Clay Mineral Distributions to Interpret Nile Cell
Provenance and Dispersal: I. Lower River Nile to Delta
Sector
Daniel Jean Stanley and Jonathan G. Wingerath

INTRODUCTION

Egypt, positioned in the northeastern Sahara desert, depends primarily on a single fluvial source, the River Nile, for its freshwater needs (HOWELL and ALLAN, 1994). Closure of the High Dam at Aswan in 1964 and subsequent control of downstream Nile flow have had profound effects on transport processes and on the volume and nature of sediment carried by the river between upper Egypt and the Mediterranean Sea. These factors directly affect agriculture and aquaculture along the Nile valley and delta and thus are clearly of concern to Egypt, which now has the lowest arable land per capita of any country in Africa (BISWAS, 1993). The river below the dam has become ever more vital to the country’s rapidly increasing population, at present nearly 60 million.

The amount of fine sand and coarse silt bedload carried by the Nile to the coast has been greatly reduced since closure of the High Dam, and only a small volume of silt and clay presently bypasses the Nile delta lagoons to the sea (LOIZEAU and STANLEY, 1993, 1994). The dam affects not only the Nile valley and delta, but sedimentation in areas to the east of the Suez Canal as well. Although nearshore currents continue to transport sediment toward Sinai, Gaza, and Israel, dispersal is increasingly disrupted by a number of structures constructed along these shores.

A highly populated and politically sensitive southeastern Mediterranean region is undergoing substantial environmental modification as a result of interaction between natural and anthropogenic forces. Of note is the recent development of a large port facility on the Nile delta coast near Damietta, dredging of the new Suez Canal bypass east of Port Fouad and harbor construction farther to the east at and near El Arish in northeastern Sinai where the Egyptian Government has formulated plans for accelerated development. Coastal protection structures, marina, port and ship docking facilities already constructed along the Israeli margin are modifying nearshore dispersal and locally induce coastal and inner shelf erosion (NIR, 1982; NIR and ELIMILECH, 1990). In addition, plans to modify the Gaza coast are now being evaluated. The long-term ramifications for these northeastern African and Levant coastal sectors have, as yet, to be clarified.

ABSTRACT


Clay minerals serve as petrological markers that can be used to measure and interpret ongoing changes in River Nile sedimentation, now largely affected by anthropogenic influences. Closure in 1964 of the High Dam at Aswan, in particular, has entailed marked changes of clay mineral assemblages along the Nile in Egypt. Size-sorting phenomena, for example, are noted in the Nile delta; reduced grain size of sediment carried by altered Nile water flow patterns across the delta plain in part accounts for increased proportions of smectite in this sector and at the coast. However, most clay assemblage changes between southern Lake Nasser and Cairo are primarily the result of recently altered source terrains and dispersal patterns along this fluvial system rather than textural factors. The new delta forming in southern Lake Nasser contains typical River Nile (smectite-rich) clay mineral assemblages. In contrast, central and northern Lake Nasser contains higher proportions of kaolinite, derived through wave erosion of the lake margin and from wind transported material. The highest proportion of kaolinite in the Nile assemblage is recorded at Aswan.

This kaolinite is derived from suspended sediment in Lake Nasser waters dispersed through the High Dam and from scouring of kaolinite-rich pre-Holocene deposits below the river below the dam. These kaolinite assemblages are deposited at least as far as Middle Egypt, about 350 km north of the dam. Relative percentages of kaolinite below Qena likely decrease as a result of progressive downriver input from smectite-rich pre-dam Nile channel and bank deposits; these eroded materials attenuate important amounts of kaolinite transported northward by the Nile. It is predicted that enhanced proportions of kaolinite will be recorded downstream of Cairo within fifty years and to the Mediterranean coast of the Nile delta by the end of the next century.

ADDITIONAL INDEX WORDS: Aswan, clay minerals, Egyptian shelf, High Aswan Dam, Lake Nasser, Levant margin, new lacustrine Nile delta, Nile delta, Nile littoral cell, Nile sediment transport.
It is unfortunate that few systematic petrological studies were made of Nile River sediments prior to closure of the High Dam. Perhaps the most noteworthy is by Shukri (1950), who detailed the heavy mineral composition of the sand fraction between the Nile headwaters and the coast. However, no comprehensive mineralogical study has been made of silt and clay, the two volumetrically dominant size fractions transported by the Nile, before and since 1964.

This is the first of a three-part study focusing on present distributions of clay minerals in modern sediments of the southeastern Mediterranean. The clay fraction is likely to be transported farthest away from the major Nile source region and from eroded coastal sectors to and north of the Israeli margin (Figure 1). In this first part of the study, we concentrate on the nature of clay mineral distributions in the modern River Nile which until recently was the primary transporter of sediments to the southeastern Mediterranean (Hurst, 1952). Special attention is paid to the Nile sector between the reservoir in southern Egypt and the Mediterranean coast north of Egypt (Figure 1, inset). Here we would expect to identify major changes induced by closure of the High Dam and sediment entrapment in the reservoir and accelerated flow of the sediment-depleted Nile below the High Dam. Clay mineral changes would also be expected farther downstream, north of Cairo, as a result of reduced river flow through the increasingly complex irrigation channel and canal drain pathways constructed across the delta.

The second investigation will present results on the clay mineral composition in modern rivers and tributaries, or rividis, in the Sinai, Gaza and Israel (Stanley, in preparation). The fluvial sources are an integral but much reduced part of the Levant provenance system. Sediment is dispersed in a counter-clockwise direction upon reaching the marine environment in the easternmost Mediterranean. Transport is primarily to the east, off Egypt and Sinai, and to the north, off Gaza and Israel. On the basis of the two provenance studies,
the third study will consider offshore distributions of clay minerals along the coast and on the shelf from the Nile delta eastward to the northern Israeli margin.

Our investigations of clay mineral distributions have been initiated to better define the ongoing coastal evolution between southern Egypt and northern Israel. Most specifically, clay minerals are viewed in these investigations as sediment provenance and dispersal indicators, which provide further precision in defining ongoing coastal changes in this region. Mapping of clay mineral distributions on the North African and Levant margins should identify mineralogical baseline markers useful to accurately assess the coastal evolution in a region which is increasingly affected by man's intervention.

