sistent with the large paramagnetic signals observed in the diamagnetic regime in samples prepared at low pressure.

During our concurrent investigation of the Na-Cu-O system, we have discovered a phase that becomes ferromagnetic at ~10 K. Thus, we carefully considered the possibility that an impurity of this phase could cause the unusual magnetic behavior of $La_{2-x}Na_xCuO_4$ samples at ~10 K. However, the observed moments at low temperature for our samples prepared at low pressure are such that the amount of ferromagnetic impurity would have to exceed by several times the amount of the host material, and our x-ray diffraction patterns show essentially single-phase $La_{2-x}Na_xCuO_4$. Thus we have concluded that the unusual magnetic behavior observed in $La_{2-x}Na_xCuO_4$ is not due to a ferromagnetic impurity.

It is possible to produce superconductivity in the La-Cu-O system by purposely preparing a phase off the ideal $La_2CuO_4$ stoichiometry (*9*). However, under our conditions of synthesis, we observe no superconductivity above 4.2 K for $La_{2-x}A_x^{1+}CuO_4$ phases over the range of $x$ from 0.0 to 0.1. The substitution of the alkali cation sodium for lanthanum apparently must exceed 5% before metallic and superconducting properties occur. Assuming no oxygen deficiency or peroxide formation, we would express the oxidation states as $La^{III}_{2-x}Na^{I}_{x}Cu^{II}_{1-2x}$-$Cu^{III}_{2x}O_4$. The measured $Cu^{III}$ concentration (Table 1) is always less than this formula predicts thus indicating that there is always some oxygen deficiency. However, the amount of oxygen deficiency may be decreased by using high oxygen pressure. The present results indicate that oxygen deficiency is a key factor in determining the sign of the magnetic interaction and thus the nature of the magnetic ground state. Lower oxygen deficiency improves the superconducting properties and also accentuates the lower temperature magnetic behavior that may be indicative of the coexistence of spin glass and superconductivity in these novel materials.

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# Subsidence in the Northeastern Nile Delta: Rapid Rates, Possible Causes, and Consequences


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**Holocene fluvial and marine deposits have accumulated in a graben-like structure on the northeastern margin of the Nile delta. This part of the delta, which includes Lake Manzala, Port Said, and the northern Suez Canal, has subsided rapidly at rates of up to 0.5 centimeter per year since about 7500 years ago. This subsidence has diverted at least four major distributaries of the Nile River into this region. The combined effects of continued subsidence and sea level rise may flood a large part of the northern delta plain by as much as 1 meter by the year 2100. The impact of continued subsidence, now occurring when sediment input along the coast has been sharply reduced because of the Aswan High Dam, is likely to be substantial, particularly in the Port Said area and as far inland as south of Lake Manzala.**


The configuration of the Nile delta in Egypt, the major depocenter in the eastern Mediterranean, has changed markedly during the Holocene and continues to evolve rapidly (*1*). Geologic evolution of the northern delta plain margin has been controlled largely by interplay of eustatic sea level fluctuations (*2*), climatic variations (*3*), which affect Nile River flow and sediment discharge (*4*), the erosional effects of eastward-directed coastal and nearshore Mediterranean currents (*5*), man's activity since pre-Dynastic time (*6*), and neotectonics. The migration of the distributary channels of the Nile River through time (*7*) has affected the morphology of the delta and the general subsurface distribution of upper Quaternary sediment facies (*8*, *9*). Recent workers have investigated the stratigraphy, petrology, and radiocarbon age of numerous drill-core sections. Studies of these cores provide a chronostratigraphic base with which to interpret more precisely recent changes that have affected this delta. These cores have been used to determine the uppermost Pleistocene through Holocene shifts of coastlines and delta lobes on the northeastern delta margin (*2*) and to show that the shoreline in the northeastern delta prograded northward by as much as 50 km during the past 5000 years (an average rate of about 10 m/year).


