Nile Delta: Recent Geological Evolution and Human Impact

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Few countries in the world are as dependent on water from a single source as Egypt. The natural Nile cycle of flow and sediment discharge has been disrupted by human intervention, including closure of the High Aswan Dam; this intervention has resulted in a series of responses that now threaten the northern Nile delta. Erosion, salinization, and pollution are inducing a marked decline in agricultural productivity and loss of land and coastal lagoons at a time when the population is expanding exponentially. Geological analyses of radiocarbon-dated cores across the northern delta are used to interpret the interaction of sea-level changes, climatic oscillations, subsidence, and transport processes during the past 35,000 years. Recognition of long-term trends of these natural factors provides a basis to evaluate the profound impact of human activity and to assess future changes in the Nile delta ecosystem.

The fan-shaped geometry of the Nile delta of Egypt records the interaction of competing processes, namely, the buildout of River Nile sediments versus coastal erosion. Since closure of the High Aswan Dam in 1964, the Nile flood cycle has been controlled north of Aswan, fluvial sediments are no longer transported to the coast, and the balance between fluvial and marine processes has been completely modified. As early as the fifth century B.C., Herodotus realized the crucial nature of this balance: "especially in the part called the Delta, it seems to me that if . . . the Nile no longer floods it, then, for all time to come, the Egyptians will suffer . . ." (*1*). Currently, widespread coastal erosion results because negligible sediment load reaches the coast and delta sediment is being removed by marine waves and currents. Hence, the Nile is no longer an active delta but, rather, a completely wave-dominated coastal plain along the Mediterranean coast. The River Nile system has been so modified that nearly all water is diverted by a dense network of irrigation channels throughout the valley and delta, and no fresh water reaches the sea. Moreover, the little Nile water that now approaches the coast is polluted agricultural runoff and industrial-municipal waste (*2*) that spills into the four coastal lagoons (Fig. 1).

In addition to loss of fluvially derived Nile sediment, land subsidence and rising sea level now threaten large areas of the low-lying northern delta with coastal erosion, increased salinization of groundwater, and incursion of salt water (*3, 4*). The livelihood and stability of Egypt's 58 million people are intimately linked to Nile water and, thus, are concentrated along the Nile valley and delta, where 100% of farmland must be irrigated (*2, 5*). These two regions account for less than 5% of Egypt's land surface and are a vulnerable oasis in the vast, inhospitable eastern Sahara Desert. With a population growth exceeding 1 million every 9 months, Egypt's complete dependency on the Nile valley and delta is ever more pressing. Because the delta constitutes two-thirds of Egypt's habitable land, any loss of the northern delta plain by coastal erosion, salt water incursion, and pollution is critical.

To protect this vulnerable region, it is necessary to identify and measure long-term trends that molded the Nile delta. In this article, we overview stratigraphic and sedimentologic analyses of numerous radiocarbon-dated cores (Fig. 1) to detail the subsurface distribution of late Quaternary Nile delta deposits. Using a multidisciplinary approach, we are able to interpret the geological history of the delta for the past 35,000 years (*3*) and to assess trends and interactions among natural factors (sea level, neotectonism, climate, and sediment transport processes) that control delta evolution.

Even without the influence of humans, who have substantially modified delta evolution since early Pharaonic time (*6*), natural factors have profoundly altered the Nile delta margin during the late Quaternary. Humans, however, are now and will continue to be a major force in controlling geological processes in the northern delta. Thus, our goal is to distinguish the relative influences of natural and anthropogenic factors because development of effective coastal protection measures requires understanding of all factors controlling Nile delta evolution.

We established the temporal and spatial configuration of subsurface sediment facies across the entire northern Nile delta from petrologic analysis of nearly 100 radiocarbon-dated cores (*3*). These borings range in length from 10 to over 50 m. A chronostratigraphic framework for the past 35,000 years is based on more than 340 radiocarbon-dated samples. We analyzed nearly 4000 samples for composition (sand- and clay-size mineralogy, fauna, flora, and trace element geochemistry) and texture (size, shape, and morphoscopy) (*7*). Integrated with these analyses are data from published well logs (*8–12*). We defined subsurface sedimentary facies and environments of deposition by comparison to present-day deltaic and nearshore marine deposits. In addition, delta geomorphology and coastal processes were analyzed using satellite image analysis (*3*).

Natural Factors

Late Quaternary subsurface stratigraphy of the northern delta consists of, from bottom

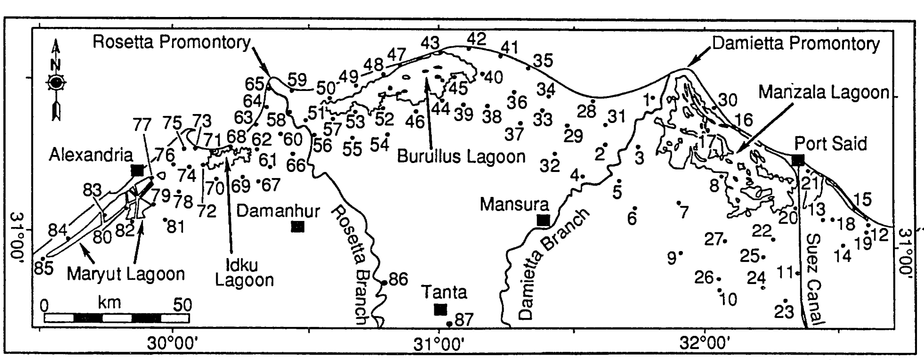

Fig. 1. Northern Nile delta of Egypt, showing positions of Smithsonian sediment borings used in this study. Also denoted are the four coastal lagoons, two main Nile distributaries, and their promontories.

