| Journal of Coastal Research | SI | 42 | 309–318 | West Palm Beach, Florida | Spring 2005 |
|---|---|---|---|---|---|

# Growth Faults, a Distinct Carbonate-Siliciclastic Interface and Recent Coastal Evolution, NW Nile Delta, Egypt

**Jean-Daniel Stanley**

Geoarchaeology-Global Change Program
E-205 NMNH, Smithsonian Institution
Washington D.C. 20560 U.S.A.

**ABSTRACT**

STANLEY, J.D., 2005. Growth faults, a distinct carbonate-siliciclastic interface and recent coastal evolution, NW Nile Delta, Egypt. *Journal of Coastal Research,* SI(42), 309–318. West Palm Beach (Florida). ISSN 0749-0208.

A sharp, well-defined interface between a late Pleistocene carbonate sandstone ridge (kurkar) and Holocene unconsolidated coastal siliciclastic sediment has formed largely as a consequence of recent structural activity along the NW Nile delta coast at Abu Qir, Egypt. Joint patterns in the coastal kurkar exposed on land, and its irregular and dislocated configuration beneath Abu Qir Bay, suggest that the ridge east of Alexandria was stretched, down-bowed and offset in a NE direction. The ridge has subsided by growth faults to shallow depths in the bay, resulting in westward coastal regression toward the Abu Qir peninsula by headscarp retreat. Deformation of the coastal margin and development of the distinct lithological interface occurred primarily from late Pleistocene to early Holocene time, although continued subsidence and disruption of the late Quaternary section has occurred locally in the bay as recently as the first millennium C.E. Both emerged land and coastal-to-shallow bay phenomena are a probable response to readjustment at depth of the thick (>5000 m) Mesozoic to Quaternary sediment section lying beneath the recent NW Nile delta. This shift deep within the underlying sediment pile has lowered the bay floor and likely accounts for some shallow to intermediate depth earthquakes along, and proximal to, the Alexandria to Abu Qir coastal margin.

**ADDITIONAL INDEX WORDS:** *Abu Qir Bay, Alexandria, basin subsidence, Canopus, carbonates, delta facies, depressed shelf platform, earthquakes, growth faults, Herakleion, Holocene, joint structures, kurkar, Nile River, Pleistocene, quartz, seismic profiles.*

## INTRODUCTION

This study examines the geological setting of an unusually well-defined and abrupt interface between a series of coast-parallel carbonate ridge and siliciclastic lithologies along the NW Nile delta coastal margin at Abu Qir, Egypt. Of specific interest is the eastern margin of Abu Qir peninsula which forms the shoreline along the western margin of Abu Qir Bay (Figure 1). Unconsolidated quartz-rich delta sequences of Holocene age in the bay and on the southern peninsula sharply abut the consolidated carbonate sandstone ridge of Pleistocene age. This linear limestone is one of 8 linear coast-parallel ridges (Figure 1, inset) that extend from Abu Qir Bay to Arabs Bay, a distance of ~100 km to the SW. Many previous investigations have focused on these coastal ridges west of the Nile delta and reported on their geographic configuration (ZEUNER, 1952; SHUKRI *et al.,* 1956; BUTZER, 1960; EL-FAYOUMY *et al.,* 1975), lithology (EL-WAKEEL and EL-SAYED, 1978; HASSOUBA, 1980, 1995; STANLEY and HAMZA, 1992), and age (HEGAB and EL-ASMAR, 1995; EL-ASMAR and WOOD, 2000). The quartz-rich fluvial and marine deltaic sediments released by Nile branches in the vicinity of Abu Qir peninsula during the Holocene also have received considerable attention (ATTIA, 1954; CHEN *et al.,* 1992; WARNE and STANLEY, 1993; STANLEY *et al.,* 2004b).

Calcareous deposits in proximity to quartzose sediment is not a unique situation on modern or ancient coastal margins. For example, a number of investigations focusing on this topic have discussed coral reef-to-clastic fluvial interfaces in tropical and subtropical settings such as the Red Sea, Australia, and Caribbean (DOYLE and ROBERTS, 1988). More commonly observed are the gradual carbonate-to-siliciclastic lithological transitions that develop on many of the world's continental shelves, including the western and eastern Mediterranean (STANLEY, 1972). Most of the latter examples involve transport of carbonate and quartzose sediment from different source terrains to coasts, followed by bottom current displacement that leads to mixing and formation of diverse carbonate to siliciclastic gradations on the contiguous shelves.

It is of interest here that neotectonic activity, rather than interaction of principally sedimentological processes, can explain the formation of the sharp, well-defined carbonate and quartz-rich sediment interface at Abu Qir. The following aspects of this margin are considered: (1) the stratigraphic and structural attributes of the sector where the carbonate terrain is in contact with quartzose-rich strata in Abu Qir Bay; (2) the stretching and arching of the carbonate ridge at its eastward edge as a possible response to loading effects by Nile River deposits that accumulated upon it during the Holocene; and (3) events that may have caused the present submergence and dislocation of the limestone stratum beneath the Holocene sediment cover in the bay east of Abu Qir.

## BACKGROUND

The modern Nile delta is a classic Δ-shaped depocenter (HERODOTUS, 5th century B.C.E.) formed at the Mediterranean

