Geochemistry of Holocene Sediments from the Nile Delta

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ABSTRACT

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Clay-size fractions of Holocene (to > 7,500 years BP) core samples (n = 173) from lagoonal/marsh, delta-front and prodelta facies in the northeast sector of the Nile delta were analyzed for 23 elements. The cores follow three distributary systems that were active at different times during delta evolution. The sediments are enriched in Fe, Mg, Ni, Cu and Zn with respect to the earth's continental crust. Factor analysis of the data show related element groups that may be interpreted as representing, for example, an aluminosilicate from a basic rock factor, a silicate-oxide factor, a clay mineral + paleosalinity factor, a biogenic factor, a redox factor and a sorption factor. The element enrichments and these factors record provenance (dominated by detritus and weathering products from the Ethiopian Highlands with its 75% Trap Series Basalts cover), physical, chemical and biological conditions in the depositional environments, and geography as it relates, in part, to subsidence and northeast tilting of the delta. This tilting, coupled with rising sea level, affected Nile channel base levels and gradients during the Holocene. Binary plots of factor scores can differentiate between the < 2 µm size samples from the different environments represented in the deltaic sequence of each distributary.

ADDITIONAL INDEX WORDS: Chemical element distributions, Holocene sedimentary facies, Nile delta evolution.

INTRODUCTION

The spatial and temporal distribution of chemical elements in core sections of Holocene age in the northeastern Nile delta of Egypt were investigated to: (1) establish the relation of sediment geochemistry to source area(s) bedrock geology, climate, subsidence, and neotectonics, (2) evaluate the influence of sedimentary processes, environmental parameters such as paleosalinity and redox conditions, and biogenic input on chemical element distribution, and (3) determine if the geochemical data can be used to distinguish between the deltaic facies deposited in distributary systems that have been active in this, the largest depocenter in the eastern Mediterranean.

Systematic geochemical data on the clay size sediment inorganic geochemistry in time and space

of deltaic sequences such as those forming the modern Nile delta are generally unavailable. Recently, DOMINIK and STANLEY (1993) studied the distribution of 14 major and trace elements in Holocene bulk sediments from Nile delta cores. They report that grain size is a major factor influencing the geochemistry of the facies studied and that the ratios of B/Be and S contents in peats are useful in paleoenvironmental interpretations. However, for the most part, geochemical analyses of sequences that were made are retained as proprietary information by industry researchers. The cores analyzed here are from the northeastern third of the delta (Figure 1) and represent about 7,500 years of delta history. It is during this period that the progradation of the depocenter evolved (COUTELLIER and STANLEY, 1987; STANLEY, 1990). Analyses were made on the <2 µm size fraction because its large surface area with respect to other size fractions would give a better chemical re-
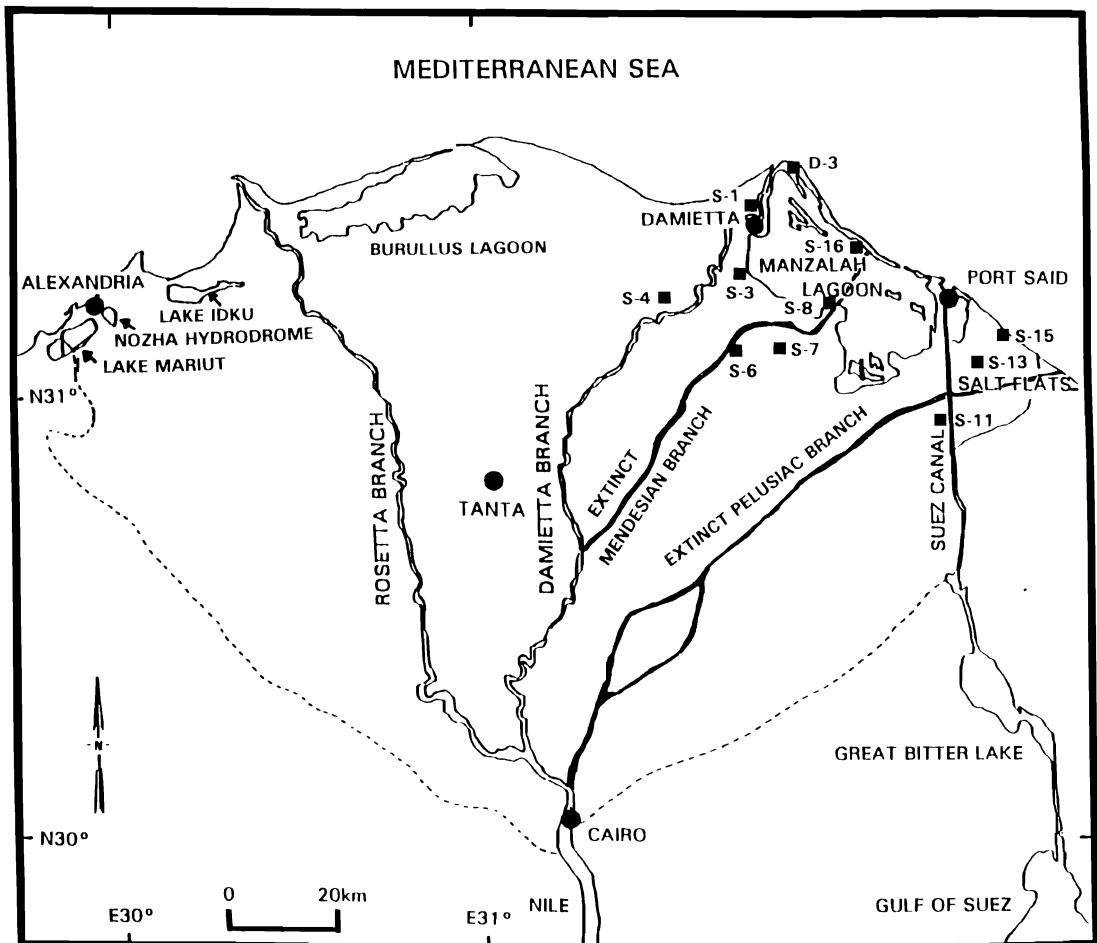
Figure 1.   General map of the Nile delta with the locations of the existing and extinct branches of the River Nile and the locations of cores used in this study from the northeastern sector between the Damietta promontory and Bay of Pelusium. Cores along the extinct Pelusiac and Mendesian branches are designated, respectively, S-4, S-3, S-1, D-3 and S-6, S-7, S-8, S-16; those along the present Damietta branch of the River Nile are designated S-11, S-13, S-15.

sponse to and reflect changes in depositional en-
vironment conditions such as climate, evapora-
tion, redox and salinity. Also its geochemistry
could suggest source area.

BACKGROUND AND COMPARISON WITH OTHER DELTAS

Geochemical analyses have been published for
a few modern delta marine sediments, primarily
from the Mississippi delta (POTTER *et al.*, 1963;
TREFRY and PRESLEY, 1976, 1982; and TREFRY *et*

al., 1986), and the data are fragmentary (Table
1). POTTER *et al.* (1963) analyzed sediment clay
size fractions, whereas total sample analyses are
presented in the other citations given above. In
addition, HIRST (1962a,b) reported the geochem-
istry of one delta clay sample from the Boca Vagre
delta off the northeast coast of Venezuela for com-
parison in a study of the major and trace element
geochemistry and mineralogy of Gulf of Paria sed-
iments.

Analyses of organic carbon- and carbonate-free
clay fractions separated from Tertiary and Qua-

ternary sediments of a well drilled in the north-western part of the delta (31°00′02″N Latitude and 30°27′23″E Longitude) include one sample which was analogous in age to the Nile delta sediments used in this study (EL SHAHAT and EL SHERBINA, 1984). This sample (at 18 m depth) is from the upper Pleistocene-lower Holocene Bilqas formation and contains 166 ppm B, 239 ppm Cr, 124 ppm Ni, 943 ppm Mn, 129 ppm Zn, 46 ppm Cu, 90 ppm Sr, 23 ppm Li, 18.2% Al_2O_3, 5.3% Fe_2O_3, 1.6% CaO, 2.0% MgO, 1.4% Na_2O and 1.8% K_2O. These concentrations are higher for all elements than in the other 16 samples analyzed which ranged from Pliocene to Oligocene in age. In these sediments, B (a possible paleosalinity indicator) is associated with montmorillonite. VILLUMSEN and NIELSEN (1976) found this B-montmorillonite association in a paleosalinity-clay mineralogy study of Quaternary sediments from Eastern Jutland, Denmark. GHEITH and EL SHERBINA (1986) analyzed 25 subsurface core samples of Pliocene and Miocene sediments from the northern part of the Nile delta basin. The concentrations of several of the components (e.g., Cr, Ni, Zn, and Al) were much lower than for the Bilqas formation sample, whereas others (Mn, Cu, Sr) had higher concentrations. This suggests that the principal provenance area(s) may have shifted sometime between late Pliocene and late Pleistocene–early Holocene time. HASSAN (1976) came to the same conclusion on the basis of a review of published data and original research on heavy minerals in Nile delta sediments.

