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Clay Mineral Distributions to Interpret Nile Cell Provenance and Dispersal: II. Coastal Plain from Nile Delta to Northern Israel

Daniel Jean Stanley, Yossi Mart, and Yaacov Nir

Deltas-Global Change
Program
E-206 NMNH, Paleobiology
Smithsonian Institution
Washington, D.C. 20560,
U.S.A.

Leon Reconati Center
University of Haifa
Haifa 31905, Israel

Geological Survey of Israel
Jerusalem 95501, Israel

ABSTRACT

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This study identifies clay mineral assemblages between the eastern Nile delta and northern Israel to complement and refine interpretations of modern sediment provenance and dispersal patterns in the SE Mediterranean. Previous petrological investigations indicate that the River Nile has been the dominant source of sediment transported to the Levant Sea, whereas sediment contributions from Sinai, Gaza and Israeli rivers and coastal cliff exposures in this region have been minor. However, this sediment dispersal pattern, modelled as the Nile littoral cell, is now being altered as a response to the High Dam at Aswan, barrages along the Nile valley and in the Nile delta, and water diversion by the high-density canal system in the Nile delta. As a result, Nile sediment input identified by high proportions of smectite is presently derived from erosion of the delta margin rather than from direct dispersal by the river proper.

The present investigation records important percentages of kaolinite in the clay fraction of samples recovered in coastal cliff exposures, from east of Bardawil lagoon and Wadi El Arish to the Lebanon-Israel border. Clay mineral assemblages in the fluvial channels on the coastal plain east of the Nile delta are considerably more variable: those west of El Arish are smectite-rich, while those on the plain east and north to the Tel Aviv region are kaolinite-rich; clay assemblages between Tel Aviv and Atlit are smectite-rich; still farther north, locally between Atlit and Haifa, assemblages in some fluvial channels comprise high percentages of illite, and those from north of Haifa to the Lebanese border record large proportions of kaolinite and illite. These laterally variable clay assemblages on the Sinai, Gaza and Israeli coastal margins are more closely related to the different source terrains in highlands that back the coastal plain than to distal Nile provenance. Modern clay minerals near the coast are derived from (1) rivers that flow seasonally from highlands in Sinai and Israel, (2) seasonally variable winds that carry dust from arid and semi-arid regions toward the coast, and (3) wave current erosion of coastal exposures. As the amount of distal Nile-derived clay from Egypt is reduced, these more proximal sources will likely to account for increasing proportions of clays supplied to Sinai and the SE Levant margin.

ADDITIONAL INDEX WORDS: *Clay minerals, coastal erosion, Egyptian shelf, eolian, Gaza, hamra, High Aswan Dam, Israel coastal plain, Israeli rivers, kurkar, Levant margin, Mediterranean, Nile delta, Nile littoral cell, Sinai margin, Wadi El Arish.*

INTRODUCTION

The southeastern Mediterranean is a densely populated region undergoing substantial environmental modification as a result of increased anthropogenic pressure. Of major importance in this region is the sediment load carried by the River Nile to the northeastern African coast, which has been greatly reduced since closure of the High Dam at Aswan in 1964. At present, only a small volume of silt and clay bypasses the Nile delta to the sea via River Nile distributaries, lagoon outlets and canals (Stanley, 1996). The High Dam and markedly altered waterway system below it directly affect sedimentation in the Nile valley and delta, and also are modifying sediment dispersal to areas east of the Suez Canal.

Nearshore and shelf currents presently continue to displace Nile-derived sediment toward Sinai, Gaza, and Israel (Sharaf El Din, 1977), but sediment transport is increasingly disrupted by man's modification of the coast east of the Nile delta. Quarrying of sand and placement of urban and industrial facilities and structures along the shore in this region modify nearshore sediment transport and locally induce substantial coastal and inner shelf erosion (Nir, 1982; Nir and Elimilech, 1990). The long-term ramifications for these northeastern African and Levant coastal sectors have, as yet, to be clearly determined.

Mapping of clay mineral distributions can refine mineralogical baselines to more accurately assess the coastal evolu-

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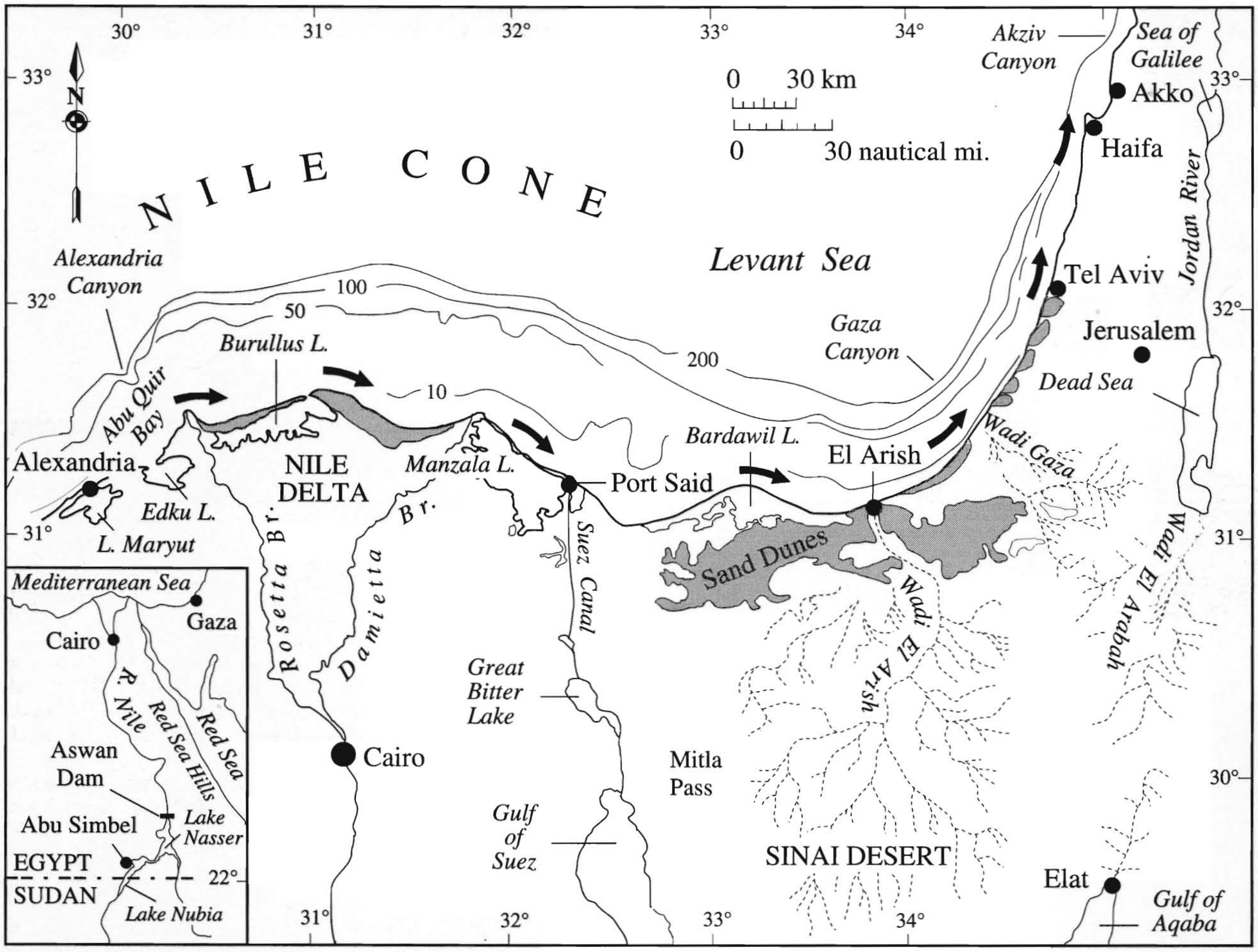

Figure 1. Simplified geographic map of the SE Levant study area (modified after Inman and Jenkins, 1984). Arrows denote dominant easterly directed coastal currents. Rivers and wadis in Israel are shown in Figure 2.

tion on North African and Levant margins. In this region the fine sediment fraction is (1) likely to be transported farther than silt and sand, and (2) sufficiently varied to help distinguish proximal/lateral from distal input from the coastal plain to the shelf. A three-part investigation has thus been initiated to map lateral changes in clay mineralogy on coastal margins and offshore, from the River Nile and Nile delta to the Israel-Lebanon border.

The initial study (Stanley and Wingerath, 1996) concentrated on clay mineral distributions in the modern River Nile system. Until recently, this was by far the largest source of sediment supplied to the southeastern Mediterranean (Hurst, 1952). Attention was paid to the increasingly altered Nile sector between Lake Nasser, the reservoir behind the High Dam in southern Egypt, and the Nile delta along the Mediterranean coast in northern Egypt (Figure 1, inset). The first article identified the major clay mineral assemblages along the Nile valley, changes induced by closure of the High Dam and sediment entrapment in Lake Nasser behind the dam, and now-altered clay mineral assemblages recorded farther down the river. Changes in the lower Nile result largely from flow of the sediment-depleted river below the High Dam and, north of Cairo, deposition of sediment in the increasingly complex irrigation channel and canal drain pathways constructed throughout the delta (Sestini, 1989; Stanley, 1996). Upon reaching the coast, sediment is dispersed in a counter-clockwise direction in the easternmost Mediterranean (Inman and Jenkins, 1984; Smith and Abdel-Kader, 1988; Frihy *et al.,* 1991). Consequently, this material is directed primarily to the east, off Sinai and Gaza coasts (Sharaf El Din, 1977), and then farther to the north on the Israeli margin (Nir, 1984).

The present article, second in the series of investigations, considers the above regional transport pattern and pays special attention to provenance of clay minerals in modern rivers and ephemeral (usually dry) tributaries, or *wadis,* east of the Nile delta (Figures 2–4). Clays derived from sediment eroded from coastal cliffs of Israel (Figure 5) are also evaluated herein. Together, these two coastal plain environments constitute the second important source of sediment (after Nile input), and herein are viewed as an integral part of the modern SE Levant sedimentation system. Clay mineral analyses in the

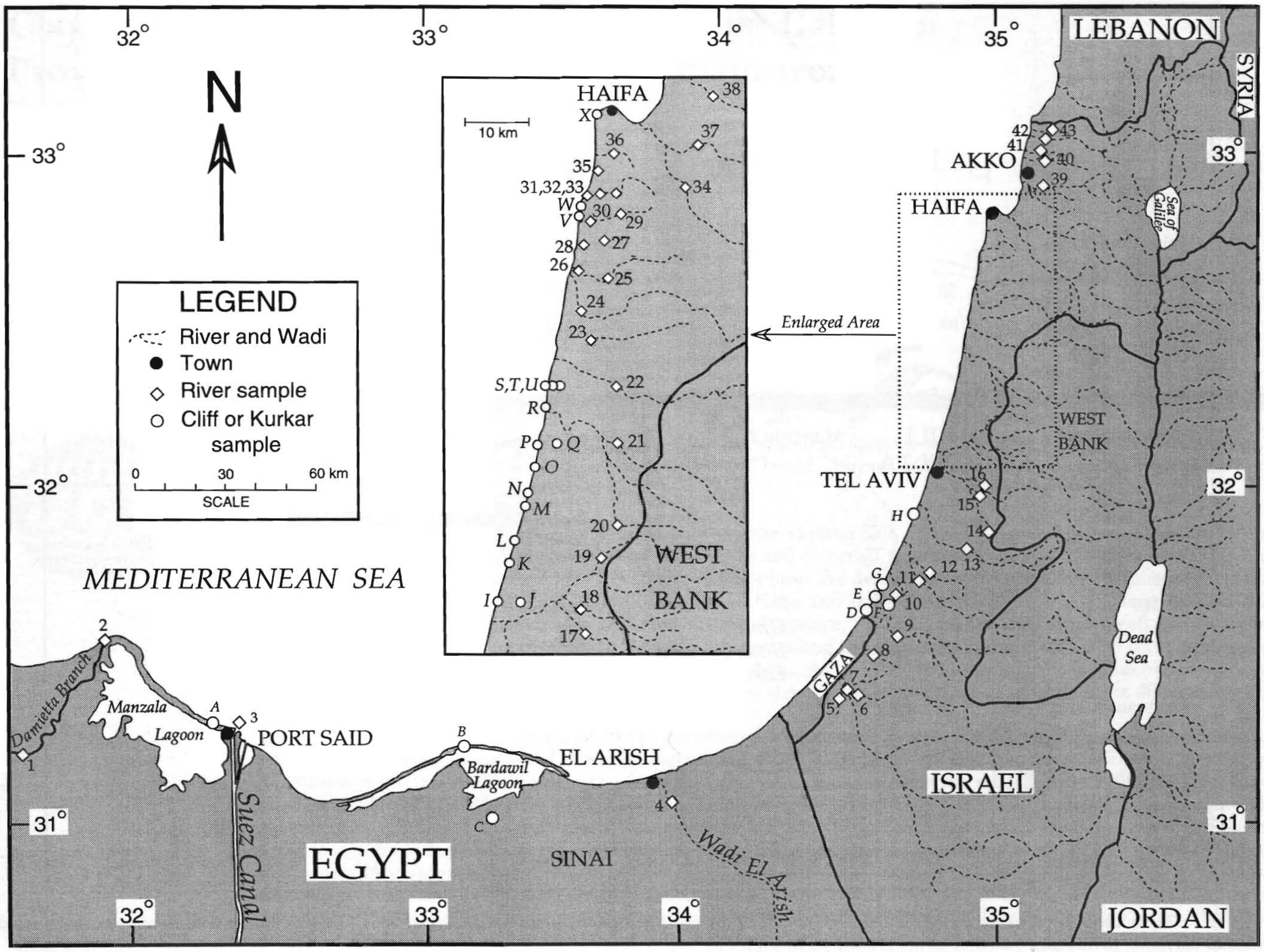

Figure 2. Fluvial channel and coastal cliff and kurkar sample locations in the SE Levant study area (location names and environments are listed in Tables 1 and 2).

present study should allow us to distinguish Nile source assemblages from those derived from coastal sectors to the east and north of the Nile delta margin (Figure 1).

The third article in this series (STANLEY *et al.*, in preparation) will evaluate offshore distributions of clay minerals, emphasizing the coast and shelf so as to complement present information on sediment provenance and dispersal patterns in the SE Mediterranean. It is anticipated that the three clay mineral studies will complement information on sediment transport patterns between the Nile delta and the northern Israeli margin, a region increasingly affected by man's activity.

NILE LITTORAL CELL—A REVIEW

Sediment transport and depositional patterns on the coast and shelf in the SE Mediterranean have been quantified by the *Nile littoral cell* model defined by Inman and Jenkins (1984). This compartmentalized sedimentation system extends from Alexandria in Egypt to Akko (Acre) in northern Haifa Bay, Israel, a distance of about 700 km (Figure 1). The model incorporates the complete cycle of littoral sedimentation in this region, including provenance, transport dispersal paths, and depositional sinks. Inman and Jenkins (1984) summarized the depositional budget primarily for the period prior to the Aswan High Dam, emphasizing eastward displacement of sediment, derived primarily from the River Nile and Nile delta coast, to the Levant margin.

