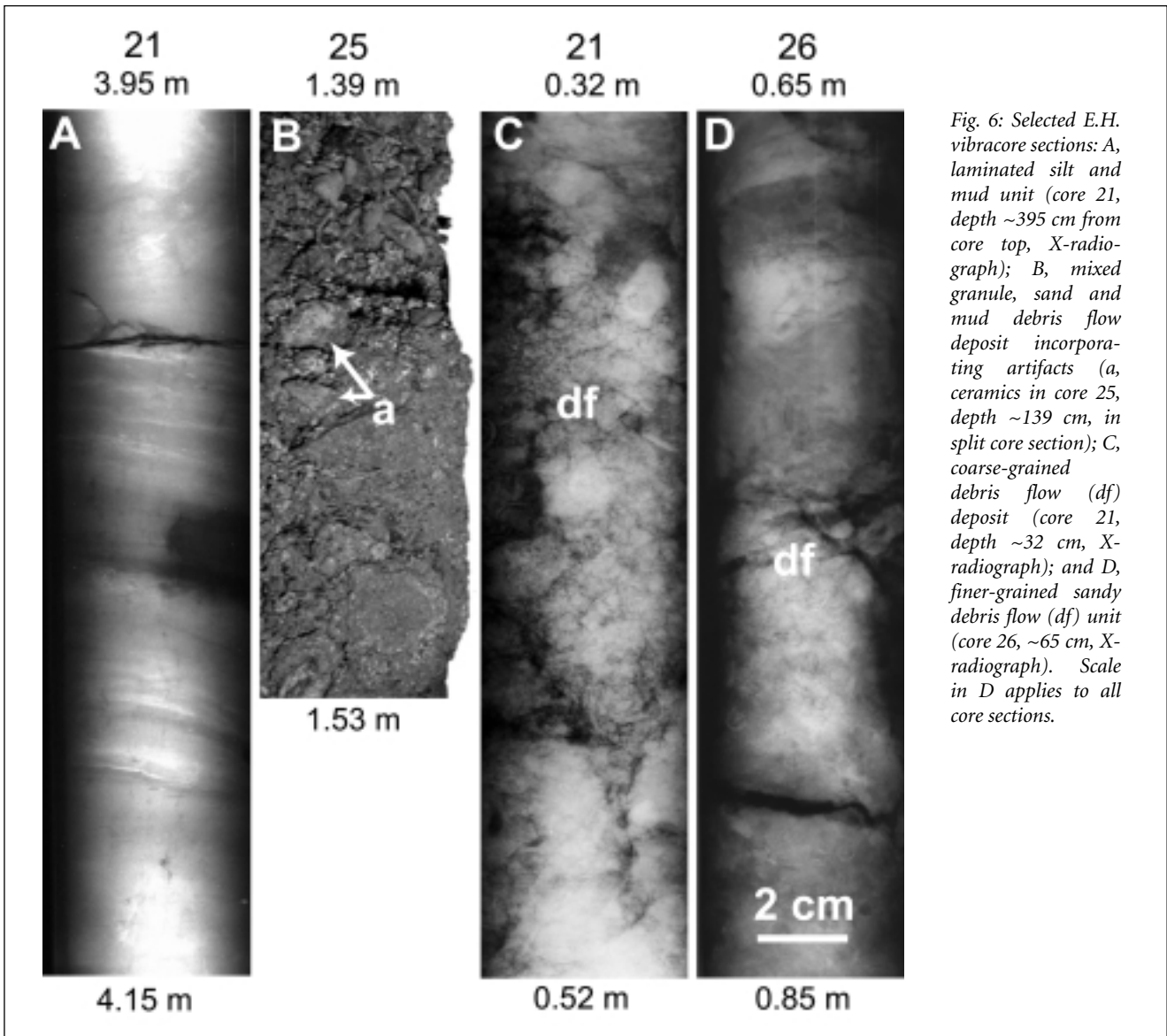
Fig. 6: Selected E.H. vibracore sections: A, laminated silt and mud unit (core 21, depth ~395 cm from core top, X-radiograph); B, mixed granule, sand and mud debris flow deposit incorporating artifacts (a, ceramics in core 25, depth ~139 cm, in split core section); C, coarse-grained debris flow (df) deposit (core 21, depth ~32 cm, X-radiograph); and D, finer-grained sandy debris flow (df) unit (core 26, ~65 cm, X-radiograph). Scale in D applies to all core sections.

