Submergence of Ancient Greek Cities Off Egypt's Nile Delta—*A Cautionary Tale*

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ABSTRACT

This geoarchaeological analysis illustrates the extreme consequences that occur when protection measures related to coastal sites and associated environmental conditions are overlooked. Two ancient Greek cities, Herakleion and Eastern Canopus, originally occupied low-lying delta coastal areas along the Canopic channel of the Nile. Both were unprotected against flooding, earthquake, tsunami, and consequent subsidence. These sites, recently discovered in Abu Qir Bay on the northwestern margin of Egypt's Nile delta, were lowered a total of 8 m during the past 2500 yr, and now lie at water depths of 5–7 m. The two cities were located along the delta coast at river mouths that flooded annually, and man-made structures were built directly on underconsolidated sediment prone to geohazards. Processes leading to their submergence are interpreted on the basis of integrated archaeological, physiographic, geological (including cores), and geophysical (side-scan sonar, nuclear resonance magnetometer, high-resolution seismic) information. Gradual subsidence due to relative sea-level rise (eustatic rise, land lowering by sediment compaction) accounted for 4–5 m of submergence. Episodic failure during floods and earthquakes by loading and sediment remobilization of the water-saturated substrate upon which the cities were situated likely caused the additional 3–4 m of subsidence. Without foundations, pilings, dikes, or other protection measures, it is not surprising that the sites, over the long term, were damaged and subsided completely into the bay. Ancient cities discussed here cause us to reflect on present-day site selection and construction practices in modern deltaic and associated wetland settings, and potential challenges related to substrate failure and other coastal hazards.

INTRODUCTION

Venice, Shanghai, New Orleans, and Bangkok are among better-known large population centers in low-lying coastal areas subject to submergence from natural (sea-level rise, land lowering) and anthropogenic (water pumping, load compression) processes (Milliman and Haq, 1996; Waltham, 2002). These and other urban areas have undergone extensive hydrological and engineering studies to implement protective measures to mitigate geohazards (Barends et al., 1995). An example is recent approval for a complex system of locks to be emplaced in Venice lagoon to minimize flood and high-tide damage.

When left unchecked, the terminal consequences of flooding processes at coastal margins are extensive damage to cities and their eventual submergence. Here, we consider two such recently discovered examples, the Greek cities of Herakleion and Eastern Canopus, now entirely submerged in western Abu Qir Bay, Egypt (Fig. 1). These localities provide useful insights into what can be viewed as an extreme result of unfavorable site selection and absence of foundation protection measures. The cities were originally built on the Mediterranean coast east of the ancient city of Canopus (present Abu Qir), along Egypt's northwestern Nile delta (Constanty, 2002). Once located at outlets of the now-defunct Canopic distributary branch of the Nile River, both are currently at water depths of 5–7 m below sea level (Fig. 2).

Historic and stratigraphic documentation of the late Quaternary of the lower Nile delta is extensive. Much of what is known of the petrology of its sedimentary deposits has been obtained by

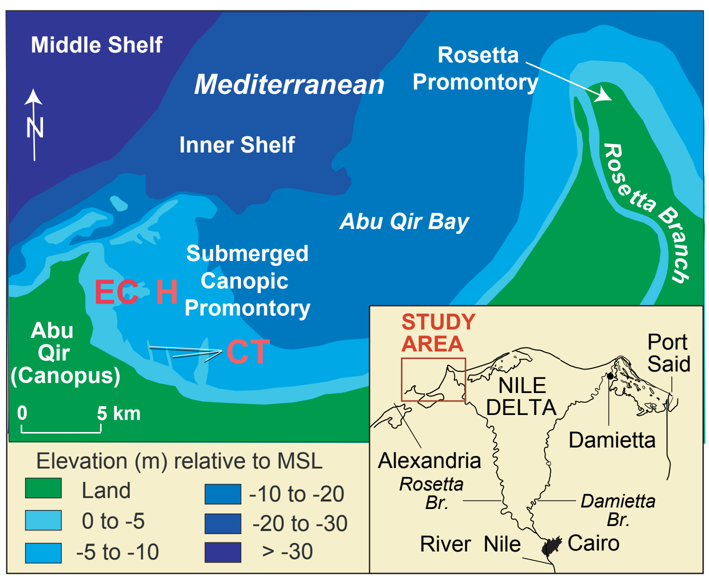

Figure 1. Abu Qir Bay on the northwestern margin of the Nile delta, Egypt. CT—traces of the relict Canopic branch, EC—Eastern Canopus, H—Herakleion.

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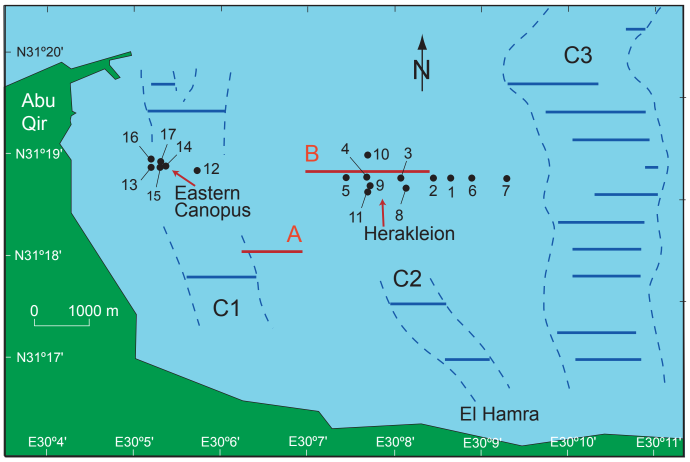

