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Shoreline changes and beach-sand sorting along the northern Sinai coast of Egypt

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Abstract Changing shoreline positions along the Sinai coast of Egypt were determined by comparing aerial photographs and historical charts with present-day conditions. The analyses identify longshore patterns wherein erosion along a protruding stretch of the coast gives way to accretion in an adjacent major embayment. This pattern defines two coastal subcells consisting of source/sink couplets. There is a general correspondence between the mineral variation, grain sizes of beach sand, and the patterns of shoreline changes. Associated with erosion/accretion shoreline change is a selective transport of different minerals according to their densities and grain sizes. Two heavy-mineral groups were obtained by applying Q-mode factor analysis on the heavy-mineral data. These two groups are influenced by transport processes, including sediment provenance from different sources: eroded Nile delta west of Sinai, relict sediments from the former Nile distributaries, and sediment supply by land valleys and from wind-blown sand.

Introduction

Heavy-mineral assemblages serve to identify the source and transport paths of sediments as well as grain-sorting processes at modern and ancient beaches. With respect to the grain-sorting processes, waves and currents selectively sort and concentrate mineral grains according to their sizes, densities, and shapes (Rao 1957; Komar 1989). Size–density sorting usually occurs in both alongshore and cross-shore directions. Wave swash on a beach may selectively concentrate fine-grained dense minerals by separating them from lighter coarse-grained minerals. This is evident in the sand deposits found along the Mediterranean beaches and on the continental shelf adjacent to the Nile delta.

With regard to the Sinai beach, systematic description, economic potential, and local distribution of heavy minerals have been discussed by Shukri and Philip (1959), El Far (1964), and El Shazly et al. (1986). Little information has been published on dispersal resulting from reworking of sediments on Sinai beaches. The investigation by Stanley (1989) was limited to an analysis of heavy minerals of shelf and coastal sands of Egypt and Israel in order to determine transport paths. Our study differs from the approach of Stanley in that he did not relate patterns of erosion and accretion to grain sorting of heavy-mineral species on the northern Sinai coast. However, to date, there has been no published information regarding relationships between shoreline changes versus sorting patterns of heavy minerals and texture of beach sands.

The aim of this study was to evaluate temporal beach changes along the northern Sinai coast on the basis of analyses of historical maps and aerial photographs that span 70 years. Another objective is to establish the relationships among position of shoreline changes, longshore sediment transport patterns, and the resulting composition of the beach sands, reflected by their heavy-mineral content and grain sizes.

Study area

The study area extends along the northern Sinai coast some 170 km from Port Said to El Arish. The generally smooth coastline is interrupted by the two protruding headlands at Port Said and the Bardawil bulge coast (Fig. 1). These headlands are separated by two large embayments, backed by sand dunes and lowlands made of salt pans (sabkha). To the east the shoreline is characterized by sandy spit formations, heading to the east, located at the eastern end of the barrier of Bardawil lagoon.