BACKGROUND AND NILE LITTORAL CELL

As early as 450 BC, Herodotus recorded that the Nile was the dominant source of sediment transported to the southeastern Mediterranean. In his The History (Book Two, 2.5) he wrote: "For the nature of the land of Egypt is this: as you approach it and are still within one's day run from land, and you drop a sounding line, you will bring up mud, though you are in eleven fathoms' depth. This shows that the deposit of earth reaches even as far as this." Twenty-four centuries would elapse before the first systematic effort was made, in the 1970s, to monitor changes along the Nile delta margin. Teams of coastal specialists were supported by international organizations and the Egyptian government's Coastal Research Institute in Alexandria (UNDP/UNESCO, 1976, 1977, 1978). These surveys emphasize the complex interaction among morphological, physical oceanography and sedimentary factors affecting this coastline.

It is known that most large sources of fluvial sediment entering the Mediterranean during the Holocene are positioned on the northern coast of this nearly land-locked sea. Until emplacement of two dams at Aswan in southern Egypt, during this century, the most important source of sand and finer sediment provided to the southern, more arid Mediterranean was the Nile, flowing to the northeastern African margin (Emelyanov, 1972; Ross and Uchupi, 1977; Stanley, 1977; Adamson et al., 1980). This south-to-north flowing river has its headwaters in central Africa and the Ethiopian Plateau, is 6,800 km-long, and crosses 35° of latitude.

Since the end of the Miocene the Nile has formed a thick (> 3,000 m), extensive depocenter on Egypt's northern margin (Saied, 1981). This is comprised of two portions, the subaerial Nile delta on the Egyptian coast (Stanley and Warner, 1993) and, farther to the north, the much larger submarine Nile Cone on the continental slope and rise (Ross and Uchupi, 1977; Maldonado and Stanley, 1979). Nile Cone deposits of upper Pleistocene age were emplaced by the Nile during the last low sea level stand (maximum low elevation at about ~120 m below mean sea level) approximately 20,000 to 18,000 years ago. At that time, Nile sediment was shed northward from a shelf-edge delta north of Alexandria (Chen and Stanley, 1993) and accumulated as a series of deep-sea fans on the slope and rise (Stanley and Maldonado, 1977; Maldonado and Stanley, 1979; Mait, 1993).

Holocene deposits did not form the Nile delta we recognize today until the rate of eustatic sea-level rise began to decelerate about 7,500 years ago (Stanley and Warnk, 1993, 1994). By ~6,000 years BP, coastal physical oceanographic and sediment transport regimes similar to present ones were established in our study area (cf. Anastasakis and Stanley, 1986). Wind-driven coastal and geostrophic currents have induced a prevailing easterly flow (Lacombe and Tchernia, 1960, 1972) along the eastern North Africa margin since that time. During the subsequent six millennia, sand has been displaced eastward along the inner shelf and the Sinai and Gaza coasts to the northern Israeli margin (Emery and Neev, 1960; Goldsmith and Golik, 1980; Nir, 1984). A highly arid climate influencing this region and the Nile system has prevailed during the past 5,000 years (Adamson et al., 1980). Finer-grained sediment, derived from the Nile and introduced by eolian transport (Venkataraman and Ryan, 1971; Chester et al., 1977), has been carried in suspension as far north as Turkey by the counter-clockwise eastern Mediterranean geostrophic eddy (Miller, 1972).

Sediment transport and depositional patterns of the coast and shelf in this region have been quantified by a model defined as the Nile littoral cell (Inman and Jenkins, 1984). This compartmentalized sedimentation system, approximately 700 km long, extends from the Alexandria region in Egypt to Akko on the northern part of Haifa Bay, Israel (Figure 2). The model attempts to incorporate the complete cycle of littoral sedimentation in this region, including provenance and sources, transport dispersal paths, and depositional sinks. Inman and Jenkins (1984) summarized the budget of deposition for pre-Aswan High Dam time. Their model emphasizes displacement of sediment, derived primarily from the River Nile, to the Nile delta coast, and then eastward to the Levant margin. Most studies of the Nile cell focus primarily on volume of sediment displaced, texture, and sand composition. Moreover, all investigations to date infer that the quartz-rich sand on the coast and shelf off Gaza and Israel is primarily of River Nile derivation (Rim, 1951; Emery and Bentor, 1960; Emery and Neev, 1960; Pomehancolum, 1966; Goldsmith and Golik, 1980; Inman and Jenkins, 1984; Nir, 1984; Golik, 1993). A first, or Low Dam, was constructed in 1902 on the Nile in Upper Egypt just south of Aswan. Its height was raised in 1907 and again in 1929. This structure, and more so the High Dam constructed in 1964, have seriously disrupted the natural flow of the Nile to the coast. Consequently, sediment dispersal has been altered in the southeastern Mediterranean Sea (Sharaf el Din, 1977). The quality of sediment carried downstream by the Nile before the High Dam's embankment varied annually (Hurst, 1952), and averaged 160 × 10^6 tons/year suspended load, plus ~2–18 × 10^6 tons/year bed load during a 60-year period (1903–1963). The average grain size of suspended sediment load in the River Nile during flood months in 1955 to 1963 was: 25% sand; 42.5% silt; and 32.5% clay (Queleoune and Kruk, 1976).

At present, less than 2% of the Nile's sediment load bypasses Lake Nasser (Figure 3A) and the High Dam at Aswan (Queleoune and Kruk, 1976; Inman and Jenkins, 1984) and, of this, the proportion of silt and clay has increased relative to sand. Barrages at Esna (Figure 3C), Naga Hammadi
and Asyut control Nile flow (Waterbury, 1979; Elassouti, 1985) and, to some extent, affect sedimentation between the two dams and Cairo. North of Cairo, the river's natural pattern is further disrupted by the Mohammed Ali delta barrage at Imbaba (Figure 4A). Sediment is no longer carried by the two Nile distributaries, the Damietta and Rosetta, as far as their principal outlets (Damietta and Rosetta promontories) on the coast. Therefore, the lower Nile coastal plain can no longer be considered an active, prograding delta (Stanley and Warne, 1993).

An increasingly complex irrigation network of canals and drains north of Cairo distributes fresh water across the entire delta but with reduced flow velocity and sediment load. Moreover, delta barrages placed across the two Nile distributaries positioned about 30 km from the coast, at Paraskour on the Damietta branch and at Edfina on the Rosetta branch, block most of the remaining flow of fresh Nile water from the sea.

