Nile River sediment fluctuations over the past 7000 yr and their key role in sapropel development

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ABSTRACT

The provenance pattern of Nile River sediments can be used as a proxy for paleoclimatic changes in East Africa. The $^{87}Sr/^{86}Sr$ ratios are particularly appropriate for such provenance investigations, because the White Nile drains predominantly crystalline basement rocks, whereas the Blue Nile and Atbara flow off the Ethiopian Highlands, which consist of Tertiary volcanic rocks. A high-resolution profile of $^{87}Sr/^{86}Sr$ and Ti/Al ratios from a well-dated core in the Nile Delta shows a close correspondence with known changes in Nile flow over the past 7000 yr. At times of higher river flow there was markedly decreased input of Blue Nile–derived and total sediment. This change was caused by northward movement of the Inter Tropical Convergence Zone, resulting in increased vegetative cover in the Ethiopian Highlands due to higher rainfall and a longer wet season. This inverse relationship between Nile River flow and sediment flux may have had important implications in the development of agricultural technology in ancient Egypt. The marked minimum in $^{87}Sr/^{86}Sr$ at 4200–4500 yr B.P. is coincident with the end of the Old Kingdom in Egypt and provides independent evidence that demise of the Old Kingdom might have been associated with an extended period of catastrophic low floods. During the Quaternary and late Neogene, there was periodic deposition of organic-rich sediments (sapropels) in the eastern Mediterranean that represent important indicators of major environmental change. Evidence from the Ti/Al ratio suggests that the pattern of erosion and sediment supply from the Nile catchment observed in this study also occurred throughout much of the Neogene and Quaternary. The reduced inputs of Blue Nile sediment during times of sapropel formation contributed to the increased primary productivity by reducing the amount of phosphate removed on particles and to the observed change to N limitation in the eastern Mediterranean, which are important characteristics of sapropel deposition.

Keywords: paleoclimate, Nile catchment, $^{87}Sr/^{86}Sr$, sediment provenance, sapropels, primary productivity.

INTRODUCTION

The Nile River is made up from two main tributaries, the Blue and the White, which drain markedly different geologic terranes and climatic zones. Because changes in the rate of erosion in a given catchment area are controlled to a large extent by climatic conditions, it is expected that information on Nile sediment provenance can help to define changes in the paleoclimate of East Africa. Previous provenance studies used amphibole/pyroxene ratios (Foucault and Stanley, 1989) to investigate such changes, but the results were ambiguous because of problems both in dating the sediment cores (Stanley and Hait, 2000) and the limited discrimination between source areas afforded by this approach. The Nile is well suited to Sr isotope tracer studies because the White Nile catchment is dominated by crystalline basement rocks with high $^{87}Sr/^{86}Sr$ ratios, whereas the Blue Nile drains a catchment area with Cenozoic volcanic rocks with characteristically low $^{87}Sr/^{86}Sr$ ratios (Palmer and Edmond, 1989; Fig. 1).

SAMPLES AND METHODS

Subsamples of sediment were taken from core 21 at Manzala Lagoon in the Nile Delta (Stanley and Goodfriend, 1997). The chronology of this core was based on seven accelerator mass spectrometry ^{14}C (calibrated) age determinations made on individual shells and wood fragments (see Stanley and Goodfriend, 1997, for details). The sedimentation rate obtained for this core was one of the few Nile cores that was close to the hypothetical continuous sedimentation line suggested by Stanley and Hait (2000) as a gauge to compare radiocarbon age data. Furthermore, the timing of the systematic changes in isotopic ratio observed in this study corresponds closely to the timing of changes in Nile flow obtained by a variety of dating techniques, including archaeological methods (e.g., Said, 1993).