SHUKRI and AZER (1952) proposed that the Ethiopian (Abyssinian) Highlands became an important source area for the montmorillonite rich, fine grained sediments of upper Egypt and the Nile delta during the Pleistocene. This Ethiopian input to Holocene sediments of the Nile delta is indicated by the high abundance of montmorillonite in late Pleistocene sediments of Abyssinia reported by FINCK (1961), by heavy minerals (FOUCAULT and STANLEY, 1989), and by rare earth element relations in the light mineral fraction in sands of several Nile delta cores (HAMROUSH and STANLEY, 1990). EMELYANOV and SHIMKUS (1986) compared bottom and suspended sediments in the Mediterranean Sea with sediment data from the Nile delta and the adjacent portion of the sea. They also concluded that the Ethiopian Highlands has a major influence on the mineralogical and geochemical composition of modern River Nile sediments.

Table 1. *Geochemical data on modern and Holocene (7) deltaic sediments. Concentrations are in parts per million (ppm) unless otherwise indicated. Some values are rounded off.*

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Al%	8.2		7.8	8.5	8.2		
As			12				
B	82	92					55
Ba	515						168
Be	7						2.7
Ca%	0.5						
Cd			1				
Co	10		19			12	59
Cr	75	68–73	80		80		122
Cs	8						
Cu	23	27	29		26	18	55
Fe%	4.2		4.3	4.2	4.2		6.5
Ga	20	21					
K%	1.6						
Li	61						
Mg%	0.7						
Mn	400		675	710	690		837
Na%	1.1						
Ni	31	43–40	39		4	3	79
P%	<0.1						0.09
Pb	17	24	35		32	1	
Rb	146						
S%							0.43
Si%	29.0						
Sr	116						
Ti%	0.5						
V	86	38					173
Zn		192	160			70	94
Zr	350						

(1) HIRST (1962a,b), bulk analysis (n = 1). (2) POTTER et al. (1963), analysis of < 2 μm fraction; Zn not detected in one sample (n = 8). (3) TREFRY and PRESLEY (1976), bulk analysis (n = 30). (4) TREFRY and PRESLEY (1982), bulk analysis (n = 58). (5) TREFRY et al. (1986), bulk analysis (n = 13). (6) BOLDRIN et al. (1988), bulk analysis, prodelta facies (n = 5). (7) DOMINIK and STANLEY (1993), bulk analysis (n = 45)

CORE LOCATIONS AND FACIES SAMPLED

The composite core section from the northern delta plain derived from petrological analysis of many cores typically shows a coarsening-upward sequence (COUTELLIER and STANLEY, 1987; FRIHY and STANLEY, 1988; and ARBOUILLE and STANLEY, 1991). These authors have described eight facies on the basis of petrologic observations and measurements (Figure 2). Of these eight facies, three receive particular attention in the present study: a lagoonal/marsh facies, a marine delta-front facies, and a prodelta facies, coded respectively 2, 3 and 4 (Figure 2). The samples we selected are from radiocarbon dated cores collected along three SW to NE transects in the northeastern section of the Nile delta. These represent the present

NORTHEASTERN NILE DELTA
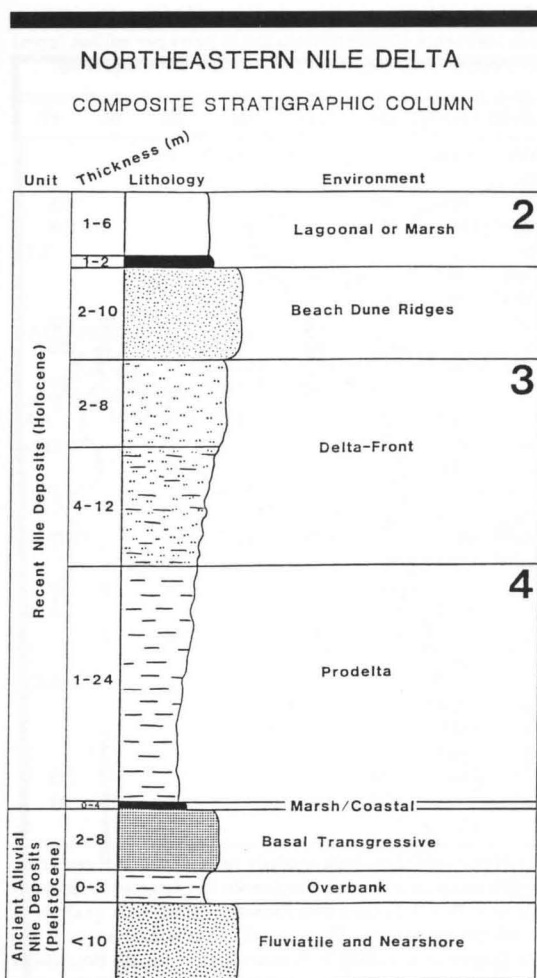
COMPOSITE STRATIGRAPHIC COLUMN

Figure 2. Composite delta stratigraphic section (COUTELLIER and STANLEY, 1987), showing coded facies 2, 3 and 4 as discussed in text.

Damietta branch of the River Nile to the west (cores S-1, S-3, S-4 and D-3) and the extinct Mendesian and Pelusiac distributaries (cores S-6, S-7, S-8, and S-16, and cores S-11, S-13 and S-15, respectively) to the east (Figure 1).

The depocenter for the Mendesian branch started developing at about 8,000–7,500 years before present (BP) and reached its maximum extension about 5,000 years BP. By that time the Pelusiac branch had developed and its depocenter reached a maximum extension at about 3,500 years BP. It coalesced with the Mendesian depocenter (COUTELLIER and STANLEY, 1987), perhaps in part as the result of a northeast tilting of the Nile delta.

The tilting was caused by a combination of subsidence from the weight of the sediments, their compaction, and fault displacement. With regard to the latter, a rhomboid area underlying the Manzalah lagoon was bounded by strike-slip faults that extended to the delta from the Mediterranean and may have been reactivated in the Quaternary (STANLEY, 1988). The Damietta distributary, developed at about 2,500 years BP and between 1,500 and 1,000 years BP, became dominant in this part of the delta (COUTELLIER and STANLEY, 1987, their Figure 7). Stratigraphic cross-sections of the three transects examined in the present study, oriented from land to sea, are shown in Figure 3.

METHODOLOGY

The <2 μm size fraction was separated from 173 samples in eleven cores by differential settling. Samples were prepared for analysis by digesting 0.5 g with 3 ml 3-1-2 HCl-HNO_3-H_2O at 95 °C for one hour and diluting to 10 ml with water. This digestion is partial for 10 (Al, Ca, Fe, K, Mg, Na, P, Ti, Ba, Cr) of the 23 chemical elements studied. Analyses were made using Inductively Coupled Plasma Atomic Emission Spectrometry (ICPAES). The analytical precision is $<\pm$ 3% for Ba; Ca, Fe, Mg and Zn; $\pm$ 3–6% for As, Cr, Cu, La, Mn, Ni, Sr, Th and V; $\pm$ 6–9% for Al, B, Co, K and Pb; and $>\pm$ 9% for Na, P, Ti and U.

The means and standard deviations of the chemical elements were calculated for the facies studied (lagoonal/marsh = coded 2, delta-front = coded 3, and prodelta = coded 4 in Figure 2). In addition, the Student's t-test was applied to determine if there were significant differences in mean concentrations between facies along each transect and between like facies in the three transects.

