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Clay Mineral Distributions to Interpret Nile Cell Provenance and Dispersal: III. Offshore Margin between Nile Delta and Northern Israel

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ABSTRACT

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Clay assemblages in Holocene sediment on southeast Mediterranean margins are generally smectite-rich and, in the past, were derived primarily from direct River Nile input to the sea. Depositional patterns in the Nile littoral cell are now undergoing extensive change, largely as a response to closure of the High Dam at Aswan (1964), increased sediment entrapment by canal systems in the Nile delta, and construction of large coastal structures between the Nile delta and Israeli margins. Although information on land-to-sea dispersal by the River Nile and other fluvial and offshore sediment sources to the east remains limited, there appears to be evidence for increased sediment input from erosion of Sinai and Levant shelves and coasts east of the Nile delta. This, the third in a 3-part study that focuses on regional clay mineral distributions, was initiated to provide baselines to measure evolving changes of sediment provenance and dispersal patterns on the shelves and upper Nile Cone between the Nile delta and northern Israel.

The investigation shows that clay assemblages are not uniformly distributed in the SE Mediterranean, likely a result of several important sediment sources in addition to the Nile. Smectite-rich clay assemblages east of the Nile delta are presently derived from storm wave and coastal current erosion of the Nile delta, reworking of Quaternary deposits along the coast and on the seafloor east of the delta, and from some Israeli rivers between Tel Aviv and Atlit. Kaolinite and illite at offshore sites are supplied in part from erosion of coastal cliff sections, river input between Wadi El Arish in Sinai and the Lebanon-Israel border, and from wind-borne dust from African and Middle East deserts released seaward of the coast. The diverse source terrains that back coastal plains provide laterally variable clay assemblages along the southeastern Mediterranean coast.

Presently evolving changes in the volume and mineralogy of sediment transported from the distal Nile region in Egypt, versus those from more proximal coastal sources on Sinai and Levant margins, are likely to be subtle. Post-Aswan High Dam changes of fine-sediment load, composition and dispersal in the eastern Mediterranean should now be determined from water samples and sediment traps set above the seafloor between the coast and upper Nile Cone. Improved quality of information can be derived from clay mineral assemblages in suspended sediment samples in conjunction with geochemical tracers. Moreover, detailed morphologic surveys will provide essential information on altered sediment transport patterns as related to sectors undergoing accelerated coastal erosion.

ADDITIONAL INDEX WORDS: *Aswan High Dam, Bardawil lagoon, clay minerals, coastal erosion, Egyptian shelf, Gaza, Israeli rivers, Israeli shelf, Levant margin, Mediterranean, Nile delta, Nile littoral cell, sediment dispersal, Sinai margin, suspended load, Wadi El Arish.*

INTRODUCTION

It has been clearly demonstrated that the River Nile was the primary source of sediment carried directly to the southeast Mediterranean until this century (HURST, 1952), when two dams were constructed at Aswan in upper Egypt. The first (Lower Dam) was emplaced in 1902, and the second (High Dam) in 1964. At present, only a small volume of silt and clay (to 15% of the original pre-1902 load) bypasses the Nile delta to the shelf via Nile distributaries, lagoon outlets and canals. Decreased sediment input in the lower Nile valley and at the Nile delta coast is largely the result of entrapment in the increasingly complex system of irrigation channel and canal drain pathways constructed throughout the delta and in wetlands in the northern delta (SESTINI, 1989; STANLEY, 1996). Most workers surmise that sediment cut-off has altered sedimentation patterns not only in the Nile valley and delta, but also on the continental shelf and slope north and east of the delta coast (SHARAF EL DIN, 1977; SUMMERHAYES *et al.*, 1978; UNDP/UNESCO, 1978). A systematic, region-wide survey of sediment and mineral distributions on Nile delta and Levant shelves, however, was not made prior to, or just after, closure of the Aswan High Dam, and therefore information about evolving sedimentation patterns in this region is seriously limited.

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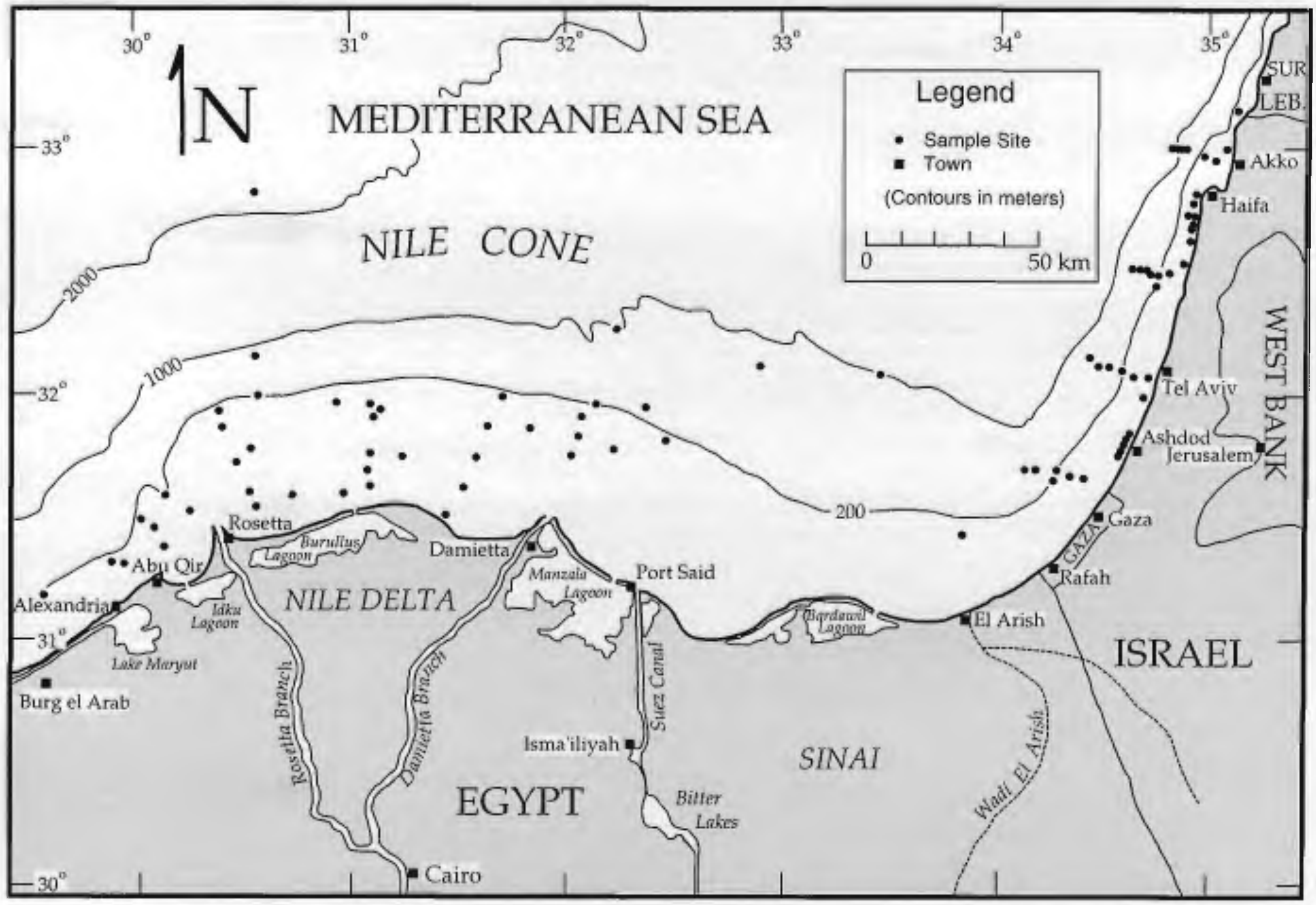

Figure 1. Map of the SE Mediterranean study area showing geographic localities discussed in text and positions of offshore sediment samples used in this study.

Clay mineral studies provide a means to measure changes in the study area that result from altered natural and anthropogenic processes in post-Dam time. It is fortunate that some sample sets were collected on SE Mediterranean margins just before and after closure of the High Dam, and these materials can now be used to establish general petrologic baselines for the Holocene until the latter part of this century. This study, third of a 3-part series, focuses on texture and clay mineral distributions in surficial sediment samples recovered on continental shelves off northern Egypt, Sinai, Gaza and Israel and the Nile Cone (Figure 1). A collage of various sediment sample sets, recovered on these continental margins between 1963 and 1995, are used here to compile a petrologic database for use in future studies.

The present investigation takes into account and builds upon textural and clay mineral data obtained in two previous and directly related studies. The first analyzed sediment along the Nile valley, from southern Egypt to the coast (STANLEY and WINGERATH, 1996) and the second focused on sediment in rivers and coastal plain exposures between the Nile delta and Israel-Lebanon border (STANLEY *et al.*, 1997). For consistency in data compilation, analyses in the three studies were performed by the same operator who applied the same petrologic procedures to all samples. These also provide comprehensive listings of texture and clay mineral data in the study area, bibliographies pertinent to the lower River Nile and Nile delta in Egypt and coastal plains of Sinai, Gaza and Israel, and discussions of potential terrestrial sources of fine-grained sediment supplied to the offshore study area. As such, the three studies together can provide a base from which to measure post-High Dam and future regional clay mineral changes.

PROVENANCE-AND-DISPERSAL CONSIDERATIONS

Selective Dispersal of Clays

Nile sediment off the Egyptian coast is dispersed in a large counter-clockwise gyre (Figure 2A) by geostrophic and wave driven currents that prevail in the easternmost Mediterranean (EMERY and BENTOR, 1960; LACOMBE and TCHERNIA, 1972; INMAN and JENKINS, 1984; SMITH and ABDEL-KADER, 1988; FRIHY *et al.*, 1991; BERGAMASCO *et al.*, 1992; POEM GROUP, 1992). Dispersal is primarily directed eastward from the Nile delta (Figure 3), toward Sinai and Gaza shelves and

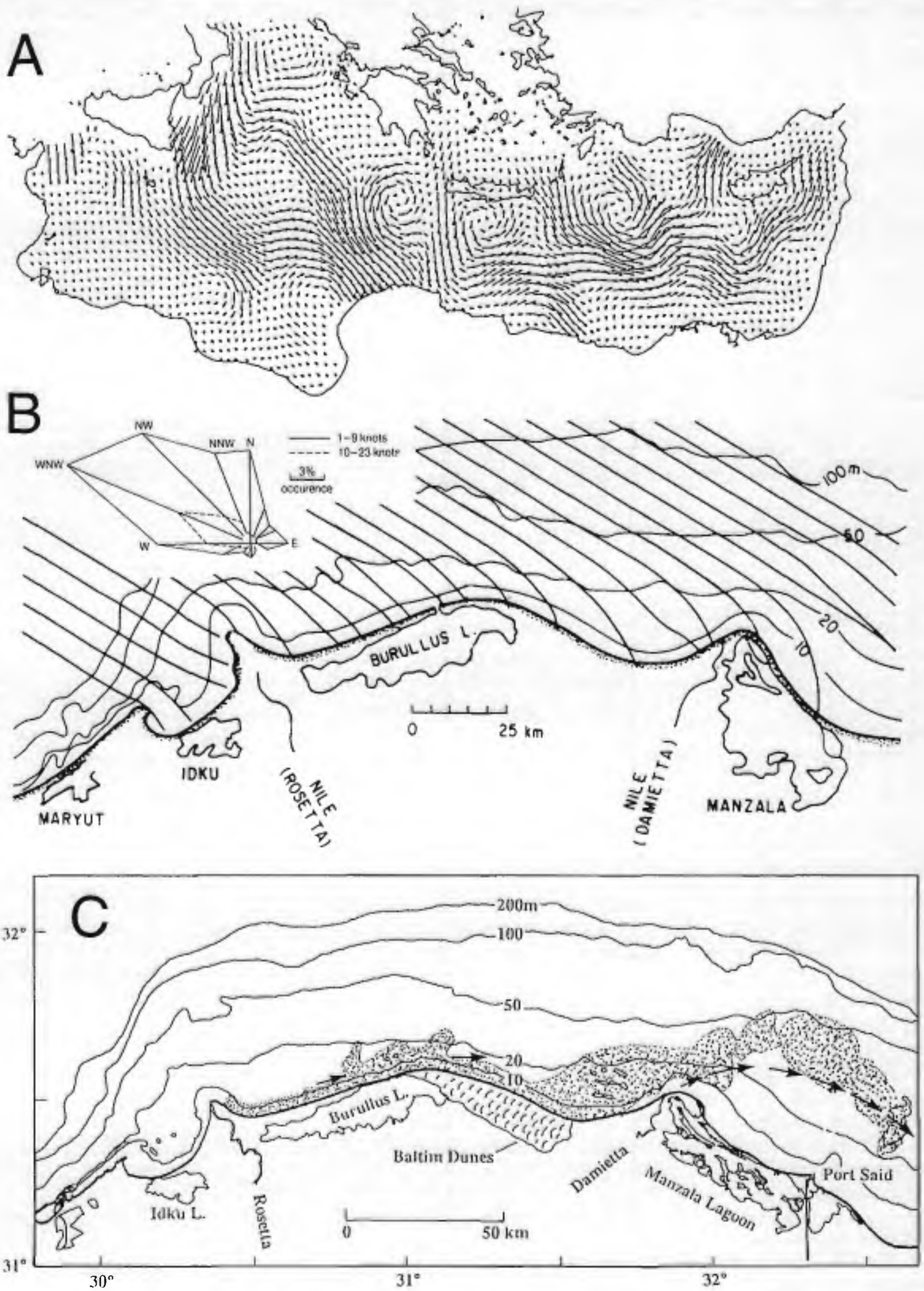

Figure 2. General watermass patterns in the eastern Mediterranean. (A) Circulation of the surface layer (upper 50 m) for the winter season (modified after BERGAMASCO *et al.*, 1992); (B) Wave refraction of longshore transport along the Nile delta coast for a 1 m high, 8 sec wave coming from N60°W (after INMAN and JENKINS, 1984); wind rose for the shelf north of the Nile delta showing prevailing path to SE (after SESTINI, 1992); (C) Sand transport path (dotted pattern) as a response to easterly-driven currents (arrows) between the coast and mid-Nile delta shelf (after INMAN *et al.*, 1992).

