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Temporal and Spatial Distribution of Clay Minerals in Late Quaternary Deposits of the Nile Delta, Egypt

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ABSTRACT

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This study examines the clay-size fraction in radiocarbon-dated argillaceous core sections of Late Pleistocene (~ 30,000–15,000 years BP) and Holocene (~ 7500 years BP to the present) age in the north-central and northeastern Nile delta, Egypt. Proportions of smectite are higher, and of kaolinite and illite are lower, in the older stiff brown muds than in the soft grey Holocene facies. Moreover, Late Pleistocene deposits comprise lower proportions of interstratified illitic layers in smectite-illite clay minerals, and show somewhat higher crystallinity indices for smectite and kaolinite than in the Holocene sediments. Clay minerals in Late Pleistocene facies show a close affinity to those in Recent River Nile samples, indicating a fluvial origin: deposition probably occurred in periodically-flooded depressions bordering incised channels of the Nile on a subaerially-exposed plain. In contrast, Holocene muds contain clay minerals which are comparable to those in Recent marine deposits: they accumulated in settings affected by marine conditions as the sea encroached on the northern delta margin. Some of the detrital smectite was transformed into smectite-illite by fixation of potassium ions present in seawater during and/or shortly after deposition.

Much higher proportions of smectite, and lower concentrations of kaolinite and illite, are recorded in the northeastern than in the north-central delta region during both the Late Pleistocene and the Recent. This may indicate a preferential flow of Nile waters toward an area presently occupied by Lake Manzala. Clay mineral distribution patterns thus reflect, in part, the effects of concurrent subsidence and tilting of the northern delta plain to the northeast and eustatic rise in sealevel. These events altered the depositional settings of the study area during the Late Quaternary, i.e. from an alluvial plain to a deltaic complex of fluvial, coastal and shallow marine environments. Sediment transport, syn-depositional conditions and provenance were more important than post-depositional diagenetic effects in controlling both temporal and geographic clay mineral composition and distribution patterns.

ADDITIONAL INDEX WORDS: *Delta tilting, Egypt Shelf clays, Manzala lagoon, Nile River clays, provenance.*

INTRODUCTION

This study focuses on the distribution of clay minerals in time and space in the Late Quaternary deposits of the north-central and northeastern Nile delta, Egypt. It is a part of an extensive investigation of the Late Quaternary evolution of the Nile delta presently being conducted largely on the basis of petrological studies of a suite of sediment cores recovered across the northern delta between Alexandria in the west and the region east of Port Said (COUTELLIER and STANLEY, 1987; STANLEY, 1988b, 1990). Sixty-five cores, most of which have been radiocarbon-dated, recover almost continuous sediment sections, some which extend back to about 30,000 years before present (BP). The compositional, textural, faunal and floral attributes of these stratigraphic sections have recently been recorded (FRIHY and STANLEY, 1987, 1988; KULYK, 1987; STANLEY *et al.*, 1987; GERBER, 1989; GUPTA, 1989; PIMMEL and STANLEY, 1989; SHERGILL *et al.*, 1989). This petrologic data is supplemented by lithologic descriptions of older borings by ATTIA (1954) and of approximately 100 more recently compiled engineering foundation core logs.

The upper stratigraphic sections in the northern delta include fluviatile, brackish (marsh and lagoonal), coastal and marine facies of Holocene age. These facies consist largely of sands

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and soft, grey shelly silty muds as defined by COUTELLIER and STANLEY (1987). The Holocene sections range in thickness to over 50 m and form part of the Bilqas Formation (*cf.* ZAGHLOUL *et al.*, 1977; RIZZINI *et al.*, 1978; SAID, 1981).

The Holocene deposits lie above grey marine (transgressive) to fluviatile sands ranging in age from about 18,000 years to 10,000 years BP. Older sections below these uppermost Late Pleistocene sands were recovered in nearly half of the cores collected in the study area: these include tan to brown sands, commonly with one or several interbedded very stiff brown and yellowish-brown silty and sandy mud layers of variable thicknesses (from 10 cm to > 10 m). The latter muds have been dated from about 30,000 to 15,000 years BP. The Late Pleistocene grey and brown sands and interbedded brown muds originally described by COUTELLIER and STANLEY (1987), comprise the uppermost part of the Mit Ghamr Formation in the Nile delta (*cf.* ZAGHLOUL *et al.*, 1977; RIZZINI *et al.*, 1978; SAID, 1981).

The objectives of the study are three-fold: (1) to compare the clay mineral assemblages in both the Late Pleistocene stiff brown muds and the Holocene soft grey muds; (2) to identify any marked geographic mineralogical changes in the north-central and northeastern delta; and (3) to use this information to better understand the history of the delta. Eighteen cores (Figure 1) of the 46 borings recovered in the region between eastern Lake Burullus and the easternmost delta east of the Suez Canal were selected for this study.

In general, deltas are sites of continuously and rapidly changing depositional conditions which range from nonmarine to marine (COLEMAN, 1982; REINECK and SINGH, 1980), and the northern Nile delta is no exception (UNDP/UNESCO, 1976). Since clay minerals may be sensitive indicators of their depositional environment, deltaic sediments such as those of the Nile could be expected to show temporal and spatial variations in the nature and distribution of their clay mineral constituents. Three major factors influenced sedimentation in the Nile delta during the Late Quaternary that may be reflected in the clay mineralogy. The first, the marked paleoclimatic fluctuations which affected much of East Africa during this period (STREET and GROVE, 1976; WENDORF *et al.*, 1977; ADAMSON *et al.*, 1980; WILLIAMS and FAURE, 1980), are known to have influenced depositional sequences of Late Quaternary age in the northern delta (FOUCAULT and STANLEY, 1989) and on the shelf and Nile Cone seaward of the delta in the eastern Mediterranean (STANLEY and MALDONADO, 1977; SUMMERHAYES *et al.*, 1978; MALDONADO and STANLEY, 1979; ROSSIGNOL-STRICK *et al.*, 1982). The second factor, the major world-wide change of sealevel, occurred during this period. This fluctuation, in essence, comprised a near-complete eustatic cycle, *i.e.* from a high sea-level stand somewhat below the present one at about 35,000–30,000 years BP, to a lowering of nearly 125 m below m.s.l. between 20,000 and 17,000 years BP, to the present high stand (*cf.* CURRAY, 1965; MÖRNER, 1971). Sedimentological studies show that Holocene sequences began to accumulate in the northern delta about 7500 years BP, in large part as a function of this eustatic factor (COUTELLIER and STANLEY, 1987). The third factor that needs to be considered is the lowering of land relative to the sea as a result of isostatic and neotectonic processes and compaction (STANLEY, 1988b; 1990). Subsidence, with rates locally approximating 50 cm/century, has affected the delta most profoundly in the Lake Manzala region.

In view of the interplay among the three above-cited factors, one would expect to find difference in the distributions of clay minerals between the Late Plistocene and the Holocene mud-rich facies in the northern Nile delta study area. The paleoclimatic changes modified River Nile flow and induced differences in loads and perhaps composition of the sediments derived from the major source terranes (Ethiopian highlands, the Central African Plateau, and Eastern Desert-Red Sea province). Eustatic oscillations resulted in the drowning of the formerly subaerially-exposed topography of the northern delta region, and modulated the transgressive-erosional and progradational development of the delta during the mid- to late Holocene. The superposed effects of neotectonics also influenced sedimentation by accelerating the incursion of the sea onto the northern delta plain, which began during the Holocene and has continued to the present time (EL ASKARY and FRIHY, 1986; STANLEY, 1988b).

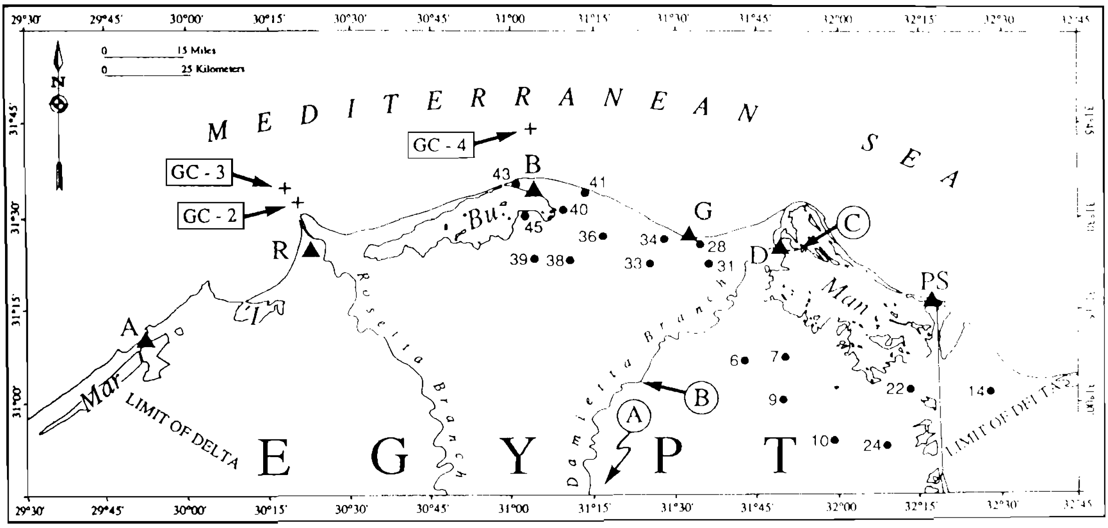

Figure 1. Map showing positions of the eighteen core sites in the north-central and northeastern Nile delta, Egypt, from which samples were selected for this study. Also depicted are locations of Recent River Nile samples (in circles: A, near Cairo; B, Mansoura; C, Damietta), and surficial offshore samples north of the delta, also of Recent age (in rectangles: GC-2 and GC-3 on the delta-front/inner shelf off the Rosetta promontory, 6 and 12 m depth, respectively; GC-4, on the mid-shelf north of Baltim, 36 m depth). A = Alexandria; B = Baltim; D – Damietta; G = Gamasa; PS = Port Said; and R – Rosetta. Northern delta lagoons, from east to west, are: Manzala (Man); Burullus (Bu); Idku (I); and Maryut (Mar).