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to top: alluvial sand and stiff mud [older than ~12 ka (thousand years ago)] unconformably (separated by a hiatus) overlain by shallow marine to coastal transgressive sand (~12 to 8 ka); this sand is, in turn, unconformably overlain by a variable sequence of Holocene deltaic sand, silt, and mud as old as ~7.5 ka (Fig. 2). The overall architecture and specific environments of deposition within these three sequences record the interplay of factors that controlled the evolution of the Nile delta. These factors include sea-level changes, subsidence, climate oscillations, and sedimentary processes.

Sea level. The core sequences span a time that included a worldwide lowering of sea level (to ~20 to 18 ka), followed by a rapid rise (to ~7 ka) and then a more gradual rise to the present (*13*), largely as a consequence of waxing and waning of continental glaciers. In the Nile delta, we defined sea-level fluctuations during the past 35,000 years by mapping the extent of facies that were deposited close to sea level and determining their age (Fig. 2). Lower sea level is recorded by late Pleistocene (>30 to 12 ka) sand and mud that were deposited on a subaerially exposed alluvial plain. The delta, during maximum lowstand, lay near the present shelf edge, as much as 50 km north of the modern coast (*12, 14, 15*). During the late Pleistocene to early Holocene (>12 to 8 ka), rapid rise in sea level caused the shoreline to shift landward and is recorded by nearshore marine (transgressive) sand. As the rise in eustatic sea level began to decelerate at ~7.5 ka (Fig. 2), the mid- to late Holocene deltaic sequence began to accumulate. This variable lithofacies sequence was initiated as overall rates of sedimentation surpassed rates of sea-level rise.

Subsidence. In contrast to the symmetrical fan shape of the modern delta, both thickness and depositional environment within the Holocene sequence vary greatly across the northern delta. The Holocene section in the northeast delta is thick (locally to >50 m) and coarsens upward from prograding open marine (prodelta, delta-front) deposits to coastal sand, silt, and mud (Fig. 2D). In the north-central delta, beach ridge, fluvial, and coastal dune sand and lagoon mud dominate, and sections are considerably thinner (Fig. 2C). In the northwest, marsh and lagoon deposits and floodplain silt and mud prevail with only minor open marine deposits (Fig. 2B). In the extreme northwest, thin (<10 m) carbonate-rich lagoon and sabkha sand, silt, and mud are common (Fig. 2A).

If sea-level rise and compaction were the only factors controlling sediment distribution, thickness of Holocene deposits would be consistant along the northern Nile delta margin. Hence, the fivefold thickening of the Holocene deltaic sequence from west to east (Fig. 2) indicates differential subsidence, that is, accelerated lowering of land surface by isostatic depression [compare with (*16*)] and faulting (*17*). Rates of subsidence across the northern delta range from <1 to >4 mm per year in the northeastern sector (Fig. 3). Differential subsidence across the northern delta resulted in a general northeastward tilting of the delta plain surface and consequent thickening of the Holocene section. The well-defined zone of highest subsidence coincides with modern Manzala lagoon and is related to major eastern Mediterranean fault systems (*18, 19*). Accelerated subsidence at the two promontories is more likely a function of isostatic adjustment associated with increased sediment thickness [to 30 m (*10*)] and loading.

Regional variations in Holocene subsidence rates reveal the location of a coastal flexure zone (Fig. 3) north of which lies a belt of thickened Nile deposits. This zone of thickened Holocene sediments does not parallel the present shoreline and ranges from about 15 km in the north-central sector to 22 km in the northwestern plain to 45 km in the Manzala lagoon region. The differential subsidence caused by this flexuring led to the variable distribution of Holocene delta plain deposits. Enhanced subsidence in the northeastern delta in-