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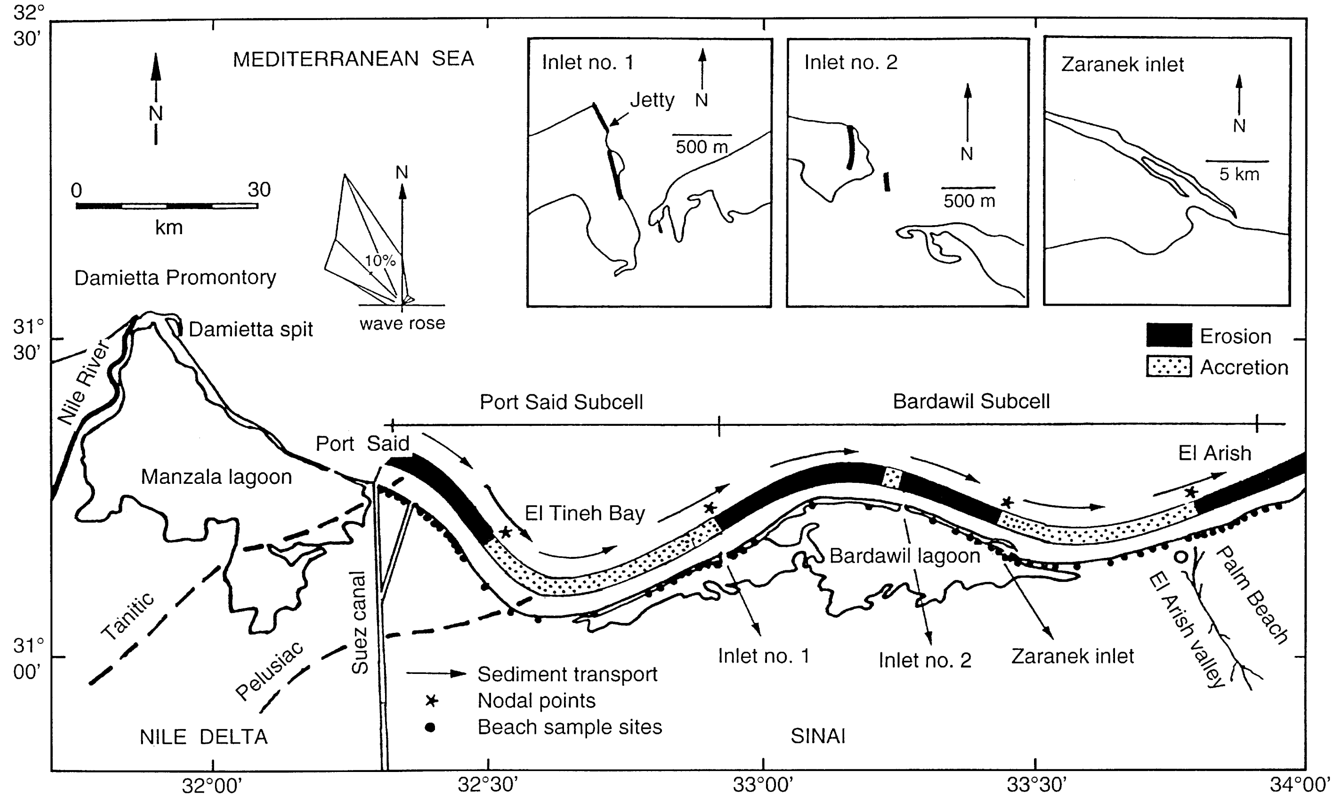


Fig. 1 Generalized map of the study area in the northern Sinai, showing sites of beach samples and trace positions of former channels (long dashes). The large-scale coast-wide erosion/accretion pattern, determined in this study, is schematically depicted parallel to the shoreline. Sediment transport directions are shown by small arrows, based on erosion/accretion patterns, petrologic parameters, and geomorphologic features in this study. The wave rose diagram is derived from the study of Fanos et al. (1993). The insets show the width of the beach west of the inlet jetties (sand accumulation) and east of jetties (beach erosion), indicating eastward sediment transport; jetties are indicated by dark lines

Except for the old jetties that were built in 1940 for stabilizing the lagoon inlets, the whole coast is essentially unprotected. The lagoon is separated from the sea by a long, curved, narrow sand barrier, about 500 m wide and 80 km long. It is connected to the open Mediterranean Sea by three inlets, two artificial (no. 1 and 2) and one a natural feature (El Zaranek; Fig. 1). Siltation problems due to waves and currents exist at these inlets, leading to closing of inlets, affecting water exchange and impacting the fish industry. This lagoon differs from other delta lagoons because it is not connected to any freshwater supply.

Sediments contributed to coastal zone

The Nile River has been the sole source of sediment, rich in heavy minerals, for the delta and the entire Nile littoral cell that extends an additional 500 km east and north to Akko, Israel (Inman and Jenkins 1984). These sediments have been discharged through the present-day Rosetta and Damietta promontories. Other now-abandoned Nile distributaries active during the Holocene brought large volumes of sediment to the coast. Subsurface studies in this region indicate that the Port Said headland developed during the Holocene (Stanley et al. 1992). At least seven Nile River channels have flowed across the broad Nile delta and discharged into the Mediterranean at various times during the middle to late Holocene (Toussoun 1922). From these distributaries, two former Nile channels, the Tanitic and Pelusiac, have contributed to the coastal area of Sinai (Fig. 1). The causes of abandonment of these branches could be related to the reduction of sediment supply and diminished flow of river water to the coast, which resulted from climatic changes over the Nile watershed, or due to the avulsion of their channels (channels avulse when their gradient becomes too gentle (Coutellier and Stanley 1987). Following their submergence, the distributary sediments have been eroded and reworked by the predominantly east-trending longshore currents (Inman and Jenkins 1984).