Figure 2. Western Abu Qir Bay, showing locations of Herakleion and Eastern Canopus and two selected high-resolution seismic profiles (red lines, shown in Fig. 4). Numbered dots show 17 vibracore sites. Three Canopic sublobe channels (C1, C2, C3) are revealed by seismic profiles (blue lines) and cores detailed in Stanley et al. (2004); these channels once extended >5 km north of the present coast. Depth and horizontal scale in meters.

cores showing that the delta is formed largely of dark organic-rich silts of Holocene age, ranging in thickness from ~10 to ~50 m (Fourtau, 1915; Attia, 1954; Butzer, 1976). Radiocarbon dating of nearly 400 delta core samples serves as a prime chronostratigraphic base (Stanley et al., 1996). Extensive coring exploration indicates that a large proportion of unconsolidated deposits in the lower delta, within 30 km of the present coast, were originally laid down in shallow lagoons. Considerable published data is available on sediment deposition and delta margin evolution, as related to climatic, eustatic, fluviatile, and coastal marine processes (Sestini, 1992; Said, 1993; Stanley and Warne, 1998). This information, serving to define the three-dimensional (temporal, aerial) anatomy of the late Quaternary delta, is also used as the base for the present and ongoing study in the bay (Stanley et al., 2004).

Herakleion and Eastern Canopus were established as navigational centers along mouths of the Canopic when this was the largest Nile delta branch and the delta shoreline was located ~5 km north of the present coast (Fig. 2). The cities were primary gateways to northern Egypt, where goods were transported to the major Greek trading center of Naukratis in the delta proper, about 55 km inland from the present coast (Coulson and Leonard, 1979). Historical documentation in conjunction with archaeological information indicates that Herakleion (Fig. 3) was active from about the sixth century B.C. to the first century A.D. Eastern Canopus, the younger city, disappeared after Greek, Roman, and Byzantine rule and shortly following the Arab conquest (Bernand, 1970). This is substantiated by writings of Sophronius of Jerusalem, who indicated that a temple dedicated to Christian Evangelists in Eastern Canopus was still upright at the beginning of the seventh century A.D. At that time, it was located on a beach with marine waters lapping against its base and coastal sand accumulating along part of its foundation (Toussoun, 1934). Dated gold coins discovered at the site indicate that the temple's final destruction and submergence occurred in the mid-eighth century A.D. (Stanley et al., 2001).

Processes that induced submergence of the two cities in Abu Qir Bay are interpreted on the basis of integrated archaeological information (1996–present), close-grid bathymetric, magnetometer, and side-scan sonar exploration (in 1996 and 1997), high-resolution subbottom seismic survey (in 2000), and sediment vibrocore recovery (in 2001).

GRADUAL SUBMERGENCE

Abu Qir Bay occupies an area that is only moderately active tectonically (Kebeasy, 1990) and is subject to recent loading and sediment compaction from large depositional input at Canopic channel mouths (Hassouba, 1980). High-resolution seismic profiles (Triton EdgeTech XStar system) show the configuration of the ~3–15 m thick Holocene sediment section of Nile derivation in the 50-km-long bay. The pro-

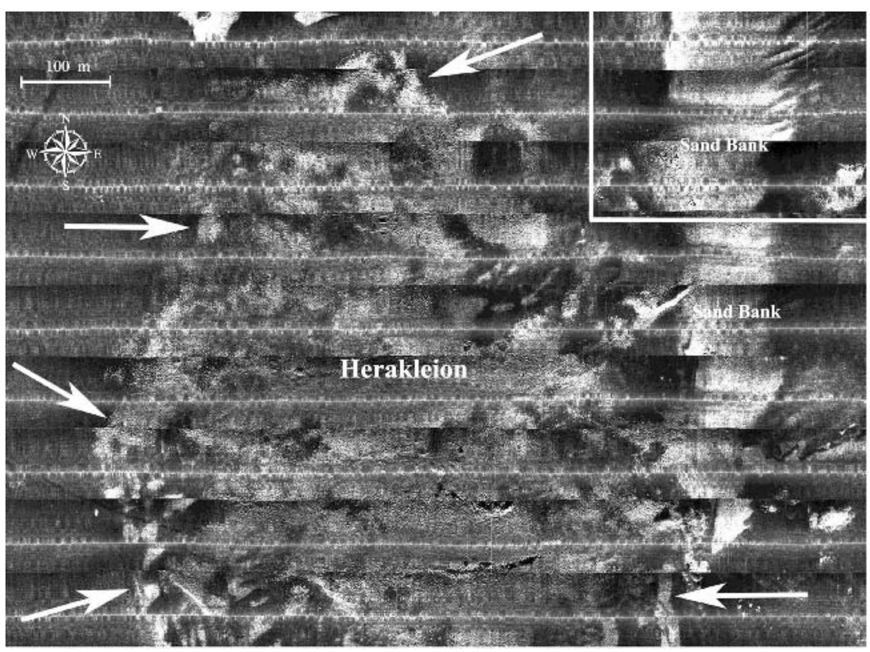

Figure 3. Side-scan sonar image partially shows the oval configuration of Herakleion ruins (arrows delineate general city limits) at water depths of 5–7 m. Diver exploration shows feathery patterns in upper right panel are tilted and uplifted mid-Holocene strata exposed on the bay floor. Each side-scan swath = 80 m.

