Journal of Coastal Research	25	1	158–170	West Palm Beach, Florida	January 2009

Ancient Archaeological Sites Buried and Submerged along Egypt's Nile Delta Coast: Gauges of Holocene Delta Margin Subsidence

Jean-Daniel Stanley and Marguerite A. Toscano

Cities Under the Sea Program (CUSP)
Paleo-E207
National Museum of Natural History
Smithsonian Institution
Washington, DC 20013-7012, U.S.A.
stanleyd@si.edu

ABSTRACT

STANLEY, J.-D. and TOSCANO, M. A., 2009. Ancient archaeological sites buried and submerged along Egypt's Nile Delta coast: Gauges of Holocene delta margin subsidence. *Journal of Coastal Research,* 25(1), 158–170. West Palm Beach (Florida), ISSN 0749-0208.

For calculating subsidence rates along the Nile Delta coastal margin, archaeological site data provide more accurate temporal and elevation control relative to Holocene sea levels than chronostratigraphic analyses of radiocarbon-dated sediment cores. Recently acquired data on the depth and age of 11 buried and/or submerged levels of human activity at seven ancient sites serve to calculate average annual rates of subsidence along the northern Nile Delta margin during the middle to late Holocene. Subsidence rates range from 0.9 to 4.3 mm/yr, varying irregularly from west to east along the northern delta coast, and averaging ~2.5 mm/yr for 11 data points on the margin as a whole.

Subsidence rate is directly related to thickness of sediment section, with highest values in the eastern part of Manzala lagoon and at coastal promontories of the Damietta and Rosetta branches. This, in large part, is a function of underlying sediment compaction plus sediment loading and readjustment of strata at depth. Short-term natural events such as earthquakes, tsunamis, Nile floods, and winter storm surges also serve as triggers of subsidence. An additional important factor is human activity, such as construction of large structures on water-saturated substrates. Most modern towns along this increasingly populous delta margin are located in low-lying vulnerable settings presently subject to subsidence, a phenomenon that warrants close monitoring and increased implementation of protective measures.

ADDITIONAL INDEX WORDS: *Archaeology, burial, chronostratigraphy, coastal towns, cores, Holocene, human impact, Manzala lagoon, radiocarbon dates, relative sea level, sediment failure, shoreline migration, submergence, subsidence, uplift.*

INTRODUCTION

The low-lying coasts of most fluvial-marine deltas in the world's nonglaciated and relatively stable tectonic settings during the Holocene have been subject to effects of both rising sea level and subsiding land elevation. As a result, settlements originally placed at or near coastal margins of large deltas in ancient time would by now be partially buried by depositional sequences and/or completely submerged. Consequently, archaeological exploration of coastal sites such as those of the Nile Delta tends to be a logistically difficult exercise (Figure 1). In discussing the Nile Delta a century ago, it was assumed that this delta is "so deeply overlaid with deposits of Nile mud that the material remains of its earliest civilization are buried forever from our reach" (Breasted, 1909, p.32).

From the early Holocene until the early to mid-1800s, the 225-km-long Nile Delta margin along the Mediterranean annually received very large volumes (~160 million tons/yr) of sediment discharged by the Nile River (Inman and Jenkins, 1984; Said, 1981). This high accumulation of fluvial sediment released on the lower delta plain and its seaward extension during the Holocene has effectively buried early human sites. Archaeological surveys along Egypt's low-lying Nile Delta coast during the past two centuries have primarily recovered vestiges of more recent historical periods, *i.e.,* after the fourth century AD, including late Roman, Byzantine, and Islamic (Baines and Málek, 1985; Butzer, 1976; Manley, 1996). Only few early Roman, Greek, and older sites, however, are now subaerially exposed on sediment surfaces of the lower deltaic plain. The emplacement of Nile barrages, construction of the two dams at Aswan, and intensified development of closely spaced water projects have diverted Nile flow such that sediment aggradation on the lower plain and inner shelf have been markedly reduced, particularly since the middle of the 20th century (Stanley, 1996). Nevertheless, the overall thick Holocene depositional cover and shallow groundwater table are factors that together continue to hamper subsurface archaeological excavation in the northern delta.

Fifteen years ago a general synthesis of the Nile River sys-

DOI: 10.2112/08A-0013.1 received and accepted in revision 3 July 2008.

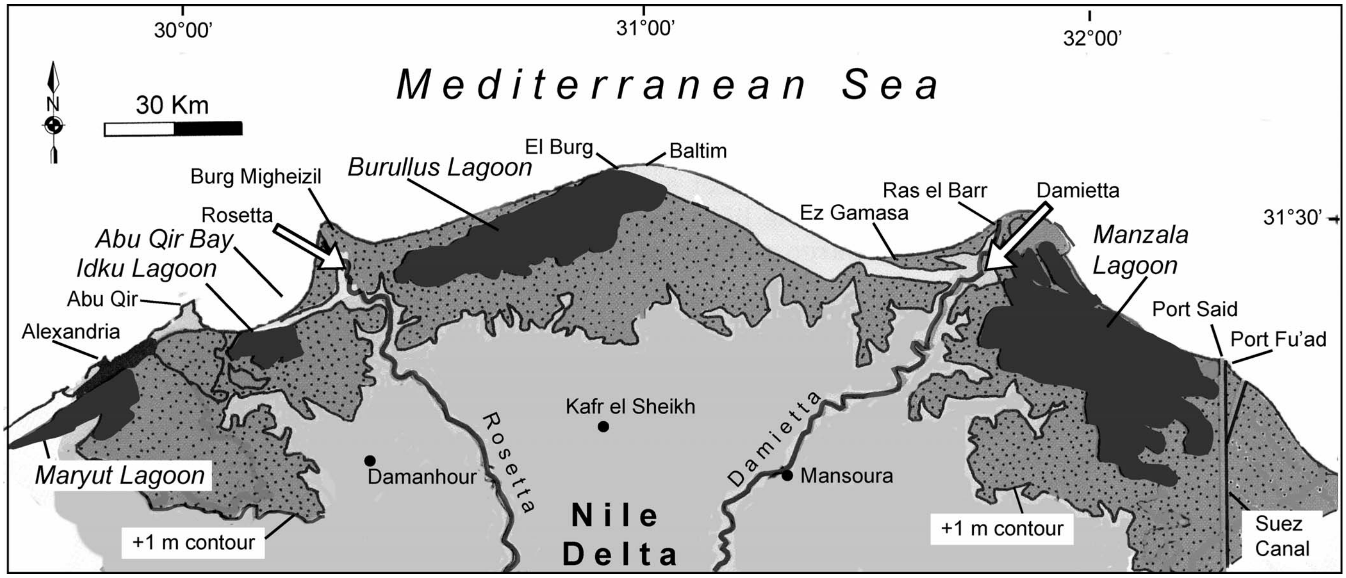

Figure 1. Map of the northern Nile Delta showing geographic features and localities cited in study.

tem proposed that the Holocene Nile Delta plain surface, including its northern margin, had not subsided (Said, 1993, p. 77–78). Since then, lithologic and chronostratigraphic analyses of numerous, long, radiocarbon-dated sediment cores collected along the lower plain (Stanley and Warne, 1998) provide clear evidence of significant regional delta margin subsidence, or land lowering, combined with local relative sea-level rise in the late Quaternary. During the Holocene, these processes led to submergence of the coast and thick accumulations of fluvial-marine sediment (10.0 to 50.0 m) along the northern delta, primarily in the sector between the inner Nile shelf and lower delta plain, to about 30 km inland from the present coast (Stanley and Warne, 1998).

More recently, systematic exploration offshore by divers (Empereur, 1998; Goddio, 1998, 2007), offshore seismic profiling, and coring along the entire length of the northern Nile Delta coast (Stanley, 2007; Stanley and Warne, 1998; Stanley *et al.,* 2007) are now beginning to reveal an early human presence along this margin. This investigation attempts to quantify differential delta plain subsidence by synthesizing newly acquired data from seven ancient sites at the northern delta plain and seaward of the coast (Figure 2). In some cases, their early occupation and foundation levels are no longer visible, while in others, the entire site is now completely buried and/or submerged.

Elevations and ages of submerged or buried ancient human activity levels have been corrected relative to present mean sea level (msl) and are used to quantify the total amount and long-term average annual rate of subsidence for each of the 11 occupational levels at the seven sites distributed along the Nile Delta margin. The archaeological ages and radiocarbon dates and elevations of these occupation levels were compared to past sea levels using the glacio-isostatic sea-level model developed along the Carmel Coast, Israel (Sivan *et al.,* 2001). Deviations of dated levels from past sea levels represent the amount of subsidence since the establishment of those levels. Determination of subsidence rates is not only a necessary element to help in archaeological research and exploration, it also bears directly on implementing coastal protection measures for existing towns positioned along the modern Nile Delta margin.

