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**Article** *in* Journal of Coastal Research · January 2014

DOI: 10.2112/JCOASTRES-D-13-00146.1



Jean-Daniel Stanley
Smithsonian Institution

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Author(s): Jean-Daniel Stanley and Pablo L. Clemente
Source: Journal of Coastal Research, 30(1):88-101.
Published By: Coastal Education and Research Foundation
DOI: http://dx.doi.org/10.2112/JCOASTRES-D-13-00146.1
URL: http://www.bioone.org/doi/full/10.2112/JCOASTRES-D-13-00146.1

| Journal of Coastal Research | 30 | 1 | 88–101 | Coconut Creek, Florida | January 2014 |
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# Clay Distributions, Grain Sizes, Sediment Thicknesses, and Compaction Rates to Interpret Subsidence in Egypt's Northern Nile Delta

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**Jean-Daniel Stanley and Pablo L. Clemente**

Cities under the Sea Program (CUSP)
Department of Paleobiology
E-205, National Museum of Natural History
Smithsonian Institution
Washington, D.C. 20013-7012, U.S.A.
stanleyd@si.edu

**ABSTRACT**

Stanley, J.-D. and Clemente, P.L., 2014. Clay distributions, grain sizes, sediment thicknesses, and compaction rates to interpret subsidence in Egypt's northern Nile Delta. *Journal of Coastal Research,* 30(1), 88–101. Coconut Creek (Florida), ISSN 0749-0208.

This study focuses on the role of clay on subsidence of Holocene sedimentary sequences in the northern Nile Delta. Proportions of clay in 1262 samples from 87 cores are much higher here than elsewhere in the delta and along the Nile in Egypt. The northern third of the delta lies at a low, near-horizontal elevation (~1 m above mean sea level), but clay content and total thickness of Holocene deposits in subsurface vary considerably in time and space. Greatest clay content (to >60%) and mud-rich thickness (to 47 m) are concentrated near Manzala lagoon. The volume of Nile water and sediment discharged annually on the delta diminished during the past two millennia as a result of climate change and intensified human activity. During the past two centuries, barrages and dams placed across the Nile and increased water diversion activities further reduced Nile flow and sediment delivery to the northern delta. Lowering at the coastal margin has also resulted from interplay of sediment compaction, regional sea-level rise, and intermittent readjustment of strata at depth. These events are ongoing, as indicated by increased erosion of extensive stretches of delta coast, salinization that affects large areas of agricultural land and groundwater, and major changes in recent sediment textural patterns as mapped in the present survey. Formerly dominant fluvial S-to-N transport during much of the Holocene has become distinctly shore parallel, recording landward shoreline advance and W-to-E sediment displacement along the delta margin. Implementing extensive coastal protective measures should take into account zones most prone to effects of subsidence, where (1) clay-rich subsurface sequences are thickest, (2) these strata are subject to high compaction rates, (3) sediment replenishment is insufficient, and (4) readjustment at depth of pre-Holocene sequences is continuing. These factors will cause the delta's NE and north-central sectors to experience continued significant surface lowering.

**ADDITIONAL INDEX WORDS:** *Coastal protection, compaction, cores, erosion, Nile River, relative sea level, sediment replenishment, sediment transport, submergence, textural patterns.*

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## INTRODUCTION

The present investigation examines the susceptibility of Holocene sediment sequences comprising large proportions of clay to subsidence in Egypt's northern Nile Delta plain (Figure 1, shaded area). It is postulated that the combination of high clay concentrations in sediments, thick sequences of such fine-grained deposits, and relatively high sediment compaction rates could potentially be the cause of historical and continued subsidence of this low-elevation delta plain margin. It is also proposed that these parameters, acting together, would likely continue to increase the vulnerability of this populated zone, which also comprises Egypt's major agricultural and wetland region to risks of relative sea-level rise.

*DOI: 10.2112/JCOASTRES-D-13-00146.1 received and accepted in revision 22 July 2013; corrected proofs received 11 September 2013.*
Published Pre-print online 18 November 2013.


The delta margin has been subject to lowering through much of the Holocene, subjecting the large population in this low-elevation depocenter to rising sea level, increased coastal erosion, and further incursion of saline groundwater into large sectors of the delta (Bohannon, 2010; El-Asmar, Hereher, and El-Kafrawy, 2012; El Nahry, Ibraheim, and El Baroudy, 2008; Hereher, 2010; IPCC, 2007; Sestini, 1989; White and El Asmar, 1999). These phenomena appear to have continued, if not accelerated, in the late Holocene as a result of the Nile's lower flow regime induced by regional climate change (Bernhardt, Horton, and Stanley, 2012; Said, 1993; UNDP, 2009) and, especially during the past two centuries, by much intensified human activity. The latter has included emplacement of barrages and dams across the Nile River in Upper and Middle Egypt, construction of large barrages north of Cairo at the mouths of the Rosetta and Damietta branches, and development of numerous canal and water-diversion structures throughout the delta. Together,

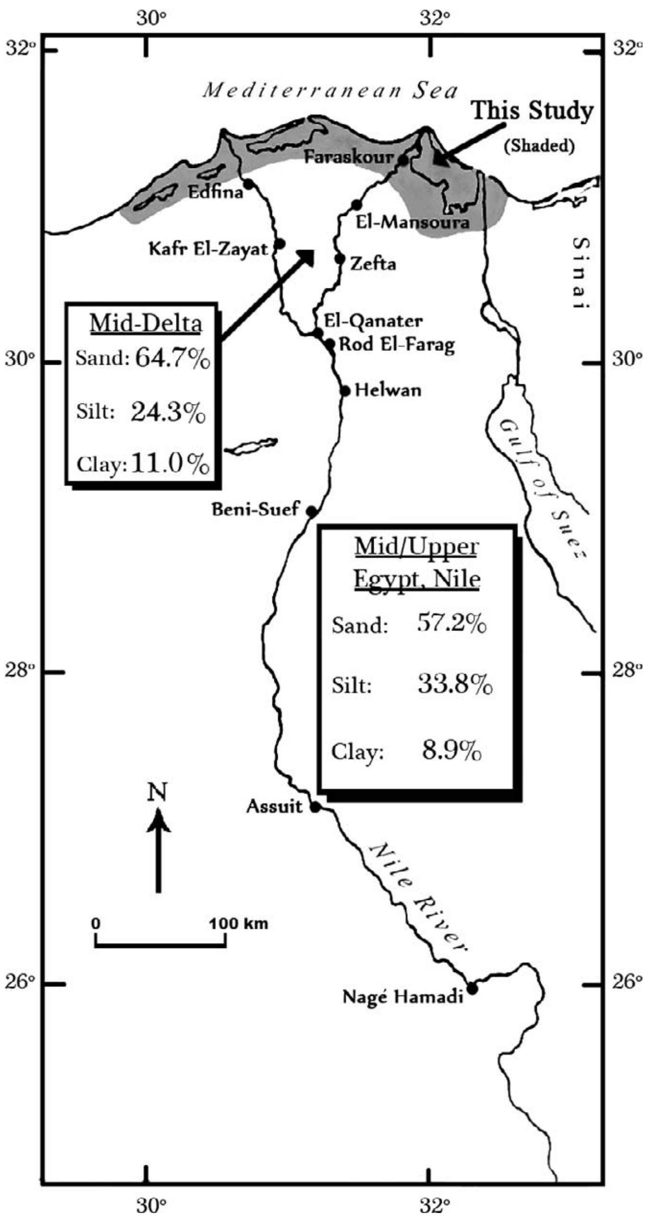


Figure 1. Map showing the Nile River in Egypt and study area (shaded) in the northern Nile Delta. The average relative percentages of sand, silt, and clay for the Nile between southern Egypt and the central delta are derived from the database of Morsy (1981). Note low proportions of clay relative to those of silt and sand along the Nile extending to as far as the central delta, south of the study area.

these projects have resulted in decreased rates of sediment replenishment and aggradation on delta plain surfaces (Stanley and Warne, 1993, 1998).

