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Nile delta margin: failed and fluidized deposits concentrated along distributary channels

La marge du delta du Nil : concentration de dépôts fracturés et fluidisés le long des paléochenaux fluviatiles

Jean-Daniel Stanley*

Abstract

Previous sediment studies on the Holocene Nile delta margin have emphasized fluvial input and coastal processes, but have overlooked the failure of depositional sequences by syn- and post-depositional events. Herein, petrologic analysis of sediment sections in cores collected along the Nile delta margin indicates the presence of disturbed strata. These modified deposits are not randomly distributed, but are concentrated along former Holocene distributary channels, and generally absent between these Nile branches. Sediment failure involving fluidization, mass flow, and fault-offset prevailed from the mid- to late Holocene, especially since ~4,500 years before present. Bedding disturbance was caused by deposition of sediment with high pore water pressure at and seaward of Nile distributary mouths, with flooding along channel mouths believed to be the major trigger of failure. These geohazards were responsible for destruction and partial submergence of the ancient cities of Herakleion and Eastern Canopus in western Abu Qir Bay from ~100 B.C. to 741 A.D. Although floods no longer occur since the closure of the Aswan High Dam, some cities constructed on older water-saturated underconsolidated sediment along the modern delta coast remain prone to failure. Protection measures for expanding population centers on the Nile margin warrant thorough civil engineering surveys, including analyses of physical properties of the sediment substrate, with implementation of viable building codes.

Key words: bottom currents, cores, diapirs, distributaries, disturbed strata, fluidization, sediment failure, Herakleion, Holocene.

Résumé

Les études réalisées jusqu'à présent sur la marge du delta du Nil ont surtout mis l'accent sur la contribution des apports fluviaux et l'importance des processus côtiers, sans véritablement s'intéresser aux phénomènes de déformations-fracturations des dépôts par des événements syn- et post-sédimentaires. L'analyse stratigraphique de plusieurs carottes sédimentaires prélevées le long de la marge deltaïque indique clairement la présence de couches dont la structure sédimentaire a été modifiée. Ces dépôts perturbés n'ont pas une répartition géographique aléatoire: ils se concentrent préférentiellement le long des paléochenaux fluviatiles originels, alors qu'ils sont généralement absents entre les anciens bras du Nil. La présence de déformations-fracturations sédimentaires, qui impliquent des phénomènes de fluidisation, des mouvements de masse et des déformations d'ordre tectonique, dues à l'activité de failles, est avérée pour ce qui concerne l'Holocène moyen et récent, plus précisément depuis 4500 ans B.P. La modification des structures sédimentaires est rendue possible par la mise en place, sur la marge externe des embouchures du Nil, de sédiments enclins à de fortes pressions par les eaux interstitielles. À ce titre, les eaux de crue dans les embouchures sont considérées comme l'élément déclenchant des déformations/fracturations. Ces aléas géophysiques furent responsables de la destruction et de la submersion partielle de l'ancienne cité d'Hérakléion et de la partie orientale de Canopus, à l'ouest de la Baie d'Abu Qir, entre ~ 100 av. J.-C. et 741 ap. J.-C. Même si les crues sont devenues plus rares depuis la mise en place du haut barrage d'Assouan, les quelques villes édifiées sur les anciens corps sédimentaires meubles et saturés d'eau, que l'on trouve le long de la frange côtière du delta moderne, peuvent être exposées à ces aléas. La protection des noyaux de population en expansion sur les marges du Nil passe par des opérations d'ingénierie adaptées, qui devront prendre en compte les propriétés physiques des sédiments, afin de respecter les normes de construction viable.

Mots clés : *courants de fond, carottes, diapirs, effluents, structure déformée, fluidisation, fissure/fracture sédimentaire, Héracléion, Holocène.*

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Les principaux résultats de cette recherche portent sur 1°) la mise en évidence de déformations et de fracturations affectant les sédiments plastiques situés le long des paléo-bras et des paléo-embouchures holocènes du Nil (fig. 1) et 2°) la quasi-absence de telles perturbations syn- et post-sédimentaires, dans les zones situées entre les anciens bourrelets alluviaux. Deux hypothèses sont envisagées pour expliquer les perturbations sédimentaires : 1) les crues du Nil et 2) les tremblements de terre et les tsunamis. L'étude privilégie la première hypothèse, à savoir que les crues annuelles du Nil ont joué un rôle majeur dans la mise en place des fractures et le déclenchement d'écoulements en masse des sédiments rendus instables par leur saturation en eau. En outre, cette hypothèse permet d'expliquer pourquoi les perturbations sédimentaires sont observées préférentiellement le long des anciens chenaux fluviatiles, à proximité de la marge deltaïque. Si des tremblements de terre et des tsunamis (hypothèse 2) étaient à l'origine des perturbations sédimentaires, leurs impacts (i.e., *déformation des strates) auraient dû être enregistrés aléatoirement, et ce sur des secteurs plus étendus de la marge deltaïque. En d'autres termes, les perturbations sédimentaires* (i.e., *structures fluidisées, micro-failles) auraient dû être observées non seulement le long des anciens bourrelets alluviaux mais aussi entre ces derniers, ce qui n'est pas le cas.*

L'utilisation pluri-séculaire des "nilomètres" par les Égyptiens a permis d'obtenir une somme d'informations colossale sur les crues passées du Nil, qui se produisaient chaque année à la fin de l'été et à l'automne (Popper, 1951). L'occurrence de crues annuelles exceptionnellement hautes (CAEH) a été attribuée à des fluctuations paléoclimatiques majeures affectant les têtes de bassin du Nil situées en Afrique centrale et orientale (Hassan, 1981 ; Hamid, 1984 ; Shahin, 1985). Les travaux de Saïd (1993) ont montré que les CAEH du Nil ont été plus fréquentes à partir du IV^e millénaire B.P. et plus précisément entre 3 840 B.P. et 3 770 B.P. puis à partir de 2 900 B.P. L'arrivée des CAEH est synchrone de la mise en place des perturbations sédimentaires, au cours de l'Holocène moyen et récent. Événements hydrologiques de haute magnitude, ces CAEH ont pu provoquer des perturbations sédimentaires au niveau des différents sous-lobes formés le long de la côte et être à l'origine de défluviations et du déplacement des chenaux sur la plaine deltaïque. À partir d'une synthèse des données de base maintenant disponibles, il apparaît que les effets de charge différentielle, les phénomènes de fluidisation et le déclenchement des écoulements en masse sont étroitement liés aux CAEH et à la rapide progradation de la marge deltaïque, en particulier durant l'Holocène moyen et récent (Stanley et al., *2003). Les stratifications inclinées, soulevées et/ou décalées, les plis diapirs et les structures fluidisées ont pu se former préférentiellement durant la progression des chenaux vers la côte, comme cela a pu être montré aux embouchures de l'ancien bras de Canopic (fig. 2 et fig. 3). Des prospections géophysiques haute-résolution et des carottages complémentaires (fig. 4, fig. 5 et fig. 6A) s'avèrent nécessaires, de façon à pouvoir confirmer (ou pas) si de telles perturbations sédimentaires existent sur la marge du delta du Nil, ailleurs que sur les sites déjà étudiés.*

L'essentiel des apports du Nil à la Méditerranée a été court-circuité aussi les inondations du fleuve ne représentent-elles plus qu'un épiphénomène le long de la frange côtière (Stanley et Warne, 1998). Mais des déformations de masse peuvent toujours se produire dans les secteurs du delta où abondent les accumulations de sédiments non-consolidés (i.e. *le long des chenaux fluviatiles et sur la marge de la plaine; fig. 6B). Alexandrie, l'une des plus importantes villes côtières d'Égypte, a été édifiée sur un substrat stable [*i.e., *calcaires pléistocènes (kurkar)], trois mètres ou plus au- dessus du niveau de la mer, de telle sorte que l'on n'y rencontre pratiquement pas de perturbations sédimentaires. En revanche, d'autres villes implantées à proximité immédiate de l'actuelle frange deltaïque, en particulier celles construites sur des sédiments saturés en eau* (i.e., *non-consolidés), restent vulnérables aux aléas naturels associés aux mouvements du sol (Waltham, 2002). Tel est le cas à Baltim, où les constructions, bâties au départ à proximité de l'ancien bras de Sebennytic, se retrouvent aujourd'hui sur la frange deltaïque, suite au recul important du trait de côte. Il en est de même à Port-Saïd, à proximité de l'ancien bras de Tanitic, dans une zone subsidente où la montée du niveau marin relatif est rapide.*