These three controlling factors produced rapid changes in the depositional environments, from dominantly continental to marine settings, during the relatively short time period considered (COUTELLIER and STANLEY, 1987). It is thus of interest here to determine the extent of variations in the nature and distribution patterns of clay minerals in this area during this phase of Nile delta evolution.

METHODS

The present study involves X-ray diffraction analyses of a total of 100 core samples from eighteen borings drilled in the northeastern and north-central sections of the Nile delta. Seven of the sites lie east of the Damietta branch of the Nile, and eleven are located between this branch and Lake Burullus (Figure 1). The cores, which recovered almost continuous stratigraphic sections, were obtained during drilling surveys in 1985, 1987 and 1988 using a trailer-mounted Acker II combination rotary-percussion machine. The borings range in total length from about 10 to 50 m, and the core diameters range from 65 to 75 mm.

Detailed lithologic logs, including textural data, were prepared for the eighteen radiocarbon-dated borings (MEDIBA data base-Smithsonian Institution; also STANLEY, 1988b). Of the 100 core samples examined, 40 were selected from argillaceous Holocene sections (most from about 7000 to 2500 years BP) and 60 from mud-rich Late Pleistocene units (most ranging from about 30,000 to 20,000 years BP). Late Pleistocene units were sampled in all of the 18 borings examined; Holocene sediments were examined in the same cores except in S-10 and S-14 where these younger sections are absent. The fine-grained Holocene sediments selected for study usually comprise soft grey mixes of silt and clay and, in a few cases, sandy muds; shell or shell fragments of marine to lacustrine origin are present in this facies (Dr. M.P. Bernasconi, 1989, *personal communication*). In contrast, the Late Pleistocene muds are usually very hard brown silt-rich units which commonly include calcareous nodules and/or gypsum, root structures and only rare faunal and floral components (*cf.* COUTELLIER and STANLEY, 1987; FRIHY and STANLEY, 1988; Dr. H.R. Davis, 1989, *personal communication*).

Samples were air-dried and dispersed in a 0.03% Calgon® solution. The clay-size fraction (< 2 μm) was collected by decantation using the settling technique based on Stokes Law. X-ray diffraction patterns were obtained using a Philips Norelco X-ray diffractometer with a copper target and nickel filter at settings of 35kV and 15mA and at a scanning speed of 1° 2θ/minute. Further information on the specific methodology and instrumentation is provided in MALDONADO and STANLEY (1981) and STANLEY and LIYANAGE (1986).

Consideration was given to procedures of sample preparation which would be most appropriate for this specific study, *i.e.* those which could be applied consistently to all samples examined. As a test, two methods were initially used to prepare clay-coated glass slides for X-ray diffractometry so as to examine differences in peak enhancement. The first technique involved the smearing of slightly wet clay onto a glass slide. In the second technique a clay suspension was applied to the glass slide with an eye-dropper to accumulate oriented aggregates. The test involved comparison of diffractograms of the clay fraction from the same five Late Pleistocene and Holocene samples selected at random. The diffractograms of these samples prepared using the eye-dropper technique displayed enhanced peaks, whereas those obtained by using the smear technique displayed very shallow peaks which are more difficult to resolve (Figure 2). Thus, with the smear technique, accurate values of the d-spacings are not clearly defined and clay minerals present in low concentrations are frequently difficult to detect.

The marked peak enhancement on diffractograms using the pipette method has been attributed to the fact that smectite particles are relatively smaller than those of other clay minerals (BISCAYE, 1965) and thus tend to settle at a slower rate. In consequence, smectite flakes are preferentially concentrated toward the top of the clay-size suspension on the glass slide when using the eye-dropper method (*cf.* GIBBS, 1965; SIEGEL *et al.*, 1968; STOKKE and CARSON, 1973). Recognizing this artifact, but taking the needs of this study into consideration (*i.e.* accurate identification of all clay mineral constituents and a systematic semi-quantitative comparison of all samples from the two different stratigraphic sequences), we selected the pipetting technique. We found this method to be the best to reliably define peak positions and also peak heights and areas.

For each of the 100 core samples, three specimen were prepared for X-ray diffraction analyses: untreated, glycolated and heated at 600°C for one hour. Identification of the major clay mineral groups is based on the method described by CARROLL (1970), and characteristic d-spacings were taken from the listing prepared by CHAO (1969). Selected samples were treated with warm 6N HCl to determine the presence of chlorite.

Two methods were used to calculate the relative percentages of clay mineral species: by peak height (example in Figure 2) and by peak area. Clay mineral ratios were calculated using peak heights (Table 1). The crystallinity index for both smectite and kaolinite (Table 1) was determined for all samples by dividing the peak height by the peak area. Examination of grain morphology of the clay-size fraction in a few representative samples was made by Scanning Electron Microscopy.

Six-mud rich samples of Recent age collected from bottom sediments in the River Nile and at the top of short cores from off the Nile delta were examined for preliminary comparative purposes. The three Nile samples were collected just south of Cairo and at Mansoura and Damietta (Figure 1). The offshore cores were recovered during the R/V *Chain* cruise 119 (1975) of the Woods Hole Oceanographic Institution. Two of these cores (GC-2, GC-3) were obtained on the delta-front margin off the mouth of the Rosetta branch in water depths of 6 and 12 m, respectively, and the third (GC-4) on the mid-shelf (water depth of 36 m) north of Lake Burullus. The clay mineral data for these 6 samples (Table 3) were obtained using identical methods as for the 100 delta core samples.

CONTRASTING CLAY MINERALOGY IN LATE PLEISTOCENE AND HOLOCENE MUDS

The relative percentages of clay minerals in the study area are determined by both peak height and peak area measurements (data listed in Tables 1 and 2). Smectite, kaolinite and illite are present in order of decreasing abundance. In most samples, the smectite mineral group accounts for more than half of the clay mineral suite (Figure 3A). In the present

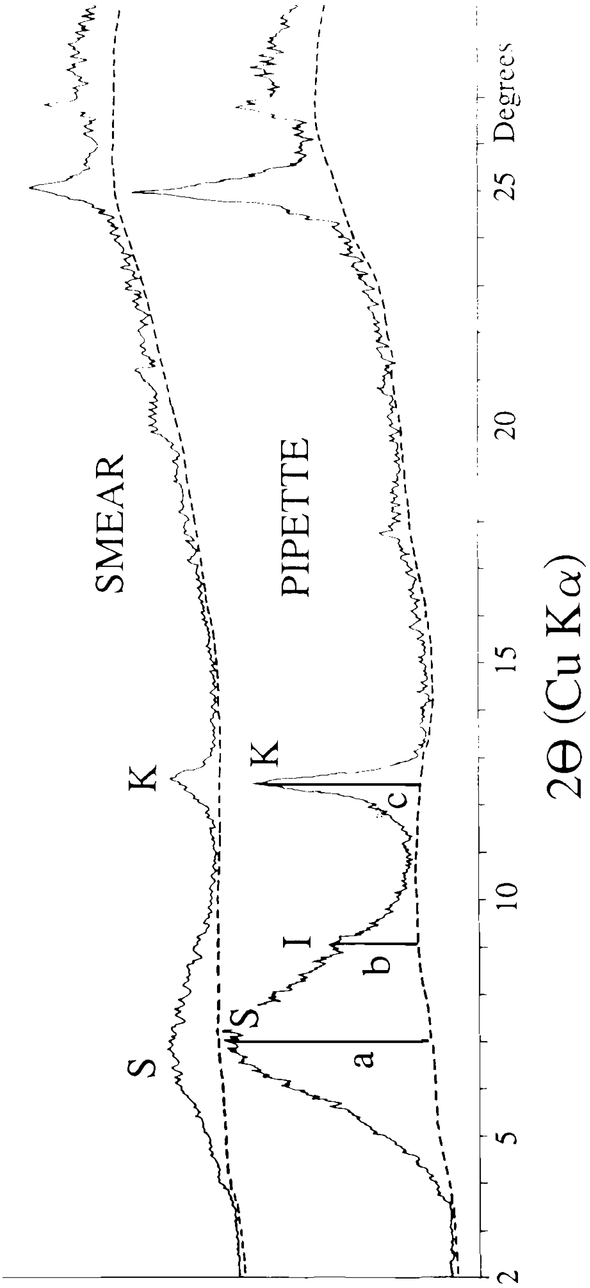

Figure 2. Two diffractograms of the same untreated Holocene sample (core S-40, sample 19) show differences in peak intensity when the smear and pipette methods are used. a, b, c = peak heights, of smectite (S), illite (I), and kaolinite (K), respectively.

study, the term smectite comprises montmorillonite plus randomly interstratified montmorillonite-illite mixed-layer clay minerals. Traces of chlorite were detected only in a few samples. This sequence of abundance of clay minerals characterizes both Late Pleistocene and Holocene deposits. It is of note that in 15 of the eighteen cores, Late Pleistocene clays contain rel-

Table 1. *Clay-mineral composition of Holocene and Late Pleistocene argillaceous sediments in the eastern and north-central Nile delta (explanation in text).*