to 0.60 m, and are confined between undisturbed strata. Some may represent slump or slide failure planes (cf. Fig. 3). Destabilization of unconsolidated deposits involves decreased grain support, usually associated with expulsion of pore fluids during phases of liquefaction or fluidization. It is recognized that strong forces, including loading, applied to unconsolidated units can result in altered cohesion between sediment particles and pore fluids. Consequently, original physical and biogenic structures are obliterated in these failed horizons (Fig. 6B-D) as commonly observed in strata remolded by slumps, debris flows and mudflows (cf. Lowe 1976; Middleton & Southard 1978; Allen 1984; Obermeier 1996).

Correlation among the numerous core sections concentrated in the small area of the W.H. serves to define the three-dimensional subbottom geometry of Holocene sediment lithofacies (Fig. 3). Lithostratigraphic analyses

of these sections show the strata, rather than being horizontal, continuous and superposed in consistent 'layer cake' fashion, are deformed and laterally off-set. This marked discontinuous stratification, with soft clay and sand irregularly shifted above more cohesive mud layers, is indicative of post-depositional destabilization. While present throughout much of the Holocene section in this sector, it is more prevalent in the upper half of the W.H. core sections. Although no radiocarbon dates were available for this set of offshore engineering borings, ages of the W.H. core lithofacies are reasonably estimated by correlation with dated Holocene sections ~2 km distant in the E.H. (Fig. 5) and adjacent Heptastadion (cf. Goiran et al. 2002). Based on this correlation, deformation of sediment layers in the upper half of W.H. core sections is dated as younger than 4000 years.

Nine failed sediment layers are observed in seven of the eight E.H. cores; lithology, structures and radiocarbon
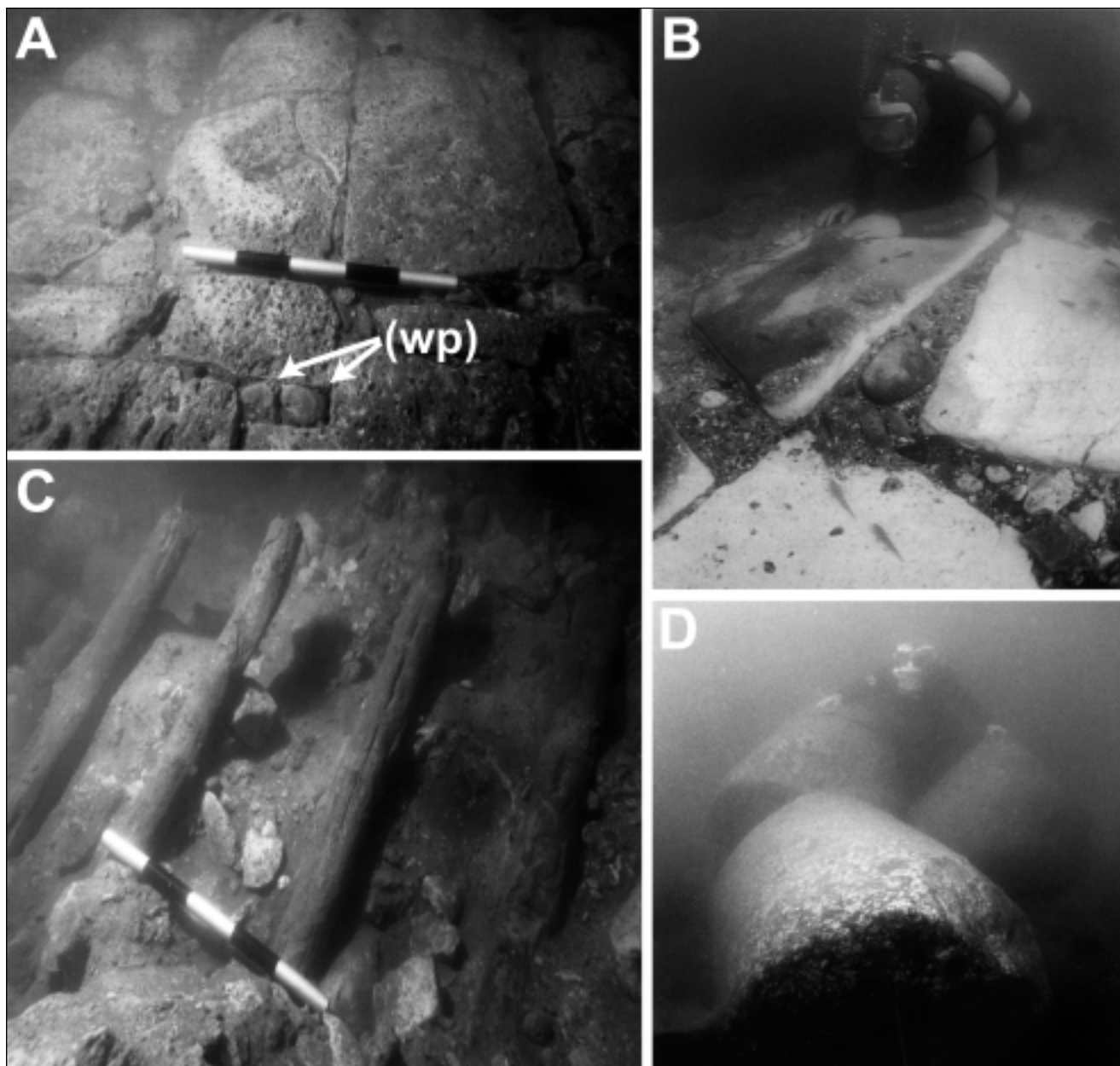
Fig. 7: Underwater photographs selected from sites in the E.H. (A, at the Navalia; B-D, in SE port sectors). A, undisturbed pavement on pier with wood posts (wp) still in place; scale is 50 cm long (after Bernand & Goddio 2002, p. 159). B, broken pavement, with diver as scale (after Goddio et al. 1998, p. 17). C, remnants of mortered retaining wall with wood posts, wall fragments and rock rubble; scale length is 50 cm (after Bernand & Goddio 2002, p. 145). D, large broken granite columns, with diver as scale (after Bernand & Goddio 2002, p. 121).