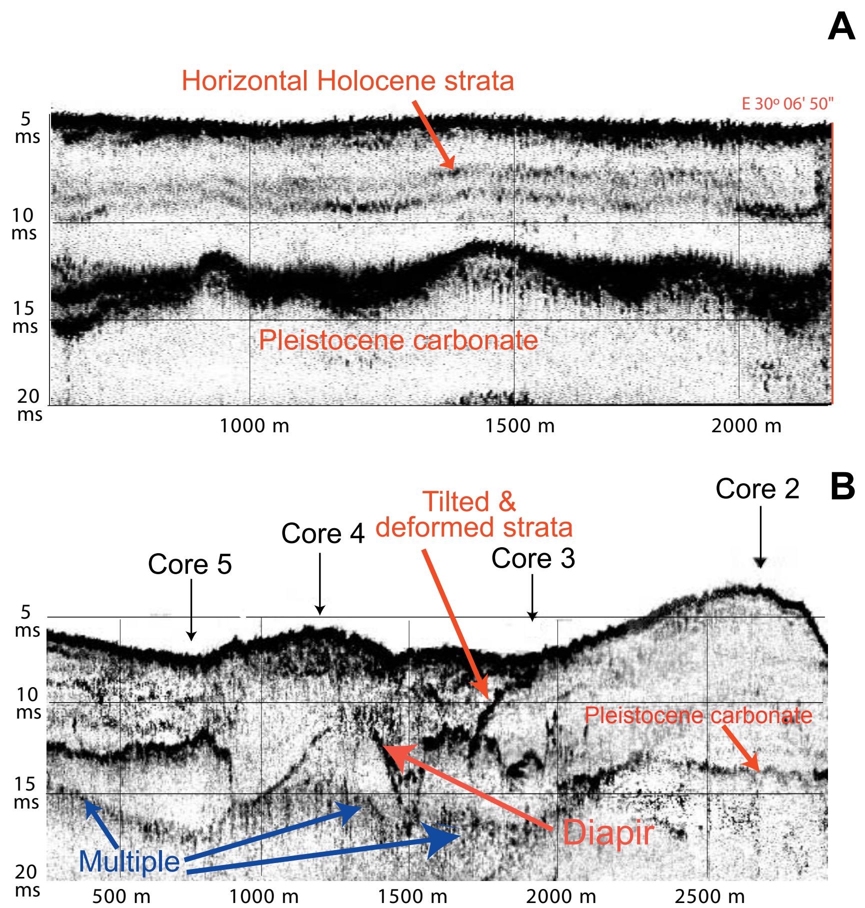

Figure 4. High-resolution profiles in Abu Qir Bay (location in Fig. 2) showing **(A)** Holocene horizontal strata above Pleistocene limestone base, between Herakleion and Eastern Canopus, and **(B)** tilted and deformed Holocene substrate directly under Herakleion ruins. Depth in milliseconds (10 ms = 7.5 m); horizontal scale at base of profiles in meters (vertical exaggeration ranges from 40 (in A) to 80 (in B).

files, collected along 15 N-S and 22 E-W oriented transects, are spaced from 100 to 1000 m apart (Stanley et al., 2004); they account for ~350 km of profile lines covering an area of nearly 100 km^2 (Fig. 2). The basal consolidated Pleistocene carbonate unit, subaerially exposed until about 10,000–8000 years ago, forms a blocky configuration (Fig. 4; note strong, well-defined basal seismic reflectors). The overlying Holocene sediment, comprised of silty muds and sands, began to accumulate about 7500 years ago, when post-glacial rise of sea level had nearly reached its present stand (Stanley and Warne, 1994). This sediment section in the bay thickens toward the east, covering Pleistocene carbonates.

More than half of the bay is covered by near-horizontal stratified Holocene deposits that parallel and subparallel the seafloor surface (Fig. 4A). Gentle downward-bowing of recent sediment sections is a function of rapid deposition, compaction, and weighting of the late Holocene section at former Canopic mouths. Core analysis indicates these are flat-lying strata of Canopic delta sublobes (mostly wetland deposits). During the past 13 centuries, strata were submerged by two gradual processes: eustatic (world) rise in sea level and concurrent lowering of land. The eustatic sea level component at that time accounts for a rate of rise of ~1 mm/yr in this Mediterranean region (Milliman and Haq, 1996). Moreover, the delta margin in the study area concurrently subsided at a rate of ~1 mm/yr (Chen et al., 1992; Sestini, 1992; Warne and Stanley, 1993), resulting in a relatively rapid cumulative rise of 2 mm/yr. This rate approximates the average ~2.5 mm/yr measured for the lower Nile delta margin as a whole, and accounts for a gradual but substantial long-term submergence component at both Herakleion and Eastern Canopus.

For more specific measurement of gradual submergence, three factors are assumed. (1) Large human-made structures at the two sites were originally emplaced at the maximum land elevation of 2 m above mean sea level (m.s.l.) (i.e., above the adjacent delta wetlands of lower [<1 m above m.s.l.] elevation). (2) A value of 6 m below m.s.l. is used for the average depth of submerged ruins presently on the bay floor. These two factors account for a total lowering of ~8 m. To measure the subsidence rate at Herakleion, it is also assumed that initial construction began after Pharaoh Psamtik (Psammetichos) I authorized Greek merchants to trade in Egypt in the seventh century B.C. It is probable that settlement was well under way by the sixth century B.C., during the reign of Amasis, when ships traveled to the port of Naukratis (Coulson and Leonard, 1979). Thus, (3) the time between construction and present discovery of ruins in the bay is ~2500 years.

