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Clay mineral distribution patterns in the southeastern Mediterranean Sea during the late Quaternary

GEORGE ANASTASAKIS

Faculty of Geology and Geoenvironment, University of Athens, Panepistimiopolis, 15784 Athens, Greece; anastasakis@geol.uoa.gr

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Abstract: The clay mineral distribution patterns in three stratigraphically well-defined piston cores containing the uppermost five sapropel sequences (70,000 years BP to the present) in the southeastern Mediterranean Sea have been studied. The temporal variations and spatial distribution of the sum of smectite plus kaolinite, the dominant clay minerals of the Nile River, can be closely related to enhanced suspended sediment transport by the Nile that occurred mostly during the transition phases from an arid to a moist paleoclimatic episode. The most pronounced input of Nilotic provenance clay occurs within and between the sapropel layers S-5 and S-4. Between circa 70,000 and 45,000 years BP this time interval marks the transition phase from the cold-arid early Würmian period to the very wet middle Würmian phase that affected the Nile drainage system and probably caused the activation of numerous wadi systems. The other most intense similar phase occurred after 12,500 years BP as manifested by the concomitant increase of hemipelagic sedimentation, due to the extensive Nile flooding and the resulting dramatic increase in suspensite delivery, leading to a pronounced increase of the Nile clay assemblages within the S-1. Major sea-level fluctuations, such as the regression at 18,000 years BP, had a pronounced effect on clay mineralogy leading to a marked increase in the deposition of illite micas plus mixed layered clays reflecting intensification of shelf erosion.

Key words: environmental provenance, late Quaternary lithostratigraphy, Eastern Mediterranean cores, XRD, clay mineral assemblages, Nile clays.

Introduction

Upper Quaternary paleoclimatological interpretation of areas bordering the eastern Mediterranean is derived mostly from the floral and faunal composition of non-marine sediments excavated at various archaeological sites. Additional data are stratigraphically related to peat bogs, lake sediments, littoral and fluvial terraces and loess deposits. Interpretations of these paleoclimatic markers must take into account many other factors and processes, such as hydrodynamic processes of sediment movement, modification of the watershed vegetation cover or stream gradient changes (base level) due to sea-level fluctuations which are rather difficult to interpret (McCoy 1980). However terrestrial data have been proven more accurate for interpreting shorter period fluctuations, while deep sea sediments have provided evidence for longer period fluctuations. Paleoclimatic interpretation from deep sea sediments is primarily based on the content and differentiation of biogenic components and their oxygen isotope record (e.g. Shackleton & Opdyke 1973; Vergnaud-Grazzini et al. 1977; Imbrie et al. 1984) and to a lesser degree on terrigenous compositional attributes (Diester-Haas & Chamley 1980).

Studies of regional clay mineral distribution in the world oceans show a general correlation between climate and mineral assemblages (Biscaye l965; Griffin et al. 1968; Rateev et al. 1968). The clay mineral associations in the late Quaternary sediments of the Mediterranean Sea lack indications of significant secondary alteration in the marine environment (Emelyanov l972; Monaco 1981) a fact in accordance with observations of older Mediterranean Upper Cenozoic sediments (Chamley & Robert 1982; Chamley 1983; Chamley et al. 1986). Clay mineralogy studies of late Quaternary sediments in the southeastern Mediterranean have identified the significant and locally dominant influence of the Nile River as a major contributor of sediment to the region (Venkataratham & Ryan 1971; Chamley 1972; Emelyanov 1972; Nir & Nathan 1972; Maldonado & Stanley 1981). The smectite rich Nile derived assemblages are supplemented by wind blown kaolinite-rich dust from the North African and Middle East deserts (Yaalon & Canor 1973, 1979). Moreover, present day desert terrains around the Nile River and the Lake Nasser reservoir provide significant amounts of wind transported kaolinite (Stanley & Wingerath 1996). Chester et al. (1977), sampled dust over the East Mediterranean Sea and found that the most significant clay mineral dust assemblages are illite and kaolinite the latter being enhanced towards the Nile Cone.

The Nile River flows 6700 km from the glaciated highlands and montane forests of Uganda (4°S) through the desert plains of Sudan and Egypt, through its delta on the Egyptian coast and into the eastern Mediterranean Sea. The Nile drains an area of about three million km^2 (Fig. 1) or about one tenth of the African continent. The main Nile north of 8°N latitude comprises flow from three major tributaries: the White Nile, Blue Nile and Atbara River (Fig. 2). Each rivers sediment load is derived from markedly different geological terrains and climatic zones. The

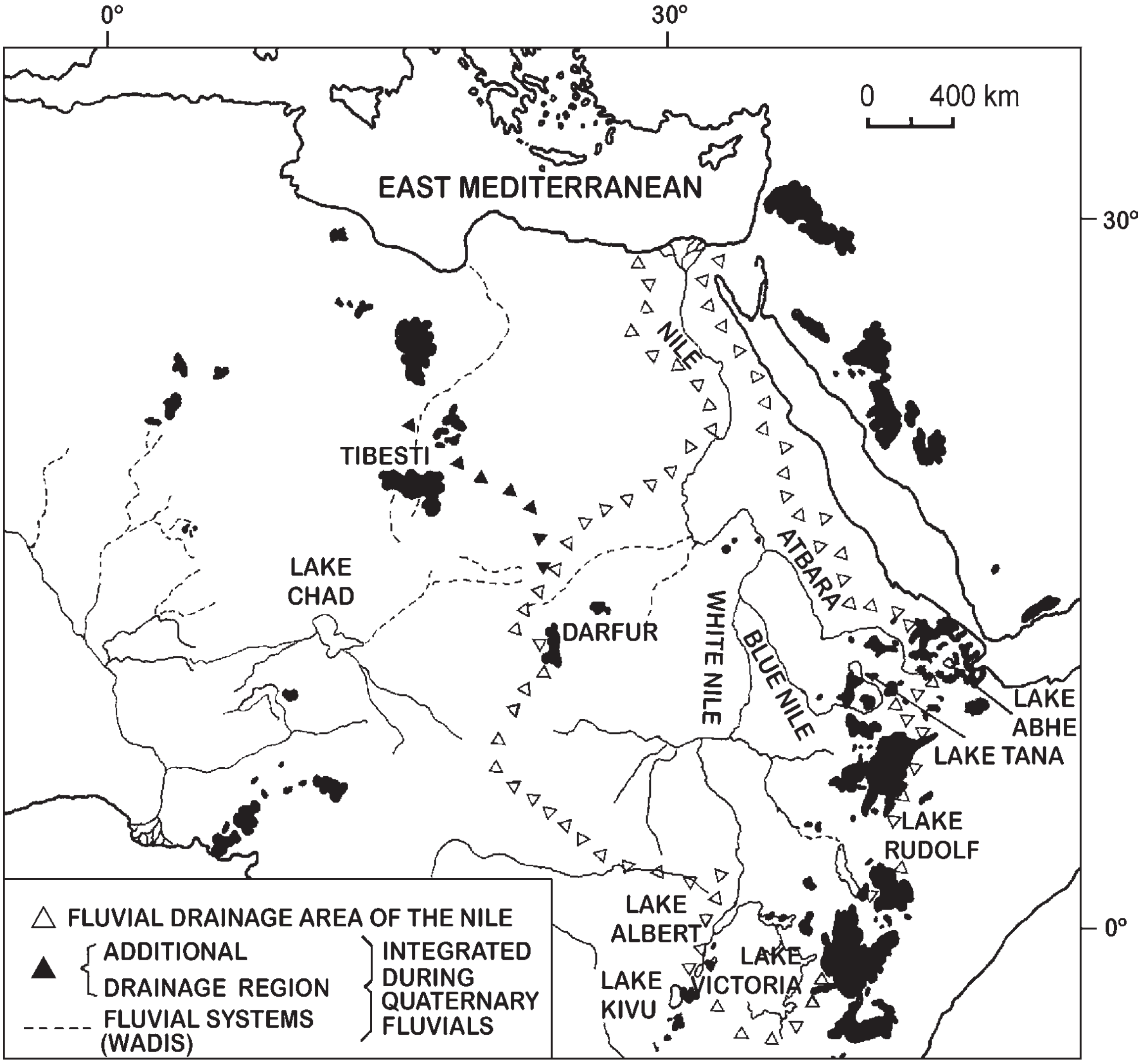

Fig. 1. Nile River drainage system and its tributaries modified after Szabo et al. (1989). The dark shaded regions show areas where Neogene volcanic rocks are present. The names of lakes and localities mentioned in the text are also shown.