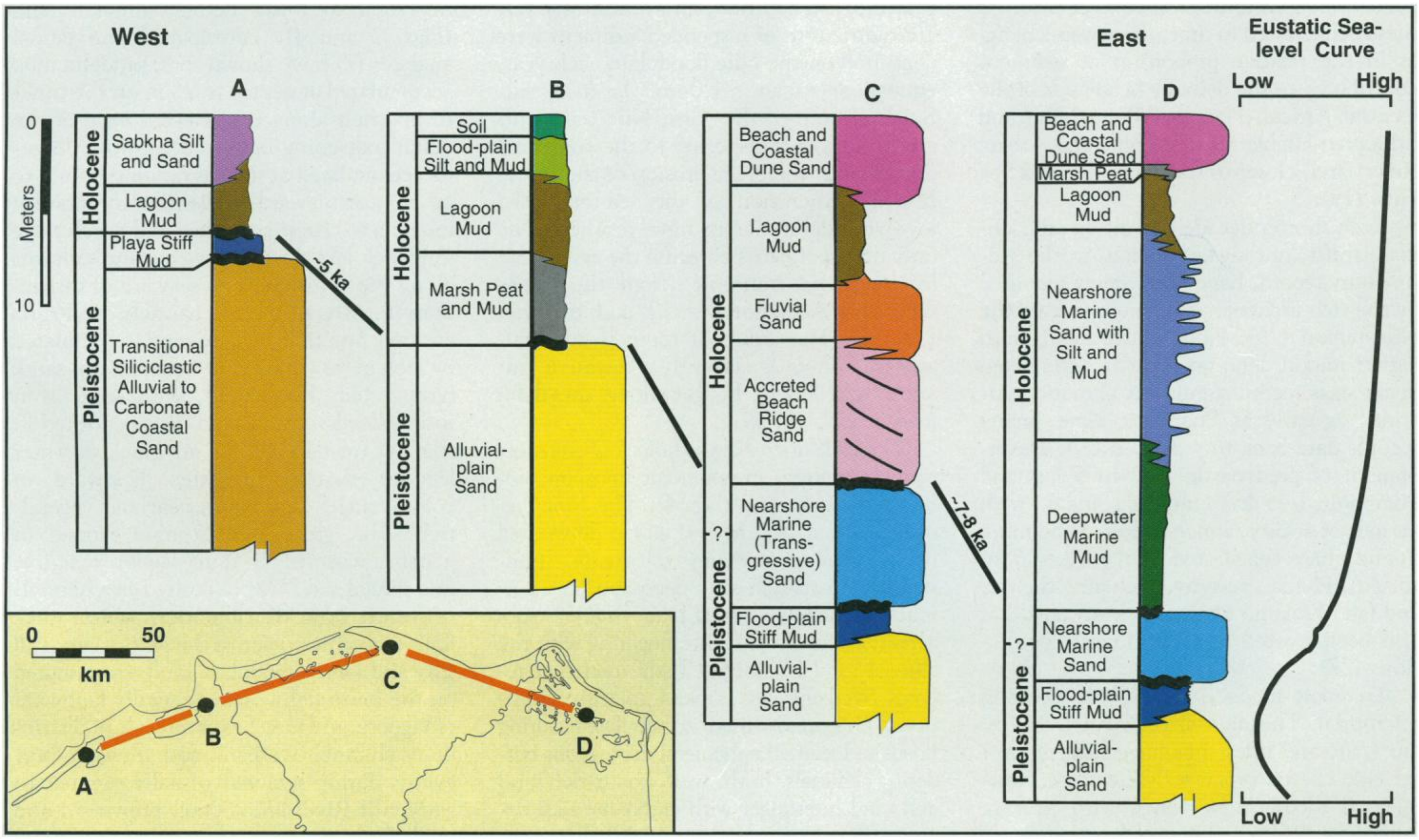


Fig. 2. Summary of late Quaternary stratigraphy of the northern Nile delta; generalized eustatic sea-level curve [after (*13*)] is shown on right.

duced deeper water conditions in this sector during the Holocene; this led to deposition of open marine delta facies (Fig. 2) and the formation of delta lobes.

Climate. Major climatic oscillations induce eustatic sea-level changes. Superposed on the long-term, climatically induced sea-level fluctuations described above are shorter term (century to millennium) climatic oscillations that affected the discharge and load of the River Nile (*20*). Climatic oscillations are recorded by marked changes in facies distributions, such as timing and location of late Pleistocene playa deposits (*21*) and Holocene Nile distributary channels. The Sebennitic branch, for example, was a major Nile distributary delivering coarse sand to the north-central delta coast from ~7 to 4.5 ka (Fig. 4, cross section A–A′). At that time, climate was generally wetter and floods higher than at present (*22*), and the Nile carried more coarse sediment. In contrast, during the past millennium smaller floods have carried less and generally finer sediment by way of the Rosetta and Damietta branches.

Marked climatic oscillations at the century to millennium scale are also recorded by petrological and geochemical variations in late Quaternary sections (*23*). These variations record changes in sediment derived from Nile basin headlands (*24*). The longest river in the world, the Nile traverses more than 35° of latitude and flows across climate belts ranging from tropical to hyperarid. As these belts shifted in time, there were changes in the relative proportion of sediment contributed to the delta by headlands of the Central African Plateau (White Nile) and Ethiopian Highlands (Blue Nile and Atbara River) and, closer to the delta, the Red Sea Hills (*19*).

Even shorter decade to century paleoclimate shifts, not always obvious in the sedimentary record, have been amply recorded by the rich archeological database from the Nile region (*25*). Flood gauge data, grain export-import data, tax records, and related documents record significant climatic variations as early as Pharaonic time (many records date back to ~3000 B.C.). Development of predynastic (~7 to 5 ka) and Pharaonic (~5 ka) cultures coincide with periods of aridity, which followed the more humid phase that lasted from ~12 to 5 ka (*6, 26*). Human activity, including the rise and fall of several Pharaonic kingdoms, has also been related to such climatic oscillations (*27*).

Transport processes. The Nile coast is microtidal: The diurnal tidal range is ~30 cm (*28*), and tides thus have little impact on Nile coastal processes. The coast, however, is modified by waves with average heights of 0.5 to 1.0 m and a maximum of ~2.0 m in winter. The dominant wind

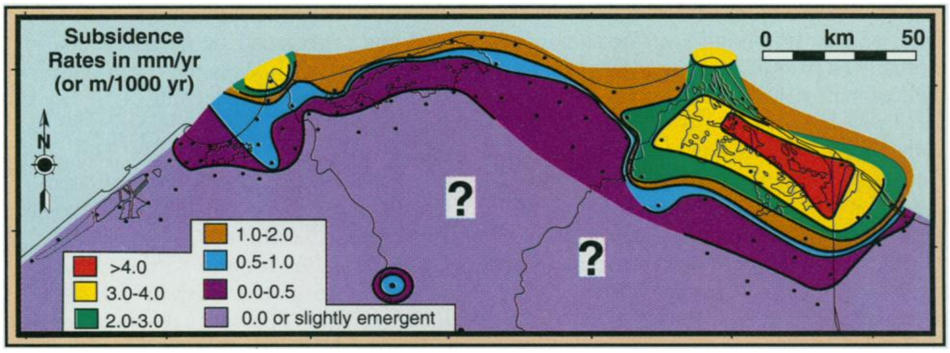


Fig. 3. Holocene subsidence rates [method of calculation in (*17*)] and flexure zone, north of which deposits thicken along the Nile delta margin.

direction is to the southeast, which drives coastal currents to the east; studies indicate that these wind and wave regimes have been generally consistent since at least early Holocene time (*3*). These coastal currents transport large volumes of delta sediment eastward toward Sinai, Gaza, and the Levant (*29*). Winds not only control strong coastal currents but also transport significant quantities of sand southeastward from the beach, which broaden strandplain and coastal dunes along the delta margin [Fig. 4, cross section A–A′ (*3*)].