Chemical element categorization was done using principal component factor analysis. Except for rare cases, a small number of factors can be derived that adequately describe most ($>$ 75%) of the variance present in the original data set (JORESKOG *et al.*, 1976; DAVIS, 1986). The R-mode type of factor analysis with varimax rotation (SAS, 1986) was used to find the associations or extract a simple underlying structure among geochemical variables and thus permit interpretation of the underlying causal influence affecting them in the delta facies studied. Factor scores were also plot-
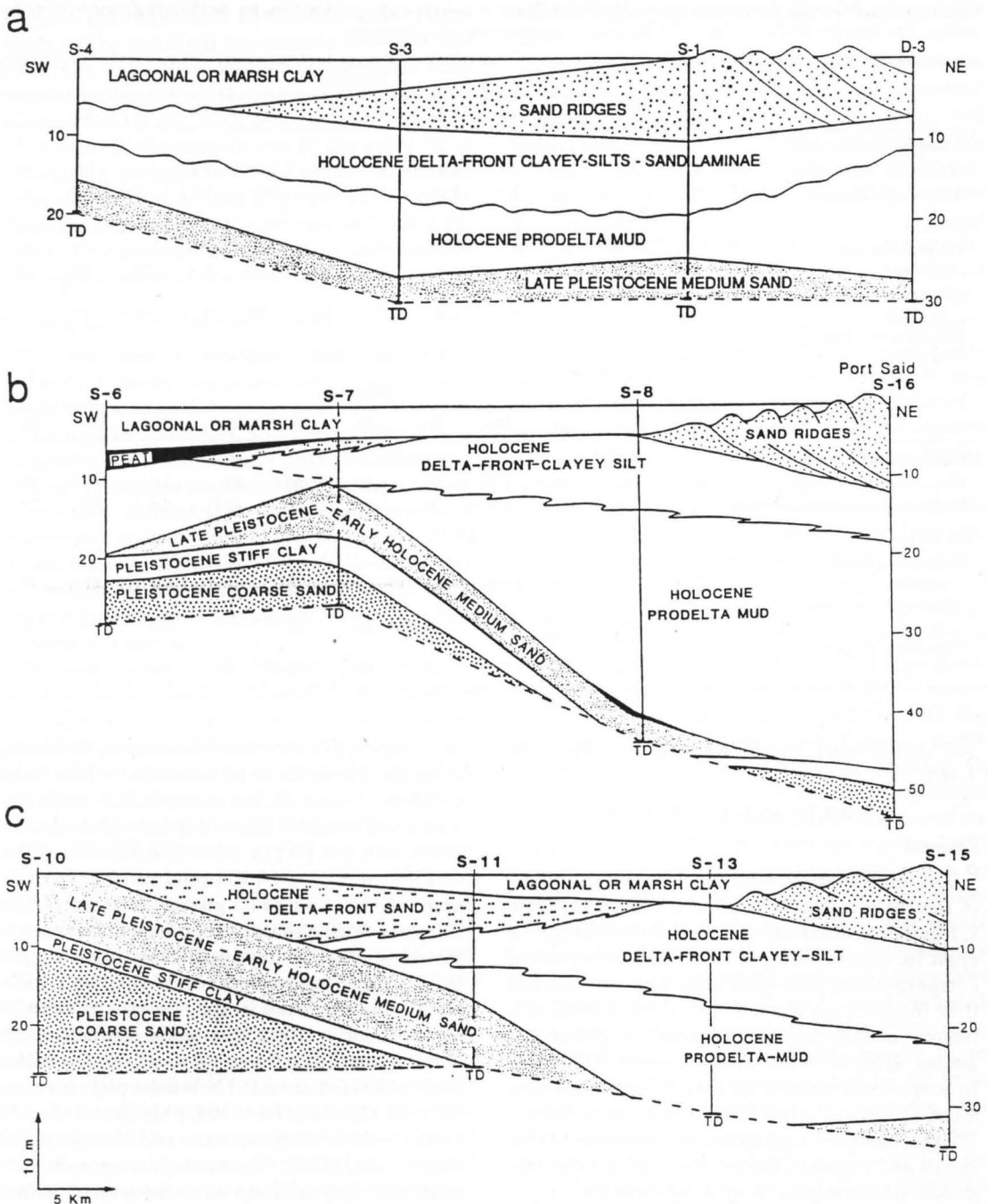
Figure 3. Stratigraphic cross-sections along the transects sampled for this study. a = Damietta, b = Mendesian, c = Pelusiac (b and c after COUTELLIER and STANLEY, 1987). Core S-10 is in Pleistocene sediments and was not analysed herein but included as part of the original figure.

Table 2. *Mean concentrations of chemical elements in Nile delta Holocene sediments $< 2\,\mu m$ fraction compared with the continental earth's crust. Concentrations for Al through Ti are in percent and concentrations for As through Zn are in parts per million. The data for Al, Ca, K, Na, P, Ti, Ba and Cr represent partial extractions.*

| | Element | | | | | | | | | | | |
	Al	Ca	Fe	K	Mg	Na	P	Ti	As	B	Ba	Co
Continental earth's crust												
WEDEPOHL (1981, 1991)	8.0	4.2	4.2	2.4	1.6	2.1	0.19	0.47	3.4	—	730	19
TAYLOR and McLENNAN (1985)	8.0	3.0	3.5	2.8	1.4	2.9	—	0.30	1.5	15	550	10
Nile delta												
Pelusiac—to east												
(n = 59)	3.6	0.7	5.4	0.6	2.7	0.6	0.05	0.05	3	73	51	20
Mendesian—central												
(n = 48)	4.1	0.5	5.7	0.5	1.9	0.4	0.05	0.09	3	69	57	22
Damietta—to west												
(n = 65)	4.6	0.5	5.9	0.5	1.4	0.2	0.04	0.05	3	48	60	22

| | Element | | | | | | | | | | |
	Cr	Cu	La	Mn	Ni	Pb	Sr	Th	U	V	Zn
Continental earth's crust											
WEDEPOHL (1981, 1991)	88	35	44	800	45	15	290	15	3.6	109	69
TAYLOR and McLENNAN (1985)	35	25	30	600	20	20	350	10.7	2.8	60	71
Nile Delta											
Pelusiac—to east											
(n = 59)	76	47	33	642	55	9	70	9	6.0	83	78
Mendesian—central											
(n = 48)	84	49	36	546	60	12	63	7	5.0	93	82
Damietta—to west											
(n = 65)	76	54	35	619	60	13	55	8	5.0	82	83

ted to find out if their attributes were facies related.

RESULTS AND DISCUSSION

General

The mean concentrations for samples from each of the three transects studied are given in Table 2, together with averages for the continental earth's crust for general comparisons. The usefulness of comparisons of Nile delta data with geochemical data from $<2\ \mu m$ size fraction of other delta sediments is questionable because of differences among delta systems. These include differences in source area bedrock geology, climate, and base level, as well as other factors that can influence the geochemistry such as active sedimentary processes and physical, chemical and biological conditions of the depositional environments.

However, comparisons with the geochemistry of a continental earth's crust comprised of 22% granitic rocks, 23% gneisses and mica schists, 17% gabbros, amphibolites and basalts and 37% granulites (WEDEPOHL, 1981, 1991) or of 75% Archean crustal composition and 25% "andesitic" model

composition (TAYLOR and McLENNAN, 1985) may show the influence of provenance on Nile delta sediments (Table 2). For example, Nile delta Holocene sediments in this study are enriched in Fe (5.7% vs 4.2% [W] or 3.5% [T&M]), Mg (2.0% vs 1.6% or 1.4%), Ni (58 ppm vs 45 ppm or 20 ppm), Cu (50 ppm vs 35 ppm or 25 ppm) and Zn (81 ppm vs 69 ppm or 71 ppm) with respect to the continental earth's crust. This suggests input from a basic rock provenance. Similar enrichments were reported in the $<2\ \mu m$ size fraction of two modern River Nile muds collected north of the Aswan High Dam, but south of a transition zone to the contaminated Nile delta plain (in ppm, Ni = 85, Cu = 66, Zn = 108, plus Cr = 183 vs 88 and Co = 35 vs 19; ELSOKKARY and MULLER, 1989; ELSOKKARY, 1992). The modern river sediments analyzed likely indicate an anthropogenic effect. The Ethiopian Highlands with a 75% Trap Series Basalts exposure are considered to be the source area for as much as 95 percent of the fine-grained sediments that have been deposited in the Nile delta and upper Egypt since mid- to late-Pleistocene time (SHUKRI, 1950; SHUKRI and AZER, 1952;

HEGAB, 1984). The geochemical enrichments cited support the hypothesis of the Ethiopian Highlands as the principal provenance zone (via the Blue Nile and Atbara rivers) for Nile delta fine-grained sediments for the more than 7,500 years represented by the cores analyzed. Distribution of rare earth elements in one of the cores (S-7) indicates a periodic influx of sediment derived from the Central African Plateau via the White Nile during this time (HAMROUSH and STANLEY, 1990). This periodic influx was not indicated by the trace elements from this study.