Nile littoral cell studies have evaluated volume of dispersed sediment, texture, and sand composition. Most indicate that quartz-rich sand on the coast and shelf off Gaza and Israel is primarily derived from the River Nile (RIM, 1951; EMERY and BENTOR, 1960; EMERY and NEEV, 1960; POMERANCBLUM, 1966; GOLDSMITH and GOLIK, 1980; INMAN and JENKINS, 1984; NIR, 1984; STANLEY, 1989; GALILI *et al.*, 1993; GOLIK, 1993; SHOSHANY *et al.*, 1996). The Nile was the most important source of sand and finer sediment provided to the southern, more arid Mediterranean until emplacement

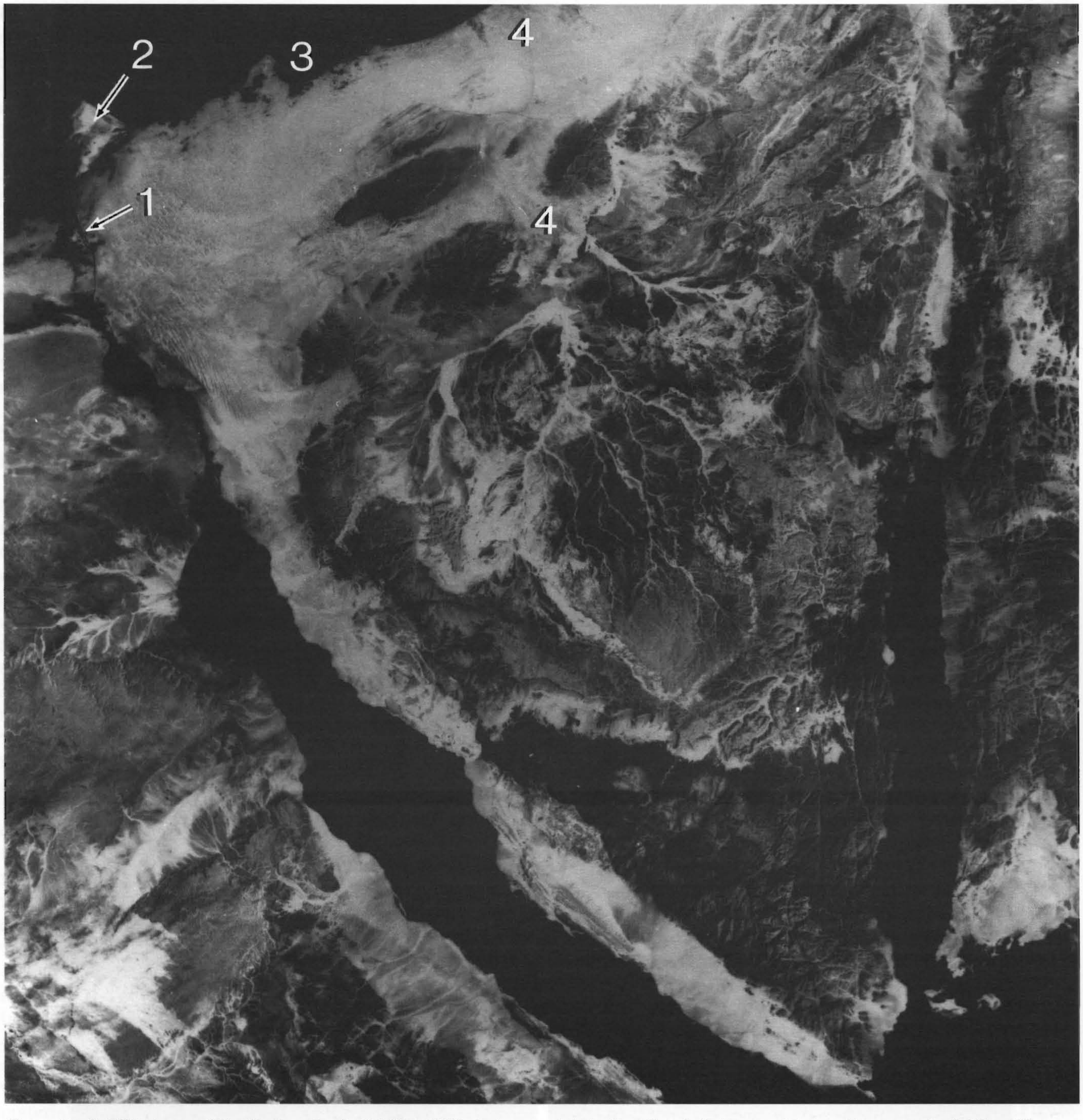

Figure 3. Satellite image of the Sinai peninsula (10 May 1978). 1, Arrow points to Suez Canal; 2, Arrow points to saline covered subsiding NE corner of Nile delta; 3, Bardawil lagoon, north of desert and dune fields; and 4, Wadi El Arish.

of the two dams at Aswan in southern Egypt during this century (HURST, 1952; QUELENNEC and KRUK, 1976; EMELYANOV, 1972; ROSS and UCHUPI, 1977; STANLEY, 1977). This south-to-north oriented river is 6800 km-long, has its headwaters in central Africa and Ethiopian Plateau, and crosses 35° of latitude (ADAMSON *et al.,* 1980).

The Low Dam constructed in 1902 and much larger High Dam emplaced in 1964 have seriously disrupted the natural flow of the Nile north of Aswan (WATERBURY, 1979; ELASSIOUTI, 1983; HOWELL and ALLAN, 1994), and also sedimentation along the SE Mediterranean coast (SHARAF EL DIN, 1977; STANLEY and WARNE, 1993). At present, <2% of the

Figure 4. Photographs of selected fluvial systems along Gaza and Israeli margins. A, Yarkon river, Tel Aviv (2 June 1995); note shifting sandbars at river mouth (NNE to left). B, Tanninim river, west of Binyamina, showing bridge destroyed by earlier flood and shifting sand at river mouth (29 May 1995). C, Poleg river south of Netanya (2 June 1995); note river mouth displaced by shifting coastal sands (NNE to left). D, Partially filled Wadi Besor, Gaza, flowing to the coast (at lower right; 2 June 1995). E, Wadi Besor near Gaza border, with fine to coarse sediment in channel (27 May 1994). F,

Nile's sediment load by-passes Lake Nasser and the High Dam at Aswan. The reduced sediment volume presently reaching the sea (< 15% of the former Nile load) is discharged primarily: (1) through Manzala, Burullus and Idku lagoon outlets (LOIZEAU and STANLEY, 1993, 1994); (2) via several large drains that empty directly at the coast (SESTINI, 1989; STANLEY, 1996); and (3) by pumping of Lake Maryut water to the sea at Alexandria (WARNE and STANLEY, 1993).

Sediment reaching the coast in this region is subject to the interplay of natural processes, including wind (Figure 6), precipitation (Figure 7), intermediate to strong coastal currents, winter storm waves, land subsidence rates ranging from 1 to 5 mm/year, and continued sea-level rise (STANLEY and WARNE, 1993). These factors, together with the marked reduction of Nile sediment input, have caused accelerated erosion during this century at both Nile promontories, and retrogradation of extensive sectors of the delta coast (INMAN and JENKINS, 1984; FRIHY, 1988; SMITH and ABDEL-KADER, 1988). As a result of sediment lost each year from the delta's shoreline, the lower Nile coastal plain is no longer an active, prograding delta (STANLEY and WARNE, 1993).

Ongoing Nile cell studies indicate that sediment eroded from Egypt's coast continues to be transported eastward (FRIHY, 1988; SMITH and ABDEL-KADER, 1988). Wind-driven coastal and geostrophic currents induce this prevailing easterly flow along the eastern North Africa margin (LACOMBE and TCHERNIA, 1972), displacing sand along the inner shelf and Sinai and Gaza coasts (SHUKRI and PHILIP, 1961) to the northern Israeli margin (EMERY and NEEV, 1960; GOLDSMITH and GOLIK, 1980; NIR, 1984; GOLIK, 1993; SHOSHANY *et al.,* 1996). Finer-grained sediment, derived from the Nile region and from eolian transport (MURRAY, 1951; VENKATARATHNAM and RYAN, 1971; CHESTER *et al.,* 1977), is carried in suspension as far north as Turkey by the counter-clockwise eastern Mediterranean geostrophic eddy (MILLER, 1972). This trend is borne out by petrologic studies of both coarse- and fine-grained surficial sediment north of the Egyptian coast (VENKATARATHNAM and RYAN, 1971; SUMMERHAYES *et al.,* 1978; MALDONADO and STANLEY, 1981; MURRAY *et al.,* 1981), and east of the delta, on the Sinai, Gaza and Israel margins (POMERANCBLUM, 1966; NIR and NATHAN, 1972; NIR, 1984; ALMAGOR and MICHAELI, 1985).

Distribution of transparent heavy minerals indicate that, east of Bardawil, input from proximal sources is more important than generally recognized (STANLEY, 1989, his Figure 4). As a hypothesis to be tested, we propose that the following changes have occurred since closure of the High Dam during the past 32 years: (1) the volume of eastward displaced Nile material has diminished on Sinai, Gaza and Israeli margins; and (2) relative proportions of sediment supplied more proximally from eroded coastal and inner shelf sectors, and perhaps also by wind and Levant rivers, have increased on margins east of Bardawil lagoon.

The sediment transport and depositional regime, now being altered as a consequence of increased anthropogenic activity, is of concern to the three countries bordering the SE Levant coast. In this respect, clay mineral baselines in the present investigation are viewed as potentially useful markers of provenance and dispersal which, in turn, can provide insight on changes of the extant Nile littoral cell.

SEDIMENT SOURCE TERRAINS IN STUDY AREA

After emplacement thirty two years ago of the High Dam at Aswan, sediment eroded from the River Nile and Nile delta are now the major contributors to the coast in the SE Levant study area. Clay minerals transported northward by the Nile into southern Egypt are derived primarily from the Blue Nile and Atbara river headwaters in the Ethiopian Plateau, and from the White Nile in central Africa. Ethiopian highlands contribute >70% of the Nile's discharge and most of its sediment load north of Khartoum (SHUKRI, 1950; FOUCAULT and STANLEY, 1989).

In late Pleistocene and early Holocene time, a network of large fluvial (now wadi) channels carried sediment to the Nile in Egypt (NAGA *et al.,* 1985). This material, derived from high-elevation Red Sea Hills to the east (COLEMAN, 1993), was dispersed by large rivers that cross Eastern Desert terrains. Evidence in support of this lateral westerly-directed dispersal during the late Quaternary is provided by studies of Nile terrace and bank deposits (BUTZER and HANSEN, 1968; SAID, 1981). With rare exception, these channels are now dry (annual rainfall in the region is < 100 mm). Most of these byways have provided only a limited sediment supply to the Nile during the past ~5,000 years, *i.e.,* since time of aridification in the mid-to-late Holocene (ADAMSON *et al.,* 1980; PAULISSEN and VERMEERSCH, 1989).

During this century, Nile flow in Egypt has been dramatically altered as a result of emplacement of the two dams at Aswan (SCHUMM and GALAY, 1994). Inevitably, the changed flow pattern induced marked textural and compositional changes of River Nile sediments. More than 98% of the sediment (including most of the coarse silt and fine sand bed load), which earlier was transported downriver all the way to the delta and coast, is now retained in southern Lake Nasser. As a consequence, waters of northern Lake Nasser and the Nile below the High Dam carry decreased volumes of bed and suspended load, and altered organic matter, planktonic content and geochemical properties.

The east-to-west trending Mediterranean coast of Sinai, from the Suez Canal to Gaza, is about 200 km long (Figure 2). Bardawil lagoon lies only ~40 km east of the Nile delta (Figure 3, *3*). River Nile distributaries during the Holocene did not extend eastward as far as the western part of this lagoon (Sneh and Weissbrod, 1973), and there is no evidence

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small bridge over Wadi Shilo, with pebbles and boulders on the channel floor and large mass of plant debris caught on bridge supports recording previous winter floods (30 May 1994). G, Wadi Megadim, north of Atlit, cuts across a coastal ridge to the shore (25 May 1995). H, Mouth of Wadi Galim, south of Haifa, where a small coarse-debris delta formed by the past winter flood deposits released at the coast (25 May 1995).

Figure 5. Photographs of selected coastal plain sections in Israel. A, Oren river, cut in Carmel hills south of Haifa, flows westward to the coast. B, River channel from Carmel hills to the coastal plain (toward W), where river flow is artificially diverted (2 June 1995). C, Cliffs bordering coastal plain south of Netanya (NNW to left; 2 June 1995). D, Well stratified kurkar cliffs along the coast (to left) in Newe Yam reserve. E, Brown oxidized soil layer (arrow) exposed along the coast near base of the Crusader cemetery at Atlit (29 May 1995). F, Broad sand dune covered strand plain on the Haifa Bay coast near Akko (1 June 1994).

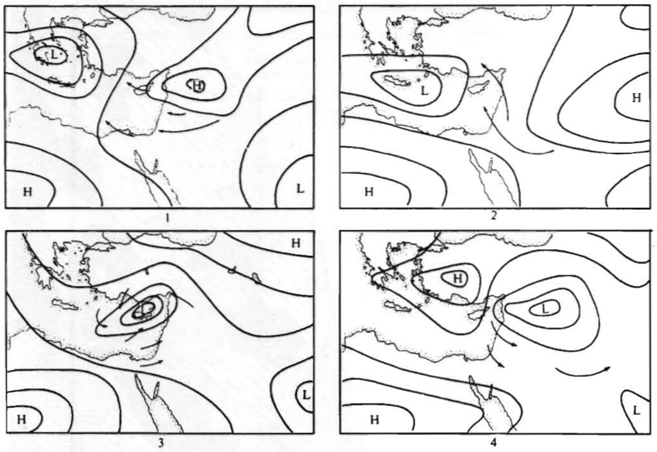

Figure 6. Isobar maps show cyclones (L) and anticyclones (H) moving over the eastern Mediterranean region. Arrows indicate variable wind directions over study area (after Orni and Efrat, 1971).

of fluvial channels flowing into the lagoon from the south, now or in the past (Levy, 1974).

Wadi El Arish (Figure 3, *4*) is the largest fluvial system in the SE Mediterranean east of the Suez Canal. Its mouth, east of the town of El Arish, is positioned about 35 km east of Bardawil lagoon. This fluvial system drains a region receiving less than 100 mm of rain per year (precipitation is < 50 mm/year over more than half the Sinai; Figure 7) and seriously floods only about once every decade. The wadi, 250 km long and locally >10 km wide, heads in highlands and mountains of south-central Sinai (El Shazly *et al.*, 1980), and drains more than a third of the peninsula (> 20,000 km^2). When flowing, this river is powerful and capable of carrying large volumes of fine to coarse sediment to the coast. At times of flood, a large temporary delta forms at the coast (description of 1977 flood event in Nir, 1982).

Geological exposures in southern Sinai (Figure 8A) include granite, diorite, porphyry, schist, and gneiss. In central Sinai the wadi and its numeous headlands (Figure 3) cut across Carboniferous (mainly Nubia Sandstone) terrains, Mesozoic limestone, chalk, and sandstone, and Tertiary chalk formations (Said, 1960; Orni and Efrat, 1971).

Sinai's Mediterranean coastal margin, backed by desert, merges smoothly with semiarid Gaza and Israeli coastal plains (Figure 2). No large topographic features disrupt the straight shoreline between the eastern Bardawil lagoon-Wadi El Arish coast and Haifa Bay. The shoreline from Wadi El Arish to the Israel-Lebanon border is 310 km long, and Gaza and Israel coasts are, respectively, ~40 and 188 km in length. These coasts are varied (Emery and Neev, 1960; Nir, 1982; Gvirtzman *et al.*, 1984; Neev *et al.*, 1987) and characterized by discontinuous steep cliffs (relief to 40 m; Figure 5C), carbonate sand ridges (Figure 5D) and gently inclined backshores, commonly covered with sand dunes (Figure 5F).

Israel's coastal plain morphology includes badland topography, dunes, low-relief bare to plant-covered plains (Figure 5B), and marshy lowlands (descriptions in Orni and Efrat, 1971). Most of the coastal plain is backed by highlands to the east, including (from south to north) Negev, Judean and Samarian Hills. Farther north, in the Haifa region, Mount Carmel (Figure 5A, B) extends northwest directly to the coast, bounding the southern margin of Haifa Bay. Proceeding toward the Lebanon border, the narrow coastal plain is delimited to the east by western Galilee highlands (Figure 8B).