Before impoundment of the High Aswan Dam, River Nile flow averaged ~84 × 10^9 m^3 per year and transported ~124 × 10^6 metric tons of sediment to the coast each year (*30*). In addition, an average of 9.5 × 10^6 metric tons of suspended sediment were deposited on the Nile floodplain each year, equivalent to an ~1.0-mm layer of silt. Since closure of the dam, Nile sediments are no longer transported to the coast and floodplain; widespread erosion of the shoreline and incursion of the sea onto the low-lying delta margin have resulted. The only new sediments entering the system are by longshore transport (from the Arabs Gulf and Alexandria shelf) and by wind (*15, 31*). The sediment input is minimal, and thus there is currently a negative balance in sediment budget along the delta margin (*15, 28, 29*).

Three distinct Nile lithofacies sequences record variations in dominant transport processes through time (Fig. 4). The lower sequence (from >35 to ~12 ka) is dominated by nonmarine medium to coarse, iron-stained, quartz-rich sand deposited on a low relief, partially vegetated plain that was subaerially exposed (*21*). Interfingering with the alluvial sand is variegated stiff mud that records overbank and sabkha (playa) deposition. This sandy mud accumulated during floods in localized ephemeral depressions bordering channels. In the west, quartz-rich sand and mud interfinger with carbonate-rich deposits (Fig. 4, cross section A–A′) that accumulated in desert environments (*3*).

An unconformity separates the lower sequence from an overlying nearshore marine to coastal sand unit (~11.5 to 8 ka). This unit contains coarse quartz-rich sand that is not iron stained but is well rounded; the unit contains abundant shallow marine fauna, typically shell debris of sand size. Composition and texture indicate that this sand is the product of reworking of late Pleistocene alluvial deposits by waves and currents in a high-energy, nearshore marine environment [(*3*), compare with (*32*)].

The transgressive sand unit is separated from the overlying Holocene sequence (<7.5 ka) by another hiatus (Fig. 4). This uppermost sequence comprises deposits that accumulated in variable settings, from inner shelf to lower deltaic alluvial plain (Figs. 2 and 4). Petrological and faunal analyses (*7*) have shown that: prodelta mud accumulated at depths to 25 m on the inner to midshelf along the seaward edge of the delta; coarsening-upward delta-front deposits accumulated at depths ranging from 5 to 10 m, just seaward of distributary mouths; medium to coarse shoreface and beach ridge sand was laid down by waves and currents along the coast and just seaward of distributary mouths of major channels; well-sorted, very fine to fine dune sand accumulated by eolian reworking of strandplain sand; bioturbated shelly mud, with some thin interbedded silt and sand, was deposited in shallow (to depths of 2 m) brackish water lagoons that accumulated landward of coastal ridges and dunes; peat and vegetal-rich, dark grey to black mud formed in marshes within and along lagoon margins; fine fluvial sand was deposited in channels of former Nile distributaries, which once flowed northward across the delta plain; stiff silty and sandy floodplain mud accumulated on the lower delta plain generally landward of lagoons and marshes as a result of distributary channel overbank and crevasse-splay events during seasonal (usually summer to early fall) River Nile floods; brown silt and mud form the soil that caps the upper sections of floodplain mud south of the