Sample (MEDIBA Number)		Depth	Sample Texture (relative %)			Clay Mineral % (using peak height)			Clay Mineral % (using peak area)			Clay Ratios (using peak height)		Crystallinity Index	
Holocene	Pleistocene	(m)	Sand	Silt	Clay	S	K	I	S	K	I	K S	I S	S	K
Core S-6															
2		1.9	2.4	32.6	65.1	59	22	19	81	8	11	0.37	0.32	0.09	0.34
17		10.6	2.9	48.1	49.0	60	26	14	76	13	11	0.43	0.23	0.12	0.30
28		15.5	1.7	49.0	49.3	59	26	15	85	11	4	0.44	0.25	0.14	0.47
	14	20.7	11.8	41.2	47.0	89	11	n.d.	96	4	n.d.	0.12	n.d.	0.11	0.39
	22	21.6	19.8	49.3	30.9	79	15	6	90	7	3	0.19	0.08	0.16	0.41
	23	22.5	27.1	47.7	25.2	84	16	n.d.	93	7	n.d.	0.19	n.d.	0.14	0.38
	24	24.5	9.0	36.2	54.9	82	18	n.d.	92	8	n.d.	0.22	n.d.	0.14	0.22
Core S-7															
3		1.8	0.5	21.6	77.9	61	21	18	76	12	12	0.34	0.29	0.12	0.27
19		7.9	17.0	43.7	39.3	62	27	11	85	12	3	0.44	0.18	0.13	0.41
	24	15.5	0.4	2.7	96.8	76	24	n.d.	89	11	n.d.	0.32	n.d.	0.12	0.32
	26	16.0	2.9	31.7	65.4	60	40	n.d.	78	22	n.d.	0.67	n.d.	0.13	0.33
	27	16.8	7.0	37.7	55.3	62	24	14	80	13	7	0.39	0.23	0.13	0.32
	28	18.0	0.7	46.4	52.9	78	22	n.d.	90	10	n.d.	0.28	n.d.	0.16	0.39
	30	19.0	2.1	50.5	47.4	71	29	n.d.	88	12	n.d.	0.41	n.d.	0.16	0.50
Core S-9															
3		1.8	2.4	21.1	76.5	70	17	13	85	9	6	0.24	0.19	0.11	0.27
7		4.1	1.2	24.0	74.8	68	18	14	84	11	5	0.26	0.21	0.14	0.33
	15	12.2	8.6	1.6	89.8	61	39	n.d.	76	24	n.d.	0.64	n.d.	0.14	0.28
Core S-10															
—		—	—	—	—	—	—	—	—	—	—	—	—	—	—
	6	7.5	7.3	35.3	57.4	87	13	n.d.	94	6	n.d.	0.15	n.d.	0.15	0.32
	7	7.8	20.2	40.4	39.4	89	11	n.d.	96	4	n.d.	0.12	n.d.	0.16	0.42
	8	8.4	53.3	19.8	26.9	88	12	n.d.	94	6	n.d.	0.14	n.d.	0.15	0.32
Core S-14															
—		—	—	—	—	—	—	—	—	—	—	—	—	—	—
	6	6.2	19.4	46.1	34.5	73	18	9	88	8	4	0.25	0.12	0.14	0.38
	9	7.5	32.5	42.2	25.3	75	15	10	87	9	4	0.20	0.13	0.19	0.34
	11	8.5	1.6	32.6	65.8	64	25	11	81	13	6	0.39	0.17	0.12	0.28
	13	10.5	10.5	17.4	72.1	61	26	13	80	14	6	0.43	0.21	0.12	0.30
	15	12.8	6.9	26.1	67.1	68	21	11	80	11	9	0.31	0.16	0.13	0.31
Core S-22															
10		5.9	0.5	74.7	24.8	78	22	n.d.	93	7	n.d.	0.28	n.d.	0.15	0.57
18		14.0	1.4	34.7	63.9	75	25	n.d.	87	13	n.d.	0.33	n.d.	0.13	0.29
22		20.5	0.2	27.6	72.2	70	30	n.d.	89	11	n.d.	0.43	n.d.	0.14	0.47
	36	31.2	33.9	45.2	20.9	78	22	n.d.	92	8	n.d.	0.28	n.d.	0.12	0.42
	39	36.9	9.0	27.2	63.7	68	20	12	82	11	7	0.29	0.18	0.12	0.26
	40	37.1	2.7	5.9	91.4	80	20	n.d.	91	9	n.d.	0.25	n.d.	0.12	0.31

Core S-24															
9		0.4	12.9	40.8	46.3	67	19	14	87	7	6	0.28	0.21	0.11	0.32
10		0.8	47.8	13.4	38.8	62	22	16	85	8	7	0.35	0.26	0.09	0.35
	11	7.9	0.6	42.2	57.2	78	13	9	90	8	2	0.17	0.12	0.13	0.25
	12	8.9	0.4	22.0	77.6	72	19	9	84	12	4	0.26	0.12	0.13	0.14
	13	10.3	3.8	34.4	61.8	76	16	8	87	10	3	0.21	0.11	0.14	0.25
Core S-28															
14		18.1	1.8	34.3	63.9	57	27	16	82	14	4	0.47	0.28	0.11	0.30
19		23.6	8.5	32.6	58.9	61	24	15	83	12	5	0.39	0.25	0.12	0.32
	24	28.0	1.0	45.3	53.7	66	23	11	86	11	3	0.35	0.17	0.10	0.29
	25	28.4	12.4	30.5	57.1	82	11	7	92	5	3	0.13	0.09	0.11	0.30
Core S-31															
12		9.5	5.8	44.9	49.3	63	22	15	82	12	6	0.35	0.24	0.12	0.30
25		21.0	1.5	29.3	69.2	48	33	19	73	21	6	0.69	0.40	0.12	0.29
31		25.9	0.4	21.1	78.5	50	32	18	75	17	8	0.64	0.36	0.12	0.32
	36	28.2	0.3	29.5	70.2	68	22	10	84	11	5	0.32	0.15	0.12	0.28
	37	28.8	0.1	21.5	78.5	74	17	9	83	12	5	0.23	0.12	0.15	0.26
	38	29.0	76.3	8.3	15.5	69	17	14	90	5	5	0.25	0.20	0.08	0.35
Core S-33															
2		2.3	8.7	22.3	69.0	39	36	25	60	20	20	0.92	0.64	0.10	0.29
5		5.8	1.0	30.6	68.5	48	30	22	71	14	15	0.62	0.46	0.10	0.30
13		11.7	26.0	53.9	20.1	43	42	15	67	23	10	0.98	0.35	0.12	0.32
	15	20.2	9.6	11.9	78.5	59	31	10	67	26	7	0.53	0.17	0.14	0.23
	17	21.1	0.4	2.4	97.2	52	38	10	75	17	8	0.73	0.19	0.10	0.31
	20	22.8	0.1	9.8	90.2	49	41	10	72	21	7	0.84	0.20	0.12	0.33
Core S-34															
2		10.4	1.9	46.1	52.0	52	34	14	73	15	12	0.65	0.27	0.10	0.33
5		13.1	2.4	65.3	32.3	51	32	17	74	16	10	0.63	0.33	0.09	0.27
	6	22.7	33.2	23.7	43.0	32	48	20	60	22	18	1.50	0.62	0.09	0.40
	7	23.6	10.7	8.9	80.4	44	39	17	74	16	10	0.89	0.39	0.09	0.37
	9	25.2	14.4	13.3	72.3	47	40	13	78	14	8	0.85	0.28	0.08	0.40
Core S-36															
2		1.8	43.7	19.8	36.6	46	33	21	66	19	15	0.72	0.46	0.12	0.29
3		12.3	0.6	39.7	59.8	51	34	15	75	13	12	0.67	0.29	0.09	0.36
5		14.1	0.8	43.7	55.5	49	36	15	66	20	14	0.73	0.31	0.12	0.26
	7	25.2	0.7	2.8	96.4	54	36	10	77	15	8	0.67	0.19	0.11	0.36
	9	34.7	15.7	20.7	63.6	57	28	15	79	12	9	0.49	0.26	0.11	0.36
	10	35.3	3.3	21.3	75.4	61	24	15	78	13	9	0.39	0.25	0.11	0.27
	11	36.5	16.3	25.9	57.8	58	30	12	74	16	10	0.52	0.21	0.13	0.33
Core S-38															
3		4.6	7.0	21.3	71.7	50	29	21	72	14	14	0.58	0.42	0.09	0.28
7		7.9	0.7	48.0	51.3	64	20	16	82	9	9	0.31	0.25	0.10	0.31
39		11.9	1.6	47.2	51.3	39	44	17	63	28	9	1.13	0.44	0.10	0.26
	15	18.6	10.1	30.6	59.3	53	36	11	81	13	6	0.68	0.21	0.11	0.45
	16	19.5	1.8	32.9	65.3	63	27	10	80	15	5	0.43	0.16	0.13	0.30
	18	21.5	1.0	33.5	65.5	67	24	9	84	11	5	0.36	0.13	0.13	0.38

	42	22.0	0.2	2.9	97.0	51	37	12	73	19	8	0.73	0.24	0.11	0.30
	19	23.0	9.6	15.8	74.6	55	34	11	77	16	7	0.62	0.20	0.11	0.31
	24	29.9	12.0	49.1	38.9	64	25	11	84	11	5	0.39	0.17	0.13	0.38
	43	31.1	10.4	46.4	43.3	64	22	14	82	12	6	0.34	0.22	0.14	0.33
Core S-39															
15		0.8	1.9	29.2	68.8	35	38	27	58	21	21	1.09	0.77	0.10	0.29
16		2.1	13.3	50.8	35.9	64	21	15	82	12	6	0.33	0.23	0.15	0.33
	17	14.0	0.2	7.8	92.0	62	29	9	81	14	5	0.47	0.15	0.11	0.33
	11	14.3	4.4	16.1	79.5	58	31	11	77	16	7	0.53	0.19	0.14	0.35
Core S-40															
1		3.1	49.9	11.4	38.7	36	32	32	65	14	21	0.89	0.89	0.10	0.38
19		14.8	4.0	48.0	48.0	46	34	20	72	16	12	0.74	0.43	0.11	0.38
	17	27.8	9.3	25.0	65.8	54	29	17	82	12	6	0.54	0.31	0.12	0.44
Core S-41															
45		8.7	4.5	37.8	57.7	38	40	22	62	24	14	1.05	0.58	0.09	0.25
46		14.3	21.5	34.9	43.6	44	37	19	68	20	12	0.84	0.43	0.10	0.27
47		19.1	19.0	45.8	35.2	45	37	18	69	18	13	0.82	0.40	0.10	0.31
	48	24.2	2.4	29.0	68.7	54	30	16	74	14	12	0.56	0.30	0.12	0.34
	23	25.0	9.3	46.3	44.5	53	32	15	75	16	9	0.60	0.28	0.13	0.36
	25	26.4	21.5	34.6	44.0	58	28	14	78	13	9	0.48	0.24	0.12	0.39
Core S-43															
4		7.0	7.6	27.8	64.6	64	22	14	83	9	8	0.34	0.22	0.11	0.32
37		13.1	1.4	36.1	62.5	49	35	16	73	17	10	0.71	0.33	0.10	0.30
	14	18.6	19.0	21.0	60.1	44	34	22	70	12	18	0.77	0.50	0.09	0.43
	20	24.4	26.0	24.8	49.2	49	33	18	73	16	11	0.67	0.37	0.11	0.35
Core S-45															
2		6.6	0.5	59.8	39.7	44	38	18	72	23	5	0.86	0.41	0.14	0.38
3		8.2	1.8	48.9	49.3	54	31	15	77	17	6	0.57	0.28	0.11	0.29
4		12.0	2.4	48.6	48.9	46	37	17	71	19	10	0.80	0.37	0.11	0.31
	5	18.6	19.0	41.8	39.2	30	41	29	58	18	24	1.37	0.97	0.09	0.40
	8	20.2	1.9	53.6	44.5	59	30	11	80	14	6	0.51	0.19	0.13	0.37
	9	21.4	0.4	19.4	80.2	44	45	11	71	22	7	1.02	0.25	0.12	0.38
	10	22.1	0.1	14.2	85.7	56	33	11	76	16	8	0.59	0.20	0.11	0.33
	11	23.1	1.2	8.0	90.8	48	41	11	71	20	9	0.85	0.23	0.12	0.35
	12	24.1	1.2	6.6	92.2	51	39	10	76	19	5	0.76	0.20	0.11	0.34