Enfin, cette étude insiste sur le fait que des mesures de protection doivent être prises pour permettre l'extension en toute sécurité des noyaux de population sur la frange côtière du delta du Nil. Les opérations d'aménagement devraient donc s'appuyer sur des études approfondies, prenant en compte les propriétés physiques des sédiments, de façon à pouvoir pérenniser la viabilité des constructions. Dans les zones exposées au risque de mouvements du sol, on préconise que les nouvelles constructions et autres grandes structures soient bâties sur des pieux profondément ancrés dans le sol. En outre, il serait nécessaire d'approfondir les causes et la nature des fissures observées sur les structures grecques, romaines et byzantines, à Hérakléion et à l'est de Canopus (fig. 2 et fig. 3), afin de déterminer s'il existe un lien entre ces fissures et les déformations qui affectent les terrains sédimentaires situés le long du bras de Canopic. Comprendre comment ces anciennes cités ont été détruites devrait donc représenter bien plus qu'un exercice strictement académique.

Introduction

The Nile, one of the world's longest rivers (6,690 km), flows northward across 35° of latitude and drains the east-central African basin with an area of ~2,880,000 km^2. The Nile delta, with an area of ~20,000 km^2, was the largest coastal depocenter in the Mediterranean until the emplacement of the High Aswan Dam. The coastline along the delta is 225 km in length, and the distance between the delta apex near Cairo and the coast is 160 km (fig. 1A). Recent delta development and evolution of its coastal sector and contiguous shelf (herein termed delta margin) are the results of several key parameters: (1) seasonally variable dispersal of River Nile flow as well as fluvial sediment to the coast and sea; (2) sufficient accommodation space to trap a considerable amount of sediment at Nile distributary mouths on the lower alluvial plain and adjacent coast and shelf; and (3) extensive erosion and redistribution of sediment by strong wave- and storm-induced erosional processes near mouths of the Nile promontories and along the coast (UNDP/UNESCO, 1977, 1978; Sestini, 1989; Stanley and Warne, 1998).

It is recognized that the arcuate coastline and fluvial-marine environments at the delta front have been shaped largely by the collective interaction of sediment input, relatively strong coastal and nearshore currents, land subsidence, and sea-level rise. To date, however, little attention has been paid to other factors that may have affected the configuration of Holocene deposits on this lower delta margin. These could include failure and disruption of strata by sediment instability and mass flow by river mouth processes, as well as Nile flooding, earthquake, and tsunami events. This investigation explores the extent to which the present current-smoothed Nile margin may have been modified during its development by soft-sediment deformation and fault offset of strata. If such evidence is found, it would be useful to determine: (1) if such processes occurred contemporaneously with (syn-depositional), or after (post-depositional), active sedimentation; (2) whether such processes occurred randomly along the delta margin or were site specific; and (3) times during the Holocene in which such failure occurred. For this study, an examination is undertaken of petrologic patterns of strata in a suite of sediment cores collected along the delta margin.

Shaping of seafloor and sediment patterns by currents

Nile delta deposits began to agrade and prograde on Egypt's coast about 7,500 years ago (Stanley and Warne, 1994). The coastline at that time was affected by a marked decrease in the rate of world sea-level rise, from ~10 mm/yr to 1-2 mm/yr, with shoreline placement between 10 m to 15 m below present sea-level stand (Fairbanks, 1989). Nile sediment input and oceanographic conditions that drive water mass flow in the SE Mediterranean have been the dominant long-term controls of Nile delta margin physiography and sedimentation patterns. Dominant water flow off the coast (fig. 1A) has been linked to regionally prevailing climatic conditions, including increased regional aridity since about 6,000 years before present (yrs. B.P.).

The present oceanographic regime off Egypt's Mediterranean margin is a response largely to wave approach (fig. 1A), where dominant east-directed longshore currents are generated with velocities from 20-50 cm/sec, and occasionally to >100 cm/sec (Sharaf El Din, 1973; UNDP/UNESCO, 1977). Winter storm waves (fig. 1A, inset), with heights to 3 m, approach the coast from the northern quadrant and also actively erode and displace sediment from the Nile delta coast eastward to as far as northern Israel (Carmel *et al.*, 1984; Nir, 1984; Fanos, 1986; Stanley, 1989; Sharaf El Din and Mahar, 1997). Seasonal variability of wave approach and topographic irregularities along the delta coast produce locally converging and diverging current patterns that modify erosive activity and sediment displacement patterns (fig. 1A). Examples include Abu Qir Bay on the NW Nile delta margin (Frihy *et al.*, 1994) and the inner to mid-shelf sector on the NE delta coast off the Damietta promontory (Murray *et al.*, 1981). Effects of tides (to ~30 cm) on the margin are minimal.

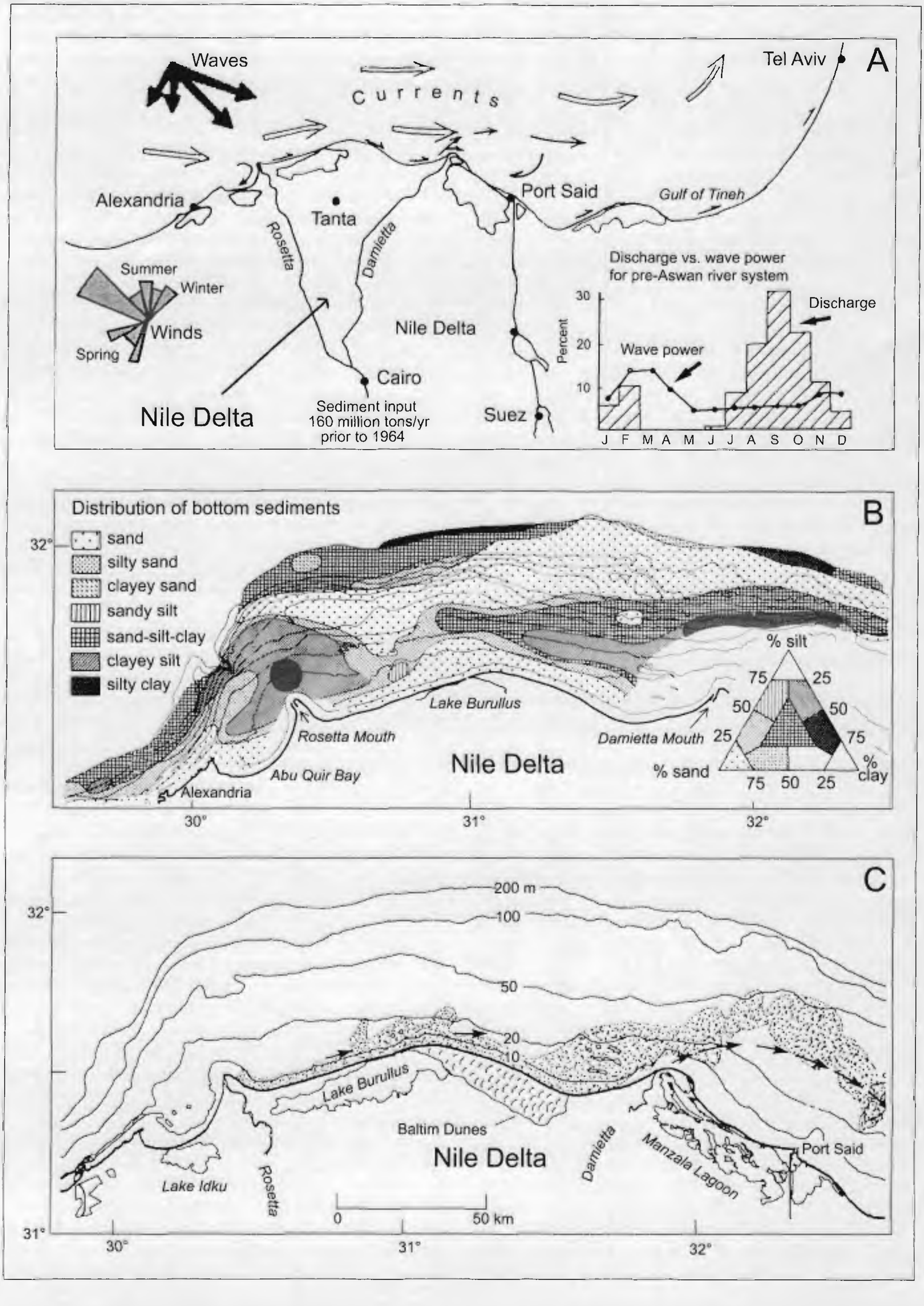
Sedimentation patterns offshore are the result of dispersal of Nile flood water and sediment from several former distributary channels of the Nile. From the early to mid-Holocene, perhaps as many as ten such channels flowed seaward, but not all of them were concurrently active (Toussoun, 1922). Oceanographic factors, riverflow and sedimentation, influencing the coastal configuration of the Nile delta and its contiguous shelf, are incorporated in a Nile littoral cell model derived for this region (Inman and Jenkins, 1984). The model takes into account sediment transport patterns influenced by river Nile sources, strong easterly flow, and erosion of the delta coast and inner shelf to as far as northern Israel.