*04-0311 received and accepted 28 July 2004.*

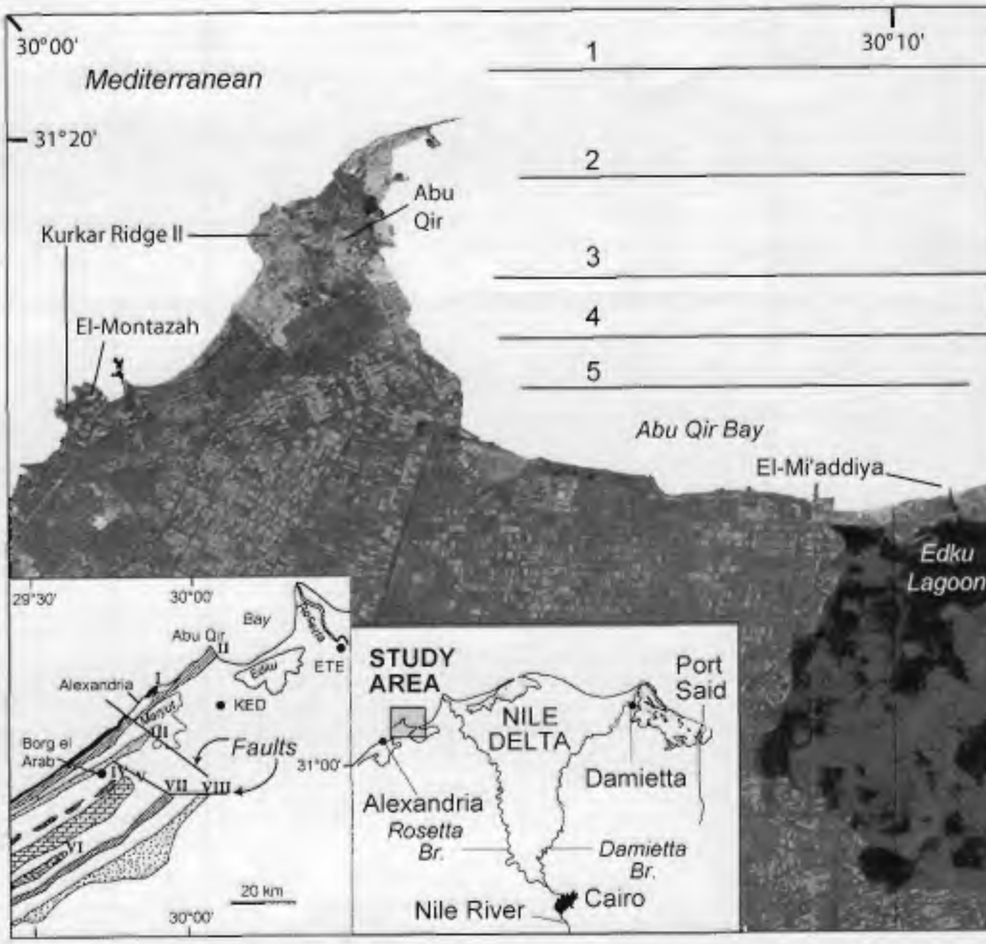


Figure 1. Landsat 5 thematic mapper (TM) image (acquired 22 December 1986) showing Abu Qir peninsula and adjacent study area in the NW Nile delta, Egypt. Cities of Abu Qir and El-Montazah are built on coastal carbonate sandstone Ridge II, one of 8 coast-parallel kurkar ridges in this region (see inset, modified after Butzer, 1960). The five W-E oriented lines in Abu Qir Bay show positions of seismic profiles 1–5 in Figure 3.

margin and bound by desert in northeastern Egypt (SESTINI, 1989; SAID, 1993; STANLEY and WARNE, 1998). The eastern delta-desert boundary is clearly delineated by the Pelusium Line fault system that is traced from the Levant toward the SW, across the southeastern corner of the Mediterranean, and then landward east of the Suez Canal toward the delta apex near Cairo (NEEV, 1975; NEEV *et al.,* 1976). Strike-slip motion, with some vertical displacement, has laterally offset the clastic desert and coastal sediment facies of Quaternary age in this region (SNEH and WEISSBROD, 1973; SNEH *et al.,* 1986; COUTELLIER and STANLEY, 1987; STANLEY, 1990). The NW edge of the Nile delta coast lies ~225 km to the west (Figure 1), adjacent to the city of Abu Qir (ancient Canopus). The Abu Qir delta sector is as geographically and geologically distinct as the one at the NE Nile delta margin, but has received little attention with regards to its recent structural evolution.

This coast is located in a warm to hot and dry setting where sediments are affected by microtidal and wave-driven nearshore current conditions. On land, the lithologic contact between the 8 coastal ridges of carbonate sandstone and unconsolidated terrigenous deltaic facies (primarily dark silty mud and sand) deposited to the east is well-defined. The moderately to well-cemented limestone is formed largely of whole and broken shell, pellets and oolites along with some quartz and heavy mineral grains (HILMY, 1951; EL-WAKEEL and EL-SAYED, 1978; HASSOUBA, 1980, 1995; STANLEY and HAMZA, 1992). In the eastern Mediterranean, such coastal ridges of strandline and eolian origin are commonly called *kurkar* (ALMAGOR, 1979; NEEV *et al.,* 1987). The largely clastic carbonate sandstone provides a record of biogenic deposition (largely shell and broken hash) associated with pelite and oolite (STOFFERS *et al.,* 1980) formation along the coast and inner shelf west of Abu Qir peninsula during the late Quaternary.

During the past 6000 years, carbonate components have been transported eastward along the coastal margin by modest to strong (to 100 cm/sec) coastal currents in this area (UNDP/UNESCO, 1978; INMAN and JENKINS, 1984; FRIHY, 1988; SMITH and ABDEL-KADER, 1988; SESTINI, 1989; POEM GROUP, 1992). However, in the earlier Holocene and periodically during the Pleistocene, coastal currents flowed to the west. Counts of mineral components of sand size in the second ridge (usually called Ridge II or El Max-Abu Sir ridge; Figure 1, inset) show that proportions of coarse silt to sand size quartz increase in a NE direction, and can reach >75% of sand-size components between Alexandria and Abu Qir (STANLEY and HAMZA, 1992). This indicates that during formation of Ridge II some silt and sand sized grains were introduced to the coast in this region from the adjacent desert by wind, and also that quartz of Nile derivation was periodically displaced westward to and beyond Alexandria by longshore currents. In marked contrast, younger silty mud and sand-rich delta deposits in the bay east of Abu Qir comprise larger proportions of quartz and other light and heavy minerals, and are more poorly sorted than the kurkar. Much of this clastic material was released at the NW delta margin by the formerly active Canopic branch of the Nile and, since the mid-Holocene, this sediment has been displaced primarily eastward by nearshore and shelf currents (TOUSSOUN, 1922; NEEV *et al.,* 1987; FRIHY, 1992; STANLEY *et al.,* 2004a, 2004b).

The two distinct facies that are in direct contact at the delta's western coastal boundary are of makedly different age. Ridge II that forms the linear high-relief carbonate upon which the cities of Abu Qir and Alexandria to the west were built is of late Pleistocene age. The ridge recently has been dated by amino-acid geochronology to about 100,000 years before present (from 110 ± 5 ka at the ridge base to 90 ± 15 ka at the ridge top) by EL-ASMAR and WOOD (2000). This unit is thus much older than the deltaic sequences of Holocene Nile delta derivation that interface with, and bury, the ridge that is now submerged in Abu Qir Bay. The base of section of the terrigenous delta deposits is dated from about 8000–7000 years before present (yr B.P.); they are of near-modern age (<3000 yr B.P.) at the upper delta plain surface and at the sediment-water interface in the bay (STANLEY and WARNE, 1998; STANLEY *et al.,* 2004b).

The sharp eastern termination of carbonate coastal ridges subaerially exposed in the Alexandria region is attributed to structural offset (Figure 1, inset). Examples include several kurkar ridges in the vicinity of Mariut lagoon bound by faults oriented perpendicular (NW-SE, E-W) to ridges (BUTZER, 1960). In similar fashion, the coastline immediately east of Abu Qir (that also defines the western margin of Abu Qir Bay) is nearly perpendicular (NNW-SSE) to the Ridge II trend (Figure 1). Also noted on satellite images are structural lineaments inland along the western margin of the Nile delta and oriented primarily N50–60W to S50–60E (EL SHAZLY *et al.,* 1975; ABDEL-KADER, 1982; NEEV *et al.,* 1987). Still other lineament directions are mapped in this desert-west delta sector: some oriented more closely to the general north-south trend of the western bay shoreline (N20W–S20E; N20E–S20W), and others more closely parallel to the west-to-east linear direction of the ridge II (N65–80E to S65–80W).

South of the Abu Qir peninsula, the WSW-ENE trending Ridge II at the delta plain surface disappears abruptly (within several hundred meters) from W to E. Nevertheless, some carbonate strata of comparable lithology to this kurkar layer (rich in sand-sized biogenic shell and other allochem, oolite and quartz components) are recovered at outcrops in the northern bay. These include Nelson (Canopus) island 4 km NE of Abu Qir, and the shallow carbonate reefs that extend ~5 km farther NE in the bay from Nelson island.