Sediments eroded from the Nile promontories and adjacent shelf have continued to be moved by longshore and offshore currents along coasts and shelves of the southeastern Mediterranean (UNDP/UNESCO 1978). Along the northern Sinai coast, the composition of the beach sand, however, reveals local contributions from other sources. These include inland sediments coming from the south (central Sinai) and discharged to the sea at El Arish during ancient times with periods of rainfall. Furthermore, wind-blown coastal dune sand is an additional source contributed to the beach during stormy seasons (Shukri and Philip 1959; Stanley 1989).

Methodology

Shoreline changes along the northern coast of Sinai were determined from an aerial photograph taken in 1955 (scale 1:20,000), a topographic map surveyed in 1992 (1:250,000), and an admiralty chart of 1922 (1:250,000). These maps were matched to the same scale, registered, and finally superimposed. The registration is based on control points of fixed geographic features such as ports, towns, and the Suez Canal. Patterns of shoreline erosion versus accretion were identified from the relative movement of shoreline in seaward or landward directions and are schematically depicted in Fig. 1. The magnitude of shoreline changes was not estimated in this study owing to the different surveying techniques of the maps examined.

A total of 72 beach samples were collected at 1.0- to 10.0 km intervals along the Sinai coast in 1990. Grain size analyses were made using standard sieving techniques at 0.5 ϕ intervals. Mean grain size, and 5th and 95th percentiles were graphically interpolated from the cumulative curves using the method of Folk and Ward (1957). Mineral separation was made for the fractions richest in heavy minerals (the 63–250 μm fractions) using sodium polytungstate (density 2.89 g cm^{-3}). The heavy-mineral separates were mounted in Canada Balsam on slides, and 400–500 grains were identified and counted in each sample using standard petrographic techniques. The number percentages obtained by point counting were then converted to a weight percentage (cf. Rubey 1933; Young 1966). The heavy-mineral concentrations (grams of heavy-minerals per 100 g in each heavy-mineral separate) were calculated for comparisons with the local shoreline changes. The weight percentages of each of the heavy minerals in the examined samples were subjected to factorial analysis. Q-mode factor analyses (Klovan and Imbrie 1971) were performed on 12 mineral data sets in order to classify samples into natural groups. These minerals are opaques, augite, hornblende, epidote, garnet, zircon, rutile, apatite, tourmaline, staurolite, sphene, and monazite. Two factors were obtained that account for 86.87% of the variations in mineral compositions. This corresponds to the major part of observed information contained in the matrix of the 12 variables.

Results and discussion

Erosion and accretion pattern

In this study, changing shoreline positions derived from historical maps and an aerial photograph were used to identify shoreline migration trends along the 170-km length of the Sinai coast. The pattern of erosion versus accretion interpreted from this analysis is depicted in Fig. 1.

The coast-wide patterns of shoreline changes reveal that significant erosion occurred down-coast east of Port Said, followed by accretion along the embayment of El Tineh Bay, the latter is interpreted as a sediment sink. This represents a simple pattern of erosion from the eastern tip of the Port Said headland, with the eroded sand moving by waves coming from the NW. The resulting eastward-flowing longshore currents produce deposition within the embayment of El Tineh Bay. This pattern is confirmed by field observations. Erosional cliffs of about 10 m height have been observed approximately 15 km east of Port Said. Chronic accretionary processes have prevailed along the coast of El Tineh Bay ince about 2000 years ago (Sneh and Weissbrod 1973), as indicated by a series of accretionary coastal sand ridges parallel to the present coastline of El Tineh Bay.

Further to the east, erosion also occurs along the arcuate bulge of the central Bardawil coast, along with localized deposition at the artificial lagoon inlets no. 1 and no. 2 (see inset of Fig. 1). Local accretion is produced at the western sides of the two inlet jetties by the blockage of the eastward longshore sediment transport. The coast of the lagoon forms a broad, arched headland and is located on a very active shoreline, which has experienced widespread erosion. The overall erosion along the tip of the lagoon barrier again reverts to accretion to the east along El Arish coast west to the western breakwater of El Arish Port. It is apparent that the pattern of erosion versus accretion along this barrier is a response to the eastward transport of sediment carrying eroded sand along the lagoonal barrier to the El Arish embayment. This embayment acts as the second sediment sink along the Sinai coast. Further to the east, local erosion was observed at El Arish Palm beach resulting from a direct effect of the breakwaters of El Arish Port built in 1984.