Climatic change affecting Africa after the mid-Holocene resulted in annual river Nile flood volumes that were reduced to one-third, or less, compared to those that had prevailed in the early Holocene (Said, 1993). This caused a reduction in rate of seaward progradation of the Nile delta margin that, until then, had ranged to ~10 m/yr (Coutellier and Stanley, 1987). Also altered were avulsion rates for different Nile branches, and promontory development at distributary mouths (Frihy *et al.*, 1988). Sediment discharge to the coast was seasonal prior to closure in 1965 of the High Dam at Aswan: more than 80% of the Nile's total sediment load was released from August to October (fig. 1A, inset), while 20% was distributed during the remaining nine months (Sestini, 1989). Average grain size of suspended load from the river Nile during past annual late summer to early fall flood periods was 25% sand, 42.5% silt, and 32.5% clay.

Average annual discharge decreased to little more than 100 billion m^3 by the 19th century, and then further reduced to an average of 84 billion m^3 during the first half of the 20th century. At present, very little Nile water (< 5 billion m^3) and sediment reaches the sea (Stanley and Warne, 1998). However, even at present, wave-related processes and erosion maintain a 2.5-7 km-wide zone of active eastwardly-moving sand and finer sediment along the coast and nearshore zone from the delta to the Levant (fig. 1C) (Manohar, 1981; Inman *et al.*, 1992; Stanley *et al.*, 1997). Active sedimentation, in some instances, reaches shelf depths of 40 m to 50 m (Murray *et al.*, 1981). Under such conditions, surficial depositional patterns on the Nile shelf are aligned along major eddy current trends, shelf bathymetry, and coastline configuration (Summerhayes *et al.*, 1978; Bernasconi and Stanley, 1997).

Syn- and post-depositional structures in Abu Qir Bay

Although smoothing of the seafloor by bottom current erosion tends to mask much of the pre-modern history of coastal margins, study of major deltas on coasts of modern world oceans record at least some evidence of disturbed Holocene



A
Waves
Currents
Tel Aviv
Alexandria
Tanta
Rosetta
Damietta
Port Said
Gulf of Tineh
Summer
Winter
Winds
Spring
Nile Delta
Cairo
Suez
Nile Delta
Sediment input
160 million tons/yr
prior to 1964
Discharge vs. wave power
for pre-Aswan river system
Discharge
Wave power
Percent
30
20
10
J F M A M J J A S O N D
B
Distribution of bottom sediments
sand
silty sand
clayey sand
sandy silt
sand-silt-clay
clayey silt
silty clay
32°
Lake Burullus
Rosetta Mouth
Damietta Mouth
Abu Quir Bay
Alexandria
Nile Delta
% silt
% sand
% clay
75 50 25
30°
31°
32°
C
200 m
100
50
20
10
Lake Burullus
Baltim Dunes
Nile Delta
Lake Idku
Rosetta
Damietta
Manzala Lagoon
Port Said
0
50 km
31°

bedding. Such features are commonly concentrated at and seaward of delta mouths, but sometimes also occur on lower land sectors of deltas and their contiguous inner to middle continental shelves. Stratal disruption of this type has been recognized on multi-beam topographic records, side-scan sonar profiles, and high-resolution seismic lines along which sediment cores have been collected (Coleman, 1988; Maestro *et al.*, 2002). To date, however, there have been only limited investigations of the late Quaternary on the Nile coastal margin and its contiguous inner shelf. Most surveys off this delta system, primarily designed for oil and gas exploration, have obtained deep seismic data and borings that focus on strata below Pleistocene deposits (Schlumberger, 1984). Low resolution, shallow penetrating, echo-sounding profiles (12 kHz) have been collected across parts of the Egyptian shelf to help identify surficial sediment patterns and patch reefs (Summerhayes *et al.*, 1978, their fig. 5). Overall, such published results of the Nile margin have been of insufficient resolution and areal coverage to reliably identify and map disturbed and/or offset Holocene strata.

An exception is the recent geoarchaeological investigation in western Abu Qir Bay off the NW Nile delta that examined attributes of sediment strata beneath submerged ancient Greek to Byzantine cities of Herakleion (cited by Herodotus) and Eastern Canopus (Constanty, 2002; Goddio *et al.*, 2003) now at depths of ~5 m to 7 m (fig. 2). These former trade centers were positioned at Canopic mouths of delta sublobes when, in the 7th century B.C., the coast was ~5 km north of the present shoreline. The cities were damaged and submerged from ~100 B.C. to 741 A.D. (Stanley *et al.*, 2003). Within this position of the bay, bathymetric, magnetometer, and side-scan sonar exploration (conducted mostly in 1996 and 1997), coupled with a sub-bottom seismic survey (fig. 2; in April and May 2000) and a sediment vibrocore program (fig. 2; in April and May 2001), were undertaken to detail attributes of Holocene deposits. Cores were collected in 7.5 cm diameter aluminum tubes. Particularly valuable for this investigation in Abu Qir Bay are high-resolution seismic subbottom profiles obtained with a Triton EdgeTech XStar system. The profiles, collected along 15 north-south and 22 east-west oriented transects, are spaced from about 100 m to 1000 m apart (fig. 2) and penetrate to depths of ~10 ms to 15 ms two-way travel time (or ~7.5 m to 10 m below the water-sediment interface). These account for a total of ~350 km of profiles covering nearly 100 km^2 in the western bay. Two of the east-west profiles are presented here (fig. 3). The location of sediment cores is shown relative to seismic lines and the ruins of the two submerged sites (fig. 2).

Fig. 1 – **Nile delta margin.** A: wave and wind regimes affecting coastal and shelf water flow patterns off Egypt's Nile delta. Seasonal variation of sediment discharge and storm wave power are shown in inset (after Sestini, 1989); B: map of the Nile shelf showing surficial sediment texture patterns (after Summerhayes *et al.*, 1978); C: bathymetry (depth in m) and sediment transport paths along the Nile delta margin (after Inman *et al.*, 1992).