Geographic Trends Along Transects

The means and standards deviations for the individual facies (lagoonal/marsh, delta-front, prodelta) along each transect (and between transects) is given in Table 3. Many geographic trends in geochemical distributions projected empirically from Table 3 are confirmed by Student's t-tests. The t-tests showed that for the populations in facies from a given transect (Table 4A) or for like facies between transects (Table 4B), mean concentrations of some elements were significantly higher (at the 99^{c_i} confidence level) than in a comparison facies.

For example, along the Damietta branch to the west, concentrations of elements from the group Al, Ba, Ca, Co, Cu, Fe, Ni, Sr and V (which could represent aluminosilicate from a basic rock source) decrease from the lagoonal/marsh seaward to the prodelta facies. Conversely, K, Mg, Na and B, for example, (elements that commonly associate with clay minerals) show an increase in concentration along this branch from the lagoonal/marsh facies to the prodelta facies. This could reflect the suspended clay mineral load that bypassed lagoonal/marsh and delta-front environments to the prodelta setting. The clay-size component of the Damietta transect prodelta environment comprises 65.2^{c_c} of the sediment versus 38.3^{c_c} and 45.3^{c_c} for the delta-front and lagoonal/marsh sediments, respectively. The B concentration increases seaward with increasing paleosalinity when moving from the more terrestrial lagoonal/marsh environment (27.4 ppm), through the transitional delta-front environment (48.2 ppm), into the marine prodelta environment (53.6 ppm). DOMINIK and STANLEY (1993) found a similar B-paleosalinity relationship in bulk sediments from a core just southeast of Port Said and another to the southwest of Damietta in the Nile delta. B contents increased seaward from the lagoonal/marsh en-

vironment (41 ppm) to the delta-front environment (47 ppm) to the prodelta environment (66 ppm).

The increase in B contents with increases in salinity is also found in the Mendesian lagoonal/marsh (40.2 ppm), delta-front (69.3 ppm), and prodelta (83.4 ppm) facies. Other geochemical relations are evident in data from this extinct branch of the River Nile. Al, Mg, K, Na and B increase in concentration from the lagoonal/marsh facies through the delta-front facies to the prodelta facies with 53^{c_c} clay-size sediment (Al, Mg, K and Na associate in clay minerals often with B). Each of these components has greater input in the prodelta environment versus other environments studied. Conversely, Ba, Cu and V, which may signal biogenic influence, decrease in concentration from the more terrestrial, possibly oxygen-deficient, lagoonal/marsh environment to the prodelta facies.

There are parallels to the geochemical trends cited for the western (Damietta) and central (Mendesian) transects. These are in the paleosalinity indicator (B) and the elements that tend to group in clay minerals (K, Mg, Na, B). Nonetheless, each River Nile distributary system is unique and this is seen in the geochemical observations along the Pelusiac transect to the east.

In Pelusiac sediments, concentrations of K, Mg, Ba, Cu, V and B decrease from lagoonal/marsh to delta-front to prodelta facies. In addition, Ca and Mg concentrations in Pelusiac lagoonal/marsh samples are the highest for any of the facies analyzed along all transects. The high B value (102.5 ppm) in the more terrestrial lagoonal/marsh facies is opposite to what is expected for a paleosalinity indicator. However, gypsum was identified in this facies which suggests hypersalinity. Calcium, Mg and Ba are elements often associated with shell material, and Cu and V may be metals of soft-part origin preserved in the Pelusiac lagoonal/marsh facies. High K, Mg and Ba values suggest a strong clay mineral input to this facies which may have originated by two processes. First, dry conditions (ADAMSON et al., 1980; FOUCAULT and STANLEY, 1989) and decreased water flow did not permit a ready sedimentological bypass of the fine-size component. Second, hypersaline conditions caused flocculation of smectite particulates and their deposition together with kaolinite, illite and a trace of chlorite (GUPTA, 1989). The Pelusiac lagoonal/marsh sediments contain 59.7^{c_c} of clay-size material. There are increases in Al, Na,

Table 3. *Mean concentrations of and standard deviations of chemical elements in Nile delta transects by facies. Values for Al through Ti are in percent; values for As through Zn are in parts per million.*

	Lagoonal/Marsh Facies					
	Damietta (to west) n = 8		Mendesian (central) n = 13		Pelusiac (to east) n = 8	
Element	X	σ	X	σ	X	σ
Al	4.94	0.25	3.91	0.56	3.13	0.21
Ca	0.72	0.15	0.81	0.58	2.08	1.05
Fe	6.38	0.53	5.65	1.04	4.39	0.49
K	0.35	0.07	0.45	0.11	0.76	0.18
Mg	1.26	0.10	1.58	0.22	3.47	0.94
Na	0.10	0.04	0.26	0.19	0.27	0.15
P	0.04	0.01	0.05	0.03	0.04	0.01
Ti	0.06	0.02	0.10	0.01	0.04	0.01
As	3.4	2.07	2.3	0.65	2.9	1.29
B	27.4	2.92	40.1	9.38	102.5	30.69
Ba	160.4	81.62	135.0	47.64	130.9	95.70
Co	22.8	3.77	21.5	4.16	17.1	3.99
Cr	75.0	3.96	81.1	9.53	61.4	7.00
Cu	90.0	92.38	55.8	6.55	54.6	2.36
La	31.2	3.54	36.1	8.44	24.8	5.50
Mn	524.1	190.54	442.3	332.58	445.0	204.75
Ni	67.4	6.70	58.9	9.01	51.9	7.27
Pb	12.6	3.81	11.5	3.02	10.9	10.08
Sr	65.5	20.11	79.1	20.57	119.0	39.51
Th	6.9	0.35	5.2	0.49	6.6	1.07
U	5.0	0.00	BDL	—	8.9	2.65
V	119.5	14.07	105.3	12.38	105.1	12.71
Zn	83.4	7.25	76.2	12.37	71.8	7.75

	Delta-Front Facies					
	Damietta (to west) n = 27		Mendesian (central) n = 10		Pelusiac (to east) n = 26	
Element	X	σ	X	σ	X	σ
Al	4.49	0.15	3.99	0.46	3.63	0.46
Ca	0.40	0.06	0.44	0.16	0.43	0.12
Fe	5.81	0.36	5.83	0.42	5.51	0.35
K	0.40	0.05	0.49	0.07	0.60	0.10
Mg	1.43	0.10	1.68	0.43	2.55	0.17
Na	0.20	0.09	0.27	0.14	0.75	0.52
P	0.04	0.00	0.05	0.01	0.05	0.01
Ti	0.05	0.01	0.09	0.03	0.06	0.02
As	2.5	1.28	3.6	1.07	2.4	0.87
B	48.2	9.90	69.3	19.99	76.0	57.46
Ba	52.3	19.98	56.3	18.81	42.0	6.24
Co	22.6	2.24	23.6	1.77	20.9	1.29
Cr	79.1	4.39	86.7	11.10	77.9	7.74
Cu	53.0	8.86	48.8	11.04	49.7	9.69
La	36.5	5.49	39.2	3.77	34.8	3.99
Mn	575.9	223.79	659.2	238.50	636.2	272.25
Ni	60.5	4.43	58.1	4.43	55.6	6.71
Pb	13.4	3.10	16.8	2.37	8.5	2.56
Sr	51.7	5.85	60.5	17.86	59.2	15.08
Th	8.2	0.89	7.0	1.65	9.0	0.78
U	5.0	0.00	BDL	—	5.2	0.58
V	81.7	7.71	88.2	8.49	82.0	11.37
Zn	82.7	2.75	81.7	4.14	76.0	3.60