S = smectite K = kaolinite I = illite
n.d. = not detected — = no sample

Table 2. *Averaged clay-mineral composition of Holocene and Late Pleistocene argillaceous sediments in the eastern and north-central Nile delta (based on data from Table 1).*

Core	Stratigraphic Horizon	Number of Samples	Clay Mineral (%) (using peak height)			Clay Mineral (%) (using peak area)			Clay Ratios (using peak height)		Crystallinity Index	
			S	K	I	S	K	I	K/S	I/S	S	K
S-6	Holocene	3	59	25	16	80	11	9	0.42	0.27	0.12	0.37
	Pleistocene	4	84	15	1	93	6	1	0.18	0.01	0.14	0.35
S-7	Holocene	2	61	24	15	80	12	8	0.39	0.25	0.12	0.34
	Pleistocene	5	70	27	3	85	14	1	0.39	0.04	0.14	0.37
S-9	Holocene	2	69	17	14	84	10	6	0.25	0.20	0.12	0.30
	Pleistocene	1	61	39	n.d.	76	24	n.d.	0.64	n.d.	0.14	0.28
S-10	Holocene	—	—	—	—	—	—	—	—	—	—	—
	Pleistocene	3	88	12	n.d.	95	5	n.d.	0.14	n.d.	0.15	0.35
S-14	Holocene	—	—	—	—	—	—	—	—	—	—	—
	Pleistocene	5	68	21	11	83	11	6	0.31	0.16	0.14	0.32
S-22	Holocene	3	74	26	n.d.	90	10	n.d.	0.35	n.d.	0.14	0.44
	Pleistocene	3	75	21	4	89	9	2	0.28	0.05	0.12	0.33
S-24	Holocene	2	64	21	15	86	7	7	0.33	0.23	0.10	0.33
	Pleistocene	3	75	16	9	87	10	3	0.21	0.12	0.13	0.21
S-28	Holocene	2	59	25	16	82	13	5	0.42	0.27	0.11	0.31
	Pleistocene	2	74	17	9	89	8	3	0.23	0.12	0.11	0.30
S-31	Holocene	3	54	29	17	76	17	7	0.54	0.31	0.12	0.30
	Pleistocene	3	70	19	11	86	9	5	0.27	0.16	0.12	0.30
S-33	Holocene	3	43	36	21	66	19	15	0.84	0.49	0.11	0.30
	Pleistocene	3	53	37	10	71	22	7	0.70	0.19	0.12	0.29
S-34	Holocene	2	51	33	16	73	16	11	0.65	0.31	0.09	0.30
	Pleistocene	3	41	42	17	71	17	12	1.02	0.41	0.09	0.39
S-36	Holocene	3	49	34	17	69	17	14	0.69	0.35	0.11	0.30
	Pleistocene	4	58	29	13	77	14	9	0.50	0.22	0.11	0.33
S-38	Holocene	3	51	31	18	72	17	11	0.61	0.22	0.10	0.28
	Pleistocene	7	60	29	11	80	14	6	0.48	0.18	0.12	0.35
S-39	Holocene	2	49	30	21	70	17	13	0.61	0.43	0.12	0.31
	Pleistocene	2	60	30	10	79	15	6	0.50	0.17	0.12	0.34
S-40	Holocene	2	41	33	26	68	15	17	0.80	0.63	0.11	0.38
	Pleistocene	1	54	29	17	82	12	6	0.54	0.31	0.12	0.44
S-41	Holocene	3	42	38	20	66	21	13	0.90	0.48	0.10	0.28
	Pleistocene	3	55	30	15	76	14	10	0.54	0.27	0.12	0.36
S-43	Holocene	2	56	29	15	78	13	9	0.52	0.27	0.10	0.31
	Pleistocene	2	47	33	20	71	14	15	0.70	0.43	0.10	0.39
S-45	Holocene	3	48	35	17	73	20	7	0.73	0.35	0.12	0.33
	Pleistocene	6	48	38	14	72	18	10	0.79	0.29	0.11	0.36

S = smectite K = kaolinite I = illite n.d. = not detected — = no samples

atively greater proportions of smectite and lower amounts of kaolinite and illite than in the Holocene clays. Exceptions to this were noted in cores S-9, S-34 and S-43. Moreover, smectite in the Late Pleistocene samples tends to display moderately sharp diffraction peaks on the patterns of untreated specimen with d-spacings within the 14–15Å range. Upon glycolation, these peaks shift to d-spacings at about 17Å. This indicates that this group of clay minerals contains relatively low proportions of interstratified illitic layers in smectite-illite mixed-layer clay minerals. The smectite in Holocene samples, in contrast, has markedly higher relative proportions of illitic layers as indicated by the lower d-spacing values (12.5 to 14.5Å) displayed by the peaks on the diffractograms of untreated specimen which shift to about 15.5 to 16.5Å upon glycolation.

With respect to Late Pleistocene samples, the average relative percentages calculated using the peak height measurements are as follows: smectite = 63%; kaolinite = 27%; and illite = 10%. The following average values are obtained when peak areas are used: smectite = 81%; kaolinite = 13%; and illite = 6% (Table 3). In the case of Holocene samples, the peak height measurements provide the following average

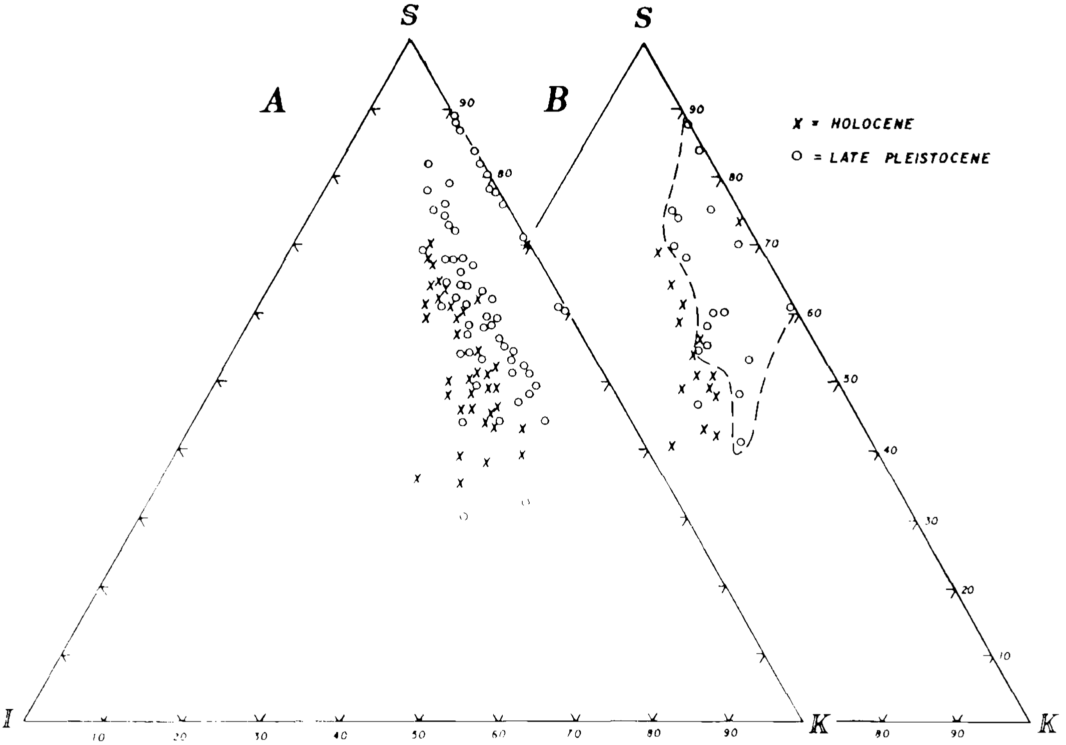

Figure 3. Ternary diagrams on which are plotted the relative proportions of dominant clay minerals (S = smectite; K = kaolinite; I = illite) for Late Pleistocene and Holocene Nile delta core samples. A, plotted data for all 100 core samples (see Table 1). B, plotted averaged data for the 18 cores (see Table 2). The two facies occupy different fields, with Late Pleistocene samples (field within dashed line) characterized by higher proportions of smectite and lower relative percentages of illite.

values: smectite = 54%; kaolinite = 30%; and illite = 18%. When the peak area method is used, the following average relative proportions of clay minerals are determined: smectite = 76%; kaolinite = 15%; and illite = 9% (Table 3).

It is recognized that all methods used for the determination of the relative percentages of clay minerals have some limitations (PIERCE and SIEGEL, 1969). In this study, the use of peak area measurements for determination of relative percentages of clay minerals generally results in abnormallyhigh values of smectite and much lower values of kaolinite and illite (see Tables 1 and 2, and the above-cited averaged data). As a consequence, we view values obtained using peak heights as somewhat more useful, particularly with regards to calculating mineral ratios.

Graphically plotted data serve to clearly distinguish the clay mineralogy of the two stratigraphic horizons. The plots on ternary diagrams of the relative percentages of clay minerals for all core samples (Figure 3A) and those of the averaged data for Late Pleistocene and Holocene samples in the eighteen cores (Figure 3B) appear to occupy fairly distinct fields. The averaged values for all 60 Late Pleistocene and 40 Holocene samples indicate that Late Pleistocene deposits comprise about 9% more smectite, and about 8% less illite than in Holocene units. These differences are statistically different as substantiated by student-T test. The proportions of kaolinite in both stratigraphic horizons, however, are not statistically different (Table 3).

