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Long-term shoreline changes and the concentration of heavy minerals in beach sands of the Nile Delta, Egypt

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ABSTRACT

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Analyses have been undertaken of shoreline positions established from beach profile surveys at 65 positions along the coastline of the Nile Delta spanning the years 1971 to 1990. The analyses identify long-term linear trends as well as any cycles in the horizontal movement of shoreline positions. The results reveal longshore patterns wherein erosion along a stretch of coast gives way to accretion in an adjacent stretch, defining a subcell within the overall littoral system of the delta. The rate of shoreline retreat has been greatest along the Rosetta promontory (− 106 m/yr) and Damietta promontory (− 10.4 m/yr). Significant erosion has also occurred along the central bulge of the delta coast, but at a lesser rate (−6.5 m/yr). Areas of accretion exist within the saddles or embayments between the promontories, with the maximum shoreline advance averaging about 13 m/yr. The identified patterns of erosion versus accretion along the delta reflect the natural processes of wave-induced longshore currents and sediment transport. Associated with this longshore sediment movement is a selective transport of different minerals according to their densities and grain sizes, with the light minerals (quartz and feldspar) having the highest advection rates and the dense opaque minerals the lowest rates, tending to remain behind as a lag within the erosion areas. As a result of this longshore grain sorting paralleling the patterns of shoreline erosion versus accretion, there are correlations between the rates of shoreline change and the heavy-mineral contents and mean grain sizes of the beach sediments. These large scale delta-wide patterns are affected somewhat by local shoreline changes and mineral variations induced by the construction of jetties or shoreline protection structures.

Introduction

The 240-km coastline of the Nile Delta (Fig. 1) consists of two pronounced promontories (Rosetta and Damietta) formed by sediments transported to the coast through the modern distributaries of the river, and a central bulge (Burullus) that is interpreted to be the erosional remnant of a former promontory associated with the now extinct Sebennitic branch that existed until about 900 years ago (Orlova and Zenkovitch, 1974). These promontories are separated by embayments in the coastal configuration, backed by large lakes and fields of sand dunes.

There have been dramatic changes in the delta shorelines during the 20th century, changes that are generally attributed to the construction of dams on the upper Nile at Aswan, but may also have been caused in part by climatic factors (Frihy and Khafagy, 1991). The massive erosion has generated considerable interest and research that has resulted in a number of reports and publications. Several of these studies have investigated volumetric changes of beach profiles (Manohar, 1976; El Fishawi and Badr, 1989; Lotfy and Frihy, 1993), shoreline changes as recorded in historic maps (Sestini, 1976; Misdorp, 1977; Frihy and Khafagy, 1991), and analyses of satellite images (Smith and Abdel Kadar, 1988; Blodget et al., 1991). However, to date no information has been published regarding delta-wide shoreline changes derived from beach profiles, including areas of accretion as well as erosion.

One objective of this paper is to present the

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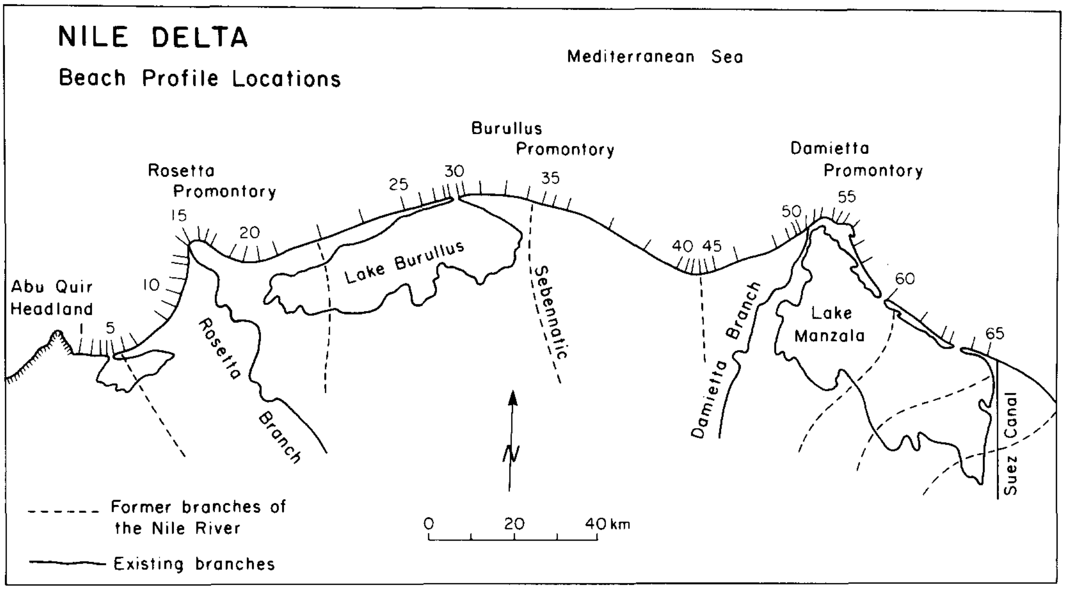