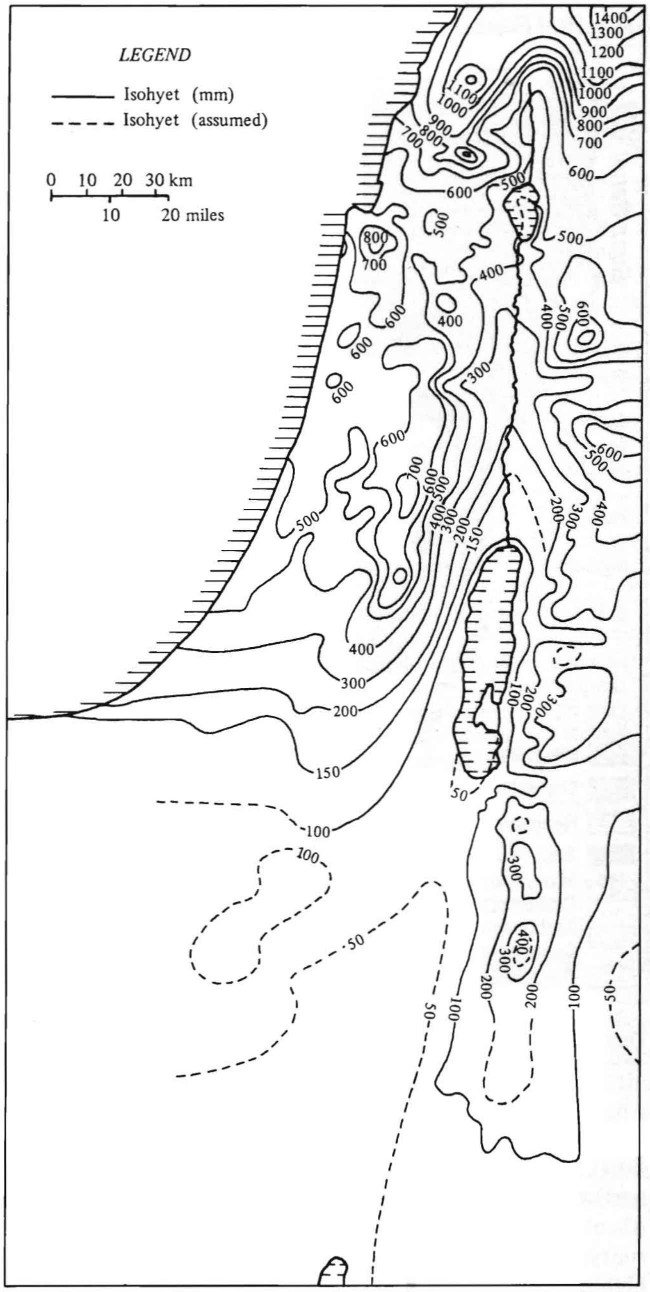

Figure 7. Annual rainfall distribution (isoyet in mm) for the eastern Sinai, Gaza and Israel (after Orni and Efrat, 1971).

Rainfall in this region (Figure 7) increases from southwest (arid) to northeast (semiarid): the low annual precipitation in

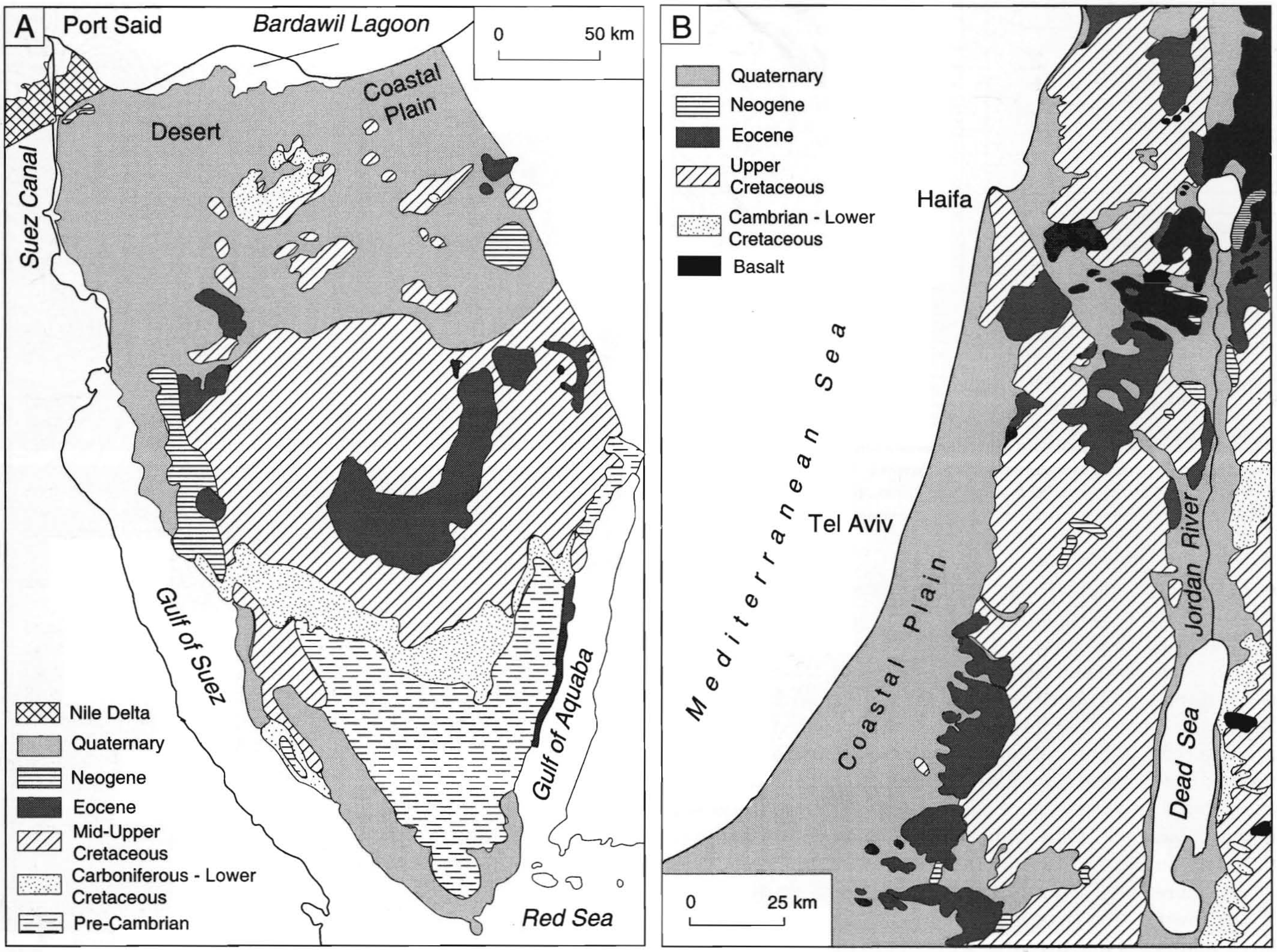

Figure 8. Simplified geologic maps of (A) Sinai (after Orni and Efrat, 1971), and (B) Israel (modified after maps by the Geological Survey of Israel).

Sinai (< 150 mm/yr) and Gaza (150–400 mm/yr) increases northward to the Israel-Lebanon border (~700 mm/yr). About 70% of the rainfall occurs between November and February, and this precipitation (including sleet and snow in highlands to the east) feeds streams on the coastal plain, primarily in winter months. Sediment transported seasonally by streams flowing to the coast (Figure 2) has shaped the Quaternary surface of the alluvial plain.

During the late Quaternary, coastal plain deposits at various times accumulated under climatic conditions that differed from those prevailing today. Dated cool-warm and wet-dry fluctuations affecting the SE Levant (detailed in NEEV and EMERY, 1995) record shifts in the monsoonal rain system within the Asiatic-African atmospheric belt. Highly arid conditions influencing the River Nile system have prevailed during most of the past 5,000 years (ADAMSON *et al.,* 1980). In the SE Levant, the present dry phase began somewhat more recently in the SE Levant, shortly before 3,000 years ago. This episode followed a short, mostly wet, phase during which important fluvial sediment loads were carried seaward.

Physical oceanographic and transport regimes similar to present ones (currents and sediment directed primarily to the east and NNE; Figure 1) were established along the coast by about 7,000 to 6,000 years B.P. (*cf.* ANASTASAKIS and STANLEY, 1986; STANLEY and GALILI, 1996). During the past three millennia, changing fluvial patterns on the Gaza and Israeli margins have altered volume and amount of sediment loads carried seaward. It is also during this period that effects of human activity have markedly intensified. Increased population pressure has produced, among other changes, artificial diversion of water, accelerated vegetal change and increased soil erosion. These anthropogenic influences have accelerated headland erosion in highlands that back the coastal plain and, consequently, modified alluviation of the plain by the short, locally high-gradient streams in Gaza and Israel (Figure 5A, B).

Table 1. *Samples collected in river and wadi channels in the SE Levant study area (sites numbered 1 to 43 shown in Figure 2).*

Number	Location	Field #
1	Damietta branch (1990)	Dam-3-Ch
2	Damietta branch (1990)	Dam-1-Ch
3	Port Said (Suez Canal)	PS1G
4	Wadi El-Arish	YN-3031
5	N. Assaf	JM-921
6	N. Besor	JM-920
7	N. Gerar	JM-922
8	N. Shiqma	JM-924
9	N. Hannun	JM-923
10	N. Evtah	JM-944
11	N. Guvrin	JM-943
12	N. Ela	JM-942
13	N. Soreq	JM-941
14	N. Nahshon	JM-940
15	N. e-Shami.	JM-939
16	N. Navalat	JM-938
17	N. Shilo	JM-937
18	Central tributary to N. Yarkon	JM-936
19	Northern tributary to N. Yarkon	JM-935
20	N. Alexander	JM-934
21	N. Shekhem	JM-933
22	N. Hadera	JM-932
23	N. Ada (N. Barkan)	JM-931
24	N. Tanninim	JM-930
25	N. Dalia	JM-929
26	Maharal river	EG-Y
27	N. Maharal	JM-928
28	Me'arot river	EG-Z
29	N. Me'arot	JM-927
30	En Carmel river	EG-W
31	Oren river, 500 m from shore	DJS-95-a
32	Oren river	EG-1-6
33	N. Oren	JM-926
34	N. Kishon	JM-952
35	Megadim river	DJS-95-d
36	Tirat HaCarmel	JM-925
37	N. Tzipori	JM-951
38	N. Eblayim	JM-950
39	N. Hilazon	JM-949
40	N. Bet Ha'Emeq	JM-948
41	N. Ga'aton	JM-947
42	N. Kziv	JM-946
43	N. Betzet	JM-945

Table 2. *Samples collected in coastal cliff and hamra exposures in the SE Levant study area (sites coded A to X shown in Figure 2).*

Number	Location	Environment	Field #
A	Port Said	Beach	PSB
B	Bardawil lagoon	Barrier island	DN(67)65
C	Bardawil I., S.-central	Near sabkha, E. of Misfak	YN-3027
D	S. Tel Ashqelon	Kurkar	YN-3048
E	N. Ashqelon (Datiyim beach)	Kurkar	YN-3049
F	Ashqelon, shore	Kurkar	YN-3047
G	Ashqelon, North	Kurkar	YN-3046
H	Palmachim, 50 m from beach	Cliff, base	EG-X
I	Tel Barukh beach	Kurkar	YN-3033
J	Tel Barukh, 100 m E. of shore	Kurkar	YN-3035
K	Herzliya, marina	Kurkar	YN-3040
L	Ga'ash	Kurkar, upper Hamra	YN-3037
M	Beit Goldmintz, E. of cliff	Kurkar	YN-3045
N	Beit Goldmintz, S. of Netanya	Kurkar	YN-3038
O	Hof Hatkhelet beach, N. of Netanya	Kurkar, top of cliff	YN-3036
P	Beit Yanay	Kurkar, above Netanya hamra	YN-3039
Q	Beit Yanay	Kurkar, Netanya hamra	YN-3034
R	North Mikhmoret	Kurkar	YN-3041
S	Give'at Olga	Kurkar, lower hamra	YN-3042
T	Give'at Olga	Kurkar, upper hamra	YN-3043
U	Give'at Olga	Kurkar, "Cafe au lait" sandy loam	YN-3044
V	Atlit cemetery	Bluff	DJS-95b,-c
W	Atlit, 300 m N. of Oren River	Below beach rock	EG-7
X	Tel Hreiz	Beach	DJS-95e

The coastal plain of Gaza and Israel is crossed by about 30 short, west-flowing rivers and wadis (the term nahal is also used, and abbreviated N. in Table 1), all of which have been sampled in this study (Figure 2). Their length ranges from ~ 50 km in the south (Wadi Besor, Gaza) to ~10 km in northern Israel. Only those positioned at and north of Tel Aviv flow during all or most of the year (Figure 4A, B). These include the Ayalon, Alexander, Hadera, Quishon, Ga'aton and Keziv. The coastal plain also narrows gradually, from about 40 km at the latitude of Gaza to less than 5 km in northernmost Israel (Figure 8B). In some cases, wadis (such as the Soreq, Alexander, and Keziv; Figure 4), become water-filled streams only along the last few kilometers of their course.

Flow direction of many channels changes markedly at the coast, sometimes by >90°, as a result of the barrier effects of coastal kurkar ridges (Figure 4G) and/or of river mouth damming by beach and dune sand transport (Figure 4C). Following powerful winter flow of rivers small deltaic deposits accumulate temporarily at their mouths (Figure 4H); storm waves and strong coastal currents subsequently alter the position of channel mouths by as much as several hundreds of meters (Figure 4A, C). Most of these fluvial systems also have been considerably modified by man, especially during this century. The volume of water has diminished as a result of dams and other structures which divert water for agricultural (Figure 5B), municipal and industrial use. Water in almost all river channels of this region is moderately to extensively polluted (KRESS *et al.,* 1990).

METHODOLOGY

Samples for this study were collected in 1994 and 1995 at 67 sites on land, from the eastern Nile delta to the Israel-Lebanon border. Forty three of the sites, coded herein 1 to 43, are primarily from modern river and wadi channel locations (Table 1): 4 in Egypt, include the Damietta branch of the Nile, northern Suez Canal at Port Said, and Wadi El Arish in Sinai; and 39 in Gaza and Israel (Figure 2). Most fluvial localities in Sinai, Gaza and Israel were selected inland, at distances > 2 km from the coastline, to minimize sediment input from the sea and eroded coastal sections. Numerical data presented for site 32 is averaged from analyses of 6 samples collected at that locality, and for site 35 from analyses of 2 samples.