With regards to clay mineral ratios, Late Pleistocene deposits are characterized by lower

Table 3. *Clay-mineral composition of Recent River Nile and Nile delta shelf samples compared with averaged values for Holocene and Late Pleistocene Nile delta core samples.*

Sediment Sampled	Clay Minerals (%) (using peak height)			Clay Minerals (%) (using peak area)			Clay Ratios (using peak height)		Crystallinity Index	
	S	K	I	S	K	I	K/S	I/S	S	K
River Nile										
South Cairo	77	13	10	92	5	3	0.17	0.13	0.14	0.44
Mansoura	68	19	13	90	7	3	0.28	0.19	0.14	0.37
Damietta	67	18	15	84	11	5	0.27	0.22	0.13	0.29
Average	**71**	**17**	**13**	**89**	**8**	**4**	**0.24**	**0.18**	**0.14**	**0.37**
Offshore										
GC-2	63	22	15	82	13	5	0.35	0.24	0.13	0.27
GC-3	67	20	13	83	12	5	0.30	0.19	0.12	0.26
GC-4	47	38	15	77	17	6	0.81	0.32	0.12	0.35
Average	**59**	**27**	**14**	**81**	**14**	**5**	**0.49**	**0.25**	**0.12**	**0.29**
Delta Cores (Averages)										
Holocene	54	30	18	76	15	9	0.57	0.32	0.11	0.32
U. Pleistocene	63	27	10	81	13	6	0.47	0.17	0.12	0.34

S = smectite K = kaolinite I = illite

K/S and I/S ratios (0.47 and 0.17, respectively) as compared to those calculated for Holocene sediments (K/S = 0.57; I/S = 0.32).

The crystallinity indices (C.I.) for both smectite and kaolinite are only slightly higher in Late Pleistocene than in Holocene facies. Average C.I. value for smectite is 0.12 and for kaolinite is 0.34 in Late Pleistocene samples, and 0.11 for smectite and 0.32 for kaolinite in Holocene mud-rich deposits. The slightly higher average C.I. values for the Late Pleistocene samples do not differ significantly.

Scanning Electron photomicrographs reveal that clay particles in the Late Pleistocene muds display a distinct crenulated and sharp-edged morphology (Figure 4A). In contrast, the clay platelets in Holocene deposits are generally more massive and rounded (Figure 4B), and many particles are oriented parallel to each other.

GEOGRAPHIC DISTRIBUTION OF CLAY MINERALS

When the mineral data are plotted on a geographic basis, clay mineral distributions in both Late Pleistocene and Holocene deposits show some distinct regional trends. The average values of the clay minerals listed in Table 2 indicate the following:

(1) Late Pleistocene muds show higher relative percentages of smectite (average = 74%; range of 61 to 88%) east of Gamasa. To the west, values are much lower (average = 53%; range of 41 to 60%). A similar distribution pattern of smectite characterizes Holocene deposits: higher percentages (average = 63%; range of 59 to 74%) east of Gamasa, and lower proportions (average = 48%; range of 41 to 56%) to the west. This east-to-west regional variation, however, is more pronounced in the case of Late Pleistocene sediments.

(2) Late Pleistocene sediments comprise higher relative percentages of kaolinite (average = 33%; range of 29 to 42%) west of Gamasa. Somewhat lower values (average = 21%; range of 12 to 39%) occur to the east. One site south of Lake Manzala (core S-9) displays an unusually high value (39%). With respect to Holocene deposits, values are also higher west of Gamasa (average = 33%; range of 29 to 38%) than to the east (average = 24%; range of 17 to 29%). This east-to-west regional kaolinite trend is somewhat more pronounced in the Late Pleistocene muds.

(3) Late Pleistocene deposits comprise markedly higher relative proportions of illite west of Damietta (average = 13%; range of 9 to 20%), than to the east (average = 4%; range of trace to 11%). In contrast, Holocene units do not

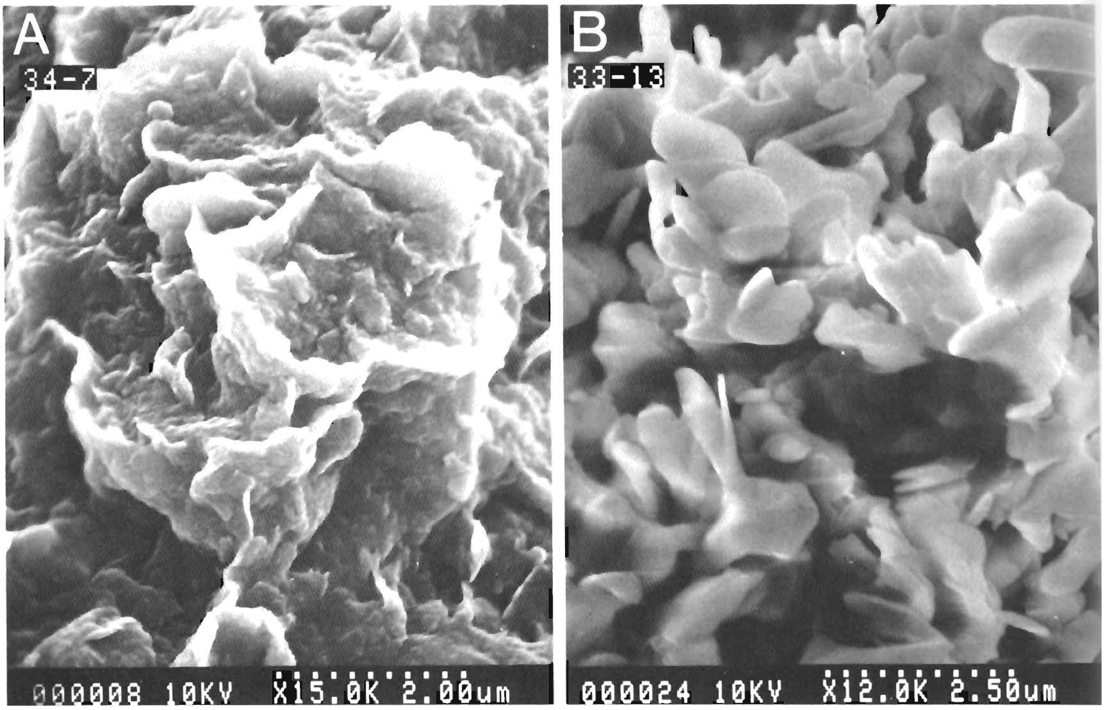

Figure 4. SEM photomicrographs of clay minerals from a typical stiff brown mud sample of Late Pleistocene age (A, core S-34, sample 7, in Table 1), and from a soft grey mud sample of Holocene age (B, core S-33, sample 13, in Table 1). The former are characterized by a sharp-edged and crenulated morphology, and the latter by rounded, massive platelets. The size scale (dotted line) in A is 2.0μm and in B is 2.5μm.

reveal a distinct regional trend, although somewhat higher values are noted in the area east of Lake Burullus.

(4) Late Pleistocene sediments display much higher K/S ratios west of Gamasa (average = 0.64; range of 0.48 to 1.02) than to the east (average = 0.29; range of 0.14 to 0.64, with the latter abnormally high value at core site S-9). Holocene deposits are also characterized by much higher K/S ratios west of Gamasa (average = 0.71; range of 0.52 to 0.90) than to the east (average = 0.39; range of 0.25 to 0.42). These trends are shown in Figure 5.

(5) Late Pleistocene deposits are characterized by much higher I/S values west of Damietta (average = 0.25; range of 0.12 to 0.43) than to the east (average = 0.05; range of trace to 0.16). In contrast, there are no distinct regional trends displayed by I/S values (range of 0 to 0.63) for Holocene sections. This latter high value is noted east of Lake Burullus. These regional patterns are depicted in Figure 6.

RECENT RIVER NILE AND DELTA SHELF CLAY MINERALOGY

The data obtained for the Nile and offshore show that both groups contain smectite, kaolinite and illite in order of decreased abundance. However, the smectite mineral group in the River Nile sediments comprises relatively lower proportions of interstratified illitic layers than those in offshore samples. In the Nile samples, the proportions of smectite decrease from Cairo in the south towards the northern delta, while proportions of kaolinite and illite increase in the same direction. These trends are recorded by a northward increase in both K/S and I/S ratios.