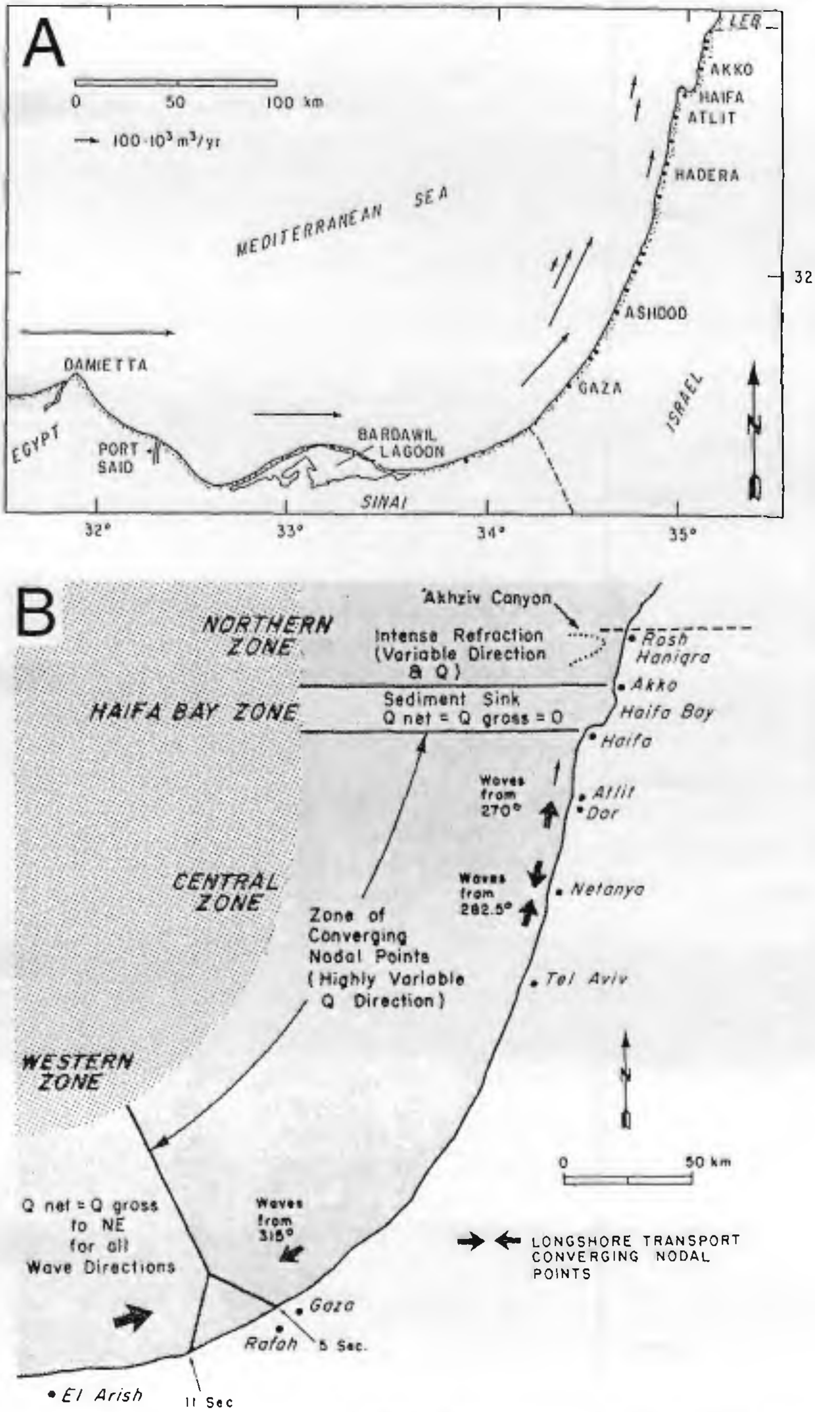

Figure 3. Geostrophic and coastal current-driven transport patterns in the SE Mediterranean. (A) estimates of the net annual longshore sand transport rate in the Nile littoral cell, pre-Aswan High Dam (after CARMEL *et al.*, 1984); (B) longshore sediment transport model along the Levant margin showing the change in location of converging longshore transport nodal points with change in wind direction and period (after GOLDSMITH and GOLIK, 1980).

slope (*cf.* SHARAF EL DIN, 1977), and then to the north on the Israeli margin (EMERY and NEEV, 1960; GOLDSMITH and GOLIK, 1980) and beyond (MILLER, 1972). It is presumed that, prior to closure of the High Dam, when Nile sediment was delivered to the coast, sand was released first along the Nile delta coast and inner shelf (Figure 2B, C; MURRAY *et al.*, 1981; CARMEL *et al.*, 1984; INMAN *et al.*, 1992; SHOSHANY *et al.*, 1996), and that a large proportion of silt and especially

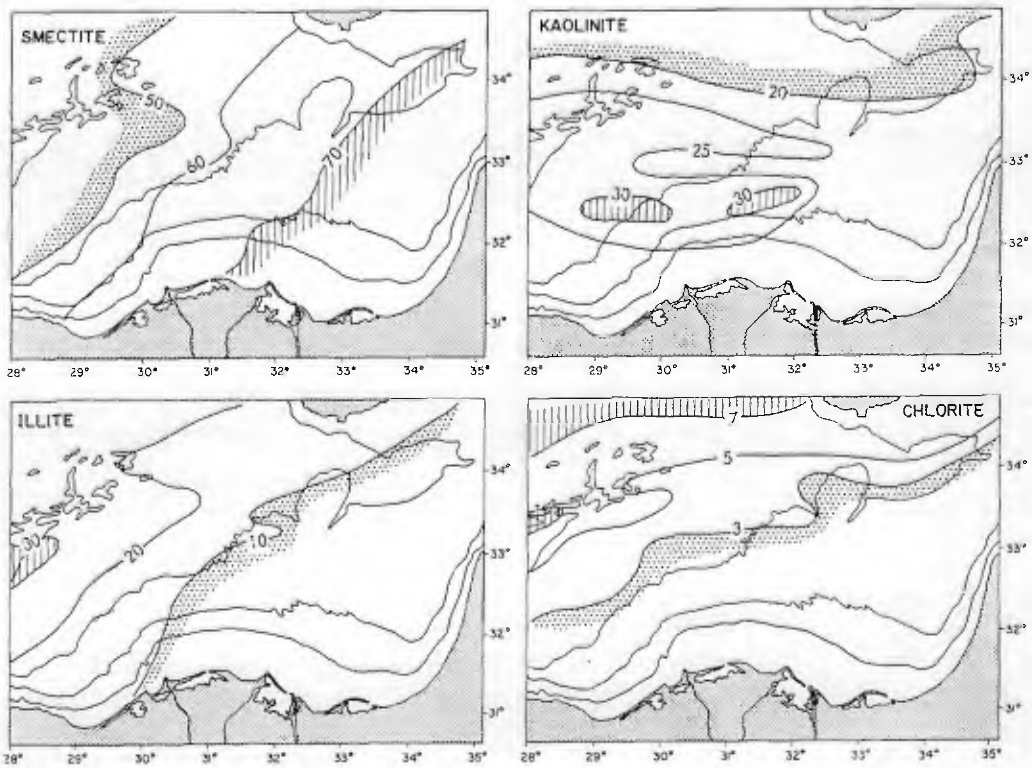

Figure 4. Smectite-rich clay mineral distribution in surficial sediment of the eastern Mediterranean, showing a regionally homogeneous assemblage. Isopleths indicate relative percentages of the four dominant clay minerals in this region; low values are indicated by stippled pattern, and high values by hachure (after MALDONADO and STANLEY, 1981).

clay-size material was transported farther by surface and bottom currents. Clays on the Nile Cone, the broad gentle slope below the shelfbreak (>200 m), are derived not only by bottom current and suspension transport but also by down-slope gravity-driven mechanisms (ALMAGOR and MICHAELI, 1985).

Surprisingly little is known about the present (post-High Dam) importance of offshore sediment distribution patterns and clay mineral input from the River Nile and from sources north and east of the Nile delta. We postulate here that clays supplied in various amounts and added to the more distally-derived, fine-grained Nile components, would derive from: (1) adjacent modern rivers and ephemeral tributaries, or *wadis,* east of the Nile delta; (2) coastal current erosion of sediment from coastal cliffs and carbonate-cemented quartz sandstone of Quaternary age (known as *kurkar*; PICARD and AVNIMELECH, 1937; PICARD, 1938; *cf.* NEEV *et al.*, 1987) that are intercalated with silty and clayey layers; (3) erosion of unconsolidated seafloor deposits; and (4) wind-blown desert dust. It is surmised that these proximal Levant coastal environments, together, are now providing an increasingly significant proportion of the offshore sediments. This investigation attempts to better identify some of the more important dispersal paths that have deposited clay-bearing sediment to the north and east of the Nile delta during the second half of this century.

Review of Clay Input in Nile Littoral Cell

Previous studies of recent offshore clay mineral distributions in the southeastern Mediterranean (VENKATARATHNAM and RYAN, 1971; NIR and NATHAN, 1972; MALDONADO and STANLEY, 1981; NIR, 1984; ALMAGOR and MICHAELI, 1985) indicate that at present: (1) the Nile remains the primary source of sediments, including clays, in this region; and (2) these smectite-rich Nile-derived assemblages are supplemented by wind-blown kaolinite-rich dust from North African and Middle East deserts (YAALON and GANOR, 1973, 1979) and by illite and chlorite transported by currents from more distal northern Mediterranean sources, such as the Hellenic region. All earlier studies have emphasized that smectite of Nile derivation is the most abundant clay mineral in homogeneous clay assemblages on Levant margins (Figure 4). Most previous work has not focused on provenance from more proximal coastal and seafloor sectors east of the Nile.

Sedimentation models depict the eastward displacement of sand and fine sediment from the River Nile to the southeastern Levant and the depositional budget between the Nile delta and southern Levant (GOLDSMITH and GOLIK, 1980; CARMEL *et al.*, 1984; INMAN and JENKINS, 1984). In what they term the *Nile littoral cell,* Inman and Jenkins quantify the sediment volumes and dispersal system that prevailed prior to the mid-1960's rather than at present, one which has experienced River Nile cut-off since closure of the Aswan High Dam. Less than 2% of the River Nile's sediment load now by-passes the High Dam (UNDP/UNESCO, 1978; ELASSIOUTI, 1983), and the much reduced sediment volume (to ~15% of the former Nile load, much of it eroded by the river below the Dam (STANLEY, 1996) is discharged to the sea primarily by: (1) outlets of Manzala, Burullus and Idku lagoons; (2) several large delta waterway drains that empty directly at the coast; (3) pumping, at Alexandria, of Lake Maryut water to the sea; and (4) some ship-induced water exchange at the northern entrance of the Suez Canal (STANLEY *et al.*, 1982). Waste products and pollutants are also increasingly released to the Nile delta coast along with fine-grained sediment (ELSOKARY, 1992).

The width of the delta between Cairo and the Nile delta coast is 160 km. The shelf is ~70 km wide off the Nile delta, and narrows to <10 km near Lebanon. The width of the Gaza and Israeli coastal plain also narrows gradually, from ~40 km at the latitude of Gaza (backed by broad strandplain; Figure 5A, C) to less than 5 km in northernmost Israel (backed by the Upper Galilee Mountains).