Samples of fine-grained Nile sediment were obtained upstream of Khartoum from the flood plain of the Blue Nile at Soba and Sennar and from the flood plain of the White Nile at Kalakla and Melut (Fig. 1). All samples were wet sieved through 20 μm sieves and dried at

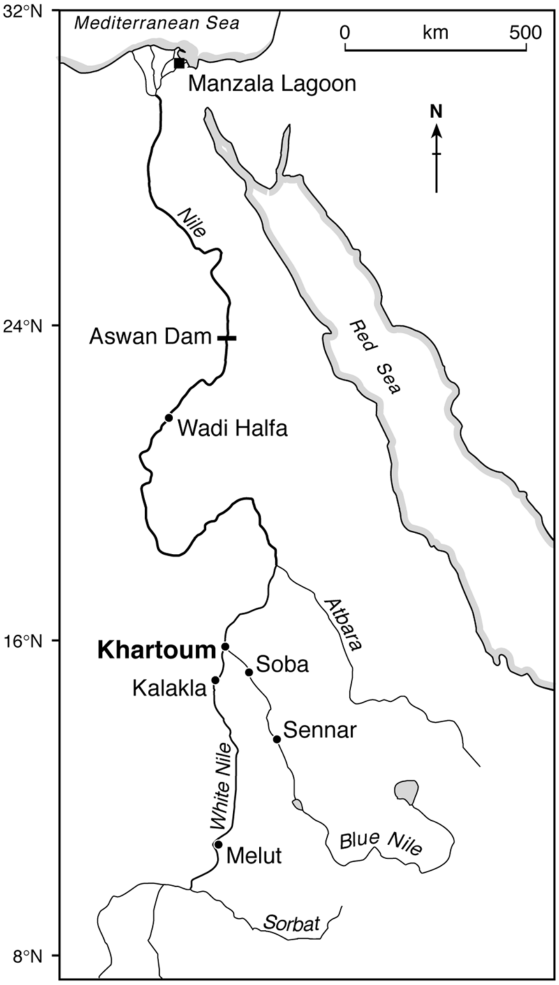

Figure 1. Map of catchment area of Nile. Samples of Nile particulate matter were obtained from floodplain of Blue Nile at Soba and Sennar and from White Nile at Kalakla and Melut. Nile Delta samples (core S-21; 49 m length) were from Manzala Lagoon (Stanley and Goodfriend, 1997).

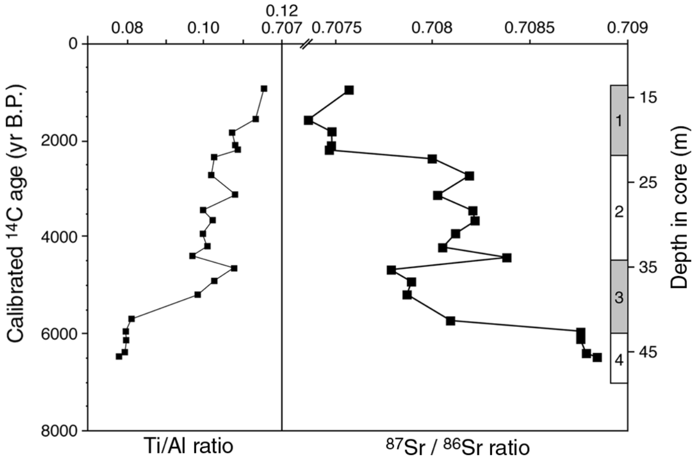

Figure 2. Depth profile of $^{87}Sr/^{86}Sr$ and Ti/Al ratios from core S-21 in Nile Delta vs. calibrated ^{14}C age. Numbered bars on right show known patterns of Nile water flow: 4—high river flow, 3—declining river flow to catastrophic minimum, 2—fluctuating moderate flow, and 1—decrease in flow to premodern levels. Acidified and leached samples show similar depth distribution, but pattern is less well defined because fewer samples were analyzed.

60–80 °C. Subsamples from the Nile Delta and Blue and White Nile particulates were ashed (450 °C) and acid leached (1.25M HCl) prior to analysis.