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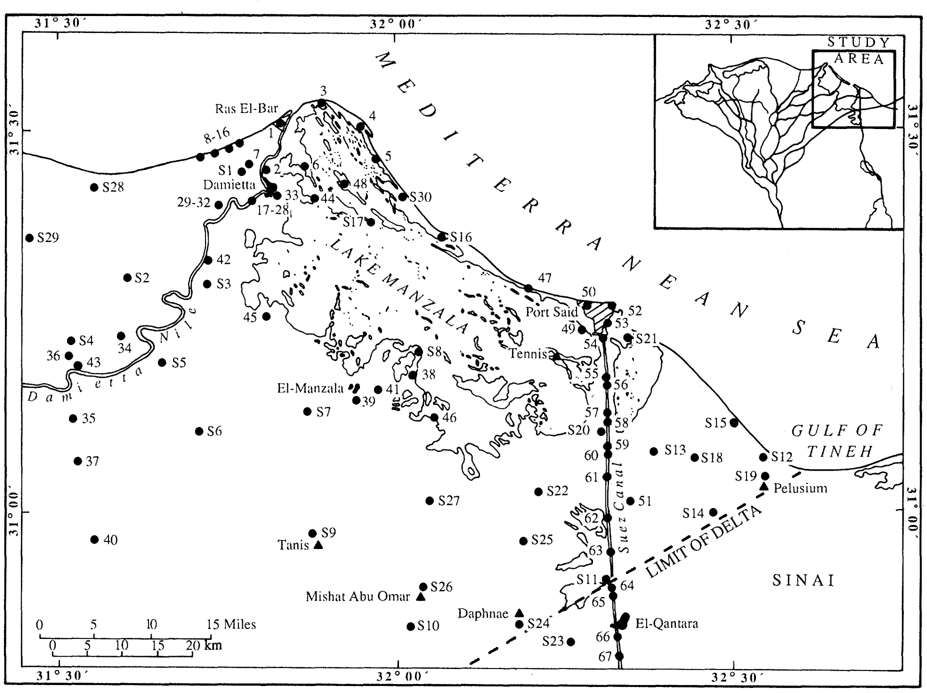


**Fig. 1.** Map of the northeastern Nile delta that shows the location of Smithsonian cores (S-1 to S-30, Table 1) and other borings (1 to 67, Table 2). Former major Nile River distributaries (4 in study area) are shown in inset.

In this report, I interpret the subsidence rates of the northeastern delta plain relative to sea level during the Holocene and assess the possible causes and consequences of such movement. Generally, deltas subside because of sediment loading and isostatic displacement, failure by faulting and flow of underconsolidated sediments, and compaction (*10*). Several investigators have alluded to subsidence in the Nile delta plain and specifically described the northward deepening of upper Quaternary facies near the coast (*11*). I focus on the possible role of neotectonics on subsidence of the delta margin.

The study area surrounds Lake Manzala and extends from west of the Damietta branch of the Nile eastward to the easternmost corner of the delta south of the Gulf of Tineh (Fig. 1). Lake Manzala is a shallow delta lagoon; much of it is only 1 to 2 m deep. Thirty continuous cores, which range in length from 10 to 60 m, were drilled in this region in two Smithsonian drilling expeditions (Fig. 1): September to October 1985 (S-1 to S-17) (*2, 12*) and April to May 1987 (S-18 to S-30; Table 1). In addition to these, a series of 67 core lithologic logs that were drilled by others (*13–16*) were consulted to enhance subsurface correlation in this region (Table 2); samples were examined from 23 of these cores. Approximately 170 radiocarbon dates plus textural and compositional data have been obtained for cores S-1 to S-26 (*12, 17*).

A generalized lithostratigraphic section (Fig. 2) shows that Holocene fluvial and marine sequences lie above a transgressive sand unit of latest Pleistocene (20,000 years ago) to earliest Holocene age (about 8,000 years ago). This unit was deposited when the sea advanced across the formerly subaerially exposed continental shelf and outer delta margin (*2, 13*). During this southward migration of the sea, coastal currents and wave erosion reworked older deposits (upper Pleistocene) that originally were emplaced as poorly sorted alluvial sediments of Nile River origin, thus forming the transgressive sand. In the cores, the sand is olive-gray, ranges in thickness from 2 to 25 m, is a medium to coarse sand, and typically contains littoral shell (predominantly molluscan) fossils.

In the cores, the deposits above the transgressive sand range in thickness from less than 5 to about 50 m (Fig. 2). These deposits are of early Holocene to modern age and are largely dark olive muds of prodelta, delta-front, and organic-rich marsh and lagoonal facies. Sands of coastal origin (upper Holocene) also are in the upper parts of many of the cores (*2, 12*). In borings that contain the most complete sequence of sediment facies, more than 60% of the Holocene sequence is prodelta and delta-front muds. The base of the Holocene mud section is time-transgressive and typically ranges from about 7800 to 6500 years ago [Table 1; (*2, 17*)]; in the Holocene, sediment accumulated at rates locally as high as 0.6 cm/year.