Table 3. *Continued.*

	Prodelta Facies					
	Damietta (to west) n = 30)		Mendesian (central) n = 25		Pelusiac (to east) n = 26	
Element	X	σ	X	σ	X	σ
Al	4.57	0.52	4.20	0.40	3.69	0.24
Ca	0.48	0.10	0.44	0.11	0.48	0.18
Fe	5.79	0.42	5.60	0.32	5.48	0.37
K	0.50	0.07	0.57	0.08	0.60	0.07
Mg	1.49	0.10	2.21	0.47	2.52	0.13
Na	0.31	0.14	0.52	0.14	0.46	0.18
P	0.05	0.01	0.05	0.01	0.05	0.01
Ti	0.04	0.02	0.09	0.03	0.05	0.01
As	2.8	1.33	3.5	1.99	2.5	0.86
B	53.6	9.20	83.4	14.78	59.2	16.26
Ba	40.1	8.77	37.4	7.29	34.2	3.91
Co	20.7	1.42	21.5	1.40	20.2	1.05
Cr	73.4	9.32	84.7	7.00	75.3	4.37
Cu	44.6	11.58	45.2	8.66	40.6	4.51
La	34.9	2.33	34.3	2.14	34.2	2.43
Mn	683.9	218.78	555.0	176.19	683.0	156.32
Ni	56.5	9.11	60.4	4.54	53.2	2.73
Pb	12.1	2.93	10.2	4.67	8.8	2.75
Sr	55.2	6.64	56.2	8.53	62.0	34.24
Th	8.1	0.51	8.1	1.20	9.4	0.75
U	5.1	0.36	BDL	—	5.7	1.19
V	71.2	10.07	88.3	5.41	74.3	5.24
Zn	83.0	5.20	81.2	5.48	79.0	4.07

Fe, Cr, Ti, Mn, La, Th, and Zn concentrations in deposits along the extinct Pelusiac distributary from lagoonal/marsh facies, through delta-front facies, to prodelta facies. This suggests that aluminosilicates (Al, Na, Fe, Cr, Ti) and elements sorbed onto manganese oxides (Th, La, Zn) may affect Pelusiac prodelta facies geochemistry.

Geographic Trends Between Like Facies

In addition to the geochemical changes in the sediments along each land-to-sea (southwest–northeast transect), there are coast parallel (east–west) trends between like facies (Table 3, Table 4B). For example in the lagoonal/marsh facies, concentrations of K, Mg and B increase towards the Pelusiac branch on the east. The K, Mg and B group can originate from an increase in clay minerals for reasons given earlier and from high salinity. The clay-size component of lagoonal/ marsh sediments is the highest for the Pelusiac transect (59.7 %); it decreases to 53.5% for the Mendesian transect and to 45.3% for the Damietta transect to the west. Conversely, concentrations of Al, Fe, Co, Cr, Ni and Zn in lagoonal/ marsh facies increase to the west in the Damietta

Table 4A. *Results of the Student's t-test on the ＜ 2 μm size fraction geochemistry between the different facies along each transect. Population means are lower in the comparison facies. Facies 2 represents the lagoonal/marsh samples, Facies 3 the delta-front samples, and Facies 4 the prodelta samples.*

Facies	Geochemical Elements	Comparison Facies
Damietta Samples—to the west		
2	Al, Ba, Ca, Fe, Ni, Sr, V	3
	Al, Ba, Ca, Co, Cu, Fe, Ni, Sr, V	4
3	B, Cr, K, La, Mg, Na, Th	2
	Ba, Co, Cr, Cu, V	4
4	B, K, La, Mg, Na, Th	2
	Ca, K, Mg, Na, P	3
Mendesian Samples—central		
2	Ba	3
	Cu, Sr, V, Ba	4
3	Pb, Th, B	2
	Pb	4
4	Th, Mg, K, B	2
	K	3
Pelusiac Samples—to the east		
2	V	3
	Cu, V, Ba, B	4
3	Fe, Th, La, Cr, Ti, Al	2
	Cu, V, Ba	4
4	Fe, Th, La, Cr, Ti, Al, Na	2
	Zn	3

Table 4B. *Results of the Student's t-test on the ＜ 2 μm size fraction geochemistry between like facies in the transects. Population means are lower in the comparison samples. Designation 1 represents Damietta samples, designation 2 represents Mendesian samples, and designation 3 represents Pelusiac samples.*

Designation	Geochemical Elements	Comparison Samples
Lagoonal/Marsh Samples		
1	Al, Th	2
	Al, Fe, Co, Cr, Ni, Zn	3
2	K, Mg, Na, Ti, B, Cr	1
	Al, Fe, Ti, Co, Cr, La, Zn	3
3	K, Mg, Na, B	1
	K, Mg, B, Th	2
Delta-front Samples		
1	Al	2
	Al, Fe	3
2	K, Na, Ti, B, V	1
	Al, Fe, Ti, Ba, Co, Pb, Zn	3
3	K, Mg, Na, B	1
	K, Mg, Na, Th	2
Prodelta Samples		
1	Al, Mn, Zn	2
	Al, Fe	3
2	Mg, Na, Ti, B, Cr, Cu, La, Ni, V	1
	Al, Ti, As, Ba, Co, Cr, Cu, Ni, V	3
3	K, Mg, Ti, Th	1
	K, Mg, Mn, Th	2

samples. This relation probably developed during times of reduced water flow resulting from a high sea level that had reached equilibrium with the modern datum and also from a drier climatic cycle (ADAMSON *et al.*, 1980). This gave a lesser gradient in the Damietta depocenter relative to the central and eastern areas during their times of predominance and sediment discharge closer to the source in this seaward tilted to the northeast delta plain sector (STANLEY, 1990). This element grouping of Al, Fe, Co, Cr, Ni and Zn in the depositional environment may represent aluminosilicates from a basic rock provenance. As speculated previously, silicates and oxides deposited in the Damietta branch lagoonal/marsh environment could contribute to the higher concentrations of these elements.

The delta-front facies has fewer elements showing geographic trends but these illustrate an increase in clay mineral components (K, Mg, Na, B) to the east towards the Pelusiac system and Al, Fe to the west. The Pelusiac transect delta-front sediment clay-size component is higher (49.8%) than in Mendesian (39.5%) and Damietta (38.3%) delta-front sediments to the west. In

a subtle way, these trends mirror those observed in the geochemistry of the lagoonal/marsh facies.

Geochemical trends in prodelta facies are similar to those in delta-front facies, with an increase in K, Mg and Th to the east (clay minerals) and in Al, Fe and Zn to the west (aluminosilicates).

The less marked coast-parallel (east–west) geographic trends for delta-front and prodelta facies compared to lagoonal/marsh facies are the result of an increasing "homogenization" of near shore and offshore sedimentological conditions in the delta-front and prodelta depositional environments. This is in contrast to the heterogeneity and individuality associated with chemical and mineralogical changes in lagoonal/marsh depositional environments. These changes are in response to several factors including a diminished discharge into an environment of deposition (climate influenced), depth of water versus surface area presented to the atmosphere and resulting evaporation-water replacement balance, and differences in vegetation and other life forms with changing ecological conditions (*e.g.*, hypersalinity).

Table 5. *Factors contributing significantly (at the 99.9% C.L.) to the variance of the chemical elements in the geochemical populations in the Damietta transect on the west, to the Mendesian transect in the center, to the Pelusiac transect on the east in the northeastern Nile delta. Interpretation of factor groupings are given below each assemblage.*

Damietta	% Var	Mendesian	% Var	Pelusiac	% Var
Mg, K, B, Na, -Ba, -V, -Fe, -Ni, -Ca CM/PS	21.3	Co, Ni, Fe, Zn, Ti, Mn, P, Cr SI-O/BR	24.3	Ni, Al, Ti, Co, Cr, Zn, Fe, -Mg AS/BR	21.1
Cr, Ni, Cu, Ti, Co, V, Fe, Ba, -K SI-O/BR	18.2	Th, Mg, B, Mn, V, -Ba CM/SO	12.3	Sr, Ca, Ba, La, -Th, -Cr, -Fe BG	18.2
La, Th, Co, -Al, -Ca SO	13.4	Ca, P, Sr BG	10.6	Cu, V, Ba, B, Mg, -Mn, -Th, -La RED/EV	15.6
Zn, -Na UN	8.7	Al, Cr AS/BR	10.0	P, Mn, Fe, Pb, Ca PN/SO	10.2
P, Mn PN	8.4	Ba, Cu, V RED	8.7	K, Pb, Mg, -Co CM	9.2
As, Pb RED	6.8	Na, P, As, B PH	7.4	Na, Ti, -B UN	7.6
Ca, Sr BG	6.5	K, Na CM	7.2	As RED	5.2
Totals	83.3%		80.5%		87.1%

Note: Abbreviations for interpreted factors: CM = clay minerals, PS = paleosalinity, AS = aluminosilicates, BR = basic rock, SI-O = silicates-oxides, BG = biogenic, RED = reducing, SO = sorption, EV = evaporite, PN = precipitation, PH = phosphorite, UN = undefined.