Table 3. *Percentages of major clay minerals and textural data for river and wadi channel samples in Egypt, Gaza and Israel.*

Sample and Field #	Major Clay Minerals (%) (semi-quantitative values)			Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
	Smectite	Kaolinite	Illite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
1 Dam-3-CH 1990	78	20	2	—	—	—	2.2	165.8	175.1	211.7
2 Dam-1-CH 1990	69	25	6	0.0	4.3	95.7	26.1	10.3	9.4	5.3
3 PS-1G	75	16	9	0.0	83.0	17.0	2.0	122.0	137.9	118.8
4 YN-3031	28	53	19	0.0	0.0	100.0	33.6	4.5	5.5	3.5
5 JM-921	31	41	28	0.3	48.6	51.1	8.6	165.3	325.0	64.0
6 JM-920	24	43	33	0.7	28.0	71.3	10.7	84.5	72.5	23.1
7 JM-922	33	42	25	0.0	32.1	67.9	7.9	81.6	72.5	44.5
8 JM-924	51	33	16	1.1	85.7	13.2	2.6	273.6	262.3	258.1
9 JM-923	36	34	30	1.0	20.1	78.9	9.7	37.4	20.0	18.9
10 JM-944	82	16	2	1.9	31.6	66.5	22.5	82.3	58.5	25.2
11 JM-943	58	35	7	8.4	54.4	37.2	6.7	270.7	618.4	250.4
12 JM-942	59	33	8	4.5	46.8	48.7	4.9	436.9	766.3	537.0
13 JM-941	64	28	8	59.8	23.4	16.8	8.1	266.3	618.4	140.9
14 JM-940	75	21	4	3.0	23.5	73.5	10.8	72.8	22.3	17.2
15 JM-939	45	41	14	4.2	22.7	73.1	6.5	242.6	618.4	69.8
16 JM-938	65	27	8	7.6	12.7	79.7	9.5	48.0	24.8	17.3
17 JM-937	48	40	12	7.8	38.4	53.8	7.1	185.4	618.4	36.8
18 JM-936	77	20	3	2.7	16.8	80.5	15.5	12.3	14.5	9.4
19 JM-935	71	22	7	0.2	60.9	38.9	10.3	146.1	211.7	174.4
20 JM-934	77	20	3	12.9	13.6	73.5	13.3	64.2	22.3	13.6
21 JM-933	71	23	6	9.0	32.4	58.6	13.9	137.3	618.4	28.3
22 JM-932	75	21	4	0.0	7.8	92.2	26.8	37.1	58.5	8.2
23 JM-931	86	13	1	0.1	38.3	61.6	16.9	67.0	190.2	23.5
24 JM-930	78	13	9	0.1	8.4	91.5	11.3	55.8	14.5	16.0
25 JM-929	72	19	9	3.0	10.9	86.1	11.8	50.9	24.8	14.8
26 EG-Y	74	18	8	0.0	52.2	47.8	30.1	65.0	211.7	5.1
27 JM-928	91	7	2	4.5	33.0	62.5	9.7	98.1	24.8	21.5
28 EG-Z	64	26	10	0.5	18.1	81.4	28.1	36.9	4.5	5.0
29 JM-927	87	10	3	0.8	18.4	80.8	11.0	74.8	22.3	16.7
30 EG-W	85	15	0	0.8	5.0	94.2	38.3	14.3	0.9	3.2
31 DJS-95-a	59	35	6	0.2	34.0	65.8	25.4	110.3	0.9	9.3
32 EG-1 to 6*	51	35	14	11.8	28.5	59.7	19.4	152.1	311.3	274.2
33 JM-926	53	28	19	14.7	28.1	57.2	15.9	117.3	10.5	18.9
34 JM-952	72	16	12	21.5	20.6	57.9	15.0	13.2	24.8	10.3
35 DJS-95-d**	47	38	15	0.5	2.7	96.8	38.9	11.1	0.9	3.9
36 JM-925	29	31	40	29.2	25.3	45.5	8.6	119.4	27.6	25.1
37 JM-951	67	28	5	12.6	16.1	71.3	10.6	120.0	24.8	20.5
38 JM-950	67	26	7	4.2	5.1	90.7	17.3	11.3	13.0	8.2
39 JM-949	43	44	13	0.8	7.2	92.0	12.3	48.8	22.3	16.3
40 JM-948	40	51	9	12.2	19.8	68.0	33.5	10.9	0.9	4.3
41 JM-947	52	41	7	0.2	31.8	68.0	10.3	107.7	22.3	21.3
42 JM-946	42	41	17	69.3	29.3	1.4	3.4	513.3	766.3	593.7
43 JM-945	60	24	16	40.3	21.4	38.3	18.8	11.7	24.8	8.6

* Average of 6 samples from Oren River at base of Carmel Mountains.
** Average of 2 samples from Megadim River.

A second group of 24 samples, coded A to X, were collected primarily from older Quaternary cliff sections (Nir, 1982; Figure 4C) and from oxidized brown to reddish brown continental layers (*hamra* and soil profiles, Figure 4E; *cf.* Neev *et al.*, 1987; Rohrlich *et al.*, 1991) interbedded in sandy carbonate coastal ridges (*kurkar,* Figure 4D; *cf.* Gvirtzman *et al.,* 1984; Neev *et al.,* 1987). Of these 24 samples, three are from Egypt and twenty-one are from Israel (Table 2).

Textural and clay mineral analyses were made using the same operator and methods as those detailed in Stanley and Wingerath (1996). Proportions (by weight) of mud [clay (< 2 μm) plus silt (2–63 μm)], sand (63–2,000 μm) and granule (> 2,000 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 volume) and grain size statistics (mean, mode, median) using a Coulter LS-100® laser particle size analyzer. These data are listed in Tables 3 and 4.

The clay-sized fraction (< 2 μm), separated by decantation and concentrated by centrifugation, was prepared as smear slide for X-ray diffraction analysis. A Scintag XDS-2000 diffractometer with a copper X-ray tube and Scintag Peltier detector was used for analyses. Settings were 40 mA and 45 kV, from 2 to 60° 2θ, at a scanning rate of 1° 2θ/minute. Samples untreated, glycolated and heated (to 550 °C for 1 hour) were analyzed. Proportions of clay minerals were determined by using measurements proposed by Moore and Reynolds (1989),

Table 4. *Percentages of major clay minerals and textural data for coastal cliff and hamra samples in Egypt, Gaza and Israel.*

Sample and Field #	Major Clay Minerals (%) (semi-quantitative values)			Grain Size (based on weight %)			Size Statistics From Fraction <1 mm (based on volume, using laser analyzer)			
	Smectite	Kaolinite	Illite	Granules	Sand	Silt + Clay	% Clay (vol.)	Mean (μm)	Mode (μm)	Median (μm)
A PS-B	87	8	5	4.7	88.2	7.1	1.9	199.3	170.8	184.1
B DN(67)65	42	39	19	0.0	39.9	60.1	14.4	108.9	8.5	9.5
C YN3027	25	45	30	0.3	92.7	7.0	0.5	489.4	555.6	512.4
D YN3048	35	38	27	5.7	62.6	31.7	12.8	293.8	618.4	293.7
E YN3049	28	50	22	0.9	40.0	59.1	29.2	35.6	65.1	6.9
F YN3047	55	33	12	0.0	38.7	61.3	35.2	13.0	47.2	3.7
G YN3046	13	56	31	26.0	71.1	2.9	4.3	248.1	235.6	239.7
H EG-X	38	36	26	0.3	48.6	51.1	11.4	126.0	235.6	53.1
I YN3033	56	33	11	0.0	59.7	40.3	10.8	123.5	190.2	140.4
J YN3035	48	31	21	2.0	15.1	82.9	43.8	8.7	0.9	2.8
K YN3040	44	46	10	0.0	55.7	44.3	11.0	134.4	211.7	158.3
L YN3037	24	57	19	0.0	83.9	16.1	3.3	207.2	211.7	204.4
M YN3045	17	58	25	0.0	55.9	44.1	10.4	193.4	235.6	211.9
N YN3038	29	60	11	0.1	74.1	25.8	5.5	196.8	235.6	218.7
O YN3036	30	49	21	0.1	68.6	31.3	10.6	168.9	211.7	187.0
P YN3039	30	46	24	3.5	50.1	46.4	19.3	104.9	170.8	126.9
Q YN3034	36	49	15	0.2	80.4	19.4	6.2	161.7	190.2	173.6
R YN3041	27	58	15	0.5	64.1	35.4	12.1	147.8	211.7	175.4
S YN3042	19	45	36	0.0	74.0	26.0	6.4	148.8	211.7	171.4
T YN3043	18	49	33	0.0	77.9	22.1	4.8	175.3	190.2	185.4
U YN3044	12	53	35	0.0	94.8	5.2	3.0	180.9	190.2	189.1
V DJS-95b,-c	40	41	19	20.1	17.1	62.8	34.2	26.0	3.0	4.0
W EG-7	36	40	24	1.6	19.8	78.6	13.3	156.5	618.4	30.2
X DJS-95e	42	35	23	1.8	73.0	25.2	7.5	128.4	190.2	145.3

and a method discussed by Pierce and Siegel (1969): integrated intensity of the 17 Å glycolated peak is equal to relative amount of smectite; the area under the 10 Å peak (glycolated trace) multiplied by 4 is equivalent to the relative amount of hydromica, including the illite group; and the area under the 7 Å peak is multiplied by 2 for the relative amount of kaolinite plus chlorite.

In this study, focus is primarily on proportions of the three dominant mineral groups forming assemblages in this region: smectite, kaolinite and illite. Examples of diffractograms are shown in Figure 9. These semi-quantitative data for samples collected in modern river and wadi deposits are listed in Table 3, and for those in Quaternary coastal cliff and hamra sections are listed in Table 4. Mixed-layered illite/smectite is recognized in some samples, but not separately quantified here. For comprehensive information on clay mineral data from the lower River Nile and Nile delta in Egypt, the major source of sediment in the study area, the reader is directed to the first article in this series (Stanley and Wingerath, 1996). The complete set of diffractograms obtained during the course of this investigation is archived in the Sedimentology Laboratory Data Bank, at the Smithsonian's U.S. National Museum of Natural History, Washington, D.C.

OBSERVATIONS

River and Wadi Channel Textural Attributes

Grain size parameters of river and wadi channel samples at the 43 sites in the study area are listed in Table 3. These were evaluated to detect any obvious regional trends as revealed by the fine fractions and, important for this study, the potential influence of size-sorting effects on assemblages of clay minerals.

Samples at ten sites comprise >10% granules, and most of these are irregularly distributed in central and northern Israel (Figure 10). Percentages of sand are relatively low, and there is no obvious regional trend. Samples from half (n = 22) the sites comprise a sand fraction of <25%; 5 sites have >50% sand, and the highest sand values (83% and 86%) are recorded for samples recovered near Port Said and Nahal Shiqma.

Percentages of the mud fraction in fluvial deposits are also highly variable, largely a function of random sampling in the channel axis of different fluvial deposits. Thus, values of this fraction range from nearly absent to 100%, and exceed 50% at more than three-quarters (n = 34) of the 43 sites. Percentages of the total clay fraction range from ~2 to 39%, and is <15% in more than half (n = 26) of the studied samples. Mean, median and modal grain sizes of samples are highly variable, a consequence of collecting only one random sample per channel in the fluvial systems throughout this extensive region. No obvious textural trends are observed east of the Nile delta (Figure 10).

Mean size values, for example, range from <10 to >500 μm (Table 3), comparable to the mean size range recorded for the lower River Nile and Nile delta samples (STANLEY and WINGERATH, 1996). Large variations between mean and modal grain size in most samples record poorly to very poorly sorted sediment, typical of seasonally active flood channel deposits.

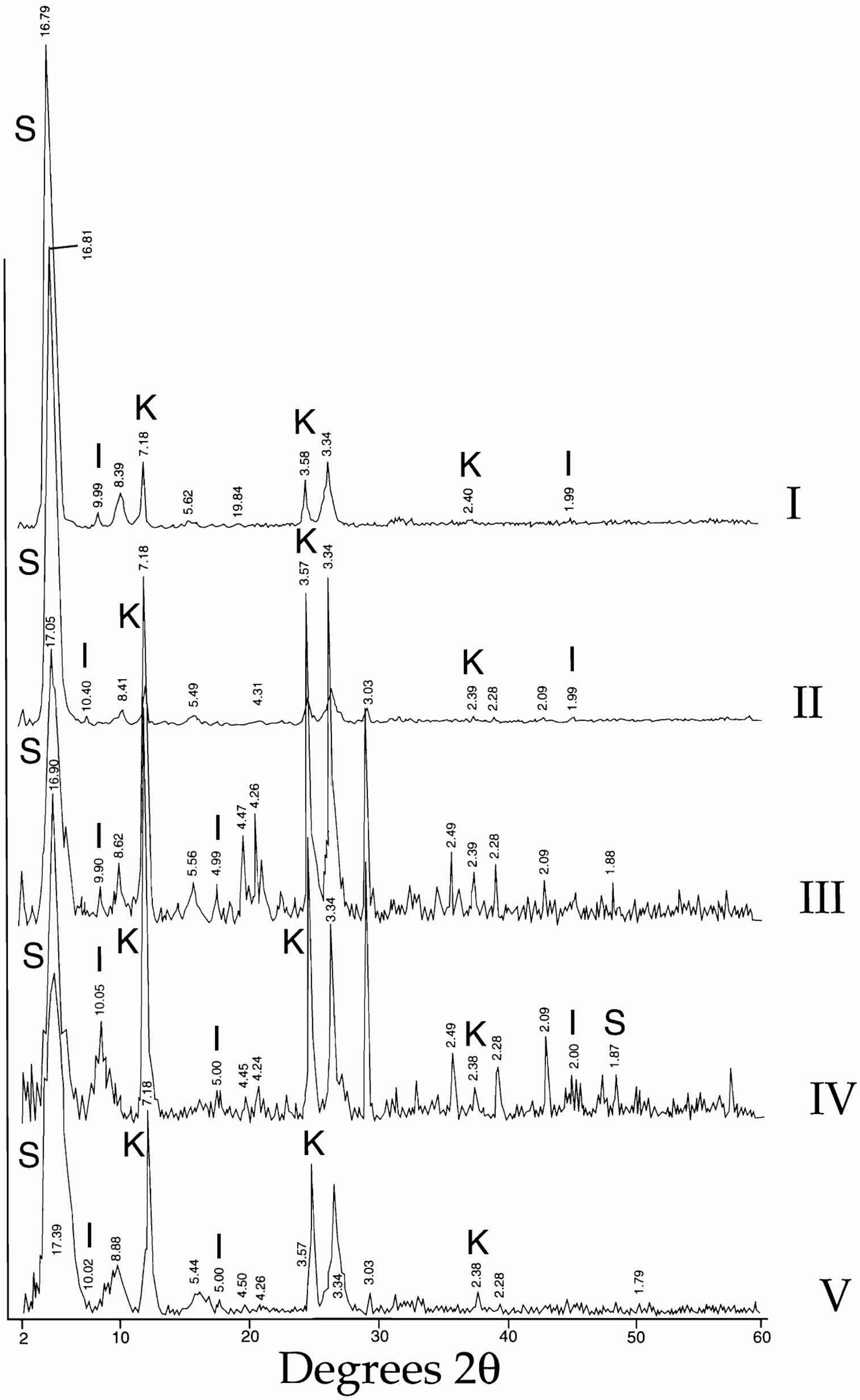

Figure 9. Diffractograms show examples of the 5 clay mineral assemblages (I to V) defined in text. Major peaks (S, smectite; K, kaolinite; I, illite) and d-spacing values (Å) are shown for five fluvial channel samples: I = sample site 1; II = 29; III = 40; IV = 6; and V = 38.

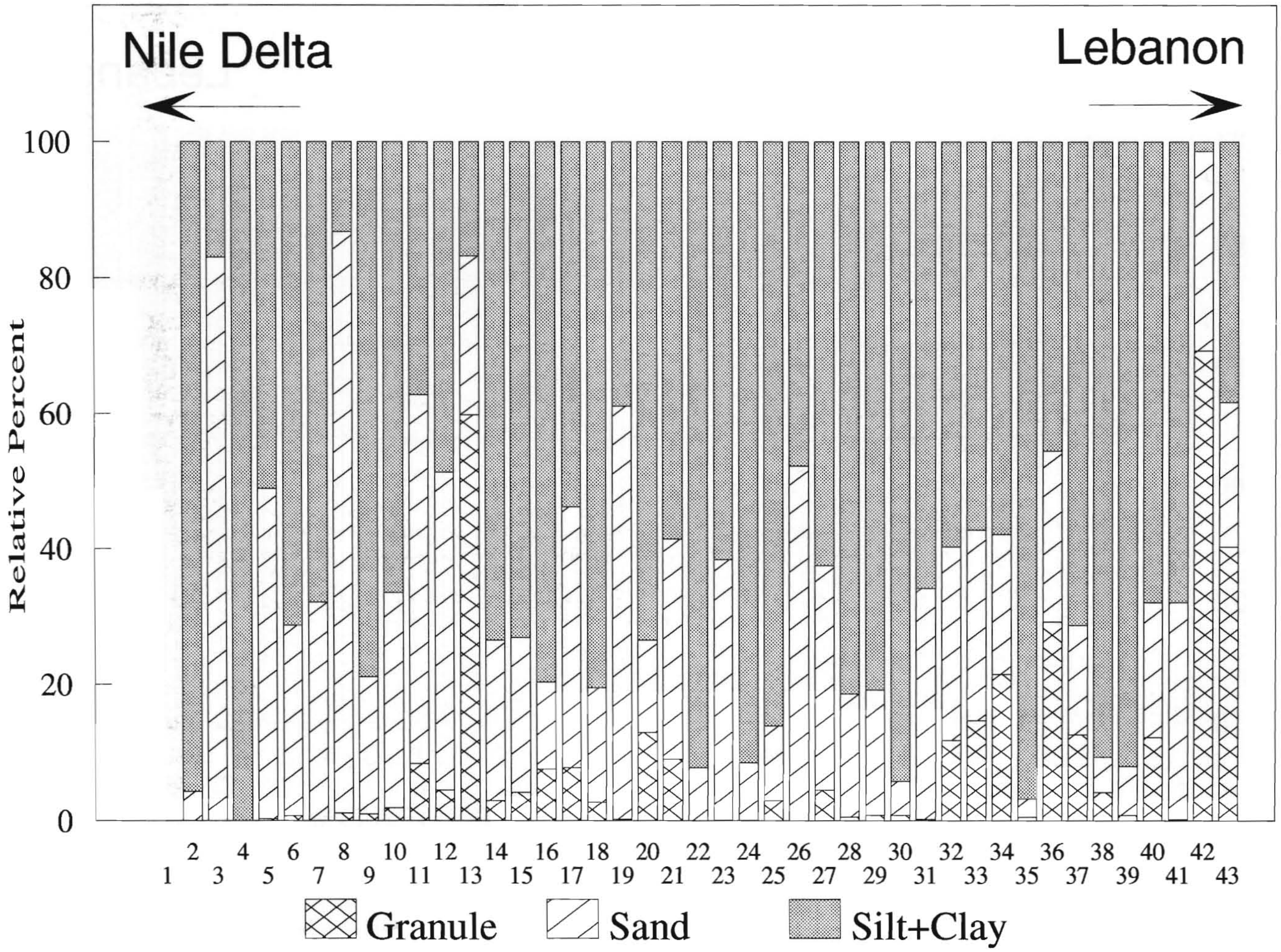

Figure 10. Bar graph showing relative percentages of granule, sand and silt plus clay fractions in fluvial channel samples (data in Table 3; localities shown in Figure 2).