As a result of marked reduction of Nile sediment input at both Nile distributaries (Rosetta, Damietta), coastal erosion has substantially cut back the two distributary promontories and modified extensive sectors of the delta coast (UNDP/UNESCO, 1978; FRIHY, 1988; SMITH and ABDEL-KADER, 1988; FRIHY *et al.*, 1991; SHARAF EL DIN and MAHAR, 1997). Geostrophic and strong wave currents drive the prevailing easterly flow (to >0.5 knots) along the eastern North Africa margin (Figure 2B), displacing sediment as coarse as sand along the inner delta shelf (Figure 2C) and Sinai and Gaza coasts to as far as the northern Israeli margin (EMERY and BENTOR, 1960; EMERY and NEEV, 1960; GOLDSMITH and GOLIK, 1980; CARMEL *et al.*, 1984; NIR, 1984; GOLIK, 1993; SHOSHANY *et al.*, 1996). Fine-grained sediment, derived from the Nile region and from North African eolian dust, is carried in suspension to as far north as the Syrian margin (*cf.* MILLER, 1972) by the large, counter-clockwise eastern Mediterranean gyre (Figure 2A).

The Gaza and Israeli coastal plain is crossed by at least 20 short (10–50 km), west-flowing rivers and wadis, of which only several positioned north of Tel Aviv (such as Taninim river) flow during most or all of the year. Others have become artificially water-filled streams (fed by electrical power stations, sewerage, *etc.*) only along the last few kilometers of their course. The overall average annual amount of sediments reaching the Mediterranean from these rivers is on the order of 1 million tons, mostly fines originating in mountains and coastal plains that back the coast (NIR, 1984). Offshore, the dispersal of clays is also affected somewhat by an irregular, coast-parallel, ridge-and-trough topography (EMERY and BENTOR, 1960; NIR, 1984; NEEV *et al.*, 1987).

Sources of sediment along the Levantine coast include short seasonally-flowing streams, and eroded steep shore cliffs (Figure 5D), including some of eolianite, hamra soils and sand dunes. Bottom currents also remove minor amounts of unconsolidated sediment from partially silt-covered exposed ridges on the seafloor and small islands (Figure 5E, F) positioned near the coast; the ridges and islands are, for the most part, formed of carbonate-cemented quartz sandstone, mostly of eolian origin (kurkar). Wind also provides sediment eroded from some of the gently inclined broad strandlines, especially those covered by sand dunes (Figure 5B, C). Sediment is introduced seasonally (primarily in winter) to Levant shelves by several high-discharge streams, intensified storm-wave erosion of coastal cliffs and kurkars, and strong winds. Haifa Bay (Figure 5B) is the major natural sand and silt sink in this Nile littoral cell (INMAN and JENKINS, 1984). The increasing number of artificial structures placed along the Sinai and Israeli (Figure 6B-D) coasts (NIR, 1982; NIR and ELIMELECH, 1990) are modifying natural transport paths of sediment, especially that moved on innermost shelves.

Higher flow of some rivers in the northern sector of the study area results, in part, from increased rainfall (from <100 to >700 mm/year) between eastern Sinai and northern Israel. Of note in this respect is the variable but locally important discharge of industrial, domestic and agricultural waste via some Gaza and Israeli rivers (Figure 6A) and dispersal pipelines. Dissolved and suspended anthropogenic material is recovered with fine-grained sediment along offshore Levant transport paths (KRESS *et al.*, 1990).

METHODOLOGY

Textural and clay mineral analyses in the two previous studies were made on 59 samples collected during 1990 and 1992 in the River Nile and Nile delta (STANLEY and WINGERATH, 1996), and on 67 samples collected during 1994 in rivers and coastal plain exposures between the eastern Nile delta and northern Israel (STANLEY *et al.*, 1997). Offshore samples analyzed in the present investigation were collected by several organizations in 1963, 1965, 1977, 1983–1985 and 1995 between Alexandria, off the western Nile delta, and the Israel-Lebanon border (Figure 7). These 85 samples are subdivided into 8 groups (coded **A-H**) on the basis of location and date of recovery. The positions, depths and dates of sample collection are provided in the references cited below:

(A) westernmost Nile delta shelf, comprises 3 RV *Chain* (1977 cruise 119) grab samples collected in the Alexandria-Abu Qir region (nos. 1–3 in Table 1; WOODS HOLE OCEANOGRAPHIC INSTITUTION, 1975; SUMMERHAYES *et al.*, 1978) (B) Nile shelf, 8 RV *Pillsbury* (1965 cruises 6508 and 6510) core-top samples (Table 2; University of Miami RSMAS 1965 cruise data, unpublished records, Miami, FL); (C) Nile shelf, 27 RV *Chain* (1977 cruise 119) grab samples (nos. 4–27 in Table 1; WOODS HOLE OCEANOGRAPHIC INSTITUTION, 1975; SUMMERHAYES et al., 1978); (D) Nile Cone proper, 6 RV *Pillsbury* (1965 cruises 6508 and 6510) core-top samples on the slope seaward of the Nile shelf (Table 3; University of Miami RSMAS 1965 cruise data, unpublished records, Miami, Florida); (E) Gaza-Israeli shelf, 13 core-top samples (Table 4; Geological Survey of Israel 1963 data collection, published records, Jerusalem, Israel; NIR, 1984); (F) Israel shallow nearshore, 10 grab samples recovered in 1983–1985 (Table 5; collected by E. Galili, Marine Branch, Israel Antiquities Authority, Atlit, Israel, unpublished records and WEINSTEIN-EVRON, 1994); (G) Israel shelf off the port of Ashdod, 5 grab samples collected in late May 1995 (Table 6; col-

Figure 5. Low altitude aerial photographs of Gaza and Israeli coasts, taken on 2 June 1995. (A) over Gaza, showing broad sandy strandplain and suspended sediment along coast and view toward NE Sinai in distance. (B) view of Akko and in distance, toward SE, dune covered coast in Haifa Bay, Israel, a major sand sink on the Levant margin. (C) broad sand strandplain and offshore suspended sediment near Gaza-Israel border (NE to right). (D) coastal cliff exposure at Natanya, Israel (NE to left). E, F, view of coastal plain at Dor, Israel, showing tombolo and natural sediment entrapment, primarily sand, behind kurkar islands (NE to left).

lected by A. Golik, Israel Oceanographic and Limnological Research, Ltd., Haifa, Israel, unpublished records); and (H) eastern Nile Cone off Israel, 13 core-top samples taken in 1963 (Table 7; Geological Survey of Israel 1963 data collection, published records, Jerusalem, Israel; NIR, 1984).

Proportions (by weight) of mud [clay (<2 μm) plus silt (2–63 μm)], sand (63–2000 μm) and granule (>2000 μm) were determined by sieving a representative cut of each bulk sample. From a separate cut, the <1 mm fraction was analyzed for grain size parameters, including percentage of clay (by

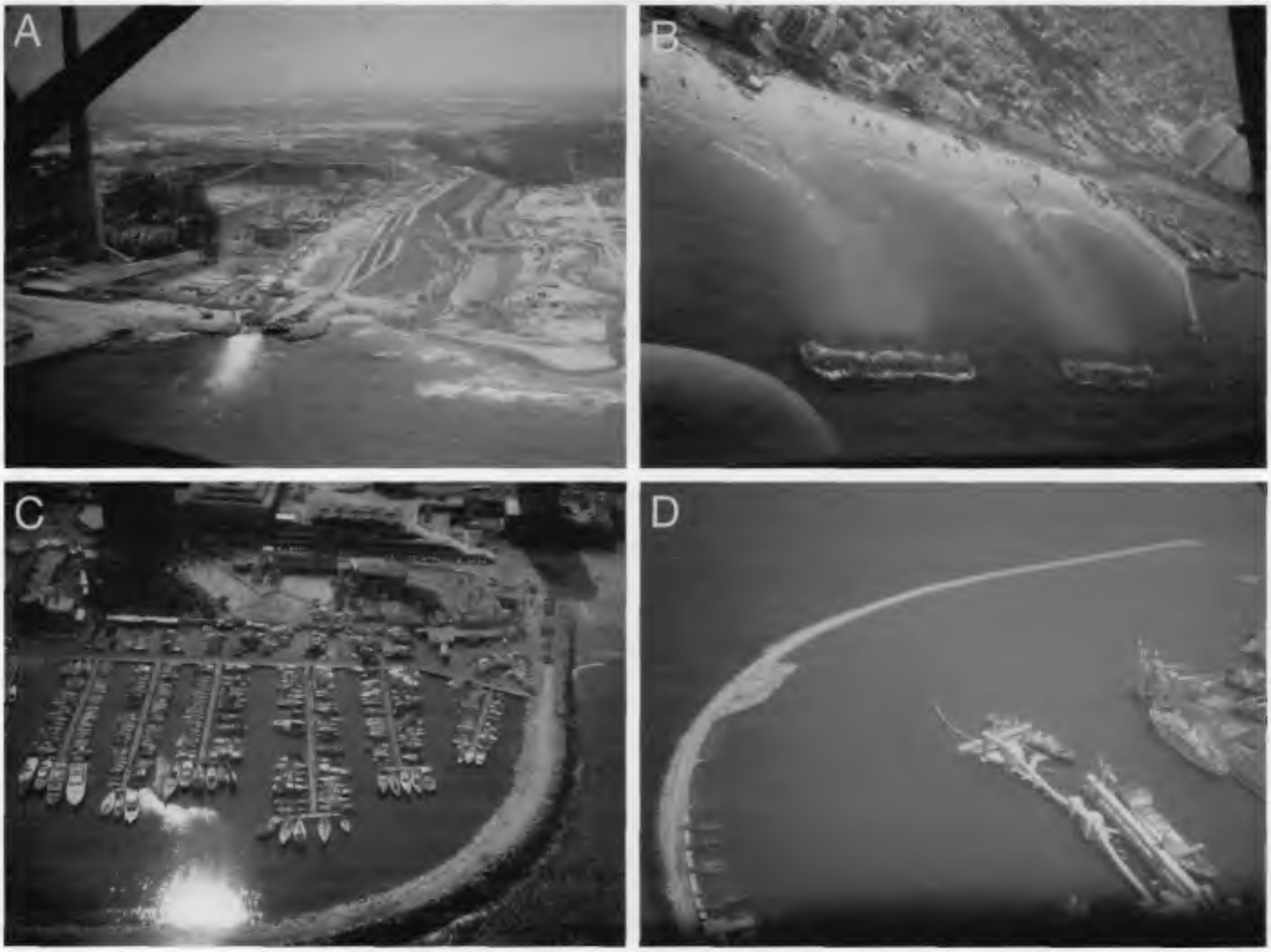

Figure 6. Low altitude aerial photographs of Israeli coast, taken on 2 June 1995. (A) coast at Hadera showing completely modified river outlet and shoreline (NE to left). (B) coastal sedimentation modified by artificial structures off Tel Aviv (NE to left). (C) coast-modified sediment dispersal at marina, Tel Aviv (NE to left). (D) long, arcuate jetty at Ashdod port (NE to right).

volume) and grain size statistics (mean, mode, median) using a Coulter LS-100® particle size analyzer.

In some earlier studies, clay mineral composition from this region was determined by settling of fine-grained particles and concentrating clay minerals (<2μm) from slurry onto a glass slide. This method tends to artificially alter the proportion of certain clay minerals as a function of settling rate and size; proportions of finer-grained smectite, for example, increased relative to other clay minerals. To minimize this artifact, the now more-commonly used smear-slide method (MOORE and REYNOLDS, 1989) has been used in our 3-part investigation. The clay-sized fraction (<2 μm) was separated by decantation, concentrated by centrifugation, and prepared as smear slide for X-ray diffraction analysis. Diffraction methodology used in the clay analyses for this 3-part study is outlined in STANLEY and WINGERATH (1996). Our primary focus here is on the four dominant mineral groups that form assemblages in this region: smectite, kaolinite, illite and chlorite. Chlorite, for the most part absent in the two previous coastal plain studies, was detected in small but variable proportions at most offshore sites. The proportion of chlorite was determined using a modification from MOORE and REYNOLDS (1989). The area of the 14.9 Å peak (heated scan) is subtracted from the smectite peak 17 Å (glycolated scan), and the proportion of smectite was made equal to the 17 Å (glycolated) peak minus the area of the 14.9 Å peak (heated). Mixed-layered illite/smectite, recognized in some samples, was not separately quantified here.