The sedimentation imbalance is more pronounced at the two lagoonal inlets located on the sandy barrier. This imbalance has impacted the ecosystem in the lagoon by causing serious shoaling problems, thus changing the ecosystem of the lagoon and fish productivity in particular (Fanos et al. 1993). Significant changes occur down-coast at the two inlets, producing movable sand bars that lead to changing the shape and width of the inlets. Large quantities of sand are being blocked on the western side of the jetties, which were built to prevent shoaling of the artificial inlets of the lagoon (Fig. 1). As a consequence, the eastern coast of each inlet has been subjected to erosion (Goldsmith and Golik 1980; Fanos et al. 1993). The rate of sediment transport at these inlets is very high. On the basis of aerial photographs, Inman et al. (1976) estimated the net sediment transport to be 0.3–0.5 million m^3 yr^{-1} in the eastern direction. The high rate of sediment transport is also confirmed from the potential accumulation of sand on the western sides of each of the inlets (see inset in Fig. 1).

Textural and mineralogical variations in beach sand

Different mineral species have been identified in beach sand samples. The dominant constituents are opaques (magnetite and ilmenite), augite, and hornblende with smaller concentrations of epidote, garnet, zircon, rutile, apatite, tourmaline, staurolite, sphene and monazite.

Q-mode factor analyses of the mineral percentages of the 12 principal minerals in the 72 beach samples was carried out to derive natural mineral groups that might reveal alongshore mineral patterns. The analyses identified two factors that account for 86.89% of variance: factor 1 accounts for 76.05%, while factor 2 accounts for 10.84% of the mineralogical information contained within the samples. The mineral compositions of these two factors, deduced from factor scores, are graphically shown in Fig. 2. Factor 1 consists of augite and hornblende with a small amount of epidote. Factor 2 contains opaques, garnet, zircon, rutile, and monazite. An inverse relationship exists between these two factors: an abundance of one corresponds to a depletion of the other (Fig. 3). Such a relationship between these two factors (mineral groups) suggests that they were generated by processes of mineral sorting during entrainment and transport (Komar 1989). This is borne out by the contrasting densities and sizes of the minerals included within the two factors. Factor 1 consists of minerals that are coarse-grained and have lower densities, while factor 2 contains minerals that are finer grained and have higher densities. Previous studies on the formation of black sand placers on beaches suggest that grains similar to factor 1 (grains of lower density and larger sizes) are selectively entrained and transported away by the swash of waves on the beach face, tending to leave behind as a lag the minerals that have higher densities and smaller grain sizes, i.e., minerals similar to factor 2 (Komar and Wang 1984; Li and Komar 1992). Similar results were obtained by Frihy and Komar (1991) in their analyses in the Nile delta beach sand.

The longshore distribution of the two mineral factors are graphically depicted in Fig. 4B. The pattern shows a longshore rhythmic variation between factors 1 and 2. In general, beaches downdrift from the zones of erosion, along El Tineh Bay and El Arish beaches, where accretion has occurred, tend to have high loading of factor 1. Conversely, the highest loadings of factor 2 correspond to the areas of shoreline erosion. This group decreases alongshore transport towards areas where there has been shoreline accretion. As expected, this mineral pattern is also reflected in the concentration of total heavy minerals of beach samples during transport (Fig. 4C). This pattern results from the overall west-to-east transport of sediments along the beaches of the Sinai coast, which tends to yield high concentrations of heavy minerals in areas of erosion with less concentration in areas of accretion.