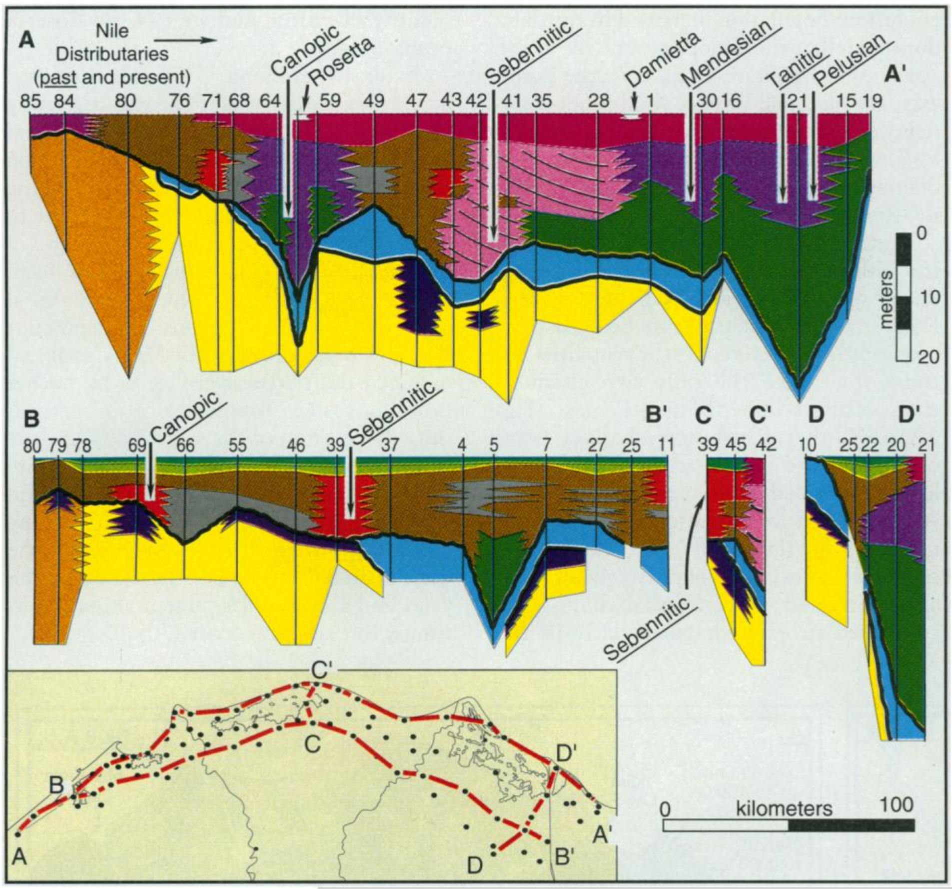


Fig. 4. Stratigraphic cross sections in the northern Nile delta, showing late Quaternary lithofacies distributions. Facies are defined in Fig. 2; locations of cross sections are shown in inset.

lagoons; and carbonate-rich and evaporite-rich sabkha silt and sand were deposited in desert settings on the western margin of the delta, largely in inter-ridge depressions.

Lithofacies Distributions and Geometry

Analysis of the three-dimensional lithofacies architecture is essential to interpret the geological history of the late Quaternary Nile delta (Fig. 4). The late Pleistocene sequence underlying the northern delta plain, dominated by rather homogeneous alluvial plain sand, is thick and widespread (9) and interfingers with thin, localized floodplain and playa mud (*21*). The boundary between late Pleistocene quartz-rich alluvial plain sand and carbonate-rich desert sand (near cores S-76, S-79, and S-80) denotes the westernmost limit of the River Nile during that period (*3*). The overlying late Pleistocene to early Holocene shallow marine transgressive sand forms a rather even, homogeneous layer (~5 m thick) in most sectors of the northern delta; this sand, however, pinches out toward the south and west (*3*).

Distribution of Holocene lithofacies is variable and discontinuous across the northern Nile delta, although some regional patterns are apparent. Seaward thickening of the Holocene section and the pinch-out of marine deposits landward (Fig. 4, cross sections C–C′ and D–D′) are characteristic of delta margins. Coarsening-upward sequences of open marine (prodelta, delta-front) to coastal facies, typical of prograding deltas (*16*, *32*), are characteristic of the northeastern Nile delta. In contrast, texturally irregular, generally retrogradational lagoon to coastal facies (Fig. 4, cross section A–A′) typify the north-central and northwestern delta (*3*). The widespread distribution of fine-grained and organic-rich lagoon and marsh deposits (*3*, *7*) indicate that wetlands were the major ecosystem in the northern delta during most of Holocene time (Fig. 4, cross section B–B′). These deposits accumulated south of shoreface, beach ridge, and dune sand. Fluvial sand, restricted in time and space, denotes former distributary channels of the Nile. Floodplain silt and soil cap the Holocene sequence south of the wetlands.

Paleogeography

From ~35 to 18 ka, most of the region was an alluvial plain across which seasonally active braided channels flowed (Fig. 5A). During sea-level lowstand, when the coast migrated by as much as 50 km to the north, floodplain mud accumulated in ephemeral, seasonally dry depressions. Carbonate-rich desert sand and sabkha mud were deposited in the west, in a generally arid climate. These desert deposits accumulated between and near older, elevated carbonate ridges (*7*). Intermittent marine incursions during this period are recorded by localized, shelly shoreline sand (*3*).

As sea level rapidly rose ~15 to 8 ka, the high-energy shoreline migrated landward (southward), and former alluvial plain deposits were reworked. The landward limit of the nearshore sand approximates the extent of the marine transgression onto the former alluvial plain; absence of this transgressive sand in the south and west (Fig. 5B) indicates that the northern delta region was tilting to the northeast as early as the late Pleistocene. Position of Nile channels during this period is currently unknown.