METHODS

Cores

Eighty-five drill cores ranging from about 20 to over 50 m in length were collected by the Smithsonian's National Museum of Natural History along the 225-km-long arcuate coastal margin of the Nile Delta (Figure 2). The cores, obtained with trailer mounted Acker II rotary-percussion equipment, penetrated complete Holocene sections and extended into the underlying late Pleistocene units of the northern delta. Most cores were obtained starting at elevations ranging from ~0.5 to 1.0 m above msl. Sediments (peat, shell, organic-rich layers) were radiocarbon dated and analyzed petrologically (Stanley, McRea, and Waldron, 1996), and these data have proved valuable to help determine rates of subsidence along the delta margin (Stanley and Warne, 1998).

Supplemental lithostratigraphic core data were obtained from sediment core logs collected earlier in this sector by Fourtau (1915), Attia (1954), and Sestini (1989, 1992), and in coastal civil engineering project reports. Also examined were logs of cores collected offshore, including those described by Attia (1954), Frihy, Moussa, and Stanley (1994), civil engineering reports, and in geoarchaeological studies (Stanley, 2007; Stanley *et al.,* 2007). In addition, numerous and closely spaced high-resolution seismic lines collected seaward of the coast, especially in Abu Qir Bay (Stanley *et al.,* 2007), have

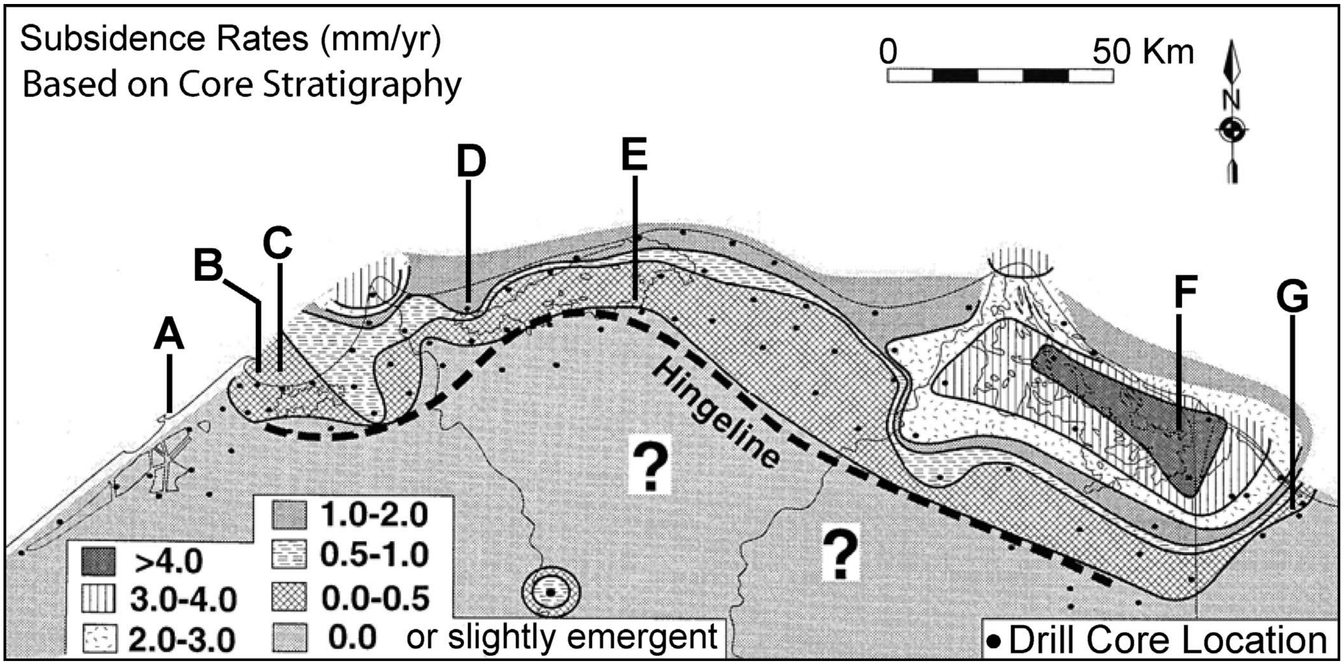

Figure 2. Long-term average Holocene rates of subsidence along lower Nile Delta plain, north of subsidence hinge-line, with rates based on stratigraphic analyses of radiocarbon-dated basal sediment core data (after Stanley and Warne, 1998). Sites A–C (Alexandria's eastern harbor, East Canopus, Herakleion) are submerged offshore, and D–G (NW Burullus lagoon, SE Burullus lagoon, Tell Tinnis, Pelusium) are buried by sediment beneath the northern delta surface.

provided additional information on now-submerged ancient sites and their Holocene sediment substrates.

Sea-Level Change

Eustatic sea level refers to the globally averaged sea level resulting from addition/subtraction of water to/from the oceans due to the melting/forming of continental glaciers, or ice-volume equivalent sea level. Along the coast, local isostatic factors (postglacial deformation of the solid earth, hydroisostatic loading) result in local relative sea levels, which exhibit spatial variations even in a limited regional context such as the Mediterranean basin or portions thereof (*e.g.,* see Antonioli *et al.,* 2007; Lambeck *et al.,* 2004; Lambeck and Purcell, 2005; Pirazzoli, 2005). No Late Quaternary geological or archaeological sea-level record has yet been reconstructed specifically from the Nile Delta region, in large part because the area is subject to significant differential subsidence due to deltaic sediment loading, tectonic activity, and sediment deformation. In addition, river floods and deltaic sedimentation processes have reworked much of the organic material normally available for radiocarbon dating, often rendering such samples meaningless for sea-level reconstruction (Stanley, 2001). Alternatively, abundant submerged and buried archaeological levels provide good to excellent age control as well as quantifiable relationships to former sea levels, but their original elevations have been displaced by subsidence.

In order to place the vertically displaced human or archaeological levels in the context of relative sea-level change we use the nearest glacio-isostatic local relative sea-level record modeled and validated for the Carmel Coast, Israel (Sivan *et al.,* 2001). The predicted/modeled sea-level contours for 20,000, 12,000, and 6000 years ago (Lambeck and Purcell 2005) generally follow the coastline in the southeastern corner of the Mediterranean, linking Israel and Egypt. This suggests that the sea-level model results for Israel (a nondeltaic coast) could be used as an approximation for the Nile Delta (K. Lambeck, 2008, personal communication). The model also accounts for residual melting of Antarctic and Alpine glaciers since 6000 years ago, representing a eustatic increase of 3 m.

We use age (archaeological date indicated by AD/BC notation or "years ago" and/or calibrated accelerator mass spectrometer [AMS] date, indicated by cal BP notation) and elevation data obtained for 11 subsurface human occupation levels at seven ancient sites coded A–G in Figure 2. The elevations of dated levels relative to present msl are measured against the regional sea-level model to determine the amount of subsidence since site occupation. Land-based core sites (D–G) represent the amount of delta margin subsidence by sediment burial. For all offshore sites (A–C), the dated horizon represents the average long-term rate of submergence at a specific locality, assuming the elevation of the original occupational level was about +1.0 m msl (similar to present delta elevations); a −1.0 m correction is thus added to the present elevation. The Carmel Coast sea-level model is then used as the framework to obtain paleo sea-level elevations at times of site occupation, from which to determine the amount of subsidence and rates at each site. Like Sivan *et al.* (2001), we corrected the present occupational elevations of each site to estimate the original elevation of the site with respect to sea level. Differences between the local relative sea-level model and the corrected elevation of each site/level represent the amount of vertical displacement the site has experienced since the dated interval. We then calculated the rate of subsidence of the level since the dated interval.

Subsidence of the delta plain over time primarily results from interaction of several factors: mass loading and isostatic depression of thick Mesozoic and Paleogene strata sequences (to over 5000 m; Schlumberger, 1984) underlying the delta surface; tectonic readjustment by faulting, slumping, and other sediment failure at depth; and compaction of unconsolidated substrate sediment. The total subsidence value, divided by the age (number of years before present) of the site's occupational level that is now buried and/or submerged then provides an average long-term annual rate of subsidence. The above data for the 11 levels at the seven sites are listed in Table 1. The table shows that at two sites (A and E) there is superposition of three anthropogenic levels of progressively younger ages.