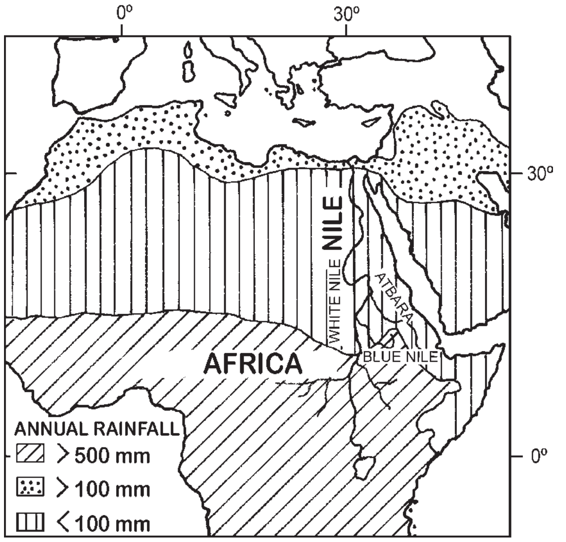

Fig. 2. Map showing the annual rainfall over the North African continent.

Lower Nile in Egypt is characterized by high smectite values (at least 60 %) with elevated proportions of kaolinite which decrease progressively to <25 % downstream near the coast (El Attar & Jackson 1973; Stanley & Liyanage 1986; Wahab et al. 1986; Stanley & Wingerath 1996). Illite values, in contrast to kaolinite and smectite are usually much lower, generally ~10 % or less along the Lower Nile and delta to the coast.

Clay mineral studies (Maldonado & Stanley 1981) in cores recovered in the southeastern Levantine-Nile Cone sector of the eastern Mediterranean suggest that depositional processes better explain the vertical fluctuations of clay mineral deposition in the uppermost Quaternary deposits (23,000 years BP to the present). Similar studies of Holocene sections in the northeastern Nile Delta indicate that depositional processes rather than the climate have been responsible for the observed vertical and lateral changes in clay mineral proportions (Stanley & Liyanage 1986; Abu-Zeid & Stanley 1990; Abdel Wahab & Stanley 1991).

More detailed work in the periphery of the Nile Delta (Abu-Zeid & Stanley 1990) demonstrated that the older soft brown muds have higher amounts of smectite and lower of kaolinite and illite compared to the soft grey Holocene sediments. Additionally, higher proportions of smectite and lower proportions of kaolinite and illite characterized the northeastern region comparatively to the north-central delta region during both the Late Pleistocene and the Recent. The north-central sector differs from the northeastern Nile Delta in that it comprises relatively higher proportions of kaolinite and lower proportions of smectite (Abdel Wahab & Stanley 1991). Investigations on the coastal plain from the Nile Delta to the southern Lebanon borders with Israel revealed important proportions of kaolinite in the clay fraction of samples recovered from coastal cliff exposures (Stanley et al. 1997). Kaolinite and illite at offshore sites are supplied in part from erosion of coastal cliff sections, river input between Wadi El Arish in Sinai and the Lebanon-Israel border and from wind-borne dust from African and Middle East deserts released seaward of the coast (Stanley et al. 1998). The present study demonstrates that the clay minerals from cores retrieved in the outer periphery of the Nile Cone, in sectors not apparently affected by redepositional processes, display significant vertical clay mineral variations. Such variations mostly record pronounced upper Quaternary fluctuations of supply of clays by the Nile drainage system. The results and interpretations of this study, further prove the value and potential that clay-mineral assemblages may hold for paleoclimatic and provenance studies of Quaternary deposits in the region (Dominik & Stoffers 1979; Maldonado & Stanley 1981).

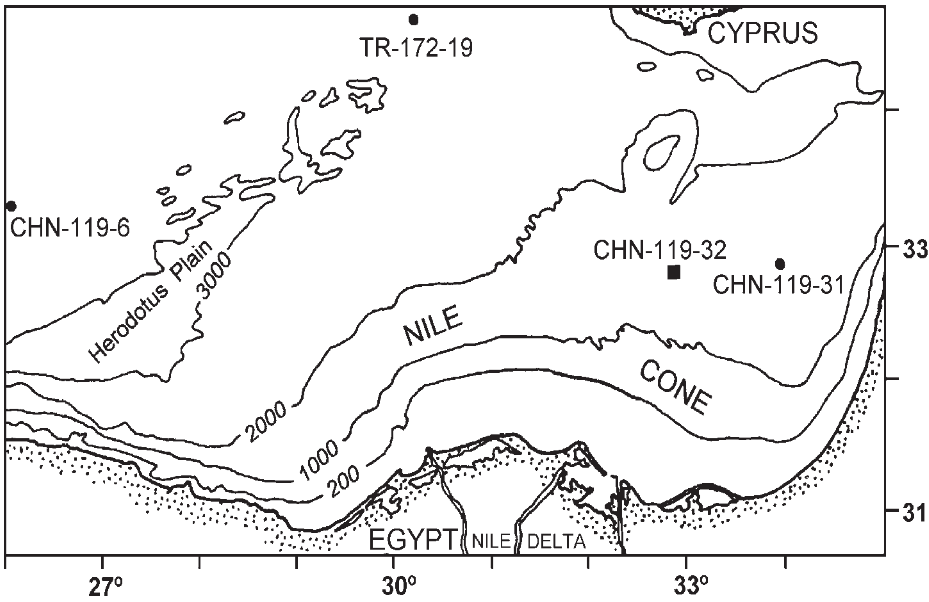

Fig. 3. Chart of the southeastern Mediterranean Sea showing general bathymetry plus major physiographic features (depth in meters). The location of cores studied in this study are shown by a solid dots. The core shown by a solid square is a core studied by Dominik & Stoffers (1979) and used also, for comparison in Fig. 7.

Materials and analytical procedure

Three piston cores (Fig. 3) were selected among several dozens of cores available in the southeast Levantine Sea. These cores were retrieved from the outer periphery of the Nile Cone. Careful examinations of their X-ray radiographs revealed that they contained no or minimal proportions of gravity emplaced and/or reworked layers. The less than 2 μm fraction of 54 samples was obtained by decantation using Stokes Law to calculate settling times. The samples were treated with 10% H_20_2 (pH=4.3) to remove organic material and then washed three times using a centrifuge (5000 rpm for 15 minutes). The carbonates were removed with a mixture of dissodium dihydrogen EDTA (pH4.5) and 10 % tetrasodium EDTA (pH=9.9) which gave an EDTA of pH=7.7, almost equal to the pH of the samples. Oriented aggregates (OA) were prepared according to Anastasakis (1987) method. Briefly this method involves: a — control of the amount of clay mineral being deposited onto the glass slide, thus obtaining clay films of optimum thickness (3.9–7.7 μm); b — rapid evaporation at temperatures below 40 °C of the clay suspension in order to avoid size segregation.