The $^{87}Sr/^{86}Sr$ ratio was determined by thermal ionization mass spectrometry. Major element analyses were performed on a sequential X-ray fluorescence spectrometer. Details of the analytical procedures for $^{87}Sr/^{86}Sr$ and Ti/Al were given in Krom et al. (1999a). Analytical reproducibility of bulk sediments, based on six replicates, was 4% (2σ) for Sr and 0.016% (2σ) for $^{87}Sr/^{86}Sr$. Analysis of a certified standard (BCS375) was better than 5.3% for all major elements with a total recovery of 99.1%. Only the Ti and Al results are presented in this study.

CHANGES IN SEDIMENT PROVENANCE AND NILE RIVER FLOW

The depth profile of $^{87}Sr/^{86}Sr$ (Fig. 2) in the Nile Delta shows high values (0.7088) for samples older than 6000 yr B.P. A rapid decrease in $^{87}Sr/^{86}Sr$ ratio to a minimum of 0.7078 occurs at 4670 yr B.P. The $^{87}Sr/^{86}Sr$ ratio then increases to fluctuating values between 0.7080 and 0.7082 for the period between ca. 4000 and 2350 yr B.P. A second rapid decrease in $^{87}Sr/^{86}Sr$ ratio to a relatively constant value of 0.7075 occurred between 2200 and 950 yr B.P. The Ti/Al ratios showed a similar pattern, varying between 0.075 for samples older than 6000 yr B.P. and 0.115 for the most recent samples (ca. 1000 yr B.P.).

The modern flow regime of the Nile was established at the onset of the Holocene wet phase (ca. 12 000 yr B.P.; Talbot et al., 2000), and Nile flows were high until ca. 6000 yr B.P. (Butzer, 1980; Williams and Adamson, 1980; Said, 1993). This wetter period, known as the Nabtian pluvial, affected not only the Nile and its catchment, but also large areas of the Sahel (Adamson et al., 1980), and was produced by a northward shift in the Inter-Tropical Convergence Zone (Rossignol-Strick et al., 1982). High water discharges were followed by a fluctuating decrease to a marked minimum at 4200–4500 yr B.P. (Butzer, 1980; Williams and Adamson, 1980; Hassan, 1996). This minimum was followed by a wetter period with higher but fluctuating discharge, interspersed with several periods of severe drought (Hassan, 1996). These fluctuations were followed by a decrease in flood discharges after 3100 yr B.P., leveling off at 1000 yr B.P. (Butzer, 1980; Nicholson, 1980; Woodward et al., 2001). As with previous marked changes in the Nile flow, this late Holocene decrease is also recorded by falling lake levels in Ethiopia (Gasse, 1977; Hassan, 1997) and in other parts of the Nile catchment (Adamson et al., 1980).

The $^{87}Sr/^{86}Sr$ ratio of modern Blue Nile particulates is 0.7059 (Fig. 3). This is similar to measurements made of Blue Nile water by using mollusks living in the river (0.7065; Talbot et al., 2000) and is consistent with a dominant contribution from the volcanic rocks of the Ethiopian Highlands (Pik et al., 1999; 0.7030–0.7043). Similar $^{87}Sr/^{86}Sr$ ratios were also obtained for recent sediment collected downstream of the confluence of the Atbara and main Nile in northern Sudan (0.7057 and 0.7066) and at Wadi Halfa (0.7062; Krom et al., 1999a). The measured $^{87}Sr/^{86}Sr$ ratio of White Nile floodplain sediment upstream of Khartoum (0.7150) is also similar to the $^{87}Sr/^{86}Sr$ ratio of White Nile waters (0.7095–0.7190; Talbot et al., 2000).

The observed profile of acidified and ashed samples from the Nile Delta core shows a rather simple mixing relationship between the White Nile end member and the Blue Nile end member (Fig. 3). The bulk core samples represent a mixture between these end members plus a lagoonal biogenic calcite component.

