by Hany Ahmed Hamroush and Daniel Jean Stanley

Paleoclimatic oscillations in East Africa interpreted by analysis of trace elements in Nile delta sediments

Instrumental neutron activation analysis of rare-earth and other trace elements in the light-mineral fraction of sands from three cores in the Nile delta provides data about climatic changes that have affected the East African headwaters of the River Nile during the past 30,000 years. The sediments of the delta originate primarily from two distinct geologic terranes and geochemical sources, one source being the Ethiopian plateau and the other being the Central African plateau. These sources are reflected by different trace-element ratios found in the sediments, and the relative contributions of sediment from these sources have varied over time depending upon climatic conditions.

Today's East African climatic belts, which are oriented in an east-west direction and differ markedly from one another, range from tropical and humid to warm and dry. These belts have oscillated north and south during the late Pleistocene and Holocene, a fact further confirmed by the distributions of chromium, scandium, lanthanum, and lutetium in the sediments, particularly the feldspars, of the Nile delta. The distributions of these trace elements reveal even greater detail about paleoclimatic oscillations than can be obtained by using heavy-mineral studies alone. (Ed.)

Figure 1.—The River Nile. A, The Nile delta, River Nile, and its tributaries, the Atbara and Blue Nile draining the Ethiopian plateau and the White Nile draining the Central African plateau. Box in A indicates area of C. B, Position of the River Nile and the present-day annual rainfall along its course (Van Chi-Bonnardel, 1973). C, Northeastern Nile delta showing the position of the studied cores.

Introduction

Instrumental neutron activation analysis (INAA) of rare-earth and other trace elements in the light-mineral fraction in sands of Nile delta sediments provides a most comprehensive and statistically reliable procedure to measure paleoclimatic changes that have affected River Nile headwaters thousands of kilometers south of the Nile delta (fig. 1A). The analytical precision and sensitivity of INAA allow for the observation of temporal variability of the absolute concentration and distribution of selected trace elements (including the rare-earth elements, REEs) in sediments, regardless of their textural composition or differences in local depositional environment. This procedure thus serves to refine stratigraphic correlation (compare Allen and others, 1989) within late Quaternary core sections from the delta. Moreover,

the availability of sand-sized light minerals in the entire late Quaternary record of the Nile valley and its delta (Hamroush and Allen, 1990) makes it possible to define better the paleoclimatic events that affected the Nile basin. Trace-element measurements on light minerals from three radiocarbon-dated sediment cores in the Nile delta document climatic changes of the River Nile headwater regions for the past 30,000 years. Chromium, scandium, lanthanum, and lutetium distributions in the light minerals of Nile delta deposits reveal four major climatic events. These events correlate closely with paleoclimatic oscillations in Africa that have been determined by other independent methods, such as studies of lake levels (Gasse and Fontes, 1989) and changes along the River Nile course in sediment yield (Adamson and others, 1980; Schild and Wendorf, 1989), grain size (Williams and Adamson, 1980), and heavy minerals (Foucault and Stanley, 1989).

Climatic belts

The Nile delta and its contiguous submarine extension, the Nile Cone, together form the ultimate repository for terrigenous deposits transported northward by the River Nile since the Pliocene (Said, 1981; Sestini, 1989). This major depocenter in the eastern Mediterranean was formed by sediments carried for more than 6,000 km across nearly 35° of latitude from south of the Equator to the Mediterranean. The river flows across markedly different climatic belts that are oriented in an east-west direction (Van Chi-Bonnardel, 1973) and range from highly humid in Central Africa to hyperarid at the eastern end of the great Sahara (fig. 1*B*). Present conditions in the Nile drainage basin, which includes Central Africa, the Ethiopian plateau, and the eastern Sahara, range from tropical and humid to warm and dry climatic extremes. East African climatic belts have migrated considerably during the Quaternary (Livingstone, 1980; Williams and Faure, 1980; Hamilton, 1982) and thus have modified Nile discharge and sediment load through time.