Fig. 1. The Nile Delta coast, showing the positions of the 65 beach-profile lines analyzed in this study. The dashed lines show the former positions of now-extinct branches of the Nile River; only the Rosetta and Damietta branches were active during this century.

results of the first systematic examination of long-term shoreline changes along the entire length of the Nile Delta coastline, based on direct beach profile surveys that span 20 years (1971–1990). Attention is paid to locate nodal points between zones of shoreline erosion and accretion, and thereby to determine areas of divergence and convergence in the patterns of the longshore sediment transport. A second objective of this paper is to explore the relationship between those longshore sediment transport patterns and the resulting compositions of the beach sands as reflected in their heavy-mineral contents and median grain sizes. Such a correspondence should be expected in view of our previous analyses that have revealed marked selective transport rates of the different minerals within the beach sands (Frihy and Komar, 1991).

Beach profiles and sand samples

In 1971 the Coastal Research Institute in Alexandria initiated a program to monitor changes in the nearshore zone of the Nile Delta. A series of beach profiles has been obtained annually or semi-annually, extending from the Abu Quir headland at Alexandria in the west to the jetties on the Suez Canal at Port Said (Fig. 1). The profile lines are perpendicular to the local coastline, and extend to a water depth of 6 m or to a distance of 1000 m from the baseline. The main series are spaced 0.5 to 10 km along the coast, but are more concentrated around areas experiencing frequent and rapid changes. The leveling and sounding data are adjusted to the mean sea level (MSL) datum using fixed bench marks of known elevation, located behind the beach area. In some profiles the positions of bench marks have had to be shifted landward due to the extensive erosion and shoreline migration. Profiles with such shifts in bench marks have been corrected to the new positions so as to avoid negative values in the surveyed profiles.

A total of 65 beach profile lines have been selected for analysis in this paper (Fig. 1), spanning the entire delta coast from 10.1 km east of the Abu Quir headland to about 240 km longshore distance at Port Said. The time periods covered by the various profiles differ somewhat as some sites have had to be abandoned due to bench mark losses, while additional sites were added; the time spans for various profile series range from a minimum of 10 years to a maximum of 20 years. The measured distance between the fixed baseline point and the shoreline provides a reliable record monitoring the changes of shoreline positions over the time frame of profile collection. The data from each profile are arranged in a 2-D graph, where Y is the shoreline position relative to the bench mark and X is the date of the survey. This permits the determination of the mean annual rate of shoreline change (meters per year) employing least squares techniques, the slope of the Y versus X plot. Cycles of shoreline changes within the otherwise mean change, or any overall accelerations or decelerations in the rate of erosion or accretion, are also readily apparent in such analyses.

A total of 65 beach-sand samples were collected during the summer of 1991 from the beach face of each profile location included in the analyses. The samples were obtained by pressing a plastic sample jar into the surface of the sand, a method that gave a uniform sample with a diameter of ~ 5 cm and 4 cm deep. These large samples were split in the laboratory to obtain smaller subsamples for grain-size analyses and heavy mineral separation. The grain size analyses were made by standard rho-tap sieving using 0.5ϕ sieve intervals. The mean grain sizes and other size statistics were calculated from the sieving distributions using the formulae of Folk and Ward (1957). The grain size fractions richest in heavy minerals (the $3.0–4.0\phi$ fractions) were subjected to heavy mineral separation using sodium polytungstate having a density of 2.9 g/cm^3 (Callahan, 1987). The heavy mineral concentrations, expressed as grams of heavy minerals per kilogram of total sample, were calculated for each site for comparisons with the local shoreline changes.