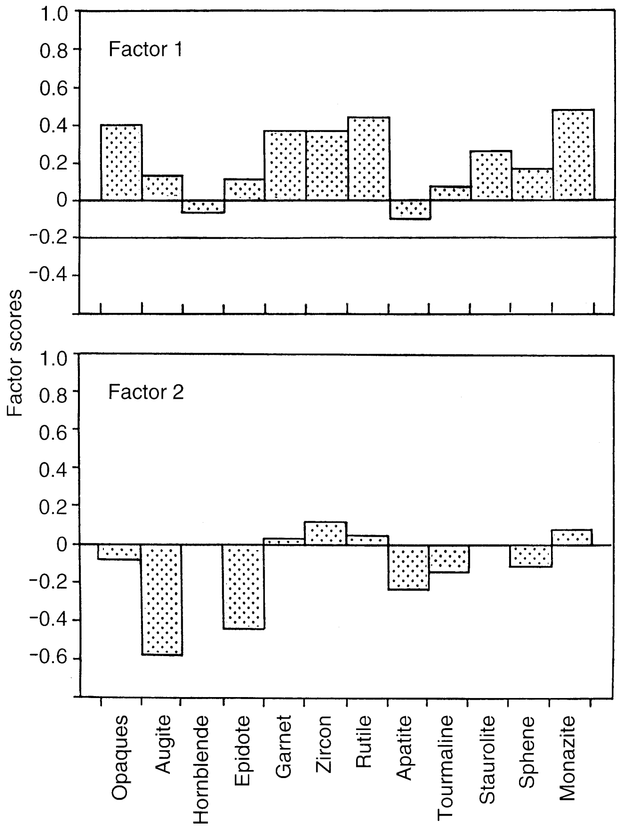


Fig. 2 The mineral compositions of the two factors "heavy-mineral assemblages" obtained by Q-mode factor analysis of heavy minerals in beach samples of the Sinai coast. The two factors account for 86.87% of the variability

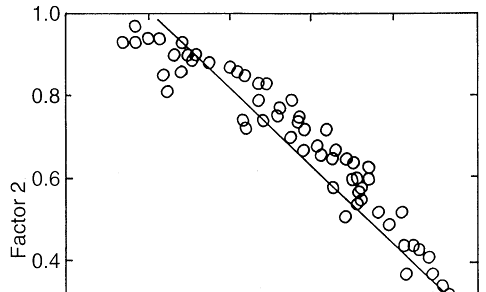
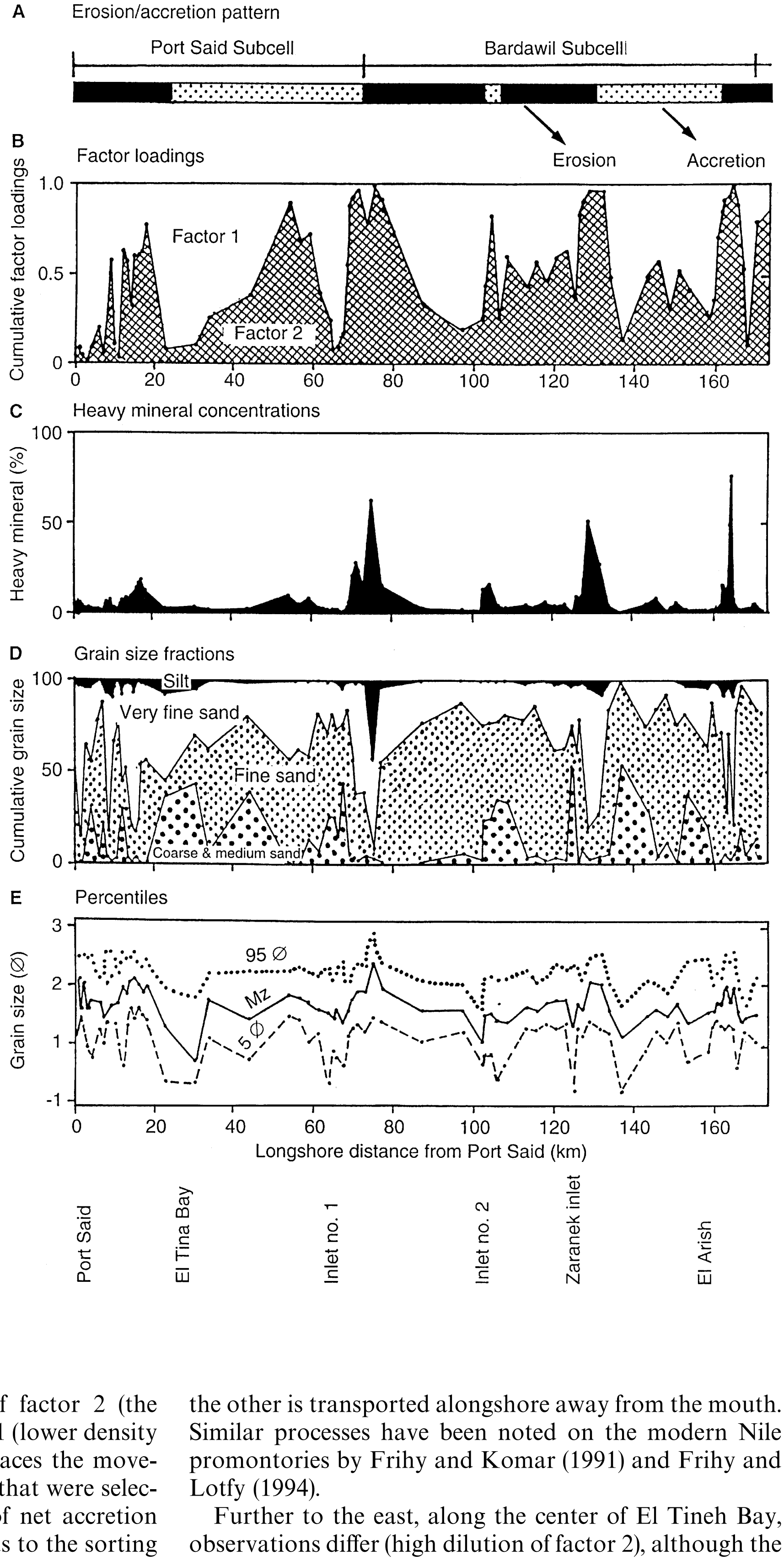