As in the two previous studies of this investigation, we recognize five clay mineral assemblages (coded **I** to **V**) on the basis of relative percentages of the three prevailing minerals (smectite, kaolinite, illite) in this region: **I** = high smectite (>70%), moderate kaolinite (20–29%), low illite (<10%); **II** = high smectite (>70%), low kaolinite (<20%), low to moderate illite (<10–19%); **III** = moderate smectite (40–69%), high kaolinite (>30%), variable amount of illite (<10%->20%); **IV** = low smectite (<40%), high kaolinite (>30%), moderate to high il-

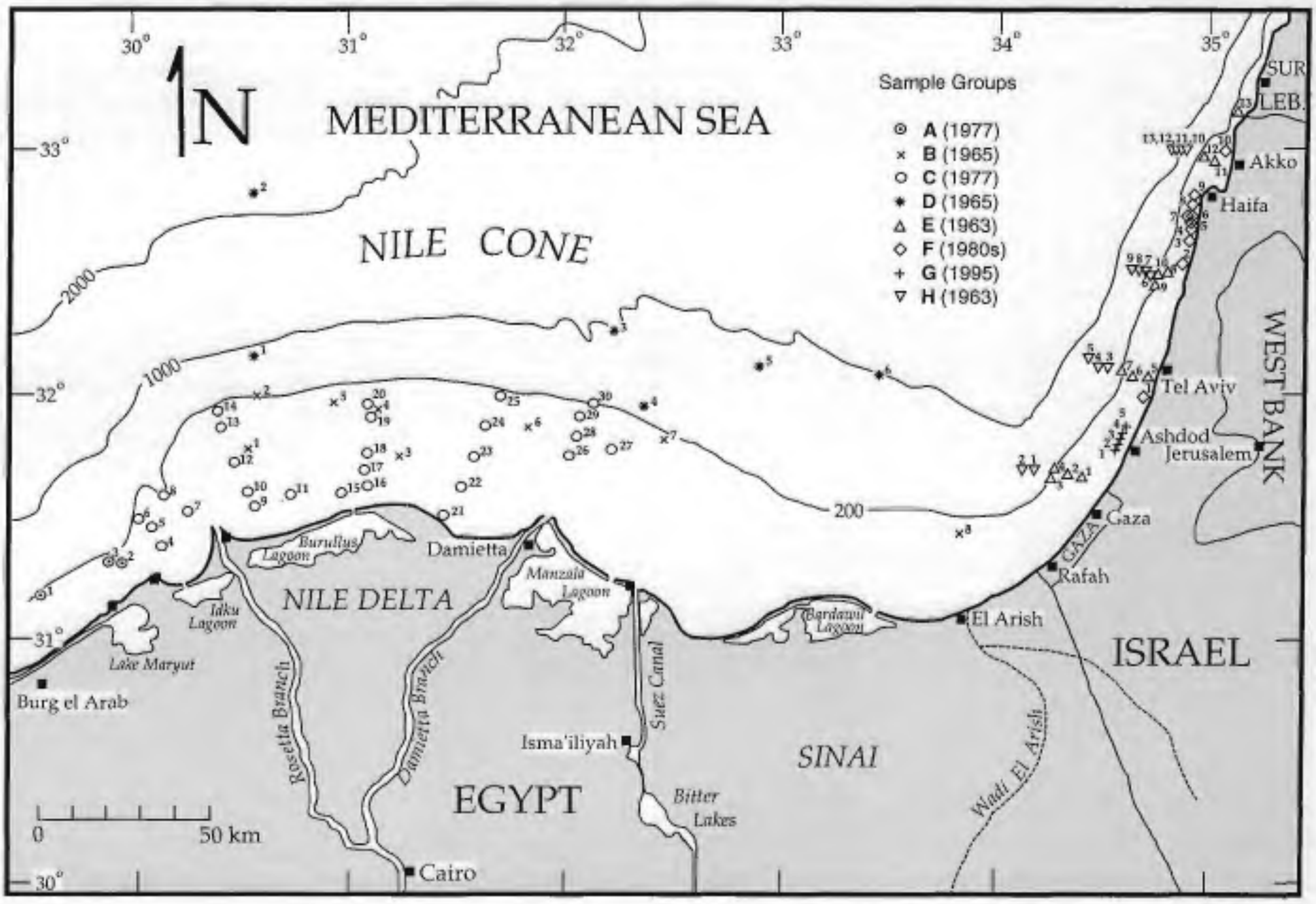

Figure 7. SE Mediterranean study area showing positions of offshore surficial sample sites (grabs, core-tops); the 85 samples collected from 1963 to 1995 are assembled into 8 groups (**A-H**; Tables 1–7).

lite (10->20%); and **V** = moderate smectite (40–69%), moderate kaolinite (20–29%), low to moderate illite (<10–19%).

Each of the 85 offshore samples examined herein is assigned one of the above five clay mineral assemblage types (Tables 1–7). Moreover, chlorite content (ranges from 1 to 9%) is also considered, and two very general groups are identified: samples with relative percentages <4% and those with >4%. Diffractograms of several representative clay assemblages are shown in Figure 8.

Mineral content is recorded as relative percentage and, accordingly, clay mineral values are inversely related, *i.e.* high proportions of smectite are usually accompanied by lower kaolinite plus illite, and vice versa. There are limitations in calculating mineral proportions, and we consider the clay mineral values presented herein only as semi-quantitative. To help further distinguish regional trends, we have compiled 3 additional average percentage values, *i.e.,* smectite + kaolinite, kaolinite + illite and illite + chlorite. Percentages for each of the 8 sample groups (**A-H**) in Tables 1 to 7 are averaged and listed in Table 8.

The complete sets of grain size analyses and diffractograms obtained for the 211 samples in this investigation are archived in the Sedimentology Laboratory Data Bank, at the National Museum of Natural History, Smithsonian Institution, Washington, D.C.

OBSERVATIONS

Texture

Seven textural parameters were measured for each of the 85 samples in the 8 sample groups (Tables 1 to 7). There is large grain-size variability within and among groups **A-H**, and textural parameters show no strong or consistent relationships among various grain-size components (granules, sand, silt+clay,% clay), nor among proportions of different grain sizes and mean, mode and median.

The range of total percent clay and mean grain size in samples of each group is as follows:

A, 16–19%; 30–215 μm, **D**, 31–40%; 7–34 μm, **G**, 2–4%; 130–144 μm, **B**, 12–39%; 6–216 μm, **E**, 11–32%; 9–136 μm, **H**, 22–38%; 6–18 μm, **C**, 8–39%; 7–398 μm, **F**, 16–39%; 7–116 μm.

These data show that only in groups **D** and **H**, collected on the Nile Cone, are moderate to high total percentages of clay

Table 1. *Clay mineral and textural data for samples (n = 3) in group A (western Nile delta shelf) and 27 samples in group C (Nile delta proper) collected on RV* Chain *cruise 179 in 1975 (Woods Hole Oceanographic Institution, 1975).*

Groups A(samples #1–3) and C(samples #4–30): Nile Delta Shelf (RV *Chain* cruise 179)													
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	189	IV	33	40	20	7	6.84	66.28	26.88	16.4	214.6	262.3	161.9
2	08	III	43	37	16	4	0.58	43.38	56.04	17.2	86.23	99.9	37.4
3	05	IV	35	39	22	4	0.0	3.2	96.8	18.8	29.6	52.5	20.0
4	33	III	55	31	11	3	0.0	27.54	72.46	28.9	23.2	4.5	6.2
5	31	III	54	32	12	2	0.32	0.97	98.71	22.8	12.8	22.3	7.8
6	30	III	45	37	16	2	2.30	14.87	82.83	26.4	44.9	5.0	5.8
7	55	V	65	25	7	3	0.10	0.10	99.80	24.2	10.9	16.2	6.6
8	60	III	53	34	11	2	0.0	0.59	99.41	25.7	15.7	5.0	6.2
9	39	III	54	30	14	2	0.0	0.22	99.78	24.2	12.1	16.2	6.5
10	41	III	56	30	12	2	0.27	25.28	74.45	17.9	73.4	291.9	15.9
11	91	V	58	27	12	3	0.0	30.60	69.40	15.1	69.1	235.6	17.8
12	45	III	50	32	13	5	35.02	46.46	18.52	12.5	398.3	766.3	468.3
13	47	III	44	37	16	3	3.74	36.93	59.33	23.3	122.6	766.3	8.6
14	48	III	54	33	10	3	4.37	53.70	41.93	18.8	187.8	688.4	17.3
15	89	II	70	18	8	4	0.22	72.62	27.16	3.8	216.2	99.9	119.8
16	106	V	61	27	9	3	0.20	79.50	20.30	7.6	97.3	111.2	91.9
17	108	III	46	36	14	4	2.42	58.3	39.27	13.2	65.7	123.8	48.3
18	87	III	54	30	14	2	0.43	22.97	76.60	22.8	24.5	13.0	9.1
19	111	III	44	34	15	7	9.95	69.69	20.36	18.5	286.2	766.3	173.9
20	112	III	46	35	13	6	8.51	77.95	13.54	9.2	383.0	766.3	383.6
21	172	V	55	26	11	8	0.0	69.34	30.66	7.7	76.0	99.9	82.5
22	169	III	50	34	13	3	0.0	2.69	97.31	23.0	14.6	20.0	8.2
23	166	III	43	33	17	7	27.41	55.27	17.32	19.9	299.3	766.3	26.9
24	164	IV	39	36	20	5	14.51	79.92	5.57	9.3	394.5	688.4	406.5
25	162	III	44	39	13	4	7.93	65.23	26.84	11.0	343.5	688.4	318.0
26	154	III	45	38	14	3	0.0	0.19	99.81	29.3	11.9	5.0	4.8
27	148	III	46	33	16	5	0.0	2.74	97.26	32.03	11.2	4.7	4.1
28	153	III	48	36	13	3	1.23	14.50	84.27	28.4	70.5	1.1	6.2
29	152	III	46	37	11	6	11.08	69.82	19.10	38.6	7.2	1.1	3.2
30	150	IV	39	39	18	4	0.05	22.51	77.44	28.6	44.9	1.1	6.3

(range=22–40%) associated with smaller mean grain size (range=6–34 μm). Textural analysis of samples in the other 6 groups record no close or consistent relationship between total amount of clay and mean grain size.

To determine if proportions of clay minerals are in some way related to grain size, 56 scatter plots were generated. These diagrams depict proportions of each of the four individual minerals (smectite, kaolinite, illite, chlorite) against (1) total percent clay and (2) mean grain size for each of samples in the 8 groups. Most of the scatter plots (36 of the 56) show highly irregular patterns with no statistically significant correlation among grain size, total percentage of clay and the four specific clay minerals considered for the 8 groups. Two examples of such random plots are shown in Fig-

Table 2. *Clay mineral and textural data for samples (n = 8) in group B (Nile delta shelf) collected on RV* Pillsbury *cruises 6508 and 6510 in 1965 (University of Miami RSMAS, 1965 cruise data, unpublished records).*

Group B: Nile Delta Shelf (RV *Pillsbury* cruises 6508 and 6510)													
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	P6508-39	V	57	30	12	2	37.90	45.35	16.75	11.8	173.0	770.7	224.3
2	P6508-38	III	45	38	14	3	0.00	3.02	96.98	21.0	55.4	190.1	8.1
3	P6508-41	III	50	37	11	2	4.08	66.46	29.46	11.9	215.5	153.4	130.1
4	P6510-08	III	51	32	14	3	4.6	61.64	33.76	36.5	6.1	16.2	3.6
5	P6510-10	III	54	32	11	3	11.96	44.31	43.73	18.4	170.7	766.3	24.6
6	P6508-42	III	54	34	11	1	9.66	28.86	61.48	30.6	13.7	5.0	4.7
7	P6508-44	III	55	36	8	1	1.14	2.66	96.2	36.5	9.4	1.2	3.3
8	P6508-48B	III	50	38	9	3	0.00	2.36	97.64	38.5	7.2	2.6	2.6

Table 3. *Clay mineral and textural data for samples (*n *= 6) in group D (Nile Cone proper) collected on RV* Pillsbury *cruise 6508 in 1965 (University of Miami RSMAS, 1965 cruise data, unpublished records).*

Group D: Nile Cone Proper (RV *Pillsbury* cruise 6508)														
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)				
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	P6508-37	III	45	37	16	2	0.88	1.23	97.89	35.8	8.6	2.9	3.2
2	P6508-36	IV	35	46	14	5	0.00	7.23	92.77	35.8	9.9	2.6	3.1
3	P6508-46	III	42	35	20	3	0.00	2.29	97.71	39.5	7.7	2.3	2.7
4	P6508-45	III	45	39	14	2	0.08	6.01	93.91	33.5	9.5	2.7	2.9
5	P6508-47	III	53	36	9	2	0.00	2.11	97.89	40.1	6.5	2.3	2.7
6	P6508-48	III	45	39	15	1	0.00	3.05	96.95	31.4	34.2	2.6	3.2

ure 9C and D. This indicates that for most samples, there is no evidence of size-sorting, *i.e.* direct relation between clay mineralogy and grain size.