Results and discussion

Measurements of annual profile surveys taken at the 65 stations over the period 1971–1990 yield an extensive data set that can be used to quantify shoreline migration trends along the full 240-km length of the delta coastline. Time series of shoreline positions for twelve representative sites are graphically presented in Fig. 2. The curves show substantial variations from site to site, with downward trends representing long-term erosion while upward sloping lines indicate shoreline accretion. It is seen that in all cases lines obtained by linear regressions can represent a long-term mean rate of erosion or accretion, although in many examples there are marked fluctuations and in some instances apparent cycles superimposed on the long-term average trends. The cycles typically represent periods of about 5 years of alternating rates of erosion or accretion. Their cause is unknown. They could reflect variations in local climatic conditions, particularly the intensity of waves and coastal currents, but the cycles would then be expected to be in phase at many sites along the length of the delta, which is not the case. The rates of mean erosion versus accretion vary greatly from site to site, with a maximum rate of erosion of -106.3 m/yr for profile no. 16 near the mouth of the Rosetta branch (Fig. 1), while accretion at a rate of 13.4 m/yr exists at profile no. 20 to the immediate east on the flank of the Rosetta promontory. Erosion returns further to the east at sites along the central Burullus bulge (a maximum erosion of -6.5 m/yr for profile no. 36), with accretion at profile no. 41 in the embayment to the east of the bulge, and again a reversion to erosion along the Damietta promontory with a maximum rate of recession of -10.4 m/yr at profile no. 53 (Fig. 2).

The delta-wide patterns of shoreline change revealed in the analyses of erosion versus accretion as depicted for individual sites in Fig. 2 are better seen in Fig. 3B which graphs the results for all 65 profile series. It is apparent here that there are many reversals between erosion and accretion along the length of the delta shoreline. The most massive erosion is centered on the Rosetta promontory, but with accretion to either side along the flanks of the promontory. This represents a simple pattern of erosion from the tip of the promontory near the mouth of the river, with the eroded sand moving alongshore as it is transport by waves and longshore currents, to the west along the shoreline of Abu Quir Bay and to the east along the eastern flank of the promontory. This movement of the sand to the east of Rosetta and the accompanying shoreline changes have been analyzed in detail by Frihy et al. (1991), demonstrating that there is a conservation of the total volume of sand involved in the longshore displacement and determining the actual longshore sediment transport rates responsible for the changes. Two massive sea walls have