An isopach map and cross sections of the thickness to the top of the transgressive sand unit reveal that the thickest Holocene mud sections are almost coincident geographically with the position of Lake Manzala and the smaller lake and low-lying sebkha terrain

**Table 1.** Depth (in meters) to the top of the uppermost Pleistocene to lowermost Holocene transgressive sands in 30 Smithsonian cores in the northeastern Nile delta (Fig. 1) (*17*). Radiocarbon dates are of the basal Holocene muds above the transgressive sands. B.P., before present.

| Core | Depth (m) | Radiocarbon date (years B.P.) |
|---|---|---|
| S-1 | 24 | 7590 ± 130 |
| S-2 | 14.5 | 7110 ± 70 |
| S-3 | 26 | 7180 ± 110 |
| S-4 | 14.5 | 7020 ± 120 |
| S-5 | 29 | 7500 ± 110 |
| S-6 | 18 | 7790 ± 110 |
| S-7 | 10 | 7610 ± 90 |
| S-8 | 40 | 7300 ± 110 |
| S-9 | 4.5 | >5140 ± 80 |
| S-10 | 0 | |
| S-11 | 14 | 6475 ± 90 |
| S-12 | 13.5 | 7280 ± 490 |
| S-13 | >30 | >7150 ± 110 |
| S-14 | ~5 (?) | |
| S-15 | 31 | 7430 ± 100 |
| S-16 | 23.5 | 7700 ± 110 |
| S-17 | >43 | 7850 ± 100 |
| S-18 | 27 | 7400 ± 80 |
| S-19 | 9.8 | |
| S-20 | 43 | |
| S-21 | 47 | |
| S-22 | 22 | 7540 ± 70 |
| S-23 | 1.5 | |
| S-24 | 1.0 | |
| S-25 | >14 | |
| S-26 | 2.5 | |
| S-27 | 10 | |
| S-28 | 23.5 | |
| S-29 | 9 | |
| S-30 | 27.5 | |

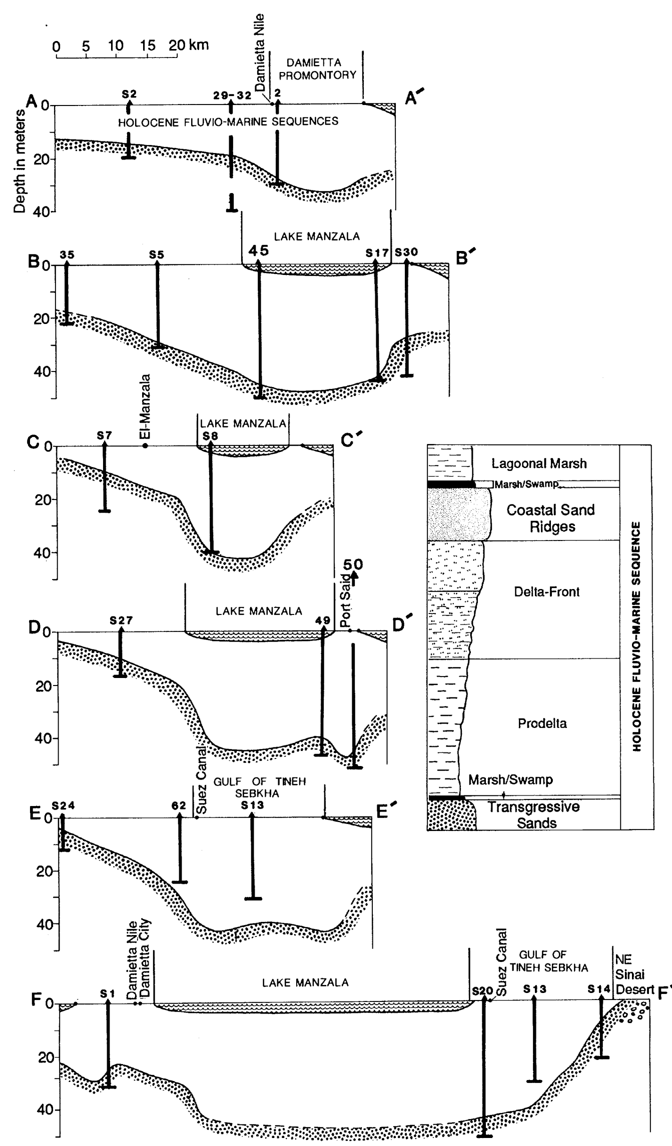


**Fig. 2.** Cross sections in the Lake Manzala region of the Nile delta that show the subsurface configuration of the uppermost Pleistocene to lowermost Holocene transgressive sand (stippled). The positions of these sections are shown in Fig. 3. A generalized lithostratigraphic log to the right indicates some of the major sediment facies that are in the study area. The base of the fluvial and marine mud section, dated at about 7500 years ago (Table 1) (*2, 17*), serves as the chronostratigraphic level used for subsidence calculations in this study.