In fact, marine water now reaches inland to as far as the delta barrages via these once-important distributaries (Figure 4B, C). What little sediment is presently transported to the sea is discharged primarily through outlets of Manzala, Burullus and Idku lagoons and pumping of Lake Maryut water to the sea at Alexandria (Stanley and Warne, 1993; Loizeau and Stanley, 1993, 1994).

As direct consequence of these large-scale anthropogenic influences, there has been a marked decline of Nile-derived sediment carried to the delta coast during this century (Friedy, 1988). At the same time, the coast has continued to be subjected to natural processes, including strong coastal currents, winter storm waves to >2 m, land subsidence rates ranging from 1 to 5 mm/year, and continued sea-level rise (Stanley, 1990). Together, these factors have caused an accelerated rate of erosion at both Nile promontories (locally to > 150 m/year) and retrogradation of several extensive sectors.
Nile Clay Mineral Distribution

Figure 3. Photographs in southern Egypt showing: (A) irregular configuration of the Lake Nasser margin north of Abu Simbel (1987); (B) swiftly flowing, sediment depleted Nile, below the two dams at Aswan (1977); and (C) barrage across the Nile at Esna which further controls River Nile flow in Upper Egypt (1987).

of the delta coast (INMAN and JENKINS, 1984; FRIHY, 1988; SMITH and ABDEL-KADER, 1988). As much as $30 \times 10^6$ tons of sediment (average for 1972–1976) are lost each year from the delta’s shoreline to an offshore depth of 6 m (INMAN and JENKINS, 1984).

It is assumed by most workers that the eroded sediment continues to be transported eastward (NEEV et al., 1987). This trend is borne out in a general way by petrologic studies of both coarse- and fine-grained surficial sediment north of the Egyptian coast (VENKATARATHNAM and RYAN, 1971; SUMMERHAYES et al., 1978; MALDONADO and STANLEY, 1981; MURRAY et al., 1981), and east of the delta, on the Sinai, Gaza and Israel margins (POMERANCBLUM, 1966; NIR and NATHAN, 1972; NIR, 1984).

The present nature of the transport regime in the study region is surely more complex than the summary provided above. For example, what proportions of sediment now displaced eastward onto the Levant margin are essentially of Nile derivation? Results from a recent study of transparent heavy minerals, for example, indicate that sediment on coastlines east of Bardawil lagoon on the Sinai coast differ progressively from Nilotic suites in a direction away from the Nile delta (STANLEY, 1989). This suggests that during eastward displacement of Nile material there is probable incorporation of sediment supplied locally from eroded coastal and inner shelf sectors and perhaps by wind and Levant rivers. The premise of the present investigation is that clay components of the extant Nile littoral cell may serve as sensitive markers of provenance and dispersal changes, especially considering how the High Dam at Aswan is modifying the regional sedimentary regime.

**METHODOLOGY**

The positions of the 59 surficial samples collected for this study along the River Nile channel floor and banks, in the delta between Cairo and the coast and in wadis flanking the Nile valley across the length of Egypt are shown in Figure 5. Samples reported on here were collected in September, 1990 and February, 1992 and include 19 channel, 20 bank, and 20 wadi samples.

The proportions (by weight) of clay (<2 μm) plus silt (2–63 μm), sand (63–2,000 μm) and granule (>2,000 μm) were determined by sieving a representative cut of each bulk sample. From a separate cut, the <1 mm fraction was analyzed for grain size parameters, including percentage of clay (by volume) and grain size statistics (mean, mode, median) using a Coulter LS-100® laser particle size analyzer. These data are listed in Tables 1 and 2.

The clay-sized fraction (<2 μm), separated by decantation and concentrated by centrifugation, was prepared as smear slide for X-ray diffraction analysis (these semi-quantitative data are listed in Tables 1 and 2). We used a Philips Norelco diffractometer with a copper target and nickel filter at settings of 48 kV and 20 mA and a scanning speed of 1°28/minute. Samples untreated, glycolated and heated (to 550 °C for 1 hour) were analyzed. Proportions of clay minerals were determined by using measurements proposed by MOORE and REYNOLDS (1989), and a method discussed by PIERCE and SIEGEL (1969): integrated intensity of the 17 A glycolated peak is equal to relative amount of smectite; the area under the 10 A peak (glycolated trace) multiplied by 4 is equivalent to the relative amount of hydromica, including the illite group; and the area under the 7 A peak is multiplied by 2 for the relative amount of kaolinite plus chlorite. Mixed-layered illite/smectite is recognized in most samples, but not discussed here. Palygorskite was detected in one sample. In this study, we focus primarily on the proportions of the three dominant mineral groups forming the assemblages in this region, smectite, kaolinite and illite. Further information on methodology and instrumentation is provided by STANLEY and LIYANAGE (1986) and ABU-ZEID and STANLEY (1990). The complete set of diffractograms is archived at the Smithsonian’s U.S. National Museum of Natural History in Washington.
Summarized in Table 3 are clay mineral data for samples collected in Recent deposits in the study area between southern Egypt and the coast. These, published in earlier studies, include lower Nile and delta, desert adjacent to the Nile valley eolian, and Lake Nasser deposits (including the new, post-High Dam fluvial Nile delta); several Pleistocene and Pliocene sections along the lower Nile valley study area are also considered. The proportions of clay minerals have been recalculated according to the method cited above in those cases where diffractograms are clearly presented in these earlier publications. Table 3 also provides averaged numerical data calculated from Tables 1 and 2 and from clay data listings in these earlier studies.

OBSERVATIONS

Textural and clay mineral data listed in Tables 1, 2 and 3 are plotted on a series of diagrams to determine regional south-to-north trends between Aswan and the Mediterranean coast (Figures 6–11).

Downstream Textural Trends of the Nile

Results of grain size analyses of 19 channel and 20 bank samples from the Nile valley (Table 1) are plotted in Figure 6. It is of note that the largest percentages (~14–29%) of granules occur in both bank and channel samples at site Nil-22 (Figure 6A). The proportion of granules in channel samples is irregular downstream from Aswan. However, from site Nil-11, about 420 km north of the High Dam, granules decrease more regularly downriver, from 6% to 0% at the coast. Moreover, granules are generally absent in bank samples north of Aswan.