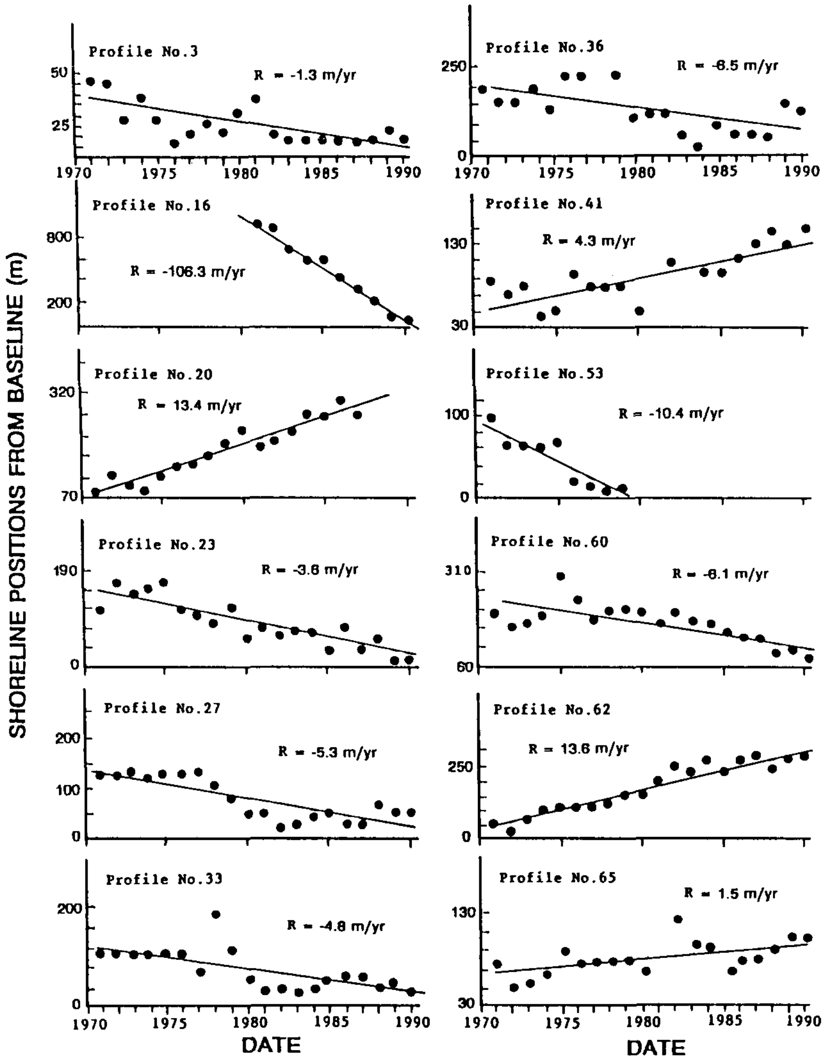

Fig. 2. Time series of changing positions of shorelines for 12 representative profile lines along the Nile Delta coast, of which the locations are given in Fig. 1. The annual rate of shoreline change, R, indicated in each graph, is derived from the least-squares regression lines shown fitted to the measurements.

been constructed during 1989–1991 to the west and east of the Rosetta mouth to reduce the erosion impacts. However, these structures were built at inland positions, and the shoreline retreat has only recently (1992) reached the end of the eastern sea wall; therefore, their presence has not affected our measurements of shoreline erosion determined from beach profiles.

The graphical presentation in Fig. 3B shows that low rates of erosion prevail along most of the western side of the Burullus bulge of the central delta, but with several local reversals at the center of this promontory. The local accretion at profile no. 29 is produced by the blockage of the eastward longshore sediment transport by the jetties that have been constructed at the inlet to Lake Burullus, with higher rates of erosion induced to the east of the jetties. Low rates of accretion are revealed by the shoreline time series at profile sites along the eastern side of the Burullus bulge, all the way to the mouth of the Damietta branch of the Nile. The maximum extent of the Damietta promontory is to the immediate east of the river mouth, and this stretch of promontory shoreline is dominated