Several exceptions are noted: (1) illite proportions in groups **B** and **F** tend to increase with increased mean grain size (Figure 9A); (2) illite in groups **B** and **F** also tends to decrease with increased proportion of clay (Figure 9B); (3) in some sample groups (**D**, **F**, **H**), percentage of chlorite increases somewhat with increased proportions of clay; and (4) kaolinite tends to increase with increased grain size in groups **A**, **C** and **F**. Of the 8 groups, only clay minerals in **F**, collected nearshore at shallow depths (Pleistocene, early Holocene) in proximity to the Israeli coast, record some general trends between clay mineral content and texture. This latter observation suggests that clay mineral assemblages in some group **F** samples have been influenced by size-sorting phenomena. This observation in group **F** records the importance of original deposition in a proximal terrestrial environment; an example is the small delta at the mouth of the Oren river now submerged offshore in the Atlit region.

Clay Mineral Distributions

Westernmost Nile Delta Shelf

Sample group **A**, the westernmost Nile shelf samples collected off Alexandria and Abu Qir in 1977 (Table 1), are distinct from all samples taken to the east, *i.e.* on the Nile shelf, and on the Nile Cone to the north (Table 8). Average mineral proportions in this sector are characterized by relatively low proportions of smectite (37%) and somewhat higher values of illite (19%) and chlorite (5%) than on the Nile delta shelf proper; kaolinite percentages (37–40%), however, are comparable to those recorded on the Nile Cone and inner Israeli shelf. Clay assemblages in this sector are primarily of type IV, and similar only to those of group **F** recovered in the 1980's in sectors of the central to northern Israeli shelf; as noted above, samples of this group originally were of shallow, nearshore terrestrial origin (Figure 10B).

Nile Shelf

Group **B**, samples recovered on Nile and Sinai shelves in 1965, record the following average mineral proportions: 52%

Table 4. *Clay mineral and textural data for samples (*n *= 13) in group E (Gaza-Israel shelf) collected in 1963 by Y. Nir (Geological Survey of Israel, 1963 data collection; NIR, 1984).*

Group E: Gaza-Israeli Shelf (Collected by Y. Nir, Geological Survey of Israel, 1963)													
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	YN1501	V	57	28	11	4	0.04	1.77	98.19	21.9	21.6	42.4	10.1
2	YN1502	III	44	34	17	5	0.00	0.43	99.57	26.4	12.7	27.6	6.4
3	YN1507	III	54	31	11	4	0.00	0.05	99.95	31.9	8.8	4.5	4.1
4	YN1504	IV	39	40	16	5	0.05	0.00	99.95	31.7	9.1	5.5	4.4
5	YN1523	III	46	36	14	4	1.66	60.45	37.89	11.0	136.2	111.2	88.2
6	YN1525	III	49	31	15	5	0.04	17.75	82.21	23.7	21.4	65.1	7.9
7	YN1526	III	49	30	16	5	0.00	1.92	98.08	24.8	16.6	38.1	7.2
8	YN1543	III	50	32	13	5	1.02	14.13	84.85	28.6	21.5	72.5	6.3
9	YN1546	III	46	34	14	6	0.00	0.60	99.40	30.4	10.6	1.2	4.8
10	YN1545	III	53	31	13	3	0.00	0.97	99.03	31.7	10.4	1.4	4.3
11	YN1569	III	51	30	14	5	0.15	28.86	70.99	16.2	40.7	72.5	38.8
12	YN1570	III	48	36	13	3	1.20	23.78	75.02	21.7	36.8	89.9	13.6
13	YN1580	III	46	35	15	4	1.86	24.90	73.24	23.9	28.5	72.5	10.0

Table 5. *Clay mineral and textural data for samples (n = 10) in group F (Israel nearshore) collected in the 1980's by E. Galili (Marine Branch, Israel Antiquities Authority, Atlit, Israel, unpublished records).*

Group F: Israel Nearshore (collected by E. Galili in 1983–1985)														
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	G17	V	58	27	13	2	0.43	33.88	65.69	30.7	14.1	47.2	5.6
2	G20	IV	15	51	33	1	0.18	45.78	54.04	15.9	115.9	190.1	128.6
3	G18	IV	33	41	23	3	0.00	33.19	66.81	20.5	75.9	170.8	32.4
4	G22	III	53	33	12	2	0.00	29.37	70.63	35.3	21.6	1.4	3.5
5	G19	IV	33	37	28	2	0.14	16.12	83.74	21.2	114.9	235.6	13.6
6	G16	IV	31	39	25	5	0.16	7.33	92.5	23.8	16.5	42.4	8.2
7	G13	III	42	34	19	5	1.08	18.16	80.76	26.4	41.3	52.5	8.1
8	G15	III	44	38	13	5	0.16	7.33	92.5	23.8	16.5	42.4	8.2
9	G14	IV	20	46	25	9	0.71	4.84	94.45	32.4	38.8	0.9	5.1
10	G21	IV	25	48	21	6	0.91	9.17	89.92	39.3	6.7	1.5	2.8

smectite, 35% kaolinite, 11% illite and 2% chlorite (Table 8). Average clay proportions of group **C** (Table 1) taken on the Nile shelf in 1977 are: 50% smectite, 33% kaolinite, 13% illite and 4% chlorite. Similarity of both textural and mineral attributes of Nile shelf groups **B** and **C**, collected twelve years apart, is of note (Table 8, Figure 10A): both are smectite-rich and record very large range of grain size (Tables 1, 2). Moreover, clay assemblages in both **B** and **C** are primarily of type III, and proportions of clay minerals are similar to those in Nile Cone and Israeli margin samples (groups **D, E, G, H**) collected in 1963 and 1965 (Figure 10A). Samples of group **C** that were collected on the inner Nile shelf are characterized by somewhat higher proportions of smectite (to 60–70%) and some are of assemblage type II; values here are intermediate between those in the Nile delta proper (>70%; type I) and those farther seaward on the mid- to outer-Nile shelf (most <55%; type III).

Nile Cone off Nile Shelf

Average clay mineral proportions of group **D** on the Nile Cone, north of the Nile shelf, collected in 1965 are: 44% smectite, 39% kaolinite, 15% illite and 2% chlorite (Table 8). Most Cone clay samples are defined by assemblage type III (Table 3), and while generally similar to those on the Nile shelf (groups **B, C**), typically comprise slightly higher proportions of kaolinite and illite. As recorded in Figure 10A, proportions of clay minerals in group **D** are also comparable to those on the Israel shelf (groups **E, G**) and eastern Nile Cone off Israel (group **H**).

Gaza and Israeli Shelves

Group **E** samples collected in 1963 on Levant shelves record the following average clay percentages: 49% smectite, 33% kaolinite, 14% illite and 4% chlorite (Table 8). These values (defining assemblage III; Table 4) are similar to those on the Nile delta shelf (groups **B, C**), Nile Cone (group **D**) and eastern Nile Cone (group **H**) seaward of the Israeli shelf (Figure 10A).

Samples of group **F** collected between 1983 and 1986 along the shallow Israeli nearshore were taken from muds of alluvial origin that accumulated primarily at the end of the Pleistocene and early Holocene (WEINSTEIN-EVRON, 1994). These pre-modern relict muds are now exposed locally as surficial patches of small to moderate size surrounded by modern sediment, usually sand (GALILI *et al.*, 1993). Average values are: 36% smectite, 39% kaolinite, 21% illite and 4% chlorite (Table 8). It is of note that group **F** clay mineral values (assemblages III, IV and V; Table 5; Figure 10B) are almost identical to those recorded for the shelf samples west of the Nile delta proper (group **A**). In contrast, group **F** clay mineral values differ markedly from those of the Nile shelf and Nile Cone

Table 6. *Clay mineral and textural data for samples (n = 5) in group G (off the Port of Ashdod, Israel) collected in 1995 by A. Golik (Israel Oceanographic & Limnological Research, Ltd., Haifa, Israel, unpublished records).*

Group G: Off Port of Ashdod, Israel (collected by A. Golik in 1995)													
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	A-A8	III	50	32	14	4	0.09	88.59	11.32	3.6	134.5	153.4	139.0
2	A-B7	III	47	33	16	4	0.0	93.32	6.68	2.4	143.6	153.4	145.7
3	A-D8	III	52	32	13	3	0.6	86.15	13.25	4.2	132.1	153.4	137.5
4	A-E7	V	54	29	14	3	0.04	93.61	6.35	2.6	139.5	153.4	140.6
5	A-E8	III	47	34	16	3	0.09	87.0	12.91	3.8	129.6	153.4	134.3

Table 7. *Clay mineral and textural data for samples (n = 13) in group H (eastern Nile Cone) collected in 1963 by Y. Nir (Geological Survey of Israel, 1963 data collection; NIR, 1984).*

Group H: Eastern Nile Cone (Collected by Y. Nir, Geological Survey of Israel, 1963)													
			Major Clay Minerals (%) (semi-quantitative values)				Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
Code #	Smpl #	Clay Mineral Assem.	Smectite	Kaolinite	Illite	Chlorite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1	YN1508	III	53	30	12	5	0.00	0.03	99.97	32.5	7.4	5.0	3.9
2	YN1509	III	50	30	14	6	0.18	0.36	99.46	24.6	13.3	22.3	6.9
3	YN1528	III	54	30	13	3	0.12	0.68	99.2	29.5	9.3	5.0	4.4
4	YN1530	V	54	28	14	4	0.00	0.15	99.85	28.7	10.3	7.6	5.1
5	YN1532	III	45	34	16	5	0.00	0.17	99.83	38.4	6.1	1.2	3.0
6	YN1547	III	51	30	14	5	0.00	0.31	99.69	31.6	9.7	4.0	4.1
7	YN1548	V	55	27	14	4	0.00	0.21	99.79	30.8	8.9	4.5	4.3
8	YN1549	III	48	32	15	5	0.00	0.13	99.87	33.4	8.6	4.5	3.7
9	YN1550	III	52	31	14	3	0.00	0.30	99.70	22.1	17.7	42.4	9.3
10	YN1572	III	51	31	15	3	0.00	6.45	93.55	31.3	9.6	4.5	4.0
11	YN1574	III	52	31	14	3	0.00	1.77	98.23	34.2	7.3	4.0	3.5
12	YN1576	III	50	34	13	3	0.05	1.89	98.06	30.8	10.2	5.0	4.4
13	YN1578	III	48	34	14	4	0.00	2.92	97.08	28.1	13.1	5.0	5.4

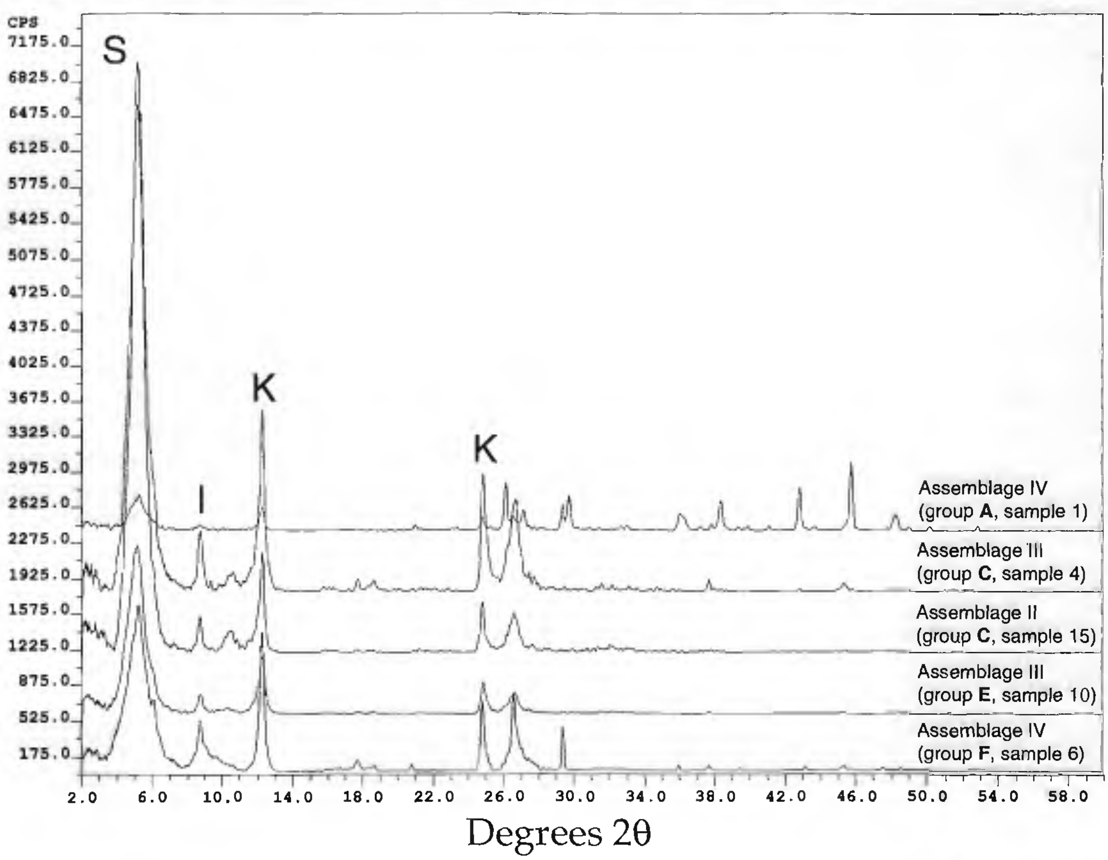

Figure 8. Selected diffractograms of 5 samples from groups **A, C, E** and **F**. Note smectite-rich assemblages in group **C** (assemblages II, III) in contrast with those of groups **A** and **F** (assemblages IV).