Cliff and Kurkar Textural Attributes

Mean, median and modal grain size values of the < 1mm fraction of the 24 coastal cliff and hamra samples collected in the study area range from <1 to >600 μm (Table 4). These textural values approximate those of the River Nile (STANLEY and WINGERATH, 1996), as well as those cited in the above section on fluvial channel systems in the SE Levant coastal plain (*cf.* Table 3).

In contrast, proportions of specific grain size fractions of the 24 cliff and hamra samples differ markedly from those of both Levant fluvial and River Nile systems. Cliff and hamra samples are generally characterized as follows (Figure 11): a lower proportion of samples with granules (most comprise < 5%); only a few (n = 3) have <25% sand fraction, while two-thirds (n = 16) have >50% sand fraction; percentages of the silt plus clay fraction tend to be substantially lower, with values of <40% at half (n = 12) of the sites. Also in contrast with Levant fluvial systems, percentages of the clay fraction in coastal exposures range from <1% to 44%, with values < 15% at three-quarters (n = 19) of the sites. No distinct regional textural trend is observed.

River and Wadi Channel Clay Minerals

Clay mineral trends in fluvial systems between the eastern Nile delta and northern Israel (Figure 12) are summarized from data for each of the 43 sites listed in Table 3. Most obvious changes from west to east are revealed by marked diminution of smectite on the Sinai margin east of the Nile delta, and increased proportions of both kaolinite and illite east of Bardawil lagoon and in the Gaza region. Also of note are high percentages of kaolinite north of Haifa Bay. In contrast, the sector between Israel's southern and northern coastal plain is characterized by greater regional clay mineral variability, including high proportions of smectite.

As a group, the fluvial samples set comprises a dominant smectite fraction. This is readily apparent where data for the 43 sites are plotted on a ternary diagram with smectite, kaolinite and illite end-members (Figure 13A). About three-

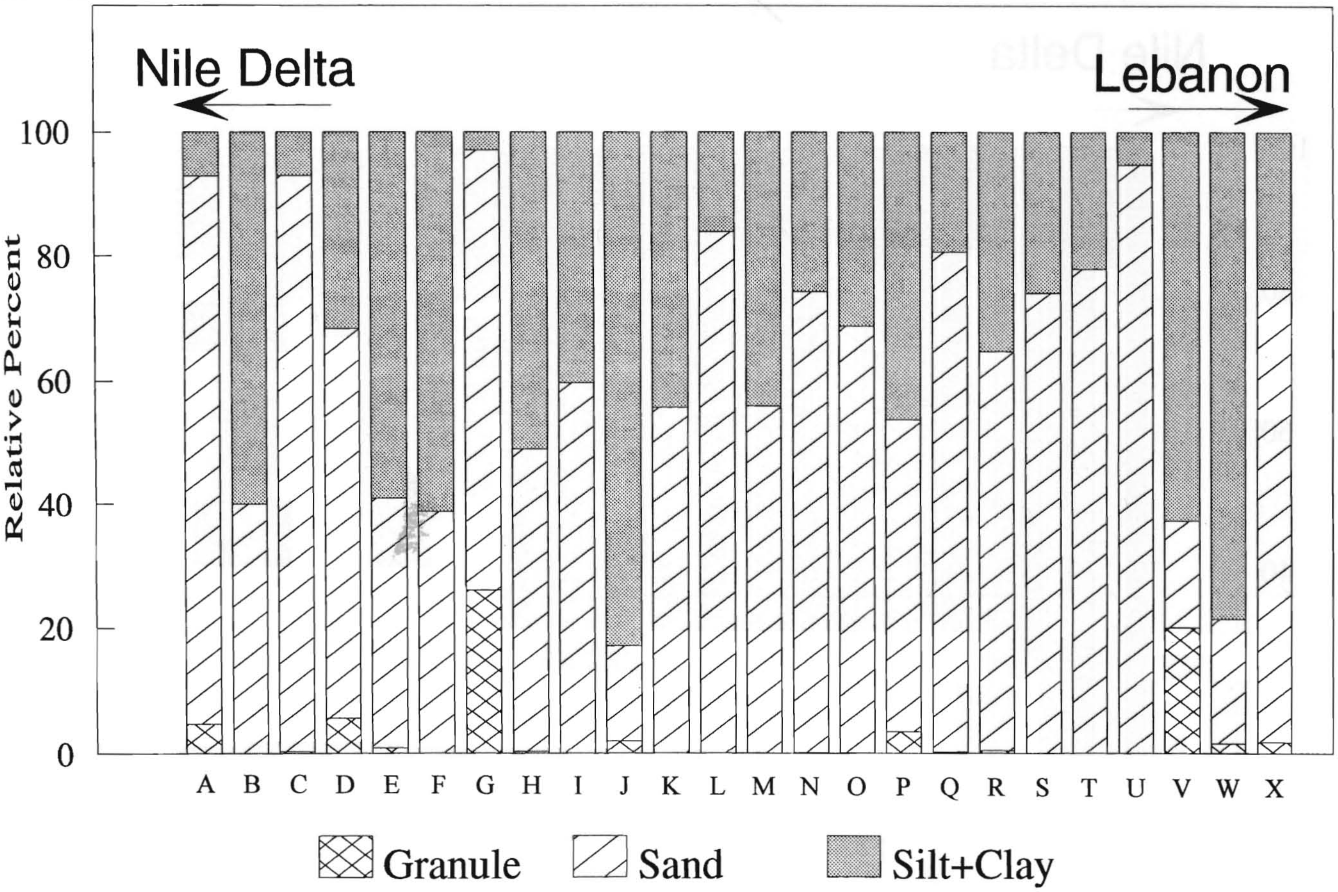

Figure 11. Bar graph showing relative percentages of granule, sand and silt plus clay fractions in coastal cliff and kurkar samples (data in Table 4; localities shown in Figure 2).

quarters of the sites (n = 32) are characterized by >50% smectite; high values (> 50%) of kaolinite are recorded at two sites (4, 40), and one site (36) comprises a particularly high proportion (~40%) of illite. About one quarter (n = 10) comprise roughly equivalent values (~40% or less) of smectite, kaolinite and illite.

Five clay mineral assemblages (coded I to V) are defined on the basis of relative percentages recorded herein for the three major minerals in fluvial deposits of this region. We define the terms *high, moderate* and *low* for proportions of each of the clay minerals:

Smectite (S): high, >70%; moderate, 40–69%; and low, <40%
Kaolinite (K): high, >30%; moderate, 20–29%; and low, <20%
Illite (I): high, >20%; moderate, 10–19%; and low, <10%

Five major *clay mineral assemblages* are identified:

I = high smectite, moderate kaolinite, low illite
II = high smectite, low kaolinite, moderate to low illite
III = high kaolinite, moderate smectite, variable amount of illite
IV = high kaolinite, low smectite, high to moderate illite
V = moderate smectite, moderate kaolinite, moderate to low illite

Diffractograms typical of the five assemblages are shown in Figure 9.

The distribution of clay mineral assemblages in fluvial systems of the study area is as follows (Figure 14):

I and II, dominant assemblage recorded at 18 sites, from the eastern Nile delta to Bardawil lagoon, and on the central Israeli coastal plain (sites 18 to 34);
III, at 14 sites, in NW Gaza (sites 8 to 12), and northern Israel (sites 31 to 43);
IV, at 5 sites, primarily from east of Bardawil lagoon to Gaza (sites 4–7), and one on the Carmel margin (site 36); and
V, at 6 sites, locally along the central to northern Israeli coastal plain (sites 13, 16, 28, 33, 37, 38).

Several factors limit interpretation of clay mineral data. These include the numerical values which are, at best, semi-quantitative ones, and mineral content which is generally recorded as relative percentages. As a result, clay mineral values are inversely related, such that high proportions of ka-

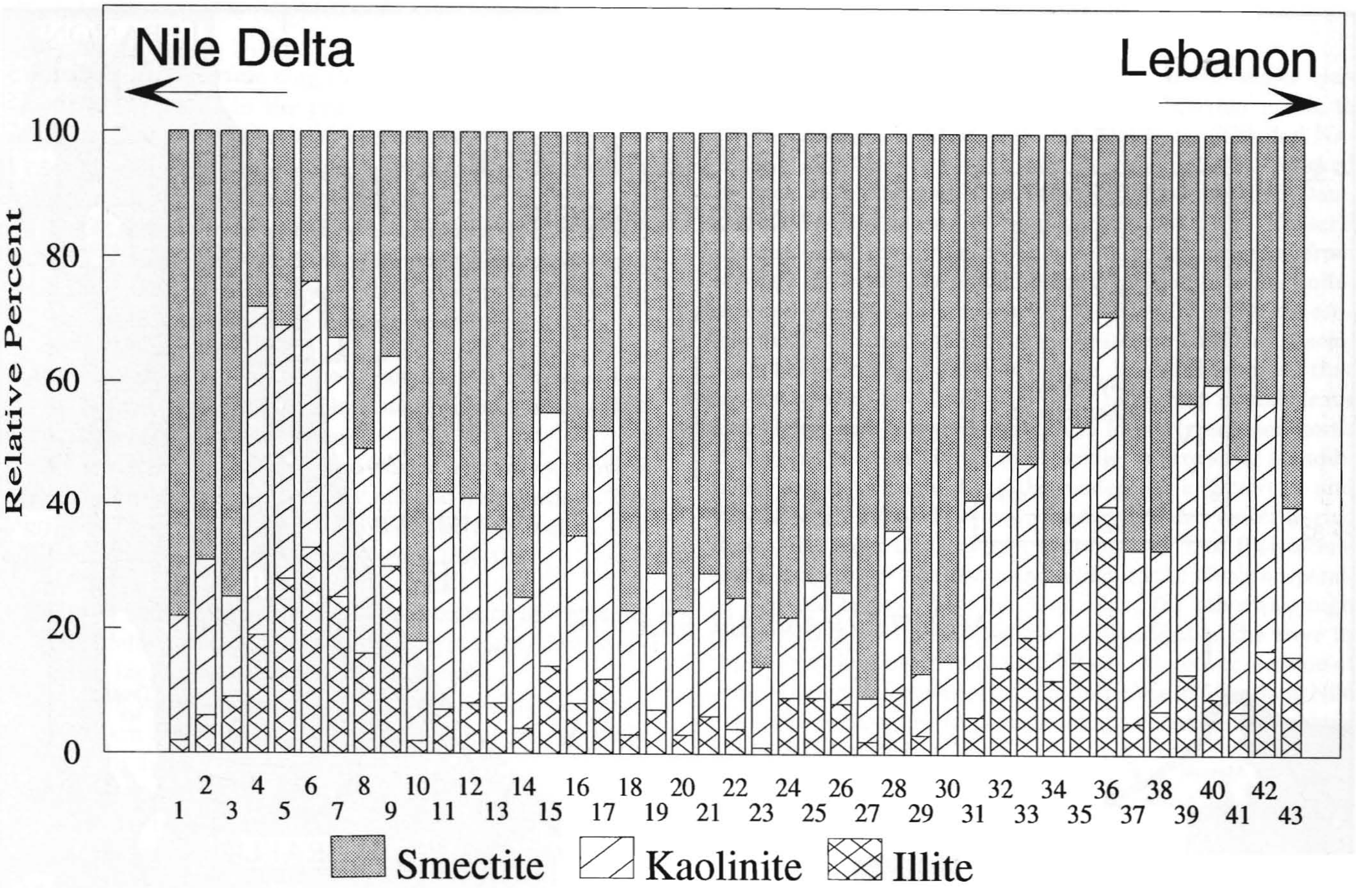

Figure 12. Bar graph showing relative percentages of the three major clay minerals in 43 river and wadi channel samples (data in Table 3; localities in Figure 2).

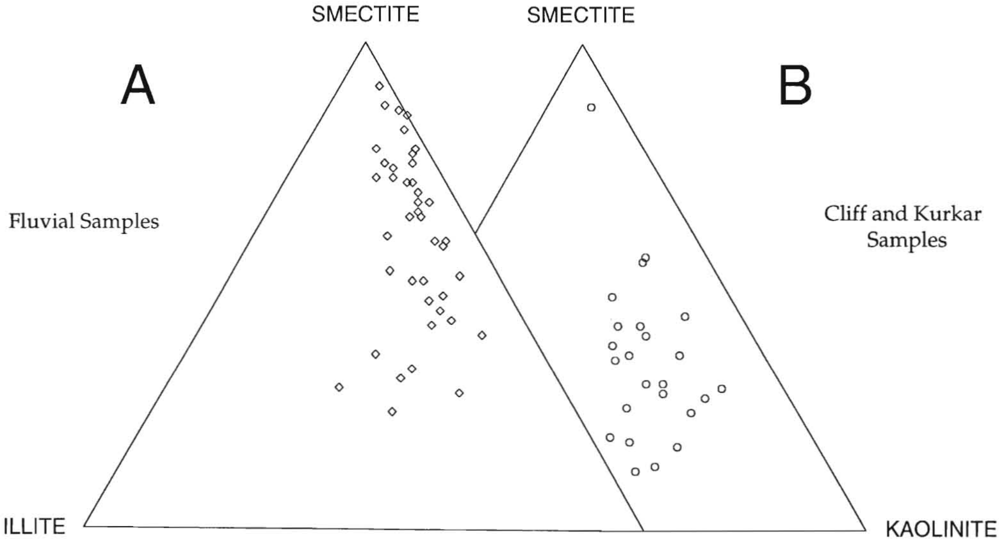

Figure 13. Clay mineral data plotted on ternary diagrams (A, 43 river and wadi channel samples, and B, 24 coastal cliff and kurkar samples).