Fig. 3 The inverse relationship between the two factors of Fig. 2, indicating an abundance of one correspond to a depletion of the other

The heavy-mineral patterns east of Port Said and along El Tineh Bay appear to be influenced, at least in part, by relict sediment supplied from the ancient Tanitic and Pelusiac Nile branches. This area, approximately 25 km

Fig. 4 Erosion/accretion pattern (**A**), alongshore variations in loadings of the two mineral factors (**B**), heavy-mineral concentrations (**C**), grain size of beach sand (**D**), and grain size in percentiles (**E**)



east of Port Said, shows an increase of factor 2 (the higher-density minerals) relative to factor 1 (lower density minerals). This alongshore distribution traces the movement of the lower-density heavy minerals that were selectively eroded and transported to areas of net accretion (Fig. 4B). This mineral pattern corresponds to the sorting patterns found near river mouths: as one mineral suit tends to concentrate near the mouth (densest minerals), the other is transported alongshore away from the mouth. Similar processes have been noted on the modern Nile promontories by Frihy and Komar (1991) and Frihy and Lotfy (1994).

Further to the east, along the center of El Tineh Bay, observations differ (high dilution of factor 2), although the mouth of the former Pelusaic branch was located in this area. Along this bay, loadings of factor 1 (accretion) decrease abruptly, due to the proximity of the mouth of the extinct Pelusaic branch of the Nile. This unexpected situation could account for the shoreline orientation of the bay, which influences the littoral drift and creates a sediment sink. The accreted embayment east of the Zaranek inlet reveals almost same proportions of factors 1 and 2. This observation probably reflects the influence of locally supplied sediment from the El Arish valley, as well as marine erosion of the Bardawil barrier. Further to the east, higher concentrations of heavy minerals, accompanied by an increase in the loading of factor 2 (erosion), reflects the local erosion along the Palm Beach east of El Arish. It resulted from the construction of the breakwaters of the El Arish Port.

Of special interest are the sorting patterns revealed by grain size distributions of beach sand in the alongshore direction. The results of the grain-size distributions (cumulative grain size and grain size percentiles) within the beach sands along the length of the northern Sinai coast are graphed in Fig. 4C and D, respectively. In general, this variation forms a series of sawtooth peaks. The finest sizes of the fine and very fine sands (higher ϕ values) tend to occur along areas of erosion west of El Tineh Bay and along the barrier of Bardawil lagoon. In contrast, areas of accretion are characterized by peaks of coarsest sizes of medium and coarse sand (lower ϕ values). It is of interest that there is a rough parallel between the variations in heavy–mineral groups, heavy-mineral concentrations, and grain-size distributions.