Table 8. *Clay mineral data averaged for each of the 8 groups (A–H) in the Levant margin.*

8 Sample Groups (by region and date)	*n* =	Dominant clay mineral assemblage	Sm	K	I	Chl	Sm + K	K + I	I + Chl
A: West of Nile delta shelf (RV *Chain,* 1977)	3	IV	37	39	19	5	76	58	24
B: Nile delta shelf (RV *Pillsbury,* 1965)	8	III	52	35	11	2	87	46	14
C: Nile delta shelf (RV *Chain,* 1977)	27	III	50	33	13	4	83	45	17
D: Nile Cone (RV *Pillsbury,* 1965)	6	III	44	39	15	2	83	53	17
E: Gaza and Israeli shelf (Geol. Survey of Israel, 1963)	13	III	49	33	14	4	82	47	18
F: Inner Israeli shelf (Galili, 1980s)	10	IV	36	39	21	4	75	61	25
G: Ashdod, Israel shelf (Golik, 1995)	5	III	50	32	15	3	82	45	18
H: East Nile Cone (Geol. Survey of Israel, 1963)	13	III	51	31	14	4	82	45	18

(groups **B, C, D**), and from samples recovered between the Nile delta and the Israel-Lebanon border (groups **E, G, H**).

Average clay mineral values in group **G** taken off the Port of Ashdod in 1995 are: 50% smectite, 32% kaolinite, 15% illite and 3% chlorite (Table 8). Although samples of this group comprise only about 4% of sediment examined in this study, the values we obtained (assemblage III; Table 6) are similar to those of groups **B-E** and **G**, collected between 1963 and

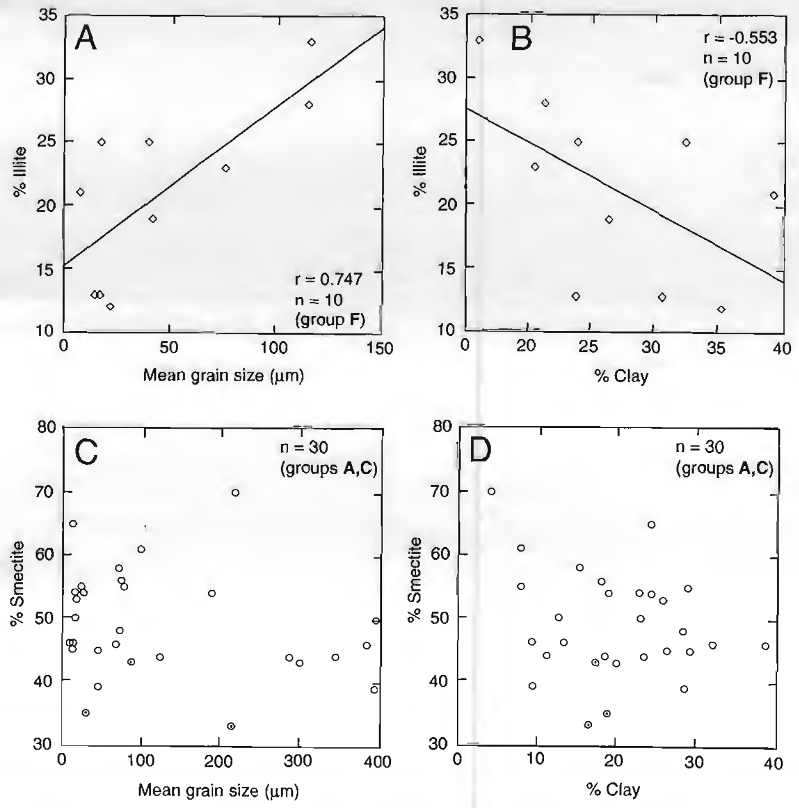

Figure 9. Scatter plots showing selected clay mineral percentages versus mean grain size (µm) and percentage of clay in samples of groups **A**, C and **F**. A, percent illite versus mean grain size for samples in group **F** indicating a positive trend; B, percent illite versus percent clay for samples in group **F** records a general negative trend (lines in plot A and B are regression lines). In contrast, C, D, scatter plots for percent smectite versus mean grain size and percent clay show no significant trends for samples in groups **A** and **C**.

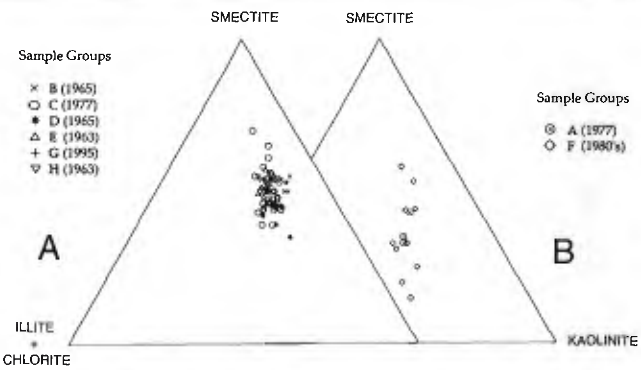

Figure 10. Ternary diagrams to distinguish (A) smectite-enriched samples in groups **B-E, G** and **H** from (B) kaolinite-, illite- and chlorite-enriched samples in groups **A** and **F**. Plots are generated using data in Tables 1–7.

1977 on Nile, Gaza and Israeli shelves and on the Nile Cone (Figure 10A).

Eastern Nile Cone Off Israel

Average clay mineral percentages for group **H,** collected on the eastern Nile Cone off Israel in 1963, are: 51% smectite, 31% kaolinite, 14% illite and 4% chlorite (Table 8). These values (assemblage III; Table 7) closely resemble those of samples in groups **B-E** and **G** collected between 1963 and 1977 on the Nile Cone north of the Nile delta shelf and on Nile, Gaza and Israeli shelves as well (Figure 10A).

Synthesis of Observations

There is considerable textural diversity from sample to sample on the shelves in the study area. The only general trend is one recorded by sediment on the Nile Cone proper (**D**) and easternmost Nile Cone (**H**): samples in these deeper sectors are characterized by finer mean grain size and larger total proportions of clay fractions than those taken on the Nile, Gaza and Israeli shelves (**A-C**, **E-G**). For the most part, textural analyses do not record a direct relation between texture and clay mineral assemblages, nor of size-sorting effects. We suggest that this results, at least in part, from the sampling procedures used; collection of surficial sediments by grabs and core tops recovers material of different Holocene age between the water-sediment interface and 10 cm depth, providing a record of mixed modern and older Holocene sediment. Biogenic activity as well as currents are responsible for this reworking and mixing. We can only infer that the data for samples collected between 1963 and 1995 and considered in the present study provides textural information primarily for surficial seafloor materials that date from the Holocene to about this mid-century, that is, until about the time of closure of the High-Dam.

With regards to mineralogy, 6 of the 8 sample groups indicate an offshore distribution over the study area of generally similar, but not identical, clay mineral assemblages. Two clay mineral suites are recognized (Figure 10). The first suite (groups **B-E, G, H**) comprises mostly assemblage III characterized by moderate proportions of smectite and high kaolinite and high smectite + kaolinite values (Table 8). The second suite (groups **A** and **F**) includes mostly assemblage IV with generally lower proportions of smectite and higher kaolinite, and high kaolinite+illite and illite+chlorite values. In sections that follow, clay distributions in each of the 8 offshore sample groups are compared with distributions of clay mineral assemblages previously mapped on the adjacent coastal plain.

COMPARISON BETWEEN OFFSHORE AND COASTAL ASSEMBLAGES

Nile Delta Shelf and Cone Sector

The northern Nile delta plain is characterized by clay mineral assemblages I and II, *i.e.* those with consistently high proportions (60–80%) of smectite (Stanley and Wingerath, 1996). Proportions of kaolinite in the Nile delta range to 25% near the coast. Illite values are usually much lower (generally ~10% or less) on the delta plain near the coast, and chlorite is either absent or present only in trace amounts. In contrast, eolian dust over NE Egypt, comprises higher proportions of kaolinite (to ~40%) and illite (to >20%) (*cf.* Chester *et al.*, 1977). This wind-blown material is derived from North African and Middle East deserts (Murray, 1951; Yaalon and Ganor, 1973, 1979; Chamley, 1988), Pliocene-Pleistocene River Nile valley sections in Upper and Middle Egypt, and some earlier geological exposures.

Composition of samples just seaward of the Nile delta is similar to that of sediment mapped on adjacent land regions. For example, the coastal plain to the north and west of Abu Qir and southwest of Alexandria is carbonate-rich and smectite-poor. In parallel, offshore clay assemblages at this westernmost boundary of the Nile delta shelf are characterized by much lower proportions of smectite and higher values of kaolinite, illite and chlorite (assemblage IV) and are markedly distinct from those in the Nile delta proper.

Smectite content increases abruptly (assemblage III) on the shelf north and east of Abu Qir bay, recording the marked input of Nile-derived sediment. Moreover, proportions of smectite are highest, and kaolinite lowest (assemblage II, III), in a delta coast-parallel belt on the inner Nile shelf (Figure 12). Examples include RV *Chain* cruise 119 samples 7 and 15, taken off Rosetta promentory and Burullus lagoon outlet (Figure 7), which are characterized by clay mineral proportions that approximate those on the adjacent Nile delta (assemblage II; Table 2). Seaward assemblages (III), including those on the Nile Cone (also III), are generally comparable with those on the Nile shelf (almost identical smectite+kaolinite values). On the Cone proper (group **D**), however, amounts of kaolinite are somewhat increased relative to smectite (Table 8).

Suez Canal to Gaza Sector

Clay minerals along the western Sinai coastal plain between the northern Suez Canal and Bardawil lagoon (assemblages II and III) are similar to those in Holocene deposits on the Nile delta proper (assemblages I and II). In contrast,