*Fig. 1 – **La marge du delta du Nil.** A : régimes des houles et des vents affectant la plate-forme continentale et la frange côtière du delta du Nil. Les variations saisonnières des apports solides et de l'énergie des houles sont indiquées sur le graphique (d'après Sestini, 1989) ; B : carte de la plate-forme continentale en avant du delta du Nil, montrant la répartition des sédiments de surface (d'après Summerhayes* et al.*, 1978) ; C : bathymétrie (profondeurs en m) et dynamique des flux sédimentaires le long de la marge du delta du Nil (d'après Inman* et al.*, 1992).*

This geological investigation of western Abu Qir Bay provides valuable baseline information on syn- and post-depositional deformation of Holocene strata localized along former Canopic distributary branches of the Nile. East-west oriented profiles show that the Holocene cover is about 5-7.5 meters thick, near the Abu Qir peninsula (western bay), and thickens (>10 m) toward the east. A hard basal layer, probably consolidated carbonate deposits of Pleistocene age, disappears at depth along eastern segments of profile lines. This configuration was caused by downward depression, folding, and/or fault offsetting of Pleistocene and Holocene strata east of the peninsula (Hassouba, 1980), resulting from rapid accumulation of delta deposits released from the Canopic branch. After the early part of the 1st millennium A.D., downward-bowing of recent sediment sections shifted toward eastern Abu Qir Bay.

Seismic surveys indicate that more than half of the western bay is covered by near-horizontal stratified muds and sands oriented as sheets lying parallel or subparallel to the seafloor surface (fig. 3A and 3B). These are normally positioned strata of Canopic delta sublobe deposits that accumulated above, and buried, irregular (faulted, folded, eroded) late Pleistocene basal sections. Typically, modern bay floor deposits such as these are of low relief (<3 m), the result of erosion and sediment redistribution by strong bottom currents (Fanos, 1986; Smith and Abdel-Kader, 1988).

Of special interest to the present investigation are seismic profiles that indicate disturbed, non-horizontal strata in localized, well defined portions of the bay. Two such areas are those that lie just beneath the submerged archaeological sites of Herakleion and Eastern Canopus (fig. 2). One anomalous surficial feature is the large domed horizon located just east of the submerged Herakleion ruins (fig. 3A). This feature is nearly 800 m wide and 4 m high, with its steeper face sloping to the east. Core 2, collected on this mounded topography, indicates that the upper part of the feature is formed of sand (at least to the core base at a depth of 3.2 m; fig. 4). In cross-section, the configuration of the asymmetrically-shaped mound resembles a broad, low-lying dune. The eastern margin is bordered by a 250-300 m wide channel-like depression (location of core 1; fig. 3A). When viewed together, E-W oriented profiles crossing the dome feature at several places (fig. 3B) identify an elongate N-S oriented sand bank, a probable coastal sand ridge that once lay parallel to one of the Canopic delta sublobe channels lying east of Herakleion. The sand ridge appears closely associated with the bay floor area of offset strata immediately to the west of it. It is of note that these highly deformed strata form the sediment substrate just beneath the Herakleion ruins (fig. 3A and 3B).

Seismic profiles indicate that strata directly under the ruins at both Herakleion and Eastern Canopus in the western bay (fig. 2) are disturbed, tilted, and uplifted to the seafloor. Also observed at depth are probable diapirs, large domed post-depositional sediment features that have been squeezed upward (fig. 3A). These now-deformed Holocene strata were originally deposited horizontally at and seaward of Canopic delta mouths, and then modified by geologically recent events. Side-scan sonar images collected in the western bay also provide evidence of anomalous stratification locally cropping out at the bay floor surface, especially north of Herakleion. What appear as large undulations comprise partially-exposed strata, probably tilted and mud-rich, that were uplifted to the bay floor. These pockets of older Holocene strata were subsequently eroded by bottom currents, and are now covered by a thin veneer of modern rippled marine sand.

A nuclear resonance magnetometer survey made across the western bay area also records distinct anomalies indicating offset Holocene stratification at, and just beneath, the seafloor surface in the vicinity of the two submerged cities. Well-defined straight and curvilinear features are mapped at both localities, some trending N-S at Eastern Canopus and ENE-WSW at Herakleion. Diver excavation of one such anomaly at Eastern Canopus showed it to be a long (~100 m), buried, sand-filled trench formed in the underlying Holocene mud substrate. Cleared of sand, this curvilinear trench is V-shaped in cross-section, about 5 m wide at the top and 2 m deep. A well-defined, rectilinear fault-like break (to ~50 cm wide and deep) is present at its base. Such

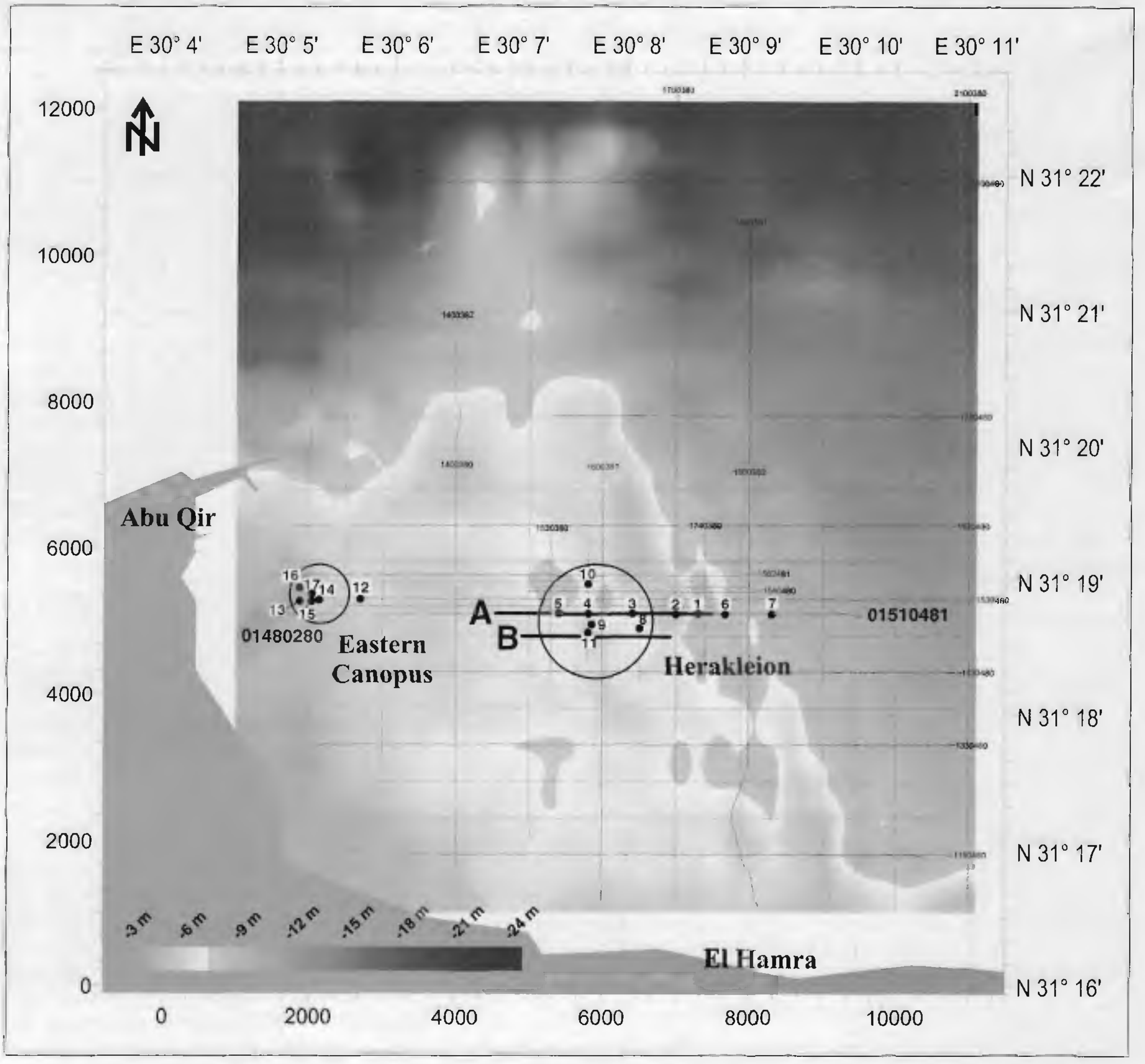


Fig. 2 – **Map of western Abu Qir Bay showing high-resolution seismic lines (including two profiles shown in bold, see fig. 3), 17 vibrocore sites and location of submerged Herakleion and Eastern Canopus.**