Sediment cores provide useful information on subsurface carbonate trends east of the Abu Qir peninsula (ATTIA, 1954; FRIHY, 1992; WARNE and STANLEY, 1993; STANLEY *et al.,* 1996). For example, limestone facies (probably Ridge III) have been recovered in borings at depth beneath quartzose deltaic sequences of Holocene age south of the bay. The limestone in this sector was encountered beneath the Holocene deltaic series along a west-to-east oriented core transect (ATTIA, 1954): at ~22–26 m below the delta plain surface at Kafr El-Dawwar Station (Figure 1, inset KED); and, at ~103–124 m beneath the surface, at ~40 km to the east, at El-Taftis Estate near the Rosetta branch of the Nile (Figure 1, inset ETE). A carbonate surface gradient of ~3 m/km toward the east is measured at depth along this W-to-E transect; this value, however, assumes that the carbonate layer between the two cores has been affected only by a simple eastward tilt of an unbroken stratum (*cf.* HASSOUBA, 1980).

## EVIDENCE OF STRUCTURAL OFFSET

### Ridge II Joint Patterns

A survey along the coast between Alexandria and Abu Qir reveals that, where exposed, Ridge II is broken by steep to near-vertical joint fractures at varying lateral intervals, but usually at a spacing of 10 m or less east of El-Montazah (Figure 2A). Compass measurements of axial fractures were made on near-horizontal surfaces of the kurkar at two localities (Figure 2D–F). Three major trends are noted at the Abu Qir peninsula (Figure 2C, shown respectively as c, s and d): near-parallel to the coastline of western Abu Qir Bay (N10–20W to S10–20E); sub-parallel (ENE-WSW) to the dominant ridge trend; and a trend intermediate between the two (WNW-ESE). Generally similar trends are recorded at El-Montazah ~6 km SW of Abu Qir (Figure 2B, respectively c, s and d): one set parallel to Abu Qir Bay's western coastline (N15–20E to S15–20W); one more closely aligned to the Ridge II trend (N80E–S80W; N50E–S50W); and one near-perpendicular to the ridge (N40–60W to S40–60E).

Joint fractures are usually less than 3 cm wide, and in the upper part of the limestone bed generally remain open and not filled with calcareous cement (Figure 2D–F). In some instances, joints at depths of several meters down from the upper surface Ridge II surface are partially filled with weathered debris. Displacement of carbonate layers along joint fractures and other obvious fault structure offset were not observed in subaerial exposures of Ridge II in this sector.

### Seismic Profiles

A geophysical survey was made in April and May 2000 in the western half of Abu Qir Bay as part of an archaeological exploration program to study submerged ancient Greek cities (Herakleion, Eastern Canopus) in this region (STANLEY *et al.,* 2004a, 2004b). A high-resolution sub-bottom profiler system (Triton Edgetech X-Star) was used to define the configuration of Holocene sediment sections that form the substrate of archaeological settlements and bury the underlying carbonate

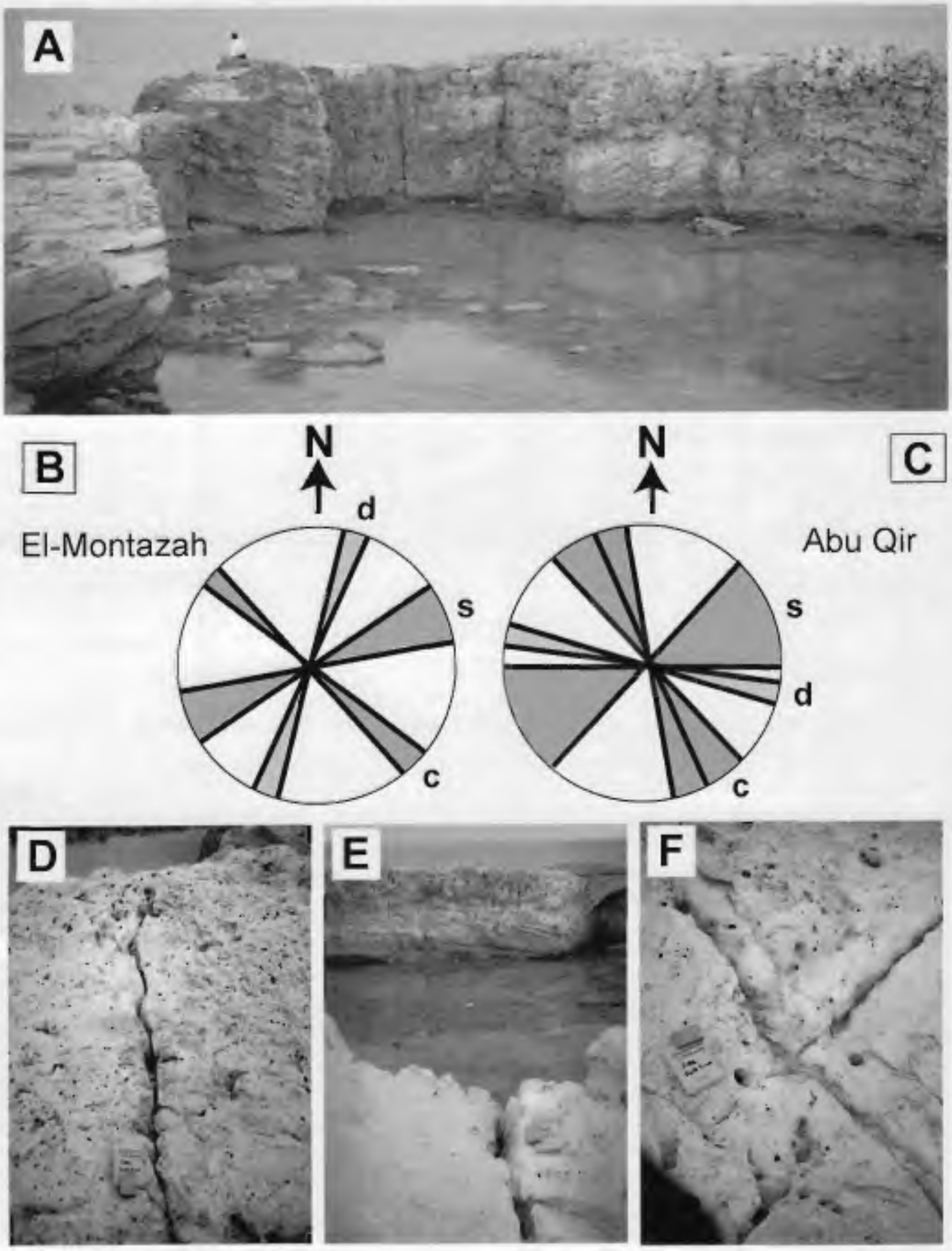


Figure 2. Photographs of carbonate sandstone coastal Ridge II showing joint fractures. A, E, F, kurkar exposures at El-Montazah and D, at Abu Qir. Field book in D–F (13 cm × 20 cm) for scale. B, C, joint fracture trends: c = cross (tension) joints; s = strike (longitudinal) joints; d = diagonal joints.

strata. Coverage in the western bay includes approximately 350 km of seismic lines (spacing ranges from 100 to 1000 m apart) over an area of ~100 km$^2$. A total of 15 N-S and 22 E-W profile lines were obtained, of which five (positions shown in Figure 1) are reproduced here (Figure 3).

