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Sediment Transport on the Coast and Shelf Between the Nile Delta and Israeli Margin as Determined by Heavy Minerals

Daniel Jean Stanley

Mediterranean Basin Program
Division of Sedimentology, N.M.N.H.
Smithsonian Institution
Washington, D.C. 20560 U.S.A.

ABSTRACT

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The main source of terrigenous sediments supplied to the southeastern Mediterranean margin was the River Nile until the emplacement of the High Aswan Dam in 1964. It is generally assumed that since cut-off of this supply, sediments eroded from the Nile delta have continued to be displaced eastward to the Sinai and Gaza margins and north-northeastward to the Israeli margin. Sands are displaced along coasts primarily by wave-driven longshore transport. This study of the regional distribution of transparent heavy minerals indicates that mineral suites on coasts east of the Bardawil lagoon differ increasingly from Nilotic suites in a direction away from the Nile delta. This records an incorporation of sediments supplied locally from coastal and inshore erosion, and also from rivers and by wind. In contrast, proportions of transparent heavy minerals in the sand fractions on continental shelves off the Nile delta, Sinai, Gaza and Israel more closely approximate those of the Nile delta. These mineral assemblages in shelf sediments are likely derived from relict or reworked relict (palimpsest) deposits, or both, of Nilotic origin. Offshore sediment displacement by bottom currents is probably episodic, involving storm wave activity coupled with more constant flow of the geostrophic East Mediterranean Current.

As the number of engineering structures placed along coasts increases, the volume of laterally transported Nilotic sand has decreased somewhat relatively to locally supplied sediment. Thus, in time, the composition of heavy mineral suites on eastern Sinai, Gaza and Israeli coasts may differ from Nile delta assemblages. Moreover, the divergence between proportions of heavy minerals on coasts and contiguous shelves would also be expected to increase. Data points summarized in the present study are largely from samples collected prior to 1964 and thus provide a pre-Aswan High Dam baseline. Recommended systematic resampling of the margins and analyses of heavy minerals one quarter-Century after closure of the High Aswan Dam would help measure recent sedimentation changes and predict future modifications likely to affect these margins.

ADDITIONAL INDEX WORDS: *Arab's Bay, High Aswan Dam, IAmph index, IPyr index, Israeli shelf, Nile delta shelf, relict sediments, Sinai shelf.*

INTRODUCTION

The River Nile and its delta in Egypt have been identified as the major sources of quartz-rich sediments on coasts and shelves of the southeastern Mediterranean (BALL, 1942; HURST, 1964; GOLDSMITH and GOLIK, 1980; SAID, 1981; NIR, 1984; ROHRLICH and GOLDSMITH, 1984; NEEV *et al.*, 1987). Until the emplacement of the High Dam at Aswan in 1964, most sand supplied to this region was transported northward by the Main Nile and then across the Nile delta to the coast by its two distributaries, the Rosetta and the Damietta branches (Figure 1). Since the sudden reduction of sand furnished by the River Nile in 1965, substantial volumes of sediment have continued to be supplied to the Mediterranean by erosion of extensive coastal sectors of the Nile delta (ROHRLICH and GOLDSMITH, 1984).

Predominant marine transport at present is easterly-directed along the delta and Sinai coasts of Egypt and on the Nile delta and Sinai shelves (SHUKRI and PHILIP, 1961; COLEMAN *et al.*, 1981; INMAN and JENKINS, 1984), and toward the north-northeast off northern Gaza and on the Israeli margin (EMERY and NEEV, 1960; GOLDSMITH and GOLIK, 1980; INMAN and JENKINS, 1984;

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NIR, 1984; ROHRLICH and GOLDSMITH, 1984). Eroded sediments are moved primarily by wave-induced longshore currents (wind and waves primarily from the northwest) and the counter-clockwise geostrophic East Mediterranean Current. Reverse current trends are mapped locally with, for example, episodic southward-directed transport toward the middle Israeli coast; this is in part a function of the concave shape of Israel's shore which receives the brunt of wave and current energy in the eastern Mediterranean (EMERY and NEEV, 1960; GOLDSMITH and GOLIK, 1980). A regional depositional model, which encompasses transport and overall sediment budget in the sector between the Nile delta and northern Israel, has been described by INMAN and JENKINS (1984) and termed the *Nile Littoral Cell*.

Various aspects of the erosion and reworking of large volumes of recent and older sediments along the low-lying Nile delta and Sinai coasts have been considered (UNDP/UNESCO, 1976, 1977; ROHRLICH and GOLDSMITH, 1984; FRIHY and STANLEY, 1987; FRIHY, 1988; SMITH and ABDEL-KADER, 1988). There is less information available on the volume of sands supplied east of the delta by (1) erosion of coastal cliffs and exposures on the inner shelf, (2) by input from wadis (rivers having intermittent flow) which are active primarily during winter floods (EMERY and NEEV, 1960; POMERANCBLUM, 1966; NIR, 1976, 1984; NEEV *et al.*, 1987; GUR and GOLDSMITH, 1988), and (3) by wind transport (CHESTER *et al.*, 1977; HOROWITZ, 1979). All authors affirm that these non-Nilotic contributions account for relatively minor to small proportions of the total coastal sand budget. Very little is known about actual quantities of terrigenous and biogenic sediments eroded and displaced by longshore and geostrophic currents on the submerged shelves north of the Egyptian and Gaza coasts (COLEMAN *et al.*, 1981; STANLEY, 1988a), and on the shelf west of Israel (POMERANCBLUM, 1966; NIR, 1984).

It has been demonstrated that mapping of the regional distributions of heavy mineral assemblages is a useful technique to interpret sediment dispersal on Mediterranean margins (STANLEY *et al.*, 1975). Heavy mineral assemblages mapped on southeastern Mediterranean coasts can be attributed to diagnostic source terrains and, in many cases, to specific wadis. Heavy mineral studies to date, however, have been local in scope. The present investigation considers the regional distribution of transparent heavy mineral suites on margins of northeastern Egypt, Sinai, Gaza and Israel to better assess the origin and major dispersal paths of sand between El Omeiyid on the north-central Egyptian coast and northern Israel (Figure 1). The study uses earlier published mineralological information and also newly acquired heavy mineral data in the Nile delta and on the Sinai shelf. Many of the published mineral analyses were made on samples collected prior to 1964.