*Fig. 2 – **Carte de la zone occidentale de la Baie d'Abu Qir, montrant la localisation des profils sismiques haute-résolution (incluant deux profils dessinés en gras, voir fig. 3), les dix-sept sites où ont été réalisés les carottages vibro-percutés et les anciennes cités submergées d'Hérakléion et de Canopus (zone orientale).***

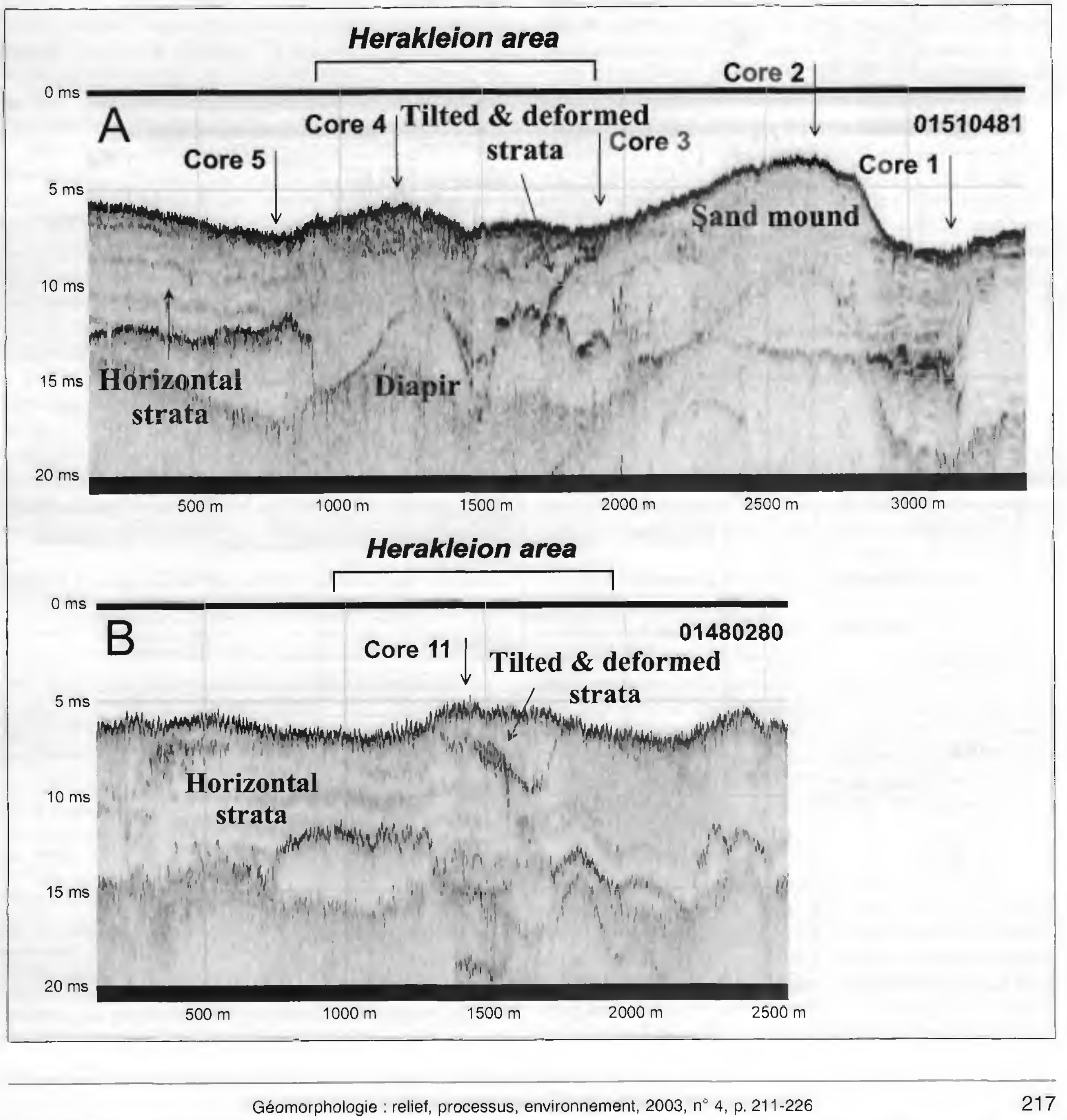
breaks at the seafloor, termed crown cracks, are interpreted as surficial expressions of growth and listric faults (Coleman, 1982; Elliot, 1986). Diver observations indicate this trench formed naturally while the city of Eastern Canopus was still above sea level: the trench walls were lined by human-emplaced mats of fresh to brackish water plant material, principally phragmites and reeds collected in adjacent wetlands, and the trench was then filled with dune and beach sand. In addition, well-preserved, cloved-hoof bovid (probably cow) tracks and bones of an antelope were present at the mud base of the trench.

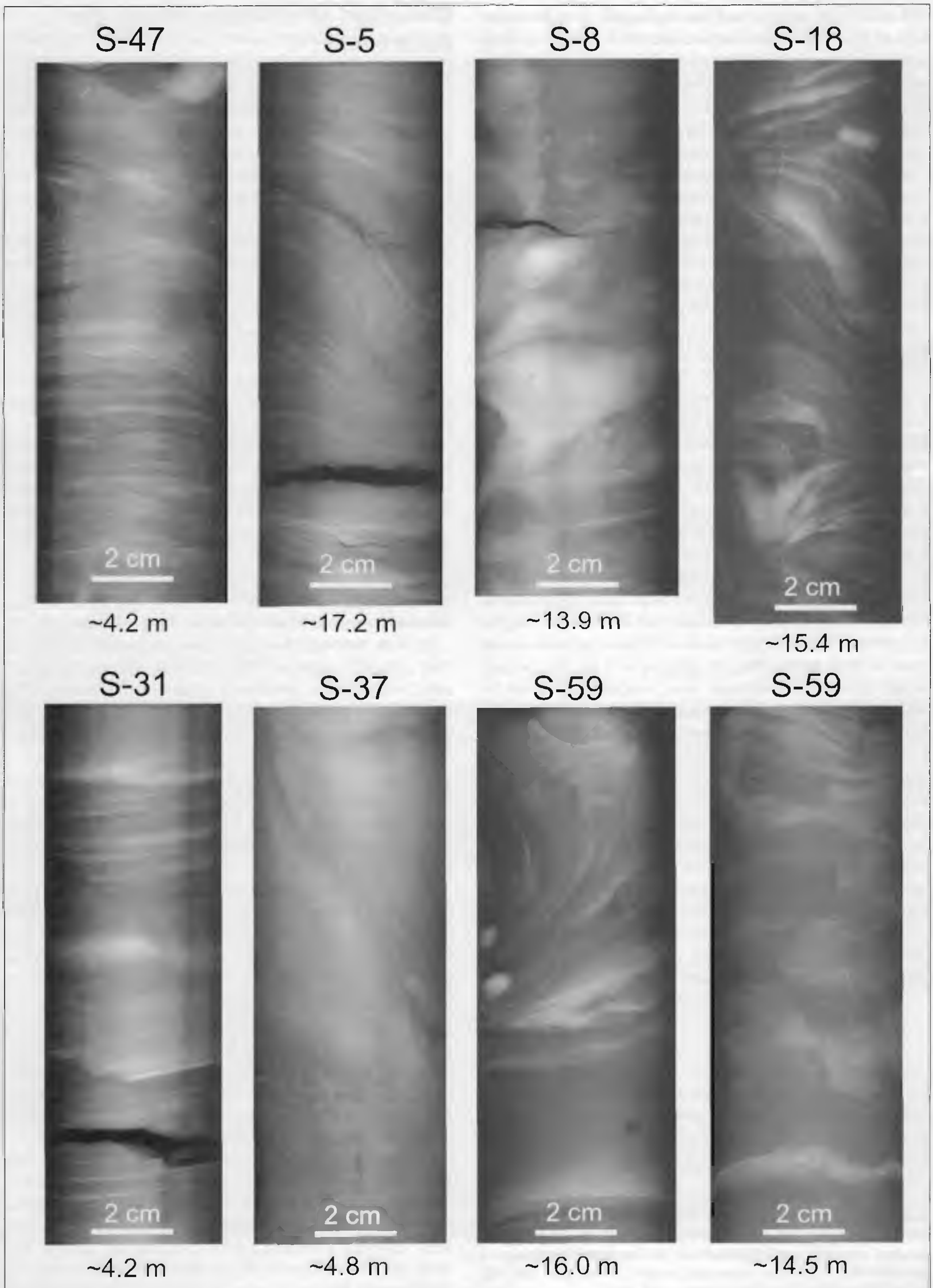
Fig. 3 – **Selected portions of west-east oriented seismic lines 01510481 (A) and 01480280 (B) and vibrocores collected in the area where the ancient coastal city of Herakleion (location in fig. 2) was damaged and submerged largely by substrate sediment failure.** Sectors with horizontal stratification are distinct from those with tilted and deformed strata and diapiric features.