dates are detailed in Jorstad & Stanley (2006) and Stanley & Bernasconi (2006). The two youngest deformed strata (dating from ~350 to 500 years B.P.) occur in cores 21 and 26. Four such layers of intermediate age (from ~900 to 2100 years B.P.) are recorded in cores 19, 20 and 21. The three oldest disrupted strata (~2500 and ~5700 years B.P.) are present in cores 25 and 18A and B (not shown in Fig. 5), respectively. From this survey, we find that the majority (7 of 9) of failed strata in the E.H. cores are dated ~2500 radiocarbon (conventional) years B.P. or younger, while the remaining failed units (cores 18A,B) are of much older age (~5700 years

B.P.). Several of these layers include potsherds, such as the one in core 21 (section at a depth of ~220 cm from core top; deposited between 900 – 2100 years B.P.), and in core 25 (Fig. 6B; deformed unit at a depth of ~140-150 cm from core top; pre-Ptolemaic age of roughly 3000-2500 years B.P.).

In sum, destabilization of Holocene sediment sections in the harbours occurred episodically throughout much of the Holocene, but with an apparent increased frequency since somewhat before the time Alexandria was developed by the Greeks.

Sediment failure caused by construction

The presence of deformed strata in core sections of late Holocene to Recent age suggests there could be a link between increased human activity, sediment failure and mass movement of material in the harbours. This would not be surprising after Greek occupation in 332 B.C. Strong evidence, however, is needed to support the postulate that anthropogenic factors were responsible for some sediment destabilization and displacement of earlier sites, since the 1st millennium B.C. Ideally, observations should include the presence of failed sediment in direct association (mixed and/or beneath) with dated human construction and/or activity now submerged.