(less than 1 m above mean sea level) east of the Suez Canal (Figs. 2 and 3). Port Said and the northern part of the Suez Canal are located above one of the thickest Holocene sequences (D–D′ in Fig. 2). The isopachs define a rhomboidal, graben-like structure with northeast and northwest trending margins that has an anomously thick Holocene section. Isopachs also reveal a separate small oval depression in the Damietta Promontory (A–A′) that has more than 30 m of Holocene sediment. A subsurface arch with a thin Holocene section trends southwest from the promontory and city of Damietta.

Rates of lowering of the land relative to the sea can be calculated on the basis of radiocarbon-dated core sections. The highest rates are for the thickest Holocene sequences (Fig. 3). In these calculations it is difficult to distinguish subsidence due to compaction (compression/dewatering) of rapidly deposited sediments from subsidence due to isostatic displacement. Compaction has clearly occurred in the sub-Holocene sediments as evidenced by stiff, brown, alluvial mud layers of late Pleistocene age (*2*). Measurements of physical properties of the fine-grained (prodelta, lagoonal marsh) Holocene muds show that they are underconsolidated and of low strength. The consistency of muds in cores from the thick Holocene section beneath Lake Manzala, however, is comparable to that in muds south and north of the lake. Furthermore, peat layers, which are particularly prone to compaction in deltaic settings (*10, 18, 19*), account for less than 2% of the total thickness of any Holocene section that was recovered in the northeastern Nile delta. From the available data it does not appear that different degrees of compaction of Holocene units in different areas can explain the marked regional variations in Holocene mud thickness that were mapped in this region.

Sea level change is an important factor to consider in subsidence calculations. The radiocarbon-dated base of the Holocene mud section (7800 to 6500 years ago, Table 1) can be used as an approximate time-stratigraphic horizon. This horizon, which is assigned an average age of 7500 years before present, can be compared with depth below mean sea level data for this time as determined by generalized eustatic sea level curves. For one such curve (*20*), this basal mud horizon would lay as much as 24 m below present sea level, which indicates an average subsidence rate of about 0.35 cm/year (50-m thickness minus 24-m lower eustatic stand equals 26 m of measurable vertical land motion in 7500 years). This is a conservatively low rate because most other curves indicate that 7500 years ago sea level was only about 15 (*21*) to 12 m (*22*) below its present stand. If these values are used, higher subsidence rates, ranging from about 0.45 to 0.50 cm/year, are calculated. An independent record of neotectonic motion (tide-gauge data at Port Said) indicates a closely comparable subsidence rate of 0.48 cm/year for a recent two-decade period (*23*).

Long-term subsidence rates of 0.4 cm/year or more are high compared to rates at other much larger, thicker delta depocenters. Radiometric dating indicates that large parts of the lower plain of the Mississippi River delta have subsided at less than 0.2 cm/year (*24*). Where thick peat sections occur, the average rate is slightly higher, about 0.3 cm/year (*18*); the subsidence rate is as high as 0.45 cm/year in a few locations (*21*).

Several stratigraphic and tectonic factors may be causing rapid subsidence in the Lake Manzala region. This part of the delta contains one of the thickest (~3000 m) lower Pliocene or Quaternary sections in the delta (*4*), which may account for differential loading and weighting. Geologic mapping of the delta has not identified any important faults at the surface in this region; however, seaward of the Lake Manzala region, geophysical surveys (*25*) indicate that the northeastern African margin has been affected by listric faults and also a dominant northeast trending fault system that extends from the Levant directly to the Nile delta study area.

One of the major offshore faults, called the Pelusium Line (Fig. 3), has been interpreted as an ancient, left-lateral strike-slip fault that appears to extend to the Gulf of Tineh and into the Nile delta east of Lake Manzala (*25*). Another fault, the Damietta-Latakia fault (Fig. 3), extends toward the Damietta Promontory and may continue inland farther to the southwest. These two, part of the Pelusium fault system, have been interpreted as large Mesozoic faults that have played a major role in formation of the southeastern Mediterranean basin (*26*). A northwest trending normal fault that is apparently related to reactivation of the above structures has been mapped along the outer shelf–upper slope boundary parallel to but northeast of the main axis of Lake Manzala (*25*).