Seismic profiles reveal the submerged eastern extension of carbonate kurkar in Abu Qir Bay, where this feature is identified by hard basal reflectors covered by unconsolidated delta sediment. In the northern bay sector, the survey records an elongate 8 km-long shallow NE-trending linear reef formed of kurkar; the reef extends in a NE direction from northern Abu Qir peninsula and includes emergent Nelson (Canopus) Island. Limestone has also been dredged from submerged reef sectors that rise above the water-sediment interface; this topographic high-relief feature is surrounded by an acoustically "hard" horizontal seafloor surface formed by current-swept sand (Figure 3, profile 1). In the western bay further to the south, limestone is identified by reflectors

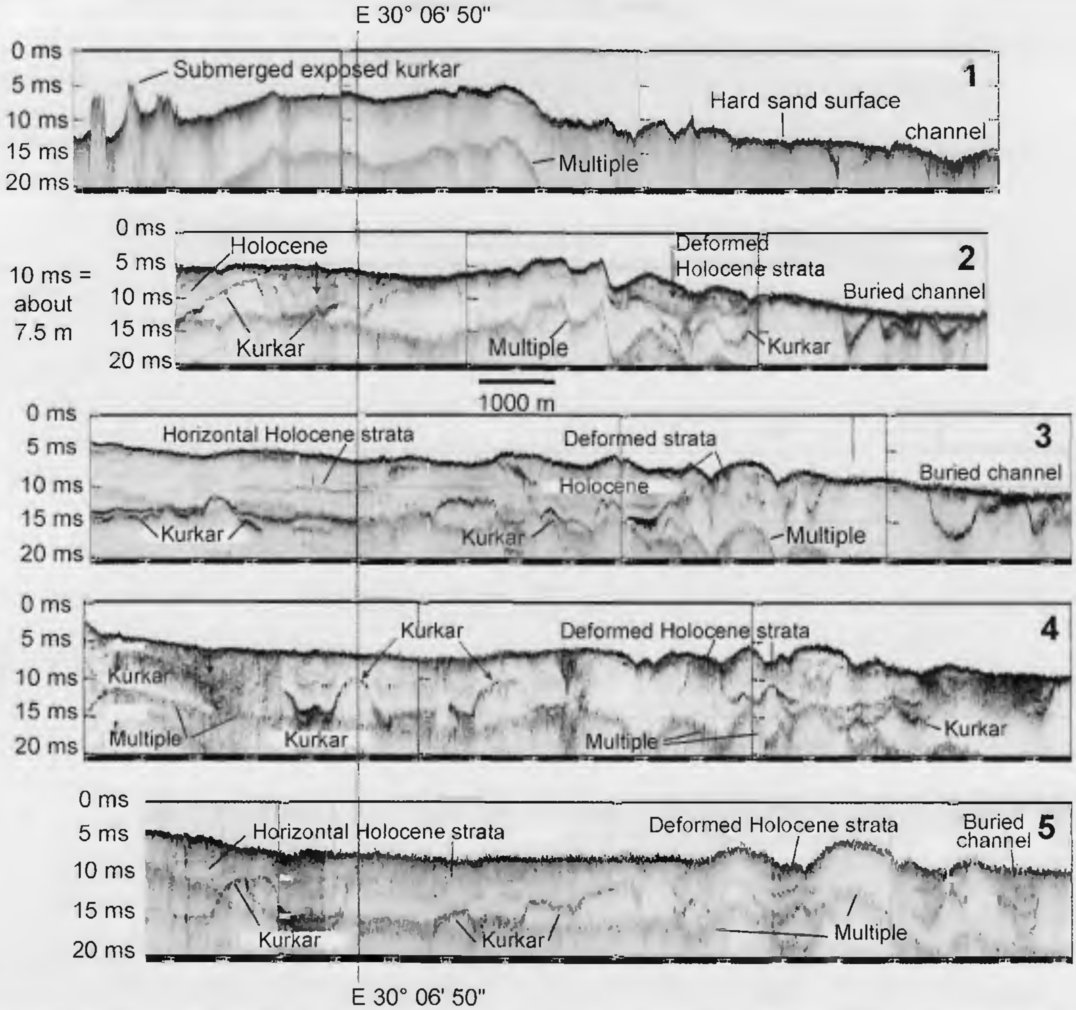


Figure 3. W-E trending seismic profiles collected in western Abu Qir Bay (transect line positions in Figure 1), showing irregular upper part of late Pleistocene kurkar sandstone covered by horizontal, and also locally deformed, Holocene deltaic silty mud strata.

(probably Ridge II) that are buried by 5 to 15 ms (two-way travel time; equivalent to ~3.5 to 10 m) or more of unconsolidated Holocene sediment. Sediment cores recovered in the bay indicate this upper acoustically near-transparent section comprises largely dark silty muds (FRIHY, 1992; JORSTAD and STANLEY, 2004).

Seismic lines show that the Holocene deltaic sediment cover becomes progressively thicker and deeper to the east. However, the underlying kurkar surface does not show a smooth down-bowing of limestone strata toward the east. On the contrary, the buried upper kurkar surface has an irregular blocky shape, and appears step-like and/or tilted (Figure 3, profiles 2–5); an up-and-down form that recalls a horst-and-graben configuration is also noted along some sectors (Figure 3, profiles 4, 5). The buried blocks usually show modest vertical relief (<7m), and range from about 400 to 800 m in length. Holocene strata that cover this kurkar surface are near-horizontal and appear generally undisturbed in more than half of the western bay. This indicates that the broken pattern of the underlying limestone of late Pleistocene age in such sectors developed mostly prior to deposition of Holocene delta sequences.

Exceptions to this general pattern are deformed Holocene strata that form the substrate directly beneath the now-submerged ancient Greek cities of Herakleion and Eastern Canopus. In these two specific western bay areas, the underlying kurkar strata as well as overlying delta deposits are offset; these latter are discontinuous and tilted almost all the way to the sediment-water interface (Figure 3, profiles 3–5). Holocene strata at these localities were once positioned horizontally at the delta coast near channel mouths of formerly active Canopic branches of the Nile; geoarchaeological investigations indicate that stratal disturbance occurred as recently as the 1st millennium C.E. Failure of these water-saturated delta coast deposits was periodically triggered by weighting effects of some high annual Nile floods associated