The effects of clay deposition, sediment-grain size, and the distribution pattern of clay-rich deposits were examined by analysis of more than 1200 subsurface samples of Holocene age recovered across the northern Nile Delta of Egypt. These samples were obtained from 87 continuous drill cores at sites positioned ∼10–15 km apart between the NW and NE margins of the delta (Figure 2). Segments of the arcuate 225-km-long coastal zone of core recovery have been subject to marine incursion of the sea landward of the present Mediterranean delta shoreline at some time during the Holocene (Stanley and Warne, 1998). This area comprising fluvio-marine deposits, narrowest (as little as ∼10–15 km landward of the present coast) in the NW delta, becomes broader (to ∼15–30 km from the coast) in the north-central sector and even wider (to ∼30–40 km) in the NE region (Figure 2). From their subsurface base to ground-surface elevation, most of the cores provide continuous sediment sequences from late Pleistocene through Holocene to recent surface sections. These materials make available a large and unique grain-size database that, examined in a systematic manner, is used here to further assess sediment compaction patterns and, thus, provides new insight into subsidence that appears to be a major phenomenon affecting this deltaic depocenter.

Special attention is paid herein to mapping changes of relative percentages of sand, silt, and clay content in Holocene core sections. Variations of grain-size distributions in the Holocene sequences would serve to identify altered temporal and spatial textural-dispersal trends, including both distinct and subtle patterns across the northern delta. This analysis could also assist in evaluating potential relationships among grain size, total Holocene depositional thickness, average thickness of strata, gravitational pressure, and rate of compaction. A recently published companion study based on examination of these same cores has indicated that the average thickness of numerous (3183) Holocene sediment strata in a dated stratigraphic context records marked effects of compaction downcore, with notable variations in both time and space in the Holocene cover of the study area (Stanley and Corwin, 2013). Two of the major observations based on strata-thickness measurements made in that study are as follows. (1) Downcore analyses indicate that, with regard to time, the highest rates of compaction have affected the most recently deposited sequences to the greatest extent, primarily from initial gravitational pressure resulting from the sediment's own weight and weight of overlying water-saturated deposits. (2) Rates of compaction determined from regional measurements of strata thicknesses record a marked increase in gravitational compression from NW to NE sectors of the delta.

Increased compaction affecting clay-rich core strata in the northern Nile Delta study area can be interpreted as a function of reduced sediment porosity and volume in the manner discussed by numerous workers during the past century and is summarized by Hedberg (1936). The present investigation explores if strata of clay-rich deposits are, in some manner, associated with total thickness and rates of gravitational compression of such Holocene fine-grained sequences (Stanley and Corwin, 2013) and to what extent these factors can lead to subsidence of the deltaic surface of this lowland setting.

## BACKGROUND

The many experimental and field studies that have addressed the role of gravitational pressure in modern and ancient environments, including deltas, show the proclivity of

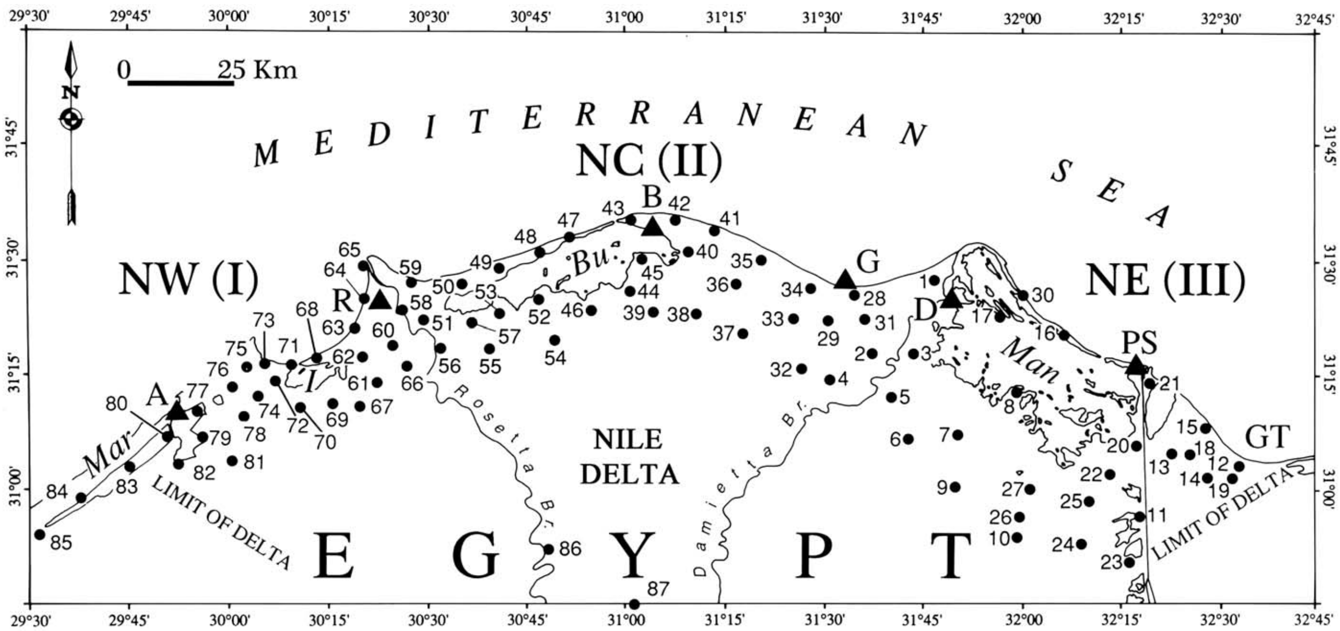


Figure 2. Map of the northern Nile Delta study area shows sites of 87 Smithsonian cores from which textural data for 1262 sediment samples have been analyzed for the purposes of this study (modified after Stanley, McRea, and Waldron, 1996). Three geographic sectors are analyzed: the NW (I), north-central (II), and NE (III). Denoted are the western and eastern limits of the delta, four coastal lagoons (Mar = Mariut; I = Idku; Bu = Burullus; Man = Manzala), the Gulf of Tineh (GT), and the two main Nile distributaries (Damietta and Rosetta branches) and their promontories. Coastal cities (black triangles) are A, Alexandria; R, Rosetta; B, Baltim; G, Gamasa; D, Damietta; and PS, Port Said.

argillaceous sediments to experience large reductions in volume, at times in excess of 80%, because of a decrease in water content and pore space (Athy, 1930; Blatt, Middleton, and Murray, 1980; Grim, 1955; Hedberg, 1936; Jones, 1944; Rieke and Chilingarian, 1974; Sorby, 1908). For example, initial porosities in muds (admixtures largely of silt and clay), and especially deposits rich in clays, may reach 70% to 90% at time of deposition and, shortly after deposition, porosities are reduced to 70% to 75% at depths as shallow as 25 cm to 30 cm below ground surface (Hedberg, 1936). This rapid reduction in volume and thickness of a deposit is most notable in the case of recently released suspensions rich in clay particles, particularly those of platy particles surrounded by films of water, which are most prone to tighter packing.

As compaction proceeds, clay particles are rearranged and both free water and water adsorbed by the particles are expelled. The increased pressure from overlying deposits induces modification of the original unstable structure of clay platelets and causes excess water in the water-rich sediment to escape. Eventually, a more stable arrangement of clay particles develops as these come in closer contact with each other. Greater packing stability develops with time and depth, resulting in porosities of 50% or less. Such dewatering and compaction phases are also affected by certain features attributed to specific clay types in the argillaceous deposits, especially the smectite (montmorillonite) species that dominate and account for about 70% of the clay components in the Holocene sections of the Nile Delta (El-Attar and Jackson, 1973; El Sabrouti and Sokkary, 1982; Fayed and Hassan, 1970; Stanley and Wingerath, 1996; Stanley, Mart, and Nir, 1997; Weir, Ormerod, and El-Mansey, 1975). This group of clay minerals is characterized by very fine-grained particles and expansion perpendicular to the layers because of interlayer water absorption. Laboratory experiments and field studies of unconsolidated and partially consolidated deposits and rock formations show that relationships between (1) porosity and the age and depth of a deposit and (2) pressure and pore spaces are usually inverse ones (Rieke and Chilingarian, 1974). These factors would have been significant in past times prior to the emplacement of barrages and two dams at Aswan when greater amounts of water-saturated deposits were released over extensive delta surface areas during annual late summer–early fall floods (Kröpelin *et al.*, 2008; Said, 1993; Schumm and Galay, 1994; Shata and El Fayoumy, 1970; Sutcliffe and Parks, 1999; Waterbury, 1979). Changes, both mechanical and chemical, that have affected clays in the northern delta and their role in subsidence since closure of the High Dam in 1965 warrant further evaluation.