The Influences on Geographic Trends

Spatial trends in the geochemical data along or between sample transects are the result of several influences, many of which have been cited in preceding sections. In essence, these influences are ultimately the result of the periods during which each of the distributary depocenters evolved and reached its maximum extension. They relate to the provenance areas that contributed the sediment load, climatic changes that affected the provenance areas (FOUCAULT and STANLEY, 1989), the physical, chemical and biological conditions in the sedimentary environments in each depocenter, and, locally, to the depositional sites.

On a large scale, these climatic changes affected weathering, erosion and transport of sediment from headwater source areas to the River Nile and its distributaries (SHUKRI, 1950; FOUCAULT and STANLEY, 1989). On a localized scale, climatic aberrations directly affected the depositional environments themselves. Finally, superimposed on these changes is the effect of subsidence that is seen in the sedimentary sequences (STANLEY, 1988, 1990; ABU-ZEID and STANLEY, 1990) and eustatic changes in sea level which was lower (by about 12–15 m) at 7,500 years BP. Sea level rose during the development of the Mendesian depocenter and continued to rise, perhaps more slowly, dur-

ing the development of the Pelusiac depocenter and the Damietta depositional system (COUTELLIER and STANLEY, 1987). In consequence, it is envisioned that the fluvial gradient was greater during the times of Mendesian distributary dominance than during the times when the Pelusiac distributary developed. This concept is supported by greater sand (11%) and silt (36%) contributions in the Mendesian prodelta sediments, versus a 4.2% sand contribution and a 30.8% silt contribution to Pelusiac prodelta sediments. A still more gentle gradient evolved recently during the evolution of the modern Damietta distributary with less sand (2.7%) and slightly more silt (32.1%) deposited in the prodelta environment, versus that in the Pelusiac prodelta environment. This eustatic factor has had a strong effect on spatial trends of geochemistry in delta sediments.

Factor Analysis for Each Transect Geochemical Population

Associated elements that influence the variance in the element populations in Nile delta sediments may not be clear from the empirical observations (Tables 2 and 3) or the Student's t-test (Table 4A, 4B) alone but can be derived by factor analysis. Factor analysis of the grouped populations can reveal the significant influences on the

Table 6. *Interpretations of factor analysis-derived chemical element groups in Recent marine sediments.*

Element Groups	Designated Factor	Alternate Designation	Reference
Al, Cr, Co, Fe, Mg, Na, Ti, V	Aluminosilicate	Basic rock source	MOORE (1963)
Al, K, Na, Cu, B, Ba, Pb	Aluminosilicate	Felsic rock source	RILEY and CHESTER (1976)
Mg, Cr, Ni	Basic igneous phase		ODADA (1990)
Al, Fe, Ti, V, Zn, Li, Be, K	Terrigenous phase		ODADA (1990)
Al, K, Zr, Fe, Ti, V, Ni, Co, Cr	Terrigenous clay (reworked)		NORMAN and DEDECKKER (1990)
Al, Si	Aluminosilicate		EL-SAYED (1988)
Ti, Al, K, Cr, Ni, Co	Heavy minerals	Basic rock source	RILEY and CHESTER (1976)
Ca, Sr	Carbonate		SPENCER *et al.* (1968)
Ca, CO_2, Sr	Carbonate		RILEY and CHESTER (1976)
Ca, Mg, Na, -Fe, -Mn	Carbonate		EL-SAYED (1988)
Ca, Sr, P	Biogenic		ODADA (1990)
Ca, Sr, Mn	Biogenic		NORMAN and DEDECKKER (1990)
Fe, Ca, P, CO_2, Sr	Aragonite-pH	Biogenic	AHRENS (1968)
Cu, Cr, Fe, Mn, Ni, V	Fe-Mn oxide		AHRENS (1968)
Fe, Co, P, V, Mn	Oxide		RILEY and CHESTER (1976)
Co, Cr, Cu, Fe, Mn, Ni, V	Oxidation potential		SPENCER *et al.* (1968)
Mn, Co, Ni, Cu	Hydrogenous phase		ODADA (1990)
Mn, P	Sorption		RILEY and CHESTER (1976)
B, Na, K, Mg, Sr	Authigenic-degraded illite-glauconite	Clay minerals/ paleosalinity	AHRENS (1968)
K, Fe, Mn	Feldspar-clay mineral		EL-SAYED (1988)

chemical variance of the total population. However, this could obscure how the impacts of these factors or others have evolved in changing depositional environments as the River Nile branches and delta depocenters have evolved with time. It is for this reason that we elected to focus on each transect population separately. Results of factor analysis on the geochemistry of the sediments along each transect are given in Table 5. In this study, all factors with an eigenvalue equal to or greater than 1 were retained. With this value, the corresponding factor is able to account for more than the original variance present in the data. The 99.9% confidence level was used to establish the variable loadings.

As shown in Table 5, seven significant factors explain 83.3% of the variance in the data for the Damietta branch sediments. This is similar to the Mendesian transect data for which seven factors explain 80.5% of the variance. For the Pelusiac branch sediments, seven factors explain 87.1% of the variance. The interpretations of what the factors represent in terms of source area, paleoclimatic oscillations, physical, chemical and biological processes, depositional environment conditions, and subsidence is in some cases straightforward. In other cases, factor assignments are subject to alternate interpretations and some are difficult to determine.

Geochemical Factor Assignments

Table 6 shows the explanations given by several authors for factor analysis extracted element associations in recent marine sediments. It is presented here only to illustrate some of the difficulties involved in factor assignments. For example, a general designation such as "aluminosilicate" is used to explain notably different element groups. One can suggest using modifiers with "aluminosilicate" to relate element associations to a probable source rock.

An element assemblage may also be attributable to more than one origin, making any single interpretation arbitrary. In Table 6, the group Co, Cr, Cu, Fe, Mn, Ni and V, assigned by SPENCER *et al.* (1968) to an oxidation potential influence, might alternately represent a heavy minerals influence. Similarly, the element group Al, K, Zr, Fe, Ti, V, Ni, Co, Cr explained by NORMAN and DEDECKKER (1990) as a reworked terrigenous clay (Table 6) could represent a reworked clay with a heavy minerals component.

In addition, factor interpretations might be better if generalized. For example, assignment of the element group B, Na, K, Mg, Sr as an authigenic degraded illite-glauconite (Table 6) could be considered as a general clay minerals component with a paleosalinity (B) input.

Specific, alternate or generalized assignments

for chemical factors are all used in geochemical investigations of sediments. However, the most logical designation is made in context of the observed and/or measured parameters of the geological-sedimentological system being studied, the provenance areas for the sediments, and other parameters such as climate and eustasy.

Geochemical Factors of Nile Delta Sediments

In the Nile delta study area, each transect has factors in common with the other two, but these factors contribute differently to the total chemical variance in each transect and may show geographical trends. For example, the clay minerals factor has greater influence on the variance to the west and also shows a paleosalinity effect (B) in the western transect (Table 5).

On the other hand, two factors that could be attributed to the influence of the source area geology (Co, Ni, Fe, Zn, Ti, Mn, P, Cr, and Al, Cr) are found together only in the Mendesian sediments (Table 5). These could represent aluminosilicates derived from a basic rock source. Because of the 4.3 to 8.3^{c_i} by weight of heavy minerals (including clinopyroxene, epidote-zoisite, ore minerals, hornblende, and zircon) in modern River Nile muds (EMELYANOV and SHIMKUS, 1986) and the greater gradient and water flow during the development of the Mendesian depocenter, these assemblages could also contain higher specific gravity clay-size silicates or oxides (not determined in this study). A similar factor (Cr, Ni, Cu, Ti, Co, V, Fe, Ba) is found for sediments deposited from a lesser water flow at a lesser gradient during the deposition of Damietta sediments and accounts for less of the geochemical variance (18.2^{c_i} vs 24.3^{c_i} in the Mendesian samples). The aluminosilicate factor is found in Mendesian sediments (Al, Cr) and in Pelusiac samples (Ni, Al, Ti, Co, Cr, Zn, Fe, -Mg) to the east (Table 5). These combined factors have the strongest influence on the element variance in the <2 μm size fraction of Nile delta sediments.