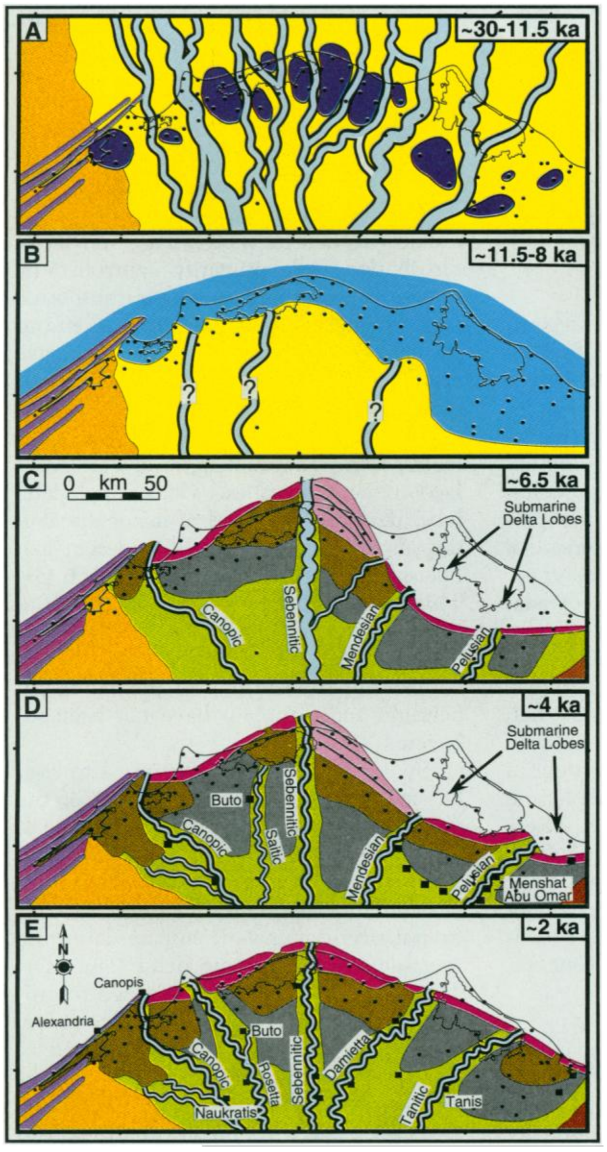
By 7.5 ka, the modern Nile delta had begun to form. Progradation of this delta occurred during deceleration in rate of sea-level rise and rapid influx of sediment; as a result, reworking of these deposits by waves and currents was limited. At ~6.5 ka (Fig. 5C), sea level was at 9 to 10 m below its present stand (*13*), the river gradient was steeper, and climate was somewhat more humid. Both delta morphology and facies distribution were primarily controlled by the Sebennitic channel, which transported large volumes of medium to coarse sand to the coast. This sand formed an extensive accreted beach ridge system at the headland of a cuspate-shaped, river-dominated delta. Sand ridges developed a nearly continuous barrier along seaward margins of widespread lagoons and marshes. Coalescing delta lobes developed seaward of major distributary mouths (such as the Mendesian and Pelusian) in the Manzala lagoon region (*3*). This preservation is in large part a result of the northeast tectonic tilt of the delta and rapid burial of these deposits. Lobe deposits off distributaries to the west (including Sebennitic and Canopic) have not been recovered.

By ~4 ka, sea level continued to rise, but more slowly, and the gradient of the delta plain diminished. Climate had become arid, flood levels subsided, and more distributary channels carried a less coarse bedload. This period records the transition from a river-dominated, cuspate delta to a wave-dominated, arcuate delta (Fig. 5D). The northeastern sector continued to prograde, whereas the north-central coast began to retrograde. The continuous belt of coastal sand along the delta margin continued to serve as a barrier for extensive lagoon-marsh environments. Humans, who had settled in the delta as early as predynastic time [~7 to 5 ka (*26, 33*)], established important population centers such as Buto and Menshat Abu Omar (*34*). Nonetheless, wetlands remained the primary ecosystem in the northern delta during early to mid-Pharaonic time (*6, 35*).

By ~2 ka (Fig. 5E), sea level had risen to about 2 m below the present level, and marine waves and currents molded the coastline so that the delta margin configuration began to resemble the modern shoreline. By this time, the delta had become more wave dominated and had a gentle, arcuate form. However, there remained at least five distributaries, most with small promontories, that continued to transport significant volumes of sediment to the coast during annual floods (*36*). Extensive coastal dune fields developed in the north-central delta from eroded Sebennitic promontory sediments. By this period, humans were significantly influencing delta evolution: Population increased in the delta during Hellenistic time, particularly in the Alexandria-Naukratis sector (*37*); the Damietta (Bucolic) and Rosetta (Bolbitine) channels were maintained by artificial excavation (*14*); and intensified irrigation and wetland drainage projects were substantially modifying the delta surface (*6*).

During the first millennium A.D., major Nile distributary channels were reduced to two, the artificially maintained Damietta and Rosetta branches. Distinct promontories accreted at their mouths because they were the only two channels transporting sediments to the coast (Fig. 6A). As other distributary channels were converted into canals and drains that no longer extended to the coast, their waters were diverted for irrigation, and flow was reduced. Wetlands of the middle and southern delta were extensively drained and cultivated (*33*). Coastal dune fields continued to expand, particularly in the vicinity of Baltim and west of the Rosetta promontory.

Extensive wetlands (*38*) still remained across the northern delta at the beginning of the 19th century (Fig. 6A). During that time an increased number of irrigation structures, including barrages and pumping stations, reduced sediment load carried to the northern delta and coast. By the end of the century, Abu Qir lagoon had been drained (*8*) and converted to agricultural land, and the other lagoons had been considerably reduced (*39*). The Suez Canal had modified the northeastern delta by further isolating eastern Manzala lagoon; as a result, this portion of the water body became a hypersaline lake and salt pan. Despite structures emplaced for flood control and irrigation, the Nile annual cycle of flooding continued, large low-lying surfaces of the delta plain received ~1 mm of new silt each year, and substantial sediment volume continued to reach the coast (*30*).