In preparing for the present survey, a number of earlier analyses that provide information on grain size in the Nile River and delta were reviewed. These include studies of surficial samples in the recent Nile, taken from its riverbed, bank, and tributary (*wadi*) settings, and in Nile Delta distributary sequences and associated settings (Abdel-Satar, 2005; El-Wakeel and Wahby, 1970a, b; Morsy, 1981; Stanley and Wingerath, 1996). Descriptions of the lithostratigraphy and sediment texture of subsurface deposits in hundreds of borings collected along the Nile Valley and in the Nile Delta were consulted (Attia, 1954; Fourtau, 1915; Said, 1981; Schlumberger, 1984; Sestini, 1989). Also useful in this respect are data provided in numerous unpublished technical reports that detail aspects for civil engineering, hydrographic exploration, and fluvial pollutant studies. It is noted, however, that the majority of articles and reports pertaining to Holocene subsurface deposits in northern delta sectors usually indicate only visual estimates of grain size rather than presenting quantitative measurements of sand, silt, and clay proportions determined by laboratory analyses. Moreover, these documents most often do not provide ages obtained by radiocarbon dating or other analysis for the examined core sections; thus, available databases generally lack a reliable chronostratigraphic framework.

Previous stratigraphic and geoarchaeological findings have indicated that subsidence affected the delta plain well before closure of the High Dam at Aswan and may be continuing at present (Becker and Sultan, 2009; El-Sayed, 1996; Jondet, 1916; Stanley, 1990; Stanley and Toscano, 2009; Wahab, Rasheed, and Youssef, 2010; Warne and Stanley, 1993a; Weill, 1919). These studies have also suggested a regionally uneven amount of subsidence of the northern delta surface relative to sea level during the Holocene, which may still be inducing landward retreat along some segments of this Nile Delta coast–Mediterranean margin (El Asmar and Hereher, 2011; El Asmar, Hereher, and El-Kafrawy, 2012; Emery, Aubrey, and Goldsmith, 1988; Frihy, 1988, 1992; Frihy *et al*., 2010;White and El Asmar, 1999). Subsidence and landward shoreline retreat are serious issues as the study area comprises an important part of Egypt's agricultural and aquacultural settings and is densely populated as well (Bohannon, 2010; CIESIN, 2009; Sestini, 1992; Stanley and Warne, 1998; UNDP, 2009). Lowering of land surface coupled with the continued rise of eustatic sea level would likely induce further land loss in this vital region (Stanley and Corwin, 2013). Additional potential hazards are envisioned, as this region is affected by recent markedly diminished Nile discharge and decrease in sediment replenishment on the low-lying delta surface.

The present investigation examines some of the above problems by focusing on the proportions of sand, silt, and clay in numerous cores collected across the northern delta's coastal margin (Figure 2). This would serve to better assess the importance of clay in subsurface strata and determine the role this grain size plays regionally in compaction rates measured at each core locality. Our database includes information on size, compositional analyses of the sand fraction, detailed lithostratigraphic logs, and radiocarbon dates for the Holocene sequences in each of the 87 cores reported in Stanley, McRea, Jr., and Waldron (1996). The vertical sequence of subsurface depositional environments has been previously interpreted at each core site based on grain size, faunal and floral components, sediment structures, and other associated features. These settings include marine (inner shelf), coastal (beach, dune), brackish (wetland lagoon and marsh), and alluvial (Nile River branch bed, levee, and interfluvial plain) deposits. Subsurface paleofacies are similar to major modern northern Nile deltaic facies, and they are detailed in a series of earlier studies (Arbouille and Stanley, 1991; Chen, Warne, and Stanley, 1992; Coutellier and Stanley, 1987; Loizeau and Stanley, 1993; Warne and Stanley, 1993a, b).

## METHODOLOGY

The data utilized herein are derived from laboratory analyses of 1262 grain-size samples taken from the 87 drill cores in this northern deltaic study area shown in Figure 2. The core numbers are officially recorded as S1 to S87, where the letter S denotes recovery by the National Museum of Natural History (NMNH), Smithsonian Institution, Washington, D.C. The cores were collected using Acker II trailer-mounted rigs during five field seasons from 1985 to 1990 (Stanley, McRea, and Waldron, 1996). The total depth of borings ranges from ~20 m to ~60 m, and these include continuous late Quaternary stratigraphic sections that, in most cases, date from the late Pleistocene at their base to the late Holocene and recent time at the top of most cores. Attention here is paid primarily to the Holocene sections that range from ~2 m to ~49 m in length, and in age they extend from approximately 8000 years before present (yr BP) to present. Ages of basal Holocene sections in the more complete sequences range from ~8000 to ~6500 yr BP, most often approximating to ~7500 yr BP. These sections are usually positioned unconformably upon older (usually 12,000 yr BP or greater) underlying late Pleistocene deposits.

The primary database used here includes the relative percentages of sand, silt, and clay, the size fractions that form the bulk of core sediment samples (listings in Stanley, McRea, Jr., and Waldron, 1996). To examine representative deposits at each core site, samples were selected down boring at each change of lithology or at about 50-cm intervals in the case of long homogeneous sections. The proportions of the three size fractions were determined based on specific size limits applied by sedimentological convention: sand ranges from 63 μm to 2000 μm (Folk, 1980); silt from 2 μm to 63 μm (Folk, 1980); and clay as 2 μm or less (standard size selected for this fraction at our facility at NMNH). The term mud, on the other hand, is a general, usually undefined one for sediment that includes predominant but variable admixtures of silt and clay fractions in contrast to largely sand-rich deposits. Samples comprising sand-to-clay size fractions were artificially disaggregated using a peptizing agent before proportions of different sizes were measured by rapid sediment analyzer (Laser RSA). Procedures were followed in consistent fashion with regard to volume of sediment-utilized, disaggregation, and particle-settling times used to gauge grain size. It is recalled that use of dispersant to disaggregate mud-rich deposits in laboratory analyses results in artificial separation of sand from silt and clay and also of individual clay particles from mixes of silt- and clay-size floccules. Thus, while an accurate measure of the original clay particle size displaced during transport to and released from flow in the delta margin area is precluded, calculations of overall averaged proportions of clay *vs*. those of silt and sand in the study area are credible. It is noted that three separate grain-size runs were made for each sediment sample selected for study. Of the results obtained from the three grain-size analyses, the two most similar were then averaged to calculate the relative percentages of sand, silt, and clay for that sample.