Certain inevitable limitations to the accuracy of the subsidence calculations should be noted. One pertains to the assumption of incremental rates of subsidence when actual lowering of the delta plain may have occurred episodically during the late Holocene period. While this study primarily employs archaeological age data, the accuracy of calibrated radiocarbon ages of plant matter and peat samples used at site D can also be raised. In an earlier study of hundreds of Holocene radiocarbon dates obtained for Nile Delta cores, it was found that ages, overall, tend to be too old (Stanley, 2001). This is largely the result of sediment reworking and storage problems (displacement of eroded older material to sites downstream) related to the discontinuous stop-and-go transport processes inherent to fluvial transport and deposition in a deltaic setting. Ongoing research indicates that AMS calibrated dates on plant matter and peat (where archaeological material is also recorded) generally provide reliable ages. Another aspect that can affect subsidence rate measurement is the variability of sediment compaction with increasing depth. It is for these reasons that emphasis is placed on archaeological age at six sites (A–C, E–G) rather than only on calibrated radiocarbon dates on peat and organic-rich deposits (site D).

BURIAL AND SUBMERGENCE OF COASTAL SITES

Seven early sites (coded A to G in Figures 2 and 3, and Table 1), of middle to late Holocene age (from ~5400–4700 cal BP [^{14}C date] to ~1400 years ago [archaeological age]) are distributed between the northwest (NW) to northeast (NE) sectors of the Nile Delta margin. Recent studies have provided new data on these localities, including period of human activity and present elevations at depth (whether due to sediment burial and/or marine submergence) relative to present mean sea level. This information on late Predynastic (~5000 years ago) to Islamic (since seventh century AD) activity has been derived from recently intensified underwater archaeological excavation along with sediment drill cores and high-resolution seismic surveys offshore and geological exploration with cores on the land margin. Findings at the seven sites, oriented from west to east, are reviewed in the following sections.

Alexandria's Eastern Harbor (A)

Alexander the Great, arriving at the western edge of the Nile Delta (Figure 1) in 332 BC, initiated the massive construction and development of Alexandria such that this city became the major population and trading center in the southeastern Mediterranean. Alexandria, built on a topographically high carbonate coastal ridge of Pleistocene age positioned 10–15 m above sea level at that time, has long provided superb examples of the Greco-Roman world preserved in Egypt (Fraser, 1972; Haas, 1997). In addition, extensive archaeological discoveries of post-Alexander age (Ptolemaic, Roman, Byzantine, Islamic [from 332 BC to after 642 AD]) have also been made by systematic underwater diver surveys on the seafloor in Alexandria's Eastern Harbor (Bernand and Goddio, 2002; Empereur, 1998; Goddio, 1998).

Until recently, the existence of Rhakotis, a mainland settlement adjacent to Alexandria in pre-Alexander time, had only been alluded to in early histories (Fraser, 1972; Haas, 1997). Recently recovered sediment cores in Alexandria's eastern harbor (Figure 2A) now provide direct evidence of human activity that long predates the time of Alexander (Stanley *et al.,* 2007). Analyses of sediment core sections reveal a variety of anthropogenic materials that date from ~3000 to 2332 years ago: ceramics, rock fragments from Upper and Middle Egypt, high proportions of heavy minerals and organic matter, and large concentrations of lead disseminated in sediment to depths of 12.0 m beneath present msl. Together, these diverse components record important human activity for at least seven centuries prior to the arrival of Alexander along the coastal margin of what was the eastern part of an open marine bay.

Above these earliest remains, and buried beneath several meters of sediment in the eastern harbor, are remnants of younger massive walls and jetties, toppled temples, and port facilities. These were constructed after the bay at Alexandria was subdivided into two separate harbors by construction of a causeway, the Heptastadion, by the Greeks and Romans after 2100 years ago (Hesse, 1998). In what became the eastern harbor, remains of Antirhodos, the Timonium, and jetties and docks of three ports are presently submerged in its eastern and southeastern sectors; the ancient Navallia and port facilities rest on the floor of the southwestern harbor area (Bernand and Goddio, 2002; Goddio, 1998). These features have been considerably lowered, with the top of some walkways and upper breakwater surfaces now at depths of 5.0 to 6.5 m beneath present msl (Goddio, 1998, p. 23). Divers working close to the present shore of the harbor have also recovered younger (Byzantine, Islamic) ceramics, amphorae, oil lamps, and other objects, at depths to 3.5 m below the water–sediment interface (*i.e.,* 5.5 m beneath present msl).

Many of the large features in Alexandria's harbor cited above (Figure 2A) were submerged from late Roman to Islamic times through sea-level rise and subsidence in this westernmost sector of the delta (Stanley and Warne, 1998). However, to accurately quantify coastal subsidence in this sector

Table 1. *Land subsidence at seven archaeological sites (A–G) on the Nile Delta margin. Sites A–C are now submerged seaward off the coast, while D–G are at depth beneath the deltaic plain surface (see Figure 2). It is assumed that all horizons of early human activity at the sites were originally occupied at an elevation of ~1.0 m above msl, with the exception of site D where a manuport was originally released at about 1.0 m below msl. Sea-level stand at time of site activity, given in m msl, is derived from the sea-level curve of Sivan* et al. *(2001).*

Site[1] (Core ID)	Age of Horizon[2]	Historical Period and Material	Corrected Elevation (m msl)	Local Relative Sea-Level Elevation[3] m msl (upper, average, lower)	Total Subsidence (m)[4]	Average Subsidence (m)	Subsidence Rate (mm/yr)[5]	Average Rate (mm/yr)
A-1 Alexandria Harbor, offshore	1600	Byzantine ceramics, amphorae, oil lamps	−6.5	0.1	6.6	6.5	4.1	4.0
				0.05	6.5		3.9	
				−0.2	6.3		4.0	
A-2 Alexandria Harbor, offshore	2000	Post-Alexander harbor features	−7.5	0.1	7.6	7.5	3.8	3.7
				−0.5	7.5		3.7	
				−0.2	7.3		3.7	
A-3 Alexandria Harbor, offshore	3000 cal BP	Pre-Alexander ceramics, rock fragments, lead	−13.0	0.2	13.2	12.8	4.4	4.3
				−0.2	12.8		4.3	
				−0.6	12.5		4.2	
B East Canopus, offshore	2650	Jewelry, gold coins, collapsed walls	−6.0	0.1	6.1	5.9	2.3	2.2
				−0.1	5.9		2.2	
				−0.3	5.7		2.2	
C Herakleion, offshore	2600	Walls, temples, artifacts	−8.0	0.1	8.1	7.9	3.1	3.0
				−0.1	7.9		3.0	
				−0.3	7.7		3.0	
D NW Burullus Lagoon (S 50), onshore	5430–4740 cal BP	lithic manuport (peat dated)	−6.3	−0.5	5.8	5.0	1.1	1.0
				−1.25	5.1		0.8	
				−2.0	4.3		1.0	
E-1 SE Burullus Lagoon, onshore	2100	Ceramic sherds, Ptolemaic	−2.0	0.1	2.1	2.0	1.0	0.9
				−0.05	2.0		0.9	
				0.2	1.8		0.9	
E-2 SE Burullus Lagoon, onshore	2500	Ceramic sherds, Late Period	−4.5	0.1	4.6	4.4	1.8	1.8
				−0.1	4.4		1.7	
				−0.3	4.2		1.8	
E-3 SE Burullus Lagoon, onshore (+1 m)	3500	Ceramic sherds, late 2nd Intermed. Period–18th Dynasty	−9.4	0.1	9.5	9.1	2.7	2.6
			7	−0.4	9.1		2.5	
				−0.8	8.6		2.6	
F Tell Tinnis, onshore (~1 m)	1400	Early Islamic ruins	−3.0 (upper limit)	0.1	3.1	3.0	2.2	2.1
				−0.05	3.0		2.0	
				−0.2	2.8		2.1	
G Pelusium, onshore	2699-2745 cal BP	Brick fragments from Roman construction	−5.5	0.15	5.7	5.3	2.1	1.9
				−0.18	5.3		1.8	
				−0.5	5.0		1.9	

[1] Sites A and E each include three superposed archaeological levels.
[2] All dates are archaeological ages except at Sites A3, D, and G. The sample at Site D is an AMS radiocarbon-dated peat whose age range is given in cal BP. Samples at Site G consist of dated brick fragments whose age range is given in cal BP.
[3] From Carmel Coast, Israel (Sivan *et al.*, 2001).
[4] Local relative sea-level elevation minus corrected elevation of archaeological level = total subsidence.
[5] Subsidence rate = total subsidence/age.