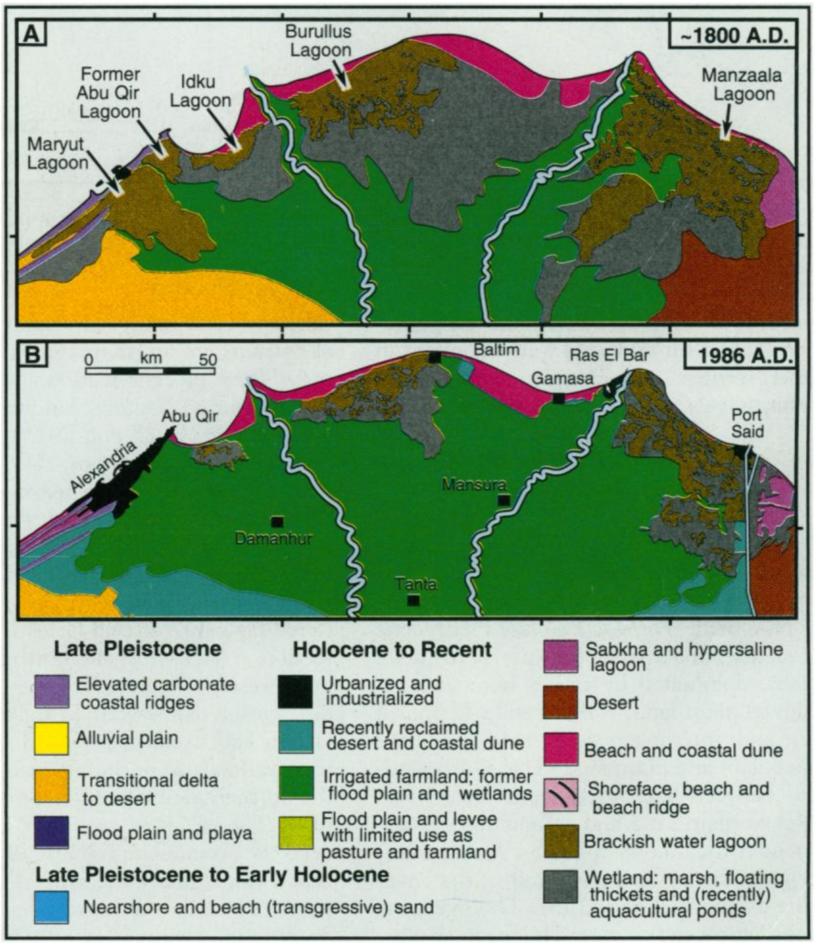


Fig. 6. (**Above**) Northern Nile delta (**A**) at about 1800 A.D. [after (*38*)] and (**B**) at present [from satellite images (*42*)].

Fig. 5. (**Left**) Time-slice paleogeographic maps detailing evolution of the northern Nile delta from ~30 to ~2 ka. Depositional environments are defined in Fig. 6.

Twentieth Century

The natural annual cycle of Nile flooding was profoundly altered during the early 20th century by construction (in 1902) and modification (in 1912 and 1934) of the Low Aswan Dam. Closure of the High Aswan Dam in 1964, providing Egypt with vital hydroelectric power, completely modified the natural cycle. Flow of River Nile water downstream of Aswan became constant rather than highly fluctuating during the course of the year; this development allowed steady irrigation, even during the dry season (*5*). However, empoundment entrapped virtually all (>98%) sediment (*30*) behind the dam in Lake Nasser, most near the Egypt-Sudan border. Changes in the natural cycle of Nile flow and sediment discharge had profound consequences, including: accelerated erosion along parts of the delta coastline (*4*); marine incursion onto low-lying northern delta plain sectors (*17*); curtailment of flood silt deposition that had formerly served as natural fertilizer and had offset land subsidence (*30*); increased salinization of cultivated land, as annual flooding no longer flushed out evaporitic salts (*40*); sharp decline in fish populations both in lagoons and seaward of the delta, as a result of decreased nutrients carried to the coast (*41*); and choking of canals and waterways by water hyacinth (*Nymphaea*). This last effect increased water loss through evapotranspiration and fostered schistosomiasis (*5*).

Although the flow of the River Nile in Egypt is now controlled, explosive population growth is placing ever greater demands on the finite supply of water (*2*). Currently, water below Aswan is increasingly diverted (*42*) for agriculture along the Nile valley, for industrial and municipal purposes in the heavily populated Cairo area, and for a growing number of irrigation projects in the delta and along its margins (Fig. 6B). As a consequence, water supplied to the northern delta is curtailed and is polluted industrial-municipal wastewater and agricultural runoff (*43*). Most of this wastewater drains into and is trapped by coastal lagoons, damaging brackish water ecosystems and, thereby, threatening vital fisheries and natural habitats for birds migrating between Europe and Africa.

Predictions

Exponential population growth in Egypt [expected to exceed 100 million by 2025 A.D. (*44*)], coupled with degrading environmental changes, augurs poorly for the delta. Obvious threats to the well-being of the region call for methods to evaluate future delta evolution. Subsurface and geomorphic data provide a basis with which to measure natural and anthropogenic trends that will impact northern Egypt in the 21st century. Natural factors that must be considered are sea-level rise, land subsidence, climate change, and sedimentary processes. Anthropogenic factors include high population density, utilization of Nile water between the Aswan Dam and the coast, pollution, and wetland conversion for aquaculture and agriculture.

The geologic data suggest that trends and rates established for natural factors during the Holocene will continue until 2050: Sea level is likely to rise at least 1 mm per year [not taking into account projected accelerated rise due to global warming (*45*)]; subsidence rates along the coast will range from 1 to 5 mm per year; climate will not significantly alter sediment volume transported below the dam; and sedimentary processes, including erosion and accretion by winds and coastal currents, will continue along the shoreline. To avoid exaggerating anthropogenic effects, we modeled changes with population levels maintained at 58 million. We also assumed that human activity and behavioral patterns (pollution, land reclamation, and so forth) will continue at current rates.

By 2050, sea-level rise and concurrent land subsidence will induce a relative rise of sea level, ranging from 12.5 cm along the north-central coast to 30 cm in the northeastern delta. These values closely approximate ranges calculated independently from tide gauge data (*4*, *46*). We predict that this projected rise will induce a series of responses over large sectors of the vulnerable, low-lying (<1 m elevation) northern delta (Fig. 7).