The percentage of sand exceeds 85% in most channel samples between Aswan and site Nil-3, ~835 km north of the

Figure 4. Photographs in the Nile delta showing: (A) Imbaba barrage system in the southern delta, important in controlling Nile flow into the Rosetta and Damietta branches north of Cairo (1990); (B) mouth of the Damietta branch at Ras El-Bar, now filled with marine rather than river water (1987), and (C) barnacles growing on bricks along the margin of the now-saline lower Rosetta branch of the Nile, almost 30 km from the coast (1989).
High Dam; sand content is particularly variable in Nile delta distributary sites (Figure 6B). There is generally a lower proportion of sand in bank samples, but no consistent downstream trend. East bank samples contain higher percentages of sand than those of the west bank.

The percentage of silt plus clay in channel samples tends to be quite low (<5%); values increase near Cairo (~50%) and reach almost 100% at two Nile delta distributary sites (Figure 6C). In contrast, silt plus clay values in bank samples tend to decrease downriver from nearly 100% just north of...
Table 1. Percentages of major clay minerals and textural data for the Nile, and Rosetta and Damietta branches.

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Notes: CH = channel, EB = east bank, WB = west bank.
Table 2. Percentages of major clay minerals and textural data for selected wadis along the Nile in Egypt.

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<tr>
<td>Wadi-95</td>
<td>46</td>
<td>50</td>
<td>4</td>
</tr>
<tr>
<td>Wadi-96</td>
<td>28</td>
<td>30</td>
<td>42</td>
</tr>
<tr>
<td>Wadi (NI-21)</td>
<td>61</td>
<td>35</td>
<td>4</td>
</tr>
</tbody>
</table>

Aswan to ~50% at Cairo. Moreover, silt plus clay percentages are markedly higher in west bank than in east bank samples. The percentage of clay by volume in channel samples is very low (for the most part <1%); in contrast, clay percentages in bank samples are higher, vary irregularly and decrease downstream toward Cairo from >20% to <15% (Table 1). West bank samples contain considerably higher proportions of clay than those of the east bank.

The mean, median and modal grain sizes of both channel and bank samples are highly variable downstream below Aswan. Mean size values, for example, range from ~10 to 500 µm (Figure 6D). These measures show that, in almost all cases, channel samples are considerably coarser than bank samples. Also, the texture of the Nile’s east bank is consistently coarser than that of the west bank. All textural data obtained for the Nile channel and bank samples between Aswan and the Mediterranean coast are highly variable, with few distinct south-to-north trends. The most significant observations pertain to samples at site Nil-22 at Aswan, which differ markedly from those downstream; both channel and bank samples at this locality contain a significantly higher percentage of granules and a lower proportion of clay. The mean, median and modal grain size of samples at this site are generally within the range of samples collected further to the north.

Textural Comparison with Wadi Samples

The mean, median and modal grain size (fraction <1 mm) values of the <1 mm fraction of the 20 samples collected in wadis bordering the Nile valley, from south of the Aswan Dam to the Cairo region, range from ~5 to 600 µm (Table 2). These values approximate those in the River Nile (Table 1). However, the proportion of grain size fractions that comprise wadi samples (Figure 7A) differs significantly from those in River Nile samples (Figure 6). Of note in wadi samples are: higher percentages of granules, commonly exceeding 8%; somewhat higher proportions of sand, usually exceeding 50%; and lower silt plus clay percentages, with values generally <40%. Wadi re-entry (khor) sediments in Lake Nasser are
Table 3. Percentages of major clay minerals for samples examined in this investigation, and other environments analyzed by other workers in the lower Nile region.

<table>
<thead>
<tr>
<th>Sample Source</th>
<th>Location</th>
<th>Source of Data</th>
<th>Data* Derivation</th>
<th>Clay Minerals, in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile System</td>
<td>Nile Channel</td>
<td>This Study</td>
<td>2</td>
<td>Smectite: 67, Kaolinite: 22, Illite: 11</td>
</tr>
<tr>
<td></td>
<td>Nil-22 Channel</td>
<td>This Study</td>
<td>1</td>
<td>Smectite: 26, Kaolinite: 71, Illite: 3</td>
</tr>
<tr>
<td></td>
<td>Nile Banks</td>
<td>This Study</td>
<td>2</td>
<td>Smectite: 68, Kaolinite: 25, Illite: 7</td>
</tr>
<tr>
<td></td>
<td>Nil-22-Bank</td>
<td>This Study</td>
<td>1</td>
<td>Smectite: 42, Kaolinite: 49, Illite: 9</td>
</tr>
<tr>
<td>Delta</td>
<td>Wadis</td>
<td>This Study</td>
<td>2</td>
<td>Smectite: 38, Kaolinite: 54, Illite: 9</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>South Cairo</td>
<td>Abu-Zeid &amp; Stanley, 1990</td>
<td>7</td>
<td>Smectite: 77, Kaolinite: 13, Illite: 10</td>
</tr>
<tr>
<td></td>
<td>Lake Edku</td>
<td>El Sabroto &amp; Sakkary, 1982</td>
<td>4</td>
<td>Smectite: 76, Kaolinite: 14, Illite: 11</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>River Nile</td>
<td>Wahab et al., 1986</td>
<td>4</td>
<td>Smectite: 59, Kaolinite: 16, Illite: 25</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>North of Abu Simbel</td>
<td>Ahmed et al., 1993</td>
<td>3</td>
<td>Smectite: 43, Kaolinite: 40, Illite: 17</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>North of Abu Simbel</td>
<td>Hassan et al., 1979</td>
<td>5</td>
<td>Smectite: 63, Kaolinite: 30, Illite: 7</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>North of Abu Simbel</td>
<td>Higazy et al., 1986</td>
<td>6</td>
<td>Smectite: 47, Kaolinite: 51, Illite: 2</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>South of Abu Simbel</td>
<td>Hassan et al., 1979</td>
<td>5</td>
<td>Smectite: 60, Kaolinite: 19, Illite: 1</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>South of Abu Simbel</td>
<td>Higazy et al., 1986</td>
<td>6</td>
<td>Smectite: 48, Kaolinite: 51, Illite: 1</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>West of Luxor</td>
<td>Elgabaly &amp; Kadr, 1962</td>
<td>6</td>
<td>Smectite: 45, Kaolinite: 41, Illite: 14</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>Eolian</td>
<td>SE Mediterranean</td>
<td>Chester et al., 1977</td>
<td>7</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>Cairo</td>
<td>This Study</td>
<td>2</td>
<td>Smectite: 29, Kaolinite: 42, Illite: 29</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Korosko Fm</td>
<td>Butzer &amp; Hansen, 1968</td>
<td>4</td>
<td>Smectite: 37, Kaolinite: 23, Illite: 40</td>
</tr>
<tr>
<td>Pleistocene</td>
<td>Masmas Fm</td>
<td>Butzer &amp; Hansen, 1968</td>
<td>4</td>
<td>Smectite: 61, Kaolinite: 12, Illite: 27</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>Delta</td>
<td>Hegab, 1984</td>
<td>7</td>
<td>Smectite: 16, Kaolinite: 68, Illite: 16</td>
</tr>
<tr>
<td>Nile Valley</td>
<td>Lower Nile</td>
<td>Ahmed &amp; Askelany, 1989</td>
<td>7</td>
<td>Smectite: 70, Kaolinite: 30, Illite: 0</td>
</tr>
</tbody>
</table>