The mineralogy was determined with a Philips Norelco X-ray diffractometer with a focusing monochromator, an automatic divergence slit and CuKα radiation at 40 kV and 30 mA. Paper speed, scale and time factors were chosen to produce optimum results. Each glass slide was X-rayed under the following conditions:

— 2° to 30° air dried and glycolated (Fig. 4);

— 2° to 14° heated to 400 °C, heated to 500 °C, K^+ saturated, Mg^{2+} saturated, K^+ glycolated, Mg^{2+} glycerolated, K^+ saturated and heated to 95 °C for several hours.

Semiquantitative estimates of the amount of clay minerals present were performed according to methods described by Biscaye (1965). The peak areas were measured by a Hewlett-Packard 9820 calculator using an X-ray plotter, digitized and stored in a cassette memory. Where clay minerals like vermiculite and illite/smectite and smectite/chlorite mixed layers (or interstratifications) occurred a modification of the original method of Biscaye (1965) technique was applied which improved semiquantification by considering that the calculated peak areas represent 100 % of the sample. Identification of these mineral assemblages was based on techniques published in various specialized textbooks

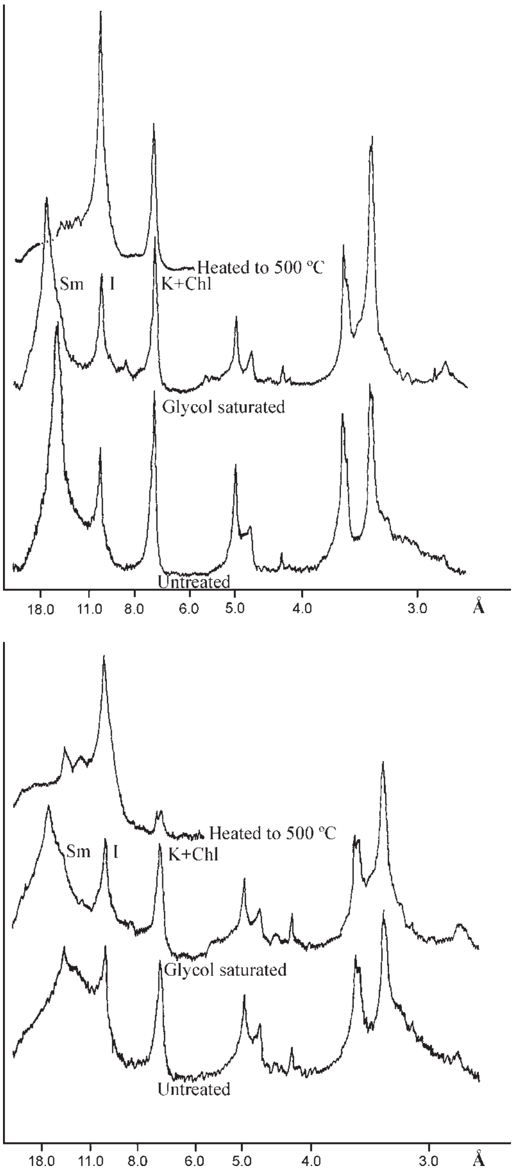

Fig. 4. Diffractograms show two examples of the clay mineral assemblages defined in the text. The two samples shown are from core TR-172-19 and display typical X-ray patterns, under three different conditions (Untreated, Glycol saturated and Heated to 500 °C) of the finer than 2 μm fraction within (a upper sample) and above (b lower sample) the sapropel S-1. Major peaks (Sm — smectite; K + Chl — kaolinite and chlorite; I — illite) are marked on the Glycol saturated sample and d-spacing values (Å) are shown.

(Carroll 1970; Brindley & Brown 1980; Moore & Reynolds 1989).

Lithostratigraphy of the studied cores

The Quaternary sediments of the Nile Cone like those of the East Mediterranean, are formed by regionally extensive repetitive successions corresponding to cyclothems (Maldonado & Stanley 1976) which are centered on organic rich sequences, the sapropels. These sapropels may be correlated from core to core over a wide area, indicating that widespread paleo-environmental conditions have affected the entire eastern Mediterranean Sea. Numerous radiocarbon dates and detailed sedimentological analyses by Stanley & Maldonado (1977) have established lithostratigraphic units that comprise the three uppermost late Quaternary cycles in the Levantine Sea.

Recently accelerator mass spectrometry radiocarbon data (AMS C14 dates) became available (Troelstra et al. 1991; Mercone et al. 2001) but was focused on the uppermost sapropel S-1. In earlier studies the organic-rich layers in the eastern Mediterranean were subdivided into two groups, namely sapropels — with more than 2.0 % organic carbon, and sapropelic — with organic carbon ranging from 0.5 to 2.0 % (Kidd et al. 1978). The 0.5 and 2.0 % values, while arbitrary, proved to be useful boundary markers separating open-marine organic-poor from organic rich layers. A definition of lithofacies types forming a sapropel sequence sensu stricto comprises the following members, from base to top (Anastasakis & Stanley 1986): a greyish-greenish yellow mud overlain by a yellow-grey organic ooze which becomes darker upward and separated from the overlying light olive-grey sapropelic or olive-grey sapropel lithofacies by a generally pronounced sharp contact. The latter is topped by a thin, light greenish-grey ooze and a pale yellowish-orange to moderate brown oxidized layer. The basal greyish-greenish yellow mud and upper oxidized end members are interbedded between lighter coloured, better oxygenated sediments below and above the sequence.

The lithofacies associations forming the idealized complete sequence are essentially of suspension-settling origin and can be distinguished on the basis of their physical and biogenic structures, textures and composition including organic content.

Table 1: Summary of C14 dates for the studied cores.

Core No.	Physiographic location	C14 Sample stratigraphic position	C14 ID number	C14 Date in yr BP
CHN-113-6	Mediterranean Ridge W Levantine	Below S-2	SI-5207	32 400 ± 1220
CHN-113-6	Mediterranean Ridge W Levantine	Above S-3	SI-5208	30 850 ± 970
TR-172-19	Central Levantine W of Cyprus	Below S-1	SI-5194	12 300 ± 125
TR-172-19	Central Levantine W of Cyprus	Below S-3	SI-5195	36 400 ± 1840
TR-172-19	Central Levantine W of Cyprus	Below S-4	QL-1686	$56\,500\ ^{+5700}_{-3300}$
CHN-119-31	East Levantine NE of Nile Cone	Below S-1	SI-5210	13 700 ± 120
CHN-113-31	East Levantine NE of Nile Cone	Below S-2	SI-5211	30 870 ± 940
CHN-113-31	East Levantine NE of Nile Cone	Below S-3	SI-5327	31 630 ± 1180

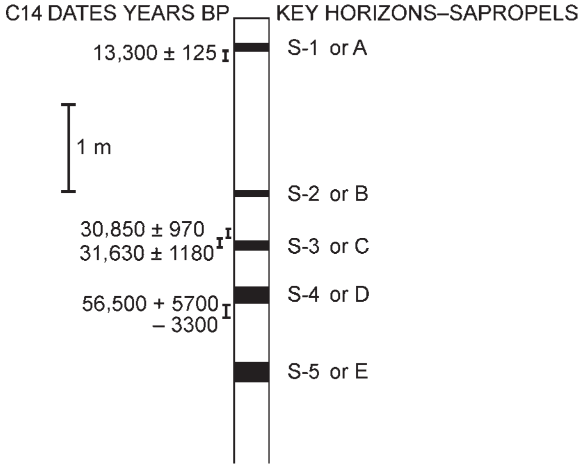

Fig. 5. Generalized Levantine Sea–Nile Cone sapropel stratigraphy displayed by the studied cores. This stratigraphy, used for regional correlation, is based on extensive petrologic and radiocarbon analysis, especially dense around late Quaternary organic rich sapropel horizons. The solid bars along side of the simplified core log indicate the sample position of the youngest radiocarbon date obtained by us, in the southeastern Levantine Sea.