Sediment transport

In this study the direction of longshore sediment transport can be inferred from multiple indicators: a change in shoreline operation resulting from erosion and accretion trend, sand accumulation versus beach erosion on opposite sides of jetties, the longshore growth of sand spit, and patterns of beach sand variations in grain sizes and mineralogy. Shoreline comparison shows remarkable erosion east of the tip of the Port Said headland followed by a significant accretion along the shoreline of El Tineh Bay. This pattern is a response to an eastward transport of sand, resulting from the prevailing wave arrival from the NW, generating eastward-flowing longshore currents (see inset in Fig. 1).

The longshore direction of sand movement along the coast is also documented from the aerial photograph of 1955: it shows a 5-km-long sand spit growing in the eastern direction, close to the Zaranek inlet (Fig. 1). Blockage of longshore sediment transport by jetties commonly provides the best indication of the transport direction. Analyses of the shorelines at the two lagoon inlets indicate that the shoreline has advanced seaward along the western side of the inlet in response to jetty construction and receded southward along the eastern sides. The accumulation of sand on the western sides of the jetties and erosion on the eastern sides also indicates sediment transport from west to east (Fig. 1).

The interpreted sediment transport pattern helps to identify locations of nodal points along the coast. Nodal points can be positioned at the change or areas of transport from erosion to deposition, or vice versa, that result from the orientation changes of the shortline. Four major nodal points were positioned along the coast (Fig. 1).

In this study two subcells can be identified based on the multiple indicators examined. Starting from the west, the first subcell is Port Said; the second is the Bardawil (Fig. 1). Each subcell consists of a zone of erosion (sediment source) followed by a zone of deposition acting as sediment sink. The Port Said subcell includes the eastward transport of sand along the down-coast east of Port Said, about 67 km, and deposition along the shoreline within El Tineh Bay. The latter acts as a sediment sink for the erosional products. The Bardawil subcell represents the general erosion along the central bulge of Bardawil lagoon barrier and the longshore transport of sand to the east, where it is deposited to produce shoreline accretion along the embayment of El Arish beach. El Arish embayment acts as a sediment sink for sand eroded from the arcuate bulge barrier of Bardawil lagoon.

Summary and conclusions

An analysis of historical charts and aerial photographs along the Mediterranean coast of the Sinai indicates that the shoreline has shifted southward (retreated) along two major protruding areas: the eastern part of Port Said headland and along the arcuate bulge of the sandy barrier of the Bardawil lagoon. In contrast, the shoreline has advanced (prograded) seaward along the major sediment sinks at the El Tineh embayment and the El Arish coasts. This general pattern has been locally interrupted by the construction of jetties placed at the inlets of Bardawil lagoon and the breakwaters of El Arish Port. The change in the coastline along the northern Sinai coast probably results from the increasing numbers of engineering protective structures along the Nile delta coast, which blocked sediment transport to the east and thus decreased sand supply to the Sinai beach. In addition, the delta coast has been substantially modified as a result of controlling the Nile flow by two dams at Aswan. Consequently, large numbers of coastal structures have been built to protect the beach and stabilize the lagoon inlets. Prior to the construction of these structures, sediment continuously nourished the entire coast of Sinai. In the absence of significant Nile sediment input, driving forces (waves and currents) actively erode the protruded coat of Sinai.

Analyses of beach samples along the Sinai coast established that there is a general correspondence between their heavy-mineral composition, as determined by factor analysis, grain sizes of beach sand, and the patterns of shoreline erosion versus accretion (Fig. 4). The correspondence between the pattern of shoreline changes and the extracted mineral groups results from the processes of selective grain sorting as the waves and longshore currents erode the sand from the beach face, transport the sand alongshore, and deposit it in areas of accretion.

The sediment transport pattern identified is inferred from the multiple indicators examined, including interpretations of large-scale change in shoreline orientation due to erosion and accretion; response of coasts to the constructions of jetties and spit features; and variation in the textural and mineralogic composition of beach sand. These indicators also help us to identify two subcells along the Sinai coastline, the Port Said subcell and the Bardawil subcell (Figs. 1 and 4A). Each subcell contains a sediment source followed by sediment sink, wherein sand eroded from a headland is transported to the east and is mostly deposited in the next embayment, resulting in shoreline accretion. The patterns of texture and composition of beach sand are affected by different sediment sources, including wind-blown sand, eastward transport of the modern Nile sediments across the Nile littoral cell, relict (palimsest) sediments on shelves and coasts, erosion of beach face Pleistocene sources, and fluvial feed from highland provenances carried from El Arish valley.