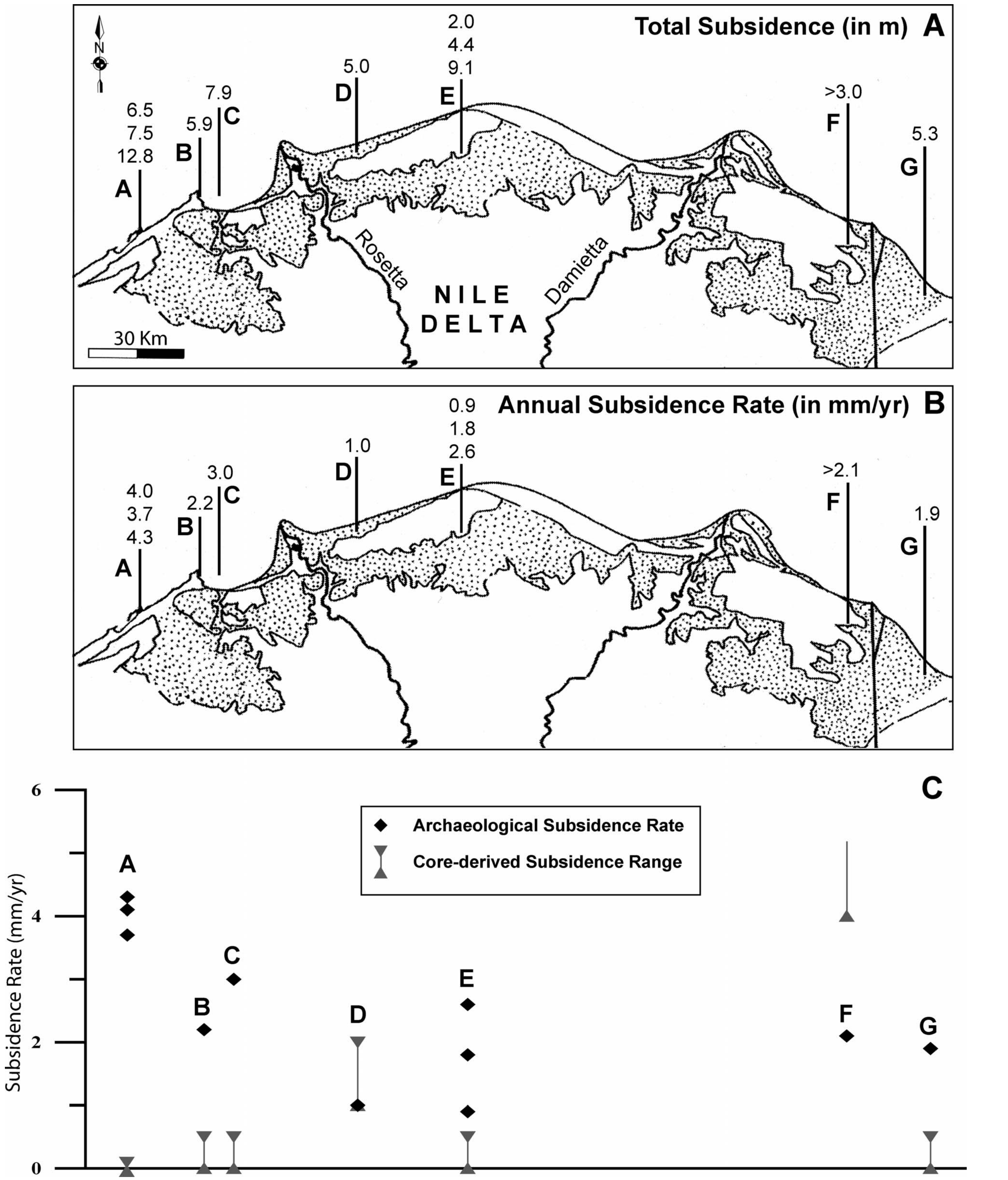

Figure 3. (A) Map shows total subsidence (local relative sea-level elevation plus local vertical land motion), in meters, at seven archaeological sites (A–G). (B) Map indicates long-term average annual subsidence rates, in mm/yr. (C) graph compares archaeological subsidence rates (from panel B) with long-term average annual subsidence rates derived from basal radiocarbon dates in cores (Figure 2), in mm/yr. Data shown on the maps are from Table 1. Sites at A and E each provide data for three superposed levels of human activity, shown from older at base to younger at top in panels A and B.

it is useful to recognize that the harbor floor was also additionally disturbed and depressed by effects of powerful earthquakes and tsunamis, such as the well-documented sudden event that seriously damaged Alexandria in 365 AD (Guidoboni, Comastri, and Traina, 1994) and those that destroyed its famous lighthouse in 1303 and 1323. Such powerful triggers (earthquake tremors, tsunamis, powerful winter wave surges) almost certainly account for some lowering of the harbor floor by sudden failure (slumping, mass flow) and subsidence of the Quaternary water-saturated substrate upon which construction features had been placed (Stanley, Jorstad, and Goddio, 2006). In addition to natural long-term progressive and damaging short-term catastrophic events, anthropogenic influences induced lowering of construction features. These latter include mass loading, weighting effects and failure of large structures placed with only modest foundations (such as wood pilings) directly on water-saturated substrates (Goddio, 1998). Modern examples of large-scale substrate failure in Alexandria's western harbor, in some instances with sudden lowering of the substrate by as much as 4.0 m, were documented and photographed by port engineers when rockfill and structures such as docks were placed on unconsolidated sediment (Malaval and Jondet, 1912).

Pre-Alexander substrate radiocarbon dated to ~3000 cal BP in the eastern harbor of Alexandria is now completely submerged to −13.0 m msl. The younger (~2000 years ago), larger, and more extensive features of post-Alexander age, originally built at least 1.0 m above sea level, record total submergence to −7.5 m msl. Some Byzantine features, dating to ~1600 years ago and also originally emplaced at least 1.0 m above sea level, now lie at depths to ~−6.5 m msl (Table 1).

East Canopus (B)

Underwater archaeological exploration by diver excavation, geophysical profiling, and vibracoring have defined the ancient ruins of a settlement approximately 1.8 km southeast of the modern town of Abu Qir. Abu Qir, known in ancient time as Canopus, was built on a high cemented limestone headland formed at the eastern edge of a coastal ridge of late Pleistocene age; the headland defines the western margin of Abu Qir Bay (Figure 1). The date when ancient Canopus was originally settled on this ridge in pre-Ptolemaic time (before 332 BC) remains poorly defined, with some scholars suggesting the Homeric Dark Age (~1100–800 BC). The underwater site, called East Canopus (Figure 2B), covers an area of 500 by 600 m and lies in water depths of ~3.5 to 5.0 m. Still being actively explored, East Canopus has revealed numerous and diverse finds including large architectural elements such as walls, building foundations, and columns, along with statuary, jewelry, and other materials (Goddio, 2007). Inscriptions on some blocks are dated to Psamtik I (664–610 BC in Egypt's Late Period), but most materials excavated on the seafloor and in cores are of Ptolemaic to Byzantine age (after 332 BC). A Christian sanctuary prospered in this sector during the seventh century AD and survived during the early Islamic period until the middle of the eighth century AD when the site was completely submerged.

Archaeological material excavated on the seafloor and recovered in sediment cores was found to depths of −5.0 m msl. Progressive submergence resulted from late Holocene sea-level rise and subsidence. Valuables such as jewelry and gold coins recovered under collapsed walls indicate that the site, at the end of its human activity but, while subaerially exposed, became subject to sudden destructive natural events as well as subsidence effects. East Canopus was positioned on unconsolidated nearshore sediment close to the mouth of the Canopic Nile branch. Powerful triggers that caused some episodic substrate failure likely included high Nile floods (Stanley *et al.,* 2004; Stanley, 2007). In addition, tsunamis and earthquake tremors documented in the eastern Mediterranean (Guidoboni, Comastri, and Traina, 1994) may also have periodically affected the settlement. Vibracore sections and high-resolution seismic lines collected in this now-submerged area record evidence of marked failure (slumps, fluidization, and flowage of water-saturated deposits) of Holocene sediment underlying East Canopus. Following submergence of the site, probably by the middle of the eighth century AD, the coastline retreated in step-like fashion landward (to the south) by almost 5.0 km to its present position (Figure 1).

Archaeological material has been recovered in seafloor sediment and at core depths of −5.0 m msl. It is assumed that construction was originally placed on a sediment substrate at least 1.0 m above msl. Total lowering of 6.0 m since ~2650 years ago is thus recorded (Table 1).

Herakleion (C)

Ancient Herakleion (Figure 2C), also submerged in Abu Qir Bay, is positioned 3.9 km east of East Canopus and covers a seafloor surface of about 1.5 km^2. Buried by sediment to >2.0 m in thickness and lying at depths of ~−6.0 to −7.0 m msl, excavation of the submerged center is revealing a rich diversity of archaeological structures, including walls, temples, and an abundance of artifacts (Goddio, 2007). The site, still actively explored, comprises marked topographic irregularities such as depressions that once served as the city's harbor and waterways. Analysis of the finds indicates that this was the town of Herakleion-Thonis, occupied from the end of the seventh century BC to the eighth century AD.