All studies of heavy minerals in this region have emphasized the Nile affinity of mineral suites, and a fairly direct transport pattern along the coast between Nile source and depositional sites. Little information is available on dispersal resulting from reworking of relict deposits on presently submerged shelves. Mapping changes in mineralogical trends from Arab's Gulf west of the Nile delta to northernmost Israel, a distance of about 700 km, is thus of value in this respect. If most sediments displaced along the transport paths were supplied by the Nile or by relict Nilotic deposits, one could expect rather gradual but consistent mineralogical changes in a direction away from the main delta point sources and toward distal-end depositional sites. If, on the other hand, irregular heavy mineral patterns are recorded along transport paths, it then becomes necessary to consider the possibility that sediment from other sources (hinterland, coastal, shelf) are contributed along transport paths between the Nile delta and northern Israeli margin.

METHODOLOGY

Heavy mineral determinations are available for numerous surface samples and cores collected on coasts, in rivers, and on the continental shelves off Egypt, Sinai, Gaza and Israel. Published papers can be grouped geographically from west to east, as follows: (1) region west of the Nile delta, *i.e.* west and south of Alexandria (SHUKRI and PHILIP, 1956; KHADR, 1961); (2) Main Nile south of the delta (SHUKRI, 1950); (3) Nile delta proper, south of the Mediterranean coast (KHADR, 1961; KHOLIEF *et al.*, 1969; STANLEY, 1988b; STANLEY *et al.*, 1988; and Smithsonian core-top samples

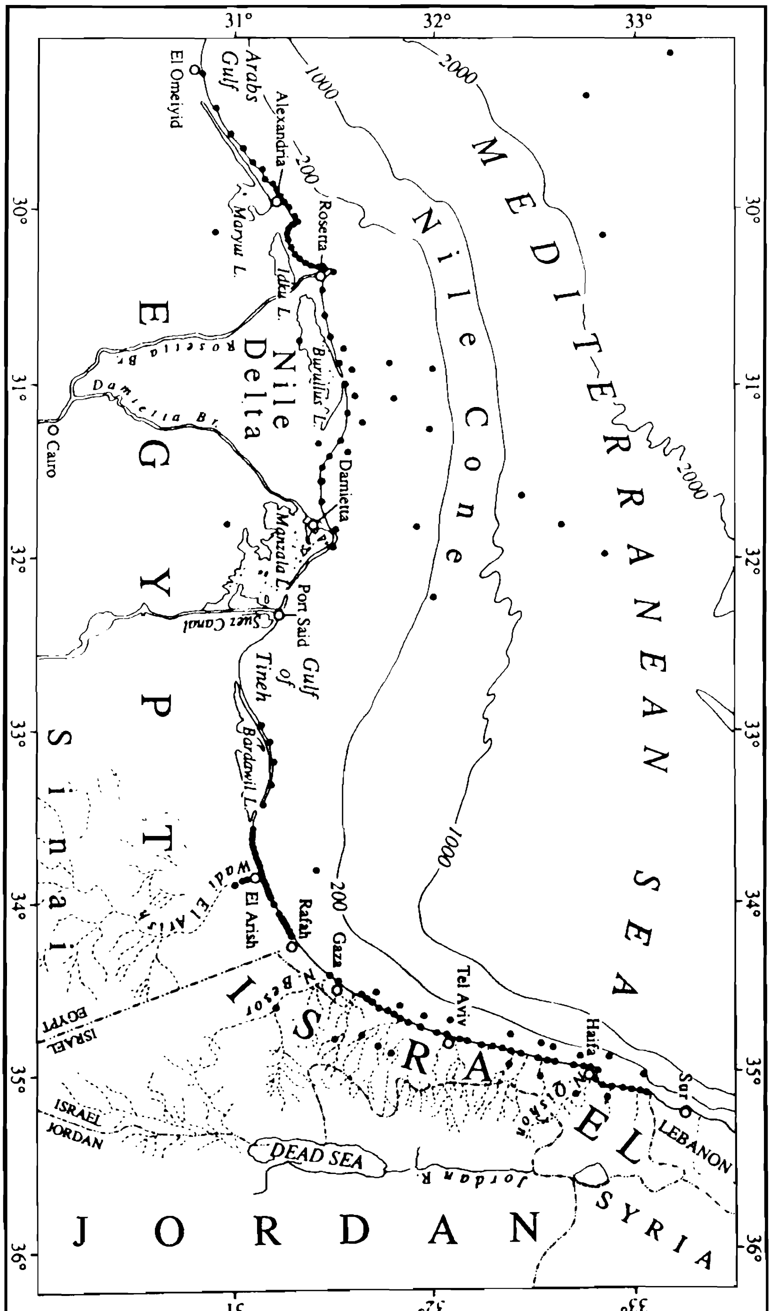

Figure 1. Map of the southeastern Mediterranean study area showing surface and core-top sample locations. Information pertaining to these samples, including published reference sources, is listed in Table 1.

selected for this study); (4) western Nile delta coast, from Alexandria to Abu Quir Bay, and the mouth of the Rosetta branch of the Nile (SHUKRI and PHILIP, 1956; INMAN and JENKINS, 1984); (5) Nile delta coast between the Rosetta and Damietta promontories (EL FISHAWI and MOLNAR, 1985); (6) Nile delta shelf and Nile Cone (STANLEY *et al.*, 1979); (7) Bardawil lagoon coast, east of the Nile delta (INMAN and JENKINS, 1984); (8) Sinai coast and the Wadi el-Arish which drains a large part of the north-central Sinai (SHUKRI and PHILIP, 1961); (9) Sinai shelf (*Pillsbury* core P6508-48, this study); (10) Israeli coast and rivers (RIM, 1950; EMERY and NEEV, 1960); and (11) Israeli shelf (POMERANCBLUM, 1966). An inventory of the more than 300 samples described and a list of published references consulted, is presented in Table 1. Sample locations are shown in Figure 1.