Systematic marine archaeological excavations in the E.H. by the European Institute of Submarine Archaeology (I.E.A.S.M.) have yielded numerous artifacts and exposed large Greek, Roman and Byzantine structures. Recovered finds in this port, such as wood dating back to ~400 B.C., are shown in photographs and their locations specified on detailed maps (Goddio et al. 1998; Bernand & Goddio 2002). Excavations have revealed exposed remnants of extensive submerged structures such as former paved walkways, walls and docks, along with statues, ceramics and jewelry. The archaeological finds, many partially buried by sediment, occur at harbour depths ranging to ~7 m. Particularly important in Alexandria's early history are: (a) three extensive port facilities built in the eastern and SE sectors of the E.H. that had been the center of navigation, trade and municipal activity, and where important structures such as the Timonium and Poseidium were constructed (Goddio et al. 1998), and (b) the Navalia port structures in the western E.H., positioned adjacent to the Heptastadion (Fig. 4; maps in Bernand & Goddio 2002, their pages 147-148). Moreover, submerged large remnants of the lighthouse famous in antiquity, built in the 3rd century B.C. and finally destroyed by an earthquake in 14th century A.D., have been identified off eastern Pharos Island (Empereur 1998).

Some of these once-emergent structures appear to have been lowered below the waves with only minimal damage. Examples in the E.H. include near-intact paved walkways (Fig. 7A), large mortar blocks with wood frames, and some rock wall and pier segments where associated sediment deformation and mass flow are not evident. One extensive structure lowered with only modest offset and damage is the NW-trending pier (~160 m long) near the Poseidium (Fig. 8). More commonly, however, ancient now-submerged structures record more obvious effects of damage. Excavated features typically include: broken and offset paved walkways (Fig. 7B); rubble layers of displaced construction debris (Fig. 7C); and broken and irregularly distributed large columns (Fig. 7D). Among other deformed and displaced structures in the E.H. are tilted framed mortar blocks, collapsed masonry comprising rock piles mixed with timber poles
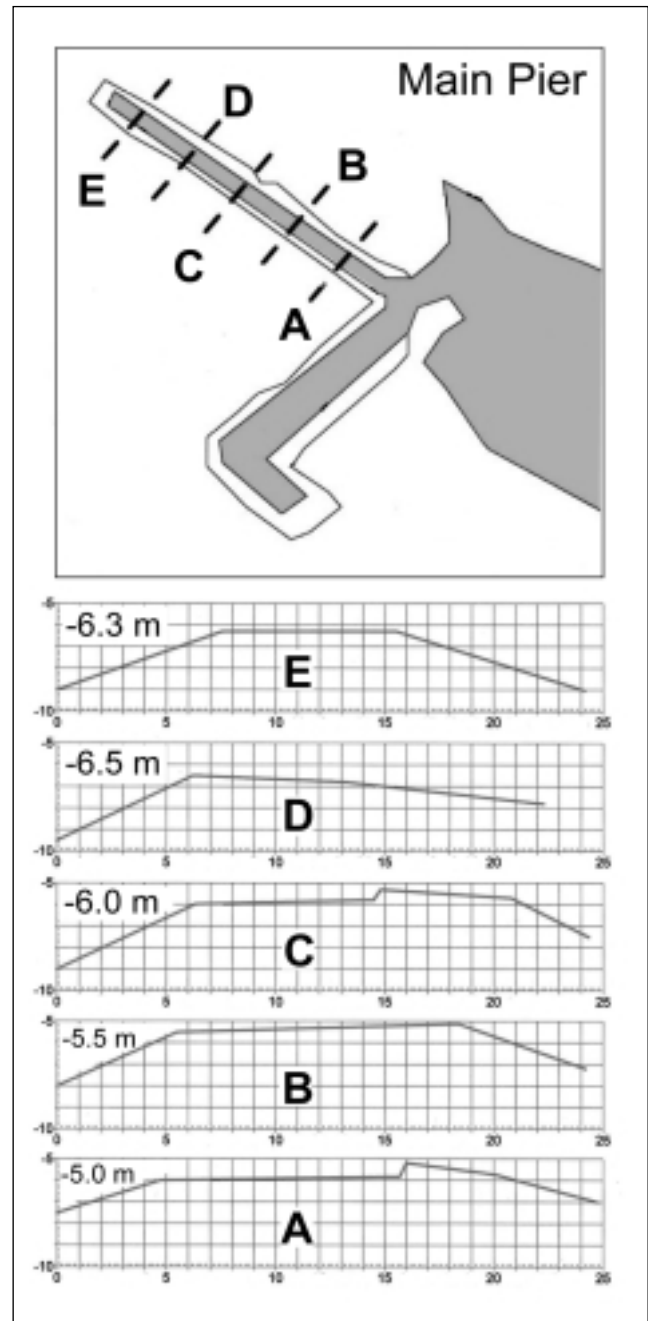