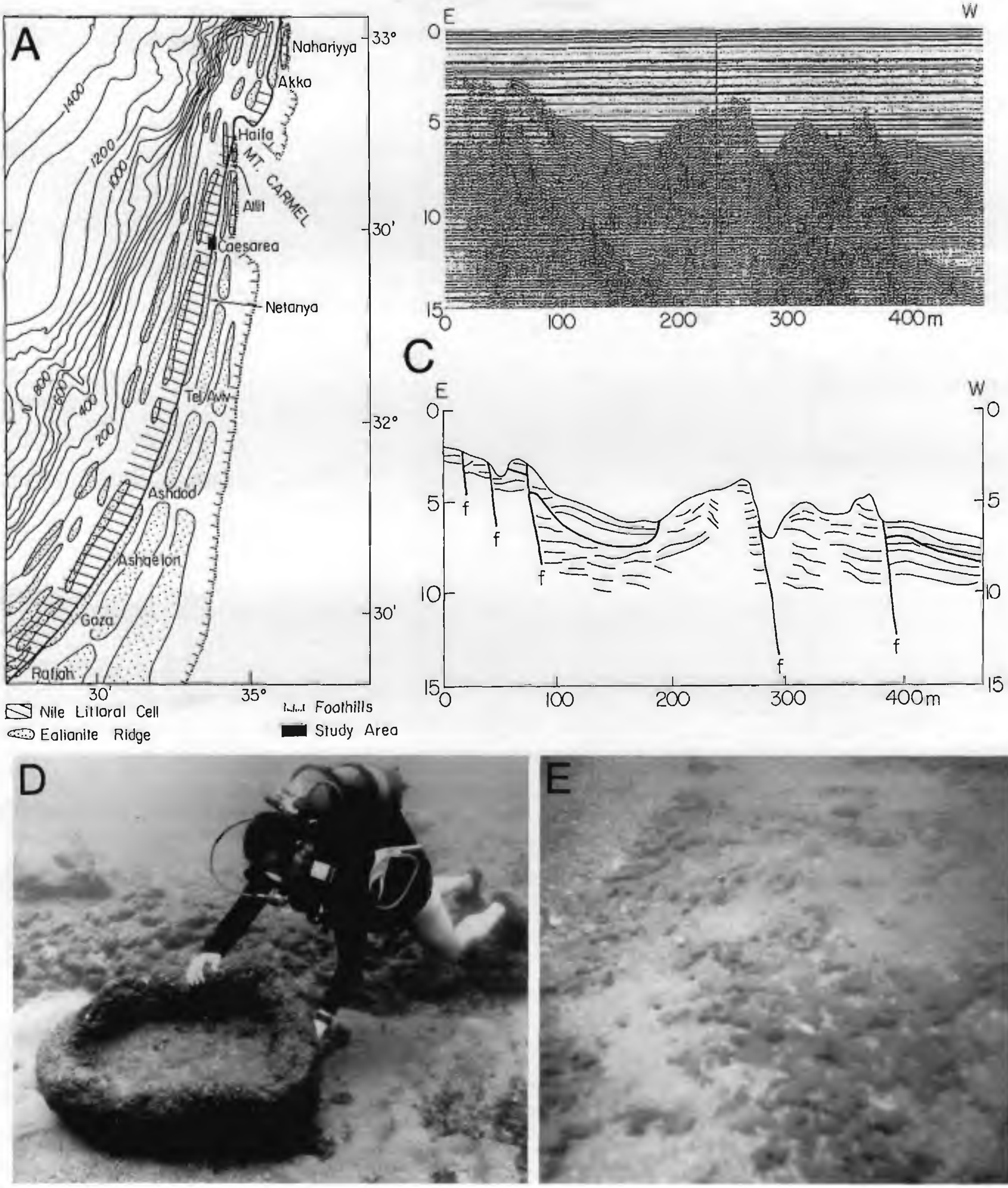

Figure 11. (A) elongate kurkar (carbonate-cemented sand) ridges on the coastal plain and shelf off the Levant margin, between Gaza and northern Israel. (B) east-to-west seismic reflection profile across ridge-and-trough seafloor topography just west of Caesarea, Israel. (C) interpretation of profile in B, showing exposed Quaternary carbonate-cemented sand ridges and sediment-filled depressions between ridges (A-C are modified after MART and PERECMAN, 1996). (D) current eroded sandy inner shelf sector off Atlit, northern Israel, on which a prehistoric stone basin, probably used for crushing olives, is exposed. (E) inner shelf sands eroded by storm currents at Atlit; sand (light) has been partially removed, revealing extensive exposures of late Pleistocene to early Holocene mud (dark) and Pre-Pottery Neolithic artifacts (see D), formerly buried by sand.

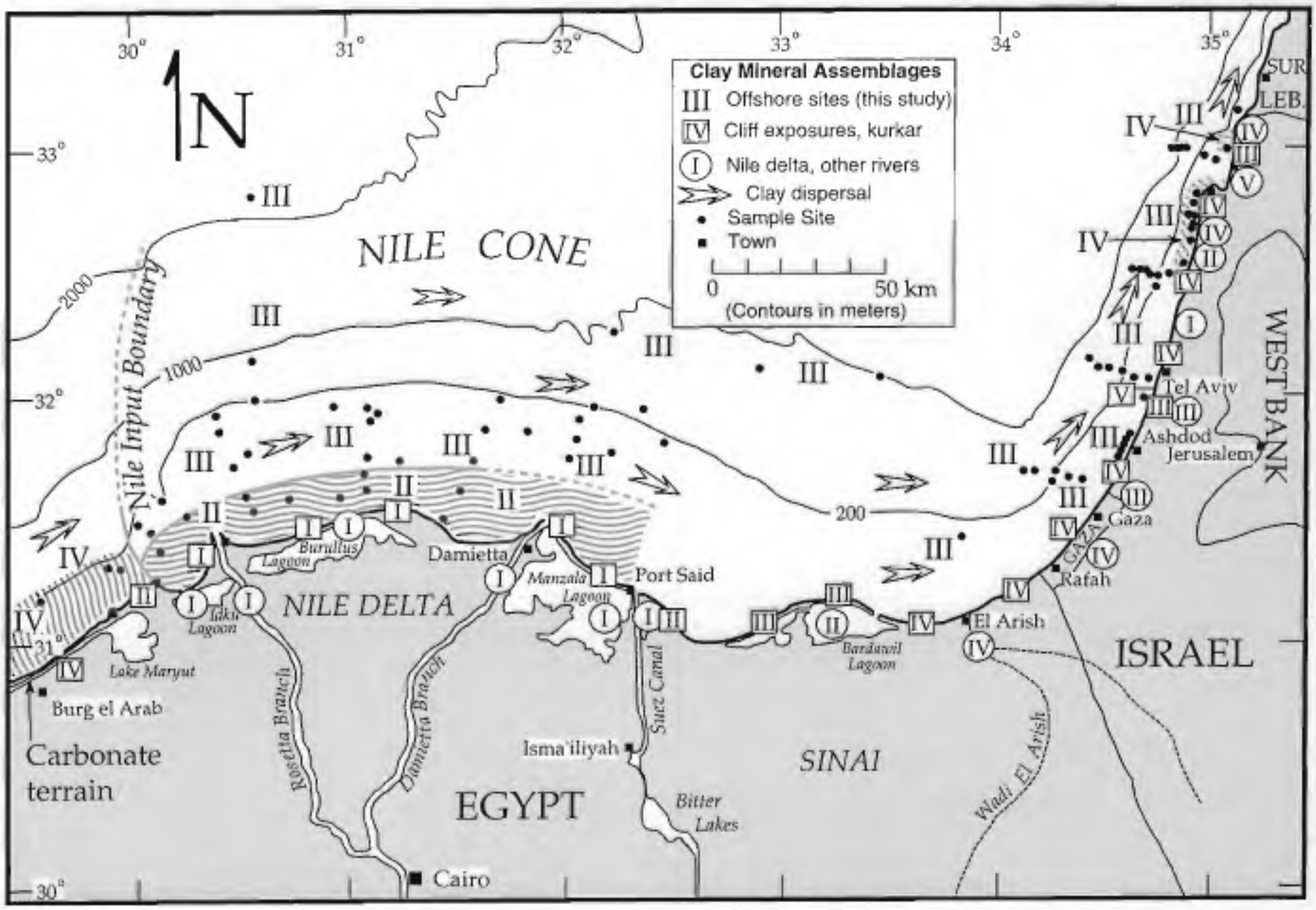

Figure 12. Synthesis of clay mineral provenance and dispersal from the 3-part study in the SE Mediterranean. Depicted dominant clay assemblages include those in the lower Nile system [Roman numerals in circles; simplified from STANLEY and WINGERATH (1996)], and in rivers (Roman numerals in circles) and coastal exposures (Roman numerals in boxes) east of the Nile delta [simplified from STANLEY *et al.* (1997)]. Some offshore clay mineral assemblages (larger open Roman numerals, this study) are derived from these coastal sources, from dust released from wind and also some submarine erosion of shelf floors. Most active dispersal (arrows) occurs along shore-parallel belts, especially between coasts and mid-shelves. Of note are clays transported from and along the Nile delta (horizontal wavy pattern). Assemblages distinct from that of the Nile occur immediately west of the delta, and off the Carmel coast of Israel (near-vertical wavy pattern).

the eastern Sinai margin east of Bardawil lagoon and along the Gaza coast is characterized by diminution of smectite and markedly increased proportions of both kaolinite and illite (assemblage IV). Clays in Bardawil lagoon and locally in the late Pleistocene-Holocene stiff muds on some coastal barriers (below Mt. Casius, for example) that separate this shallow wetland from the sea (assemblages III, IV) comprise markedly increased proportions of kaolinite (to 45%) and illite (to 30%), and smaller amounts of smectite (<45%). Larger proportions of kaolinite and illite in the eastern part of this coastal sector record an important input of dust released from seasonally variable winds that blow across the wide desert expanse south of Bardawil lagoon. Also in sharp contrast with the Nile is the clay assemblage at Wadi El Arish, farther to the east, which comprises to 53% kaolinite, 19% illite and only 28% smectite (assemblage IV). Enhanced proportions of kaolinite in the Wadi El Arish drainage area are derived primarily from the varied source terrains exposed in the Sinai, mainly Upper Cretaceous clays, marls and Holocene loess layers.

Clays in shelf and Nile Cone samples off Sinai (assemblage III) are generally similar to those of the Nile shelf to the west (III). However, they can be readily distinguished from clays on land to the south, *i.e.* the western Sinai coastal plain (smectite-rich assemblage II), and the Wadi El Arish margin (kaolinite-rich assemblage IV) on the eastern Sinai plain.

Gaza to Northern Israel Sector

Clay mineral assemblages between Gaza and Israel's northern coastal plain are much more variable than along the longer stretch extending from the western Nile delta to the eastern Sinai plain (BENTOR, 1966). This is in part related to sediment input from the diverse fluvial network along this margin (STANLEY *et al.*, 1997). Small channels on the coastal plain in Gaza and southernmost Israel and, farther to the north, on the Carmel plain to the Israel-Lebanon border, comprise relatively high proportions of kaolinite, and only moderate to low amounts of smectite (assemblage IV). Comparably high proportions of kaolinite (assemblage IV) also characterize most coastal cliff exposures and some inland kurkar ridges, from Gaza to north of Haifa Bay in northern Israel (Figure 11A). The relatively high percentages of kaolinite and illite and smaller proportions of smectite in many Gaza to northern Israel coastal exposures are comparable to clay mineral assemblages in some eolian dust transported in the SE Levant region (YAALON and GANOR, 1973, 1979; CHESTER *et al.*, 1977). Clay mineral values in Israeli coastal cliff and kurkar ridge deposits and a few rivers sampled east of the Nile delta more closely resemble eolian dust assemblages than Nile sources (STANLEY *et al.*, 1997).

In contrast with the above-cited kaolinite-rich coastal sources are fluvial sites on the Israeli margin characterized by >50% smectite. Several small river and wadi channels flowing across the central Israeli plain, mostly from south of Tel Aviv to the Carmel coast, transport higher amounts of smectite and lower proportions of kaolinite and illite (assemblages II, III) than coastal exposures in the same area (III, IV). In particular, the 50 km-long stretch of Sharon plain north of Tel Aviv is characterized by large smectite values (assemblage I), comparable to those recorded along the Nile delta coast.

About one quarter of the fluvial samples in Gaza and Israel comprise roughly equivalent values (~40% or less) of smectite, kaolinite and illite (assemblage IV). Moreover, a particularly high proportion (to~40%) of illite was recorded south of Haifa (near Atlit) in both nearshore (group **F**) and coastal exposures on the northern Israeli coast; it is recalled that these include some late Pleistocene to Holocene fine-grain materials.

Clay mineral assemblage III defines most offshore surficial samples east of the Nile delta, as well as those on the mid- to outer-Levant shelf and on the eastern Nile Cone (Tables 1–7). Many samples taken on the innermost Israeli shelf (group **F**) differ from the above in that they are characterized by assemblage IV. It is noted that clays in these nearshore Israeli samples are more similar to samples collected in adjacent Israel coastal plain exposures and fluvial systems (I-V) than to offshore Levant assemblages (III). We also find that group **F** samples resemble those of group **A** (also assemblage IV) on the shelf immediately west of the Nile delta, a sector not directly influenced by provenance from Nile source material.

DISCUSSION

Several sediment provenance-dispersal scenarios are proposed for the study area on the basis of observations made on clay mineral distributions. These pertain to the shelves and contiguous deeper Nile Cone for the late Holocene until about the time of High-Dam closure. It is most likely that, on shelves, fine sediment fractions are likely to be transported farther than silt and sand. Moreover, clay assemblages should be sufficiently varied mineralogically to help distinguish proximal input (adjacent Sinai, Gaza and Israel coastal and offshore sectors) from more distal provenance. Distal clay input comprises two types: minerals displaced by coast-parallel current transport for more than 700 km, from the River Nile and delta to the Israel-Lebanon border, and eolian dust from African and Middle East deserts.