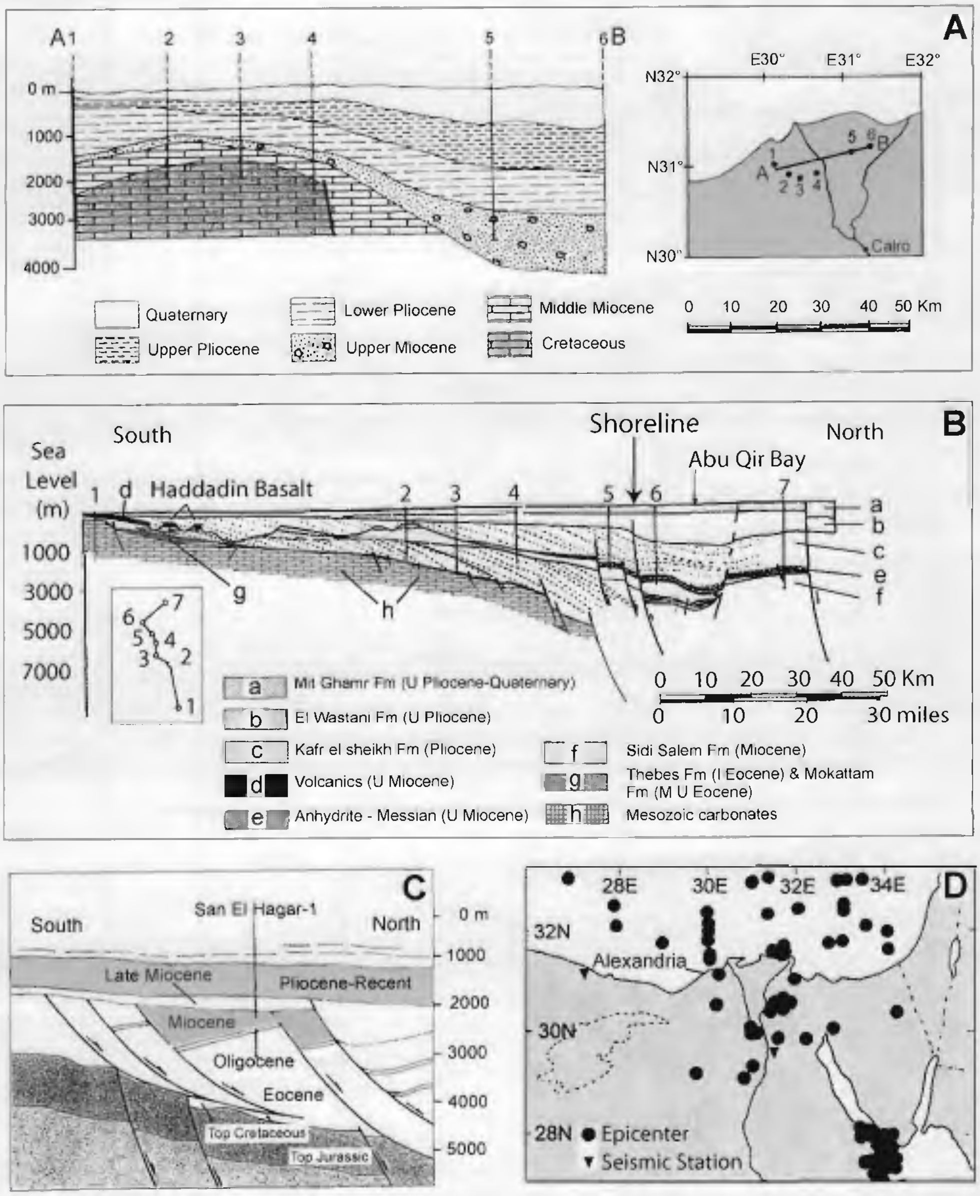


Figure 4. A. geological transect (WSW-ENE) from desert to Nile delta showing rapid thickening to E beneath delta (after Said, 1981; Schlumberger, 1984). B. geological section (S-N) across the western Nile delta flank and C. across the west-central part of the delta; note importance of growth faults affecting thick Tertiary and Mesozoic section at depth (after Schlumberger, 1984). D. location of seismic stations and epicenters of historical and recent small earthquake epicenters (after Kebeasy, 1990).

with large sediment discharge. Earthquake tremors (Figure 4D) and tsunami events may also have caused deformation of depositional sequences (Guidoboni, 1994; Kebeasy, 1990).

## DISCUSSION

What factors would have produced the remarkably abrupt lithological interface observed along the Abu Qir coast? The interaction of climate-related phenomena such as sea-level and geostrophic current changes and physical oceanographic, biological and chemical processes (Sestini, 1989, 1992) is influential in forming a gradual, but not sharp, lateral carbonate to quartzose transition on the coastal margin. For example, surficial sediment on the coast and inner Egyptian shelf at, and west of, Alexandria comprises high proportions of carbonate components, and this material is transported eastward along the coastal margin by wave-driven bottom currents to and around Abu Qir peninsula. As sediment is displaced farther to the east, the carbonate components are diluted by siliciclastic sediment of Nile derivation, producing a mixed surfical lithological type over a distance of several tens of kilometers (SUMMERHAYES et al., 1978; UNDP/UNESCO, 1978; BERNASCONI and STANLEY, 1997).

Sediment cores in the northern Nile delta have not yet recovered evidence of a distinct interface between Pleistocene carbonate sediment and pre-Holocene quartzose material fed by an earlier Nile system. A sharp contact between carbonates and siliciclastic material of comparable Pleistocene age may have formed to the east of the study area, between the Rosetta and Damietta branches, and perhaps such a feature will be located by additional coring to depths exceeding 100 m in the north-central delta. It is more likely, however, that subsurface Pleistocene deposits will show a gradual lithological carbonate-to-siliciclastic transition spread over several tens of kilometers in response to transport and lateral mixing, as in the case of surficial sediment on the delta's present coastal-shelf margin.

The distinct stratigraphic discontinuity observed between late Pleistocene deposits and the much younger deltaic facies at the Abu Qir coast is best explained by structural offset. Coastal development of this coastal margin can be interpreted by the joint structures in the exposed Ridge II carbonates (Figure 2B, C) that occur in close proximity to the broken, irregular configuration of the now-submerged kurkar ridge in the bay (Figure 3). The joint patterns are a likely response to pull-a-part movement in a direction generally perpendicular to the fractured surface (*cf.* DAVIS and REYNOLDS, 1996). Joint types include: (1) cross joints (NNW-SSE) oriented perpendicular to the coastal ridge and identified as pull-apart tension features caused by stretching; (2) strike (or longitudinal) joints (NE-SW) that dip steeply with axes oriented parallel and sub-parallel to the predominant ridge trend; and (3) joints that trend in directions diagonal to structures (1) and (2). A study by SANFORD and ARKELL (1939) called attention to decreased surface elevations of kurkar ridges toward the east; they attributed this to downward bending of ridges under the load of younger delta sediment deposited upon them. It is possible that the decreased elevation of Ridge II toward the ENE along a distance of ~20 km, from ~25 m at Alexandria to ~15–10 m at Abu Qir, and the presence of associated joint patterns cited above, are a result of stretching and down-bowing of the kurkar layer in an eastward direction.

The Holocene delta sediment load factor alone does not appear to be a fully adequate explanation for stratal arching and formation of tension-induced joint structures in the kurkar. It is recalled, for example, that the Holocene sediment cover of the consolidated kurkar in the bay is relatively thin (<20 m) and comprises a large proportion of water-saturated silty mud of low density (STANLEY *et al.,* 2004a, 2004b). The cause of tension may become somewhat better understood when taking into account the broken, offset nature of the kurkar's upper surface offshore, to the east in Abu Qir Bay, as indicated in seismic profiles (Figure 3). Rather than primarily a function of the Holocene sediment overburden load factor, it is proposed here that the observed structural patterns are more likely a response to what transpires beneath the kurkar. Of note in this respect is the marked thickening at depth of underlying Quaternary and Tertiary sequences, from the western desert margin to the Nile delta. Firm evidence for this W-to-E increased subsurface sediment thickness is provided by deep borings and geophysical profiles (Figure 4A) collected in this region for gas and petroleum exploration (ZAGHLOUL *et al.,* 1977; SAID, 1981; DEIBIS, 1982; EL-ELLA, 1990; HARMS and WRAY, 1990). Moreover, different available subsurface stratigraphic sections all record structural displacement by normal faults in the >5000 m thickness of Cretaceous to Quaternary sediment units beneath the coastal margin near Abu Qir (Figure 4B). Such faults are also identified beneath the delta proper south of the coast (SCHLUMBERGER, 1984; HARMS and WRAY, 1990) and on the continental margin north of the present coastline (ROSS and UCHUPI, 1977).