Submergence occurred incrementally with various sectors of the city subsiding at different rates. Artifacts occur in cores to depths of −6.0 m msl (Stanley *et al.,* 2007). The lowering of Herakleion, as at East Canopus, resulted from progressive natural events, primarily sea-level rise, subsidence, and effects of episodic powerful short-term events. Establishment of the town in proximity to the mouth of the Canopic channel, largest of the Nile branches, suggests that high floods at times may well have triggered sediment substrate failure. Moreover, the weighting effects of large structures placed directly onto a water-saturated substrate could also have periodically induced liquefaction followed by sediment collapse and failure (Stanley, Jorstad, and Goddio, 2006; Stanley *et al.,* 2007). As the inner Nile shelf floor was lowered, the delta's shoreline near Herakleion retreated southward by about 5.0 km to its present position.

Assuming the original construction lay ~1.0 m above sea level, total substrate lowering to about −8.0 m msl has occurred since ~2600 years ago (Table 1).

Northwest Burullus Lagoon (D)

Smithsonian drill core S-50 (Figure 2D), positioned inland of the coast east of the Nile's Rosetta branch in a sector between the Mediterranean coast and northwestern margin of Burullus Lagoon (Figure 1), unexpectedly recovered a lithic manuport, *i.e.,* a rock object created and displaced by human agency. The long (to at least 11.0 cm), thin (about 1.0 cm), relatively fragile feature could not have been displaced to the site without breaking by either coastal marine or fluvial Nile transport processes. Formed of dolomite and collected more than 160 km south of the core locality, the object was released after human transport and buried by 7.3 m of sediment. Sedimentary structures of this core section recorded by X-radiography and associated compositional components indicate the object was released south of the Mediterranean coastline on a shallow brackish lagoon floor, likely at a water depth of ~1.0 m. Its subsequent burial by a wetland marsh peat layer was rapid.

The presence of well-defined horizontal laminations formed by plant-rich sediment and peats are present beneath and above the manuport, indicating the object was released landward of a low-lying coastal sand ridge and close to a marsh. Sediment core sections recovered at this site do not record obvious postdepositional disturbance of sediment. This sector, a more tectonically stable area than the Alexandria (A) and western Abu Qir Bay (B, C) regions to the west, subsided primarily by gradual subsidence/compaction effects.

Peat immediately above the manuport's level was dated between 5430 to 4740 cal BP (Table 1), *i.e.,* from the late Predynastic (~3000 BC). The feature provides evidence of the oldest human presence yet recorded at the Nile Delta coast (Stanley *et al.,* 2008). Unlike the six other sites discussed in this study that originated at ~1.0 m above msl, the manuport at site D was originally released on a lagoon floor at a depth of ~1.0 m beneath msl. Thus, total lowering at this locality is about 6.3 m.

Southeast Burullus Lagoon (E)

Smithsonian drill core S-44 (Figure 2E), located inland almost 17 km in a modern marsh along the southeastern margin of Burullus lagoon, unexpectedly recovered an abundance of archaeological material. The core was not positioned at or near a known ancient site or major mound, but was collected in a flat, low-lying area (about +1.0 m msl) without distinctive surface topographic features. Ceramic sherds ranging from the late Second Intermediate Period to the 18th Dynasty (~3600 to 3500 years ago) were found at a depth of approximately 9.4 m below msl. These are the oldest Pharaonic materials encountered in the north-central delta (Stanley, Arnold, and Warne, 1992). Above these lie sherds of Late Period (2700–2300 years ago) at ~4.5 m beneath present msl, and of Ptolemaic age (~2100 years ago) at ~2.0 m beneath present msl.

Core X-radiographs revealed the prevalence of horizontal laminations without disturbance by sediment failure. The ceramic fragments are in upward-younger stratigraphic position and do not appear to have been displaced or mixed by the drilling operation. Deposits containing the sherds accumulated in or adjacent to a wetland setting typical of the northern Nile Delta during the middle to upper Holocene, *i.e.,* lagoon-marine coastal margin environments, influenced by seasonal flooding of the Nile's Sebennitic branch (Figure 1) that once flowed northward across this delta sector. Sediment accumulation occurred on a deltaic plain surface that was progressively buried by sediment because of effects of sea-level rise and compaction of underlying deposits.

A lowering of 9.4 m msl is recorded by the oldest archaeological material in the core. Moreover, sherds of intermediate age (~2500 years ago) are at 4.5 m, and ceramic fragments of Ptolemaic age (2100 years ago) are at 2.0 m beneath the deltaic plain (Table 1).

Tell Tinnis (F)

The ruins of the ancient town of Tinnis (also known as Tell or Kom Tennis; Figure 2F) are positioned at and mostly beneath the surface of a low-lying island (<1.0 m elevation) of the same name in the northeastern part of Manzala lagoon. Materials on the island surface are for the most part poorly preserved and comprise largely late Roman, Coptic, and Islamic material. Excavations indicate the town was walled and included rounded towers, brick cisterns, streets, and waterfront docks. A geophysical survey indicates the lower parts of relatively young (Roman, Islamic) constructed structures are buried at depth by sediment (Gascoigne, 2005). Part of the town, including an extension of walls on the island, presently lies offshore beneath lagoon waters, and Manzala fishermen working their nets in the area continue to recover archaeological material (J.-M. Mouton, 2008, personal communication). The island of Tinnis lies in a sector of Manzala lagoon where calculated rates of sediment accumulation based on dated core analyses are the highest in the northern Nile Delta, with average long-term subsidence of ~4.0 mm/yr (Goodfriend and Stanley, 1999; Stanley and Warne, 1998). The high subsidence rate is attributed to active tectonic displacement in this northeastern delta sector, where structural motion may be associated with displacement along the Pelusium Line, a major fault system that extends from the Levant to the eastern Nile Delta sector (Neev, Bakler, and Emery, 1987; Neev, Greenfield, and Hall, 1985). Cores show the early Holocene marine transgressive surface, radiocarbon dated to ~8000 yr BP, has been lowered to a depth of ~45.0 m in the vicinity of Tinnis Island. This vertical displacement includes effects of neotectonics and those induced by sediment compaction of thick underlying sequences of water-saturated silty muds. The large depressed rectangular area beneath the lagoon has received accumulations to 50.0 m of sediment thickness since the early Holocene (Figure 2). Remarkably high rates of sea-level rise (4.8 mm/yr from tide gauges; Emery, Aubrey, and Goldsmith, 1988) are recorded for this delta margin sector.

The bases of early Islamic ruins, from ~1400 years ago, were originally emplaced at ground level, and excavations indicate a subsequent lowering of 3.0 m, and possibly more, beneath present island surface elevation (Table 1).

Pelusium (G)

The ancient fortified port city and trade center of Pelusium (Figure 2G), also known by its Arabic name as Tel Farama, now lies about 3.0 km inland (south) from the coast. Excavations during the past century have revealed that most ruins at and just beneath the surface of this large archaeological site are primarily of late Roman and Byzantine ages. Most obvious is a large late Roman fortress with a major construction phase that dates to the second half of the sixth century AD (Carrez-Maratray, 1999). Recent analysis of radiocarbon-dated sediment sections recovered by drill cores on the site indicates the presence of archaeological material to depths of about −5.5 m msl. These include brick fragments and angular scoria particles dated to approximately 2700 cal BP (Stanley, Bernasconi, and Jorstad, 2008). The city's founding phase is thus attributed to the 22nd and 23rd Dynasties in Egypt's Third Intermediate Period.

The dated paleogeographic setting indicates that construction of early Pelusium could not have occurred much before ~2800 cal BP since, prior to that time, the site still lay beneath marine waters of the inner shelf (Moshier and El-Kalani, 2008). A major phase of delta margin uplift occurred between 3000 and 2800 years ago along the major tectonic system, the Pelusium Line, that extends across this region (Stanley *et al.,* 2008); the trace of this fault is clearly visible at ground elevation just south of Pelusium. Uplift led to retreat of the sea and a northward coastal build-out, at which time port facilities were developed. The city's primary role as a coastal harbor and frontier fortress lasted almost 1600 years, until about 800 AD, followed by Pelusium's decline until total abandonment somewhat before the 12th century AD. Now positioned 3.0 km south of the shoreline, at about +0.5 m msl, Pelusium's ruins indicate that downward vertical motion has periodically continued to offset this sector. Thus, initial construction and subsequent decline at this locality in the NE corner of the delta are linked to structural activity that, at times, has had a greater imprint than local relative sea-level rise effects. A period of tectonic inactivity coupled with continued sea-level rise and coastal erosion, in little more than a century, could result in progressive coastal retreat landward to the site locality and cause eventual submergence of the base of the ruins by marine incursion.