Within the uppermost three Quaternary cyclothems, in the Nile Cone, the assigned ages (Maldonado & Stanley 1976) in years before present to the top of the extensive stratigraphic horizons, the sapropels, are: for the S-1 7000 yr BP; S-2 23,000 yr BP; S-3 38,000 yr BP. Our more recently obtained radiocarbon dates on the cores discussed here (Table 1) suggest that the top of the sapropel S-3 would be younger, dated at about 31,000 yr BP; and also the top of sapropel S-4 would be dated at around 45,000 yr BP; (Fig. 5).

Clay mineral provenance in the southeast Levantine Sea

The most significant clay mineral contribution in the southeastern Levantine Sea (Fig. 8) is the injection of smectite-rich Nile River sediment into the counter-clockwise eastern Mediterranean water mass gyre (Venkatarathan & Ryan 1971). High concentrations of smectite off Lebanon reflect the transport of suspended sediments derived from the Nile Delta by surface waters (Emelyanov & Shimkus 1972). More detailed regional studies (Nir & Nathan 1972; Chester et al. 1977; Maldonado & Stanley 1981; Nir 1984; Abu-Zeid & Stanley 1990; Abdel Wahab & Stanley 1991; Stanley & Wingerath 1996; Stanley et al. 1998) suggest that besides smectite, kaolinite is also transported to the sea by the Nile. However there is unambiguous evidence that airborne dust has a significant impact all over the East Mediterranean and originates mostly from African terrains such as the region of the Tibesti Mountains in southern Libya–northern Chad and Niger, eastern Libyan Desert (El Katara Depression) as well as Sudan and the Ethiopian Highlands (Yaalon & Ganor 1973, 1979; Ganor 1991; Ganor et al. 1991; Prospero 1996; Chester et al. 1996). Ganor & Foner (1996) have quantified the mineralogical properties of Saharan dust over Israel noting average smectite (40–80 %), kaolinite (15–55 %) and illite (10–30 %). Kubilay et al. (1997) have systematically sampled airborne dust on a station located in southeastern Turkey and reported the prevelance of smectite-palygorskite plus the persistence of subordinate kaolinite of Saharan-Arabian provenance. The above results generally comply with earlier dust results in the sea region between the Nile Cone and Cyprus (Chester et al. 1977). These authors distinguished a "northeastern Mediterranean assemblage" that is illite dominated and a major "southeastern assemblage" that is kaolinite dominated. Even present day clay sedimentation in the Nile Aswan technical lake is significantly affected by wind sweeping adjacent desert terrains (Entz 1976) incorporating a fine silt and clay composed largely of kaolinite (Stanley & Wingerath 1996). Other local land derived assemblages (Fig. 7) consist predominantly of: smectite (35–70 %), illite (25–45 %), chlorite (7–25 %) for Cyprus rivers (Chester et al. 1977; Shaw 1978); illite (35–65 %), smectite (35–65 %) for the Cilician Basin (north of Cyprus) and Seyhan Delta (southeastern Turkey, Shaw 1978), (Fig. 8). Samples collected on the Gaza and Israeli shelf prior to Aswan record average percentages: 49 % smectite, 33 % kaolinite, 14 % illite and 4 % chlorite (Stanley et al. 1998). These values are similar to the Nile shelf. Stanley et al. (1997) have shown that after the construction of the Aswan Dam proximal clay mineral assemblages derived from local sources (Sinai, Israel and Lebanon) are supplied in enhanced proportions to the SE Levant margin.

Clay mineral associations

Clay mineral abundances

Core CHN-119-6 was retrieved from the Mediterranean Ridge west of the Herodotus Abyssal Plain (Fig. 3) at a water-depth of 2372 m. Illite is the most abundant clay mineral, ranging from 37 % to 57 %. Smectite is quantitatively the second clay mineral ranging from 24 to 42 %. Kaolinite varies from 15 to 28 % and its occurrence generally increases in the deeper part of the core. Chlorite is the least abundant clay mineral (less than 15 %). Traces of vermiculite and random mixed layers of the illite-smectite and chlorite-smectite type are locally present.

Core TR-172-19 is located on the northern flank of the Mediterranean Ridge north of the termination of the Herodotus Plain (Fig. 3) and west of Cyprus, at a water depth of 2354 m. Smectite is the dominant clay mineral (Fig. 4) and ranges from 23 to 56 %. Illite is present in lesser amounts, and ranges from 17 to 33 %. Chlorite and kaolinite are present in about similar proportions; more specifically chlorite ranges from 9 to 22 % and kaolinite from 11 to 21 %. Random mixed layers of smectite-illite and chlorite-smectite are present; often encountered in sapropels and quantitatively reach the highest percentages (up to 30 %) above the S-2 layer.

Core CHN-119–31 (Fig. 4) was recovered from the eastern distal continental margin of the Nile Cone (Fig. 3) at a depth of 1637 m. The clay assemblage is dominated by smectite which ranges from 52 to 65 %. Kaolinite ranks second in importance and varies from 9 to 22 %. Illite ranges from 6 to 15 %. Chlorite is present in subordinate amounts only (less than 5 %). Small amounts of random mixed layers illite-smectite and probably chlorite-vermiculite are also present.

Lateral and vertical clay mineral variations in the cores

In the cores under investigation the eastward decrease of illite is accompanied by a concomitant decrease of the chlorite content. Kaolinite does not display marked lateral variations suggesting a similar widespread source area. The observed lateral changes in the proportions and distribution of the dominant clay groups are in accordance with the published data on the clay mineralogy of the Recent and late Quaternary sediments of the region that show highest scores of smectite close to the Nile and illite enhancement towards the northern shores of the East Mediterranean Sea (Rateev et al. 1968; Venkatarathnam & Ryan 1971; Chamley 1972; Emelyanov 1972; Nir & Nathan 1972; Cita et al. 1977; Dominik & Stoffers 1979; Maldonado & Stanley 1981; Buckley et al. 1982).

The vertical distribution of clay minerals also displays important but consistent fluctuations in the cores under consideration (Figs. 6, 7). In core CHN-119–6, the stratigraphic level upwards of S-5 displays an important increase of the sum of smectite+kaolinite within sapropels S-5 to S-1. Two low smectite intervals occur in-between