About 12 centuries elapsed between construction at 2 m above m.s.l. in the sixth century B.C. and the time when Sophronius of Jerusalem described the temple of the Evangelists as still standing at the shoreline at the beginning of the seventh century A.D. (Bernand, 1970). This records a relative sea-level rise of ~2 m in 1200 years (i.e., a minimal mean rate of rise of 1.7 mm/yr). A comparable rate of annual relative sea-level rise (2.0 mm/yr) for this region has been calculated independently on the basis of radiocarbon-dated cores for the mid to late Holocene period, including the time span from 700 A.D. to the present (Chen et al., 1992; Warne and Stanley, 1993). By applying the value of 2.0 mm/yr during the past 13 centuries (from Byzantine time to present), an additional amount of relative sea-level rise of 2.6 m is derived. This would account for submergence of 4.6 m in 2500 years, or only somewhat more than half of the total lowered elevation (~8 m) since initial construction at Herakleion. The gradual rise component would have caused submergence of large areas of low-lying delta margin and considerable shoreline retreat in a southward (landward) direction.

Thus, gradual processes alone would not explain the lowering to ~6 m below m.s.l. Submergence to this depth by only relative sea-level rise would have required a mean annual sea-level rise of at least 3.2 mm/yr, or one much higher than calculated (1.7–2.0 mm/yr) on the basis of radiocarbon-dated core sections and archaeological finds. Or, alternatively, an additional 1500 years (not 2500, but at least 4000 years) would have been needed for a total gradual lowering of the structures by 8 m at the calculated average rate of 2.0 mm/yr. In sum, sea-level rise and gradual sediment compaction account for little more than half of total submergence (4–5 m of the 8 m) in 2500 years. Nevertheless, sea-level rise of this magnitude would have induced migration of channels, delta lobes, and the coastal margin in this region. Seismic profiles and shallow-water coring indicate that at least three shifts of major Canopic channels occurred since the mid-Holocene (Stanley et al., 2004): two older channels were mapped in the western bay, one flowing toward Herakleion and the other toward Eastern Canopus prior to 2500 yr B.P. (Fig. 2, C1 and C2). A third, younger channel (Fig. 2, C3) is detected to the east, in the central bay (El-Bouseily and Frihy, 1984; El Fattah and Frihy, 1988; Chen et al., 1992).

RAPID SUBSTRATE FAILURE

In light of the above findings, other mechanisms in addition to gradual submergence must have contributed to lowering of sites to their present depths. A significant clue is provided by the Holocene sediment substrate observed specifically under Herakleion and Eastern Canopus (each area covers ~1 km^2) that is highly disturbed by offset, tilted, uplifted, and/or lowered strata recorded on seismic profiles (Fig. 4B). Also noted are diapirs, large domed, post-depositional, squeezed-upward sediment features, growth and normal faults, and scarps. The bedding, originally laid down horizontally at and seaward of the delta mouths, was deformed by syn- and post-depositional events. Of note are exposed strata on the bay floor of mid-Holocene or older age (tilted and diapiric) uplifted to the bay floor, as noted on side-scan sonar images (Fig. 3) and on seismic profiles (Fig. 4B). Such offset affected deeper (including early to mid-Holocene) layers that once lay well beneath (at least 5 m) the two cities.