SEDIMENT FLUX TO THE DELTA

In the modern Nile River, ~95% of the sediment transported is derived from the Ethiopian Highlands (Adamson et al., 1980). By using

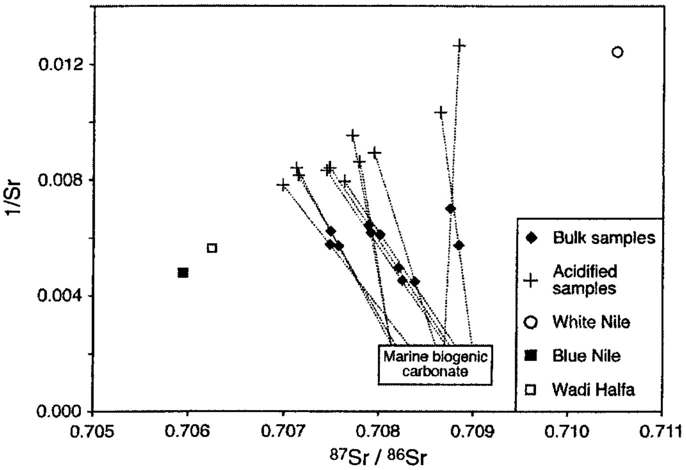

Figure 3. Mixing plot of $^{87}Sr/^{86}Sr$ vs. 1/Sr for Nile River system. Samples shown are ashed (450 °C) and acid leached (1.25*M* HCl) samples and for bulk samples from Nile Delta, together with ashed and leached samples of Blue and White Nile particulates. Plotted lines from each acidified sample through corresponding bulk sample converge at narrow range of $^{87}Sr/^{86}Sr$ and Sr content that corresponds to measured values for biogenic calcite from Nile Delta (Reinhardt et al., 1998).

a simple mass-balance calculation based on the $^{87}Sr/^{86}Sr$ ratio, it can be shown that the highest sedimentation rates (Table 1) correspond to those periods with high sediment input from the Blue Nile (1000–2050 and 4750–5650 yr B.P.) and low river flow. Conversely, the sedimentation rate was lowest between 2050 and 4750 yr B.P. and especially between 5650 and 6550 yr B.P., when river flow was higher. During the Nabtian pluvial, annual rainfall was higher and the wet season was longer in the Ethiopian Highlands (Leng et al., 1999). Pollen data have shown that the vegetative cover prior to 6000 yr B.P. was more complete than at present (Adamson et al., 1980), which resulted in stabilized slopes and reduced sediment yield. Such changes may also have increased conveyance losses of suspended sediment to the main floodplain downstream (Woodward et al., 2001). Our data show that a reduction in erosion rate and transport from the Blue Nile catchment continued until ca. 6000 yr B.P. The changes in the White Nile system have been less dramatic because its catchment has remained within a single climatic belt throughout this period.

Subsequent fluctuations in paleoclimate on a 200 yr time scale (the resolution of our data) resulted in systematic and measurable changes in the composition and amount of fluvial suspended sediment deposited in the delta. This finding has important implications for cultural development in the Nile Valley during the Holocene. It is known that fluctuations in the height of the summer flood had an important influence on the prosperity of ancient Egypt (Hassan, 1981, 1997). Our study suggests that long-term changes in the sediment load may have affected the agricultural technology that was developed to utilize the flood waters. For example, canals are more efficient at times of high flow and low sediment load. It is also noted that the marked minimum in $^{87}Sr/^{86}Sr$ at 4200–4500 yr B.P. is coincident with the end of the Old Kingdom in Egypt. This provides independent evidence that the demise of the Old Kingdom might have been associated with an extended period of catastrophic low floods (Said, 1993).

The increase in the Blue Nile component (and sedimentation rate) at 2500 yr B.P. was coincident with both falling lake levels in the Ethiopian Highlands (Gasse, 1977) and with deforestation caused by Semitic tribes invading the region (Lamb et al., 2001).