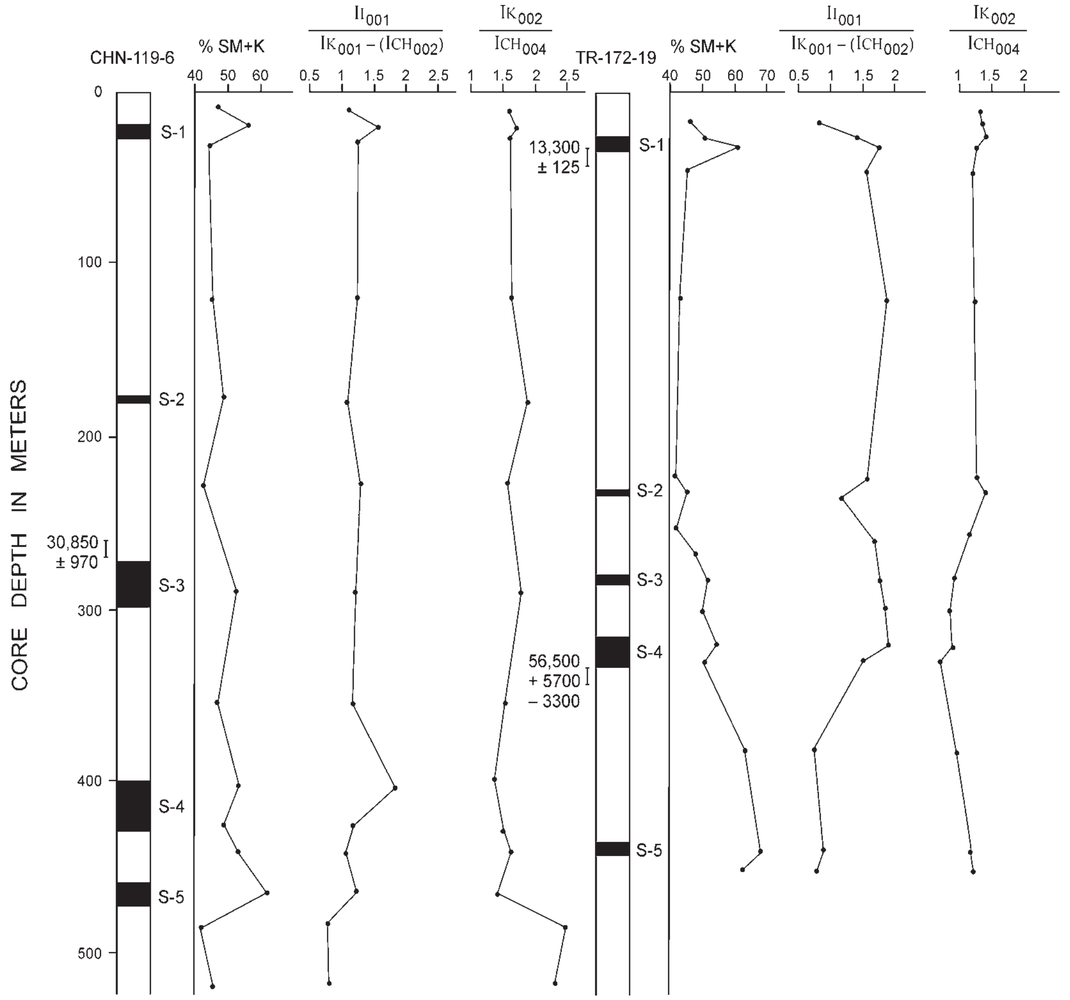

Fig. 6. Clay mineral variation contents of cores CHN-119–6 and TR-172–19. The simplified, sapropel based lithostratigraphy, is given alongside with: **a** — **% Sm+K** which indicates the relative percentage of smectite plus kaolinite; **b** — $I_{I001}/I_{K001}-I_{CH002}$ indicates the ratio of the integrated intensity (peak height) of the 001 illite and the 001 kaolinite peaks. The 001 kaolinite peak intensity was found by dividing the 7 Å peak intensity in proportion to the kaolinite/chlorite ratio of the 3.57 Å and 3.53 Å peaks; **c** — I_{K002}/I_{CH004} gives the intensity ratio of the 002 kaolinite and 004 chlorite peaks (heights). The black dots indicate the sampled interval. Where two samples were taken at closer than 10 cm intervals, the average clay mineral composition and/or peak intensity is plotted. The solid bars alongside the cores indicate the radiocarbon dated interval.

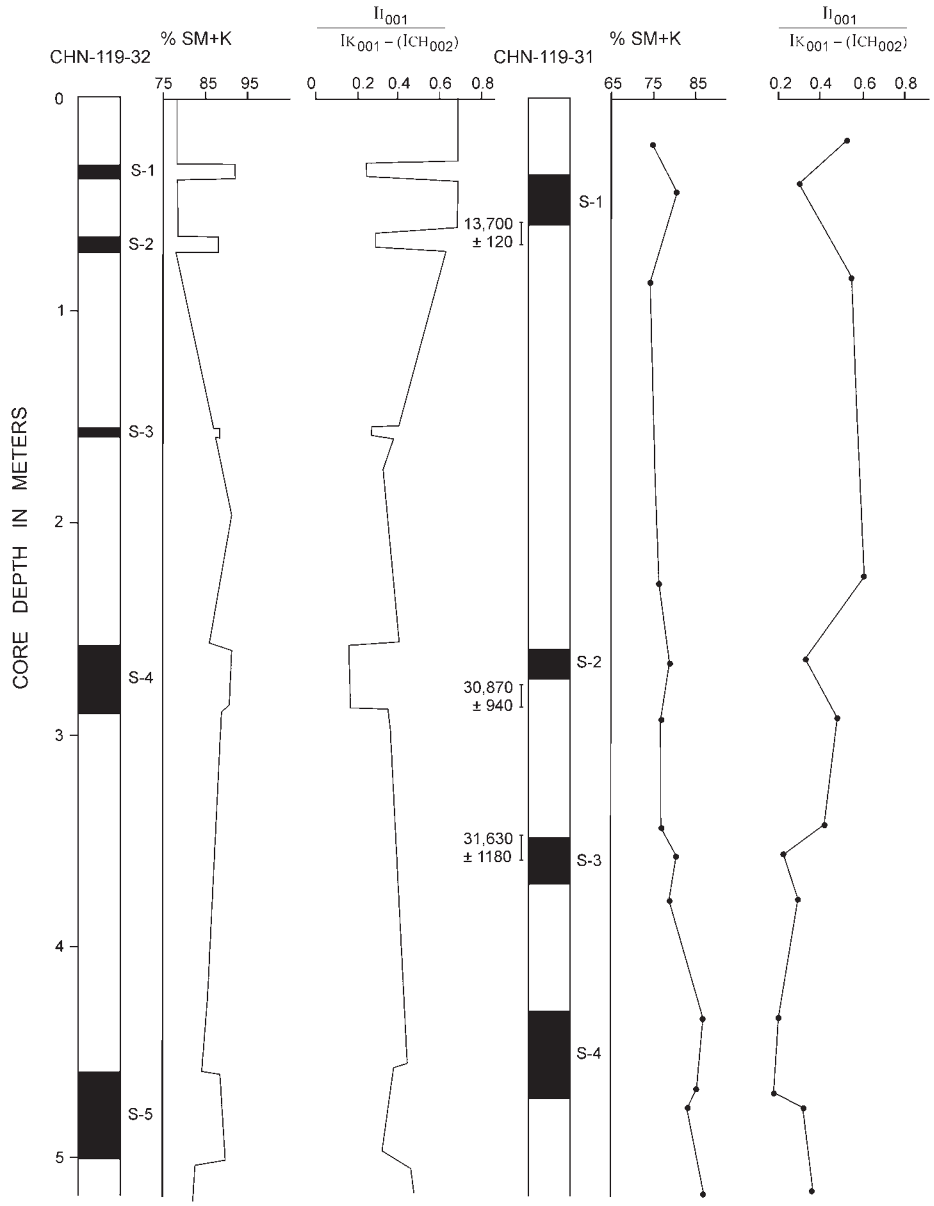

Fig. 7. Clay mineral variations in cores CHN-119-32 and CHN-119-31 recovered in the eastern Nile Cone. The clay mineralogy and lithostratigraphy of core CHN-119-32 are plotted after Dominik & Stoffers (1979). Symbols and other explanations are as in Fig. 6.

the sapropel layers S-3 and S-2 as well as S-2 and S-1. High kaolinite abundances occur below the sapropel S-5 while elevated values of this clay mineral are encountered in-between the sapropel layer S-4 and S-5. Other variations include the pronounced increase of illite content in the uppermost part of sapropel S-4 and to lesser extent within sapropel S-1 while chlorite contents are relatively enriched in the upper part of sapropel S-4 and S-5.