References

Coutellier V and Stanley DJ (1987) Late Quaternary stratigraphy and paleogeography of the eastern Nile Delta, Egypt. Marine Geology 27:257–275

El Far DM (1964) The black sands of north Sinai Mediterranean coast with an appendix on some new findings in Sinai. Desert Institute Bulletin Egypt 46:1–27

El Shazly EM, Kmel AF, Morsy MA, and Attia SH (1986) Studies on beach and dune sands on the Mediterranean Sea coast at El Masaid, west of El Arish. Egyptian Journal of Geology 30:1–8

Fanos A, Khafagy A, Anwar N, Naffaa M, and Dean R (1993) Assessment and evaluation for the enhancement of the Brardawil lagoon outlet. Egypt. Coastal Dynamics Conference, Spain, pp 189–203

Fanos A, Khafagy A, and Dean R (1995) Protective works on the Nile delta coast. Journal of Coastal Research 11:516–528

Folk RL and Ward WO (1957) Brozos River bar; a study in the significance of grain size parameters. Journal of Sedimentary Petrology 27:3–27

Frihy OE and Komar PD (1991) Patterns of beach-sand sorting and shoreline erosion on the Nile Delta. Journal of Sedimentary Petrology 61:544–550

Frihy OE and Lotfy MF (1994) Mineralogy and texture of beach sands in relation to erosion and accretion along the Rosetta Promontory of the Nile Delta, Egypt. Journal of Coastal Research 10:588–599

Goldsmith V and Golik A (1980) Sediment transport model ofthe southeastern Mediterranean coast. Marine Journal 37:147–175

Inman DL and Jenkins SA (1984) The Nile littoral cell and man's impact on the coastal zone of the southeastern Mediterranean. Scripps Institution Oceanography Reference Series 31:1–43

Inman DL, Aubrey DG, and Pawka SS (1976) Application of nearshore processes to the Nile Delta. UNDP/UNESCO Proceedings Seminar on Nile Delta Sedimentology, pp 205–255

Klovan JE and Imbrie J (1971) An algorithm and FORTRAN-VI program for large scale factor analysis and calculation of factor scores. Journal of Mathematic Geology 3:61–67

Komar PO (1989) Physical processes of waves and currents and the formation of marine placers. Review of Aquatic Science 1:393–423

Komar PD and Wang C (1984) Processes of selective grain transport and the formation of placers on beaches. Journal of Geology 92:637–655

Li Z and Komar PD (1992) Longshore grain sorting and beach placer formation adjacent to the Columbia River. Journal of Sedimentary Petrology 62:429–441

Rao CB (1957) Beach erosion and concentration of heavy mineral sands. Journal of Sedimentary Petrology 27:143–147

Rubey WW (1933) The size distribution of heavy minerals within water-laid sandstone. Journal of Sedimentary Petrology 3:3–29

Shukri NM and Philip G (1959) The mineralogy of some recent deposits in the Arish-Gaza area. Cairo University of Faculty of Science Bulletin 35:73–85

Sneh A and Weissbrod T (1973) Nile Delta: the defunct Pelusiac branch identified. Science 180: 59–61

Stanley DJ (1989) Sediment transport on the coast and shelf between the Nile delta and Israeli margin as determined by heavy minerals. Journal of Coastal Research 5:813–828

Stanley DJ, Warne AG, Davis HR, Bernasconi MP, and Chen Z (1992) Nile Delta: the Late Quaternary north-central Nile delta from Manzala to Burullus Lagoon, Egypt. National Geographic Research and Exploration 8:22–51

Toussoun O (1922) Memoires sur les anciennes branches du Nil. Epoque Ancienne. Memoire Institut d'Egypt 4, 212 pp

UNDP/UNESCO (1978) Coastal protection studies. Final Technical Report, Paris, No. 1, 155 pp

Young EL (1966) A critique of methods for comparing heavy mineral suites. Journal of Sedimentary Petrology 36:57–65