It is not surprising that some variability in proportions of clay minerals are recorded along Nile to northern Israeli margins, a zone where current velocities in excess of 0.5 knots are measured (SHARAF EL DIN, 1977; MURRAY *et al.*, 1981; GALILI and WEINSTEIN-EVRON, 1989). Size-sorting effects in such transport systems are expected as a response to (1) long-distance displacement of clays by fluvial, coastal current and wind processes in the Nile littoral cell, and (2) inherent differences in size of the prevailing clay minerals. We find that illite proportions in certain settings, such as the shallow nearshore, diminish somewhat with decreased grain size (Figure 9A, B). However, size-sorting is not recorded by the bulk of textural and clay mineral data generated for the 8 groups of offshore sediment. This is surprising since smectite particles tend to be smaller than kaolinite in Nile sediment (MALDONADO and STANLEY, 1981; ABU-ZEID and STANLEY, 1990), and proportions of smectite would likely increase from west to east in parallel with decreased mean grain size. Finer grain-sizes on the Nile Cone do not record increased proportions of smectite. Moreover, proportions of smectite and kaolinite values appear to be independent of mean grain-size and total amount of clay in samples on Nile, Gaza and Israeli shelves. Perhaps size-sorting effects are muted because: (1) sample procedures used (*i.e.* grab and core-top recovery) which, as discussed earlier, recover material deposited during an extended, but undefined, period during the Holocene, and not just over a few decades; and (2) post-depositional mixing by currents and organisms have altered the original petrology of the deposits.

The data clearly indicate a widespread offshore distribution of assemblage III (moderate smectite, high kaolinite, variable amount of illite), from east of Abu Qir to the northern Israel margin. *A priori*, this would suggest predominant longitudinal coast-parallel input from the Nile system to at least as far as the Israel-Lebanon border (*cf.* NIR and NATHAN, 1972; NIR, 1984; MALDONADO and STANLEY, 1981). INMAN and JENKINS (1984) have proposed that local derivation of sediment in the Nile cell is insignificant.

The present investigation, however, reveals mineralogical variations between the Nile delta and northern Israel with some relation between adjacent coastal plain and offshore assemblages (Figure 12). Our clay mineral databases do not indicate a truly homogeneous region-wide distribution pattern, nor do they support the single Nile source postulated by most previous research as an explanation for fine sediment distributions on Levant margins. Rather, lateral clay mineralogical changes east of the Nile delta call attention to the influence of some proximal sediment input introduced along transport paths. In the western part of the study area, fines of Nile derivation are supplied by erosion of Holocene deposits along the 225 km-long Nile delta coast, and by flow of suspension-rich water from delta wetlands to the sea via lagoon and canal outlets. These processes provide a continuous supply of smectite-rich clays that tend to be deposited

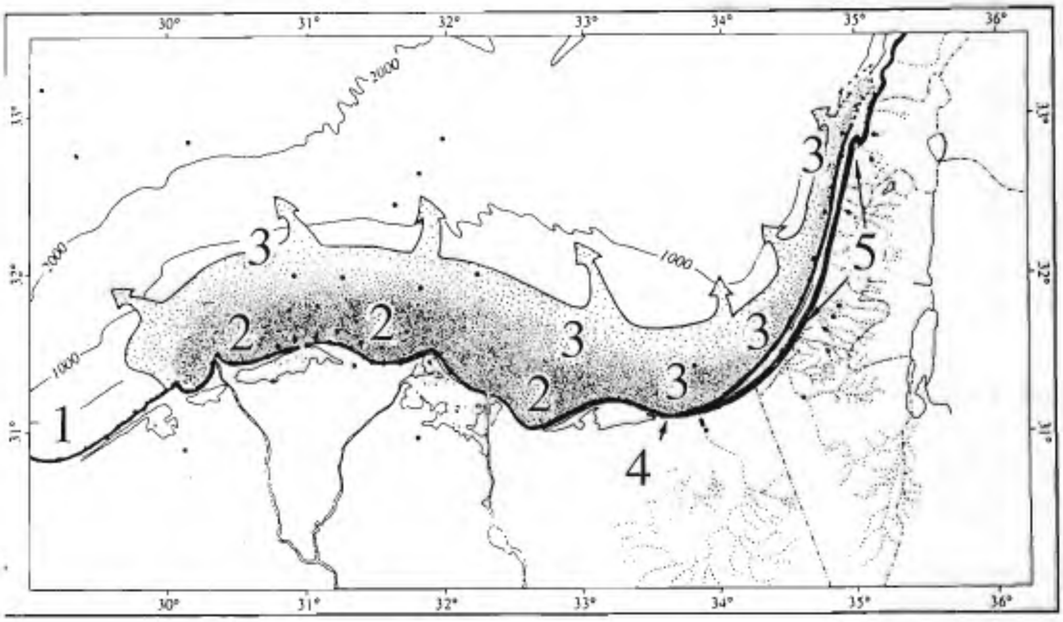

Figure 13. Sediment dispersal scheme showing dominant coast-parallel path for the SE Mediterranean, during the late Holocene until about the time of Aswan High Dam construction. Some shelf-to-slope sediment transport is denoted by arrows. Patterns are based on regional, near-parallel distributions of clay mineral and heavy mineral assemblages. Nile material (2) floods area east of the dominant carbonate terrains at and west of Alexandria (1). Smectite-rich sediment is concentrated on inner- and mid-shelves between the Nile delta and eastern Bardawil lagoon (2), and also on mid- to outer-shelves at least as far as northern Israel (3). The coast east of Bardawil lagoon (4) is a boundary between zones of Nile and of Levant provenance. The mineralogical province in the nearshore sector from Bardawil lagoon-Wadi El Arish to northern Israel records some influence of proximal sources (5), *i.e.* from the northern and eastern Sinai, Gaza and Israeli margins as well as distal Nile and eolian desert sediment.

primarily landward of the sandy strand plains and seaward of the silty and sandy inner Nile delta shelf; this is recorded by the shore-parallel belt of assemblages II and III in Figure 12. These are displaced eastward to at least as far as Bardawil lagoon (Figure 13[2]), where a major change in proportion of smectite relative to kaolinite occurs (Figure 13[4]).

In parallel with clay studies, sand mineral analyses have shown that during mid- to late-Holocene, continental margins of the eastern study area (Sinai, Gaza and Israel) contributed at least small amounts of sediment to this region (STANLEY, 1989) relative to the much larger supply from the River Nile system (RIM, 1951; SHUKRI and PHILIP, 1960; POMERANCBLUM, 1966; NIR, 1984). An investigation of sand-sized heavy mineral distributions, using some of the same samples that were analyzed for clays in the present study (STANLEY, 1989), has indicated that wave and current-eroded coastal cliffs, and to a lesser extent kurkars and surficial seafloor sediment, are important contributors of sediment to the margin east of the Nile delta. These interpretations of sediment dispersal patterns are independently supported by physical oceanographic studies of GOLDSMITH and GOLIK (1980) and by petrologic study of samples off Israel by NIR (1984). Thus, independent study of the clays (some modern, others pre-Holocene; *cf.* WEINSTEIN-EVRON, 1994) and of the heavy minerals indicate that at least some sediment was supplied along the coast east of Bardawil lagoon to northern Israel even before closure of the High Dam (Figure 13[5]).

Quantitative data of the type needed to measure ongoing changes of sediment input into the Nile littoral cell are sorely lacking. The type of information needed to interpret modern transport patterns, however, cannot be obtained only from mineralogical analyses of grab and core-top samples. For measurement of the amount of distal Nile and eolian versus more proximal Levant clay input to the study area we recommend the following: (1) systematic collection of sediment at specific locales and at set intervals on shelves and upper Nile Cone; (2) recovery of suspended sediment from water samples and from sediment traps set above the seafloor; and (3) analyses of samples made in a consistent manner for reliable comparisons. Additionally, (4) detailed mineralogical and chemical identification should be made of smectite particles in Nile sources to determine if these are different from those on the mid-Israeli coastal plain; this, although difficult to access, may provide an additional way to distinguish distal Nile from proximal Levant clay tracers. Finally, distribution of anthropogenically-derived geochemical tracers and pollutants (Table 9) can help define the position of proximal input along a coast and, thus, (5) geochemical mapping of trace elements and pollutants should be made in conjunction with clay analyses. Together, these would provide additional tools to detect what may be subtle changes of ongoing (post-Aswan High Dam) provenance-dispersal patterns.

Interaction of increased anthropogenic activity and natural processes, such as current erosion and possible rising sea level (STANLEY and WARNE, 1993; FRENCH *et al.*, 1995) are almost certainly continuing to alter former patterns of sedi-

Table 9. *Artificial material dispersed along and near the coast, between the Nile delta and Levant margins.*

Material	Source	Mode of Transport
Chemicals	diverse industries and factories	river, piped dispersal
Fill material for land reclamation and coastal construction	natural rock (limestone, etc.) sediment from land, and artificial material from abandoned structures (old concrete, etc.)	dumping by truck and barge
Dust	emission from factories, quarries, etc.	wind
Raw sewage	industrial, agricultural and domestic waste	waste outlet, piped dispersal, river
Industrial and domestic sludge	purifying stations, factories	dumping, piped dispersal
Charcoal dust	power stations, ports	dumping, wind
Ship waste	ships at sea and in port (solid and liquid)	dumping
Fish waste and organic matter	nutrients accumulating in fish ponds	waste outlet, piped disposal system
Contaminated cooling water	power stations	piped disposal

ment transport and offshore deposition in this region. We postulate that the diminished total volume of Nile sediment displaced eastward from the delta is associated with relatively increased amounts of more proximally supplied Levant sediment on the inner shelves of Sinai, Gaza and Israel. In fact, the present study indicates that, even by the time of High Dam construction, margins east of Bardawil lagoon were receiving important proportions of clays from rivers flowing east of the Nile (Wadi El Arish, numerous small Israeli fluvial systems), eroded coastal exposures and eolian transport. Moreover, direct evidence of escalating seafloor erosion is the appearance off the Israeli coast of an increasing number of large, sand-free patches of pre- to early-Holocene dark alluvial mud, on which some archaeological sites (Figure 11D, E) are now exposed (GALILI *et al.,* 1993). Combined sedimentological and archaeological surveys, in conjunction with detailed morphological surveys of the coast and inner shelf, offer an effective approach to measure ongoing changes along the Nile littoral cell. These data will also be used for implementing protection measures for coastal sectors undergoing active erosion and for detecting the increasingly important offshore dispersal of pollutants.

CONCLUSIONS

Until the closure of the Aswan High Dam in the mid-1960's, large volumes of smectite-rich clay distributions from the lower Nile and Nile delta were transported seaward and then eastward to Levant margins. The present investigation indicates that clay assemblages are not uniformly distributed in the SE Mediterranean. Reduction of the sediment input by the Nile resulting from closure of the High Dam has increased the relative contributions of several other sources of clay supplied to the Nile littoral cell between the Nile delta and northern Israeli margin. In the Levant well to the east of the Nile delta, several sources of smectite-rich assemblages are identified, and these may account for some smectite-rich assemblages mapped seaward of the Israeli coastal plain (STANLEY *et al.,* 1997). In addition to smectite-rich Nile-derived materials, wind releases large amounts of kaolinite and illite-rich dust originating in the African and Middle East deserts over broad areas of the SE Mediterranean. Clay assemblages along some Levant sectors also suggest that coastal shoreface cliff exposures, and to some extent the Quaternary seafloor, are eroded by coastal and longshore currents throughout the region. Cliff erosion during the past 6000 years is estimated to have been on the order of 2–6 cm/yr (NIR, 1984); at present, erosion of the same cliffs has increased substantially to 20–40 cm/yr (NIR, in press). We propose that these more proximal sources supply an additional, but as yet undefined, amount of kaolinite and illite, as well as smectite, to the Nile cell.

It is of special note that a provenance-dispersal pattern comparable to that interpreted from clays is recorded by heavy minerals (STANLEY, 1989). It is postulated here that cut-off of the Nile sediment supply and evolving transport processes, perhaps related to rising sea level, account for increased proportions of kaolinite, illite and chlorite introduced in the Nile littoral cell. Whether proportions of Nile-derived smectite carried offshore toward Sinai, Gaza, and Israel (SHARAF EL DIN, 1977) have in fact decreased since closure of the High Dam will require additional study.

Continued human modification of the coast east of the Nile delta has increasingly disrupted original sediment dispersal and depositional patterns on Levant margins. Construction of industrial and artificial structures and increased introduction of wastes and pollutants along the shore in this region are inducing substantial coastal and inner shelf changes. There is much to be learned about the complex interplay between anthropogenic effects and natural factors such as currents and sea-level rise. The use of more sophisticated sampling and mineralogical approaches is advocated to determine current patterns of sediment supply and dispersal in the Levant. This should include examination of suspended sediment and distinguishing Nile-derived smectite from that supplied from Levant margins. Probably the most precise information on post-High Dam changes affecting clay mineral distributions and sediment loads will be gained by measuring clay minerals in conjunction with geochemical tracer analyses.

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