Large-scale structural features formed at depth in the Abu Qir area are observed on deep-penetration seismic profiles. Some are identified as synsedimentary (or contemporaneous) growth faults in the thickened sections underlying the Nile delta and offshore margin as seen by are (DEBEIS, 1982; SCHLUMBERGER, 1984; EL-ELLA, 1990; HARMS and WRAY, 1990). These faults are characterized by rotated blocks (Figure 4C), commonly are coast-parallel, and usually display thickening of sediment on the downthrown basinward side of structures. Viewed from above, growth faults tend to be concave and scope-shaped toward the basin (Figure 4C), typically with a listric profile, *i.e.* steep in their upper part and flattened, sometime to near-horizontal, at depth (COLEMAN *et al.,* 1998; MAESTRO *et al.,* 2002). Growth faults tend to migrate basinward by gravity extensional sliding as the delta front progrades (ELLIOTT, 1991), with motion along shear (slip) planes that act as detachment layers (MAESTRO et al., 2002). Such structural features generally occur in thickened sediment sequences formed by rapid accumulation and effects of basin subsidence. Thick depositional piles in such settings are subject to differential compaction and crustal loading at depth (*cf.* BRUCE, 1973). These conditions are typically associated with many of the world's deltas, such as the Mississippi and Texas systems in the northern Gulf of Mexico (FISHER and MCGOWEN, 1969; WORALL and SNELSON, 1989) and the Niger delta in west-central Africa (EVAMY *et al.,* 1978).

It is proposed here that sets of growth faults have modified sections of kurkar and deltaic sediment at shallow depths in western Abu Qir Bay. Growth faulting at the Abu Qir coast is suggested by the irregular form of the hard reflectors identified as the upper part of kurkar layers in the high-resolution seismic profiles (Figures 3, 5A). The shear plane depths along which motion has occurred, however, remain undefined at this time (Figure 5B) due to subbottom penetration limitations of the seismic system used for the study. Deformation and breaks of kurkar Ridge II appear to have occurred in the late Pleistocene, well before accumulation of the Holocene cover over the bay floor. It should be noted that these structures are quite unlike the steeply-dipping coast-parallel normal faults that have broken linear kurkar ridges along the coast of Israel, and along which important oscillatory up-and-down land motion has been interpreted (NEEV et al., 1987).

Offset of both kurkar and overlying Holocene cover are observed locally in the western bay, providing evidence of more recent motion and deformation of layers by growth faults and recording what MAESTRO and others (2002) refer to as a 'domino effect.' Two probable triggering events that have led to

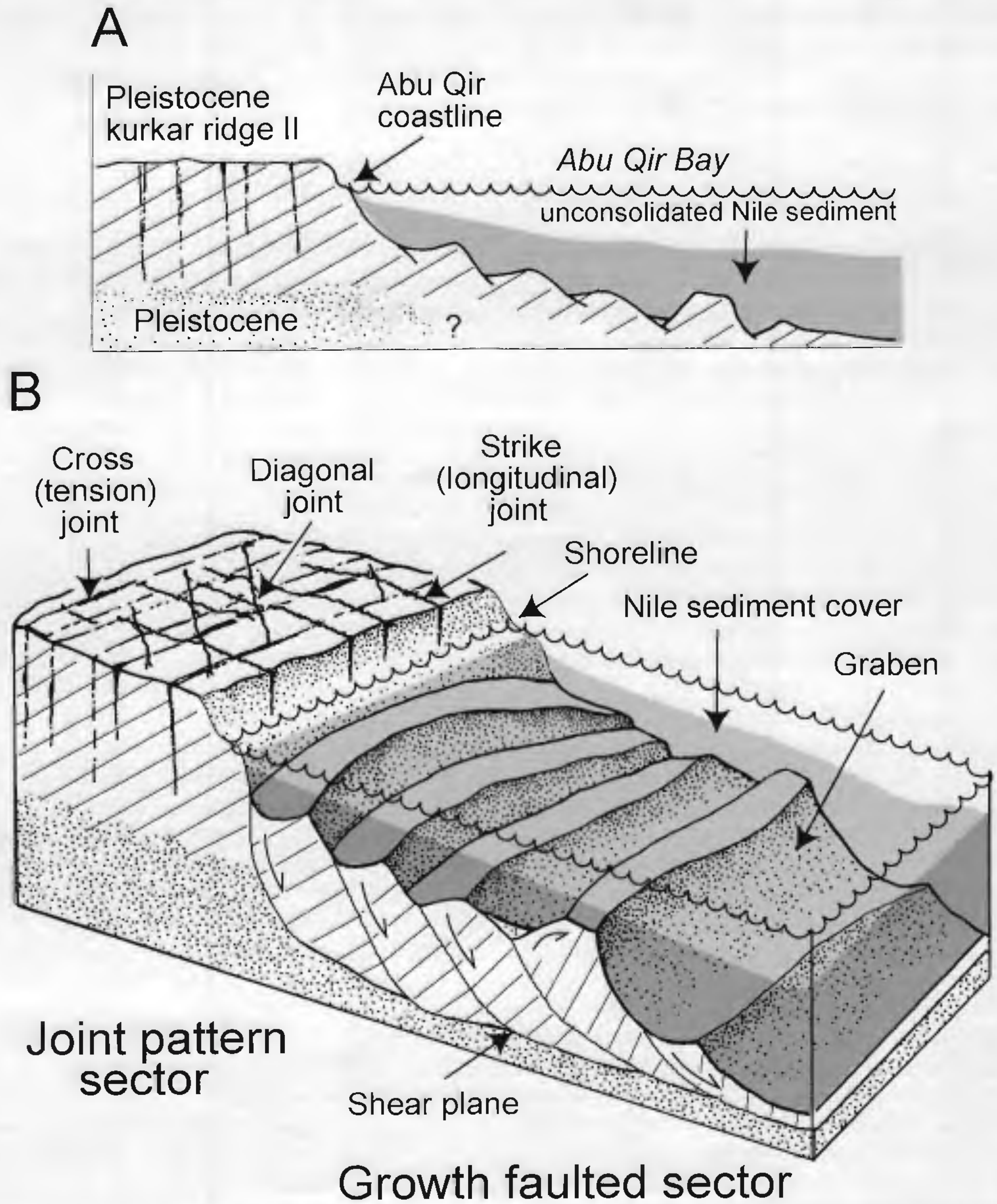


Figure 5. A, simplified scheme highlighting field and seismic observations of structures in kurkar coastal Ridge II in the vicinity of Abu Qir. B, interpretation of (A) showing joint fracture patterns and growth fault sets oriented toward the center of Abu Qir Bay; the shoreline at Abu Qir has continued to shift its position since the late Pleistocene by headscarp retreat toward the WSW.

lowering of the Abu Qir Bay floor during the Holocene are sudden weighting phenomena by high floods of the Nile river and deposition of their large sediment loads (STANLEY *et al.*, 2004a, 2004b), and differential basin subsidence at depth. Additionally, shallow (Figure 4D) to intermediate depth earthquake epicenters between Abu Qir and Alexandria, and in the contiguous shelf to the north (EL-ELLA, 1990; KEBEASY, 1990), record responses to periodic structural readjustment of the delta pile and consequent evolution of the coastal margin in this region. Substantial bay floor submergence (>5m) that occurred from Hellenistic time (~2500 yrs B.P) to the recent is the result of land subsidence coupled with eustatic sea-level rise. This is recorded by archaeological evidence, primarily two ancient Greek settlements now submerged in the western bay (STANLEY *et al.*, 2004a, 2004b). As a consequence of the above-cited factors, the coastline of the bay has retreated ~5 km southward at a rapid long-term average rate of ~2 m/yr. Moreover, during this time-span, the somewhat higher relief of the western Abu Qir Bay coast along the peninsula is the result of shoreline migration by more than one kilometer to the west by headscarp retreat (Figure 5B).