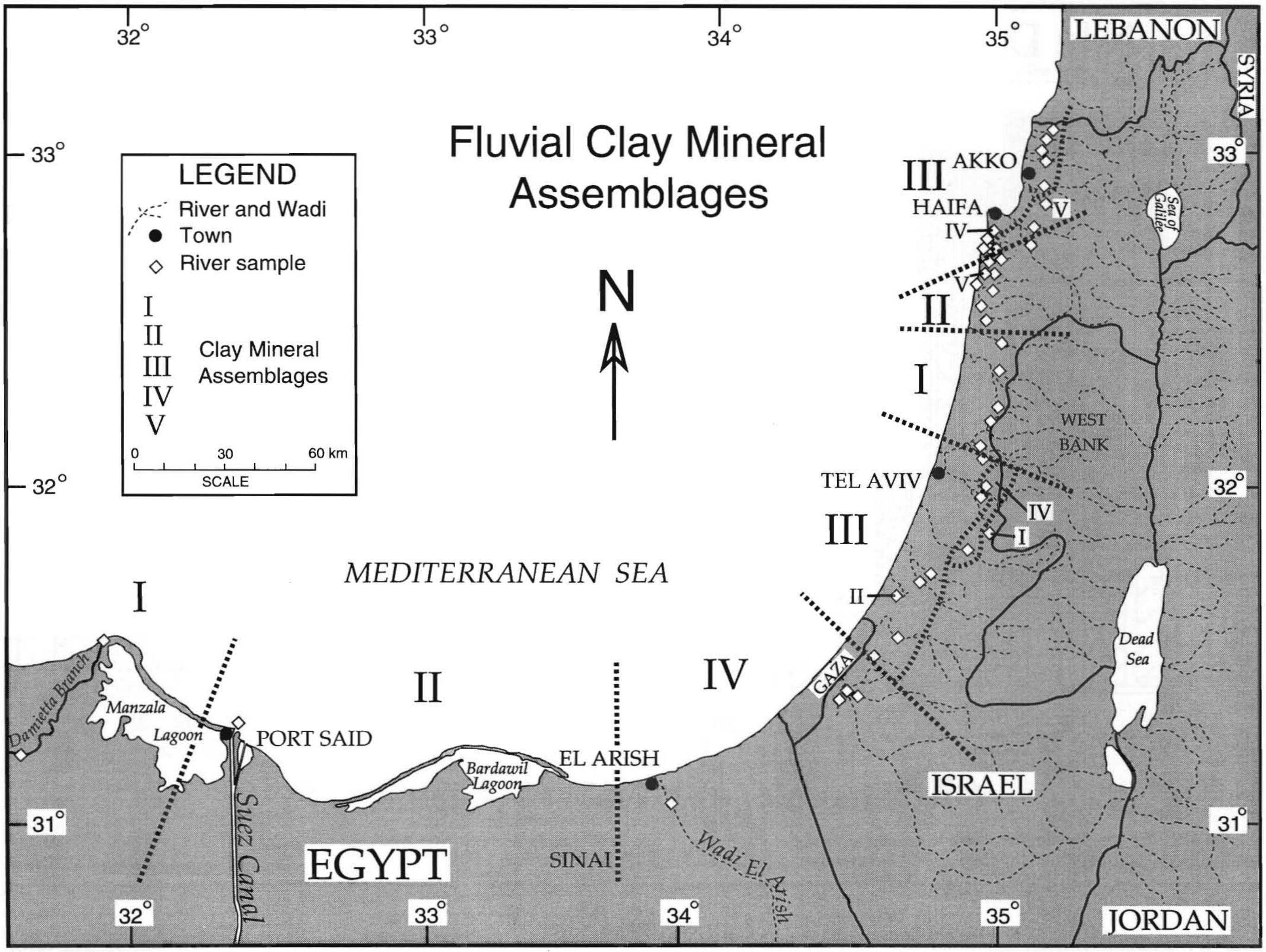

Figure 14. Regional distribution of clay mineral assemblages based on data for river and wadi channel samples (see text for definition of types I to V).

olinite are accompanied by low smectite plus illite, and vice versa. It is useful, therefore, to employ clay mineral ratios to help determine modern trends in the study area (Figure 15A–D):

S/K + I, high values (> 2.0) at 20 sites in the eastern delta and most of the Israeli central coastal plain, and low values (< 1.0) at 11 sites in eastern Sinai-Gaza and southern and northern Israeli coastal plains;
K/S, high values (> 1.0) at 8 sites in eastern Sinai-Gaza and northern Israel, and low values (< 0.6) at 23 sites in the eastern delta and most of the central Israeli coastal plain;
I/S, high values (> 0.6) at 4 sites in eastern Sinai Gaza and at site 36, and low values (< 0.3) in the eastern Nile delta and most of the central and northern Israeli coastal plains; and
K/I, high values (> 5.0) at 13 sites, irregularly distributed on the central and northern Israeli coastal plains, and low values (< 2.0) at 10 sites in the Gaza region and locally on the northern Israeli coastal plain.

Cliff and Kurkar Clay Minerals

Clay mineral trends in the 24 cliff and kurkar coastal exposures in the study area are summarized here from data listed in Table 4. Proportions of the three major clay minerals, depicted by means of bar graph (Figure 16) show more uniformity than the fluvial sites (Figure 10), and no obvious regional west-to-east or south-to-north trends.

It is of note that data for samples collected at coastal exposures plotted on bar graph and ternary diagram (Figure 13B) record generally high kaolinite values. The range of relative percentages of smectite (12–87%) and of kaolinite (8–60%) are somewhat greater than those recorded for fluvial samples; the range of illite (5–36%) is somewhat smaller. About one third (n = 7) contain >50% kaolinite, and only 3 sites record >50% smectite. More than half of coastal samples (n = 14) comprise roughly equivalent proportions of the three clay minerals.

By applying the same clay mineral proportions and definitions as presented in the previous section on fluvial clay minerals, only 3 of the five clay mineral assemblages are recorded for cliff and kurkar deposits (Figure 17):

II, at 1 site, in the eastern Nile delta;
III, at 7 sites, on the Sinai coast and irregularly distributed on the southern and northern Israeli coastal plains; and
IV, the prevailing assemblage, at 16 sites, primarily along the south to central Israeli coast.

This distribution highlights the importance of increased kaolinite proportions from the Sinai margin, east of the Nile delta, to the northern Israeli coast.

Clay mineral ratios of cliff and kurkar exposures provide additional insight on regional clay mineral distributions. Using the same values as those used to define fluvial sites, the following observations are made (Figure 18A–D):

S/K + I, high value at site A, on the northern and eastern Nile delta coast, and low values for 21 sites, from Bardawil lagoon to the northern Israeli coast;
K/S, high values at 16 sites, from Bardawil lagoon to the northern Israeli coast, and a low value at site A in the eastern delta;
I/S, high values at 14 sites, from Bardawil lagoon to the northern Israeli coast, and low values at 4 sites, including the eastern Nile delta and southern Israeli coasts; and
K/I, one high value at site N on the central Israeli coast, and low values at half of the sites (n = 12) distributed between Bardawil lagoon and the northern Israeli coast.

Nile Delta Clay Mineral Trends

The River Nile is characterized along most of its length in Egypt by high values (at least 60%) of smectite (EL ATTAR and JACKSON, 1973; MORSY, 1981; WAHAB *et al.*, 1986; STANLEY and LIYANAGE, 1986; STANLEY and WINGERATH, 1996). Overall highest relative percentages of smectite are recorded in the Nile delta, with values reaching ~80% in the Rosetta branch in the northwestern Nile delta coast. Proportions of kaolinite decrease progressively to <25% downstream near the coast. Illite values, in contrast to kaolinite and smectite, are usually much lower, *i.e.*, generally ~10% or less along the lower Nile and delta to the coast.

The predominant clay mineral assemblage in the Nile delta is of the smectite-rich type I, and ratios for delta samples are: S/K + I, ~3.0 (high); K/S, ~0.3 (low); I/S, ~0.1 (low); and K/I, ~4.0 (moderate). These observations (summarized from Stanley and Wingerath, 1996) are closely comparable to those determined for both fluvial and coastal samples in the northern and eastern Nile delta, and also for a few sites localized on the central and northeastern Israeli coastal margin (as described in the two previous sections of the present article).

CLAY MINERAL PROVENANCE

Nile Drainage Basin

During the Holocene, smectite has been the major clay mineral transported to the Nile delta and farther north, to the contiguous Egyptian shelf and Nile Cone (NIR and NATHAN, 1972; MALDONADO and STANLEY, 1981). Marked changes have occurred since construction of the High Dam. Cumulative influences of wave erosion of Lake Nasser's shoreline and release into the lake of eolian material from adjacent deserts have resulted in deposition of a kaolinite-rich assemblage on the northern lake floor. This pattern contributes to accumulation of the kaolinite-enriched clay assemblage below the High Dam at Aswan. It is also proposed that erosion of some late Quaternary and older Nile fluvial strata underlying and below the dam, and formerly exposed north of the structure and in adjacent wadis, is providing an additional source of kaolinite to the modern Nile (STANLEY and WINGERATH, 1996). However, recently eroded smectite-rich River Nile bank and channel sediments of late Pleistocene and Holocene age are also being added to the Nile's suspended and bed loads. These mask or dilute the otherwise high proportion of kaolinite presently being added to the river in the vicinity and north of the High Dam. Moreover, erosion of smectite-rich Holocene deposits forming the 225 km-long Nile delta coast continues to provide a high smectite assemblage to the shore and inner shelf.

Sinai Sources

Clay minerals in samples collected between the Suez Canal and Bardawil lagoon (Figure 2) are similar to those in the Nile delta. For example, the assemblage at site 3 recovered in the northern Suez Canal near Port Said comprises ~75% smectite, 16% kaolinite, and 9% illite (Table 3). These values, and those of samples collected in the northern canal (STANLEY *et al.*, 1982), are nearly identical to clay mineral proportions in Holocene deposits of the Nile delta farther to the west (ABU-ZEID and STANLEY, 1990; STANLEY and WINGERATH, 1996). This similarity is not surprising since the northern 42 km section of Canal (Figure 3, arrow *1*) is cut across the northeastern corner of the Nile delta (Figure 3, arrow *2*). Moreover, only the Sweet Water Canal flows from the smectite-rich delta east to the Suez Canal sector, while no major channels enter the Suez Canal from the arid Sinai (EL SHAZLY *et al.*, 1980).

Nevertheless, clay assemblages in Bardawil lagoon and on coastal barriers that separate this shallow wetland from the sea are significantly different from those of the Nile delta. Of note are the markedly increased proportions of kaolinite (to 45%) and illite (to 30%), and much smaller amounts of smectite (< 45%), such as those at sites B and C. Some smectite in assemblages along and within Bardawil likely originated from the Nile delta: this mineral was transported by east-driven coastal currents and seawater flow into the lagoon via inlets cut across barrier bars. It is proposed here that the larger proportions of kaolinite and illite in this sector are derived primarily by strong, seasonally variable winds (Figure 6) which blow across the wide desert expanse and dune

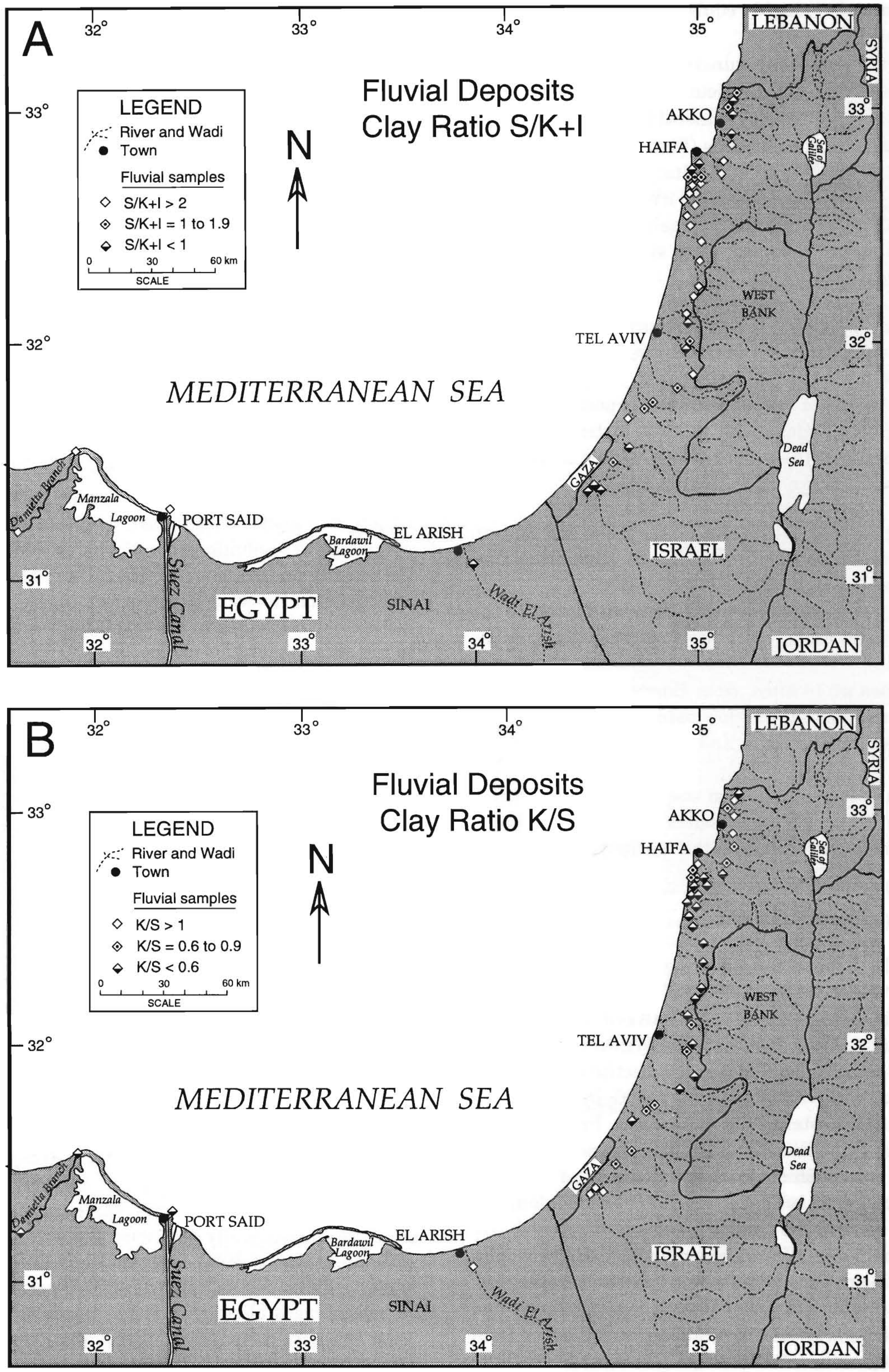

Figure 15. Four clay mineral ratios for river and wadi channel samples (explanation in text).

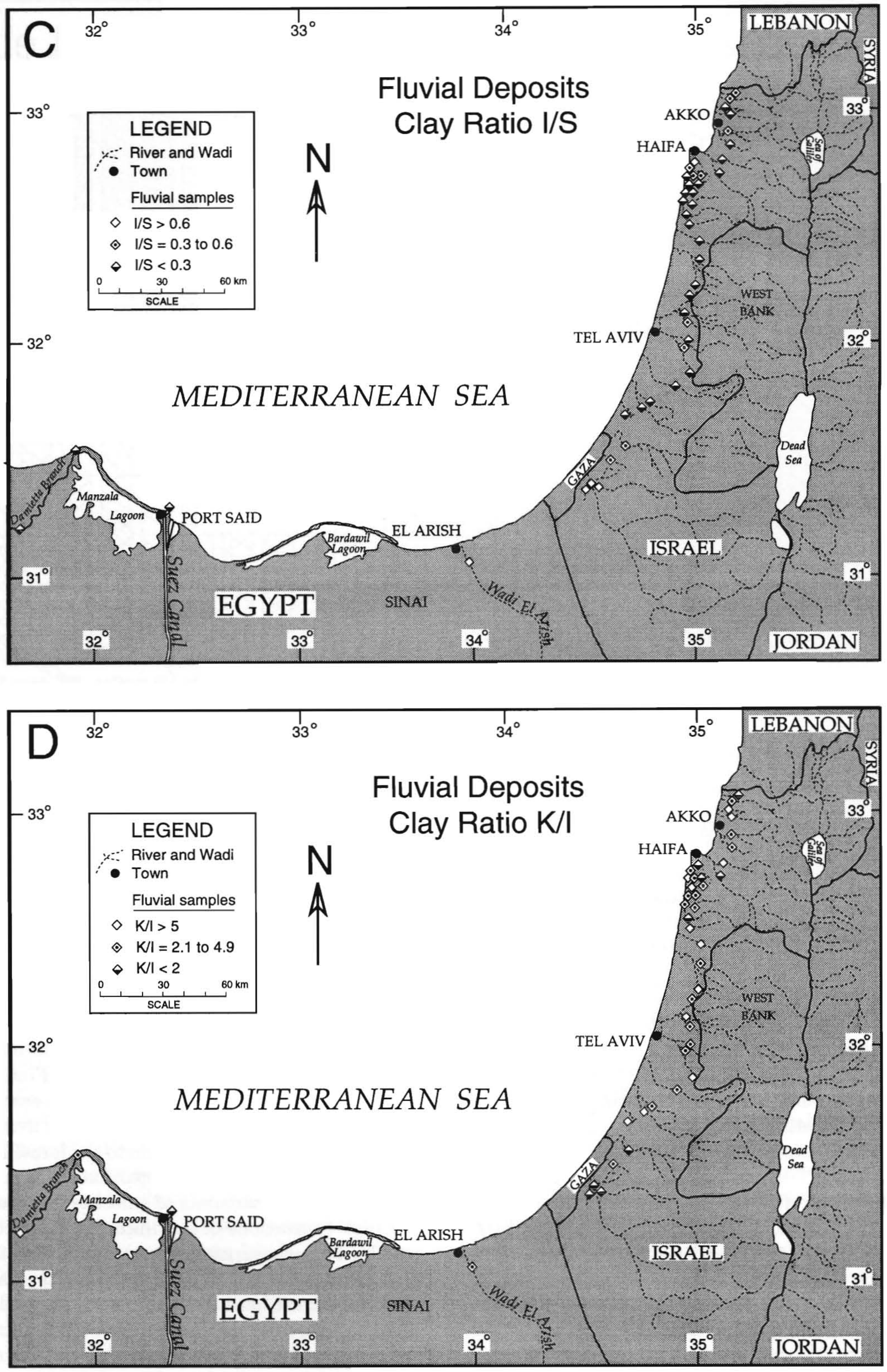

Figure 15. Continued.