Offshore samples, on the other hand, show a

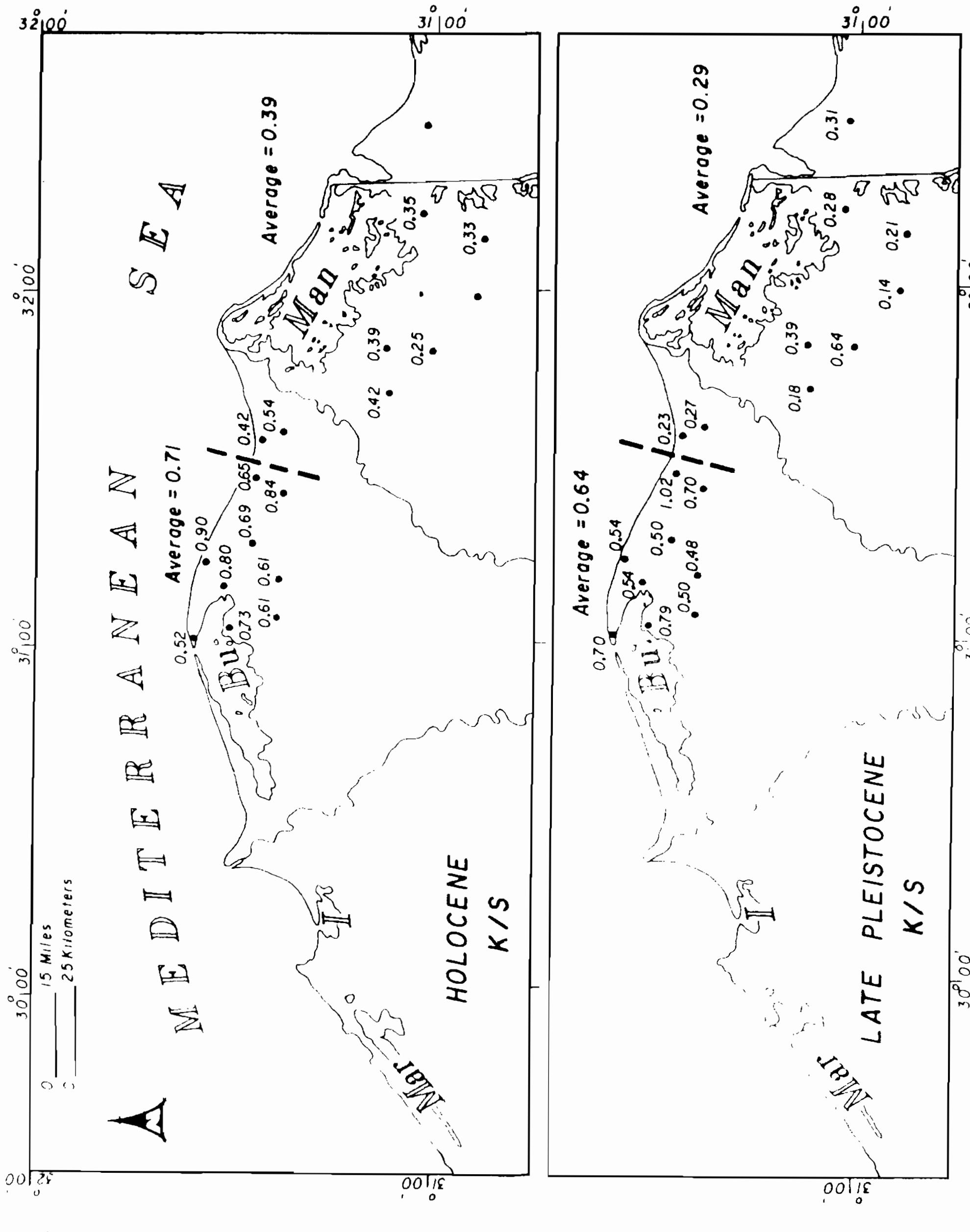

Figure 5. Averaged K/S (kaolinite/smectite) values for Late Pleistocene and Holocene samples are plotted at each of the examined core sites (see Table 2). These values are higher in the north-central area for both time periods, as noted by comparing the calculated averages for all samples west and east of Gamasa (dashed line).

marked decrease in proportions of smectite and an increase inthose of kaolinite from the delta-front/inner shelf sector (GC-2, GC-3) toward the mid-shelf (GC-4). Illite proportions remain constant. These variations are recorded by a notable increase in the K/S and I/S ratios in a sea-

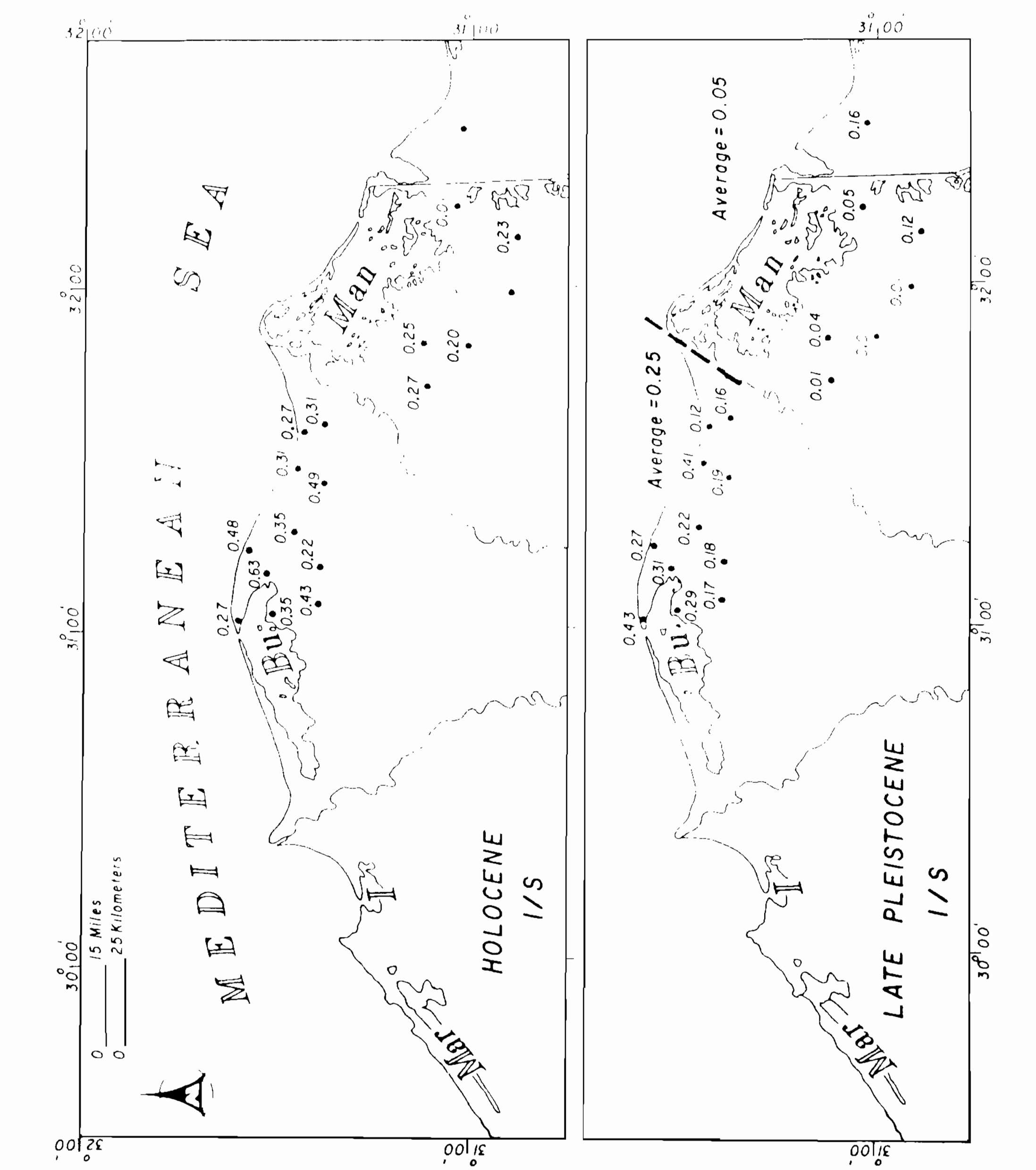

Figure 6. Averaged I/S (illite/smectite) values for Late Pleistocene and Holocene samples are plotted at each of the examined core sites (see Table 2). Values for the Late Pleistocene facies are higher in the north-central area as noted by comparing the calculated averages for samples west and east of Damietta (dashed line). In contrast, I/S values for Holocene samples do not reveal marked geographic trends.

ward direction between the inner and middle shelf.

Comparison between the above fluviatile and marine samples reveals that the River Nile deposits contain higher relative proportions of smectite (average = 71%; range of 67 to 77%)

than offshore sediments (average = 59%; range of 47 to 67%). The kaolinite content in Nile samples (average = 17%; range of 13 to 19%) is lower than in offshore sediments (average = 27%; range of 20 to 38%). The K/S and I/S average values for the Nile samples (0.24 and 0.18, respectively) are notably lower than those recorded for the offshore sites (0.49 and 0.25, respectively). It is noted that the most significant changes occur not between land and sea, but (a) within the River Nile south of Cairo, and (b) along the seafloor north of the inner shelf (Table 3).

Crystallinity indices for smectite are only slightly higher in fluviatile (average = 0.14) than in offshore samples (average = 0.12). The C.I. values for kaolinite in the six samples reveal a progressive decrease from Cairo northward to the inner shelf (0.44 to 0.26), and then a substantial increase from the inner shelf (0.26 at GC-3) to the middle shelf (0.35 at GC-4).

DISCUSSION

The observed differences in the proportions of dominant clay minerals in time and space in the northeastern and north-central Nile delta help shed light on the evolving paleogeographic conditions which affected this region during the Late Quaternary. At least from about 30,000 years ago to the present, the River Nile system provided the bulk of clay minerals, as recorded by the types and order of abundance of the major clay minerals. Generally comparable assemblages have been found in every study of the River Nile system, *i.e.* in the White and Blue Nile Tributaries and the Main Nile between Upper Egypt and Cairo (EL-ATTAR and JACKSON, 1973; FARKHONDA *et al.*, 1979), in the delta (ELGABALY and KHADR, 1962; BUTZER and HANSEN, 1968; FAYED and HASSAN, 1970; WEIR *et al.*, 1975; STANLEY and LIYANAGE, 1986), and in the offshore area north of the delta (VENKATARATHNAM and RYAN, 1971; NIR and NATHAN, 1972; MALDONADO and STANLEY, 1981). This Nile assemblage is also reported in some deltaic stratigraphic sections of older Pleistocene and Pliocene age (GHEITH and EL SHERBINI, 1986).

Of particular note in the study area are the higher proportions of smectite and lower concentrations of kaolinite and illite in the Late Pleistocene muds relative to those in Holocene deposits (Table 3; Figure 7). This difference was noted independently in a study of delta cores S-6 and S-7 by GERBER (1989). Also recorded are relatively lower proportions of interstratified illitic layers in the smectite-illite clays, and slightly higher crystallinity indices for both smectite and kaolinite in Late Pleistocene deposits. It appears that the clay mineralogy of these Late Pleistocene facies is more closely similar to River Nile muds of Recent age, while that of Holocene sediments more closely resembles samples of Recent age collected in and around the lagoons of the northern Nile delta (STANLEY and LIYANAGE, 1986) and offshore north of the delta (MALDONADO and STANLEY, 1981; Table 3 and Figure 7).

These observations strongly suggest that the stiff brown muds of Late Pleistocene age are primarily of River Nile derivation and that this facies most likely accumulated in a fluviatile/terrestrial setting rather than in an environment influenced by the sea. It is of note that Late Pleistocene deposits of nearly comparable age in the Kom Ombo region of Upper Egypt also show higher proportions of smectite than in some Recent River Nile and surficial northern delta sections (EL-ATTAR and JACKSON, 1973). This non-marine setting for the brown muds indicated by their clay mineralogy is confirmed by a series of petrological analyses made independently. These include sedimentary structures (such as the traces of plant roots) and associated calcareous nodules and gypsum (COUTELLIER and STANLEY, 1987) and specific assemblages of mineralogical and biogenic components (FRIHY and STANLEY, 1988; faunal and floral studies in preparation).