Although there were episodic uplift phases during the late Holocene, the base of the occupation elevation dated at 2700 cal BP shows an overall lowering to ~5.5 m beneath present msl (Table 1).

EVALUATION OF FINDINGS

Modeled late Holocene sea levels (Sivan *et al.,* 2001; Figure 4) are within −0.05 to −0.5 m of present msl from 3500 to 1400 years ago, the timeframe represented by the human occupation levels at sites A–C and E–G. The exception is Site D, dated to 5400 cal BP, when sea level was −1.25 m msl. Removal of the sea-level elevation from the present elevation of each site/level gives the total subsidence at each site (Figure 3A; Table 1). All 11 occupation levels were initially within 1 m of sea level and now rest between 2.0 and 13 m below sea level, indicating that all seven sites have been subject to subsidence and that rates of delta plain lowering vary irregularly from west to east along the delta margin (Figure 3B).

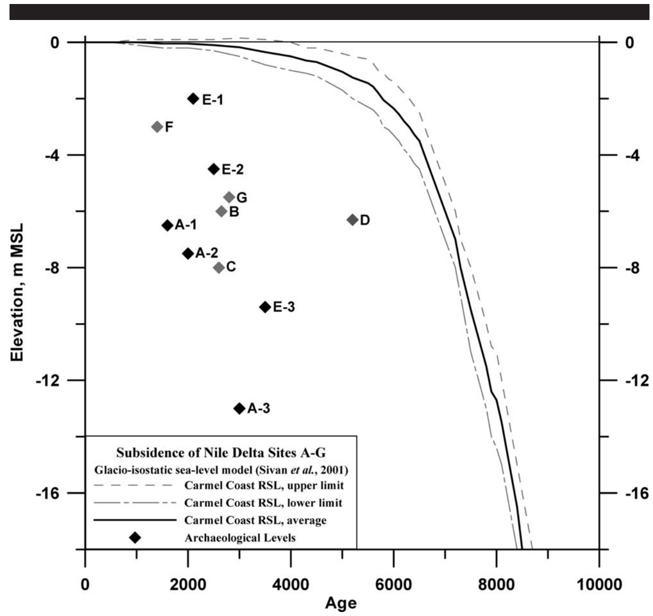

Figure 4. Corrected elevations of archaeological sites A–G plotted against relative sea-level model for the Carmel Coast, Israel (Sivan *et al.,* 2001). Sea levels were within −0.05 to −1.25 m msl for the periods represented by the archaeological levels. Most vertical displacement at all sites is due to subsidence. Site D has been submerged by 1.25 m of sea-level rise in addition to the subsidence indicated by its present elevation.

The total subsidence (Figures 3A and 4) ranges from 2.0 m at the upper part of the site at southeast (SE) Burullus Lagoon (Site E-1) to 12.8 m in Alexandria's eastern harbor (Site A-3). The average rate of subsidence recorded through time since the date of occupation is also variable. Highest average annual rates of subsidence are recorded in the eastern harbor of Alexandria (Site A; ~3.7 mm/yr to 4.3 mm/yr) and at Herakleion (Site C; 3.0 mm/yr) in Abu Qir Bay (Figure 3B). The regional sectors with lowest annual subsidence rates are in the north-central delta along Burullus lagoon (sites D, 1.0 mm/yr, and E, 0.9 to 2.6 mm/yr) and in the NE Delta's upper section at Pelusium (Site G, 1.9 mm/yr).

The annual subsidence rates for 11 data points at the seven sites (Table 1) were averaged, providing an overall annual subsidence rate for the delta margin in the late Holocene of about 2.5 mm/yr. In all cases, subsidence (including all forms of episodic events) is the principle mechanism for present elevation of the sites, as compared to modeled sea-level changes (Figure 4) and rates (Figure 3C). At site A, the rate of subsidence has remained essentially steady, from 4.1 mm/yr (level A-1), 3.7 mm/yr (level A-2), to 4.3 mm/yr (level A-3). These high rates at Alexandria's eastern harbor are likely due to neotectonics such as earthquake-triggered fault offsets (Empereur, 1998; Guidoboni, Comastri, and Traina, 1994). At site E, the three superposed levels of human occupation show increasing rates of subsidence with depth (0.9 mm/yr [level E-1], 1.8 mm/yr [level E-2], 2.6 mm/yr [level E-3]; Figure 3B). This, in part, may result from somewhat higher sedimentation rates and greater compaction of deltaic sediment strata, especially peats and organic-rich deposits, with increased subsurface depth.

The annual subsidence rate data obtained at archaeological sites in the present study (Figure 3B) correlate poorly with subsidence rates based on chronostratigraphic analysis of core data (Figure 2). Values in mm/yr in Figure 2 are compiled using data averaged from basal peat or organic matter that ranged in age from lower Holocene (~8000–7000 years ago) to the present, thus representing a much longer period than those constrained by archaeological dating. Only at site D, where the subsidence rate is 1.0 mm/yr, is the chronostratigraphic rate suggested by core data (1.0–2.0 mm/yr) reasonably close. Interestingly site D, dated to the oldest period (5400 cal BP), is the only site that has been significantly submerged by sea-level rise (of 1.25 m) in addition to subsidence (Figure 4). The rate of subsidence at Tell Tinnis (Site F; 2.1 mm/yr) is markedly lower than that measured from core data in the area (>4.0 mm/yr); this has resulted from averaging of higher deposition rates measured in the lower part (lower to middle Holocene) of core sections. Overall, the subsidence values and rates based on archaeological information in the middle to late Holocene sections are higher than those indicated by the core data alone in areas near four sites (B, C, E, G; Figure 4). This difference may stem from the extended time period, which may include periods of earlier low rates of subsidence, of core data used in the calculations. Other factors affecting the calculations include radiocarbon dates on components that might be older than the date of sediment burial, a known delta-related phenomenon that is due to sediment reworking and storage of organic components during down-river transport (Stanley, 2001). Given the age errors and stratigraphic inconsistencies inherent in deltaic paleogeologic reconstructions, the present investigation indicates that archaeologically dated levels are much more likely to provide reliable gauges of past elevations with respect to sea level than subsidence rate calculations based on radiocarbon-dated core sections alone.

Subsidence rates of the Nile Delta margin, while important, are for the most part substantially lower than those of some other large deltas in temperate zones. A case to consider is the modern Mississippi Delta, which has received most attention with regards to changes of its present surface elevation relative to msl and where abundant data have been collected on recent delta surface subsidence during the past century. For example, during the period 1908–1988, sea-level rise rates determined from tide gauge stations along the Louisiana coast have exceeded 10.0 mm/yr, and even ranged to as high as 17.7 mm/yr in the Teche basin (Penland and Ramsey, 1990). Very high subsidence values in the Mississippi Delta region have been attributed largely to compaction of the considerable thickness of underlying Holocene sediment sections, some locally exceeding 150 m. New data, using space geodesy and leveling, substantiate high levels of delta plain mobility and record remarkably high values of land subsidence for New Orleans and other parts of the delta: ~5.0 to 25.0 mm/yr, of which up to 2.0 mm/yr are now attributed to recent substantially increased global average sea-level rise. These geodetic data are believed to be representative of rates during the past 150 years (Dixon and Dokka, 2008).

It is of note that in both Nile and Mississippi deltas, total Holocene sediment thickness is closely linked to accommodation space, *i.e.,* depressed sectors where more rapid rates of subsidence are recorded are also those where higher rates of sediment accumulation and/or submergence by coastal water occur. Areas in the Mississippi Delta system where the lowest annual subsidence rates are recorded commonly occur in areas where sediment thickness is considerably reduced (Penland and Ramsey, 1990). A similar relationship is noted in the Nile Delta. There, areas of shortest Holocene core thicknesses and lowest subsidence rates occur along its north-central coastline where erosion and shoreline retreat southward have been particularly rapid.

POPULATION CENTERS ON THE MODERN MARGIN

The Nile Delta coastal margin is positioned in a generally tectonically stable area (Biju-Duval and Montadert, 1977; Robertson and Grasso, 1995; Udias, 1985). Nevertheless, there are sectors of recent structural offsets, primarily those at the delta extremities, in the NW near Alexandria and NE near Pelusium. Moreover, data presented in this study confirm that the margin is a subsiding one. It is thus appropriate to consider the recent evolution of modern towns positioned along this vulnerable low-lying delta coast (Figure 1).