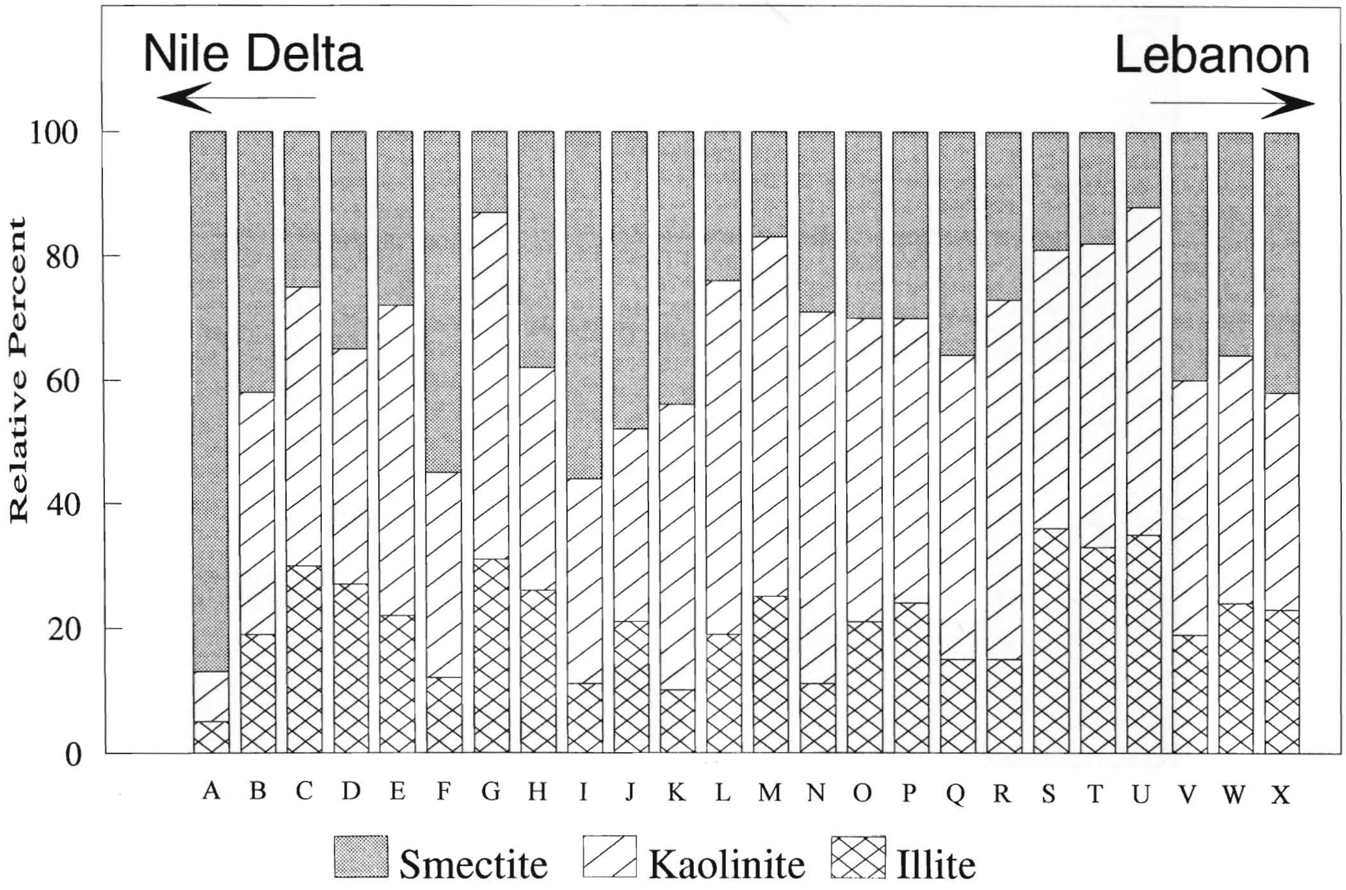

Figure 16. Bar graph showing relative percentages of the three major clay minerals in the 24 coastal cliff and hamra samples (data in Table 4; localities in Figure 2).

fields south of the lagoon (*cf.* FAYED and HASSAN, 1970; ORNI and EFRAT, 1971; VENKATARATHNAM and RYAN, 1971; CHESTER *et al.,* 1977; KHALIL and NOMAN, 1981; WAHAB *et al.,* 1986).

To the east, for example at site 4, the clay assemblage of Wadi El Arish, in marked contrast with that of the Nile, comprises 53% kaolinite, 19% illite and only 28% smectite (Table 3). Enhanced proportions of kaolinite and illite (also recorded in Wadi El Arish by Abdel Salam and Allison, 1959) are derived in part from the distinct south-to-north sequence of geological source terrains exposed in its drainage area (Figure 8A).

Important proportions of kaolinite in the clay fraction near the Sinai coast are derived as products of weathering (*cf.* MELSON and VAN BEEK, 1992) and mechanical disintegration of parent rock (including feldspars). A major source of clay is the thick cover of Quaternary alluvium forming the large Sinai desert lowland that lies immediately south of the Mediterranean coast (Figures 3, 8A). This wide (> 100 km) east-west belt, sparsely covered by vegetation, includes extensive sand dune fields (EL SHAZLY *et al.,* 1980). Seasonally shifting wind patterns (MURRAY, 1951; ORNI and EFRAT, 1971) result in active dune migration and eolian transport, and at certain times of the year, important volumes of wind-borne sediment are driven toward the coast (Figure 6).

Gaza and Israeli Sources

No systematic regional study has previously been made of clay minerals in modern fluvial systems and coastal plain sectors between the Sinai and Lebanon. Findings in the present study indicate that, as in central and eastern Sinai, channels on the coastal plain near Gaza and in southernmost Israel, and from the Carmel plain to the Israel-Lebanon border, comprise relatively high proportions of kaolinite, and only moderate or low amounts of smectite (Figure 14). Comparably high proportions of kaolinite also characterize most cliff and kurkar exposures (also recorded in this facies by Shoval and Erez, 1989), from Sinai all the way to Haifa Bay (Figure 17). In contrast, most river and wadi channels in the central Israeli plain, from south of Tel Aviv to the Carmel coast, comprise high relative percentages of smectite and lower proportions of kaolinite and illite (Figure 14). High smectite values comparable to those in the Nile delta occur along a 50 km-long stretch west of the Samaria hills, from sites 18 to 22 on the Sharon plain north of Tel Aviv.

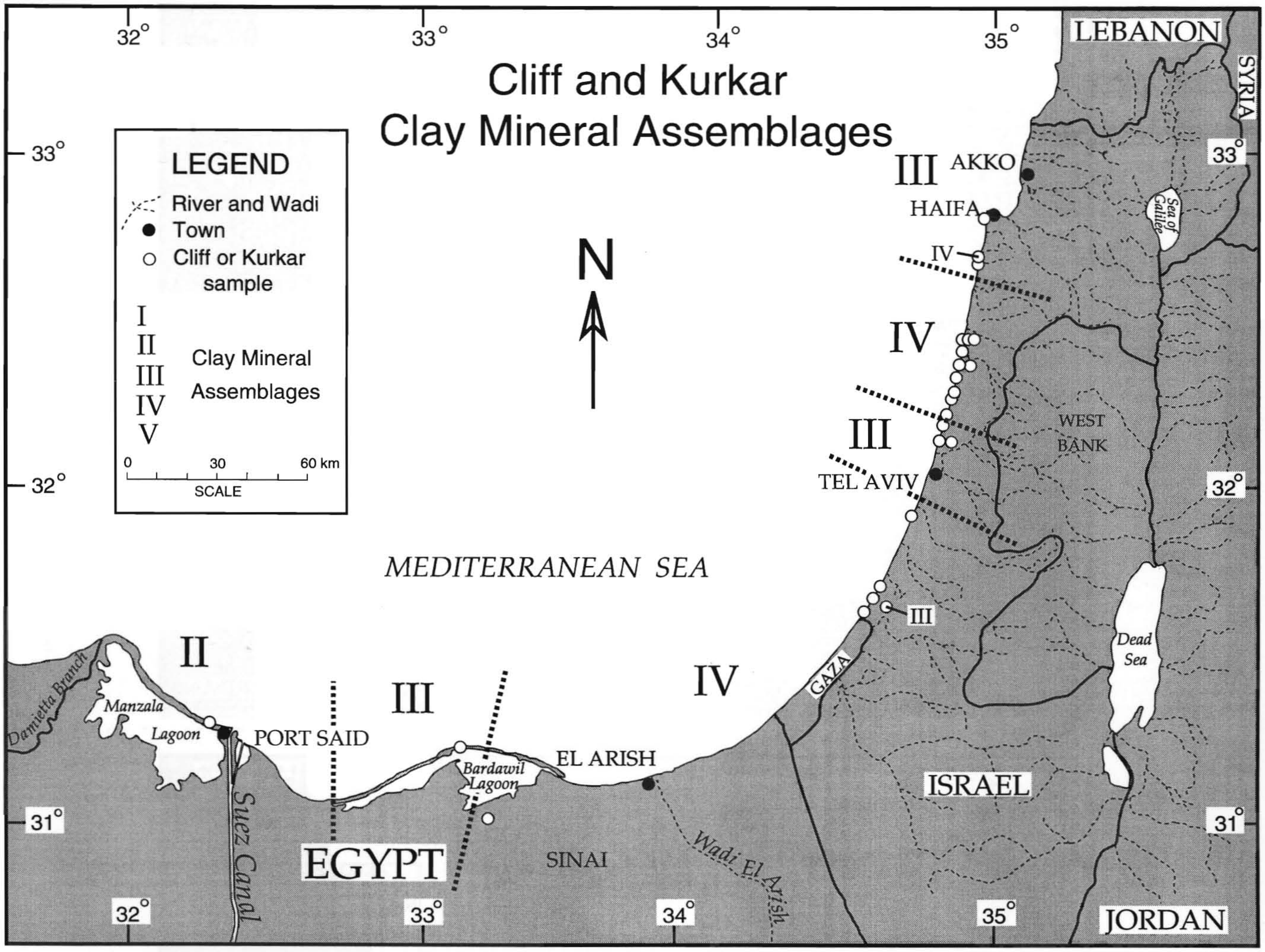

Figure 17. Distribution of clay mineral assemblages for coastal cliff and kurkar sites (see text for definition of types II, III, and IV).

Fluvial processes transported sediment recovered at the sample sites primarily from two distinct adjacent terrains: Quaternary alluvium forming the coastal plain, which covers the largest surface area crossed by rivers and wadis (Figure 5B); and older rock terrains exposed in highlands east of the coastal plain (Figure 5A). The younger (Quaternary plus Tertiary) sediment sequences forming the upper coastal plain are at least 2,000 m thick and lie above an older Mesozoic series. Drilling and seismic surveys on the Israeli margin show that the Plio-Quaternary sequence accounts locally for >500 m (NEEV *et al.,* 1976; GVIRTZMAN and BUCHBINDER, 1978).

The most widely exposed rock formations eroded by river channels in source terrains close to the coastal plain are Upper Cretaceous units (Figure 8B) that include a thick sequence of carbonates, shales and marls. Eocene and younger clastic and carbonate formations are also exposed, but these comprise much smaller source areas. More distal parent rock includes Nubia Sandstone outcrops in the Negev. Volcanics in the Carmel and Galilee hills of northern Israel account for an even smaller source of westwardly transported material.

A summary of clay mineral distributions in Gaza and Israel by BENTOR (1966) indicates that smectite is an important constituent of almost all clay assemblages in Triassic to Tertiary units. Volcanic and basaltic terrains and associated soils in the Carmel and Galilee, and widespread exposures of weathered Upper Cretaceous shales and marls, are sources of smectite. Kaolinite prevails in fossil laterites and, together with illite, are dominant clay minerals in Mesozoic Nubia Sandstone (BENTOR, 1966; AZMON, 1990). Illite is a major constituent of clay assemblages in the Paleozoic Nubia Sandstone; it is also a weathering product of Precambrian igneous and magmatic rocks, and of Upper Turonian series in Judea and northern Negev (SANDLER, 1988).

It is also of note that high percentages of kaolinite and illite, with only limited proportions of smectite, constitute the dominant clay mineral assemblage in eolian dust transported

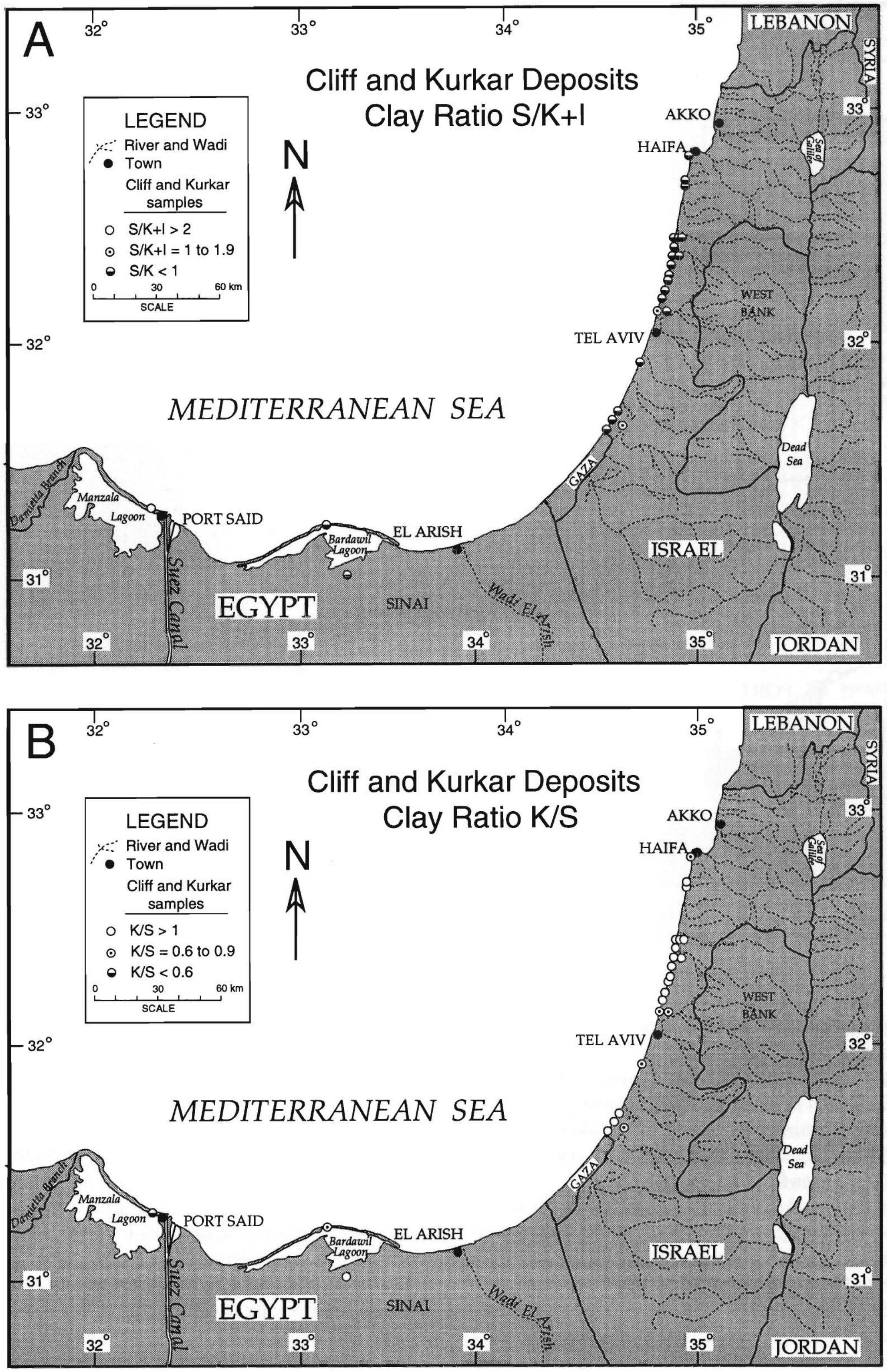

Figure 18. Four clay mineral ratios for coastal cliff and kurkar samples (explanation in text).