## CONCLUSIONS

The sharp, well-defined carbonate-siliciclastic interface at the Abu Qir coast is a response primarily to geologically recent structural activity rather than to the interaction of climatic-related events and physical oceanographic, biological or chemical processes. The carbonate coastal Ridge II of late Pleistocene age that extends from Arab's Gulf to the Abu Qir study area appears to have been stretched and down-bowed in a NE direction east of Alexandria. This deformation, however, is viewed as only a partial response to weighting by younger Nile delta deposits that accumulated upon the ridge in Holocene time. A more significant, but less obvious, cause of kurkar ridge lowering is readjustment at depth of the thick Mesozoic to Quaternary sedimentary pile (> 5000 m) that lies beneath the NW Nile delta region.

As a consequence, the carbonate ridge has subsided and been offset by growth faults at shallow depths in Abu Qir Bay. The bay's southern shoreline has progressively retreated toward the south, primarily by combined lowering of land and eustatic sea-level rise, while coastal regression toward Abu Qir peninsula in the west has developed by headscarp retreat largely as a response to coast-parallel growth faults. Subsidence and offset of kurkar Ridge II have resulted in formation of the sharp carbonate-siliciclastic interface between late Pleistocene and early Holocene time. Locally important deformation of this Quaternary section in the study area has occurred as recently as the first millennium C.E.

Large-scale subsurface growth faulted complexes are typically associated with deltas. The Abu Qir margin provides an example of small-scale growth fault evolution at shallow depth along the coast within such depocenters. Readjustment of the sediment pile in this area likely involves periodic release of energy, and, in some cases, may account for the concentration of shallow to intermediate depth earthquakes recorded along the Alexandria to Abu Qir coastal margin and contiguous shelf to the north.

## ACKNOWLEDGMENTS

The author thanks Dr. C. Finkl for the invitation to contribute to this special issue in honor of our friend, Rhodes W. Fairbridge. Seismic records were generously provided by Messrs. F. Goddio, Institut Européen d'Archéologie Sous-Marine, Paris, and G. Schnepp, Arcocea, Grenoble, France. Assistance with illustrations was provided by Mr. T.F. Jorstad and Ms. M. Parrish, and with the typescript by Ms. J. Yanoshik, National Museum of Natural History (NMNH), Smithsonian. My gratitude is also expressed to Ms. N.A. Ellis and Mr. T.F. Jorstad for their helpful reviews. Funding was provided by a Walcott Grant award from the NMNH.

## LITERATURE CITED

ABDEL-KADER, A., 1982. *Landsat analysis of the Nile delta, Egypt.* Masters thesis, University of Delaware, 260p.

ALMAGOR, G., 1979. Relict sandstone of Pleistocene age on the continental shelf of northern Sinai and Israel. *Israel Journal of Earth Sciences*, 28, 70–76.

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

BERNASCONI, M.P. and STANLEY, D.J., 1997. Molluscan biofacies, their distributions and current erosion on the Nile delta shelf. *Journal of Coastal Research*, 13, 1201–1212.

BRUCE, C.H., 1973. Pressured shale and related sediment deformation: mechanism for development of regional contemporaneous faults. *American Association of Petroleum Geologists Bulletin*, 57, 878–886.

BUTZER, K.W., 1960. On the Pleistocene shorelines of the Arab's Gulf, Egypt. *Journal of Geology*, 68, 626–637.

CHEN, Z.; WARNE, A.G. and STANLEY, D.J., 1992. Late Quaternary evolution of the northwestern Nile delta between the Rosetta promontory and Alexandria, Egypt. *Journal of Coastal Research*, 8, 527–561.

COLEMAN, J.M.; WALKER, H.J. and GRABAU, W.E., 1998. Sediment instability in the Mississippi River delta. *Journal of Coastal Research*, 14, 872–881.

COUTELLIER, V. and STANLEY, D.J., 1987. Late Quaternary stratigraphy and paleogeography of the eastern Nile delta, Egypt. *Marine Geology*, 77, 257–275.

DAVIS, G.H. and REYNOLDS, S.J., 1996. *Structural Geology of Rocks and Regions.* New York: John Wiley & Sons, Inc., 776 p.

DEBEIS, S., 1982. Abu Qir Bay, a potential gas province area offshore Mediterranean, Egypt. *WEPCO, 6th Exploration Seminar of EGCP*, Cairo, Egypt, 50–65.

DOYLE, L.J. and ROBERTS, H.H., 1988. *Carbonate-Clastic Transitions.* Amsterdam: Elsevier Science Publishers B.V., 304 p.

EL-ASMAR, H. and WOOD, P., 2000. Quaternary shoreline development: the northwestern coast of Egypt. *Quaternary Science Review*, 19, 1137–1149.

EL-ELLA, R.A., 1990. The Neogene-Quaternary section in the Nile Delta, Egypt: Geology and hydrocarbon potential. *Journal of Petroleum Geology*, 13, 329–340.

EL-FAYOUMY, I.F.; EL-SHAZLI, M.M. and HAMMAD, F.A., 1975. Geomorphology of the coastal area between Abu Qir and Rasheed (northwest of the Nile Delta, E.A.R.). *Bulletin of the Faculty of Science, Mansoura University*, 2, 135–147.

EL SHAZLY, E.M.; ABDEL-HADY, M.A.; EL GHAWABY, M.A.; EL KASSAS, I.A.; KHAWASIK, S.M.; EL SHAZLY, M.M. and SANAD, S., 1975. *Geologic Interpretation of Landsat Satellite Images for West Nile Delta Area, Egypt.* Cairo: The Remote Sensing Research Project, Academy of Scientific Research & Technology, 38p.

EL-WAKEEL, S.K. and EL-SAYED, M.K., 1978. The texture, mineralogy and chemistry of bottom sediments and beach sands from the Alexandria region, Egypt. *Marine Geology*, 27, 137–160.

ELLIOTT, T., 1991. Deltas. *In:* H.G. READING, (ed.), *Sedimentary Environments and Facies.* Oxford: Blackwell Scientific Publications, 113–154.

EVAMY, B.D.; HAREMBOURE, P.; KAMERLINE, P.; KNAAP, W.A.; MOLLOY, F.A. and ROWLANDS, P.H., 1978. Hydrocarbon habitat of Tertiary Niger delta. *American Association of Petroleum Geologists Bulletin*, 62, 1–39.

FISHER, W.L. and MCGOWEN, J.H., 1969. Depositional systems in Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas. *American Association of Petroleum Geologists Bulletin*, 53, 30–54.

FRIHY, O.E., 1988. Nile delta shoreline changes: aerial photographic study of a 28-year period. *Journal of Coastal Research*, 4, 597–606.

FRIHY, O.E., 1992. Quaternary evolution of the Abu Quir Bay, Egypt. *GeoJournal*, 27, 339–344.

GUIDOBONI, E., 1994. *Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century.* Rome: Istituto Nazionale di Geofisica, 413 p.

HARMS, J.C. and WRAY, J.L., 1990. Nile delta. *In:* R. SAID, (ed.), *The Geology of Egypt.* Rotterdam: A.A. Balkema, 329–343.

HASSOUBA, A.M.B.H., 1980. *Quaternary sediments from the coastal plain of northwestern Egypt (from Alexandria to El Omayid).* Doctoral thesis, Imperial College, London, 320p.

HASSOUBA, A.M.B.H., 1995. Quaternary sediments from the coastal plain of northwestern Egypt (from Alexandria to El Omayid). *Carbonates and Evaporites,* 10, 8–44.