Heavy mineral data are available for coastal samples throughout the study area but this information has been collected in somewhat different ways by the various authors cited above. In most cases, average cumulative percentages are compiled for the sand-size fractions of studied samples. The lower size limit of the sand fraction in these studies, however, is variable, *i.e.* ranging from 50 μm (KHADR, 1961) to 90 μm (EL FISHAWI and MOLNAR, 1985). The proportions of mineral types as related to specific grain sizes of samples analyzed are considered by, among others, SHUKRI and PHILIP, (1956); KHADR, (1961); SHUKRI and PHILIP, (1961); EMERY and NEEV, (1960); POMERANCBLUM, (1966); EL-SHAZLY and WASSEF (1982); and EL FISHAWI and MOLNAR (1985). POMERANCBLUM (1966) focused on comparative size attributes of selected light and heavy minerals. In some studies, heavy mineral data are listed more specifically for different environments at coastal sites such as breaker zone, beach, backshore, and dune (SKURKI and PHILIP, 1961; EL FISHAWI and MOLNAR, 1985).

Authors studying the Nile delta and Sinai sectors generally list percentages of dense opaque and iron oxide minerals along with transparent heavy minerals as part of the total counts. This is not the case for samples collected on the Israeli margin (*cf.* EMERY and NEEV, 1960; POMERANCBLUM, 1966). Moreover, in some studies on the Egyptian margin, percentages of micas are listed as part of the total heavy mineral assemblage, while on the Israeli margin, percentages of micas are usually listed separately (*cf.* POMERANCBLUM, 1966).

Amphiboles, pyroxenes, epidotes and opaque heavy minerals (not necessarily in this order) constitute the bulk of heavy mineral suites in samples of recent age throughout the study area, from the Nile delta eastward to the Israeli margin. The percentage of opaque minerals, however, varies extremely from sample to sample within any one area. This very high variability is less a function of provenance than of local transport processes and of depositional selectivity resulting in placer concentration of denser opaque species and the winnowing of less dense transparent mineral types (HILMY, 1951; EL-SHAZLY and WASSEF, 1982; EL FISHAWI and MOLNAR, 1985). Proportions of mica also vary, in large part, as a function of local depositional processes (POMERANCBLUM, 1966). For this reason, most attention is paid here to regional variations of the dominant transparent mineral group (amphiboles, pyroxenes and epidotes). These minerals, which at all sites account for more than 50% (in some examples, to $>$ 90%) of the total relative percentages, are of generally comparable density and stability (*cf.* PETTIJOHN, 1957).

In evaluating the proportions of minerals, ratios help standardize the magnitude of variability for the different suites of samples. Ratios are particularly useful in view of the somewhat different methods employed in the various heavy mineral studies. Two indices, termed *I*Pyr and *I*Amph, are used here to study the various sets of Recent samples of River Nile derivation. These are particularly useful in that they emphasize the variability of all three dominant transparent heavy mineral groups (pyroxenes, amphiboles, epidotes) that occur throughout the study area. The two indices were defined by Hassan (1976) as follows:

*I*Pyr index = (frequency of pyroxenes/frequency of pyroxenes + epidotes) × 100

*I*Amph index = (frequency of amphiboles/frequency of amphiboles + pyroxenes) × 100

These two indices were determined for all samples listed in the above series of published studies and for several core-top samples examined during the course of this study (Smithsonian

Table 1. *I*Amph and *I*Pyr index values for samples collected on beaches, in rivers, and on offshore continental margins of Egypt, Sinai and Israel. General positions of sample sites are shown in Figure 1; specific sample locations and numbers are shown in the references cited below.

Location Samples Collected on Beaches and in Nile Delta	*I*Amph	*I*Pyr	Data Source
Egypt Coast, west of			
Alexandria and Delta	79	38	Shukri and Philip (1956)
Sites 35-38			
South of Alexandria			
Nubarya	62	41	Khadr (1961)
Alexandria to Abu Qir	62	49	Shukri and Philip (1956)
Sites 1-33			
Rosetta Mouth	50	71	Inman and Jenkins (1984)
Rosetta to Damietta	56	82	Fishawi and Molnar (1985)
Sites 1-13			
Burullus	42	78	Inman and Jenkins (1984)
North-central Delta	46	84	This study
Core S-36			
Damietta Mouth	50	67	Shukri (1950)
Manzala Lagoon	44	61	Stanley et al. (1988)
Core S-6			
Bardawil Lagoon	53	75	Inman and Jenkins (1984)
Sinai Coast			Shukri and Philip (1961)
Sites 37-39	46	51	
Sites 33-36	63	38	
Sites 29-32	60	41	
Sites 25-28	42	59	
Sites 21-24	58	51	
Sites 17-20	53	48	
Sites 13-16	52	42	
Sites 9-12	57	43	
Sites 5-8	64	42	
Sites 1-4	59	37	
Israel Coast			Emery and Neev (1960)
Sites 1-5	85	37	
Sites 6-10	88	45	
Sites 11-15	85	45	
Sites 16-20	85	57	
Sites 21-25	86	47	
Sites 26-30	92	39	
Sites 31-34	89	45	
Samples Collected in Rivers			
Major Tributaries of Nile			Hassan (1976)
White Nile	97	5	
Blue Nile	79	58	
Atbara River	8	99	
Blue Nile & Atbara	41	88	
Main Nile, North of Atbara	52	83	
Wadi El-Arish (Sinai)	72	31	Shukri and Philip (1961)
Israel Coast			Emery and Neev (1960)
N. Besor	93	12	
N. Shikma	88	30	
N. Lakhish	100	< 4	
N. ha-Ela	91	~ 4	
N. Qidron	96	10	
Alexander	100	~ 2	
N. Daliya	95	13	
N. Quishon	27	83	
N. Na'aman	95	11	