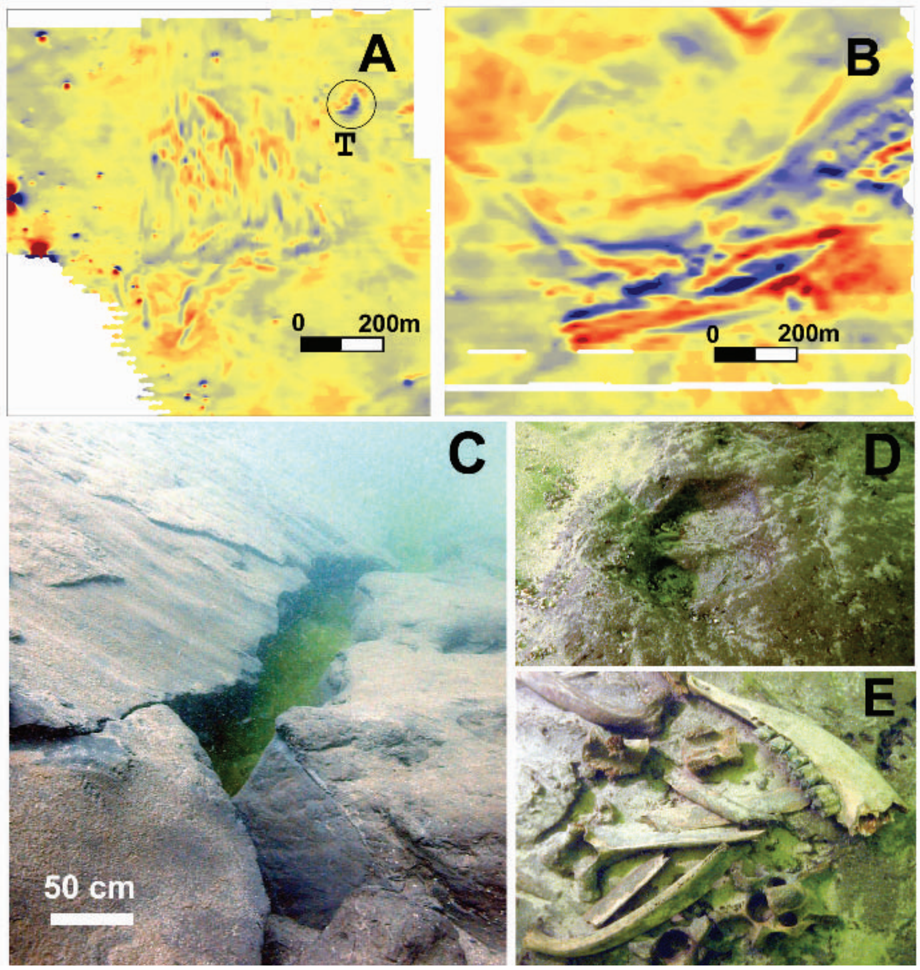

Figure 5. Evidence of important substrate failure restricted to areas underlying the two cities in Abu Qir Bay. **A:** Resonance magnetometer survey showing distinct N-S and E-W anomalies and the diver-excavated trench (T) at Eastern Canopus (details in C–E). **B:** ENE-WSW trending anomalies in the Herakleion area (areas affected in A and B are ~1 km^2). **C:** Bay-floor photograph showing base of trench (fault scarp) after removal by divers of artificially-introduced sand fill; note rectilinear fault-like feature in the firm mud base of the trench (~50 cm wide and deep). **D:** Cloven-hoofed bovid (probably cow) track in mud at bottom of trench. **E:** Antelope bones in trench base (radiocarbon dated to first century A.D.).

Moreover, a nuclear resonance magnetometer survey (which images differences in density in the shallow subsurface) of the entire western bay (method and coverage detailed in Stanley et al., 2004) was made to detect anomalous signals that record marked natural and anthropogenic features otherwise not visible on and within the Holocene cover in the study area. It is of note that the only two major distinct anomalies were those observed at the seafloor in the immediate vicinity of the two submerged cities (Fig. 5: in A, oriented E-W and N-S; in B, NE-SW). Although the anomaly at locality T at Eastern Canopus (Fig. 5A) is well defined on the records, exploration of this seafloor area showed only a smooth, sand-covered surface. Diver excavation at anomaly T, located near a large temple, identified a long (~100 m), well-defined trench buried in the underlying Holocene mud substrate (Fig. 5C). Cleared of overlying sand, this curvilinear trench is V-shaped in cross section, about 5 m wide at the top and 2 m deep from the bay floor surface to its base. Moreover, a well-defined, rectilinear fault break (~50 cm wide and deep) is present in the mud that forms its base (Fig. 5C). Diver surveys, along with grain size and compositional analyses of the sand, indicate that the trench (a probable fault scarp; cf. Coleman, 1988) had been artificially filled with sand when the adjacent man-built structures were at the coast and still positioned at an elevation above sea

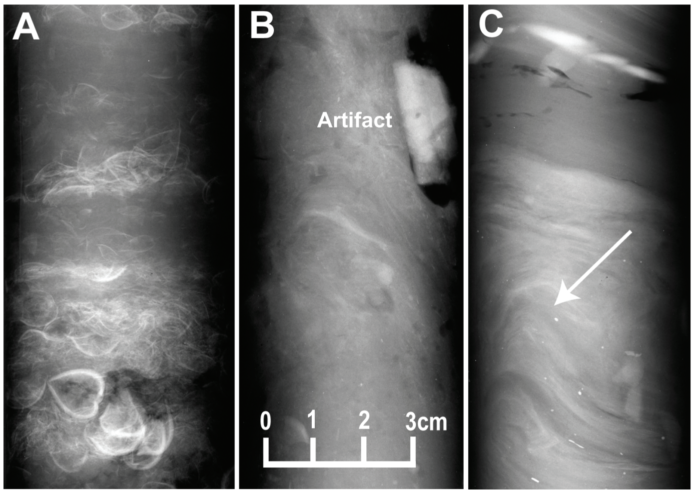

Figure 6. X-radiographs of split-core sections in study area (core sites in Fig. 2). **A:** Core 15 (depth ~110 cm from core top), showing typical delta wetland facies comprising bedded shell horizons in organic-rich silty mud matrix. **B:** Core 5 (depth ~13 cm from core top), with potsherd artifact in sediment-remobilized mud section. **C:** Core 9 (depth ~100 cm from core top), illustrating fluidized section with well-developed flame structure (arrow).

level (Stanley et al., 2001). Additionally, the trench walls were originally lined with mats of fresh and brackish water plants, mainly phragmites, before sand was added in the depression. Well-preserved cloven-hoofed bovid tracks (Fig. 5D) and bones of an antelope (dated to the first century A.D.) were also present on the trench floor (Fig. 5E).

Sediment vibracores (lengths 1.5–5.5 m) were collected at and between the two ancient cities in the study area (Fig. 2). Seven of the 17 core localities were positioned at Herakleion (numbers 3–5 and 8–11), four at and near Eastern Canopus (14–17), and six in bay sectors away from the two submerged sites (1, 2, 6, 7 east of Herakleion, and 12 and 13 between Herakleion and Eastern Canopus). A thin (<1.0 m), surficial marine sand layer at most core tops contains terrigenous components of Nile derivation, carbonate particles, and shell debris of mollusks and other organisms. This sand covers typical delta wetland and margin lithologies: fine to medium grain sand, moderately to well sorted and laminated; dark organic-rich mud (silt and clay components), uniform and non-laminated; mud formed of well-laminated alternating silt and clay; and fine-grained mud with interbedded whole and broken mollusk shells (Fig. 6A).