*Fig. 3 – **Extrait des profils sismiques (orientés W-E) n° 01510481 (A) et n° 01480280 (B) et carottes prélevées par vibro-percussion dans la zone où l'ancienne ville côtière d'Hérakléion (localisation fig. 2) a été détruite et largement submergée à cause de la fracturation des sédiments sous-jacents.** À noter l'opposition entre les secteurs où prédominent les stratifications horizontales et ceux caractérisés par des stratifications inclinées, déformées et affectées de micro-plis et diapirs.*

Disturbed strata in Abu Qir Bay cores as example

Sediment cores obtained in western Abu Qir Bay also provide evidence of syn- and post- depositional deformation of Holocene strata. The seventeen vibrocores were collected at and between now-submerged sites of Herakleion and Eastern




S-47
2 cm
~4.2 m
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2 cm
~14.5 m

recognized (fig. 5, S-5, S-18, S-31) to those that have been subject to extensive liquefaction and where original stratification has been almost entirely obliterated (S-8, S-37). In addition to flowage features, several sections show fault-offsets that occurred in the strata at the time of, or after, deposition (fig. 5, S-31, S-59). Examples of combined flowage and fault offset are also recorded in several of the twenty-two cores. Undisturbed horizontal lamination in one boring (S-47 in fig. 5, location shown in fig. 6A), typical of most Holocene core sections, is shown for comparison with the seven units that illustrate various deformed bedding types (fig. 5).

Regional distribution of disturbed stratification

Northwestern Nile delta

Major characteristics of the NW Nile delta margin, between Alexandria and the Rosetta promontory, during the mid- to late Holocene are: (1) relatively modest tectonic activity, except in the Alexandria region west of the Abu Qir peninsula (Kebeasy, 1990); (2) a major lithologic change, from primarily carbonate to mostly terrigenous material, east of Abu Qir peninsula (Hassouba, 1980; Stanley and Hamza, 1992); (3) rapid accretion of sediment from Nile floods and delta coastal erosion, with materials transported eastward into Abu Qir Bay and farther east onto the eastern Nile shelf (UNDP/UNESCO, 1978; Sestini, 1989; Frihy *et al.*, 1991); and (4) active progradation of Canopic branch sediment in the bay to more than 5 km north of the present shoreline until about 1,500 years ago (Stanley *et al.*, 2003).

Long drill cores were collected landward of the coastline at twenty-three sites between the city of Alexandria and the Rosetta branch (fig. 6A). Although this is the most heavily concentrated area of core recovery on the lower delta, only three (13%) cores (S-71, S-72, S-73) south of western Abu Qir Bay present some deformed and offset layers, most less than 50 cm in thickness. It is of note that the three cores were recovered along the path of the former Canopic branch of the Nile (fig. 6B). They are also located just landward of where offshore cores and geophysical data (figs. 2 and 4) provide evidence of syn- and post-depositional phenomena at what were once migrating channels of Canopic branches. Holocene sections in the other twenty (87%) cores collected in this NW delta region do not record disturbed stratification.

Fig. 5 – **X-radiographs of Smithsonian cores collected on and landward of the Nile delta coast**. Section in S-47 shows undeformed laminae; the core was collected north of Burullus lagoon between distributary branches (see fig. 6A). In contrast, seven Holocene core sections show various disturbed bedding (locations in fig. 6B): S-5, Phatmitic/Damietta branches; S-8, Mendesian branch; S-18, Pelusiac branch; S-31 and S-37, Athribitic branch; and S-59, Bolbitic/Rosetta branches. Note fault offsets in S-31 and S-59.

*Fig. 5 – **Radiographies des carottes prélevées par le Smithonian de Washington sur la frange côtière et sur la plaine deltaïque du Nil**. La section de la carotte S-47 montre des laminations non-déformées ; la carotte a été prélevée au nord de l'Étang de Burullus, entre deux bras fluviatiles (localisation fig. 6A).* A contrario, *sept sections de carotte (S-5 : bras fluviatiles de Phatmitic/Damiette ; S-8 : bras de Mendesian ; S-18 : bras de Pelusiac ; S-31 et S-37 : bras de Athribitic ; S-59 : bras de Bolbitic/Rosette) montrent que plusieurs types de déformations affectent les terrains holocènes situés à proximité immédiate des paléochenaux du Nil.*

North-Central Nile delta

Attributes of the north-central Nile delta margin, between Rosetta and Damietta branches, during the mid- to late Holocene are: (1) relatively low rates of land subsidence, except at the promontories of the two modern distributaries (El Askary and Frihy, 1986; Chen *et al.*, 1992); (2) a smooth arcuate coastline that, in the western half of the sector, separates Burullus lagoon from the sea (Arbouille and Stanley, 1991); and (3) the presence of two relict Nile branches, including the larger south-to-north trending Sebennytic that formerly bisected the delta, and the smaller northeast trending Athribitic (Toussoun, 1922; Stanley and Warne, 1998). The margin sector has experienced considerable modification by coastal and shore-parallel current erosion. Characteristics of this margin are a continuous sequence of sand barriers and the large Baltim dune fields between the eastern shore of Burullus lagoon and Gamasa (fig. 1C).

A set of 35 long drill cores collected on and south of the coast between Rosetta and Damietta branches were examined (fig. 6A). Of these, twelve (34%) show sediment sections that are deformed and/or offset, most with soft-sediment deformation ranging from 20 cm to 50 cm in thickness. Eleven of the twelve borings are positioned (fig. 6B) as follows: cores S-51, S-56, and S-59 close to the SSE to NNW Bolbitic/Rosetta branches; core S-52 near an unnamed relict channel; cores S-39, S-41, S-43, and S-44 along the path of the relict Sebennytic branch; and cores S-31, S-33, and S-37 near the path of the former Athribitic branch. Only one of the cores with disturbed bedding (S-50) is not associated with a relict channel.

Northeastern Nile delta

During the Holocene, the dominant characteristics of the northeastern Nile delta margin, from the Damietta branch to the Gulf of Tineh, are: (1) large fault-related subsidence rates (to 5 mm/yr) at the Manzala lagoon and northeastern corner (south of the Gulf of Tineh) of the delta (Stanley and Goodfriend, 1997); (2) input of large volumes of sediment by Nile floods at mouths of several branches, including Bucolic/Damietta, Mendesian, Tanitic, and Pelusiac (Toussoun, 1922); and (3) delta coastal erosion and transport of fluvial material to the east of this region, with seaward deltaic progradation at an average rate that locally exceeded 10 m/year (Coutellier and Stanley, 1987).