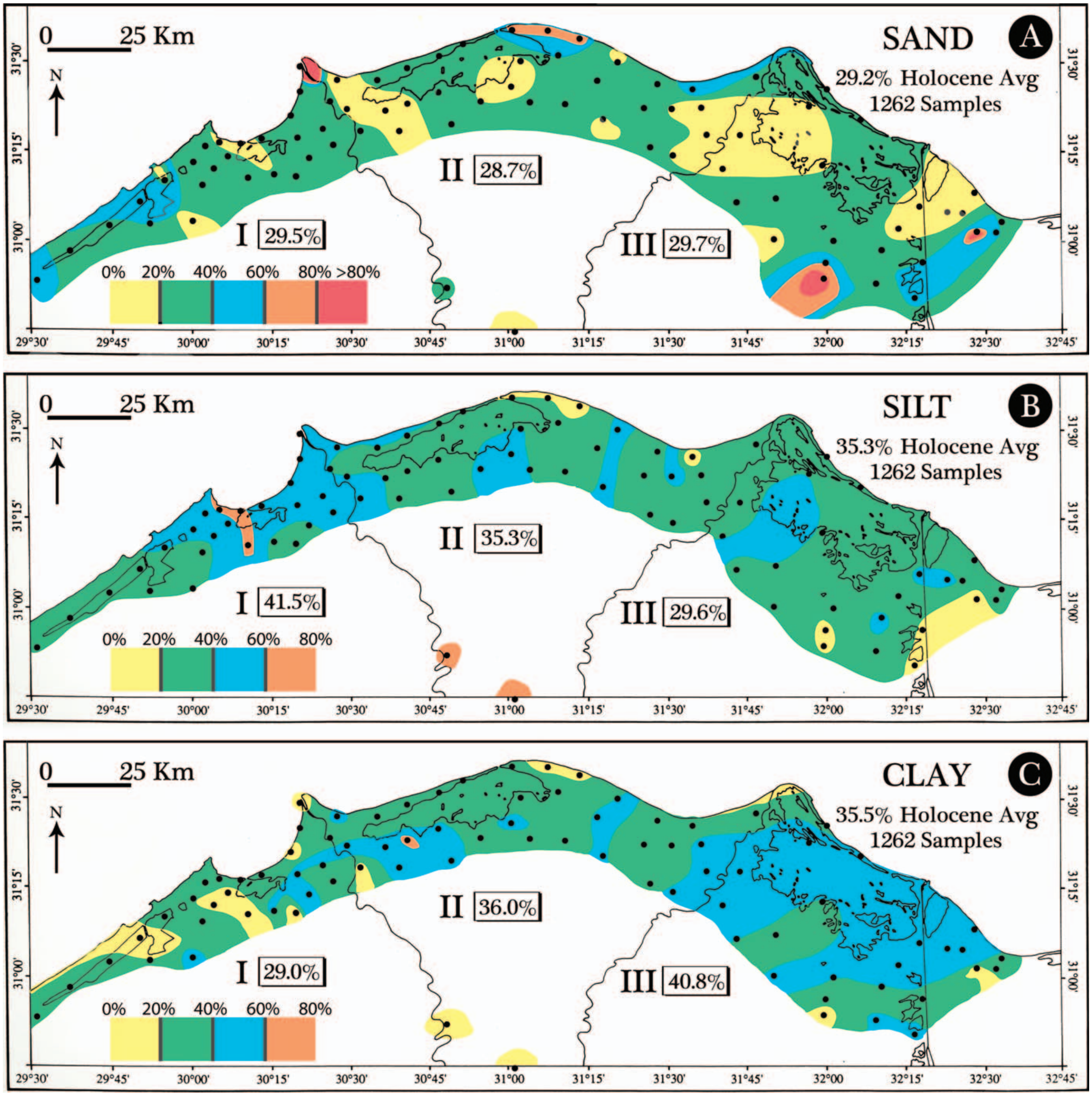


Figure 3. Maps depicting relative percentages of sand, silt, and clay averaged for the overall (total) Holocene sequence at the 87 core sites and for each of the three sections (I, II, III). Details are summarized in "Observations."

Two average grain-size values were calculated for the Holocene section at each core site: (1) for all sample data examined in the entire Holocene core section (termed *overall Holocene average*); and (2) for the sample data in the upper 2 m of core dating at least to the past 1500 years (termed *late Holocene average*). These two average values for each core site are plotted separately in Figures 3 and 4. The number of samples examined to obtain the overall Holocene average at each core site ranged from 2 to 50, and values obtained from the 1262 samples are plotted in Figure 3. The number of samples averaged for the upper 2 m of Holocene core sections, totaling 180 samples, ranged from 1 to 8, and values are shown in Figure 4. Both figures depict average relative percentages of sand (Figures 3A and 4A), silt (Figures 3B and 4B), and clay

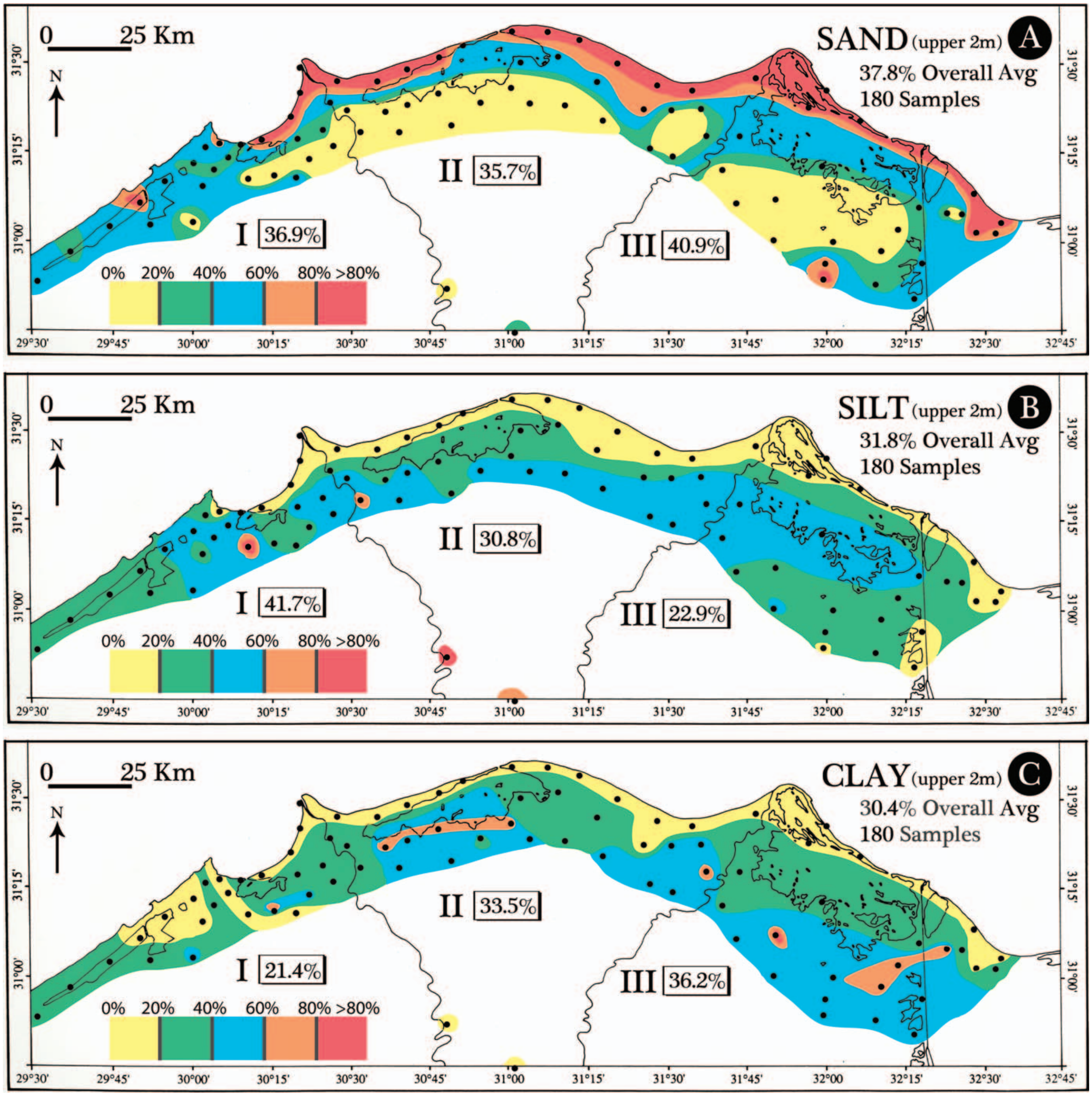


Figure 4. Maps depicting relative percentages of sand, silt, and clay averaged for the late Holocene (upper 2 m) sequence at the 87 core sites and for each of the three sections (I, II, III). Details are summarized in "Observations."

(Figures 3C and 4C) by means of contour lines plotted at intervals of 20%.