Table 1. *Continued.*

Location Samples Collected Offshore	*I*Amph	*I*Pyr	Data Source
Inner to Middle			
Egyptian Shelf	35	56	Stanley et al. (1979)
Outer Egyptian Shelf	36	67	Stanley et al. (1979)
Western Nile Cone	45	64	Stanley et al. (1979)
Eastern Nile Cone	48	75	Stanley et al. (1979)
Sinai Shelf	44	67	This study
Core P6508-48			
Israel Shelf Traverses			Pomerancblum (1966)
Ashqelon Traverse			
9m	56	55	
18m	55	77	
27m	65	70	
35m	63	94	
37m	72	93	
46m	75	96	
64m	68	97	
82m	90	42	
110m	89	83	
130m	73	63	
Ashdod Traverse			
9m	63	71	
18m	79	62	
27m	83	50	
49m	75	96	
60m	80	95	
70m	79	95	
82m	80	94	
Rubin Traverse			
27m	67	77	
55m	85	74	
64m	68	94	
82m	70	93	
132m	73	96	
183m	76	92	
Tel Aviv Traverse			
18m	79	71	
27m	67	79	
46m	64	73	
55m	70	93	
91m	93	93	
106m	84	88	
110m	90	83	
136m	84	83	
140m	81	90	
183m	77	91	
Netanya Traverse			
9m	70	64	
18m	70	59	
27m	70	68	
37m	76	46	
46m	55	82	
66m	57	93	
73m	48	96	
84m	50	90	
90m	61	95	
106	53	87	
117m	65	86	
137m	66	94	
150m	61	93	

Table 1. *Continued.*

Location Samples Collected Offshore (cont'd)	*I*Amph	*I*Pyr	Data Source
Caesarea Traverse			
9m	71	71	
18m	64	75	
29m	69	83	
37m	79	60	
46m	78	65	
55m	66	69	
64m	81	64	
73m	64	80	
82m	66	88	
93m	52	90	
104m	62	92	
112m	73	89	
119m	81	82	
132m	82	85	
143m	67	91	
183m	71	90	
Dor Traverse			
9m	73	86	
18m	75	65	
27m	70	90	
37m	67	80	
46m	70	76	
55m	69	90	
64m	52	89	
73m	56	86	
84m	60	90	
95m	67	86	
106m	69	90	
113m	53	91	
135m	72	90	
Atlit Traverse			
11m	81	74	
18m	71	74	
27m	78	83	
37m	76	96	
59m	67	80	
73m	80	76	
91m	77	76	
102m	78	72	
Tira Traverse			
84m	58	88	
110m	65	86	
135m	62	87	
155m	61	82	
183m	60	88	
Nahariya Traverse			
50m	65	86	
73m	73	89	
82m	62	82	
92m	66	91	
101m	63	87	
110m	69	97	
119m	53	88	
143m	61	88	

cores S-6 and S-36 in the north-central delta and *Pillsbury* core 6508-48 on the Sinai shelf). *I*Pyr and *I*Amph values are listed in Table 1, and depicted on maps of the region (Figures 2 and 3). The values obtained here may be compared with those calculated for the River Nile load and Nile valley formations of late Quaternary age (*cf.* HASSAN, 1976).

Information on provenance and sediment transport can also be provided by the regional distribution of other, albeit minor, transparent heavy mineral species. Useful are those comprising the metamorphic (sillimanite, staurolite, kyanite, *etc.*) and the resistate (zircon, tourmaline and rutile, identified as ZTR) minerals. Percentages of these and other minor heavy mineral types are listed in the published studies cited earlier in this section.

OBSERVATIONS AND DISCUSSION

*I*Pyr Index

The *I*Pyr index is perhaps the most useful marker of the River Nile source and is thus a valuable criterion to identify transport trends away from the delta (Figure 2). Very high *I*Pyr values (61–84) characterize samples of the Main Nile and the northern Nile delta between the mouths of the Rosetta and Damietta branches. This indicates that proportions of pyroxenes (augite, hypersthene, enstatite) are about 2 to 5 times higher than epidotes (epidote, clinozoisite, zoisite). Epidotes are supplied from more diverse Ethiopian and Central African sources than are the pyroxenes (SHUKRI, 1950). The predominant contributions of pyroxene-rich sediment are from the Atbara River (*I*Pyr = 99) and the Blue Nile (*I*Pyr = 58) draining the Abyssinian (Ethiopian) Plateau (SHUKRI, 1950; HASSAN, 1976) in East Africa. Pyroxenes that include yellowish green and brownish violet variaties of augite, characteristic of the Abyssinian Plateau (SHUKRI, 1950) and River Nile (SHUKRI and PHILIP, 1961) derivation, have been traced all the way to the Levant margin (POMERANCBLUM, 1966).

Values along the coast immediately west of Alexandria and the western Nile delta margin, south of Arab's Gulf, are notably lower (<50) than on the delta coast (67–82). The much lower proportions of pyroxenes relative to epidotes in the sector immediately west of the delta substantiates that Nile-derived sediments are displaced primarily eastward, and not to the west, by the coastal transport system.

*I*Pyr values increase abruptly (>60) north of Lake Idku, that is, in the proximity of the mouth of the former Canopic branch of the Nile (EL FATTA and FRIHY, 1988), and even higher values (71) characterize the present Rosetta promentory. In contrast with the region west of the delta, *I*Pyr values remain high east of the delta proper, *i.e.* between the NW Sinai coast east of the Suez Canal and the eastern part of Bardawil lagoon (INMAN and JENKINS, 1984). The index decreases on the Sinai coast east of Bardawil: this most likely records some influx of locally supplied heavy mineral assemblages from Wadi El Arish which drains a large part of the northern and central Sinai. This, the most important fluvial point source between the Nile and southern Israeli coast, is active episodically; its load is characterized by much lower proportions of pyroxenes (12–16%) relative to epidotes (30–32%) (SHUKRI and PHILIP, 1961).

*I*Pyr Values more comparable to those west of the delta characterize samples along the eastern Sinai coast (<50), near El Arish, the Gaza coast, and along most of the coast of Israel (<47). It is suggested here that low values on the Israeli coast most probably record the influence of locally supplied sediment sources (wadis and eroded coastal sections) which typically reveal very low *I*Pyr values (Figure 2). One important exception is the Quishon River in northern Israel; this fluvial system drains some basaltic terrains and transports sizable quantities of augite (EMERY and NEEV, 1960).