In six of the 17 borings, there are contorted units (~30–60 cm thick) that show soft-sediment deformation. Contorted strata formed of mud and sand show vertical sediment flow (Fig. 6B) and flame (Fig. 6C) structures, evidence of sediment remobilization (including fluidization) where water-saturated material has flowed upward in liquid-like fashion. They occur in cores 3, 5, 7, and 9 at and near Herakleion and in cores 15 and 16 at Eastern Canopus. Moreover, unusually old radiocarbon dates, ranging from >5000 to ~6880 yr B.P. (uncalibrated dates), were obtained for samples near core tops at both archaeological sites (Stanley et al., 2004). In contrast, much younger dates (to 1980 ± 40 yr B.P.) were obtained in the upper parts of some cores collected in the bay away from the ruins (e.g., core 13). Samples of peat and organic-rich sediment were also collected by divers in the substrate just beneath archaeological structures at the bay floor. Of 12 such samples, three were dated at ~2000 yr B.P. and five from 2250 to 2360 yr B.P., and these eight appear consistent in that they are within an expected age range for the substrate of a Hellenistic settlement. However, four of the 12 surficial samples were older: one >3130 yr B.P.; and three much older, to 6750 yr B.P. Thus, some unexpectedly old (mid to late Holocene) deposits that lie immediately beneath the two ancient cities probably resulted from tilting to the bay floor (Fig. 4B) and sediment remobilization (Fig. 6, B and C). Moreover, mollusks and microfauna (ostracods, foraminifera) collected in these same core samples are primarily mixes of brackish and fresh-water delta margin species, with only small proportions of open-marine bay forms (M.P. Bernasconi, R. Mellis, and N. Pugliese, 2003, personal commun.).

The disturbed beds, restricted to substrates of the two settlements, were originally deposited close to distributary mouths in Canopic deltaic sublobes. During high and extremely high flood stages, delta mouth settings are characterized by increased outflow velocities, bed shear, and fluid turbulence,

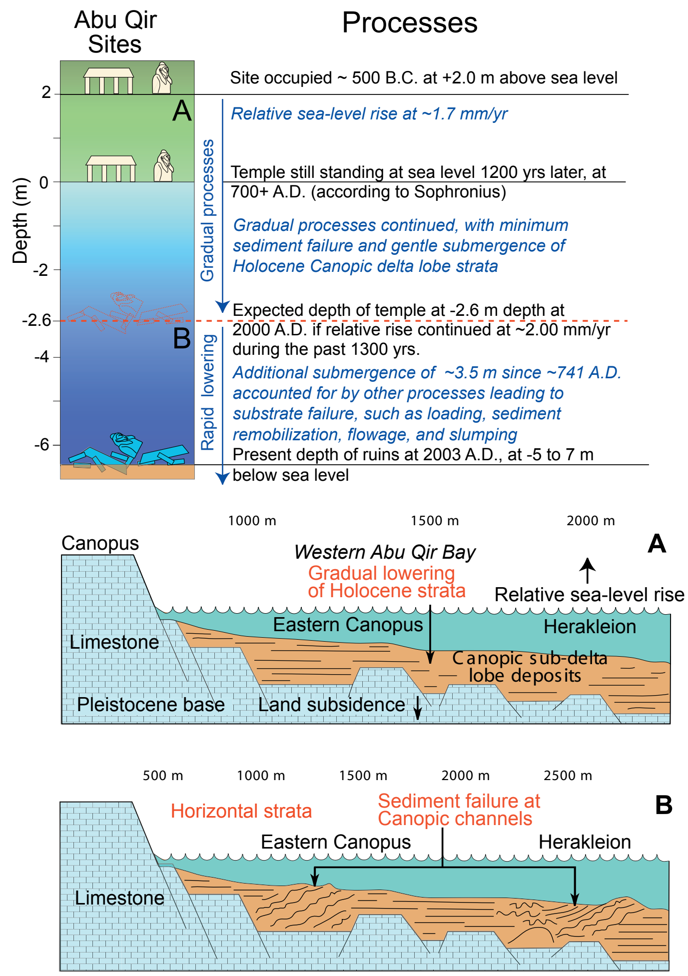

Figure 7. Interpretation of processes that submerged Herakleion and Eastern Canopus to depths of 5–7 m below sea level, from ca. 500 B.C. to the present. Processes involved: **(A)** gradual lowering of strata (as in Fig. 4A) and substrate failure (as in Fig. 4B). Discussion in text.

along with increased and commonly prolonged discharge of denser sediment-laden river waters (Wright and Coleman, 1974). Some water-saturated muds that lose coherence are squeezed upward by differential loading (Fig. 4 B), especially where layers of sandy deposits are added, such as along an advancing river channel and seaward of the mouth (Morgan et al., 1963; Coleman and Wright, 1975). Even in tectonically tranquil regions and on horizontal surfaces, such sediment records rotational slumping, mud flow (Wright and Coleman, 1974; Coleman, 1988), growth, and normal fault offset (Maestro et al., 2002). Sudden sediment displacement commonly occurs from subaerial and submerged natural levees (elevations of +2 to –2 m), displacing strata to the adjacent deeper seafloor.

In addition to natural processes, it is highly probable that subsidence at Herakleion and Eastern Canopus occurred from placement of heavy structures, such as temple columns and large walls, directly on the under-consolidated mud substrate. Even when positioned on special raft foundations, buildings underlain by soft, compressible mud in such settings can subside by 3 m or more in less than a century (Waltham, 2002). Surveys of the two cities made thus far, however, indicate no evidence of solid foundations or pilings emplaced beneath massive structures, including granite columns. Thus, while sites were still occupied, some structures probably tilted or failed under their own weight, thus requiring periodic readjustment or abandonment, even before the overall settlement areas were finally covered by the bay waters.

CONCLUSIONS AND RAMIFICATIONS

Submergence of Herakleion and Eastern Canopus to their present depth involved (1) gradual relative sea-level rise and land subsidence in Abu Qir Bay (Fig. 7A), plus (2) periodic failure events involving lateral displacement of unstable water-saturated sediment at Canopic mouths (Fig. 7B). Geological exploration together with analysis of archaeological data indicate that at least some destruction of settlements and subsidence occurred abruptly. Evidence for sudden and unexpected substrate shifts includes human skeletal remains and gold, jewelry, statuary and other valuables discovered beneath damaged and toppled walls.