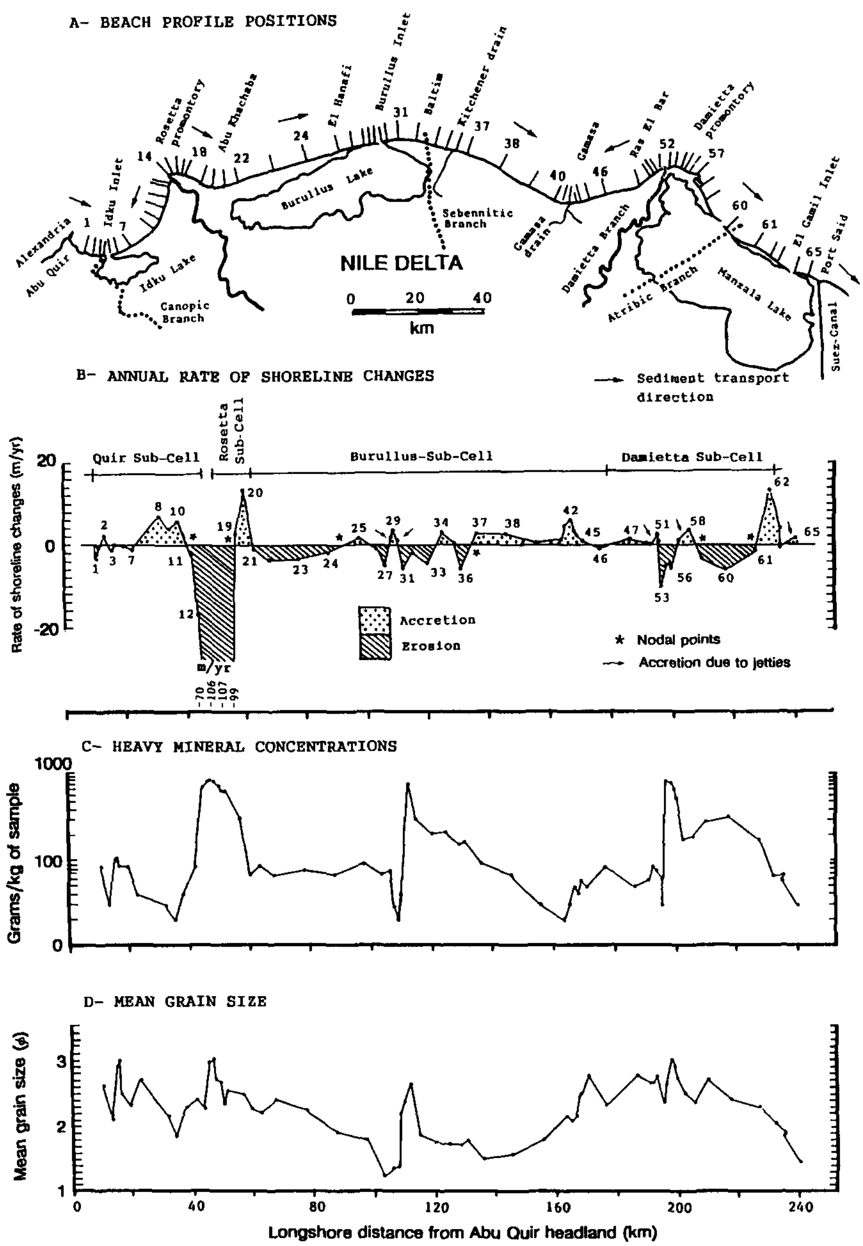

Fig. 3. (A) The locations of the beach profiles included in the analyses. (B) Alongshore variations in the rates of shoreline change, alternating between erosion and accretion. (C) Alongshore variations in heavy mineral concentrations of the beach samples collected at the profile locations. (D) Alongshore variations in mean grain sizes of beach samples.

by erosion, although at significantly lower rates than being experienced on the Rosetta promontory. These lower rates result from the smaller obliquity of the wave approach compared with that experienced along the Rosetta promontory shoreline, and in part to the sea walls and other structures that have been installed beginning in 1941 on the Damietta promontory to protect the developments found there. The erosion of the promontory again reverts to accretion to the east (Fig. 3B), which is followed by another stretch of shoreline experiencing erosion, and finally significant accretion results from blockage of the longshore sediment transport by the large jetties constructed at the entrance to the Suez Canal at Port Said.

The patterns of erosion versus accretion revealed by analyses of profile time series and shown graphically in Fig. 3B, correspond for the most part to the series of subcells defined by Frihy et al. (1991) based on considerations of several lines of evidence including directions of sand movements inferred by its interruption at jetties and groins, the deflection of inlets and drain mouths, by patterns of mineral changes along the length of the shoreline, and as inferred by changes in mapped shorelines. Beginning at the west, the Abu Quir subcell includes the westward transport of sand along the flank of the Rosetta promontory and deposition along the shoreline within Abu Quir Bay. The Rosetta subcell is the corresponding erosion and movement of sand to the east along the eastern flank of the promontory. The Burullus subcell represents the general erosion along the western side of the central bulge and the longshore transport of sand to the east where it is deposited to produce shoreline accretion along the eastern flank of the central bulge. Although this is the general pattern, we have seen in Fig. 3B that there are local interruptions to this pattern due to jetty construction and shoreline structures. The final subcell exists along the eastern flank of the Damietta promontory, and again consists of a pattern of shoreline erosion, transport of the sand toward the east, and the deposition of that sand to produce shoreline accretion.

The results of the analyses of heavy mineral concentrations and mean grain sizes within the beach sands along the length of the delta are graphed in Fig. 3C and D. The variations in heavy-mineral concentrations (Fig. 3C) form a series of saw-tooth peaks, with the highest concentrations corresponding to the areas of shoreline erosion and decreasing alongshore toward areas where there has been shoreline accretion. There is a broad pattern of variations in mean grain sizes (Fig. 3D), with the finest sizes (higher ϕ values) centered on the Rosetta and Damietta promontories, with generally coarser sizes (lower ϕ values) along the central delta region of the Burullus bulge. There also are local peaks of finer grain sizes that tend to correspond to profile locations that have experienced greater erosion.