The higher values (> 60) of samples on the Nile delta and Sinai shelves and on the Nile Cone north of the Nile delta are generally comparable to those of the delta proper and delta coast. In contrast, the *I*Pyr values of sand samples on the shelf west of the delta (a carbonate-rich province, *cf.* SUMMERHAYES *et al.*, 1978; ANWAR *et al.*, 1981) are generally low (<50).

Data from surface samples collected along the 10 cross-shelf traverses off Israel are of note (*cf.* POMERANCBLUM, 1966): The sand fraction in one or two samples along each traverse presents *I*Pyr values (70 to 88) that are comparable to those of the Nile delta coast (Table 1). These "Nile delta-affinity" samples are concentrated on the shallow (10–20 m) inner Israeli shelf close to shore northeast of Gaza, and occur at progressively greater depths (to ~80 m) on the middle to outer shelf off northern Israel (Figure 2). These *I*Pyr values are much higher than those of samples on the adjacent Israeli coast (<47). This difference is not a function of operator error since heavy mineral analyses on both the Israeli coast and shelf were made by the same specialist (M. POMERANCBLUM, *in* EMERY and NEEV, 1960).

These observations indicate that heavy minerals on the Sinai and Israeli shelves have been derived from River Nile sources with relatively little change during displacement. Direct land-to-sea displacement from the coast to the middle and outer shelf east of Bardawil lagoon is excluded. Several explanations are proposed for these "delta-like" sediments on Sinai and Israeli shelves: they are derived from (a) recent lateral transport (episodic or continued) away from the delta region by offshore currents such as the East Mediterranean Current, or (b) exposure of much older (relict) littoral deposits, or (c) recent reworking by offshore currents of relict deposits and formation of palimpsest deposits (*cf.* SWIFT *et al.*, 1971). The latter two possibilities are favored.

*I*Amph Index

*I*Amph values ranging from 42 to 56, indicative of near-equal proportions of amphiboles and pyroxenes, characterize northern Nile delta and delta coast samples (Figure 3). These values approximate those of mineral suites (52) in the Main Nile (HASSAN, 1976). Amphiboles, in contrast with pyroxenes, are supplied from (a) more numerous fluvial sources draining diverse terrains in River Nile and Sinai drainage basins, (b) the Levant hinterland and (c) eroded coastal sections.

Much higher *I*Amph values (to > 70) are noted on the coast immediately to the west of the Nile delta, where sands are derived in large part from Pleistocene coastal ridges that border the shoreline in this area and from erosion of Miocene and Pliocene sections further to the west (SHUKRI and PHILIP, 1961). In contrast, *I*Amph index values remain low (< 50) on the eastern delta coast and contiguous Nile delta and Sinai shelves and Nile Cone.

*I*Amph values of coastal samples increase progressively from east of the delta, at the Bardawil lagoon (> 50), toward El Arish and Gaza (> 60). Markedly higher *I*Amph values (to > 80) characterize samples on most of the Israeli coast, probably recording the influence of locally supplied sediment from wadis and coastal erosion of older cliff sections.

*I*Amph values for samples collected along the 10 Israeli shelf traverses generally are markedly lower than on the adjacent coast (Figure 3, Table 1). Of note are *I*Amph values (55–67) of one or two samples along each traverse that are more closely comparable to those of samples on the Nile delta (*cf.* HASSAN, 1976; FOUCAULT and STANLEY, 1989) than the more proximal Sinai and Israeli coasts. Thus, both *I*Amph and *I*Pyr indices indicate "Nile delta-affinity" sediment locally restricted on the Israeli shelf along axes oriented subparallel to the coast. From south to north, these samples are located progressively further from shore and in deeper water.

Minor Heavy Minerals

Changes in the lateral distribution of minor transparent heavy minerals in the Main Nile (SHUKRI, 1950) and northern delta (analyses made for this study) indicate generally very low proportions of metamorphic and resistate ZTR species; the total of all these mineral species, together, usually accounts for less than 8% of total counts.

In contrast, SHUKRI and PHILIP (1956) recorded a marked increase in the proportion of resistate minerals (>15%) immediately west of the delta, and an absence of sillimanite and apatite grains that are usually encountered, albeit in minor amounts, in Nile sediments. Sediments west of Alexandria are probably derived from sources further to the west, *i.e.* from Miocene and Pliocene sections which, in turn, may have been derived from the Nubian Sandstone (SHUKRI and PHILIP, 1961).

Coastal sediments east of Bardawil lagoon appear influenced, at least in part, by the addition of materials from the Wadi El Arish. These latter, in comparison to River Nile sediments, include lower proportions of pyroxenes, equivalent amounts of metamorphic minerals, and substantially higher contents of amphiboles, epidotes, ZTR and monazite (SHUKRI and PHILIP, 1961). The margin north of Gaza comprises higher proportions of metamorphic (to