I propose that the rhomb-shaped basin mapped in this study (inset map in Fig. 3) may have formed during the Quaternary in association with reactivation of the northeast trending faults that border the Lake Manzala area. Continued development of this graben [probably a pull-apart basin (*27*)] during the late Pleistocene and Holocene would have caused the high subsidence rates that are described in this study.

Rapid lowering of the northeastern part of the delta was likely responsible for the diversion and concentration of former dis-

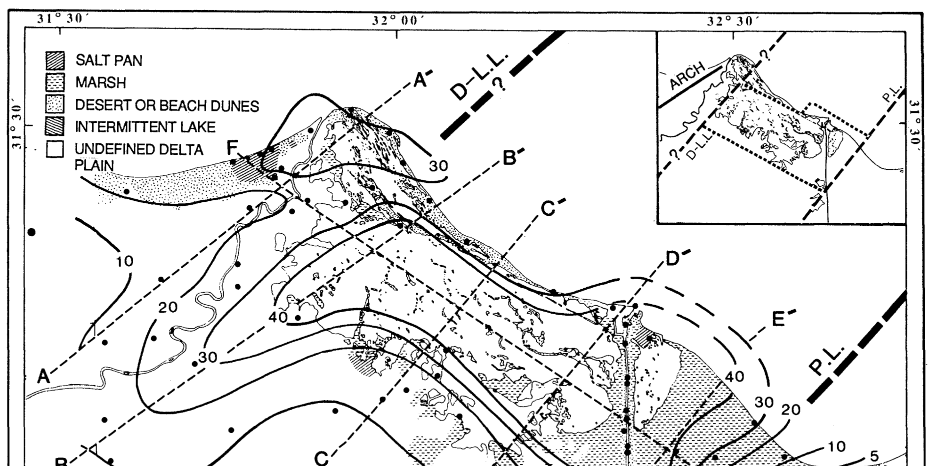


**Fig. 3.** Isopach map of the Holocene fluvial and marine sequences in the northeastern Nile delta. Note that a thick section underlies the Lake Manzala–northern Suez Canal–Port Said plain south of the Gulf of Tineh. Contoured thicknesses are in meters. Two major strike-slip faults that extend to the delta, the Pelusium line (P.L.) and Damietta-Latakia line (D.–L.L.) are shown. These features were mapped in earlier offshore geophysical surveys (*25, 26*). The rhomboidal configuration of the subsiding area in the delta (interpreted structure in inset) and its possible association with reactivation of shears offshore suggest a pull-apart basin origin.

tributary channels of the Nile (at least four major ones) in this region (inset in Fig. 1) and coalescence of their delta lobes between the Damietta Promontory and the Gulf of Tineh (*2*). The Nile delta may also have been tilted toward the northeast. Facies distribution patterns and the shallow depth of Lake Manzala indicate that deposition kept up with subsidence so that fluvial and marine deposits continued to accumulate on the delta margin during the Holocene.

The Damietta bird-foot promontory (*13*), Port Said headland (*2*), and coastal ridges, which separate Lake Manzala from the sea, were formed recently by sediments that were supplied by the Nile. Emplacement of the Aswan High Dam in 1964 has cut off a major part of the fluvial sediment supply; as a result, strong, predominantly eastward-directed coastal currents have accelerated erosion along extensive sections of the Nile delta and Sinai coasts (*1*). Now, of added consideration is continued land surface subsidence at up to 40 to 50 cm per century, as indicated in this study, and a projected eustatic rise in sea level, which is conservatively estimated at from 4 to 8 cm during the next 40 years (*28*) and at least 50 cm by the year 2100 (*19, 29*). Acting together, subsidence, eustatic sea level rise, and the reduced sediment supply could cause a relative rise in sea level of 1 m or more by the end of the next century, a level that would submerge much of the delta region within 30 km of the coast.

The Port Said–northern Suez Canal–Lake Manzala region, with a population estimated at over 1 million, may be particularly susceptible to flooding because, on the basis of this study, it lies over one of the more rapidly subsiding parts of the delta. Coupled land subsidence and sea level rise will almost certainly affect some present and planned agricultural, irrigation, channelization, and land-reclamation projects. It could also affect northern Suez Canal maintenance (*30*) and the intensified urban development along the coast and margin of Lake Manzala. A rise in sea level will affect both the course and flow patterns of the Damietta branch of the Nile and the depth and salinity of the water table. Additional study is needed to precisely measure present subsidence and better determine its possible effects.