All studies of this region have shown that the climatic belts have oscillated north and south during the late Pleistocene and Holocene. These oscillations have been recorded, for example, by changes in sediment yield and grain size along the course of the Nile (Adamson and others, 1980; Williams and Adamson, 1980; Schild and Wendorf, 1989) and by well-defined depositional cycles (Stanley and Maldonado, 1977) that have included sapropels (Rossignol-Strick and others, 1982) in the eastern Mediterranean. These climatic shifts also are indicated by measurements of relict lake levels (Gasse and others, 1980; Gasse and Fontes, 1989) and by studies of playa and wadi deposits (Butzer, 1980; Wendorf and Schild, 1980; Banks, 1984; Haynes, 1987; Paulissen and Vermeersch, 1987; Pachur and Kropelin, 1987; Petit-Maire, N., 1988) using radiocarbon dating, ¹⁸O and ¹³C data, pollen, and vertebrate and invertebrate taxa. As a consequence of these climatic shifts, major changes have taken place in the dominant contribution of sediments from the Ethiopian plateau by way of the Atbara and Blue Nile and from the Central African plateau by way of the White Nile to the northward-flowing main Nile. Therefore, the sediments that have accumulated in the Nile delta of Egypt provide evidence of the paleoclimatic oscillations in East Africa during the past 30,000 years (Foucault and Stanley, 1989).

Amphibole index and paleoclimatic change

Provenance studies based on petrologic analyses of heavy minerals in the sand-sized fraction of sediments in the Nile delta show that the Blue Nile and Atbara rivers drain a basaltic terrane that provides very different minerals compared to those resulting from the White Nile draining largely igneous and metamorphic terranes (Shukri, 1950; Hassan, 1976). In this respect, ratios of the dominant transparent heavy minerals are useful, and one of these is the amphibole index (*I*Amph), defined by Hassan (1976) as (frequency of amphiboles/frequency of amphiboles+pyroxenes)×100. In an earlier study, high *I*Amph values indicated that more humid phases have affected the Ethiopian plateau in the past, values that imply longer and heavier rainy seasons and denser vegetation cover (Foucault and Stanley, 1989). It would appear that an increased vegetal cover reduces erosion and removal of sediments. Thus, wetter conditions would have resulted in a decreased sediment load carried by the Blue Nile and Atbara rivers, even if their discharge were to have increased.

The decreased sediment load in the Blue Nile and Atbara rivers can be demonstrated by a study of heavy-mineral ratios in sediment

cores (Smithsonian Institution borings S-36, S-7, and S-22) that, on the basis of radiocarbon dating, range from about 30,000 years B.P. to the present. The cores for this study were selected at three diverse localities (fig. 1*C*) from a suite of about 100 borings available in the northern Nile delta (Stanley, 1990; MEDIBA, 1991). The *I*Amph values were measured for a total of 93 samples from the three cores. The vertical *I*Amph distribution is shown in relation to radiocarbon-dated lithostratigraphic sections for the three cores (fig. 2). The *I*Amph values reveal a comparable tendency in the three cores, that is, an overall decrease from the late Pleistocene to the early Holocene (segment A to B in fig. 2), followed by a general increase between 7,000 and 4,000 years B.P. (segment B to C in fig. 2). This variability is attributed to paleoclimatic oscillations in East Africa that controlled River Nile discharge and relative sediment-load contributions. The vertical distribution of *I*Amph values correlates closely with lake level variations, such as those of Lake Abhe (fig. 1), the Ziway-Shala basin (fig. 1), and Lake Chad (north-central Africa; see Van Chi-Bonnardel, 1973). For example, high *I*Amph values between 7,000 and 4,000 years B.P. (compare Foucault and Stanley, 1989; fig. 2) correspond to a period of high lake levels (Gasse and Fontes, 1989). Note, however, that the *I*Amph data for core S-36 are much less obvious than are the data for cores S-7 and S-22 (fig. 2), although all these core sites were fed by the River Nile during a comparable time period.

Problems do exist in using heavy minerals for paleoclimatic interpretation in the Nile drainage basin, because they are not always present in sufficient abundance and because their proportions are very small compared to the total bulk of sediments (usually <1 percent of the sand-sized fraction). Their abundance is irregular and subject to modifications by local transport processes, particularly in active depositional sectors like deltas. Moreover, because there are only a few main transparent heavy-mineral components, their proportions and ratios are of limited statistical reliability.

Instrumental neutron activation analysis

INAA of the light-mineral fraction of the sand-sized sediments provides a much more comprehensive and statistically reliable procedure to measure paleoclimatic changes in terrigenous sediments (Allen and others, 1989). Feldspars are particularly good because they usually occur in much greater abundance than do the heavy minerals. And because almost all the Nile delta core samples contain ample amounts of light minerals of sand size, the INAA procedure lends itself particularly well to the study of the Nile basin. INAA can reveal the temporal variability in the relative distribution of numerous trace elements (including the REEs) in the light-mineral fraction. In the case of the Nile basin, this would record the input from specific source terranes located in distinct geographic areas.