Fig. 8: Five SW to NE oriented cross-sections (A-E, trending away from coast; map location in Fig. 4) of the main pier of the Poseidium in the E.H. (after Goddio et al. 1998, their p. 23). This now-submerged structure was once emerged above harbour sea level by at least 1 m above m.s.l. Note upper pier surface deepening away from shore (vertical, horizontal scaled in m). Pavement surfaces at A to D are somewhat tilted and/or offset (depths from -5 to - 6.5 m below present m.s.l.), and at E is relatively undisturbed (depth to – 6.3 m).

and planks, and offset foundation bases which incorporate a mix of the once underlying rock fill and substrate sediment (Bernand & Goddio 2002).

Observations based on archaeological excavations in this setting suggest that large-scale construction was

originally placed with only minimal foundations on rock fill and/or natural sediment substrate (Fig. 9A). This design contributed to instability of both construction and substrate. Although the age of many ancient submerged structures can usually be determined quite precisely, the actual timing of their failure and subsidence (either shortly, or a long period, after construction) have not yet been determined.

Discussion and interpretations

Studies on the causes of submerged ancient coastal sites such as harbours located elsewhere have commonly cited progressive sea-level rise, or land subsidence, or both (relative sea-level rise) as major responsible factors. Investigations of drowned structures have also invoked the primary role of powerful episodic natural events such as earthquakes (Clark 1995; Reinhardt & Raban 1999), tsunamis (Boyce et al. 2004), and river floods (Stanley et al. 2004). Direct influence of human activity has not usually been considered a primary cause for submergence of early settlements and ports built in coastal settings.

In this respect, observations in the W.H. documented a century ago by port engineers provide valuable insight on mechanisms directly associated with failed construction, mass flow and subsidence (Malaval & Jondet 1912; Jondet 1916). At the time Alexandria's port facilites were being expanded, engineers carefully recorded various physical aspects of pier and seawall failures as they occurred either during or shortly after construction. Structures emplaced directly on the Pleistocene cemented limestone usually remained stable, whereas those built on unconsolidated sediment substrate often experienced subsidence and damage. In the latter case, construction instability and failure were primarily attributed by engineers to specific physical properties of the underlying sediment.

For example, the petrology and physical properties of sediment borings in the drydock sector of the W.H. (Fig. 3) show considerable variability in density, water content, compressibility and shear strength between the base and top of individual cores, and from core to core (data in Anonymous 1987). Core sampling records the link between deformation of emplaced structures and construction on substrates that contain high amounts of water-saturated silt and clay. A high incidence of failure prevailed where finer-grained sediment preferentially accumulated in the eastern part of the W.H during the Holocene. Instability and sudden subsidence in this sector were directly affected by compaction, expulsion of water and shearing of substrate sediment caused by loading effects where large, heavy materials or structures were emplaced. The extent of vertical lowering and

amount of structural displacement and associated damage varied from point-to-point along a building site (Fig. 8; Goddio et al. 1998). This resulted in part from temporal and spatial variations in lithology, physical properties of the substrate and weight of the overlying constructed structure.

Port engineering reports (Malaval & Jondet 1912) and mapping by divers (Goddio et al. 1998) indicate failed sediment and cultural material flowed laterally in some instances for tens of meters or more, especially where large structures were placed on weak, more saturated silt and clay-rich substrates. Over time, subsidence and lateral displacement would occur successively three or four times at the same locality, usually without warning. Remarkably, rock fill, large wood-framed cement blocks and pilings placed upon a massive rock fill base could settle as much as 5 to 10 m into an underlying water-saturated mud. A notable example of this phenomenon was photographically recorded when a 10-m thick pier section suddenly sank beneath harbour water level, leaving a large depression about 150 m in length by 30 m in width and 4 m in depth (Fig. 9B). From these documented modern examples, one can envision that a less solidly anchored ancient Greek or Roman pier, palace or other structure built in the E.H. (Fig. 9A) could readily give way and collapse in similar fashion.

By the late 19th century, several engineering measures were taken during construction in the ports to minimize such damage. Where present, non-cohesive mud was initially dredged and removed from a building site, and replaced with sandy and/or coarser sediment fill (including dredged sandy material derived from other port sectors). Then, several massive loads of large-size rock fill were placed at the site, in succession, until the substrate became sufficiently compact and subsidence into the underlying sediment ceased (Fig. 9C,D). Even with such precautions, the construction base could continue to subside by a series of small downward step-like pulses, until final compaction was achieved and lowering reduced to < 0.4 m. Over time, pressure by the overlying layers of rock fill and port structure depressed the substrate base in concave-upward fashion, with most deformation usually occurring beneath the center of the emplaced feature (Fig. 9D).