Each map subdivides the delta into three geographic sectors identified as follows (Figure 2): NW (NW = sector I), north-central (NC = sector II), and NE (NE = sector III). For sector I, textural data are averaged from the following 26 cores from west of the city of Alexandria to the western bank of the Rosetta Branch of the Nile: S60 to S85. Sector II includes data from 34 cores from the east bank of the Rosetta Branch to the west bank of the Nile's Damietta Branch: S1, S2, S4, S28, S29, S31 to S59. Sector III comprises data from the following 25 cores recovered in the delta from east of the Damietta Branch to the delta that extends into the NW Sinai: S3, S5 to S27, S30. For comparison purposes, data are also plotted for samples in the Holocene sections of two cores, S86 and S87, recovered in the central part of the Nile Delta, south of the northern delta study area (Figure 2).

## OBSERVATIONS

Published studies of sediment distribution in the modern Nile River and its seasonally or intermittently flowing, much smaller tributaries (*wadis*) south of Cairo indicate that sand and silt may comprise as much as 90% or more of the fluvial bedload (Morsy, 1981; Stanley and Wingerath, 1996). The sand and silt fractions are also important in southern and central delta regions and can range to about 80% to 90%. Most published studies of sediment along the Nile between southern Egypt and the central delta record much lower relative percentages of clay than of either silt or sand (Figure 1). The few articles that record proportions of the silt- and sand-size fractions separately, among them the one by Morsy (1981, his Table 1), indicate that Nile riverbed sediments commonly comprise about 65% very fine-to-medium grade sand, 20% or less fine to coarse silt, and generally less than 15% clay.

In the present study, the distributions of sand, silt, and clay as measured in core samples of the northern third of the delta differ markedly from those recorded above for the central and southern delta and the Nile valley south of Cairo. Most obvious is the much higher relative percentage of clay in both the overall Holocene averages (Figure 3C) and the late Holocene averages (Figure 4C). The relative proportions of grain sizes in the overall Holocene sections averaged for all core sites in the northern deltaic study area are as follows (Figure 3): sand, 29.2%; silt, 35.3%; and clay, 35.5%. Descriptive names assigned to samples with such near-equivalent percentages of the three size fractions include sandy silty clay, sandy clay silt, and silty clay sand based on usage of the ternary diagram nomenclature (Pettijohn, 1957, p. 24). Proportions of grain sizes that make up the bulk of samples in the late Holocene sections across the northern delta are also shown (Figure 4): sand, 37.8%; silt, 31.8%; and clay, 30.4%. These data indicate that relative percentages of sand increased considerably in recent time (Figures 3A and 4A). Proportions of silt (Figures 3B and 4B), on the other hand, remain similar overtime and also approximate the range of modern silt percentages measured along the Nile in Middle and Upper Egypt (Figure 1). It is also noteworthy that while proportions of clay are similar in the overall Holocene and late Holocene averages (Figures 3C and 4C), in both cases these values are markedly increased (about threefold) in comparison to those in samples recovered south of the northern delta along the Nile system (Figure 1).

To more clearly identify major temporal and spatial textural variations in the study area, average relative percentage data were compiled separately in geographic sectors I, II, and III for the overall Holocene and late Holocene sequences. The following summarizes both time-related and geographic distributions of the three grain sizes plotted in Figures 3 and 4:

(1) Sand—Averaged proportions for the overall Holocene (Figure 3A) are closely comparable in the three northern sectors, with values ranging from 28.7% (sector II) to 29.7% (sector III) and in the late Holocene (Figure 4A) from 35.7% (sector II) to 40.9% (sector III);
(2) Silt—Proportions decrease from 41.5% (sector I) to 29.6% (sector III) in the overall Holocene and from 41.7% (sector I) to 22.9% (sector III) in the late Holocene (Figures 3B and 4B); and
(3) Clay—Proportions increase substantially from 29.0% (sector I) to 40.8% (sector III) in the overall Holocene and from 21.4% (sector I) to 36.2% (sector III) in the late Holocene (Figures 3C and 4C).

The two most obvious grain-size distribution differences in the northern delta cited previously are the decrease in silt proportion (by ~19%) from the NW (sector I) to the NE (sector III) delta during the late Holocene (Figure 4B) and the increase in clay percentage (by ~15%) from sector I to sector III, also in the late Holocene (Figure 4C).

In addition to the previous changes in relative percentages, further observations pertain to specific temporal and geographic distribution patterns of grain size, as observed in Figures 3 and 4:

(1) Sand—This coarser fraction, averaged for the overall Holocene time span, is distributed fairly evenly across the northern delta, as indicated by laterally more extensive areas comprising relative percentages that range from 20% to 60% sand (Figure 3A). The largest zone of low sand proportion (<20%) is distributed across the western part of Manzala lagoon (sector III) and the adjoining area west of it (Figure 3A). Only a few small localized sites show percentages that record >60% sand. One of these (>80% sand) is at the Rosetta promontory, and another south of the present Manzala lagoon may be positioned near the trace of a now-relict Nile branch, possibly the Tanitic. In marked contrast, the averaged relative percentage of sand is considerably higher in the late Holocene (40% to >80%) than in the averaged overall Holocene sequences, and is distributed in distinct linear fashion parallel to the present coast (Figure 4A). Of note are the progressively increased proportions of sand toward the coast. Moreover, areas with percentages <20% are more extensive than in the averaged overall Holocene map (Figure 3A); these are generally positioned south of Manzala, Burullus, and Idku lagoons with somewhat more coast-parallel trends (Figure 4A).
(2) Silt—The distribution patterns of silt proportions averaged for the overall Holocene sections are, for the most part, quite evenly distributed across the northern delta, with predominant proportions ranging from 20% to 60% (Figure 3B). Several linear zones locally defined by this high silt content indicate a general S-N trend. In contrast, the distribution patterns of silt percentages averaged for the late Holocene show a marked alignment parallel to the present coast (Figure 4B). Unlike that of sand distribution in the late Holocene, however, there is a NW decrease in relative silt percentages toward the sea, resulting in a narrow coast-parallel belt defined by low values (<20%).
(3) Clay—The largest area comprising high relative proportions of clay (40% to 60%) averaged for the overall Holocene sections is positioned in NE sector III and

extends seaward from south of and across the modern Manzala lagoon toward the coast (Figure 3C). The north-central sector II is more evenly covered by clay percentages ranging from 20% to 60%, while areas to the west in sector I comprise even lower percentages (<20% to 40%) of clay. Additionally, some localized distribution patterns across the northern delta show a S-N trend. In contrast, clay distribution patterns depicted for the late Holocene (Figure 4C) tend to resemble the coast-parallel trends of silt during this period (Figure 4B). In addition, two small linear patches of >60% clay are noted, one appearing to parallel former trends of the relict Tanitic and Pelusiac branches of the Nile, the other bounding the southern margin of modern Burullus lagoon.

## NORTHWARD INCREASE OF SILT AND CLAY

The study area during late Pleistocene to early Holocene time was part of a broad, sub-aerially exposed alluvial plain characterized by seasonally active braided channel facies interbedded with sandy flood plain and finer-grained playa deposits. The delta's coastline during that transitional period was positioned farther to the north than at present on what is now the submerged Nile Shelf. By ~8000 yr BP, the shoreline had retreated southward toward its present position attributed primarily to continued rising sea level and active erosion along the moderate- to high-energy coastal setting (Stanley and Warne, 1998). The inland extent of nearshore sand-rich depositional facies helps define the southern marine advance onto land areas of the study area that previously had been occupied by the alluvial plain. It is of note that this marine to nonmarine boundary is also one that, to the south, is characterized by a reduction in the overall total thickness of Holocene fluvio-marine deltaic sequences. Whereas average Holocene core thicknesses in areas north of the boundary covering much of the study area range from about 10 m to 50 m, those to the south are about 10 m or less. This arcuate W-to-E boundary identified on land is a critical hingeline (Figure 5A).

Associated with these S-to-N sedimentary trends are the marked textural changes, including those of grain-size and textural distribution patterns of the Holocene deposits after 8000 yr BP, as described in the observations section of this study. North of the hingeline, proportions of both silt and clay fractions are considerably greater and cover areas that are larger than in most other areas of the delta and of the valley south of Cairo that have received sediment from the Nile River. For example, silt plus clay percentages in this northern delta-front depocenter (~70%) account for almost double (~35%–40%) those measured in nonmarine Holocene sections of decreased thickness in the central and southern delta and the Nile River valley (Mid-Delta and Mid/Upper Egypt in Figure 1).