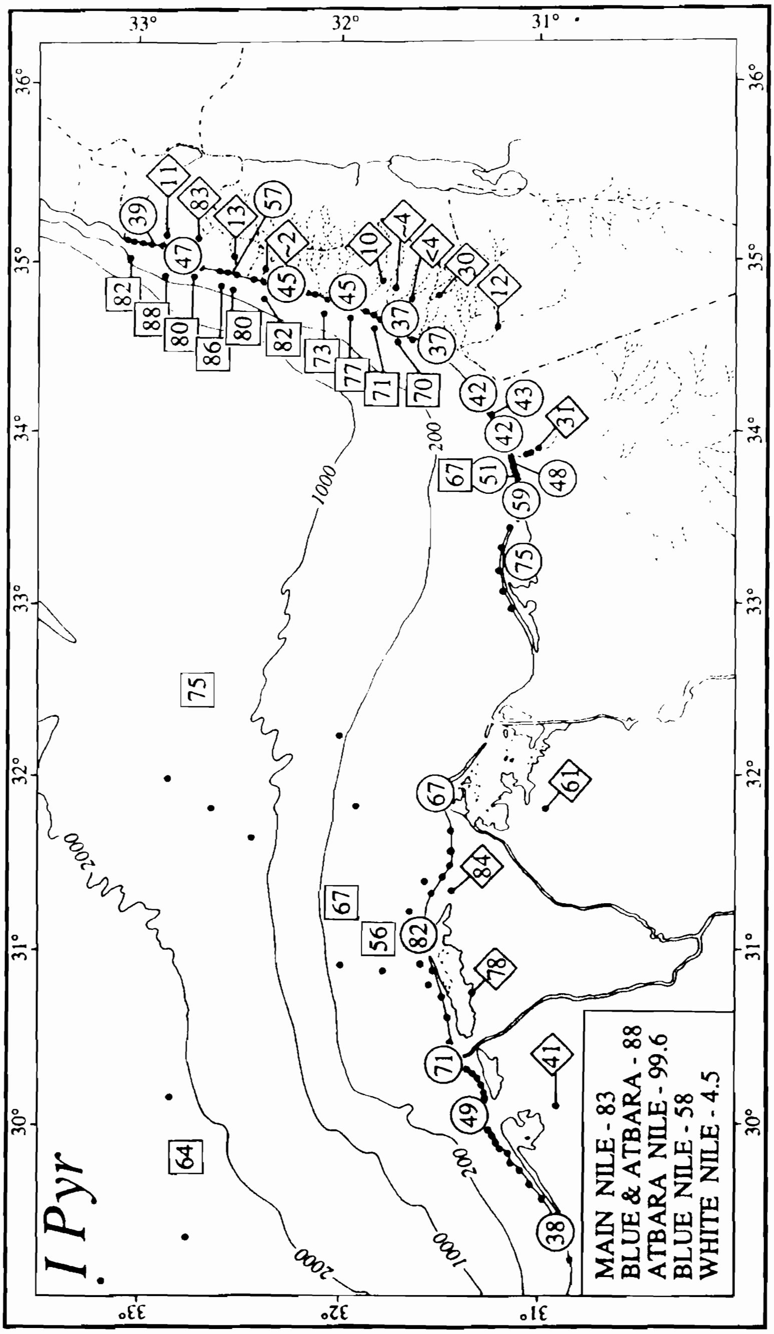

Figure 2. Regional variation of *I*Pyr index as determined in this study. Nile delta, Wadi El Arish and Israeli river samples, in diamonds; coastal samples, in circles; offshore samples, in squares. *I*Pyr values in inset pertaining to Nilotic sources are from Hassan (1976), derived from Shukri (1950).

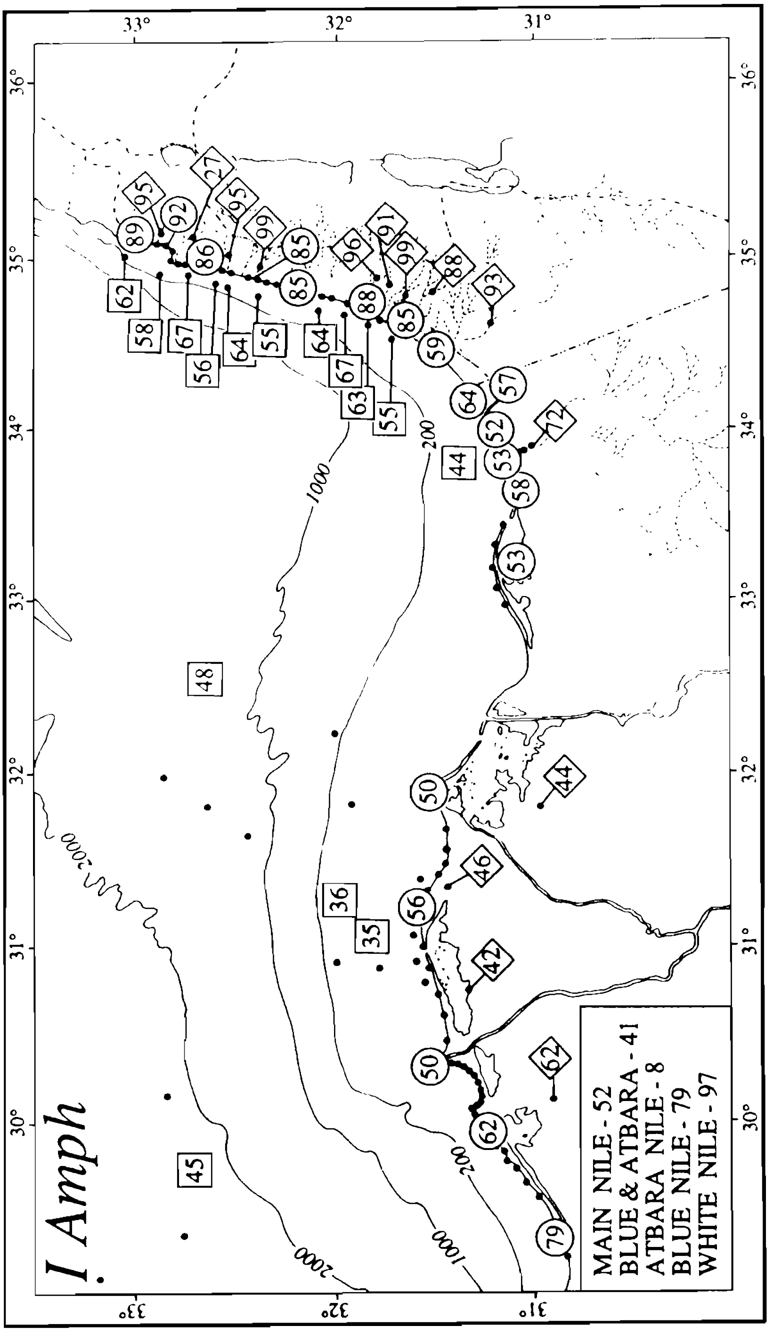

Figure 3. Regional variation of *I*Amph index as determined in this study. Nile Delta, Wadi El Arish and Israeli river samples, in diamonds; coastal samples, in circles; offshore samples, in squares. *I*Amph values in inset pertaining to Nilotic sources are from Hassan (1976), derived from Shukri (1950).