* Notes:
1. Derived from this study, Table 1
2. Averaged from data in Tables 1 and 2
3. Calculated from published diffractogram.
4. Averaged from more than one published diffractogram.
5. Recalculated from published data.
6. Averaged from published, tabulated data.
7. Used directly from published data.

also coarser than those in the Nile channel (cf., PHILIP et al., 1978).

River Nile Clay Trends

We summarize below the more obvious downstream trends made with regard to clay mineral assemblages in the Nile system, between southern Egypt and the Mediterranean coast.

The River Nile depositional system has been characterized along most of its length by high values of smectite. Values generally approximate 60% (see, for example, Figure 8A; also EL ATTAR and JACKSON, 1973; MORST, 1981; WAHAB et al., 1986). However, data reveal a diminution of this mineral from about the latitude of Abu Simbel in Lake Nasser (positioned about 280 km south of the High Dam), to site 19, about 86 km north of the dam (Figure 8A). A significant finding along this 310-km long stretch is the markedly increased proportion of kaolinite relative to both smectite and illite.

Smectite percentages decrease from a maximum of ~80% in southern Lake Nasser, to as low as 43% behind the High Dam, to ~26% at channel site Nil-22 below the dam at Aswan (Figures 8B and 9). Smectite content in Nile channel samples remains low (~50%) to site Nil-14 (307 km north of the dam), then increases substantially downstream (Figure 6A) to ~75% at site Nil-9 before reaching a high value of ~84% in the Rosetta branch near the coast. From Aswan to site Nil-11, proportions of smectite in channel samples are usually lower than those in bank samples; farther downstream, the
Figure 6. Graphs showing downriver (south-to-north) Nile textural trends: (A) % granules; (B) % sand; (C) % silt plus clay; and (D) mean grain size, in μm. Data from Table 1.

Figure 7. Wadi sample (A) textural trends and (B) clay mineral distributions, from south to north. Data from Table 2.

Figure 8. Comparison of 3 diffractograms (glycolated samples): (A) smectite-enhanced assemblage typical of River Nile deposit, site Nil-20 channel; (B) kaolinite-rich River Nile assemblage below the High Dam, Aswan channel site Nil-22; and (C) kaolinite-rich wadi sediment, Wadi-49.
Figure 9. Clay mineral histograms of (A) Nile channel and (B) bank samples (left and right banks, averaged).

The proportion of smectite in the channel becomes higher than that in banks (Figure 9) of the study area. Overall highest relative percentages of smectite are recorded in the Nile delta (see also WEIR et al., 1975; EL SABROUTI, 1984).

Proportions of kaolinite increase from as low as ~20% in southern Lake Nasser, to 30–50% behind the dam, to ~70% at site Nil-22 at Aswan (Figures 8B and 9). The highest values of kaolinite (inversely proportional to those of smectite plus illite) are found along a short distance between the High Dam and Aswan. This mineral then decreases to ~22% at site Nil-20 (~30 km below the dam), increases to ~30% at site Nil-19, and then decreases progressively to <25% downstream near the coast. Kaolinite percentages in channel samples downriver of site Nil-13 (360 km north of the dam) approximate those of samples recorded by other workers and are deemed typical of the lower Nile and delta system (see Table 3). Proportions of kaolinite in bank samples closely parallel those of channel deposits below the High Dam (Figure 9).

Proportions of illite, in contrast to kaolinite and smectite, have a much more limited range: ~1% in southern Lake Nasser, 2–17% behind the High Dam, ~3% in the channel just below the dam, and generally <15% along the lower Nile and delta to the coast (Figure 9). Highest values in the Nile channel (>16%) are recorded along the Nile between sites Nil-19 and Nil-11, in the large river bend at Qena (~29% at site Nil-14; see Figure 5). Proportions of illite are generally higher in Nile channel than in bank samples, but differences become attenuated downstream, particularly between Nil-13 and Cairo.

The kaolinite/smectite + illite ratio, calculated for channel and bank samples, reveals that values decreased from ~1.0 to 0.3, from site Nil-22 to Nil-20 (Figure 10). Values remain constant from about 350 km downstream (Nil-13), just below the River Nile bend at Qena to Cairo. North of Cairo, ratio values fluctuate and indicate a decrease locally in the proportion of kaolinite relative to illite and smectite in the delta (Table 1, Figure 9).

Wadi Tributaries of the Nile

In contrast to River Nile sediment (Table 1), most wadi samples contain less smectite (<50%) and illite (<10%), and more kaolinite (>40%). There is a considerable variability of clay mineral values among wadis (Figure 7B). Notable in this respect are assemblages in wadi samples from about 100 km south to 100 km north of the dam in the Aswan region. In this sector, approximate clay mineral percentages range as follows: smectite, from 9–70%; kaolinite, from 21–87%; and illite, 0–42% (Table 2).

Plotting these data on a ternary diagram, with smectite, kaolinite, and illite as end-members, serves to distinguish the River Nile channel and bank from wadi samples (Figure 11A). Nile channel samples are generally characterized by somewhat higher percentages of illite than are the bank samples. The ternary data points also reveal that channel and bank samples, as a group, contain higher proportions of smectite than do wadi samples. In contrast, most wadi samples contain higher percentages of kaolinite than do the Nile channel and bank samples.