The advantage of using INAA in this study of Nile delta cores is the possibility of analyzing a sample whether it comprises several hundreds to thousands of grains of light minerals of sand size or only a few grains. The method does not require special sample treatment or any chemical solutions and, therefore, keeps the contamination level to a minimum (Haskin and others, 1971). It is a reproducible and nondestructive technique, so samples can be reanalyzed as needed. It also has an advantage over X-ray fluorescence, which limits examination primarily to the surface of a grain. In INAA, the penetration of neutrons through a series of grains results in the activation of the entire sample. Thus, the method is used to analyze the bulk of a sample and not just the surface of selected grains. The REEs, along with many other trace elements such as chromium (Cr), cobalt (Co), hafnium (Hf), scandium (Sc), thorium (Th), and uranium (U), occur at low concentrations in silicate minerals and oxides found in geologic materials. Nevertheless, INAA can measure accurately the above elements

in small samples in parts per million or even parts per billion, and values are in absolute concentrations, not relative percentages.

In this study, 90 samples of the light-mineral fraction of the sand-sized sediments (35, 23, and 32 samples, respectively, from cores S-36, S-7, and S-22) were subjected to INAA in order to measure the concentrations of Cr, Co, Hf, Sc, Th, and U, as well as cerium (Ce), europium (Eu), lanthanum (La), lutetium (Lu), neodymium (Nd), samarium (Sm), terbium (Tb), and ytterbium (Yb), in parts per million (ppm), and the percent of iron oxide. The concentrations for each of the measured elements are compiled in computer listings, and 15 elemental ratios have been plotted graphically against depth and time for the 3 cores (all data are in MEDIBA, 1991).

Results of INAA

As mentioned earlier, sediments in the Nile delta are derived largely from two distinct geologic terranes and geochemical sources. Compilations of geochemical data on average trace-element abundances in different types of rocks (Fairbridge, 1972) indicate that Cr occurs in markedly different concentrations in basaltic rocks (such as those of the Ethiopian system) compared to concentrations in granitic and quartzitic rocks (such as those of the Central African system). Thus, differences in trace-element distributions as a function of time would be expected in Nile delta sediments, and diagnostic trace-element ratios would highlight changes in the relative sediment contributions from these different Nile sources.

In this study, we focus on two trace-element ratios of selected elements: Cr/Sc and La/Lu. Analyses of changes through time of the lanthanides, such as La and Lu, and of some other trace elements, such as Cr and Sc, should be particularly revealing for interpreting the geochemical characteristics of Nile delta deposits. From the data in table 1, it is apparent that, in the case of greater sediment-load contributions from the Ethiopian system, one would expect high values for the ratio of Cr/Sc in sediment samples of the Saharan Nile and its delta and low values of the La/Lu ratio. In contrast, higher contributions of sediments from the Central African system would likely result in lower values of the Cr/Sc ratio and higher La/Lu ratios in delta samples.

A major value of the INAA procedure is that ratio values are independent of each other. The relative distribution of the two ratios as a function of time indicates that the two may increase or decrease in an opposite fashion (such as the peaks in fig. 3 that are indicated by numbers 1 to 5). In some cases where the two ratios show an opposite behavior, such as peaks 1, 2, and 3, we see a marked increase in the Cr/Sc ratio and a decrease in the La/Lu ratio. This pattern indicates a predominance of sediment flux contributed from the Ethiopian plateau at these times. In contrast, peaks 4 and 5 that have a high La/Lu ratio

indicate a prevalent sediment-load contribution from Central African sources. Most of the above listed peaks are present in the three cores, and we consider these to be time-correlatable events.

In the case of the Holocene record, events marked by peaks 3 and 4 span a time period from about 7,000 to 4,000 years B.P. (see fig. 2). In the late Pleistocene record, the event marked by peak 2 spans a period from younger than 24,000 to older than 14,000 years B.P., the latter being based on a radiocarbon date in core S-7. The event marked by peak 1 has not been dated by the radiocarbon method, but on the basis of data available from correlated sections in other cores, it is older than 25,000 years B.P. (MEDIBA, 1991).