The above-cited observations by engineers pertain primarily to sediment destabilization by loading that affected specific, and localized, construction sites in the W.H. We also postulate that other human factors, such as dredging, may have triggered or induced more widespread sediment failure. Moreover, one can readily envision more extensive sections of underconsolidated Holocene sediment shifting laterally over a wider area of the harbour, perhaps in concert with natural factors such as powerful earthquakes and tsunamis. The damaging tsunami of 365 A.D. comes to mind (Guidoboni et
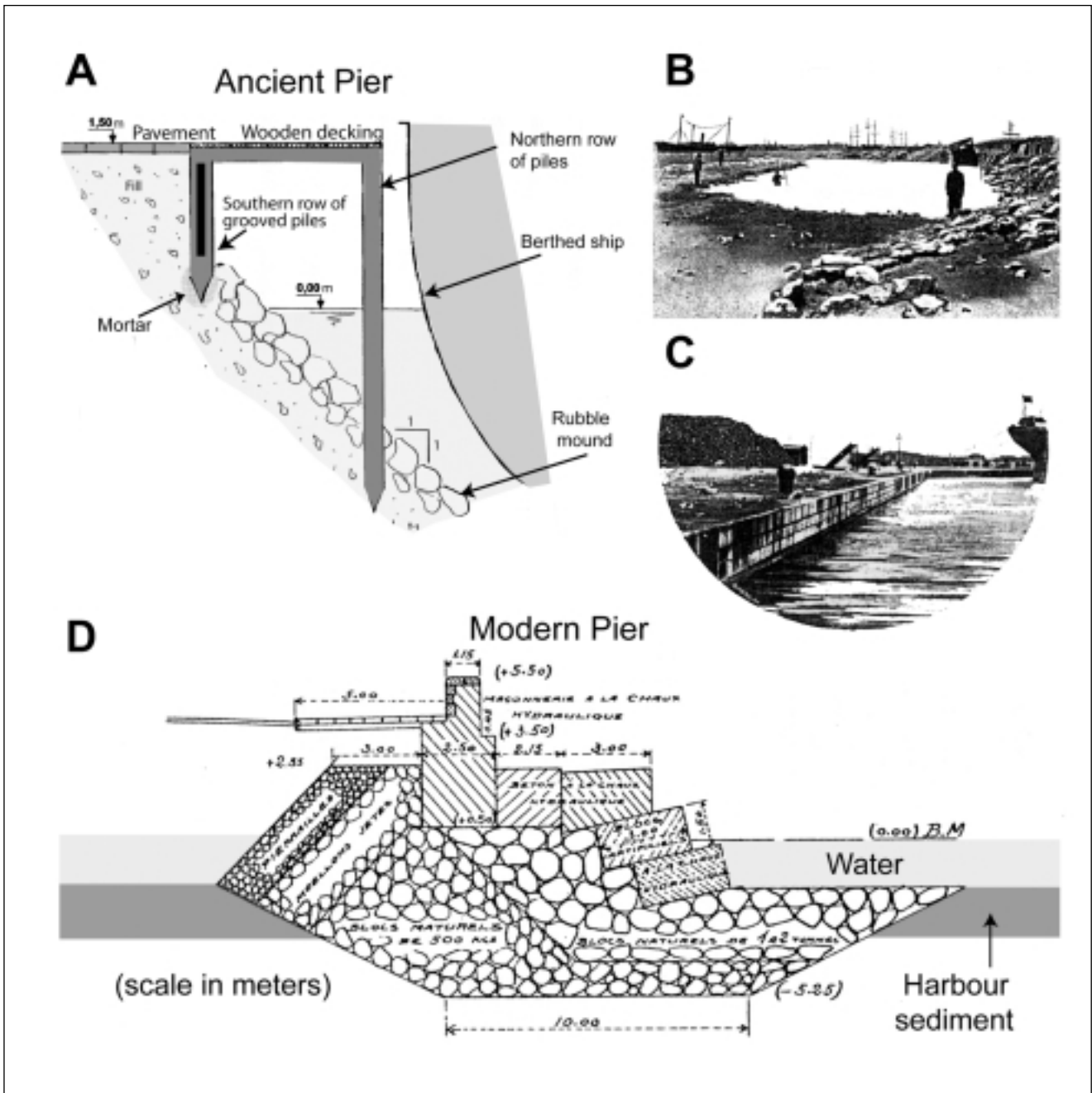
Fig. 9: A, section of ancient pier in the E.H. showing construction method using shallow pilings and a minimal fill thickness (after Goddio et al. 1998, their p. 57). B, recent failure to depths below harbour water level occurred suddenly during construction of a section of the Quais à Charbons in the W.H.; depression is 150 m long, 30 m wide and 4 m depth; people in photo provide scale (after Malaval & Jondet 1912). C, same pier following application of upgraded construction techniques. D, cross-section showing enhanced construction design in the W.H., using multiple emplacement of coarse rock-fill to progressively increase compaction of substrate and minimize successive subsidence events. Design takes into account longer-term substrate settling below center of structure (after Malaval and Jondet 1912). Scale in meters.