Other Environments in the Lower Nile Region

Our clay mineral data on wadi samples and Nile channel and bank samples are compared with clay mineral data for this region obtained from other studies (Table 3). This information is plotted on a second ternary diagram, using smectite, kaolinite and illite end-members (Figure 10B). Modern environments considered are River Nile and Nile valley, Nile delta, Lake Nasser, new delta in Lake Nasser and eolian.
Data for selected Pliocene and late Pleistocene sediments are also plotted.

Of note are the wadi, eolian, desert, Lake Nasser and Nil-22 samples which, as a group, plot toward the >40% kaolinite sector of the diagram. In contrast, data from most samples in the River Nile, Nile delta and new Nile delta in Lake Nasser plot closer to the smectite end-member. The diagram also shows that eolian samples and several river Nile, late Pleistocene and Pliocene samples contain high proportions of illite.

**MAJOR SOURCES OF NILE CLAYS IN EGYPT**

Clay minerals transported northward by the Nile into Egypt are derived primarily from the Blue Nile and Atbara river headwaters in the Ethiopian Plateau and from the White Nile in central Africa. The Ethiopian highlands contribute at least 70% of the Nile’s discharge and most of its sediment load north of Khartoum (Hurst, 1952; Shukri, 1950; Foucault and Stanley, 1989). The clay assemblage transported across Egypt and to the Mediterranean coast by the Nile prior to and shortly after closure of the High Dam was composed of >50% smectite and complemented by smaller proportions of kaolinite and illite (El-Attar and Jackson, 1973) and mixed clay minerals.

Smectite, in large part derived from volcanic terrains in Ethiopian highlands drained by the Blue Nile and the Atbara River, was transported during the Holocene to the Nile delta and farther north, to the contiguous Egyptian shelf and Nile Cone (Butzer and Hansen, 1968; Fayed and Hassan, 1970; Venkataramnam and Ryan, 1971; Weir et al., 1975; Khalil and Noman, 1981; Maldonado and Stanley, 1981; El Sabrouti and Sokkary, 1982; Stanley and Liyanage, 1986).

As observed in this study (Table 1), the east Nile bank samples are consistently coarser than those of the west bank, recording powerful discharge from the Red Sea Hills. In fact, most of the large wadis that join the Nile valley in Egypt are fluvial systems that drain the high-elevation Red Sea Hills to the east and cross Eastern Desert terrains. With rare exception, the wadis are now dry (annual rainfall in the region is < 100 mm) and most of these byways have not provided a significant sediment supply to the Nile during the past ~5,000 years, i.e., since the time of aridification in the middle-late Holocene (Murray, 1951; Hurst, 1952; Butzer and Hansen, 1968; Adamson et al., 1980; Paulissen and Vermeersch, 1989). In late Pleistocene to early Holocene time, however, valleys drained the Red Sea Hills east of the Nile valley and a few cut across the Eocene plateau and Nubia Sandstone terrains west of the Nile (cf. Philip et al., 1978; Howell and Allan, 1994). These served as floodways for substantial volumes of sediment introduced to the Nile valley. Strong evidence in support of this lateral dispersal during the late Quaternary is provided by studies of the Nile terrace and bank deposits.
NILE SEDIMENT ENTRAPMENT IN LAKE NASSER

It would be expected that the much altered Nile flow resulting from closure of the High Dam induced marked textural and compositional changes of river sediments. However, it is not known to what extent this structure and control of river flow has modified clay mineral assemblages. Unfortunately, the petrology of the river's sediment was not systematically analyzed prior to or shortly after emplacement of the structure. The most obvious changes recorded since the late 1960's are in response to the sudden decrease in flow velocity of the river as it enters the standing body of water behind the dam, known in Sudan as Lake Nubia and in southern Egypt as Lake Nasser (Figures 1 and 3A). This decreased velocity releases most of the river's sediment load, beginning in the southern sector of the reservoir and extending northward (ENTZ, 1976; MANCY and HAFEZ, 1983; ELDARDIR, 1994). More than 98% of the sediment (including most of the coarse silt and fine sand bed load), which earlier was transported downriver all the way to the delta and coast, is now retained in the lake.

Consequently, a new Nile delta, about 200 km long and for the most part subaqueous, has formed between Dal Cataract in Lake Nubia and Abu Simbel in southern Lake Nasser (Figure 12). It primarily contains Nile fluvial sediment, largely of Ethiopian derivation. In contrast, the ~280 km-long lake floor sector between Abu Simbel and the High Dam to the north has accumulated very little sediment since 1964 (MANCY and HAFEZ, 1983).

A series of studies has called attention to the dramatically decreased volume of bed and suspended load (ENTZ, 1976; SHALASH, 1982; ELDARDIR, 1994), reduced bed load grain-size (MORSY, 1981; ELDARDIR, 1994), marked changes in organic matter and planktonic content (ENTZ, 1976; MANCY and HAFEZ, 1983; ELDARDIR, 1994), and altered geochemical properties (HASSAN et al., 1979; ELSOKKARY, 1992; Ahmed et al., 1993) in the waters of northern Lake Nasser and the Nile below the dam. Clay and fine silt are now the major textural fractions transferred from the lake to the lower Nile north of the High Dam.

INCREASED KAOLINITE CONTENT IN NORTHERN LAKE NASSER

Sediment with the typical smectite-rich fluvial Nile clay assemblage has accumulated in the new Nile delta in Lake Nubia and southern Lake Nasser (HASSAN et al., 1979; HIGAZY et al., 1986). In contrast, a 280 km-long stretch of Lake Nasser floor, extending north of the new Nile delta to the High Dam (Figures 1 and 3A), has been one of overall low fluvial sediment accumulation from post-1964 Nile flow (ELDARDIR, 1994). It is of special note that kaolinite has mark-
edy increased relative to smectite in deposits filling central and northern Lake Nasser (HASSAN et al., 1979; HIGAZY et al., 1986). We interpret this and other changes of clay mineral assemblages in lake bottom sediments to be the result of several processes that have prevailed since emplacement of the High Dam.

It is proposed here that cumulative influences of lake margin erosion and addition of eolian material have resulted in deposition of a kaolinite-rich assemblage on the northern lake floor during the 28-year period, from 1964 to date of sampling in 1992. Especially in winter and spring, wind in the reservoir region sweeps adjacent desert terrains (MURRAY, 1951; ENTZ, 1976) and releases into the lake (average width, 12 km) a clay and fine silt load, abundant in kaolinite (cf. CHESTER et al., 1977). An example of the high kaolinite content in wind-blowen deposits is recorded by the composition of a khamsim silt storm deposit collected in 1992 by the senior author (STANLEY, 1993) in Cairo (Table 3; Figure 11B). Kaolinite-rich deposits in the Fayoum depression (WAHAB et al., 1988) may be one potential source of this mineral.