This margin, which experiences the highest rates of land lowering, is affected by a major structural system involving fault motion (Neev *et al.*, 1976) and active isostatic loading during the late Quaternary. Subsidence produced a lowered

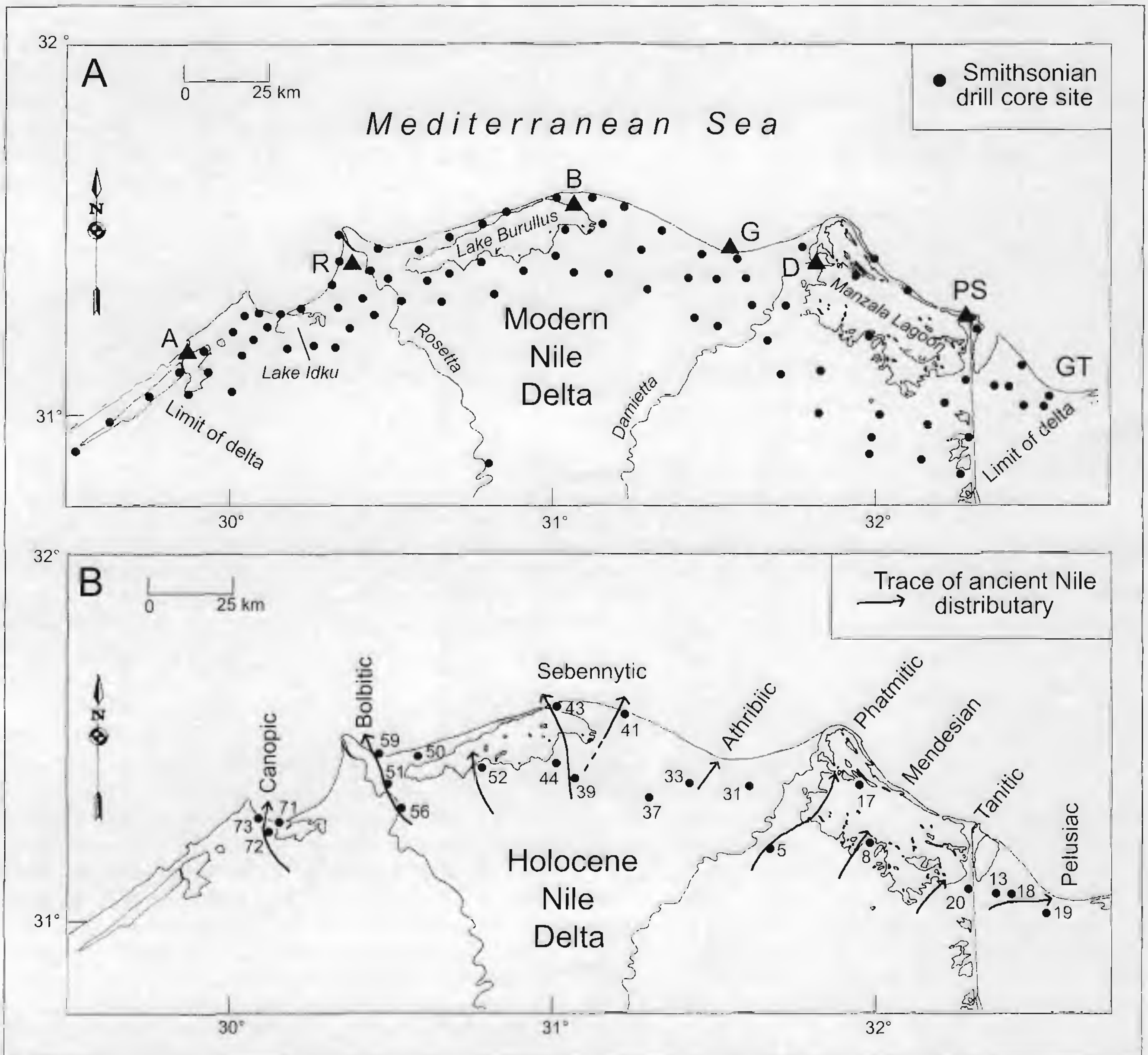

Fig. 6 – **Smithsonian sediment cores collected at and landward of the Nile delta coast (after Stanley *et al.*, 1996).** A: location of the 83 borings recovered between Alexandria and the Gulf of Tineh and examined in the study. A: Alexandria, R: Rosetta, B: Baltim, G: Gamasa, D: Damietta, PS: Port Said are coastal cities; Mar : Mariut, I : Idku, Bu : Burullus, Man : Manzala are lagoons; GT: Gulf of Tineh. B: position of the 22 cores between Alexandria and the Gulf of Tineh with sections of disturbed stratification. Of these, 20 are positioned close to traces of former Nile distributary channels as shown by O. Toussoun (1922) and other sources.

*Fig. 6 – **Carottes sédimentaires collectées par le Smithonian de Washington sur la frange côtière et sur la plaine deltaïque du Nil (d'après Stanley** et al.**, 1996)**. A : localisation des quatre-vingt-trois carottes prélevées entre Alexandrie et le Golfe de Tineh prises en compte dans l'étude. A : Alexandrie, R : Rosette, B : Baltim, G : Gamase, D : Damiette, PS : Port-Saïd sont des villes côtières. Mar : Mariut, I : Idku, Bu = Burullus, Man : Manzale sont des lagunes. GT : Golfe de Tineh. B : Localisation des vingt-deux carottes entre Alexandrie et le Golfe de Tineh montrant des déformations sédimentaires. Vingt d'entre elles sont situées à proximité immédiate des tracés des paléochenaux fluviatiles du Nil, comme le montrent les travaux de O. Toussoun (1922) et d'autres sources bibliographiques.*

surface on which a thick sequence (to ~50 m) of Nile-derived sediment accumulated during the past ~7 millennia (Stanley and Goodfriend, 1997; Stanley and Warne, 1998). The Holocene sediment accumulation rate of ~5 to 7 mm/yr is much higher than recorded elsewhere on the margin. The position of the Holocene shoreline, once 30 km to the south, prograded rapidly seaward. The sediment sequence in this part of the delta provides a record of overlapping delta lobes that formed seaward of several distributary mouths (Coutellier and Stanley, 1987; Pugliese and Stanley, 1991).

Of twenty-five cores collected east of the Damietta branch (fig. 6A), seven (28%) show strata with soft-sediment deformation. As on delta margins to the west, most units display deformed and/or offset layers that are less than 50 cm thick. The following are identified: one (S-5) near the Phatmitic/Damietta branches; one (S-8) along the Mendesian branch; one (S-20) near the Tanitic; and three (S-13, S-18, S-19) east of the Suez Canal in proximity to the Pelusiac (fig. 6B). The seventh boring with disturbed structures

(S-17) was recovered along the NW margin of Manzala lagoon, at some distance from distributary traces.

The where, when, and why of strata disruption

Petrological analysis of drill cores indicates the large majority of Holocene subsurface sections with disturbed sediment stratification distributed quite specifically on the lower Nile delta. Twenty (91%) of the twenty-two cores that show soft-sediment and fluidized structures and/or fault offsets are positioned near traces of ancient Nile distributaries that once channelized water northward across the delta. Evidence of sediment failure is found along each distributary channel and/or mouth of these former branches, from the Canopic in the west to the Pelusiac in the easternmost margin. In contrast, ~99% of recovered Holocene core strata in the sixty-one other cores recovered at a distance from Nile distributaries do not show disrupted stratification. It thus can be reasonably deduced that processes and physical properties of sediment most favorable for sediment failure prevailed along ancient distributaries.