The event marked by peak 4, clearly denoted in figure 3, correlates well for this time period with the high *I*Amph peaks in cores S-7 and S-22 but not with *I*Amph data in core S-36 (fig. 2). The high *I*Amph values were interpreted previously (Foucault and Stanley, 1989) as a record of a humid phase in Ethiopia, which also is supported by a high lake level of Abhe V (Gasse and Fontes, 1989).

The INAA data reflect greater detail about the corresponding climatic conditions than can be determined from heavy-mineral studies and *I*Amph values. For example, each wet phase in the Nile headwaters in the Ethiopian plateau should be recorded by the geochemical characteristics of Nile delta sediments as follows. Initially a sharp increase is seen in the Cr/Sc ratio as sediment increases from the Ethiopian plateau, and this is followed by an increase in the La/Lu ratio and a concurrent decrease in the Cr/Sc ratio as increased vegetal cover causes a decrease in sediment transported from this plateau. This is manifested in the Holocene record of the Nile delta at times of peaks 3 and 4 in the three cores, which coincide with a high lake level (Abhe V) in the Ethiopian plateau.

In the case of the late Pleistocene, a marked paleoclimatic event is denoted by peak 2 in the three Nile delta cores. The high Cr/Sc ratio correlates with the high lake level of Abhe III (Gasse and Fontes, 1989) in the Ethiopian plateau. However, the subsequent increase of the La/Lu ratio is not accompanied by a concurrent decrease in the Cr/Sc ratio. This could indicate the following events. The time span from about 17,500 to 13,000 years B.P. was one during which the sediment-load contributions from the two major Nile headwater sources were both affected by the same climatic conditions (drier than now). Thus, both Cr/Sc and La/Lu ratios would have behaved in a parallel fashion. Subsequently, a climatic event (humid phase) seems to have occurred in Central Africa at about 12,500 years B.P. This event, denoted by the high lake levels in Lake Victoria of east-central Africa (Adamson and others, 1980; Williams, 1982; fig. 1), also is recorded in Nile delta deposits by the increase of the La/Lu ratio, as particularly well indicated in core S-7. As the wet climatic phase continued, the development of an increased vegetal cover would have induced a decrease in the sediment-load contribution from Central African sources.

Table 1.—Elemental concentrations in four rock types

[Data taken from Fairbridge, 1972, p. 278–280]

Rock type	Chromium ¹	Scandium ¹	Lanthanum ²	Lutetium ²		
	Cr	Sc	La	Lu	(Cr/Sc)	(La/Lu)
Ultramafic	1,600.00	15.00	0.91	97.94	106.67	0.01
Basaltic	170.00	30.00	137.73	588.24	5.67	0.23
Granitic (high-calcium)	22.00	14.00	413.21	1,078.53	1.57	0.38
Granitic (low-calcium)	4.10	7.00	505.06	1,176.47	0.59	0.43

¹ Values are in parts per million (ppm by weight).

² La and Lu absolute concentrations are normalized to concentrations in chondritic meteorites: La, 0.330 ppm; Lu, 0.034 ppm.

Figure 2.—Amphibole index (IAmph) patterns plotted along radiocarbon-dated lithostratigraphic sections (values at arrows in years B.P.) of cores S-36, S-7, and S-22 (simplified from MEDIBA, 1991).

Figure 3.—Instrumental neutron activation analysis (INAA) patterns plotted along lithostratigraphic sections of cores S-36, S-7, and S-22 (simplified from MEDIBA, 1991). A, La/Lu ratio distribution pattern. High La/Lu values indicate a high sediment-load contribution from the Central African plateau. La and Lu

absolute concentrations are normalized to concentrations in chondritic meteorites: La, 0.330 ppm; Lu, 0.034 ppm. B, Cr/Sc ratio distribution pattern. High Cr/Sc values indicate a high sediment-load contribution from the Ethiopian plateau. Arrows in A and B locate radiocarbon-dated sections shown in figure 2.

INAA as used in trace-element analysis of light minerals serves to refine stratigraphic correlation between late Quaternary core sections in the Nile delta. This, the first such analysis applied to the Nile drainage basin, shows that INAA is the most sensitive method for detecting climatic events, including those that affected distal source headwaters thousands of kilometers away from the Nile delta depocenter. Moreover, we expect that this procedure will serve to detect any possible input of sediment from other sources, such as the Red Sea hills, that enters the course of the main Nile between the two Nile headwater sources and the Mediterranean Sea.

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