al. 1994; Stanley & Landau 2006). In such cases, uncon-solidated sediment sections slipped above the underlying 'fixed' Pleistocene consolidated kurkar bedrock in a manner resembling a laterally displaced, soft, pliable rug that slides over a wooden floor and is wrinkled during motion (Fig. 3, lower). To determine whether this more laterally extensive process occurred and if

human and/or natural triggers were involved will require a high-resolution seismic survey, with closely-spaced profiles that detail the geometry of Holocene strata upon the underlying 'fixed' Pleistocene kurkar limestone.

Conclusions

Petrological examination of radiocarbon-dated sediment cores shows that substrate destabilization has occurred irregularly during the past 8000 years in both Alexandria harbours. Against a background of episodic natural events active in this region, we record an increased number of sediment failure events since the beginning of anthropogenic activity. This may explain the apparent increase in the number of failures from somewhat before the time of the city's development by the Greeks in the 4th century B.C. to the present. This study proposes that aspects of the lithology and physical properties of the Holocene substrate, at times in conjunction with events such as earthquake tremors, storm waves and tsunami surges, were key factors responsible for deformation and failure. A clarification of this past substrate instability in the study area is provided by archaeological surveys of ancient sites in the two harbours and also by geological and engineering studies of port construction. Together, these suggest sediment failure and associated mass flows could in some instances be triggered during and shortly after structures were emplaced on relatively weak, water-saturated substrates.

Historic documentation indicates that structures in Alexandria and its ports periodically experienced effects of powerful natural events (Guidoboni et al. 1994). Important examples include the cluster of earthquake tremors in Byzantine time (Pirazzoli et al. 1996) and several tsunami wave surges in the 1st millennium A.D. that caused major destruction in Alexandria and along the coast, presumably in part by liquefaction and soft sediment failure. On the other hand, sediment failure during the past century has occurred independently of such natural impact events (cf. Malaval & Jondet 1912). From all available information, it appears that since human occupation of the area in the 1st millennium B.C., construction activity as well as episodic seismic tremors and tsunami surge loading increased the incidence of failure. Laterally displaced mass flows on harbour floors commonly occur where a structure was emplaced on a weak, water-saturated mud-rich substrate. Many of the now-submerged archaeological structures in Alexandria's E.H. show a mix of broken construction material with deformed sediment and rubble fill that failed as a likely result of loading on an insufficiently reinforced and/or anchored base. Core sections record mass movement by slumps, debris flows and mudflows associated with such substrate destabilization. Failed sediment and construction debris could be displaced laterally away from an immediate construction site for at least tens of meters by means of these mechanisms.

This study of human and natural triggers leading to sediment failure and submergence of structures in the Alexandria harbors may perhaps shed light on how some ancient port facilities and nearshore settlements subsided in other world margin settings. As in the Alexandria harbours, a strong relationship is to be expected elsewhere among construction design, physical properties of underlying sediment, and substrate failure. Returning to Lyell, we propose that the reverse of his principle, that is, "the past is the key to the present," should be considered. The present-day selection of port sites and construction methods, especially those applied to low-lying vulnerable coastal margins, would benefit from such study of ancient harbours.

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