>10%) and resistate minerals (to >30%). These are transported to the coast by wadis draining the Israeli hinterland, and also by erosion of coastal cliff sections (*cf.* EMERY and NEEV, 1960; GUR and GOLDSMITH, 1988).

Lower proportions of both ZTR and metamorphic minerals characterize samples collected along the 10 Israeli shelf transects (POMERANCBLUM, 1966). This observation suggests a Nile delta origin for these offshore sediments rather than a much more proximal Israeli coastal affinity.

CONCLUSIONS

This investigation confirms that, on the basis of the regional distribution of transparent heavy minerals, the bulk of sediments on the southeastern Mediterranean margin have been derived from Nilotic sources. Of note, however, is the general lack of uniformity of heavy mineral assemblages from west to east. The proportions of minerals on the coast of eastern Sinai, Gaza, and Israel differ substantially from those of the River Nile and Nile delta. Moreover, these changes become progressively more pronounced along the coast in a direction east of Bardawil lagoon and away from the dominant Nile sources. Proportions of transparent heavy minerals in offshore samples, on the other hand, are generally comparable on shelves off the Nile delta, Sinai, Gaza and, locally, Israel. These offshore assemblages are similar to those of the delta coast but differ markedly from coastal samples east of Bardawil lagoon.

This mineralogical difference between coast and shelf samples is depicted graphically by plotting the regional variations of the *I*Pyr index (Figure 4, upper). The divergence is interpreted as follows: (1) a substantial amount of sediment is introduced locally along the coastal transport path by erosion of coastal deposits of eastern Sinai, Gaza and Israel (particularly cliffs on the latter margin, *cf.* GUR and GOLDSMITH, 1988), and by episodic input, sometimes important, by the Wadi El-Arish on the Sinai margin (NIR, 1984) and several Israeli rivers; (2) it is possible that erosion rates are affected to some extent by uplift of coastal sections on the Israeli margin (HOROWITZ, 1979; NEEV *et al.*, 1987), and by subsidence of the northeastern Nile delta (STANLEY, 1988b); (3) locally introduced sands are displaced eastward and then northward by wave-induced longshore currents and thus mixed with Nile-derived sediments along dispersal paths; (4) it is suggested that both modern and relict sediments on the shelf are reworked by offshore bottom currents; (5) the counter-clockwise flow of the East Mediterranean Current, perhaps in conjunction with storm waves, may erode older deposits of Nilotic origin exposed on the seafloor (NIR, 1984; STANLEY, 1988a), including those laid down during lower Quaternary stands of sea level; (6) irregular displacement of modern and reworked relict (palimsest) sediments on the shelves would form offshore belts of fairly uniform heavy mineral suites that extend as far west as off the Rosetta branch of the Nile to at least as far as the northeastern Israeli margin (INMAN and JENKINS, 1984).

Differences in paths of net sediment transport [*i.e.* particularly differences of longshore currents and of geostrophic current flow (*cf.* GOLDSMITH and GOLIK, 1980; INMAN and JENKINS, 1984; NIR, 1984; ROHRLICH and GOLDSMITH, 1984)] would best explain the progressively-increased divergence between proportions of transparent heavy minerals on coasts and on shelves off the eastern Sinai, Gaza and Israel. Closure of the High Aswan Dam has resulted in cut-off of quartz-rich sediments supplied to the coast by the Nile but heavy minerals of Nilotic derivation, nevertheless, have continued to be supplied from eroded sectors of the Nile delta coast (FRIHY and STANLEY, 1987) and shifted eastward by longshore sediment transport (EL ASKARY and LOFTY, 1980; EL ASKARY and FRIHY, 1986; FRIHY, 1988; SMITH and ABDEL-KADER, 1988). Longshore currents are believed to carry such materials along the coast at least as far north as Haifa Bay, which is interpreted as a major "sediment sink" (*cf.* GOLDSMITH and GOLIK, 1980; INMAN and JENKINS, 1984; RORHLICH and GOLDSMITH, 1984).

Further offshore, older sediments (Holocene and Pleistocene) are primarily of Nilotic terrigenous derivation and, to a lesser extent, biogenic and carbonate-rich (NIR, 1984; NEEV *et al.*, 1987). Since the Holocene eustatic rise in sea level, fine-grained sediments have been introduced to the Israeli shelf by the East Mediterranean Current (RORHLICH and GOLIK, 1984) and by wind transport (CHESTER *et al.*, 1977). These relict deposits, along with modern