The more conspicuous clay mineral distribution in core TR-172-19 is the stepwise decrease of the sum of smectite + kaolinite from the sapropel S-5 to within the sapropel lithofacies S-2 and an increase within sapropel S-1 (Fig. 4). An antithetic relation is observed between smectite-kaolinite and illite-chlorite. Illite contents are minimized below S-4 down to and within S-5 and around the S-2 while the highest percentages occur within and in-between S-4 and S-3 layers.

The prominent feature about the clay mineral distribution in core CHN-119-31 is the gradual upward decrease of smectite + kaolinite from below the S-4 upwards to the base of S-1 (Fig. 7). The interval confined between S-4 to S-3 displays the lowest I/K ratio due mostly to an increasing kaolinite contribution, while the I/K ratio reaches its highest value between the sapropels S-2 and S-1 due to a marked increase in illite (Fig. 7). Kaolinite + smectite contents show the most pronounced enrichment within sapropel layers S-4 and S-1.

Core CHN-119-32 studied by Dominik & Stoffers (1979), displays comparable clay assemblage trends to CHN-119-31 (Fig. 7). These variations include a general decrease in smectite + kaolinite from above sapropel S-4 to below S-1. Within and in-between the sapropels S-4 and S-3 the sediments display their lowest I/K ratio, due to increasing kaolinite. The highest I/K ratio observed between sapropels S-2 and S-1 is attributed to a significant increase in illite content.

Variability with time of clay mineral assemblages

The oldest stratigraphic interval examined in this study is the organic rich sapropel layer S-5 present in two of the studied cores (CHN-119–31 and TR-172–19). This S-5 layer (equivalent to E sapropel of Thunell et al. 1977) is thought to represent cold conditions from the contained fauna. Based on the new C14 dates (Table 1), sapropel layer S-5 was deposited within the lower pleniglacial (59,000–73,000 yr BP) equivalent to the Deep Sea record Stage 4 (Martinson et al. 1987). This early Würmian period was dry, as shown by low lake water levels, both in East Africa (Lake Abhe, Gasse 1977) and Central Africa (Lake Chad, Durand 1982). The deposition of extensive fluvial sands in basins in East Africa (Central Afar and South Rift, Gasse et al. 1980) corresponds to high erosion-high sediment yield. Pollen counts in a core (Conrad-9–174, Rossignol Strick 1974) recovered from the outer Nile Cone reveal extremely low contents of tree pollen but very high grass pollen contents, especially of steppe species. The cores studied in this work display the highest smectite + kaolinite contents within sapropel S-5 (Figs. 6, 7), denoting the increased influence of Nile clay mineral assemblages as far west as the Mediterranean Ridge south of Crete. This increase is caused in the Nile Cone mainly by high smectite contents while in its outer northwest periphery and further west it is due to higher kaolinite percentages. The I/K ratio within S-5, in the Nile Cone and its outer margin displays reduced values (Figs. 6, 7) caused by enhanced kaolinite content not matching a concomitant increase in illite. This is attributed to enhanced proportions of wind blown kaolinite rich dust getting into the Levantine Sea and its eastward transport by the counter-clockwise gyre (Bergamasco et al. 1992; POEM 19992). In the western Levantine (core CHN-119–6, Fig. 6) this trend is reversed due to increased illite percentages transported by currents from more distant northeastern Mediterranean sources such as the Hellenic region (Venkatarathnam & Ryan 1971; Nir & Nathan 1972; Dominik & Stoffers 1979). I/K ratios are generally reduced within the S-5 to S-4 interval in cores from the outer periphery — distant province of the Nile Cone area (cores TR-172–19 and CHN-119–6, Fig. 6), as well as in the vicinity of the Nile Cone (cores CHN-119–32 and CHN-119–31, Fig. 7).

The influence of Nile clay mineral assemblages persists within the sapropel S-4 and is further enhanced in the southeast Levantine area as demonstrated by the fact that the sum of smectite+kaolinite reaches peak values in S-4 (cores CHN-119–32 and CHN-119–31, Fig. 7). The sapropel S-4 (equivalent to the sapropel D of Thunell et al. 1977) is faunistically a warm sapropel and pollen counts within this layer reveal the most elevated tree pollen counts in the Nile Cone area (Rossignol Strick 1974). The C14 date obtained from the base of S-4 in core TR-172–19 (Fig. 6) yielded an age of 56,500 yr BP. The extrapolated age for the deposition of S-4 suggests that it was initiated well after 55,000 yr BP, within the lowest warming interval of Stage 3. During this period lake levels both in Central Africa (Lake Chad, Durand 1982) and East Africa (Lake Abhe, Gasse 1977) clearly denote highest water levels after 50,000 yr BP, persisting or increasing up to 35,000–32,000 yr BP. Moreover, dating of lake levels in Upper Egypt, at Bir Tarfani (Kowalski et al. 1989) and authigenic carbonates in nearby paleovalleys (Wadi Arid and Wadi Safsaf) indicates significantly elevated freshwater deposits around 45,000 yr BP (Szabo et al. 1989). This phase of increased rainfalls affected the White Nile drainage system as far south as Lake Victoria as demonstrated by palynology studies on Lake Kivu (Bonnefille et al. 1990) west of Lake Victoria (Fig. 1) This humid interval is also verified by a Late Pleistocene lacustrine episode, recorded in a lake in southeastern Libya and, dated about 40,000 yr BP (Gaven et al. 1981).

Periods of highest sediment yield from the Ethiopian highlands and lowlands seem to correspond to times of maximum aridity, minimum water yield, but highly seasonal runoff during the coldest Pleistocene intervals (Adamson et al. 1980). Wetter conditions would have resulted in increased vegetation cover leading to reduced erosion and decreased sediment load carried by both the Ethiopian tributaries even if their discharge would have increased (Foucault & Stanley 1989). According to Butzer & Hansen (1968a,b), the primary source area of Nile sediments is the sub-tropical Voina region at an altitude of 1800–2700 m, in Ethiopia, where vertisols rich in montmorillonitic (smectite) clay predominate. At higher elevations in the temperate Dega region, red clay soils with dominantly kaolinite minerals predominate. White Nile sediment load fluctuations are also due to changing climatic/geographical factors. However, because of a more constant vegetation cover on its drainage basin during most of the late Quaternary (Livingstone 1980; Bonnefille & Riollet 1988) and of its extensive swamp area acting as a sediment trap, its load remained generally low, even when its discharges increased considerably. During humid periods when the vegetation cover in the drainage systems of the Blue Nile and Atbara River increased and their transported sediment loads decreased, the White Nile sediment contribution increased but nevertheless remained insignificant.

The envisioned scenario regarding clay mineral input and dispersal pattern in the southeastern Levantine Sea during the S-5 to S-3 stratigraphic interval directly correlates the observed clay mineral variations, along the cores mainly to the evolution of the Nile River drainage system. Thus, increased proportions of Nile clay mineral assemblages were transported into the sea during the deposition of S-5 and of post S-5 sediments. During this arid phase, the Nile which derived fine-grained fraction exerted a much stronger and wider influence all over larger areas of the southeastern Mediterranean Sea. Cores recovered in the outer periphery of the Nile Cone, as far as the Mediterranean Ridge south of Crete (CHN-119–6, Fig. 3) display strongly elevated sums of smectite + kaolinite, coupled with the lowest ratios of illite/kaolinite. This is also an indication of a subdued eastern Mediterranean anticyclonic water movement, during this cool interval, as illite rich Ionian Sea waters (Emelyanov & Shimkus 1972; Dominik & Stoffers 1979) apparently did not deposit clay minerals in significant amounts in the eastern basin. During and after the deposition of sapropel S-5 clay mineral wind transport must have exerted a stronger influence on the clay mineral deposition in the Levantine Sea, as the clay mineralogy of cores recovered in the outer periphery of the Nile Cone and further west displays a significant enrichment in kaolinite.