The northward increase of fine fractions results from a decrease in slope that occurs in the central delta between an elevation of ~18 m near Cairo and the low (~1 m above mean sea level [msl]) near-horizontal surface of the northern delta. The near-flat plain extends from the coast to about 20–35 km inland. This delta morphology likely resulted in reduced-transport competence of flows unable to displace the same proportions of sand, silt, and clay loads the entire distance from the main Nile River channel south of Cairo northward to the coast via the delta distributaries. Consequently, proportions of bedload relative to those of suspended load were altered, resulting in a decrease in size of material transported across the northern plain. Altered dispersal capacity of flows affected a number of textural variables, including size, shape, and density of particles that would have led Nile waters, once they reached the central to northern delta, to release sediment in a seaward direction via a more selective bypassing process. It is envisioned that greater proportions of finer silt and flocculated clay were released from fluvial suspension further to the north than coarse silt and sand. The latter coarser fractions were discharged in larger proportions somewhat more landward in southern and central deltaic areas (Figures 1 and 3).

The selective textural bypassing process apparently prevailed during much of Holocene time, as indicated by the core sample data used to compile the textural distribution maps in Figures 3A, B and 4A, B. The higher proportions of fine silt and clay fractions were released from distributary branches in the northern delta by overbank flow and crevasse-splay processes, with finer fractions accumulating preferentially on the somewhat lower elevation settings positioned between active distributary channels. Some of the narrow, linear S-N trends observed on the overall Holocene average silt and clay maps suggest this dispersal pattern (Figures 3B, C). Also of significance in the case of clay sedimentation are coastal margin wetland environments such as the shallow brackish lagoons that are in contact with the inner shelf. This zone where mixing of fresh, brackish, and salt waters prevails is one of enhanced clay particle flocculation, release from flow, and deposition.

In addition to the role of transport processes are the effects of altered climatic conditions and increased influence of human activity that affected water flow and sedimentation patterns in the delta during early to mid-Holocene time. Impacts of decreased Nile flow regimes associated with increased regional aridification (Marriner *et al*., 2012; Said, 1993) and continued pressures of population growth (Warne and Stanley, 1993b), with a shift from pastoralism to crop cultivation and, eventually, an almost total dependence on produced rather than gathered foods (Butzer, 1976, p. 87) are significant since late Predynastic time (*ca*. 5000 yr BP). These factors led to augmented water management activities and altered cultivation practices necessary to feed Egypt's increasing population living along the Nile and in the delta. Expansion of settlements across the southern and central delta during the Old Kingdom (~4700–4200 yr BP) was followed by increased occupation of the northern delta during dynastic time and especially during the Late Period and Ptolemaic rule (~2700–2030 yr BP). The demographic center of gravity had shifted from the Nile valley to the delta in Hellenistic time according to Butzer (1976, p. 109). In most areas having access to Nile water, these changes resulted in the transition from natural to artificially regulated irrigation, an activity involving channelization and diversion of water by flooding and draining controlled by sluice gates (Butzer, 1976, p. 107). The accelerated rates of human alteration of natural depositional patterns have modified the upper few m of soil across extensive tracts of the delta surface from Dynastic time to the present.

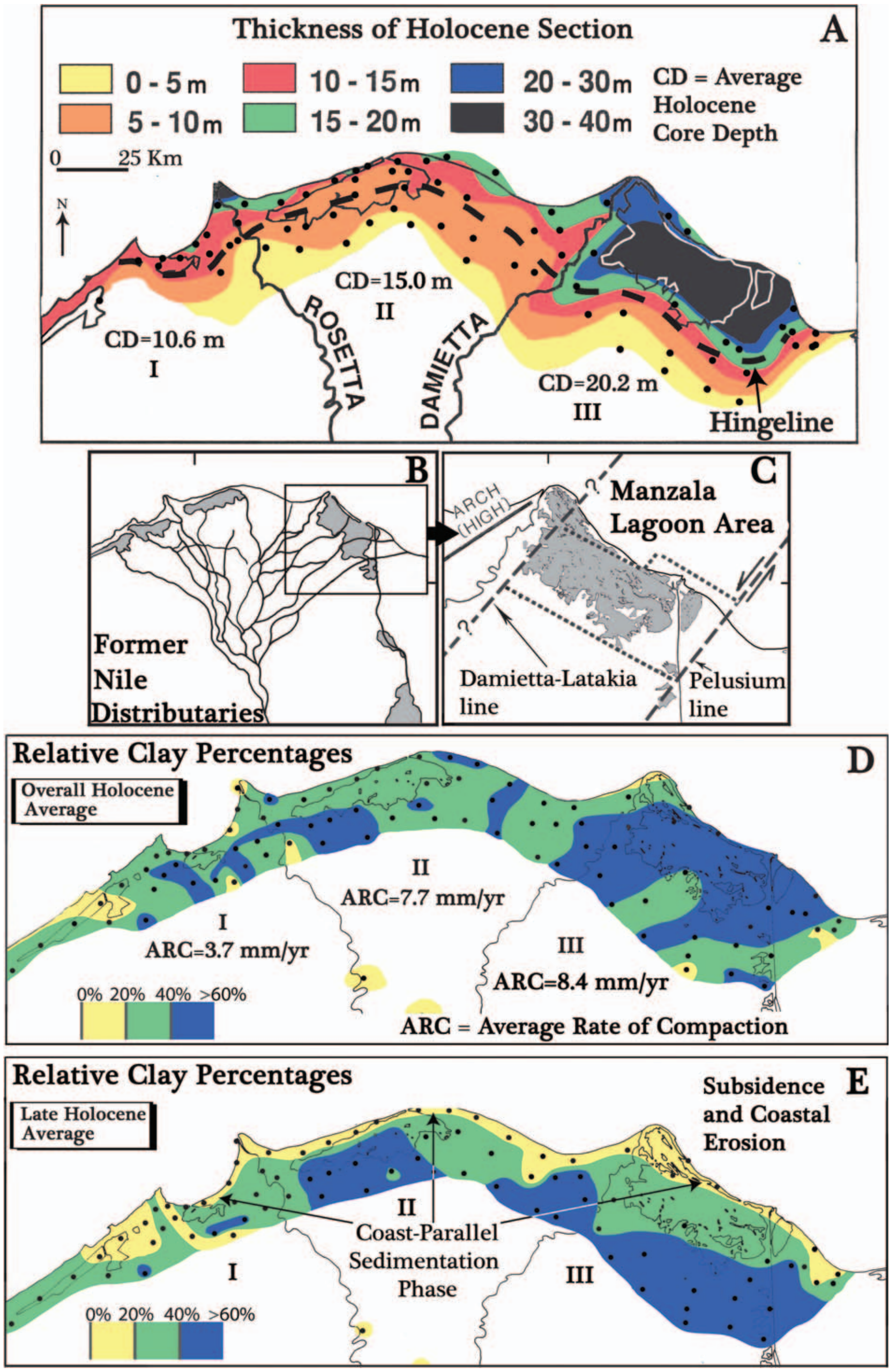


Figure 5. Five panels highlighting major aspects of Holocene sediment sequences and proportions of clay in the study area discussed in text. (A) Map showing average thickness of Holocene sequence (CD = average Holocene core depth) measured for each of the three sectors and position of the hingeline north of which deposits thicken. (B) Map showing irregular distribution of former Nile distributaries, most now abandoned or transformed into canals, which flowed at different times during the Holocene from south to north. (C) Manzala lagoon region indicating the neotectonic formation of a rhomboidal-shaped subsiding grabenlike area that has served as the major accumulation space for Holocene sediment deposited in the NE delta (after Stanley, 1988). (D) Map showing overall average Holocene clay percentages across the study area; distribution patterns show S-to-N trends. Average rate of compaction (=ARC) in the three sectors, recording highest values in the NE and north-central delta (data from Stanley and Corwin, 2013). (E) Map showing late Holocene average clay percentages across the study area; distribution patterns show a coast-parallel trend with much decreased proportions of clay trending northward toward the coast that are associated with recently increased rates of subsidence, relative sea-level rise, and consequent coastal erosion.