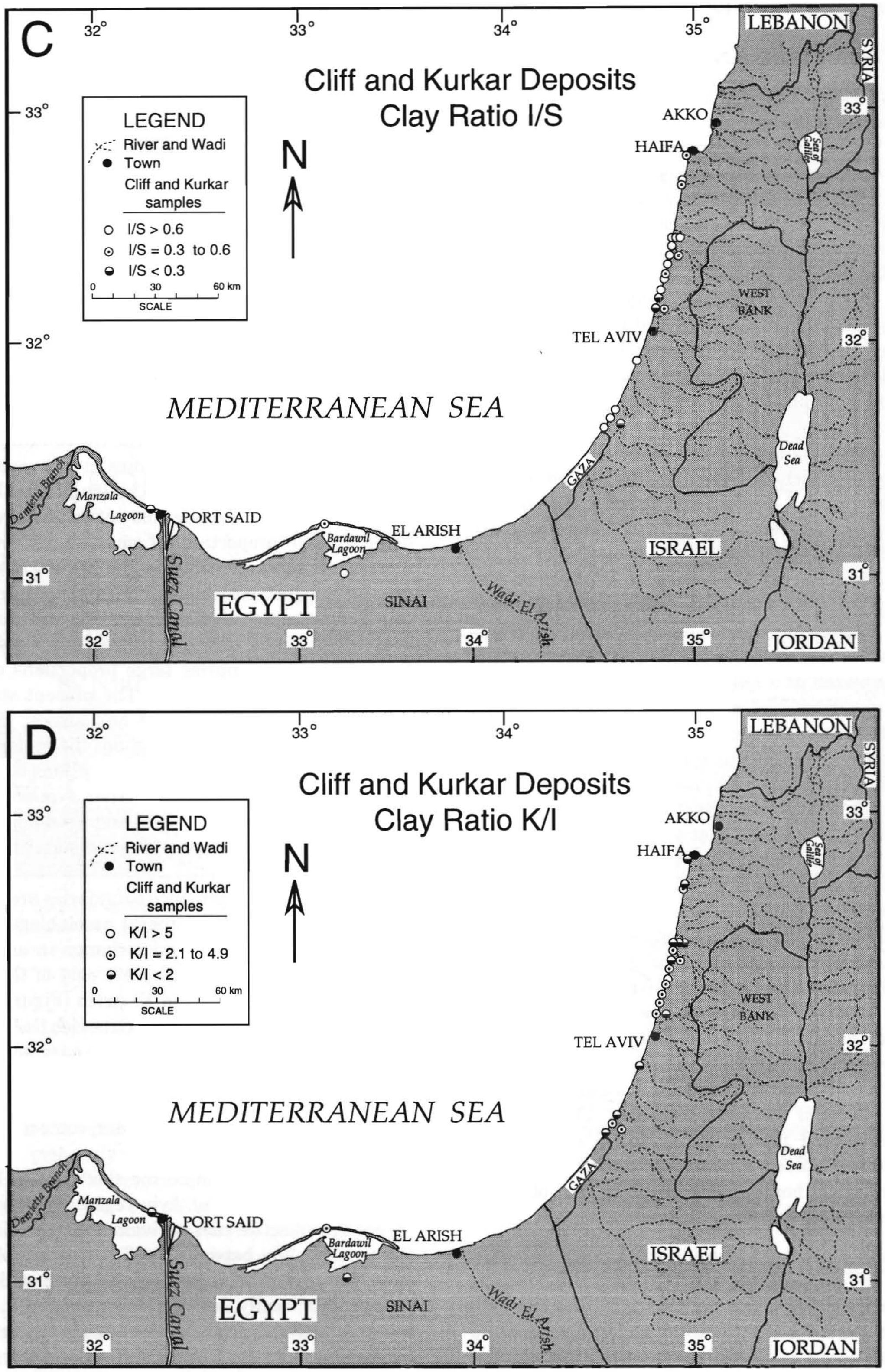

Figure 18. Continued.

in the SE Levant region (*cf.* CHESTER *et al.,* 1977; CHAMLEY, 1988; MELSON and VAN BEEK, 1992; OFFER *et al.,* 1993).

CLAY DISTRIBUTIONS AND SEDIMENTATION

The petrology of clay minerals in the study area is influenced by at least three factors: parent rock inheritance, authigenic (*in situ*) formation, and sediment transport size-sorting effects. Previous sections of the present study show that there is a correlation between clay minerals east of Bardawil lagoon and geological source terrains in regions backing the coast. Only a modest to minimal role of authigenic formation (primarily weathering) is suggested for recently deposited clays deposited in the unconsolidated Holocene fluvial and late Quaternary coastal samples analyzed in this investigation. Size-sorting, however, is not discounted since clay minerals that are transported for any distance are usually affected in some way by physical processes active along their dispersal path.

Involved in size-sorting are effects related to energy levels of transport agents, which can alter the original proportion of clay minerals dispersed from source terrains. Size-sorting also results because of different inherent sizes and mineralogy of clay particles, and overall textural attributes of the sediment being displaced (*cf.* WHITEHOUSE *et al.,* 1960; and others). As a consequence, a clay assemblage is likely to record progressive to extremely rapid changes along its transport path. At least some indication of size-sorting in the study area would be expected as a response to (1) transport of clay by fluvial, coastal current and wind processes, and (2) inherent differences in size of the prevailing clay minerals. It was shown, for example, that kaolinite particles tend to be larger than smectite in the lower Nile system (MALDONADO and STANLEY, 1981; ABU-ZEID and STANLEY, 1990). *A priori,* some clay mineral assemblages east of the Nile delta would record size-sorting phenomena as well as inheritance (*i.e.* where composition is imparted directly by parent rocks in source terrains).

A substantially larger sampling density will be required to quantitatively test for size-sorting in the case of fluvial and wadi samples. Sampling must take into account the relatively short transport distance between source area and coastal sample site, and the widely different flow characteristics in each of the sampled channels. Clay mineral and textural attributes of coastal cliff and kurkar samples measured here also record the effects of transport processes. These coastal deposits were emplaced primarily by coastal current and wind processes that involve a greater dispersal distance (and consequent petrological homogenization) than that affecting fluvial channel samples.

DISCUSSION AND CONCLUSIONS

Most previous investigations have indicated that the bulk of sediment transported along the Sinai to Israeli coast and shelves to as far north as Haifa is primarily of River Nile derivation. In recent time Israeli rivers have contributed little material to this region as compared with the Nile (RIM, 1951; POMERANCBLUM, 1966; NIR, 1984). However, there is only a limited amount of information to determine the role of Sinai, Gaza and Israeli coasts as additional sediment sources. Some view cliffs and kurkars in this region as potentially important contributors of sediment (GOLDSMITH and GOLIK, 1980), while others consider these as generally insignificant (INMAN and JENKINS, 1984). A more recent study of the sand fraction, however, strongly suggests that there is some land-to-sea input of sediment along the coast east of Bardawil lagoon (STANLEY, 1989).

With available petrologic information, two depositional scenarios applicable to the study area are envisioned: (1) a dominant longitudinal-distal input from the Nile system reaching the Gaza and Israeli coast would be denoted by a generally consistent clay mineral assemblage between the Nile delta coast and Israel-Lebanon border; and (2) a dominant lateral-proximal input along this coastal margin would be recorded by marked mineralogical variations between the Nile delta and northern Israel. Thus, identification of clays in sediment east of the Nile delta can help refine interpretations of Nile littoral cell sedimentation in the SE Levant.

All earlier clay mineral studies in this region have emphasized the first scenario, *i.e.* the longitudinal-distal effect of Nile sediment input along this entire offshore margin, as denoted by high proportions of smectite. However, lateral clay mineral changes identified in the present investigation (Figure 19) suggest possible lateral-proximal input in the Nile cell. For example, winds release silt- and clay-size minerals over broad areas of the southeastern Mediterranean, and these generally comprise large proportions of kaolinite and illite (CHESTER *et al.,* 1977). The present study shows that the shoreface of coastal cliffs and kurkar ridges eroded by strong coastal currents throughout the region release assemblages characterized by large proportions of kaolinite and illite (Figure 19). It is probable that availability of clay minerals from these eroded coastal and wind-borne sources would diminish the relative percentage of smectite in both coastal and shelf deposits.

Several petrologic province boundaries are recognized herein on the basis of clay mineral assemblages in both fluvial and coastal deposits. A major change in assemblages is recorded on the Sinai coastal plain east of the Nile delta, between Bardawil lagoon and El Arish (Figure 19). The region to the west of this sector is smectite-rich (to 70%, clay mineral assemblages I and II), while to the east it is enhanced with kaolinite (to > 30%, assemblages III and IV), and illite (to > 20%, assemblage V). The entire coast, from east of Wadi El Arish to the Israel-Lebanon border, comprises important proportions of kaolinite.

The coastal plain behind the shore is also kaolinite-rich to as far north as the Tel Aviv region. However, clay assemblages are smectite-rich in rivers and wadis farther north, on the coastal plain between the Tel Aviv and Atlit coast of Israel. Fluvial assemblages comprise unusually high percentages of illite locally, between Atlit and Haifa, and are kaolinite- and illite-rich from north of Haifa to the Israel-Lebanon border.

It is useful to recall the curtailment of sediment volume that has by-passed the Nile delta coast to the sea west of the study area during the past century (SHARAF EL DIN, 1977; STANLEY, 1996). The diminished amount of Nile material is

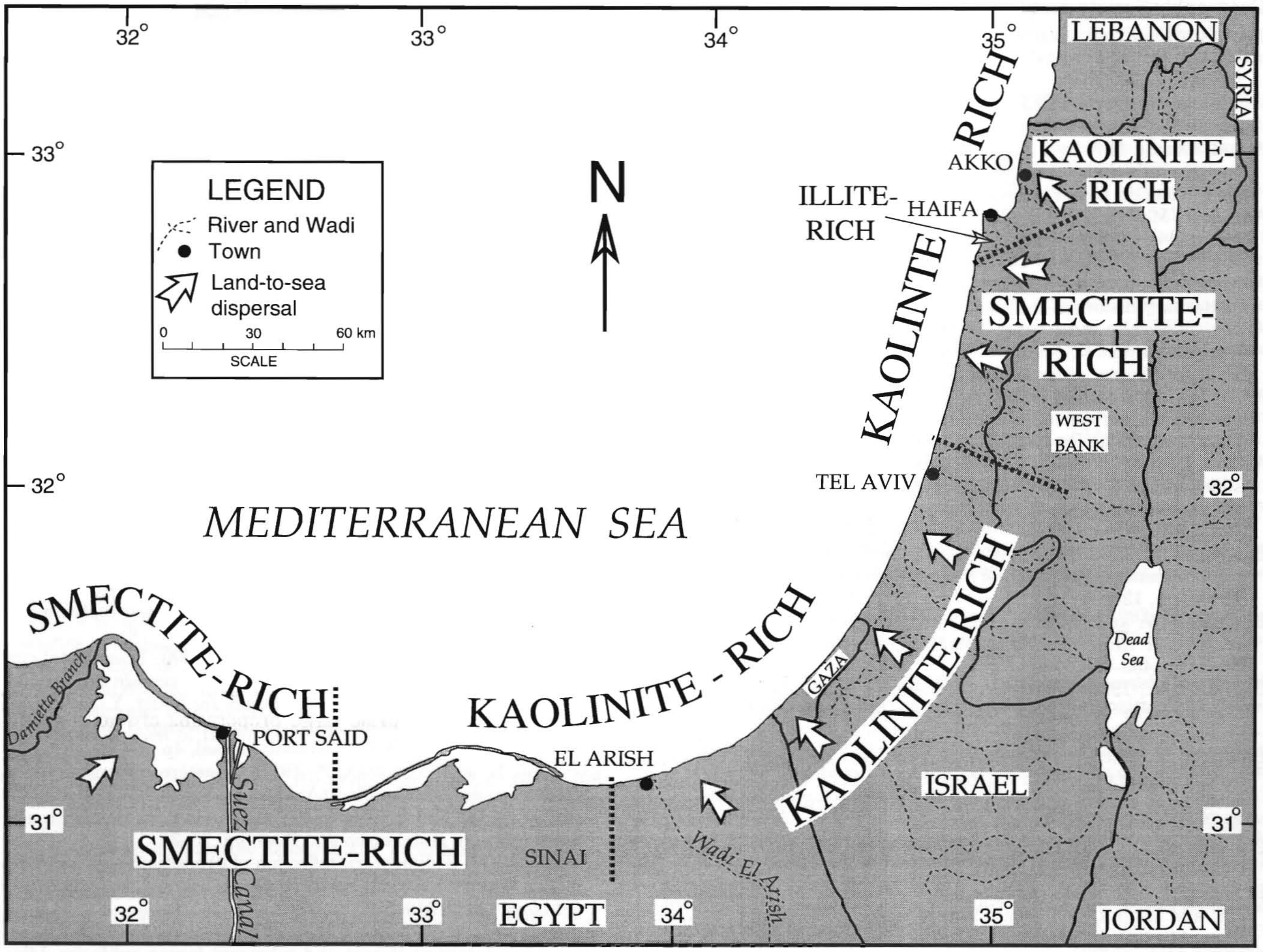

Figure 19. Summary diagram showing clay mineral distributions along the coast between the eastern Nile delta to northern Israel. Coastal exposures record a generally homogenous, regionally consistent (kaolinite-rich) composition, resulting largely from coastal and eolian processes. In contrast, clays in coastal plain sites are more varied, indicative of numerous fluvial systems draining proximal highlands south and east of the coast.

coupled with marked regional changes in clay mineral assemblages recorded here on coastal margins east of the delta. This interaction could lead to some increased lateral input from adjacent source terrains as proposed in depositional scenario 2 cited earlier. Derivation of these laterally variable coastal deposits is primarily from terrains in highlands that back the coastal plains. This provenance is indicated by moderate to good correlation between clay minerals in coastal deposits and those of parent rocks exposed in proximal source areas, with only a modest imprint of size-sorting effects.

It is concluded from these observations that clay minerals transported at sea eastward from the Nile delta (distal source) are probably supplemented by clays derived in more proximal terrains. Clays on the Sinai, Gaza and Israeli margins are dispersed from (1) some modern rivers that seasonally drain highlands in the Sinai (with flow to the north) and in Israel (flow to the NW and west), (2) variably directed seasonal winds that blow across this region to the coast, and (3) marine erosion of coastal exposures. Together, these sources could account for at least a modest input of clays presently transported to SE Levant shores. Land-to-sea dispersal of clay minerals into the Nile cell on the continental shelf off these anthropogenically-altered coastal sectors is the object of the next clay mineral study in this series.

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