The factor attributed to biogenic input (Ca, Sr with Ba or P) has its strongest effect on the chemical variance in the eastern transect sediments (18.2^{c_i}) and least effect on the chemical variance in the western sediments (Table 5).

The influence of elements that may be grouped because of a reducing environment (*e.g.*, As, Pb, Ba, Cu and V) increasingly affects the chemical variance from the Damietta samples (6.8^{c_c}) on the west, to the Pelusiac samples (15.6^{c_i}) on the east. The factor loading is strongest in the lagoonal/marsh sediments, especially from the Mendesian (central) and Pelusiac (eastern) transects. In Pelusiac samples, the inclusion of B and Mg with Cu, V, and Ba suggest that hypersaline conditions also affected the lagoonal/marsh depositional environment there.

Sorption is significant in the western (Damietta) transect sediments with two element groups that account for 21.8^{c_i} of the geochemical population variance. The sorption factor influence decreases to the east where it accounts for 10.2^{c_i} of the geochemical variance in the Pelusiac population (Table 5).

We are unable to assign the element groups Zn, -Na in the Damietta samples, and Na, Ti, -B in the Pelusiac samples.

Interrelated Controls on Element Distributions and Groupings

As previously mentioned, there are several possible physical, chemical and biological controls on element distributions and groupings. In addition, subsidence and tilt of the delta to the northeast (STANLEY, 1988) coupled with a rising sea level affected the gradients of the distributary systems as they evolved (STANLEY, 1990; STANLEY and WARNE, 1993).

Submergence, for example, was more pronounced as the Mendesian and Pelusiac depocenters developed (and overlapped) from about 7,500 to 3,500 years BP. In addition, sea level rose to the present datum from about 15 m below sea level about 7,500 years BP to about 6 m below sea level about 5,000 years BP (*i.e.*, 30 cm/100 yr during the time of Mendesian distributary development and maximum influence). Sea level rose further, to about 3 m below sea level, from about 5,000 years BP to about 3,500 years BP (*i.e.*, 20 cm/100 yr during the time of Pelusiac distributary development and maximum influence). Sea level reached about 2 m below sea level when the Damietta distributary developed to the present (*i.e.*, 8 cm/100 yr) (STANLEY, 1990, calculated from his Figure 2). This activity resulted in stronger gradients to the northeast so that clay-size detritals, possibly with a higher specific gravity aluminosilicate and oxide component, together with clay minerals were transported to the depocenters more effectively than to the west. As the Damietta depocenter began to evolve at about 2,400 years BP, it subsided less than had the other depocenters so that base level was higher and waters flowed

along a more gentle gradient. As a result, the clay minerals were transported to the depocenter in greater loads with respect to any coarser or heavier load. In this way subsidence from neotectonics (STANLEY, 1988), compaction, and a rising sea level (changing base level) together affected the transport of fluvial sediments and had a strong effect on the clay-size sediment geochemical factors.

Dominant Factors and Their Development

The factor attributed to aluminosilicates from a basic rock provenance, perhaps with a higher specific gravity silicate and/or oxide component, together with a clay mineral factor, represent 39.5% of the geochemical variance in the west (Damietta transect), 46.6% in the central (Mendesian transect), and 30.3% to the east (Pelusiac transect) in clay-size detritals (Table 5). This relation reflects source area(s) geology and was probably abetted by the climate (ADAMSON et al., 1980; PAULISSEN and VERMEERSCH, 1989) in the evolving depocenters.

A wetter climate prevailed during the development of the Mendesian and Pelusiac distributary and depositional systems which coalesced and reached maximum extentions sometime after 5,000 years BP and before 3,500 years BP. Climate has become considerably drier since about 4,000 years BP. With greater discharge during Mendesian and Pelusiac activity, a greater load of clay-size sediment could be moved towards the depositional environments, helped by a northeast tilting due to subsidence, a changing base level (sea level) in the study area, and increased gradient to the northeast. This is shown by the influence of the factors assigned to aluminosilicates and silcates-oxides, perhaps with higher density components on chemical variance, with 34.3% and 21.1% for the Mendesian and Pelusiac sediments, respectively, and 18.2% for the western (Damietta) transect sediments (Table 5). As described previously, localized geographic and climatic aberrations resulted in evaporite conditions in the lagoonal/marsh environment of the Pelusiac system. This is recorded by the presence of abundant gypsum in the sediments and also high concentrations of Ca and Mg and the B paleosalinity indicator there. The hypersalinity that developed in the Pelusiac lagoonal/marsh facies during a climatic aberration resulted in the concentration of shell detritus and possibly soft-part metal components in sediments. This is indicated by high shell-originated Ca, Sr and Ba contents (with Ca and Mg abetted by evaporite formation) and Cu and V contents in the Pelusiac lagoonal/marsh sediments.

Thus for the Nile delta, analysis of chemical data from individual transects yields interpretative data important to analyze the spatial and temporal geochemical evolution of the delta as a whole. Regional geochemical studies of deltaic sediments should evaluate each distributary comprising a deltaic environment.

Factors and Facies

Plots of factor scores (or factor loadings) of samples from each transect can show partitioning into facies fields. Factor scores represent estimates of the contributions of factors to the system being evaluated. A higher score indicates a greater contribution. For example, the dominant factor in the Damietta samples, the clay minerals/paleosalinity factor, when plotted against depth in cores (from the lagoonal/marsh environment to the prodelta environment) highlights two points: (1) the factor scores in general increase from the lagoonal/marsh to prodelta sediments; (2) the factor scores separate a lagoonal/marsh facies field, a delta-front facies field, a transitional zone to the prodelta facies, and a prodelta facies field (Figure 4). A parallel but less marked relation was found for the factor in Pelusiac samples and attributed to aluminosilicates from a basic rock provenance. In Damietta samples, scores from the aluminosilicate factor, show an opposite change with depth in core, with a decrease in importance from the lagoonal/marsh and delta-front facies to the prodelta facies. This distribution may be explained by relating it to the lesser gradient and base level and reduced stream flow conditions that prevailed during the evolution of the Damietta distributary. Under these conditions in the Damietta depocenter, more of the detritus carrying the Cr, Ni, Cu, Ti, Co, V, Fe, Ba, -K factor were deposited closer to the discharge areas, whereas lighter components carrying the clay minerals/paleosalinity factor accumulated farther offshore (Figure 4).

Plots of scores for the less dominant factors may also show a relation to facies. The scores for the reducing-evaporite factor in the Pelusiac transect sediments, plotted against depth in cores in general, decrease in importance from the lagoonal/marsh facies to the delta-front facies through a transition zone to the prodelta facies (Figure 5). The designated reducing factor (Ba, Cu, V) for
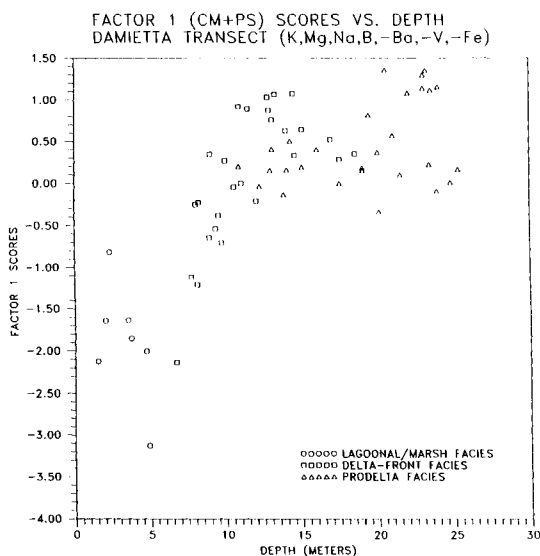
Figure 4. Plot of factor scores against depth in cores (landward to seaward facies) for the clay minerals-paleosalinity factor from Damietta samples (shows increasing importance seaward).
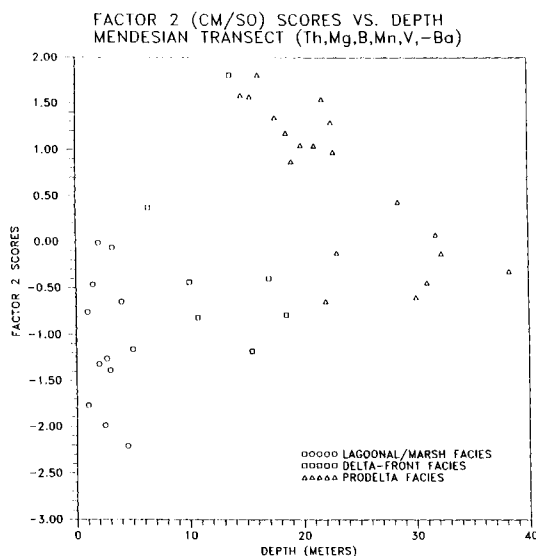