The annual Nile floods, carrying much-increased volumes of water and sediment, peaked for millennia in late summer–early fall. This process had long enriched the delta's soil cover, maintained natural depositional accretion, and served to protect sectors of the coast by active sediment build-out especially at and near distributary mouths. Widespread changes to this hydrographic regime occurred from the 19th century to present because of the construction of a series of large structures that have profoundly modified Nile flow. Among the more important were a series of barrages emplaced across the Nile in Middle and Upper Egypt in the 19th century and subsequent construction of the two large dams at Aswan (in 1909 and 1965); the most recent presently regulates the volume of Nile water flowing to Cairo and northward to the delta throughout the year. Natural flow and sedimentation processes, essential for maintenance of balanced deltaic development, were seriously disrupted after closure of the High Dam in 1965. Nile River flows from the southern Egyptian border to the sea are now almost completely controlled, with large volumes of Nile River sediment accumulating mostly at the southern end of the elongate Lake Nasser reservoir. It is here that the Nile's new delta has been forming during the past half-century. Water from this reservoir that is now released through the High Dam at Aswan carries a much reduced sediment load, but this condition changes rapidly along the Nile channel below the High Dam. As the Nile flows northward of the structure, the river once again scours its bed and banks (Schumm and Galay, 1994) and resumes transport of Nile channel floor sand, silt, and clay as bed and suspension loads downriver to Cairo and onto the delta. At Cairo and to the north, the dense network of irrigation canals, water diversion structures, pumping stations, and two barrages (Edfina and Faraskour Sudd structures) emplaced on the two still-active distributaries additionally control Nile flow across most of the delta surface (Waterbury, 1979).

Thus, the once powerful annual-peak discharge of water and sediment is no longer a major phenomenon for the natural replenishment of soil, fertilization of cultivated fields, and accretion of the delta surface by new deposits in the study area. Only the proportion of wind-blown dust distributed across the region (Guerzoni and Chester, 1996) is presently increasing relative to that of fluvial-sediment input. The thousands of km of canals of variable dimensions that crisscross the delta for irrigation and disposal of municipal, agricultural, and industrial sewage from Cairo and other centers are progressively diverting water and sediment, much of it polluted, toward the northern delta (Elewa, 2010; Stanley, 1996). Evidence that some clay-rich mud entrapment presently occurs in delta canals is provided by observing extraction locally of recent deposits from such channels by farmers for enhanced fertilization of their fields and for local production of bricks. In addition, recent accumulation of small silt-and-clay deltas at mouths of some canals positioned along wetland margins, such as at Burullus lagoon, indicates that fine-grain deposits actually reach the delta-front wetland settings. However, as a result of much intensified anthropogenic modification, only about 10% of the once natural Nile flow and a much reduced sediment load, including the clay fraction, now reaches the sea (Bohannon, 2010; Stanley, 1996).

## GEOGRAPHIC AND TEMPORAL VARIATIONS OF CLAY DISTRIBUTION

The distribution of clay in space and time in Holocene sections of the delta study area is important for assessing subsidence inasmuch as this is the textural fraction most likely to be affected by syn- and postdepositional gravitative compression. Maps of Holocene sediment texture distributions show that neither clay, silt, nor sand are evenly distributed across the delta front but, rather, that these grain sizes tend to display asymmetrical patterns (Figures 3A–C and 4A–C). The marked increase in relative percentages of clay from NW (<20% to 40%) to NE (>20% to >60%) sectors (Figures 3C and 5D) recalls the distributions of two other parameters determined in earlier studies. One of these is total thickness of Holocene subsurface sequences; the other is average rate of downcore strata thinning as a measure of sediment compaction. Calculations of both parameters were obtained using the same 87 cores analyzed for the present textural analysis, and, like proportions of clay, both show regional increases from NW to NE. With these data, one finds that delta plain sectors composed of the highest proportions of clay have also formed the thickest Holocene subsurface sequences, and these are likely to be the ones subject to the greatest amount of compaction. From these observations, it may follow that the near-horizontal delta plain underlain by thicker mud-rich sequences of Holocene age is at the greatest risk of being additionally lowered relative to msl.

The average thickness of Holocene sequences, indicated as the average Holocene core depth (CD in Figure 5A), varies laterally as follows (after Stanley, 1988, 1990): in sector I, the CD is 10.6 m, with a range of thickness from 1.5 m to 49 m; in sector II, it is 15.0 m, with a range of thickness from 3.6 m to 24.5 m; and, in sector III, it is 20.2 m, with a range of thickness from 1.3 m to 47 m. The two zones north of the hingeline that record the greatest thicknesses of Holocene sequence include a large area underlying the Manzala lagoon and adjacent region (to a depth of 47 m) and another of a much smaller area positioned at the Rosetta promontory near that Nile distributary's mouth (to a depth of 49 m). Of the two, only the former zone includes core sections composed of large proportions of clay-rich sediment. The three-dimensional configuration of a broad and thick sediment sequence beneath Manzala lagoon (Figure 5A), the largest of the present delta wetlands, presents a rhomboid shape and is the depositional fill of a grabenlike structure. It is bound by two major NE-SW trending strike-slip faults, the Pelusium and Damietta-Latakia lines (Figure 5C), that extend from offshore in the SE Mediterranean landward into the delta (Neev, 1977; Neev, Greenfield, and Hall, 1985). This depression is interpreted as a geologically recent (Holocene) feature, a pull-apart basin, resulting from tectonically active motion of the landward-trending shears (Stanley, 1988, 1990). This lowered area in sector III was filled largely by sediment discharged from a number of NE-flowing distributary branches (Figure 5B), including the Pelusiac, Tanitic, Mendesian, and Bucolic, which were active at different times during Holocene delta formation (El-Nasharty, Abdel Daiem, and Issa, 1990; Said, 1981, 1993; Toussoun, 1922). The large substrate area comprising the greatest concentration of clay (Figure 5D) is also the one centered in this zone that has trapped the greatest amount of Holocene thickness (Figure 5A). Some textural distribution patterns of clay are suggested by linear bands that cross this part of the study area from SW to NE (Figure 3C). The sum of observations shed light on a previously dominant paleogeographic configuration, where NE dispersal paths and enhanced discharge of fine fractions were directed from the central delta towards the Manzala lagoon region (Figures 5B, C).

The second parameter that appears to be related to clay-rich zones is the average rate of downcore strata thinning, a measure used as a proxy for annual average rate of compaction (average rate of compaction [ARC] in Figure 5D), as detailed in Stanley and Corwin (2013). In that study, thicknesses of 3183 sediment layers were measured in the borings recovered in the study area. The calculated downcore m-by-m changes appear to be closely associated with the depth of strata at and beneath the delta surface and with their increased age downcore as determined by radiocarbon dating. The thickest layers are usually positioned at near-surface depths of 1 to 2 m and are dated, for the most part, at <2000 yr BP. Layers in the next m below the uppermost 2 m of strata thin markedly downcore. The initial and rapid reduction in strata thickness at these upper depths of ~3 m results from expulsion of interstitial pore water from the layers caused by overburden weight from overlying sediment and also by significant evaporation of water from near-surface sections attributable to hyperarid conditions that prevail in this region. Another observed pattern at each core site is one of further irregular downcore decrease in strata thickness from depths of ~3 m to ~5 to ~6 m, and this is then followed by a more gentle decrease in strata thickness from those depths to the base of the Holocene core section. The more gradual reduction of strata measured at mid- and lower core depths may nevertheless account for as much as 50% of the total annual Holocene compaction rate. The ARC values averaged for the strata between top and base of cores in the three sectors are summarized as follows in Figure 5D (data from Stanley and Corwin, 2013): ~3.7 mm/y for sector I; ~7.7 mm/y for sector II; and ~8.4 mm/y for sector III. It is of note that this average range of compaction rates is comparable to the range of annual land subsidence rates obtained by means of satellite surveys of the northern delta (Becker and Sultan, 2009).