During the time of brown mud deposition, the Nile delta coast was located considerably further (about 50 km) to the north; during the maximum eustatic sealevel low-stand at about 20,000 to 17,000 years BP the coast was positioned near the outer shelf/continental slope break (SUMMERHAYES *et al.*, 1978; MALDONADO and STANLEY, 1979). Regional studies of East African paleoclimates (STREET and GROVE, 1976; ADAMSON *et al.*, 1980; WILLIAMS and FAURE, 1980) and of sedimentation in Upper Egypt indicate that between about 28,000 and 17,000 years BP, River Nile water is believed to have frequently overflowed its channel banks (SAID, 1981). This was fol-

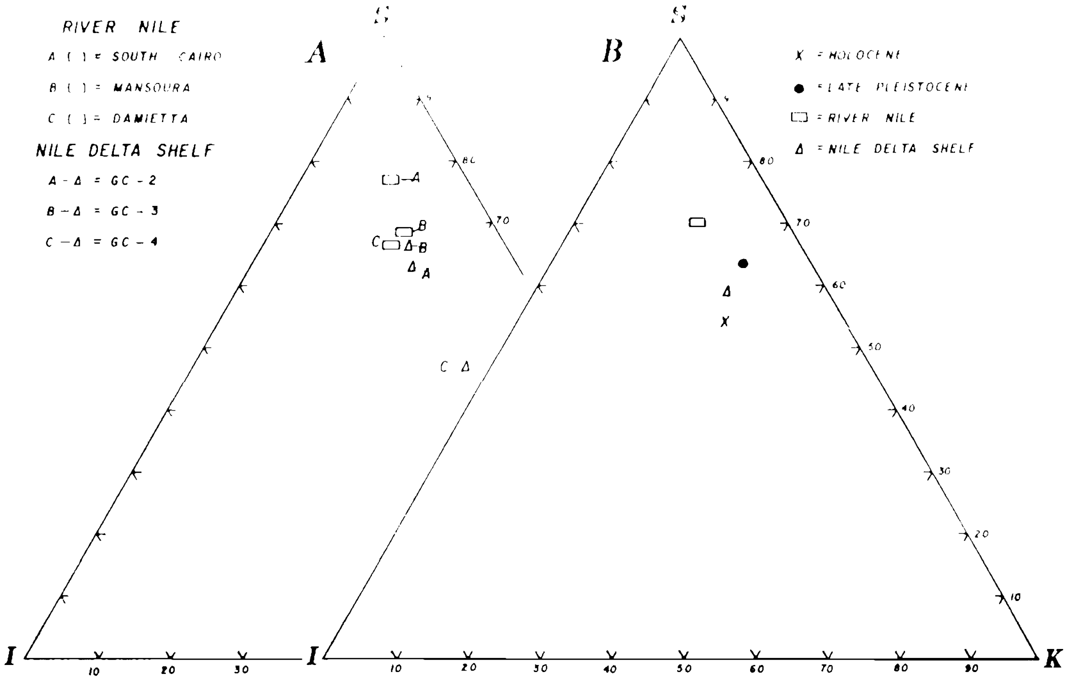

Figure 7. A, ternary diagram depicting relative proportions of smectite (S), kaolinite (K) and illite (I) for the clay mineral fraction in Recent River Nile and Nile delta shelf samples (data in Table 3; positions shown in Figure 1). B, ternary diagram on which are plotted the averaged percentages of major clay minerals for all Late Pleistocene and Holocene core samples, and for all River Nile and delta shelf samples (data in Table 3). Late Pleistocene core and River Nile samples show relatively higher proportions of smectite, while Holocene core and delta shelf samples are characterized by somewhat higher relative percentages of kaolinite and illite.

lowed by a drier period, and then by a more moist phase from about 12,000 years BP to 5000–4000 years BP.

There is surprisingly little information on the nature and proportions of clay minerals presently carried by the major river sources feeding the Nile system. It is suggested that the White Nile transports somewhat higher relative proportions of kaolinite than the Blue Nile (EL-ATTAR and JACKSON, 1973). It also should be recalled that during humid phases numerous now-dry wadis drained the Eastern Desert-Red Sea terranes to the east and flowed to the Main Nile. The relative importance of their sediment load contribution to deposits such as the stiff brown muds in the Late Quaternary as yet remains undefined.

Available information indicates that the Late Pleistocene brown muds probably accumulated in settings such as periodically-flooded depressions bordering more incised Nile channels (*cf.* BUTZER, 1976), when sea-level was substantially lower than at present (MÖRNER, 1971) and when the northern delta study area was subaerially exposed. This setting favored oxidizing conditions and the formation and preservation of the brown to yellowish brown coloration of this facies. Moreover, it is likely that repeated flooding and subaerial exposure was partly responsible for the marked consolidation of these muds. This consolidation also may have resulted from the fact that this facies contains higher proportions of the fine-sized smectite clay mineral group. Moreover, both kaolinite and smectite are characterized by relatively high crystallinity. This is indicated by their somewhat higher C.I. values (Tables 1, 2) and by their sharp-edged morphology (Figure 4A). Of note, HINCKLEY (1963) emphasized that muds rich in well-crystallized kaolinite are usually harder than those containing less-well crystallized kaolinite.

It is probable that the grey coloration of the soft muds of Holocene age indicates deposition under oxygen deficient conditions such as those recorded in some modern northern Nile delta margin settings (*cf.* EL-WAKEEL and WAHBY, 1970). This is attested by the presence of high organic content, well-preserved plant remains and pyrite (in both crystal and disseminated form) in some Holocene facies. The relative proportions of clay minerals in these soft grey muds (with a lower smectite and a higher illite content than in the stiff brown muds) are generally comparable to those values cited in other studies (EL-ATTAR and JACKSON, 1973; STANLEY and LIYANAGE, 1986). We propose here that the lower proportions of smectite in the Holocene muds may be attributed to their deposition in an environment influenced by seawater, under conditions which would favor the formation of illite. In this respect, we recall that brackish and coastal to marine deltaic sections in the study area accumulated during the past 7500 years. Their deposition thus began at a time when sealevel was about 15 meters below its present stand (LIGHTY *et al.*, 1982); these argillaceous sediments continued to accumulate as rising sealevel inundated the northern delta plain. It is thus possible that a part of the detrital smectite carried by the river was affected by syn-depositional and early diagenetic processes involving transformation into illite by fixation of potassium ions present in sea water. The first stage of this transformation involves formation of smectite-illite mixed layer clays (MILLOT, 1970).

This study reveals more marked regional variations of clay minerals in the Late Pleistocene than in the Holocene as recorded by the values of both K/S and I/S ratios (Figures 5 and 6). Much higher proportions of smectite, and lower percentages of kaolinite and illite, characterize the northeastern delta Late Pleistocene facies. This could suggest that dominant flow paths of the pre-Holocene River Nile was toward the subaerially-exposed northeastern delta sector, perhaps directed by way of a series of channels located in an area east of Gamasa and presently occupied by Lake Manzala. This northeasterly-directed flow may have been a response to the proposed neotectonic tilt of the delta to the northeast (*cf.* NEEV *et al.*, 1987; STANLEY, 1988b, 1990). High proportions of smectite in this same sector also characterize the Holocene facies. As noted earlier, the Holocene facies contain higher proportions of illite than Late Pleistocene deposits, and this may be attributed to the influence of marine conditions affecting these younger deltaic facies during their deposition. Unlike those in the Late Pleistocene, the illite values in Holocene sections do not show a marked geographic trend or abrupt lateral changes across the study area. This illite distribution may record the effect of sediment transport by an increased number of Nile branches over a broader delta plain area as sealevel approached its present stand, *i.e.* increasingly large sectors of the northern delta, as we know it today, became influenced by both fluviatile and marine processes. The changes in topography of this area during the mid-to-upper Holocene are depicted in a series of paleogeographic maps (COUTELLIER and STANLEY, 1987). Since about 7500 years BP, Nile channel flooding and migration, switching of delta-lobe positions, shifting of the coastline, and displacement of coastal ridges and lagoons would have resulted in the reworking and homogenization of clay mineral distributions across the north-central and northeastern delta sectors. The importance of this reworking factor resulted from transport processes that involved the recycling of sediments between markedly different deltaic (fluvial, coastal, and shallow marine) environments (*cf.* FRIHY and STANLEY, 1987; STANLEY, 1988a).

In support of this reworking factor is the observation of a northward decrease in smectite in the modern River Nile between Cairo to the south and the present coast (Table 3). This may have resulted from erosion of earlier Holocene sediments by channels migrating northward across the delta. Also to be noted are the regional variations of smectite values which very likely record the importance of transport and flocculation processes, as aggregates of this mineral tend to settle preferentially in some sectors just seaward of deltas (*cf.* PORRENGA, 1967; SIEGEL *et al.*, 1968; EMELYANOV and SHIMKUS, 1972; ROBERTS, 1985). Earlier work in the northeastern Nile delta (STANLEY and LIYANAGE, 1986), and also this study, suggest that the unusually high proportions of smectite recorded at several core sites southeast of Lake Manzala may indicate proximity to the mouth of a former branch (perhaps the Tanitic) of the Nile. Moreover, the marked decrease in smectite between the inner- and mid-shelf (Table 1) is also explained by current activity and the differential settling attributes of this mineral group seaward of the delta-front (*cf.* WHITEHOUSE *et al.*, 1960).

Mineralogical analyses of mud-rich samples collected further to the west, in cores of the northwestern sector of the delta, will be made to test the hypothesis that a northeast tilting of the Nile delta has been an important factor affecting the distribution patterns of clay minerals during the Late Quaternary.

SUMMARY

(1) Study of the clay-size fraction in radiocarbon-dated mud core sections recovered in the north-central and northeastern Nile delta records marked differences in the proportions and distribution patterns of clay minerals in this region during the Late Quaternary.

(2) Proportions of smectite are higher, and of kaolinite and illite are lower, in stiff brown muds of Late Pleistocene age (~ 30,000 to 15,000 years BP) than in soft grey muds of Holocene age (~ 7500 years BP to present).

(3) Late Pleistocene facies contain relatively lower proportions of interstratified illitic layers in smectite-illite mixed-layer clay minerals than do the Holocene mud-rich deposits.