Early foundations of many population centers presently lie at depths beneath the deltaic plain surface and also beneath shallow groundwater level. Subsidence that has occurred in the past and may presently be affecting these modern centers is not quantified here due to insufficiently precise data on depth and age of their early occupational levels. For example, the early origins of some still-active coastal towns are believed to date to Classical Greek, or even earlier, time. However, some population centers are not as old as suggested by historic records and/or the presence of early archaeological vestiges, some dating to Dynastic age (pre-332 BC), found in their vicinity. These older features are not necessarily reliable markers to date the early history of towns, since in some cases such materials originated elsewhere in older inland localities of Egypt and were then transported to younger population centers along the coast.

Although a number of localities are cited in early written documents, surprisingly little firm information is available on their precise geographic position in early history (before Byzantine and Islamic time). There is limited documentation for towns such as Rosetta and Burg Migheizil near the mouth of the Rosetta branch, Ez Gamasa on the NE delta coast, and Damietta and Ras el-Barr near the Damietta branch outlet (Figure 1). It is recognized that delta coastal towns mentioned in early documents were purposely emplaced along lower stretches of Nile branches but, since Dynastic and Greco-Roman periods, some of these centers were displaced from their original location. One reason for such geographic shifts was lateral migration of large fluvial channels along which some towns had originally been built (Stanley, 2007; Toussoun, 1922). This abandonment due to migration of distributary branches away from population centers has been a recurring problem for those established along fluvial branches in the world's large deltas. This has thus led, where possible, to artificial stabilization of flow by channelization and build-up of levees.

Parts of some presently active coastal towns of the Nile Delta now lie submerged on the inner shelf. This occurred in the case of several north-central delta centers, including the coastal resort of Baltim and El Burg positioned north of Burullus lagoon (Figure 1), as a result of continued effects of sea-level rise and subsidence coupled with an increased rate of coastal erosion. An increased rate of landward retreat of the arcuate, seaward-extending coast in this sector occurred during the past century, following markedly reduced sediment discharge at sea resulting from emplacement of Nile barrages and the two dams at Aswan (Inman and Jenkins, 1984; Sharaf El Din, 1974; UNESCO, 1978; unpublished technical studies and reports prepared by Egyptian agencies).

Modern Alexandria at the NW delta margin is periodically affected by earthquake activity but is positioned on a cemented Pleistocene carbonate ridge that forms a linear, coast-parallel topographic high well above sea level. Not as fortunately placed are Port Said, the most economically vital city on the NE delta coast, and its sister city, Port Fu'ad. These, constructed on low-lying surfaces $<$1.0 m above msl, are very recent population centers, dating primarily to the period of Suez Canal construction and opening in 1869. Civil engineering reports indicate that construction in some sectors of these two cities is subject to damage associated with recent subsidence of their low-lying unconsolidated and locally unstable substrates. It is clear that here, as along other world delta coasts, effects of accelerated rates of sea-level rise, predicted to double for the 21st century due to global climate change (IPCC, 2007), are an additional threat to already vulnerable coastal population centers along the Nile Delta margin.

CONCLUSIONS

Archaeological ages and present elevations of 11 buried and/or submerged levels of human activity at seven sites along the northern Nile Delta plain or on the inner shelf are used to calculate rates of subsidence. Calculations provide average annual rates of subsidence that range from 0.9 to 4.3 mm/yr based on the glacio-isostatic sea-level model from the Carmel Coast of Israel. Subsidence rates appear to be almost entirely responsible for the displacement of these sites because (with the exception of Site D) sea levels ranged within $\pm$0.5 m msl, from 3500 to 1400 years ago (Figure 4). The contribution of relative sea-level rise to this displacement has therefore been negligible during that time. At Site D, dated to $\sim$5000 years ago, however, sea-level rise contributed 1.25 m of submergence in addition to subsidence. Subsidence rates vary irregularly from west to east along the delta's margin, with the lowest rates occurring on the north-central delta margin (Figure 3B, 3C). The overall average rate of subsidence along the northern Nile Delta coast during the Holocene is approximately 2.5 mm/yr.

Calculated rates of subsidence are notably higher at five of seven archaeological sites than rates of subsidence determined by chronostratigraphic analyses of dated sediment cores recovered in proximity to those sites (Figure 3C). The lower rates calculated on the basis of Holocene basal organic-rich core samples are likely to be largely a function of radiocarbon ages that, because of reworking and storage effects during fluvial transport, tend to provide older-than-actual dates of deposition and burial. In addition, the longer time period represented by the full Holocene section likely results in a more time-averaged rate of subsidence than the shorter, well-dated intervals represented by archaeological data. More rapid subsidence rates (to $>$4 mm/yr) determined for radiocarbon-dated cores in the Manzala lagoon result from measurements determined for particularly long sections (to 45 m and more in length) dating back to the early Holocene. Calculations using radiocarbon dates at these Manzala core bases provide subsidence rates that are higher than for their overlying middle and late Holocene sections.

A direct relation between thickness of sediment section and subsidence rate is indicated, with largest land lowering values in Nile Delta margin areas of thickest and most rapid Holocene deposition and lowest subsidence rates in sectors of reduced sediment thickness. As in other deltas, such as the Mississippi, this relation is at least in part a function of underlying sediment compaction. In addition, gradual natural processes such as sediment loading and readjustment of strata at depth are also important. Rapid and seriously damaging natural triggers that additionally contribute to subsidence include earthquakes and tsunamis (at Alexandria and Pelusium), Nile floods (at Herakleion and East Canopus), and powerful winter storm surges. It is now also recognized that sudden sediment failure at several sites (Alexandria's harbor, East Canopus, Herakleion, Pelusium) has resulted, at least in part, by human activity. Triggers include build-up of insufficiently supported massive human construction in areas such as Alexandria's eastern harbor and at Herakleion. That the role of weighting by large structures built on water-saturated substrates can lead to sediment failure at ancient sites in this region warrants further attention.

In this actively subsiding region, calculated subsidence rates for the seven localities may be used on a site-specific basis as a means to reconstruct the original elevations of archaeologically dated levels from their present vertically displaced elevations. Because most archaeological finds along this low-lying coast have definable relationships to sea level, the availability of quantitative subsidence corrections opens up the possibility of reconstructing a historic and possibly Holocene sea-level record specifically for the Nile Delta region.

The present Nile Delta margin, as in the past, constitutes a vulnerable setting for some of the more recently built towns and modern construction projects. The reverse of Lyell's principle, the past as a key to understanding present or predicting future conditions, may be applicable with regard to the protection of these younger population centers. Their vulnerability to subsidence, even in recent time, has been noted, especially when such lowering induces the shoreline to shift rapidly inland onto the low-elevation coast. Continued monitoring and implementation of protective measures are needed along this increasingly populous delta margin subject to relatively significant rates of subsidence and predicted acceleration of local relative sea-level rise.

Sediment coring projects associated with civil engineering and coastal protection efforts, as highlighted here, may provide new evidence of early Nile Delta coastal sites. Most encouraging in this respect are the recently discovered vestiges of ancient Rhakotis beneath Alexandria's eastern harbor and findings of early levels of human activity presently buried at depth in two sectors of the Burullus area. Additional geoarchaeological findings of this type made in other coastal sectors of the Nile Delta margin would serve to complement these calculations of recent subsidence.

ACKNOWLEDGMENTS

Valuable technical assistance was provided by Mr. J. Cannon and Mr. T.F. Jorstad in the preparation of text script and illustrations for this article. Drs. A. Gascoigne and J.-M. Mouton are thanked for information they shared on the archaeological site of Tinnis. Dr. I.G. Macintyre kindly reviewed an earlier manuscript draft and is thanked for his constructive suggestions. Partial funding for the study was obtained from the National Museum of Natural History, Smithsonian Institution, Washington, DC.

LITERATURE CITED

Antonioli, F.; Anzidei, M.; Lambeck, K.; Auriemma, R.; Gaddi, D.; Furlani, S.; Orru, P.; Solinas, E.; Gaspari, A.; Kariinja, S.; Kovacic, V., and Surace, L., 2007. Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data. *Quaternary Science Reviews,* 26, 2463–2486.

Attia, M.I., 1954. *Deposits in the Nile Valley and the Delta.* Cairo: Geological Survey of Egypt, 356p.

Baines, J. and Málek, J., 1985. *Atlas of Ancient Egypt.* New York: Facts on File, Inc., 240p.

Bernand, A. and Goddio, F., 2002. *L'Égypte Engloutie—Alexandrie.* London: Arcperiplus Publishing, 191p [in French].

Biju-Duval, B. and Montadert, L., (eds.), 1977. *Structural History of the Mediterranean Basins.* Paris: Edition Technip, 448p.