As to timing of sediment failure, the deformed strata are dated from early Holocene (prior to 6,000 yrs. B.P.), until near-present, but determining the exact age of strata and date of their disturbance remains problematic. Although all cores have been radiocarbon dated (Stanley *et al.*, 1996), ages have generally proven to be unreliable (commonly too old) and provide only an approximate time of deposition (Stanley, 2001). For dating by other methods, it is necessary to take into account the considerable core-to-core variation of total Holocene thickness (10 m to 50 m). Herein, a rough estimate of age of core strata is determined by (1) assigning a date of 7,500 yrs. B.P. to the base of the Holocene section, and then (2) calculating an approximate date of the disturbed layer based on its relative depth (% depth down-section from core top) in that core. This assumes a constant depositional rate and no erosion of strata, which in most cases is an unrealistic scenario. However, if this approach is used, one finds that most deformed horizons are positioned at depths from 60% to 30% down from core tops, suggesting a very approximate age of deposition ranging roughly from mid- to late Holocene (*i.e.* from ~4,500 to ~2,250 yrs. B.P.). For example, a disturbed stratum in core S-71 collected along the Canopic branch occurs at a relative depth of ~38% from the core top, suggesting an approximative depositional date of ~2,850 yrs. B.P. As to the timing of deformation of that stratum, it can only be surmised that such an event would likely have occurred since 2850 yrs. B.P. In this respect, it is recalled that archaeological evidence of destruction along the Canopic of ancient cities in Abu Qir Bay, lying to the north of core site S-71, indicates a time from about 2,000 to 1,300 yrs. B.P. (Goddio *et al.*, 2003).

Several processes may have been involved in failure of sediment, including earthquake tremor or sudden loading (weighting) by addition of new sediment during flood, tsunami, or storm surge. For example, earthquake and tsunami events (including the famous one in 365 A.D. and in subsequent periods) were probably significant factors in destruction and submergence of human-built structures in the eastern harbour of Alexandria, a seismically more active region 20 km west of Abu Qir Bay (Kebeasy, 1990; Guidoboni, 1994). Although in recent years there has been a concerted effort to document important ancient earthquake and seismicity-related phenomena in the Eastern Mediterranean (Guidoboni, 1994; Soloviev *et al.*, 2000), no direct correlation has yet been established between such earth tremor and/or tsunami wave surge triggers and sediment failure along the delta margin east of Alexandria.

More likely triggers of failure were unstable depositional conditions at delta mouth settings, especially those resulting at times of high flow and extreme high flood. In this respect, observations made in western Abu Qir Bay and described in the earlier section of this article provide information to help interpret events in delta sectors elsewhere along the Nile margin. It is probable that it was failure of unstable sediment and mass flow, mostly at Canopic river mouths, that resulted in subsidence and shifts of Holocene sections toward adjacent Abu Qir Bay floor settings. During flooding, mouths of powerful rivers such as the Canopic are characterized by hydraulic changes that involve much increased outflow velocities, bed shear and fluid turbulence along with increased, and commonly prolonged, discharge of denser sediment-laden river waters (Bates, 1953; Wright and Coleman, 1974). The rapidly deposited materials at and seaward of channel mouths are commonly characterized by excess pore water pressure, especially in clay and fine silt deposits, resulting in underconsolidation and low sediment strength. Rapid addition of a new sediment layer during flooding (differential loading, weighting) induces change in the particle-to-particle configuration of the underlying channel mouth deposits; this, in turn, leads to dewatering of buried clays and silts and sediment flowage (Morgan *et al.*, 1963). Burial of organic matter, released with fine-grained particles at river mouths, can result in formation of methane gas which contributes to generation of excess pore pressure that can further weaken delta-front deposits.

Such conditions, especially at and seaward of delta mouths, can induce a stratum to suddenly fail, even on near-horizontal (<1 to 2 degrees) surfaces (Morgan *et al.*, 1963; Coleman, 1982, 1988; Maestro *et al.*, 2002). Thus, even relatively tectonic tranquil regions, such as the Nile margin, experience rotational slumps, mud flows (Wright and Coleman, 1974; Coleman, 1982), along with growth and normal faults (Maestro *et al.*, 2002). Sudden differential loading by younger distributary mouth sands deposited in such settings can cause, in addition to physical disruption of Holocene strata, deformation of underlying sediment into diapiric domes (fig. 3A; Morgan *et al.*, 1963). It is likely that diapiric features and associated tilted beds of delta sublobes in western Abu Qir Bay formed primarily during periods of Canopic channel outgrowth when loading and sediment flowage prevailed (Stanley *et al.*, 2003). It is suggested here that, on the basis of the present core analyses, similar conditions of sediment instability and failure also occurred along the other Nile channel mouths at various times during the delta's Holocene formation.

Conclusions and ramifications

The major findings in this investigation are (1) the concentration of failed and disturbed stratification located along relict Holocene Nile distributary channel and mouth settings, and (2) the low frequency of such syn- and post-depositional soft-sediment structures between channel traces. This suggests that annual floods of the river Nile periodically played a major role in triggering failure and mass flow of unstable water-saturated sediment that had been preferentially distributed along distributary traces at the delta margin. It is postulated that if earthquakes and tsunamis had been the significant triggers, their effects, especially deformed strata, would be recorded more randomly over wider sectors of the delta coast and shelf. Moreover, if this were the case, disturbed bedding should be found in cores not only along, but also between, distributary channels.

The use of Nilometers (structures designed to measure the level of the Nile) by Egyptians for many centuries has provided considerable information on ancient floods that occurred each year in late Summer and Fall (Popper, 1951). Exceptionally high annual floods have been attributed to major paleoclimatic fluctuations affecting Nile headwaters in central and eastern Africa (Riehl and Meitin, 1979; Hassan, 1981; Hamid, 1984; Shahin, 1985). Notable among such events since the 4th millennium B.P. are the unusually high floods that occurred between 3,840 yrs. B.P. and 3,770 yrs. B.P. and since 2,900 yrs. B.P. (Said, 1993). These dates are well within the prevailing mid- to late Holocene period of delta margin failure indicated in the present study. Such events of large magnitude could have induced sediment failure in different sublobes formed along the coast and also could have caused avulsion and switching of channels in the delta. From the preliminary data now available, it appears that differential loading, fluidization, and mass flow were closely associated with high floods and rapid build-out along the different delta margin sectors, especially in the mid- to late Holocene (Stanley *et al.*, 2003). Tilted and uplifted, and/or offset beds, diapirs and soft-sediment structures may have formed preferentially during the outgrowth of channels at the coast, such as those recorded at former Canopic mouths. Additional high-resolution geophysical surveys and cores are now needed to better assess whether such deformation could also have occurred elsewhere along the Nile margin.

River Nile flow to the sea has now been virtually cut off and flooding is no longer a major event along the coast (Stanley and Warne, 1998), although mass failure could still affect localized sectors along distributary channels in the delta and at the margin where unconsolidated sediment remains prone to failure. Alexandria, Egypt's major coastal city built on a consolidated base of Pleistocene limestone (kurkar) three or more meters above sea-level, remains relatively safe from such failure. However, other cities close to the present low-lying delta coast, especially those built on water-saturated underconsolidated sediment, remain vulnerable to geohazards associated with sediment instability (Waltham, 2002). Examples include Baltim city undergoing construction near the ancient Sebennytic branch and now positioned along a rapidly eroding coast, and Port Said near the trace of the former Tanitic branch located in an area subject to rapid land subsidence and relative sea-level rise (fig. 6A). Increased protection for such expanding Nile coastal population centers requires thorough civil engineering surveys, including analyses of sediment physical properties, and implementation of viable building codes. These precautions will result in placement of new buildings and other large structures on deeply anchored pilings, where needed. It could thus be useful, in this respect, to further investigate causes and nature of failure of the Greek, Roman, and Byzantine structures at Herakleion and Eastern Canopus as a result of substrate sediment failure along the Canopic branch. Understanding how these cities were destroyed would surely be more than a purely academic exercise.

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