There is a rough parallelism between the variations in heavy-mineral concentrations and mean grain sizes (Fig. 3C versus Fig. 3D), and this is further established by the graph in Fig. 4 of the concentration of heavy minerals versus the mean grain sizes for all beach-sand samples analyzed as part of this study. Although there is considerable scatter, a definite trend exists of increasing heavy-mineral concentration with decreasing grain size (increasing ϕ). Such a relationship is expected from the patterns of selective grain entrainment and transport, a sorting of grains by their contrasting densities and sizes. This has been established by the detailed analyses of Komar and Wang (1984) and Li and Komar (1992) for beach sands on the Oregon and Washington coasts, demonstrating that the wave swash on the beach preferentially entrains and transports away the coarser grains of light minerals (quartz and feldspars), tending to leave as a lag the dense, finer-grained heavy minerals. This was also shown in part by the study of Frihy and Komar (1991) on the Nile Delta, wherein the entrainment and longshore transport of different minerals depends on their densities. Similar to the results on the Oregon beaches, it was established that quartz and feldspar, and lower-density heavy minerals such as hornblende, tend to be selectively entrained and transported from areas of beach erosion to areas of accretion. More important, the bulk of the heavy minerals, and in particular the dense, opaques that form black sands, tend to remain in areas experiencing erosion. It follows that the greater the cumulative erosion, the more concentrated these dense heavy minerals become. Although we did not measure the grain sizes of the different minerals involved in our analysis (Frihy and Komar, 1991), the study by Anwar et al. (1979) had earlier demonstrated that erosion along the delta tends to yield beach sands that are finer in their mean grain sizes. These established trends of selective sorting by mineral densities and grain sizes would explain the delta-wide patterns seen in Figs. 2 and 3, with the greatest heavy-mineral concentrations and finest grain sizes found in the areas of shoreline erosion.

These results and interpretations further suggest

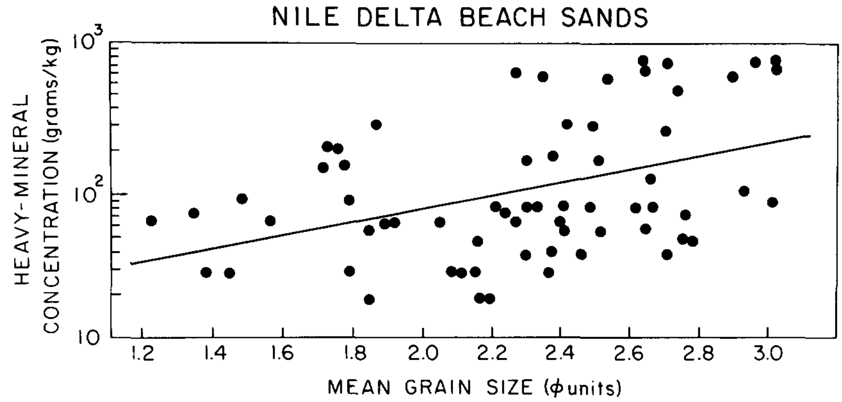

Fig. 4. The concentration of heavy minerals in the beach sands versus the mean grain sizes of the total samples.

that there might be correlations between the long-term rates of erosion or accretion established by our analyses of beach-profile time series, and the concentrations of heavy minerals and mean grain sizes of the beach sands. This can be seen in Fig. 5 for the series of samples from the Damietta subcell; similar correlations are found for the other subcells. As expected, the greater the rate of erosion, the higher the concentration of heavy minerals and the finer the mean grain size of the sand. The data for the shoreline change versus the mean grain size are seen to be highly scattered, and this is true also for the other subcells, and in two cases statistically significant trends could not be established. In all subcells there are statistically significant trends establishing increasing concentrations of heavy minerals with increasing rates of erosion. However, the empirical correlations are different for the respective subcells. This results from the fact that the overall concentrations of heavy minerals not only reflect the rates of shoreline change during the past 20 years as measured by our profile time series, but are also the product of the long-term history of erosion experienced within the subcell, one century for the Rosetta and Damietta subcells but nearly ten centuries for the Burullus