Breasted, J.H., 1909. *A History of Egypt, from the Earliest Times to the Persian Conquest.* New York: Charles Scribner's Sons, 636p.

Butzer, K.W., 1976. *Early Hydraulic Civilization in Egypt: A Study in Cultural Ecology.* Chicago: University of Chicago Press, 134p.

Carrez-Maratray, J.-Y., 1999. *Péluse et l'Angle Oriental du Delta Egyptien.* Cairo: Institut Français d'Archéologie Orientale, Bibliothèque d'Etude, no. 124, 491p [in French].

Dixon, T.H. and Dokka, R.K., 2008. Earth scientists and public policy: Have we failed New Orleans? *Eos,* 89(10), 96.

Emery, K.O.; Aubrey, D.G., and Goldsmith, V., 1988. Coastal neotectonics of the Mediterranean from tide-gauge records. *Marine Geology,* 81, 41–52.

Empereur, J.-Y., 1998. *Alexandria Rediscovered.* New York: G. Braziller Publisher, 253p.

Fourtau, R., 1915. Contribution à l'étude des dépôts nilotiques. *Mémoires de l'Institut Egyptien,* 8, 57–94 [in French].

Fraser, P.M., 1972. *Ptolemaic Alexandria* (3 vols.). London: Oxford University Press, 2136p.

Frihy, O.E.; Moussa, A.A., and Stanley, D.J., 1994. Abu Qir, a sediment sink off the northwestern Nile Delta, Egypt. *Marine Geology,* 121, 199–211.

Gascoigne, A., 2005. An archaeological survey of Tell Tinnis, Manzala, Egypt. *Antiquity,* 79, http://antiquity.ac.uk/projgall/gascoigne/index.html (accessed October 6, 2008).

Goddio, F., (ed.), 1998. *Alexandria the Submerged Royal Quarters.* London: Periplus, 274p.

Goddio, F., 2007. *Underwater Archaeology in the Canopic Region in Egypt, the Topography and Excavation of Heracleion-Thonis and East Canopus (1996–2006).* Oxford: Oxford Centre for Maritime Archaeology, 136p.

Goodfriend, G.A. and Stanley, J.-D., 1999. Rapid strand plain accretion in the northeastern Nile Delta in the ninth century A.D. and demise of the port of Pelusium. *Geology,* 27, 147–150.

Guidoboni, E.; Comastri, A., and Traina, G., 1994. *Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century.* Bologna: Instituto Nazionale di Geofisica, 504p.

Haas, C., 1997. *Alexandria in Late Antiquity, Topography and Social Conflict.* Baltimore: Johns Hopkins University Press, 494p.

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

Inman, D.L. and Jenkins, S.A., 1984. The Nile littoral cell and man's impact on the coastal zone of the southeastern Mediterranean. *Scripps Institution of Oceanography, References Series,* 31, 1–43.

IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K. and Reisinger, A. (eds.)]. Geneva, Switzerland: Intergovernmental Panel on Climate Change, 104p.

Lambeck, K.; Antonioli, F.; Purcell, A., and Silenzi, S., 2004. Sea-level change along the Italian coast for the past 10,000 yr. *Quaternary Science Reviews,* 23, 1567–1598.

Lambeck, K. and Purcell, A. 2005, Sea-level change in the Mediterranean Sea since the LGM: model predictions for tectonically-stable areas. *Quaternary Science Reviews,* 24, 1969–1988.

Malaval, B. and Jondet, M.G., 1912. *The Alexandria Port.* Cairo: Administration des Ports et Phares, Imprimerie Nationale, 153p [in French].

Manley, B., 1996. *The Penguin Historical Atlas of Ancient Egypt.* New York: Penguin Group, 144p.

Moshier, S.O. and El-Kalani, A., 2008. Paleogeography along the ancient Ways of Horus (late Bronze Age) in northwest Sinai, Egypt. *Geoarchaeology,* 23, 450–473.

Neev, D.; Bakler, N., and Emery, K.O., 1987. *Mediterranean Coasts of Israel and Sinai.* New York: Taylor and Francis, 130p.

Neev, D.; Greenfield, L., and Hall, J., 1985. Slice tectonics in the Eastern Mediterranean Basin. *In:* Stanley, D.J. and Wezel, C.F., (eds.), *Geological Evolution of the Mediterranean Basin.* Berlin: Springer, pp. 249–269.

Penland, S. and Ramsey, K.E., 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research,* 6, 323–342.

Pirazzoli, P.A., 2005. A review of possible eustatic, isostatic and tectonic contributions in eight late-Holocene relative sea-level histories from the Mediterranean area. *Quaternary Science Reviews,* 24, 1989–2001.

Robertson, A.H.F. and Grasso, M., 1995. Overview of the Late Tertiary-Recent tectonic and palaeo-environmental development of the Mediterranean region. *Terra Nova,* 7, 114–127.

Said, R., 1981. *The Geological Evolution of the River Nile.* New York: Springer-Verlag, 151p.

Said, R., 1993. *The River Nile, Geology, Hydrology, and Utilization.* New York: Pergamon Press, 320p.

Schlumberger, 1984. *Well Evaluation Conference Egypt.* Paris: Schlumberger Middle East, Editions Galilée, 248p.

Sestini, G., 1989. Nile Delta: A review of depositional environments and geological history. *In:* Whateley, M.G.K. and Pickering, K.T. (eds.), *Deltas: Sites and Traps for Fossil Fuels.* London: Geological Society of London, Special Publications, vol. 41, pp. 99–204.

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, 535–601.

Sharaf El Din, S.H., 1974. Longshore sand transport in the surf zone along the Mediterranean Egyptian coast. *Limnology and Oceanography,* 19, 182–189.

Sivan, D.; Wdowinski, S.; Lambeck, K.; Galili, E., and Raban, A. 2001. Holocene sea-level changes along the Mediterranean coast of Israel, based on archaeological observations and numerical model. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 167, 101–117.

Stanley, J.-D., 1996. Nile Delta: extreme case of sediment entrapment on the delta plain and consequent land loss. *Marine Geology,* 129, 189–195.

Stanley, J.-D., 2001. Dating modern deltas—Progress, problems and prognostics. *Annual Review of Earth and Atmospheric Sciences,* 29, 257–294.

Stanley, J.-D. (ed.), 2007. *Geoarchaeology.* Oxford: Oxford Centre for Maritime Archaeology, 128p.

Stanley, J.-D.; Arnold, D., and Warne, A.G., 1992. Oldest Pharaonic site. *National Geographic Research and Exploration,* 8(3), 264–275.

Stanley, J.-D.; Bernasconi, M.P., and Jorstad, T.F., 2008. Pelusium, an ancient port fortress on Egypt's Nile Delta coast: its evolving environmental setting from foundation to demise. *Journal of Coastal Research,* 24(2), 451–462.

Stanley, J.-D.; Carlson, R.W.; Van Beek, G.; Jorstad, T.F., and Landau, E.A., 2007. Alexandria, Egypt, before Alexander the Great: A multidisciplinary approach yields rich discoveries. *GSA Today,* 17, 4–10.

Stanley, J.-D.; Goddio, F.; Jorstad, T.F., and Schnepp, G., 2004. Submergence of ancient Greek cities off Egypt's Nile Delta—A cautionary tale. *GSA Today,* 14, 4–10.

Stanley, J.-D.; Jorstad, T.F.; Bernasconi, M.P.; Stanford, D., and Jodry, M., 2008. Predynastic human presence discovered by core drilling at the northern Nile Delta coast, Egypt. *Geology,* 36, 599–602.

Stanley, J.D.; Jorstad, T.F., and Goddio, F., 2006. Human impact on sediment mass movement and submergence of ancient sites in the two harbours of Alexandria, Egypt. *Norwegian Journal of Geology,* 86, 337–350.

Stanley, J.-D.; McRea, J., and Waldron, J., 1996. *Nile Delta Drill Core and Sample Database for 1985–1994: Mediterranean Basin (MEDIBA) Program.* Smithsonian Contributions to the Marine Sciences, number 37. Washington, DC: Smithsonian Institution Press, 428p.

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

Toussoun, O., 1922. *Mémoire sur les anciennes branches du Nil.* Mém oires de la Société Géographique d'Egypte, 4, 144p [in French].

Udias, A., 1985. Seismicity of the Mediterranean Basin. *In:* Stanley, D.J. and Wezel, F.C. (eds.), *Geological Evolution of the Mediterranean Basin.* New York: Springer-Verlag, pp. 55–63.

UNESCO, 1978. Coastal Protection Studies. Project Findings and Recommendations. UNDP/EGY/73/063, Paris, 483p.