Figure 6. Plot of scores for a less dominant factor such as the sorption factor against depth in core (landward to seaward facies) for the Mendesian sample suite (suggests increasing sorption efficiency seaward).
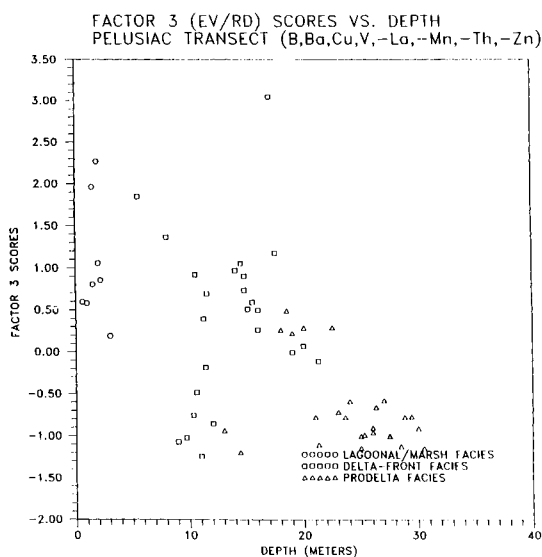

Figure 5. Plot of scores for a less dominant factor such as the reducing-evaporite factor against depth in core (landward to seaward facies) for the Pelusiac sample suite (shows environmental control on element distribution, *i.e.*, increasing importance landward to the lagoonal/marsh environment).

Mendesian sediments shows the same relationship to facies. This is expected because of the characteristics of a lagoonal/marsh facies in which evaporites have been found (such as described for the Pelusiac lagoonal/marsh environment) and the likely oxygen-deficient nature of the lagoonal/marsh environment. In contrast, the clay minerals/sorption factor (Th, Mg, B, Mn, V, -Ba) scores in the Mendesian transect sediments, when plotted against depth in cores, increase in importance from the lagoonal/marsh environment to the delta-front environment through a transition environment to an oxygen-sufficient prodelta environment (Figure 6). Similarly, the sorption factor (La, Th, Co, -Al, -Ca) for Damietta samples shows a marked increase in factor scores from the lagoonal/marsh to the delta-front and prodelta facies.

Factor Score Scatter Plots

Plots of factor scores against each other may, in some cases, show distinct fields for the facies involved. For example in Mendesian samples, the clay minerals/sorption factor plotted against the reducing factor effectively distinguishes the lagoonal/marsh from the prodelta facies (Figure 7).

This is expected because of the greater probability of a reducing factor being present in a lagoonal/marsh environment and transport and deposition of clay-size sediment farther seaward during the time of greatest gradient. A similar relationship is found in the Damietta transect for which the clay minerals/paleosalinity and sorption factor scores are lowest in lagoonal marsh samples and increase in samples from offshore oxidizing environments. Such factor score plots can be useful in deciding the best designation for a geochemical factor.

Limitations of Factor Score Plots

Factor scores plotted against depth in core (facies) or plotted factors against each other may show a clear partitioning of a factors' importance to facies studied. The division may be easily interpreted on the basis of factor preference for a given depositional environment. Conversely, the division may not be well-defined making interpretations less obvious. Factor scores can be useful to corroborate and clarify conclusions made from data on petrological observations and measurements alone.

CONCLUSIONS

Relatively high concentrations of Fe, Mg, Ni, Cu and Zn in the $<2\ \mu m$ size fraction of Nile delta sediments compared to the continental earth's crust (Table 2) suggest an important input from a basic rock provenance. This corroborates the Ethiopian Highlands with a 75% Trap Series Basalts cover as the source area for the dominant mass of fine-size sediment for the Nile delta during the approximately 7,500 years BP represented by the cores analyzed.

Geochemical factors that explain significant percentages of the variance in the chemistry of fine-size sediments of the northeastern Nile delta are the result of one or more than one process. Principal among these is source area geology; in addition, climatic conditions in provenance area(s) are important. This is reflected in the aluminosilicate factor possibly with higher specific gravity silicate or oxide components. These, together with clay minerals factor, have a major influence on the Nile delta sediment geochemistry.

Clay minerals in the Nile delta distributaries responded to changing paleosalinity conditions in the depositional environments as measured by an association of B with the clay minerals factor. Physical, chemical (vis-a-vis the B relation), and
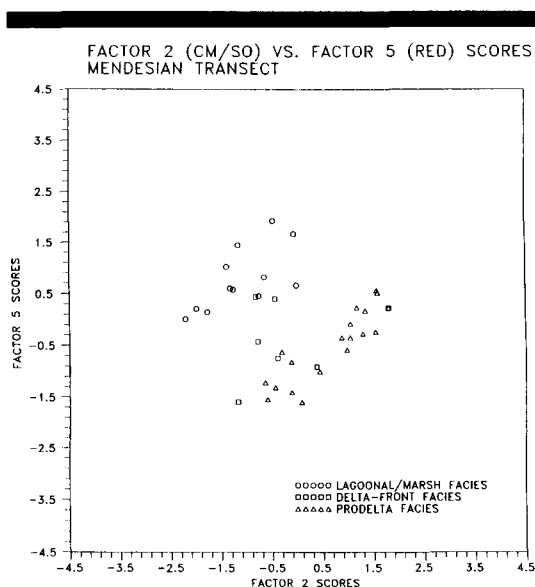

Figure 7. Plot of factor scores for the clay minerals-precipitation-sorption factor against the reducing factor for the Mendesian sample suite for two facies (shows that each factor falls into a distinct field for the lagoonal/marsh and prodelta facies). The clay minerals-paleosalinity-sorption factor increases in importance seaward, whereas the reducing factor is more important in the lagoonal/marsh depositional environment.

biological conditions in sedimentary environments have a marked influence on significant factors derived for Nile delta fine-size sediment geochemical populations. For example, the biogenic factor originates with shell matter. In a lagoonal/marsh environment that is oxygen deficient, this factor may also record the preservation of soft-part derived metals. In a lagoonal/marsh environment where subaerial exposure under arid conditions resulted in hypersaline conditions, evaporite elements associate with the biogenic factor. During periods of aridity or decreased water flow (a climatic influence), the lagoonal/marsh environment with its reed species and other vegetation may present a physical barrier to sediment bypass. This is especially true for fine-size higher specific gravity aluminosilicates, silicates or oxides such as those which comprise 4.3 to 8.3% by weight of modern River Nile muds. Sorption can be a significant factor in the geochemical distributions, especially in a delta-front or prodelta oxidizing environments. Some factors which do not affect sedimentary geochemistry as much as those just given may be readily explained. Other factors

are not clearly defined, especially when comprised of one element or two elements, one with positive and the other with negative loading (*e.g.*, As, or Zn, -Na).

The interdependence of climate and subsidence resulting from sediment loading, compaction, and abetted by neotectonic fault offset plus a rising sea level (changing base level) also influences factor development and importance in a geographic setting. Subsidence and tilting of the Nile delta to the northeast together with a lower sea level provided a stronger distributary gradient towards the evolving depocenter during the lower to mid-Holocene. Sea level rose during the time of delta progradation when distributary systems progressively formed and waned (COUTELLIER and STANLEY, 1987; STANLEY and WARNE, 1993). The gradient and rate of sea level rise increased with time from Mendesian to Pelusiac to Damietta activity. This, together with a wet climate in the principal sediment source area(s), stimulated transport of a larger sediment load by Mendesian and Pelusiac systems until about 3,500 years BP. This is preserved in the greater importance attributed to an aluminosilicate factor from a basic rock provenence (*e.g.*, Ni, Al, Ti, Co, Cr, Zn, Fe, -Mg) together with input from higher density silicate or oxide components (Co, Ni, Fe, Zn, Ti, Mn, P, Cr) in explaining the geochemical variance in the populations studied.

Plots of factor scores against depth in core (*i.e.*, from the lagoonal/marsh facies to the prodelta facies) or plots of factor scores against each other according to facies may show a good partitioning of factors to facies.

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