In addition to this wind-borne supply, kaolinite-enriched material, including weathered soils (ELGABALY and KHADR, 1962; BUTZER and HANSEN, 1968; AHMED and ASKALANY, 1989; AHMED et al., 1993), is eroded by wave action (ELDARDIR, 1994) along the lake shore and wadi re-entries, or khors. Wave-eroded, kaolin-enriched lenses in the Nubia formation (Upper Cretaceous age), including those exposed in the Kalabsha khor along the western lake shore margin (ISSAWI and OSMAN, 1993), are also a potentially important source of kaolinite. Evidence of seasonally-intensified wave erosion is provided in part by lake water turbidity measurements (ELDARDIR, 1994). Some of these silt- and clay-sized sediments are displaced from the wave-eroded lake margins to the deeper central lake floor, formerly the main channel of the Nile. Kaolinite-rich wind-borne and eroded lake shore material is also distributed in the seasonally stratified water of the lake (cf. SHALASH, 1982; ELDARDIR, 1994) and transported northward as suspended load.

Together, these processes account for markedly increased proportions of kaolinite in lake-bottom sediments accumulating in the low deposition lake sector north of Abu Simbel (Figure 13). We surmise that some of this kaolinite-rich clay assemblage in the northern part of Lake Nasser, derived from adjacent desert terrains and some wadis, is carried northward toward the High Dam (Figure 13). The suspended sediment in the water column behind the dam contains terrigenous material of fine silt to clay size, plus an organic fraction, mostly phytoplankton (ENTZ, 1976; ELDARDIR, 1994). Some of these fines are eventually carried by lake water to the High Dam’s diversion canal and through the turbine tunnels positioned above the lake floor (cf. UNITED ARAB REPUBLIC, 1964; ELSHAER, 1983). This pattern of dispersal, directly related to the dam, contributes to the accumulation of the kaolinite-enriched clay assemblage at Aswan site Nil-22 (Figures 8B and 9). It is also of note that channel and bank samples at Aswan are comparable to some kaolinite-rich wadi samples along the Nile valley of Upper Egypt, such as wadi-77 and -90 (Table 2; Figure 7).

Figure 13. Schematic highlighting sediment dispersal, from south to north across Egypt, and summarizing downriver changes in clay mineral assemblages. Lake configurations and delta channels and drains are exaggerated for emphasis. See discussion in text.

KAOLINITE FROM SCOUR BELOW THE HIGH DAM

The turbulent, swiftly-flowing and almost sediment-free Nile water, discharged from the turbines, scours the channel floor below the dam as it flows swiftly toward Aswan (Figure 3B) and farther to the north (GASSER and WAHY, 1983; STMONS and LI, 1983). Evidence of scour is discerned by our grain-size analyses which show that the river channel floor at Aswan (site Nil-22) is characterized by a fine pebble- and granite-sized cover (Figure 6A). The “armor layer”, expected below a dam of this type, is the coarsest deposit we observed along the present lower Nile channel in Upper Egypt (Table 1).

Scouring action, particularly intense between the dam and Aswan, has eroded some Quaternary fluvial sequences underlying the Nile channel (cf. LITTLE, 1965; BUTZER and HANSEN, 1968) and has also locally exposed Aswan plutonic
rocks (Figure 3B). Many of the pre-Holocene sections in this region contain higher proportions of kaolinite than do late Holocene to modern Nile fluvial deposits (cf. Britzen and Hansen, 1968). Thus, it is likely that erosion of some late Quaternary and older Nile fluvial strata, underlying and below the dam and formerly exposed north of the structure and in adjacent wadis, is providing an additional source of kaolinite to the modern Nile (Figure 13).

CLAY MINERAL CHANGES BETWEEN THE DAM AND NILE DELTA

To interpret clay mineral assemblages and their distributions below the dam, it is necessary to consider the possible influence of textural effects such as size-sorting. It is recognized that clay minerals are of different sizes. For example, smectite is smaller than kaolinite. Thus, if size-sorting were the dominant factor in controlling proportions of clay minerals in a downstream direction, a reasonably close correlation would be expected among textural attributes and composition. This textural effect is noted primarily in Nile delta sediments where generally high proportions of smectite (69–84%) are a response to reduced grain size deposited in the delta plain. This is in contrast with the absence of distinct textural trends and highly irregular grain-size patterns, including percent silt plus clay (Figure 6C), along the River Nile south of the delta. Grain size and moment measures do not correlate with recorded downstream clay mineral composition (Figures 9 and 10).

From our observations, it appears that size-sorting and textural effects per se are not the dominant factors. Most important are altered post-High Dam source terrain and provenance and process as related to bank and channel erosion and downriver transport of older reworked fluvial deposits. It is primarily these latter phenomena which account for the increased proportion of kaolinite and reduced content of smectite below the dam at Aswan, increase of illite near Qena, and increase of smectite from below the large river bend north of Qena (Figure 5) to Cairo and the Nile delta.

Kaolinite-rich clay mineral assemblages are particularly useful markers of altered provenance and dispersal patterns resulting from the High Dam and altered Nile flow. For example, the volume of kaolinite-rich suspended sediment supplied from the Lake Nasser side of the dam to the scoured Nile channel below is quite small. Nevertheless, this transfer of material is the major factor resulting in high kaolinite values (to 71%) at Aswan. Also of note are the kaolinite-rich wadis, entering north and south of the dam, potentially adding this mineral to the Nile system. Moreover, it may also explain the higher than typical River Nile values of kaolinite detected in this study as far north as site Nil-13, about 350 km north of the High Dam, i.e., below Qena and the large river bend of the Nile in Middle Egypt.

We also note that, in contrast to kaolinite-rich deposits at Aswan, much clay-size sediment presently carried by the river from Qena to Cairo and the delta retains a typical pre-dam Nile clay assemblage with a high smectite content. We surmise that the sediment load along this stretch of the Nile apparently includes a large proportion of reworked fluvial material. A large component of fines presently displaced by the river below the dam are derived from post-1964 scours of the present Nile of its former Holocene channel and banks. These older pre-dam Nile valley deposits are characterized by higher proportions of smectite (Table 3). It appears that contribution downriver of eroded smectite-rich deposits to the Nile’s suspended and bed loads masks or dilutes the otherwise high proportion of kaolinite presently being added to the river in the vicinity of the High Dam. For this reason, we observe a clay assemblage between Cairo and the delta that closely resembles the pre-dam Nile assemblage.