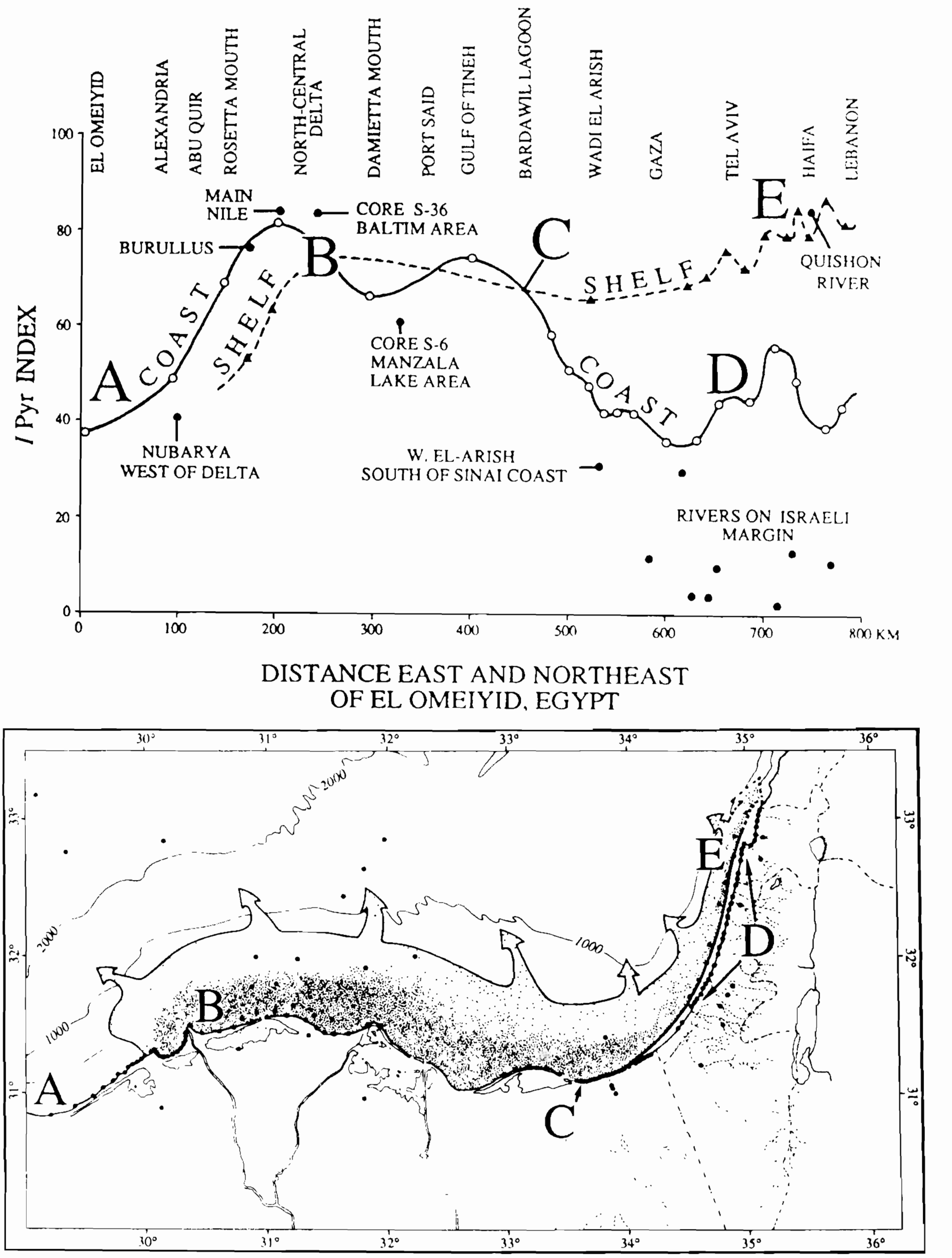

Figure 4. *Upper*, diagram showing *I*Pyr indices versus distance east and northeast of El Omeiyid, Egypt. Note marked divergence of coastal (solid line) and shelf (dashed line) values east of Bardawil lagoon (C). High *I*Pyr values occur on shelves, from Nile delta sources (B) to as far as the northern Israeli margin (E), while *I*Pyr values decrease in the same direction (to D, off Israel) along the major coastal transport path. *Lower*, map showing the dominant southeast Mediterranean depositional trend. The main supply of sediment from Nile sources (B) is introduced east of the carbonate margin (A) that lies west of Alexandria. The proportions of heavy minerals in sediment transported largely by wave-driven longshore transport to eastern Sinai, Gaza and Egypt coasts (D) differ from those west of Bardawil (C). Heavy minerals on shelves in relict and reworked relict deposits may be displaced by currents driven by storm wave activity in conjunction with flow of the East Mediterranean Current.

sediments, are winnowed and displaced along the margins (INMAN and JENKINS, 1984, their Fig. 1) leaving patchy sectors of texturally-clean sand lag deposits (COLEMAN *et al.*, 1981; STANLEY, 1988a). It is envisioned that palimpsest sediments have been dispersed along broad zones of shelves, while some sediment near the shelf-edge is probably transported onto the slope (Figure 4, lower) and deeper parts of the Levantine Basin (MALDONADO and STANLEY, 1979; ALMAGOR, 1980; ALMAGOR and MICHAELI, 1985), thus explaining the presence of "delta-affinity" sediments in Holocene sections cored on the lower Nile Cone (STANLEY and MALDONADO, 1977; STANLEY *et al.*, 1979).

Reworking of relict Nilotic sediments with a minimum of laterally introduced sand-size material could explain the generally consistent proportions of major transparent heavy minerals between the Nile delta and northern Israeli shelves. However, direct measurements on movement of sand-sized sediment on the middle and outer shelf sectors off southeastern Mediterranean coasts are limited (*cf.* COLEMAN *et al.*, 1981). The *I*Pyr and *I*Amph distributions suggest possible displacement of sands along paths subparallel to the Israeli coast. The present study indicates that "Nile delta-affinity" sediments north of the Gaza-Ashqelon sector trend progressively seaward, from the inner toward the middle to outer shelf, which narrows toward the north. With respect to the above observations, a series of linear depressions parallel the coast (EMERY and BENTOR, 1960), and these are interpreted as depositional ponds, formed between and partially covering kurkar ridges, which are elongate carbonate-cemented sandstone structures (NEEV *et al.*, 1987). It has been suggested that these linear sediment ponds are thicker and their tops lie at shallower depths on the southern Israeli shelf as a result of more direct sediment transport from Nile delta sources (EMERY and BENTOR, 1960). Further investigation is needed to confirm if and to what extent sedimentation has been guided northward by this submerged "swell and plain" topography (EMERY and BENTOR, 1960; NIR, 1984).

Most heavy mineral data on Gaza and Israeli coasts were obtained from samples collected prior to closure of the High Aswan Dam in 1964. Since then, an increasing number of harbor, coastal protection, and other man-made structures have been emplaced along the coast, such as at Damietta, El Arish and along the Israel margin (NIR, 1984). These structures directly impact on nearshore processes and modify the volume of laterally displaced sediment. The supply of sediments derived from the delta likely has been reduced somewhat relative to the volume of sediments (more modest) supplied along the coastal transport path by beach erosion, input of nearshore terrigeneous and biogenic deposits, and transport by wadis and wind. As a consequence of this relatively increased local sediment input, the proportion of heavy mineral species, particularly between Gaza and the northern Israeli coast, and perhaps even as far as Lebanon, may differ progressively from those derived from eroded Nile delta beaches.

Changes which may have occurred during this first quarter-Century of High Aswan Dam operation could be measured by a systematic close-grid resampling of the southeastern Mediterranean coastal and offshore sectors and by uniformly performed analyses of heavy minerals. This petrographic approach would serve to monitor recent responses to present conditions and help predict future modifications of the sediment budget and long-term transport patterns.

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