The cores recovered in the periphery of the Nile Cone display, upwards within the sapropel lithofacies S-4, the most elevated smectite + kaolinite sum plus the lowest I/K ratio due to the enhanced kaolinite contents (Fig. 6). It is recalled that during the warming trend of the lower part of Stage 3 which ended in-between events 3.3 and 3.13 according to the detailed chronology of Martinson et al. (1987) in the marine record spans the interval from 59,930 to 44,829 yr BP. During this period there is unequivocal evidence for enhanced rainfall throughout the Nile drainage system. At such times it is also very probable that an additional drainage region, especially between Darfur and Tibesti (Fig. 1), comprising the eastern Sahara Desert along the western flank of the main Nile, became incorporated into the Nile drainage due to the activation of large river valleys — wadis (Burke & Wells 1989; Szabo et al. 1989) bringing enhanced kaolinite together with numerous wadis draining the eastern Desert–Red Sea to the east that further increased the supply of smectite and kaolinite. All these factors could have increased significantly the supply of sediment into the Lower Nile. Nilotic provenance assemblages are relatively elevated up to within the S-3 lithofacies in the Nile Cone cores (Fig. 7). West of Cyprus there is a marked illite (mainly Mg-rich trioctahedral-celadonite) and chlorite (possibly including serpentinite) content increase (Fig. 6) suggesting enhanced clay mineral contributions from local sources in Cyprus and/or northeastern Mediterranean Sea during the S-4–pre S-2 statigraphic interval (Fig. 6, core TR-172–19). The I/K ratio displays higher values in the stratigraphic interval between the sapropel layers S-3 and S-2. The accumulation of the sediments between the S-3 and S-2 sapropels coincides with the end of marine oxygen isotope Stage 3 (Bard et al. 1990) which is characterized by a sea-level drop below −80 m. Further to the West, core CHN-119–6 does not reveal any significant clay mineral variation within the post S-4–pre S-2 stratigraphic interval.

Towards sapropel layer S-2, the deposition of which is placed around 23,500 yr BP (Stanley & Maldonado 1977), all the studied cores show a more or less pronounced decrease in the Nile clay mineral assemblages. Moreover, especially in the distal eastern Nile Cone cores (CHN-119–31 and CHN-119–32, Fig. 7) there is a marked increase in the illite/kaolinite ratio caused by enhanced illite percentages. This is attributed to a stronger anticyclonic gyre of eastern Mediterranean surface waters, driven by the strengthening of westerly wind directions (Rognon & Williams 1977) bringing more illite from the northeastern Mediterranean sources. Nevertheless some old (27,000–25,000 yr BP) Nile River terraces (Butzer & Hansen 1968b; El Atar & Jackson 1973) and boreholes from the delta (Weir et al. 1975) reveal lower values of smectite and enhanced illite when compared to overlying uppermost Pleistocene and Holocene sediments.

The sediments between sapropel lithofacies S-2 and S-1 in all studied cores which present the lowest Nilotic province clay assemblages (Figs. 6, 7) display an increase of illite-micas. This increase is regular over the entire Nile Cone area and is more pronounced in the 23,000 to 18,000 yr BP stratigraphic interval (core CHN-119–31, Fig. 7) which is also characterized by a sharp decrease of gravitational sediment input on the Nile Cone area as demonstrated by Maldonado & Stanley (1981). The adjacent to the east Israel–Sinai shelf (Stanley et al. 1997, 1998) most probably provided enhanced contributions of clay minerals such as illite and mixed layers. Moreover in the wider Nile Cone area and its present day Nile Delta this time interval is characterized by higher percentages of kaolinite (Maldonado & Stanley 1981; Abdel Wahab & Stanley 1991). Although enhanced illite contents suggest a general decrease of soil formation, both in upstream and downstream areas (Chamley et al. 1986) this assumption, on the basis of the observed sediment yield, cannot be concluded for the Nile drainage system. Adamson et al. (1980) and Williams & Adamson (1980) pointed out that the relatively dry, cold conditions around the Nile headwaters between 20,000 and 13,000 yr BP and low total but high peak discharges by the Nile drainage, are consistent with high sediment input to the headwaters and the downstream aggradation as far as Egypt.

Thus there are indications suggesting that there was a decrease in the amount of suspended sediment carried into the East Mediterranean by the Nile, despite the fact that the total sediment yield may have been high. The enhanced kaolinite content in the stratigraphic interval under discussion may be due to wind transport of kaolinite (Chester et al. 1977; Stanley & Wingerath 1996). The increased I/K ratio and the lowest percentages of the sum of Sm + K during the post S-2 to pre S-1 stratigraphic interval might record both the diminution of the supply of suspended sediment by the Nile added to the effects of a lowering base level of erosion during the last major sea-level drop, around 18,000 yr BP (Berger et al. 1985). As a result the climatic signal that may be inferred from the changes in the composition of clay minerals is believed to have been severely reduced during major sea-level cycles as demonstrated by Chamley (1983). Such effects were even more dramatic in the case of the Nile Delta where, during this time span, eustatic changes involving fluctuation ranging from a maximum low to a maximum high sea level entailing an extensive migration of the Nile Delta depocenters on the Egyptian shelf (Summerhayes et al. 1978; Coutellier & Stanley 1987). Clay mineral studies of the

Nile Delta (Abdel Wahab & Stanley 1991) suggest that the Late Pleistocene Nile River transported northward growing proportions of kaolinite and decreasing amounts of smectite. Moreover due to the transgressive erosional phase the post 18,000–pre 12,000 yr BP time span in the Nile area is characterized by similar clay mineralogy.

However, the most pronounced clay mineral variations in this stratigraphic interval occur in core TR-172-19 which consistently displays the highest I/K ratio (Fig. 6). Moreover, in this core, sediments between the sapropels S-2 and S-1 contain a high percentage of random mixed layers most notably of illite-smectite. The enhanced supply of illite and mixed layers is most plausibly attributed to the input of increased amounts of clay minerals derived from Cyprus and its margin (Fig. 8). The margin south-southwest of Cyprus is characterized by low upper Quaternary sedimentation rates (Buckley et al. 1982) plus intense recent tectonic activity (Anastasakis & Kelling 1991). Thus sediment erosion and removal during the main low sea-level stand at about 18,000 yr BP, reaching the deeper layers in near coastal areas is demonstrated by similar cases elsewhere (Diester-Haas & Chamley 1980). The illite plus mixed layers enrichment in core TR-172-19 requires a mechanism for clay mineral transport from the Cyprus shelf into the Levantine area. The most plausible mechanism is a strengthening of the anticyclonic, sub-basin scale gyre known to exist west-southwest of Cyprus (Moskalenko 1974; Gerges 1977; Ozsoy et al. 1989; Robinson et al. 1991). Thus it apperars that during major sea-level falls, like during Stage 2, surrounding exposed continental shelfs to the north and the east of the Nile Cone had an enhanced impact on the clay mineral composition of the southeastern Mediterranean Sea.

The distribution pattern of the clay mineral groups within the uppermost sapropel layer S-1 reflect an abrupt and increased influence of clay minerals of Nilotic provenance, especially smectite (Figs. 6, 7). In the southwestern Levantine Sea (core CHN-119-6, Fig. 6) the increase of smectite, within the S-1, is accompanied by a concomitant increase of illite, mostly derived from the eastward inflow of Ionian illite-rich waters (Dominik & Stoffers 1979). This illite enrichment diminishes west of Cyprus and does not affect the clay mineralogy of the Nile Cone cores (see also Maldonado & Stanley 1981) which displays an additional enrichment in smectite and kaolinite further east. This stratigraphically latest change in the clay mineralogy of the studied cores records the extraordinary amount of suspended sediments brought into the southeastern Mediterranean Sea by extensive Nile River floods. After 12,500 yr BP, an extensive overflow from Lake Victoria (Fig. 1) into the White Nile and higher rainfalls in Ethiopia (Adamson et al. 1980) drastically affected sedimentation in the Nile Cone area resulting in a proportional increase in the role of hemipelagic sedimentation (Stanley & Maldonado 1977).