Ilmatite also records the effects of some recent sedimentation patterns below the dam. Particularly high values of this mineral occur between sites Nil-16 and Nil-14, about 200 to 300 km north of the dam. These high proportions indicate active erosion by the river of illite-rich Holocene and older deposits south of and along the large Nile bend in the Qena region. Ilmatite in this region was likely derived from the Proterozoic terrains in Red Sea Hills to the east (Coleman, 1993), and transported to the Nile Valley via large tributaries that flowed westward to the Qena region in Pre-mid Holocene time.

CLAY MINERALS TO MEASURE ANTHROPOLOGICAL CHANGES

Changes in clay mineral assemblages in the Nile in Egypt, between Lake Nasser and the coast, denote sectors of the river in Upper and Middle Egypt which have been affected by closure of the High Dam and other anthropogenic activity (Figure 13). To date, the most significant factors modifying the clay assemblages are: (1) formation of the new lacustrine Nile delta in Lake Nubia and southern Lake Nasser; (2) increased lake margin erosion and capture of wind transported material which particularly affect deposition and suspended sediment content in northern Lake Nasser; (3) scouring of the Nile channel, particularly below the dam; (4) input of scoured and reworked (pre-dam) channel and bank deposits between Aswan and Cairo; and (5) reduced flow across the delta resulting in a diminished sediment load of fine grain size carried from the Nile to the coast.

Kaolinite is a particularly useful marker mineral for interpreting present sediment dispersal. We expect that the distribution of enhanced proportions of kaolinite will continue to extend progressively northward along the Nile channel; i.e., from the already-modified Aswan to Qena sector ~350 km north of the dam in Middle Egypt, toward Cairo ~600 km farther downriver (Figure 10). Observation of somewhat increased expansion of kaolinite values northward will depend in part on two factors: the amount of river erosion and reworking, below the dam, of older smectite-rich bank deposits which mask the otherwise relatively high kaolinite fluvial load. Monitoring the distribution of kaolinite- versus smectite-enriched Nile deposits and their texture at channel and bank stations positioned along the Nile will serve to measure the rate of response to ongoing sediment transport changes occurring below the dam. On the basis of observations made in this study, we predict that increased proportions of kaolin-
ite, progressing northward at 10 km per year, will be recorded at Cairo within fifty years.

Monitoring of clay mineral changes north of Cairo will be more difficult. Most of the Nile water below the barrage at Imbaba no longer flows across the delta to the coast through the Rosetta and Damietta distributaries. Rather, river flow is diverted, with considerable loss of water, through a highly complex irrigation network and then across the Nile lagoons before it reaches the coast. It is not likely that kaolinite enrichment from Lake Nasser and the dam area will be traced at the Mediterranean coast before the end of the twenty-first century.

In all such interpretations, it is necessary to consider the limiting factors of clay mineral data: numerical values are, at best, semi-quantitative ones and mineral content is generally recorded as relative percentages. As a result, clay mineral values are inversely related, such that high proportions of kaolinite are accompanied by low smectite plus illite and vice versa. We find it useful to employ clay mineral ratios (such as in Figure 10) to help determine ongoing downstream Nile trends. Moreover, to more accurately assess changes in fine-grained sediment below Aswan will require supplementing clay mineral data with measurement of other parameters.

Geochemical trace elements (ELSOKKARY, 1992; SIEKEL et al., 1994) and pollen content of Nile water and deposits are promising.

This record of modern clay mineral assemblages along the Nile will be coupled with that of clay mineral patterns on land to the east, in Sinai, Gaza and Israel (study in progress). These will provide essential baselines with which to refine interpretations of ongoing sedimentary dispersal in the now anthropogenically altered Nile littoral cell.

**SUMMARY**

1. This study records the nature and locations of substantial changes of clay mineral assemblages along the lower River Nile, which have occurred between Lake Nasser in southern Egypt and Cairo to the north since the emplacement of the High Dam at Aswan.

2. Present downstream trends of clay minerals along the Nile between the High Dam and Cairo are primarily related to provenance and source terrains rather than to textural and size-sorting factors; however, in the Nile delta below Cairo, increased proportions of smectite (smaller in size than kaolinite) are primarily a function of reduced grain size of sediment carried by Nile water now diverted and moving slowly across the delta plain.

3. The new Nile delta forming in southern Lake Nasser contains the clay mineral assemblage typical of the pre-dam Nile, with large proportions of smectite and decreased amounts of kaolinite and illite; in contrast, assemblages in central and northern sectors of Lake Nasser, an area of low deposition, contain markedly increased proportions of kaolinite.

4. The increased kaolinite content in Lake Nasser results, in large part, from wave erosion of lake margin deposits surrounding the lake and from wind transport.

5. The highest proportion of kaolinite, recorded at Aswan, is derived from the suspended load of Lake Nasser waters and from scouring and reworking of kaolinite-rich pre-Holocene deposits below the dam.

6. Kaolinite-rich assemblages forming clay and fine silt fractions are transported northward by suspension in the lake, passed through the High Dam, and observed as far as the Qena region in Middle Egypt about 350 km north of the dam.

7. Proportions of kaolinite are attenuated below Qena due to a masking phenomenon, i.e., by progressive input of smectite-rich pre-dam Nile channel and bank deposits presently eroded and reworked northward by the Nile toward Cairo and the delta.

8. Unusually high proportions of illite recorded along the large bend of the Nile, in the Qena region, were originally derived from the Red Sea Hills to the east; these sediments were transported via large tributaries across the eastern desert and accumulated in the Nile valley prior to the mid-Holocene time of increased aridification.

9. Kaolinite is a useful marker mineral to evaluate the rate of Nile sediment dispersal, which is now largely altered by anthropogenic influences; it is predicted that enhanced proportions of kaolinite will be recorded at Cairo within 50 years and at the Mediterranean coast of the Nile delta by the end of the next century.

10. Mapping the distributions of trace elements and pollen along with clay minerals, in Nile waters flowing across Egypt will provide a means to more accurately measure the rate of ongoing sedimentary change below the High Dam.

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