Along the coast. Erosion will dominate along the coast as more sediment leaves the delta system than enters it. Input of carbonate-rich sediment from the Alexandria region by longshore currents will not equal output of relict delta sediments to Sinai, Gaza, and Levant (*29*). The shoreline will be cut back at promontories, and lagoons will be infilled on their seaward margin with storm washover sand. Although coastal erosion prevails, local accretion will occur (*4*); widening strandplains with increased development of coastal dunes are expected near Rosetta, east of Baltim, and east of Damietta (*3*). Accreting strandplains will act as natural barriers retarding marine incursion onto low-lying lagoon and delta plain margins. However, the shifting sand of these shoreline bodies will be difficult to stabilize by coastal protection measures. Alexandria will also experience sea-level rise (*47*) and modest erosion but will remain relatively unaffected, as it is located on a semiconsolidated carbonate ridge >5 m in elevation. Erosion and concomitant accretion will further straighten the completely wave-dominated coast and produce a smoother, more gentle arcuate shoreline (Fig. 7).

Lagoons. The area of the four remaining delta lagoons will be reduced, and pollution levels will substantially increase. As sea-level rise and land subsidence continue, coastal sand barriers will migrate landward, and northern parts of lagoons will be filled. Concomitant aquacultural and agricultural projects will drain and infill lagoons on their southern, eastern, and western margins. Construction of roads, canals, drains, impoundment structures, and dredge and fill activity will further subdivide existing lagoons, primarily in the Port Said, Damietta, and Alexandria regions. Fragmentation will accelerate conversion of natural wetlands to anthropogenic use, as is exemplified by Maryut and the now completely reclaimed Abu Qir lagoon (Fig. 6A). Nile waters will flow into ever smaller, fragmented lagoons

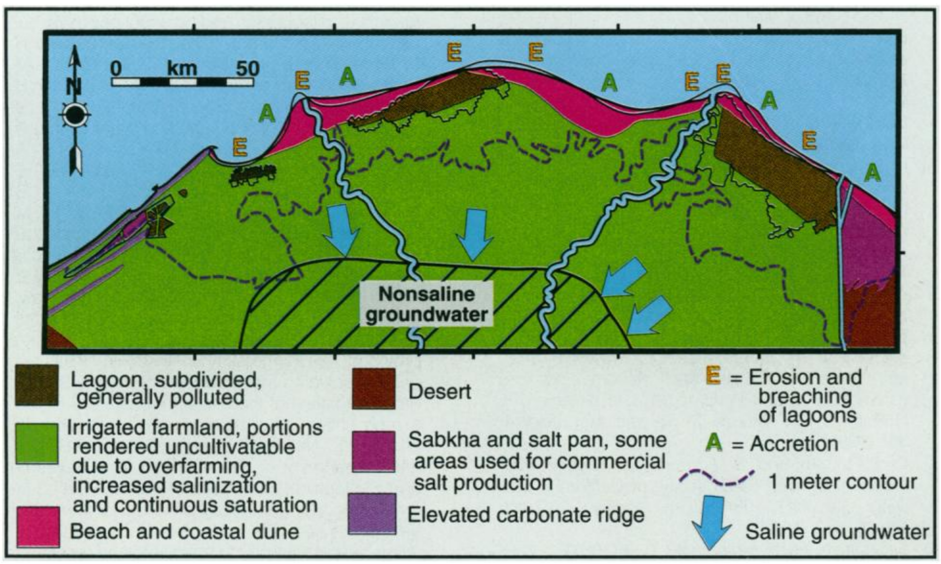


Fig. 7. Changes in the northern Nile delta, projected for ~2050 A.D. Explanation is given in text.

and deposit their sediment load of municipal, agricultural, and industrial wastes. Highly polluted sediments and toxic heavy metals (43) will be increasingly concentrated in the diminishing water bodies. In places, potentially toxic concentrations will be reached in fish, which will pose increasing public health risks. As marshes and lagoons disappear, the already decimated ecological reserves for waterfowl and migrating birds will be lost.

Lower delta plain. Land will be lost in the lower delta plain, and agricultural production will decline. Lack of nutrient-rich, Nile flood silt and year-round farming will accelerate exhaustion of soils. Productive land will be lost as evaporitic salts, which once were flushed by Nile floodwaters, will continue to concentrate in the delta plain. Concomitant subsidence and rising sea level, aggravated by lack of alluviation, will result in continuous saturation of soils, as the shallow saline ground-water table and sediment-starved delta surface become nearly coincident. Poor drainage will necessitate additional pumping of waters from drains and canals. Municipal-industrial waste and chemical fertilizers will increase pollution of ground water in the delta plain and lagoons. Pumping of ground water is likely to entrain the migration inland of marine-derived saline ground water along the northern delta. Moreover, the shrinking agrarian land area will be transformed to industrial and municipal use, and a larger proportion of freshwater will be used for non-agricultural purposes.

Ongoing natural factors have and will induce substantial changes in the Nile delta. Human intervention, however, has caused northern Egypt to cease as a balanced delta system. Further evaluation of long-term trends affecting the delta is necessary in order to devise measures to regain conditions of equilibrium. We can envision reversal of declining conditions by implementation of measures such as emplacement of coastal protection structures on the scale of Netherlands' Great Delta Works (48), strict regulation of the limited Nile water supply, increased ground-water exploitation along the delta margins, and construction of artificial wetlands and treatment facilities for recycling wastewater. At current levels of population growth, however, these measures will be inadequate.

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