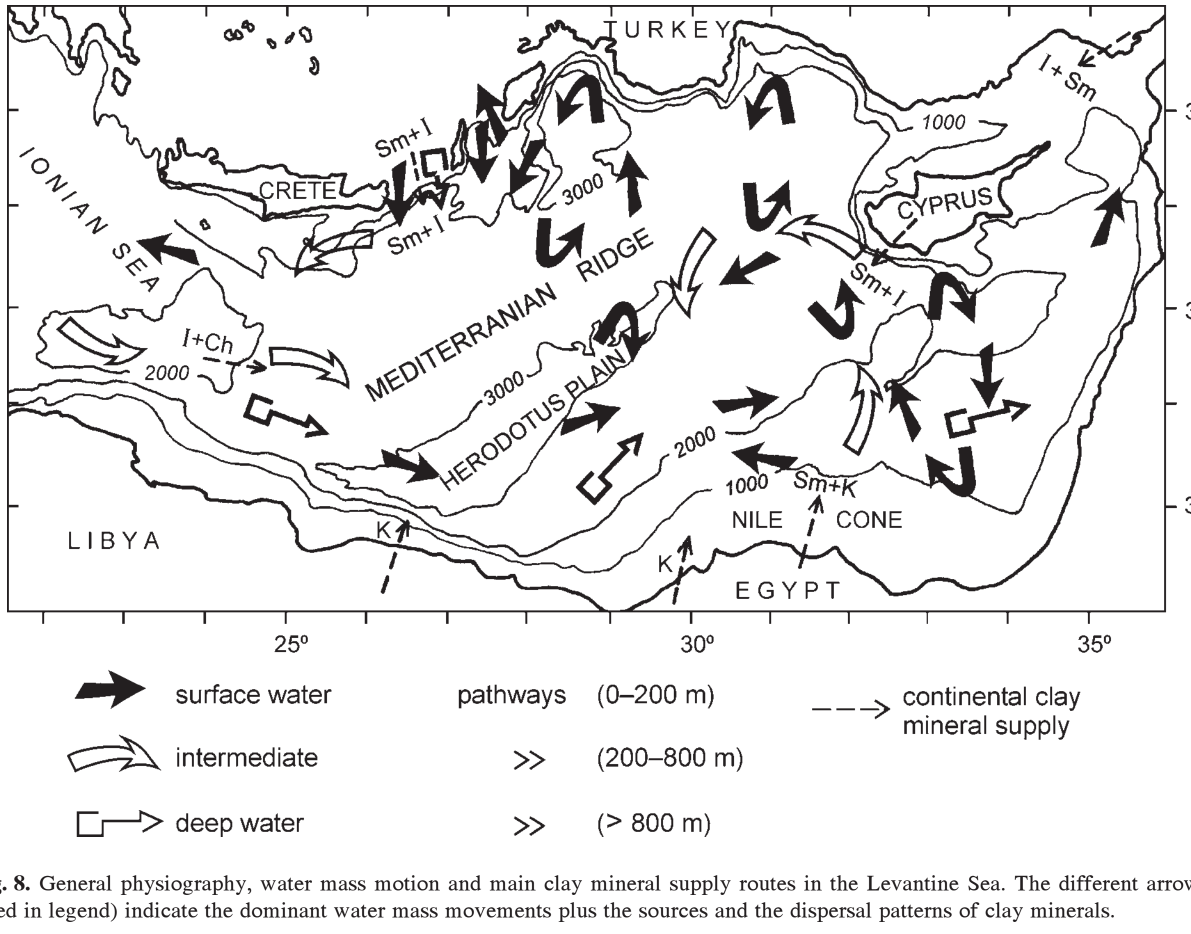

Fig. 8. General physiography, water mass motion and main clay mineral supply routes in the Levantine Sea. The different arrows (defined in legend) indicate the dominant water mass movements plus the sources and the dispersal patterns of clay minerals.

Radiocarbon dating of southeastern Levantine cores indicate that accumulation of the sapropel S-1 begun at about 11,800 yr BP (uncorrected C14 dates, Anastasakis & Stanley 1986), which roughly coincides with Nile flooding that caused a significant increase of smectite and to a lesser extent, kaolinite contents. This enhanced Nile assemblage influence persists throughout the sapropel S-1, whose deposition ended at about 7000–6000 yr BP. Post S-1 sediments display reduced sums of smectite and kaolinite but the relative percentages of kaolinite tend to increase. This is an indication that after 7000 yr BP the relative contribution of wind blown kaolinite increased.

Summary and conclusions

The vertical clay mineral fluctuations in cores recovered in the Nile Cone that are dominated by upper Quaternary hemipelagic sedimentation reflect the supply of suspended matter yield by the Nile. The most pronounced increase in proportions of the Nile derived clay minerals resulted from significantly enhanced suspension loads conveyed by the Nile River during the transition from dry to wet climatic periods. Smectite and kaolinite are the predominant clay minerals of Nilotic East African (Ethiopian) origin. The pronounced abundance of these clays infers a Nilotic provenance that is recorded within and in between sapropel layers S-5 and S-4. These correspond to a time interval ranging between 70,000 and 45,000 yr BP and mark the transition in the marine sediments from the cold Stage 4 to a warming trend displayed by the lower part of Stage 3 (Imbrie et al. 1984). The Nile drainage system experienced a similar phase resulting in a dramatic increase of the Nile suspension load into the eastern Mediterranean Sea. As a result, clay mineral assemblage within the sapropel S-5 reveals the highest contribution of smectite and kaolinite associated with extremely low I/K ratios. For sapropel S-4, the eastern Nile Cone displays high contents of smectite and kaolinite while westwards, in the Levantine Sea, there is a sharp increase in the I/K ratio. This resulted from the maximum wet phase, which affected the Nile drainage system, intensified around 45,000 yr BP and probably activated numerous wadis especially along the western flank of the Lower Nile. The observed westward increase, within the S-4, of the I/K ratio is a strong indication that there was a gradual increase of the Levantine waters that brought a larger amount of illite from the northwest. Upwards, within the sapropel S-3, the proportions of Nile clay minerals slowly declined in the Nile Cone and so recording the decrease of suspension delivered by the Nile into the Levantine Sea. This resulted from the dry phase experienced by the White Nile drainage basin coupled with the continuing humid conditions that prevailed over the Blue Nile and Atbara Depression and led to a net reduction of the suspension delivered by the Nile. The pronounced lower percentages of smectite and the significant increase in illite contents observed between sapropels S-2 and S-1 indicate both a diminution of the sediment delivered by the Nile into the Levantine Basin and the enhanced contribution of the surrounding continental shelfs to the North and the East due to lowered sea level. The last major sea-level drop around 18,000 yr BP lowered the base level of erosion and increased the proportion of illite-micas plus mixed layer illite-smectite. Hence the climatic signal that would have been inferred from the clay mineral changes is severely obliterated. The pronounced increase in the Nile clay mineral assemblages within the S-1 reflects the dramatic increase of suspended sediments delivered by the Nile and related to extensive floods in the drainage systems, from about 12,500 to 6000 yr BP. After 6000 yr BP enhanced contributions of wind blown kaolinite are recorded.

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