HEGAB, O.A. and EL-ASMAR, H.M., 1995. Last interglacial stratigraphy in the Burg el-Arab region of the northwestern coast of Egypt. *Quaternary International,* 29/30, 23–30.

HERODOTUS, 1987. *The History* (GREEN, D., translator). Chicago: The University of Chicago Press, 699p.

HILMY, M.E., 1951. Beach sands of the Mediterranean coast of Egypt. *Journal of Sedimentary Petrology,* 21, 109–120.

INMAN, D.L. and JENKINS, A.A., 1984. The Nile littoral cell and man's impact on the coastal littoral zone in the SE Mediterranean. *In: Proceedings, 17th International Coastal Engineering Conference.* Sydney: ASCE, 1600–1617.

JORSTAD, T.F. and STANLEY, J.-D., 2004. Vibracores in Abu Qir Bay: description and analyses. *In:* GODDIO, F. *et al.,* (eds.), *Canopus I, the Submerged Western Canopic Region.* London: Periplus Ltd., pp. 313–317, plus Appendix.

KEBEASY, R.M., 1990. Seismicity. *In:* SAID, R., (ed.), *The Geology of Egypt.* Rotterdam: A.A. Balkema, 51–59.

MAESTRO, A.; BARNOLAS, A.; SOMOZA, L.; LOWRIE, A. and LAWTON, T., 2002. Geometry and structure associated to gas-charged sediments and recent growth faults in the Ebro delta (Spain). *Marine Geology,* 186, 351–368.

NEEV, D., 1975. Tectonic evolution of the Middle East and the Levantine basin (easternmost Mediterranean). *Geology,* 3, 683–686.

NEEV, D.; ALMAGOR, G.; ARAD, A.; GINZBURG, A. and HALL, S.K., 1976. The geology of the southeastern Mediterranean. *Geological Survey of Israel Bulletin,* 68, 1–55.

NEEV, D.; BAKLER, N. and EMERY, K.O., 1987. *Mediterranean Coasts of Israel and Sinai.* New York: Taylor & Francis, 130p.

POEM GROUP, 1992. General circulation of the Eastern Mediterranean. *Earth-Science Reviews,* 32, 285–309.

ROSS, D.A. and UCHUPI, E., 1977. Structure and sedimentary history of southeastern Mediterranean Sea-Nile Cone area. *American Association of Petroleum Geologists Bulletin,* 61, 872–902.

SAID, R. 1981. *The River Nile.* Berlin: Springer-Verlag, 151p.

SAID, R. 1993. *The River Nile, Geology, Hydrology and Utilization.* Oxford: Pergamon Press, 320p.

SANDFORD, K.S. and ARKELL, W.J., 1939. Paleolithic man and the Nile Valley in lower Egypt. *Chicago Oriental Institute Publication,* 36, 1–105.

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

SESTINI, G., 1989. Nile delta: a review of depositional environments and geological history. *In:* WHATELEY, M.K.G. and PICKERING, K.T., (eds.), *Deltas: Sites and Traps for Fossil Fuels.* London: Geological Society Special Publication, 41, 99–127.

SESTINI, G., 1992. Implications of climatic changes for the Nile delta. *In:* JEFTIC, L.; MILLIMAN, J.D. and SESTINI, G., (eds.), *Climatic Change and the Mediterranean.* London: Edward Arnold, 535–601.

SHUKRI, N.M.; PHILIP, G. and SAID, R., 1956. The geology of the Mediterranean coast between Rosetta and Bardia, Part II, Pleistocene sediments; Geomorphology and microfacies. *Bulletin de l'Institut d'Egypt,* 37, 395–427.

SMITH, S.E. and ABDEL-KADER, A., 1988. Coastal erosion along the Nile delta. *Journal of Coastal Research,* 4, 245–255.

SNEH, A. and WEISSBROD, T., 1973. Nile delta: the defunct Pelusian branch identified. *Science,* 180, 59–61.

SNEH, A.; WEISSBROD, T.; EHRLICH, A.; and many others, 1986. Holocene evolution of the northeastern corner of the Nile delta. *Quaternary Research,* 26, 194–206.

STANLEY, D.J., 1972. *The Mediterranean Sea, A Natural Sedimentation Laboratory.* Stroudsburg, Pennsylvania: Dowden, Hutchinson & Ross, Inc., 765p.

STANLEY, D.J., 1990. Recent subsidence and northeast tilting of the Nile delta, Egypt. *Marine Geology,* 94, 147–154.

STANLEY, J.D.; GODDIO, F.; JORSTAD, T.F. and SCHNEPP, G., 2004a. Submergence of ancient Greek Cities off Egypt's Nile delta—A cautionary tale. *GSA Today,* 14, 4–10.

STANLEY, D.J and HAMZA, F.H., 1992. Terrigenous-carbonate sediment interface (late Quaternary) along the northwestern margin of the Nile delta Egypt. *Journal of Coastal Research,* 8, 153–171.

STANLEY, D.J.; MCREA, J.E. Jr., and WALDRON, J.C., 1996. *Nile Delta Drill Core and Sample Databases for 1985–1994: Mediterranean Basin (MEDIBA) Program.* Smithsonian Contributions to the Marine Sciences, 37. Washington D.C.: Smithsonian Institution Press, 428p.

STANLEY, J.-D.; SCHNEPP, G., and JORSTAD, T.F., 2004b. Submergence of archaeological sites in Abu Qir Bay, the result of gradual long-term processes plus catastrophic events. *In:* GODDIO, F., *et al.,* (eds.), *Canopus I, the Submerged Western Canopic Region.* London: Periplus Ltd., 289–312.

STANLEY, D.J. and WARNE, A.G., 1998. Nile delta in its destruction phase. *Journal of Coastal Research,* 14, 794–825.

STOFFERS, P.; SUMMERHAYES, C.P. and DOMINIK, J., 1980. Recent pelletoidal carbonate sediments off Alexandria, Egypt. *Marine Geology,* 34, M1–M8.

SUMMERHAYES, C.; SESTINI, G.; MISDORP, R. and MARKS, N.,1978. Nile delta: Nature and evolution of continental shelf sediment system. *Marine Geology,* 24, 37–47.

TOUSSOUN, O., 1922. Mémoire sur les anciennes branches du Nil. *Mémoires de la Société Géographique d'Egypte,* Cairo, 4, 144.

UNDP/UNESCO, 1978. *Arab Republic of Egypt: Coastal Protection Studies, Project Findings and Recommendations.* Paris: UNDP/ EGY/73/063 Final Report, FNR/SC/OSP/78/230, 483p.

WARNE, A.G. and STANLEY, D.J., 1993. Late Quaternary evolution of the northwest Nile delta and adjacent coast in the Alexandria region, Egypt. *Journal of Coastal Research,* 9, 26–64.

WORRALL, D.M. and SNELSON, S., 1989. Evolution of the northern Gulf of Mexico, with emphasis on Cenozoic growth faulting and the role of salt. *In:* BALLY, A.W. and PALMER, A.R., (eds.), *The Geology of North America—An Overview,* Boulder, Colorado: Geological Society of America, 97–138.

ZAGHLOUL, Z.M.; TAHA, A.A.; HEGAB, O. and EL-FAWAL, F., 1977. The Neogene-Quaternary sedimentary basins of the Nile Delta. *Egyptian Journal of Geology,* 21, 1–19.

ZEUNER, F.E., 1952. Pleistocene shorelines. *Geologische Rundschau,* 40, 39–50.