Comparing the proportions of sand, silt, and clay in the overall Holocene averages (Figure 3) with those in the late Holocene averages (Figure 4) provides a means to identify temporal changes that occurred in the study area following the major depositional phases in the early and middle Holocene. The present study reveals that a significant change in textural distribution patterns occurred within the past ~2000 years (compare Figures 3 and 4). A modest decrease in the overall percentages of both clay (from 35.5% to 30.4%) and silt (from 35.3% to 31.8%) is recorded from the lower and middle Holocene to more recent time in the three geographic sectors (I–III), while proportions of sand increased more substantially (from 29.2% to 37.8%). More remarkable, however, are regional textural distribution patterns of sand, silt, and clay that show a significant change from the dominant influence of S-to-N dispersal across the northern delta (~8000–2000 yr BP; Figure 3) to one that, in more recent times, has become distinctly coast-parallel (after *ca*. 2000 yr BP; Figure 4). This more recent pattern records markedly increased coastal marine influences along the northern margin.

## RAMIFICATIONS AND CONCLUSIONS

The major point of the present study has been to explore whether any relationship exists among northern delta regions that are characterized by (1) high concentrations of Holocene clay-size fractions, (2) thick stratigraphic sequences, and (3) large measured average rates of compaction. That these three attributes are closely linked is indicated (Figures 5A, D), and from this it is proposed here that the greatest amounts of ongoing delta-plain subsidence may still be occurring in zones where these three parameters prevail. It is recalled that the delta area between the hingeline (Figure 5A) and the coast to the north has received the greatest amount of sediment accumulation (locally to nearly 50 m). The present delta plain surface is near-horizontal, while the thickness and base of Holocene clay-rich deposits underlying that surface vary considerably. This implies that while accumulation spaces of variable lateral and temporal dimensions formed and were lowered, they were being filled with sediment. From these observations it appears that active sediment deposition and filling of the deepest accumulation spaces prevailed in zones of the northern delta for extensive periods of time during the past ~8000 years of deltaic aggradation and development. The most prominent example of this syn-depositional lowering-and-fill phenomenon is recorded in the NE region (sector III), under and in proximity to the Manzala lagoon (Pelli and Carletti, 1998; Stanley and Warne, 1998; Warne and Stanley, 1993a).

The body of work presented here does not support conclusions of some workers who propose that subsidence has played only a minor role, if at all, in the recent history of the Nile Delta. For example, R. Said (1993, p. 78) indicates that the Nile Delta "is not subject to compaction and does not seem to depend on sediment supply to sustain itself." His argument is based on the assumption that the Nile Delta is composed of a core of sand and gravel with only a thin veneer of silt and clay, but one for which he provides no supporting evidence for or against compaction. Nor does Said discuss the possibility of lowering of underlying subsurface sequences by other factors such as isostatically driven motion, strata readjustments at depth, neotectonics, and other processes that can induce elevation changes of this depocenter relative to sea level. Finally, Said rules out that the northern delta presently continues to be subject to lowering relative to sea level, at least in part, because sediment loads now being transported to and accumulating upon depressed areas are substantially reduced and do not presently replenish near-surface deposits subject to compaction.

The amount of sediment displaced downriver and released on the northernmost delta surface has diminished in recent centuries, especially after closure of the High Dam. It has been estimated, for example, that the Nile River's long-term annual peak discharge of 8430 $m^3$/s before High Dam closure has now been reduced to a maximum release of 2550 $m^3$/s, and the pre-High Dam peak suspended sediment concentration of 3500 mg/L is now only ~100 mg/L (Schumm and Galay, 1994, p. 81).

Thus, even a modest sea-level rise and low-to-moderate compaction rates of clay-rich sequences producing relative sea-level rise would become apparent and could be readily measured at the coast.

Three independent observations provide evidence, albeit indirectly, for ongoing subsidence, especially in the north-central and NE sectors. The first pertains to a large zone in NE sector III that records salinization between the coast and agricultural zone south of the Manzala lagoon, which appears to be increasing in size (salinity values >2500 ppm; Mohamedin, Awaad, and Ahmed, 2010; Shata and El Fayoumy, 1970; Wahab, Rasheed, and Youssef, 2010). The second involves the decrease in delta build-out and increased rates of coastal erosion as recorded along extensive stretches of the delta margin (Frihy, 1992; Frihy *et al.*, 2010; UNDP, 2009). The third is the remarkable change in sediment-texture distribution, as mapped in the present study. This records a change from a dominant fluvial-marine transport trend directed from south to north during much of the Holocene (Figures 3 and 5D) to one that recently became distinctly coast-parallel (Figures 4 and 5E). This more recent (late Holocene) textural distribution is interpreted as recording a reduction of land-derived sediment that now reaches the coast and that is increasingly reworked and shaped by ongoing nearshore marine processes.

Mapped textural distributions indicate that coastal stretches were built out or relatively stabilized by fluvial-marine processes during most of the Holocene, and delta development was maintained as a reasonably balanced system where construction, rather than erosion, prevailed. The latter, inducing a landward shoreline advance, appears to have evolved during the past two millennia or perhaps more recently, as the coast became subject to greater rates of erosion. The marked increase of sand deposition (as opposed to silt-clay dominant deposition) aligned along the coastal margin, some of it comprising fauna and fragments of marine origin, attests to the increased role of sand redistribution, mostly from west to east (Inman and Jenkins, 1984; UNDP/UNESCO, 1978). There is ample evidence of rapid shoreline cutback, including the following: recent submergence of stretches of the former Damietta to Port Said coastal road; accelerated destruction and partial submergence of dwellings and other structures in the Baltim resort area (B in Figure 2); high annual rates of erosion of the once long Rosetta and Damietta promontories that, until recently, extended out to sea; and increased marine-induced damage to sectors of Port Said.

In summary, increased relative sea-level rise, resulting from lowering of the delta plain surface and lack of sediment replenishment, is critically altering delta-front development. Indication that this scenario is continuing is provided by the measured annual average compaction rates of Holocene subsurface sections and consequent lowering of segments of the northern delta coastal margin at rates of 3.7 mm/y to 8.4 mm/y (Figure 5D). Such rates are much greater than those of regional sea-level rise proposed for this region that range from 1.7 mm/y (Wöppelmann and Marcos, 2012) to as much as 3.1 mm/y (Nerem *et al.*, 2010) or even more as determined from geophysical modeling. If the above conservative rate of ongoing regional sea-level rise (1.7 mm/y) is combined with average rates of Holocene strata compaction (Figure 5D), the resulting rates of relative sea-level rise would range to ~5.4 mm/y in sector I, ~9.4 mm/y in sector II, and ~10.1 mm/y in sector III. Based on these measurements, it has been predicted that the northern third of the delta, which lies at elevations of ~1 m above msl, would be submerged in little more than a century (Stanley and Corwin, 2013). In the north-central and NE delta study areas, this elevation extends as far inland as >30 km from the coast.

The above estimate of marine encroachment assumes that no additional extensive and coast-continuous protection measures are constructed to impede Mediterranean water from entering further into the delta. Considering the database presented in this investigation, it would thus be beneficial for coastal managers involved in the planning and implementation of such needed protective structures to take into special account those locations of thick clay-rich subsurface sections near the coast where rates of compaction are high. These northern delta plain surfaces are designated as among the most prone to effects of subsidence. It would be important for those primarily concerned with this issue, and in a position to assist, to be made aware of measurable ongoing changes affecting this vital Egyptian region so that those living in this vulnerable sector can be better prepared and less susceptible to possible undesirable outcomes. The fifth century BC Greek historian Herodotus, commenting on some of the issues pertaining to the delta, wrote in *The History* (2.12–14) "if…the Nile no longer floods it, then for all time to come, the Egyptians will suffer…" It need not come to that.

## ACKNOWLEDGMENTS

The authors thank K.A. Corwin and M.R. Senatore for their constructive reviews that helped us improve earlier versions of the manuscript.

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