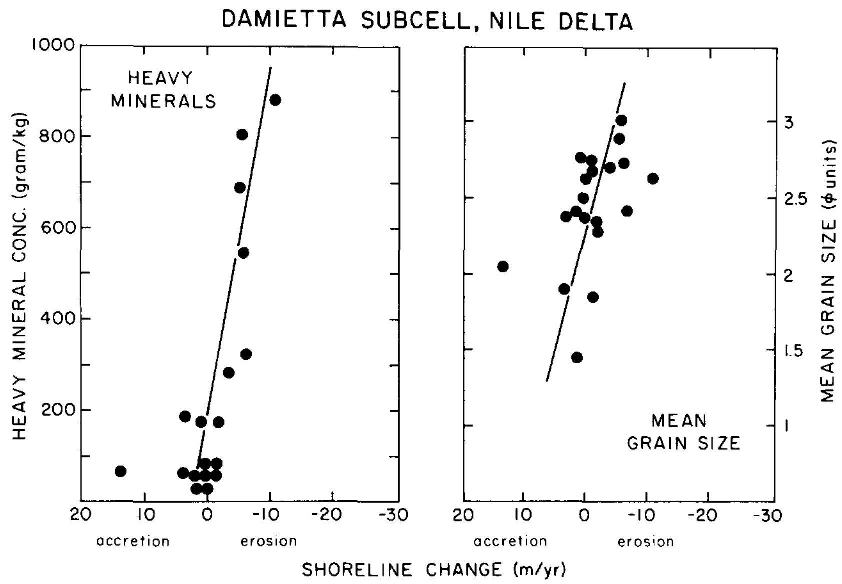

Fig. 5. Correlations for the Damietta subcell of the concentrations of heavy minerals and mean grain sizes of the beach sands with the rates of shoreline change at the corresponding profile lines.

bulge. Furthermore, the correlation for each subcell reflects the patterns of longshore grain sorting, which may differ from subcell to subcell, and can be expected to evolve with time.

Summary and conclusions

Measured distances of shoreline positions have been obtained from successive beach surveys spanning 10 to 20 years at 65 locations along the 240 km length of the Nile Delta. These measurements provide an accurate means for establishing long-term shoreline changes. Linear statistical estimates have been applied to the data on shoreline change with time to determine average rates of erosion or accretion. The results indicate that of the 240 km length of coastline, approximately 54% is experiencing erosion, while 46% is undergoing some accretion. The highest rate of erosion is occurring on the Rosetta Promontory (−106 m/yr) as waves and longshore currents transport sand away from the Rosetta branch of the Nile which is no longer supplying new sand to the adjacent beaches. Similar erosional processes are occurring on the Damietta Promontory and on the central Burullus region of the delta, but at substantially lower rates (−10.4 and −6.5 m/yr, respectively). Areas of accretion exist mainly within the saddles or embayments between the promontories, with rates of shoreline advance ranging up to 13 m/yr. These general coast-wide patterns reflect the existence of subcells along the delta coastline as identified by Orlova and Zenkovitch (1974) and Frihy et al. (1991), wherein sand eroded from a promontory is transported to the east and is mostly deposited in the next embayment, resulting in shoreline accretion. This general pattern has been locally affected by the construction of jetties and by the placement of shore-protection structures.

Analyses of beach-sand compositions and grain sizes at the profile sites have established that there is a general correspondence between these sediment properties and the patterns of shoreline erosion versus accretion. The eroded areas are associated with finer-grained beach sands rich in heavy minerals, the greater the rate of erosion the finer the beach sand and the richer its total heavy-mineral content. Inversely, the areas of shoreline accretion are characterized by coarser sands that are depleted in heavy minerals, and richer in quartz–feldspar light minerals. These relationships result from the processes of selective grain sorting as the waves and longshore currents first erode the sand from the beach face, transport the sand alongshore, and finally deposit it in areas of accretion (Frihy and Komar, 1991). The beach-sand compositions and grain sizes reflect the long-term erosional history of the delta as well as the erosion within historic times established by the beach profile surveys. This long-term factor accounts for the high concentrations of heavy minerals along the central Burullus region where erosion of a promontory deposited by the ancient Sebennitic branch has continued since the 9th century, and also accounts for minor concentrations such as that in Abu Quir Bay at the former mouth of the Canopic branch. The results demonstrate that the beach sand compositions and grains sizes can be used as evidence for the ancient evolution of shoreline changes as well as reflecting the major shoreline erosion and accretion experienced during the 20th century.

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