Rapid episodic subsidence would have occurred at Canopic mouth settings, in part, from rapid accumulation of water-saturated sediment, depositional loading, and associated conditions of sediment remobilization that commonly prevail in deltaic settings. Floods, so critical for development of Egyptian civilization, occurred each year in late summer to fall, and their levels were carefully recorded (Popper, 1951). Exceptionally high annual floods are correlated with climatic fluctuations in central and east Africa (Shahin, 1985; Said, 1993). Sudden weighting on unstable channel mouth deposits during, or subsequent to, flood stage was a likely trigger of sediment failure. In the first century A.D., high floods of this type would likely have affected Herakleion by inducing channel migration, substrate failure, and damage to structures. Final destruction of Eastern Canopus is attributed to a particularly high Nile flood (~1 m higher than normal high flood stage) in 741 or 742 A.D. (Stanley et al., 2001), a hypothesis supported by data from the Roda Nilometer in Cairo (Popper, 1951).

Sediment subsidence at these localities may not necessarily have resulted from a single catastrophic event but perhaps a sequence of episodic events. Earthquake tremors possibly also affected the Abu Qir Bay area. Seismo-archaeological surveys in sectors of the Eastern Mediterranean have suggested that the period from the fourth to sixth centuries A.D. was one of unusual clustering of destructive earthquakes (Pirazzoli, 1986; Stiros, 2001). An example of such an event is provided by the August 17, 1999, earthquake that resulted in massive damage of structures and sudden subsidence at Izmit, a Sea of Marmara coastal city in northwestern Turkey (Holzer et al., 2000).

A natural devastating event such as an earthquake or tsunami that could have destroyed these cities likely would have been recorded in historic accounts, but no earthquake activity, for example, is recorded in Egypt during the 741 or 742 A.D. period (Guidoboni, 1994). Moreover, we believe effects of earthquakes and tsunamis would be observed not only in deposits forming the substrate specifically beneath ruins of the two ancient cities built at river mouths (Fig. 4B), but over a much broader area of the bay and adjacent delta margin. This latter observation, however, is not the case (see Fig. 4A; Stanley et al., 2004).

Combined effects of gradual and sudden events likely resulted in lowering of some settlement areas below the waves, while other parts of the cities remained inhabited on low islands, perhaps as Herodotus described Herakleion around 450 B.C. Recovery of archaeological artifacts such as Byzantine and Arabic coins at Eastern Canopus indicates that habitation of some partially submerged islands in the bay may have continued for decades, or even centuries, following major phases of submergence and abandonment of parts of the original cities.

This geoarchaeological analysis illustrates extreme consequences that occur when carefully implemented protection measures related to coastal sites and associated environmental conditions are overlooked. In the examples presented here, the Greeks and subsequent inhabitants built and maintained their sites on unstable wetland sediment, without foundations and pilings, at distributary mouths that experienced powerful annual Nile floods. Given the remarkable Greek and Roman building and engineering tradition, it is difficult to fully comprehend the decisions that led to emplacement of large, monumental structures directly on underconsolidated and unstable sediment prone to soil instability and associated geohazards. Most likely, this action was taken for specific economic gains and advantages, including collecting tolls and associated trade benefits; ramifications for the long-term were not likely a prime consideration. At this point, it is easy for us to look back two millennia and find fault. However, we know that Greek and Roman engineers were accustomed to other geohazards, such as earthquakes, in many of their population centers landward of the coast where they usually built on a solid base. They were less accustomed to repairing damage caused by coastal geologic factors, and had not fully acquired the experience to foresee hazards associated with floods, storm surges, tsunamis, and sea-level rise.

Moreover, they had not acquired building techniques, such as deep pilings, for construction of heavy structures on soft-sediment based deltaic sites and the building of protective dikes and polders. It is remarkable that, in spite of these deficiencies, the sites at the Canopic mouths remained active for several centuries.

Some old but still active cities in deltaic and wetland settings, such as Venice, are facing comparable hazards. Although remaining extremely vulnerable to coastal geohazards, most have not yet reached the ultimate phase involving toppling of structures followed by complete submergence, as experienced by Herakleion and Eastern Canopus. What is perhaps even more surprising is that, in so many cases, engineers and municipalities still do not fully implement appropriate protection and construction measures, after centuries of building and engineering experience since Hellenistic time. Perhaps the cautionary tale is the extent to which short-term economic exigency remains a recurring element in our cultural and historic traditions.

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REFERENCES CITED

Attia, M., 1954, Deposits of the Nile Valley and Delta: Cairo Geological Survey, Publication 65, 356 p.

Barends, F.B.J., Brouwer, F.J.J., and Schroeder, F.H., editors, 1995, Land Subsidence: International Association of Hydrological Science, Publication 234, 492 p.

Bernand, A., 1970, Le delta Egyptien d'après les textes Grecs: Cairo, Institut Français d'Archéologie Orientale du Caire, p. 117–327.

Butzer, K.W., 1976, Early Hydraulic Civilization in Egypt: Chicago, University of Chicago Press, 134 p.

Chen, Z., Warne, A.G., and Stanley, D.J., 1992, Late Quaternary evolution of the northwestern Nile Delta between Rosetta and Alexandria, Egypt: Journal of Coastal Research, v. 8, p. 527–561.

Coleman, J.M., 1988, Dynamic changes and processes in the Mississippi River delta: Geological Society of America Bulletin, v. 100, p. 999–1015.