TABLE 1. SEDIMENTATION RATES IN THE NILE DELTA OVER THE PAST 6500 YR

Age intervals (^{14}C age in calibrated yr B.P.	Gross sedimentation rate (mm/yr)	Calculated sedimentation rate for Blue Nile component (mm/yr)	Calculated sedimentation rate for White Nile component (mm/yr)	Patterns of Nile water flow (from Fig. 2 legend)
1000–2050	6.9	4.3	2.6	1
2050–4750	5.0	2.0	3.0	2
4750–5650	9.1	3.8	5.3	3
5650–6550	2.9	0.6	2.3	4

Note: The ^{14}C data from Stanley and Goodfriend (1997) were used to calculate incremental sedimentation rates for periods between each of the dated depths of core 21 in Manzala Lagoon. The sedimentation rate for the Blue and White Nile components was determined by calculating the percentage due to the Blue Nile using a simple mass-balance equation and the $^{87}Sr/^{86}Sr$ mixing curve (Fig. 3). Calculated error (1σ) on gross sedimentation rate based on stated uncertainty of the individual data is $<6\%$.

PALEOCLIMATIC CHANGES IN EAST AFRICA

The sediment provenance and total sediment flux data can be used as a proxy for paleoclimatic changes in East Africa and most particularly in changes in the position of the Inter-Tropical Convergence Zone. During the Quaternary and late Neogene, there was periodic deposition of organic-rich sediments in the eastern Mediterranean. The most recent period of sapropel deposition (S-1) ended ca. 6000 yr B.P. (Thomson et al., 1999) at the end of the Nabtian pluvial. This time corresponds with a major change in the Ti/Al ratio (Krom et al., 1999a) in our data (Fig. 2). It has been shown that there is a close correlation between high Nile flow and deposition of the latest sapropel in the eastern Mediterranean (Rossignol-Strick et al., 1982). Our data show there was also reduced total sediment influx from the Nile and that the sediment composition changed to include a higher fraction of White Nile sediment at this time. It has been suggested that there was also high Nile flow during previous sapropel deposition events that corresponded to times of high summer insolation in the Northern Hemisphere caused by the Milankovitch cycle. The Ti/Al ratio and the sedimentation rate have been shown to be systematically lower during several periods of sapropel deposition in the southeast Levantine Basin (Wehausen and Brumsack, 1999, 2000), an area where the sediment is derived predominantly from the Nile (Krom et al., 1999b). Our results show for the first time direct evidence for both high Nile flow and low Nile sediment input during periods of sapropel deposition.

SAPROPEL DEPOSITION

Deposition of sapropels requires both a stagnation of the deep water (>500 m) and an increase in primary productivity (Thomson et al., 1999). At present, the eastern Mediterranean is P limited (Krom et al., 1991). Before the completion of the Aswan High Dam, the Nile was a major source of nutrients (N and P) to the eastern Mediterranean Basin (Halim, 1991). It was also a major source of fine-grained particulates (Krom et al., 1999b). Particulate labile iron reacts with phosphate and is deposited on the Egyptian shelf (Eijsink et al., 2000), and this sink represents ~30% of the total input of P to the eastern Mediterranean. In this study we have shown that during the Nabtian pluvial, the flux of Blue Nile particulates, which are much higher in total Fe (4.17% versus 1.02% in the White Nile) and labile Fe (2.42% versus 0.78%), was reduced. We conclude that during the pluvials, less phosphate would have been removed from the eastern Mediterranean by adsorption onto iron-rich particulates compared to the present, thus increasing the overall productivity of the system (Thomson et al., 1999; Calvert et al., 1992). These changes would also drive the system to N limitation, which has been shown, based on $*^{15}N$ and $*^{13}C$ of organic matter deposited across the eastern Mediterranean basin during S-5 sapropel times, to be a further characteristic of periods of sapropel deposition (Struck et al., 2001). It is thus concluded that the major changes in sediment sources and erosion pattern in the Nile basin that we have described occurred during many periods of sapropel deposition and played a key role in the environmental conditions that resulted in widespread sapropel formation.

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