**Table 2.** Depth (in meters) to the top of the uppermost Pleistocene to lowermost Holocene transgressive sand in 67 core logs from the northeastern Nile delta that were consulted for this study. Listings that are followed by dates are internal Egyptian engineering reports for the specific site.

| Core | Core site location | Depth (m) | Core | Core site location | Depth (m) |
|---|---|---|---|---|---|
| 1 | D-1, Damietta Promontory (*13*) | >30 | 34 | A-3, Zervudaki Estate, el Quadi | 25 |
| 2 | D-2, Damietta Promontory (*13*) | >30 | 35 | A-5, Kafr el-A'gar | ~18 |
| 3 | D-3, Damietta Promontory (*13*) | 28 | 36 | A-6, Basandilla | >25.8 |
| 4 | D-4, Damietta Promontory (*13*) | >30 | 37 | A-7, Mahallet Damana | 19 |
| 5 | D-5, Damietta Promontory (*13*) | >30 | 38 | A-8, El-Matariya (1899) | 21 |
| 6 | D-6, Damietta Promontory (*13*) | 27 | 39 | A-9, Gedidet el-Manzala | ~20 |
| 7 | Site 5, Ras-el-Barr Bridge (1983) | 33 | 40 | A-10, Timal el-Amdid | ~2–12m |
| 8 | D-6, Port of Damietta (1979) | 27 | 41 | 123, El Amra/el-Manzala | 22 |
| 9 | E-5, Port of Damietta (1979) | ~24 | 42 | 129, Farescour | 29 |
| 10 | G-7, Port of Damietta (1979) | 27 | 43 | 252, Shirbin | 12 |
| 11 | C-5, Port of Damietta (1979) | 21 | 44 | I, Manzala Lake Sites (*14*) | 25 |
| 12 | 101, Port of Damietta (1981) | 27 | 45 | II, Manzala Lake Sites (*14*) | 44.5 |
| 13 | 102, Port of Damietta (1981) | 34 | 46 | III, Manzala Lake Sites (*14*) | 16 |
| 14 | 103, Port of Damietta (1981) | 25 | 47 | IV, Manzala Lake Sites (*14*) | 27 (?) |
| 15 | 104, Port of Damietta (1981) | 27 | 48 | V, Manzala Lake Sites (*14*) | 26 |
| 16 | 119, Port of Damietta (1981) | 27 | 49 | P.S. 7, Port Said (1979) | 39.5 |
| 17 | 101, Damietta Dam (1982) | 21 | 50 | P.S. 16, Port Said (1979) | 46.5 |
| 18 | 102, Damietta Dam (1982) | 22 | 51 | F-1, Fadda Well (*15*) | 42 |
| 19 | 103, Damietta Dam (1982) | 21 | 52 | Km0*, Suez Canal (*16*) | >25 |
| 20 | 104, Damietta Dam (1982) | 23 | 53 | Km2 | >25 |
| 21 | 105, Damietta Dam (1982) | 20 | 54 | Km5.4 | >25 |
| 22 | 106, Damietta Dam (1982) | 17 | 55 | Km10.0 | >25 |
| 23 | 107, Damietta Dam (1982) | 21 | 56 | Km10.3 | >25 |
| 24 | 108, Damietta Dam (1982) | 21 | 57 | Km15.3 | >25 |
| 25 | 109, Damietta Dam (1982) | 21 | 58 | Km15.6 | >25 |
| 26 | 107B, Damietta Dam (1982) | 15 | 59 | Km19.5 | >25 |
| 27 | 110, Damietta Dam (1982) | 16 | 60 | Km20.6 | >25 |
| 28 | 114, Damietta Dam (1982) | 19 | 61 | Km25.2 | >25 |
| 29 | 1, Kafr El Batick (1986) | 18 | 62 | Km30.6 | >25 |
| 30 | 2, Kafr El Batick (1986) | 19 | 63 | Km35.4 | 19 |
| 31 | 3, Kafr El Batick (1986) | 19 | 64 | Km40.8 | 9.5 |
| 32 | 4, Kafr El Batick (1986) | 19 | 65 | Km45.4 | 0 |
| 33 | A-1, Damietta (1886) (*9*) | 24.8 | 66 | Km49.8 | 0 |
| | | | 67 | Km50.7 | 0 |

*In kilometers south of Port Said.

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