(4) The smectite and kaolinite in the stiff Late Pleistocene muds display slightly higher crystallinity indices than those in the soft Holocene facies; moreover, SEM photomicrographs show that the older stiff muds are characterized by a crenulated and sharp-edged morphology in contrast to the more massive and rounded forms of the clay minerals in the soft Holocene muds.

(5) Late Pleistocene clay minerals show a close affinity with those in River Nile samples of Recent age, suggesting that the brown muds were deposited in a terrestrial setting directly affected by fluvial transport processes.

(6) Late Pleistocene muds accumulated on the subaerially-exposed northern delta plain surface during the time of low eustatic stands prior to 10,000 years BP; their depositional environments, favoring oxidizing and evaporitic conditions, included periodically flooded depressions bordering the incised channel system of the River Nile.

(7) Holocene muds were deposited in lagoons (oxygen-deficient conditions) and coastal to open marine settings; exposure to marine conditions may have favored the transformation of smectite into smectite-illite by fixation of potassium ions present in sea water.

(8) In Late Pleistocene muds, the proportions of smectite are much higher, and relative percentages of kaolinite and illite are lower, in the northeastern than in the north-central delta region; this could suggest the influence of preferential flow of pre-Holocene River Nile water toward an area presently occupied by Lake Manzala.

(9) Comparable geographic trends are noted during the Holocene, indicating that clay mineral distribution patterns in the northern delta have been controlled by factors more closely related to in-situ sediment transport, syn-depositional conditions and provenance than to post-depositional diagenesis.

(10) The geographic distribution patterns of the clay minerals in the study area during the Late Quaternary also suggest that they may be related to environmental conditions affected by preferential subsidence and neotectonic tilting of the northern delta plain toward the northeast.

(11) This regionally asymmetric subsidence, coupled with the eustatic rise in sealevel, produced a rapidly evolving complex of inter-related fluvial, coastal and shallow marine environments on the northern delta plain; encroachment of the sea upon this once subaerially-exposed delta margin during the Holocene induced some changes in clay mineral composition and distribution patterns.

(12) The postulated strong temporal and spatial responses of clay mineral composition and distribution patterns in Late Quaternary sections to transport processes (especially as related to neotectonic and eustatic factors) needs further testing. Mineralogical investigation of the clay minerals in sections of comparable age in

the northwestern sector of the Nile delta and Upper Egypt has been initiated.

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RÉSUMÉ

Examine la fraction argileuse de sondages datés au radiocarbone du Pléistocène récent (~30 000 – 15 000 BP) et de l'Holocène (~7500 BP à l'actuel), et prélevés dans le centre Nord et le Nord Est du delta du Nil (Egypte). Les proportions de smectite sont plus fortes, cells d'illite et de kaolinite plus faibles, dans les vases dures brunes plus anciennes que dans les faciés holocénes gris et mous. Comparés aux dépôts holocènes, les dépôts du Pléistocène récent présentent moins souvent des couches d'illite interstratifiées dans les minéraux argileux de smectite-illite, et ont des indices de cristallinité quelque peu plus élevés pour la smectite et la kaolinite. Les minéraux argileux des faciès du Pléistocène récent montrent une étroite parenté avec les échantillons récents du Nil, ce qui indique une origine fluviale: leur dépôt a probablement eu lieu dans des dépressions périodiquement inondées qui bordent les canaux sur la plaine du Nil exposée aux agents subaériens. Au contraire, les vases holocènes contiennent des minéraux argileux qui sont comparables à ceux des dépôts marins récents: ils se sont accumulés dans des sites affectés par les conditions marines (par exemple, empiétementes de la mer sur la marge Nord du delta). Une partie de la smectite détritique a été transformée en smectite—illite par fixation, pendant our peu après le dépôt, des ions potassium présents dans l'eau de mer. Dans le NE du delta, quelque soit la période (Pléistocène récent ou Actuel), les proportions de smectite sont bien plus élevées, et les concentrations en kaolinite et en illite beaucoup plus faibles que dans la région du delta centre Nord. Ceci pourrait indiquer un écoulement préférentiel des eaux du Nil vers la zone actuellement occupée par le lac Manzala. La répartition de la distribution des minéraux argileux reflète donc en partie les effets concurrents de la subsidence et de l'inclinaison de la plaine du Nord delta vers le NE, ainsi que la montée eustatique du niveau de la mer. Les dépôts de la zone étudiée ont été altérés pendant le Quaternaire récent par ces événements, c'est à dire que l'on est passé d'une plaine alluviale à un complexe deltaïque combinant environments fluvial, côtier et de mer peu profonde. Le transport des sédiments et les conditions de dépôt étaient des facteurs bein plus importants que leur provenance et les effets de la diagenèse postérieure au dépôt, parce que contrôlant à; la fois dans l'espace et le temps la composition des minéraux argileux et la répartition de leur distribution.—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

RESUMEN

En este estudio se examina la fracción arcillosa de los núcleos arcillosos, datados mediante carbono radiactivo y pertenecientes al Pleistoceno Superior (aprox. 30.000–15.000 a.C.) y al Holoceno (del 7.500 a.C. a la época actual), encontrados en la parte central y oriental al norte del delta del Nilo, Egipto. Las proporciones de esmectita son superiores, mientras que las de caolinita e illita son menores, en los lodos marrones más antiguos y duros frente a las facies holocénicas más grises y blandas. Más aún, los depósitos del Pleistoceno Superior tienen menor proporción de capas illíticas interestratificadas en minerales arcillosos de contenido esmectítico e illítico y muestran asímismo unos mayores índices de cristalización por la esmectita y la caolinita que en los sedimentos holocénicos. Los minerales arcillosos correspondientes a las facies del Pleistoceno Superior muestran una gran afinidad con las muestras de la época actual del río Nilo, indicando un origen fluvial: los depósitos se produjeron probablemente en depresiones periódicamente inundadas y rodeadas por canales del Nilo. Por el contrario, los fangos holocénicos contienen minerales arcillosos comparables a los de los depósitos marinos actuales: se han acumulado en zonas afectadas por las condiciones marinas en la parte norte del delta. Parte de la esmectita depositada se transformó en esmectita-illita debido a la fijación de los iones de potasio en el agua durante o inmediatamente después de producirse la deposición. Se ha encontrado mucho mayores proporciones de esmectita y más bajas concentraciones de caolinita e illita en la parte nororiental que en la nor-central del delta, tanto durante el Pleistoceno Superior como en la época actual. Esto indica la existencia de un flujo preferencial de las aguas del Nilo hacia un área ocupada por el lago Manzala. La forma de la distribución de los minerales arcillosos refleja, en parte, los efectos producidos por la acción simultánea del hundimiento y basculamiento de la planicie al norte del delta y de la sobreelevación eustática del nivel medio del mar. Estas acciones alteraron las zonas de deposición en el área de estudio durante el Cuaternario Superior, es decir, pasando de una planicie aluvial a un complejo deltaico fluvial y el desarrollo del medio costero y marino a poca profundidad. El transporte de sedimentos y las condiciones de deposición han sido más importantes que el origen y los efectos post-deposición a la hora de controlar la composición temporal y geográfica de los minerales arcillosos así como su forma de distribución.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

ZUSAMMENFASSUNG

In der vorliegenden Studie wird die Tonfraktion in C-14-datierten tonreichen Bohrkernsegmenten des Jungpleistozäns im Zeitabschnitt von ca. 30.000 bis 15.000 a B.P. und des Holozäns von ca. 7.500 a B.P. bis zur Gegenwart aus dem nördlich-zentralen und nordöstlichen Nildelta untersucht. Der Anteil von Smektiten ist im älteren und leicht verfestigten braunen Schlamm höher und der Anteil an Kaolinit und Illit geringer als in der weichen und grauen Holozänfazies. Außerdem beinhalten die jungpleistozänen Ablagerungen geringe Anteile von zwischengeschalteten Illitlagen in Smektit-Illit-Tonmineralen und zeigen eine etwas höhere Kristallinisierung für Smektit und Kaolinit als in den holozänen Sedimenten. Die jungpleistozänen Tonminerale zeigen eine starke Ahnlichkeit mit denen aus aktuellen Nilablagerungen und inidizieren somit einen ebenfalls fluviatilen Ursprung. Die Ablagerung geschah wahrscheinlich in periodisch überfluteten Vertiefungen entlang eingeschnittener Kanäle der subaerisch exponierten Flußebene des Nils. Im Gegensatz dazu enthalten die holozänen Schlämme Tonminerale die vergleichbar sind mit denen in rezenten marinen Ablagerungen. Sie reichern sich in Gebieten an, die von marinen Bedingungen geprägt sind, die herrschten, als das Meer in den nördlichen Deltabereich eindrang. Ein Teil des detritischen Smektits wurde in Smektit-Illit während oder kurz nach der Ablagerung durch die Fixierung von Kaliumionen, die im aktuellen Meerwasser ausreichend zur Vergügung stehen, umgewandelt.—Im nordöstlichen Teil des Nildelta existieren—im Gegensatz zur nördlich-zentralen Deltaregion—sehr viel größere Anteile von Smektit und geringe Konzentrationen an Kaolinit und Illit sowohl in den jungpleistozäne als auch in den rezenten Sedimenten. Dies mag als Indiz dafür zu werten sein, daβ der Nil einen Abluβ bevorzugte, der in ei Gebiet ging, welches z.Z. vom Manzala-See eingenommen wird. Die Tonmineralverteilung zeigt auch den Effekt von gleichzeiti stattfindender Absenkung, Verstellung der nördlichen Deltaebene nach Nordosten und einen eustatischen Meeresspiegelanstie an. Diese Ereignisse veränderten die Ablagerungsbedingungen des Untersuchungsgebietes während des Jungpleistozäns vo einer Aufschüttungsebene hin zu einem Deltakomplex, in dem sich fluviatile Einflüsse, Küstenprozesse und Flachwasserbedingungen widerspiegeln. Sedimenttransport und die Umgebungsbedingungen zum Zeitpunkt der Ablagerung waren bei der Steuerung der zeitlichen und räumlichen Tonmineralzusammenstezung und—verteilung wichtiger als die Herkunft der Sediment und diagenetische Effekte nach der Ablagerung.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*