Coleman, J.M., and Wright, L.D., 1975, Modern river deltas: variability of processes and sand bodies, *in* Broussard, M.L., ed., Deltas Models for Exploration: Houston, Houston Geological Society, p. 99–149.

Constanty, H., 2002, Héracléion, les trésors de la ville engloutie: GEO, v. 283, p. 148–158.

Coulson, W.D.E., and Leonard, A., 1979, A preliminary survey of the Naukratis region in the western Nile delta: Journal of Field Archaeology, v. 6, p. 151–168.

El-Bouseily, A.M., and Frihy, O.E., 1984, Textural and mineralogical evidence denoting the position of the mouth of the old Canopic Nile branch on the Mediterranean coast, Egypt: Journal of African Earth Sciences, v. 2, no. 2, p. 103–107.

El Fattah, T.A., and Frihy, O.E., 1988, Magnetic indications of the position of the mouth of the old Canopic branch of the northwestern Nile delta of Egypt: Journal of Coastal Research, v. 4, p. 483–488.

Fourtau, R., 1915, Contribution à l'étude des dépots nilotiques: Mémoires de l'Institut Egyptien, v. 8, p. 57–94.

Guidoboni, E., 1994, Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century: Bologna, Istituto Nazionale di Geofisica, 504 p.

Hassouba, A.M.B.H., 1980, Quaternary sediments from the coastal plain of northwestern Egypt from Alexandria to El Omayid [doctoral thesis]: Imperial College London, 320 p.

Herodotus, The History, translated by David Grene, 1987: Chicago, University of Chicago Press, 699 p.

Holzer, T.L., Barka, A.A., Carver, D., Çelebi, M., Cranswick, E., Dawson, T., Dieterich, J.H., Ellsworth, W.L., Fumal, T., Gross, J.L., Langridge, R., Lettis, W.R., Meremonte, M., Mueller, C., Olsen, R.S., Ozel, O., Parsons, T., Phan, L.T., Rockwell, T., Safak, E., Stein, R.S., Stenner, H., Toda, S., and Toprak, S., 2000, Implications for Earthquake Risk Prediction in the United States from the Kocaeli, Turkey, Earthquake of August 17, 1999: Reston, Virginia, U.S. Geological Survey Circular 1193, 65 p.

Kebeasy, R.M., 1990, Seismicity, *in* Said, R., ed., The Geology of Egypt: Rotterdam, A.A. Balkema, p. 51–59.

Maestro, A., Barnolas, A., Somoza, L., Lowrie, A., and Lawton, T., 2002, Geometry and structure associated to gas-charged sediments and recent growth faults in the Ebro Delta (Spain): Marine Geology, v. 186, p. 351–368.

Milliman, J.D., and Haq, B.U., editors, 1996, Sea-level rise and coastal subsidence: Dordrecht, Kluwer Academic Publishers, 369 p.

Morgan, J.P., Coleman, J.M., and Gagliano, S.M., 1963, Mudlumps at the mouth of South Pass, Mississippi River; sedimentology, paleontology, structure, origin, and relation to deltaic processes: Baton Rouge, Louisiana State University, Coastal Studies Institute Series 10, 190 p.

Pirazolli, P.A., 1986, The early Byzantine tectonic paroxysm: Zeitschrift für Geomorphologie, N.F., supplement 62, p. 31–49.

Popper, W., 1951, The Cairo Nilometer: Los Angeles, University of California Press, 269 p.

Said, R., 1993, The River Nile: Geology, hydrology and utilization: New York, Pergamon Press, 320 p.

Sestini, G., 1992, Implications of climatic changes for the Nile delta, *in* Jeftic, L., Milliman, J.D., and Sestini, G. eds., Climatic change and the Mediterranean: London, Edward Arnold, p. 535–601.

Shahin, M., 1985, Hydrology of the Nile Basin: Amsterdam, Elsevier, 575 p.

Stanley, D.J., Goddio, F., and Schnepp, G., 2001, Nile flooding sank two ancient cities: Nature, v. 412, p. 293–294.

Stanley, D.J., McRea, J.E., Jr., and Waldron, J.C., 1996, Nile Delta drill core and sample databases for 1985–1994: Mediterranean Basin (MEDIBA) Program: Washington, D.C., Smithsonian Institution Press, Smithsonian Contributions to the Marine Sciences 37, 428 p.

Stanley, J-D., Schnepp, G., and Jorstad, T., 2004, Submergence of archaeological sites in Abu Qir Bay, the result of gradual long-term processes plus catastrophic events, *in* Goddio, F., et al., eds., Canopus I, The submerged western Canopic region: London, Periplus Publishing (in press).

Stanley, D.J., and Warne, A.G., 1994, Worldwide initiation of Holocene marine deltas: Deceleration of sea-level rise as principle factor: Science, v. 265, p. 228–231.

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

Stiros, S.C., 2001, The AD 365 Crete earthquake and possible seismic clustering during the fourth to sixth centuries AD in the Eastern Mediterranean: a review of historical and archaeological data: Journal of Structural Geology, v. 23, p. 545–562.

Toussoun, O., 1934, Les ruines sous-marines de la Baie d'Aboukir: Bulletin de la Société Royale d'Archéologie, Alexandrie, v. 29, p. 342–352.

Waltham, T., 2002, Sinking cities: Geology Today, v. 18, p. 95–100.

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, v. 9, p. 26–64.

Wright, L.D., and Coleman, J.M., 1974, Mississippi River mouth processes: effluent dynamics and morphologic development: Journal of Geology, v. 82, p. 751–778.

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