Late Quaternary Environments in the Nile Basin

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Abstract The Late Quaternary history of the Nile has been reconstructed using well-dated sedimentary, stable isotope and fossil records and associated archaeological remains. The White Nile flows over the bed of an ancient lake dating to ~ 400 ka (Marine Isotope Stage 11). High flood levels in the White Nile since that time appear to coincide with times of sapropel accumulation in the eastern Mediterranean. During times of aridity, the most recent phase being roughly coeval with the Last Glacial Maximum, the large lakes in Uganda either dried out or were too low to provide flow into the White Nile, which became a highly seasonal river, as did the main Nile.

The sediments of Lake Albert, from where the White Nile starts its long journey to the Mediterranean, preserve critical evidence on the discharge history of this river. The lake's sedimentary record confirms the coincidence between overflow of Lake Victoria and reestablishment of flow in the White Nile north of Khartoum at ~14.5 ka and also shows a lake low-stand at ~ 4.2 ka that, by cutting off flow to the White Nile, may have contributed to the fall of Egypt's Old Kingdom. The modern hydrological regime in the Nile was thus re-established at ~14.5 ka, with strengthening of the summer monsoon and overflow from Lake Victoria. A modest number of calibrated radiocarbon ages on White Nile gastropod shells indicate that White Nile levels were high around 14.7–13.1 ka, 9.7–9.0, 7.9–7.6, 6.3 and 3.2–2.8 ka. The Blue Nile and main Nile flood records, albeit less complete, accord with those of the White Nile. Preliminary OSL ages obtained by us from the upper 2 m of dunes west of the White Nile and main Nile show discrete phases of Holocene dune activity that seem to correlate with at least three of six significant periods of rapid global climatic change during 9–8, 6–5, 4.2–3.8, 1.2–1.0 and 0.6–0.15 ka, the first five of which coincided with polar cooling and tropical aridity. The intervals in between were wetter in the tropics and, allowing for dating errors, tally reasonably well with the intervals of high White Nile floods identified here.

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1 Introduction

Big rivers provide useful sedimentary records of past environmental changes and the Nile is no exception (Williams et al., 1998). The Nile is the longest river in the world (ca 6,670 km), spans 35 degrees of latitude (3°S to 32°N) and crosses a climatic gradient from equatorial to Mediterranean. It also has the longest historic flood record of any river in the world (Hassan, 1981). The Nile consists of three very distinct hydrological systems: the Ugandan headwaters and White Nile, the Ethiopian headwaters and Blue Nile, and the main or Saharan Nile (Fig. 1a). The Blue Nile rises in the volcanic uplands of Ethiopia (Fig. 1b) and flows through a

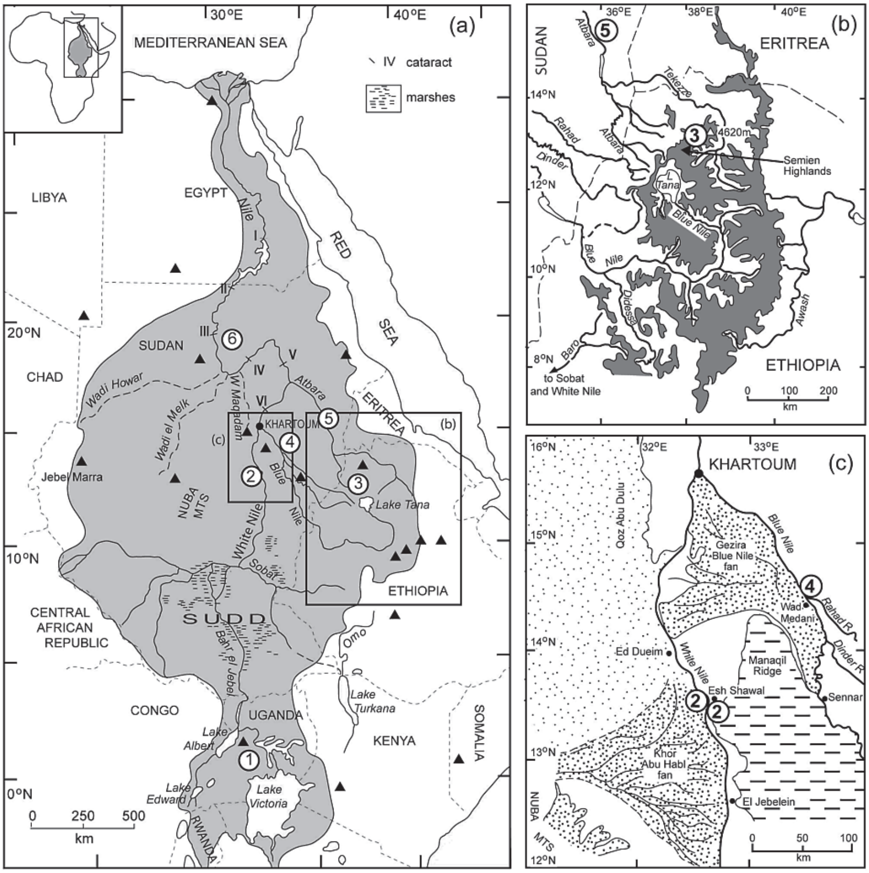

Fig. 1 Location maps. (**a**) Locations 1–6 are discussed in the text (*numerals in white circles*). The dark grey shading shows the extent of the Nile basin. Black triangles show localities already studied by the two authors. (**b**) Detail of the Blue Nile headwaters. The dark shading represents land >2,000 m, dashed lines show international boundaries. (**c**) Detail of lower White and Blue Nile. Light stippling indicates sand sheets and dunefields, heavy stippling alluvial fans, and dashed infill the Manaqil Ridge

gorge nearly 2 km deep and 35 km wide, from which it has eroded some 100,000 km^3 of rock (McDougall et al., 1974; Gani et al., 2007), before it emerges from the highlands onto a vast alluvial fan (Fig. 1c). It then flows across this fan through the semi-arid plains of the central Sudan to join the White Nile at Khartoum. In strong contrast to the highly seasonal Blue Nile, the White Nile emerges from the equatorial lake plateau of Uganda and disappears into the extensive swamps of the southern Sudan whence it emerges as a river of nearly constant flow throughout the year, but with a much diminished sediment load.

The White Nile provides 83% of Nile discharge during the month of lowest flow and is responsible for maintaining perennial flow in the Nile during drought years in Ethiopia (Williams and Adamson, 1982). The two major Ethiopian tributaries of the Nile (the Blue Nile and the Atbara) provide, respectively, 68% and 22% of the peak flow and 61% ($140 \pm 20 \times 10^6$ t a^{-1}) and 25% ($82 \pm 10 \times 10^6$ t a^{-1}) of the sediment load of $230 \pm 20 \times 10^6$ t a^{-1} (Garzanti et al., 2006). North of the confluence of the Blue and White Nile rivers at Khartoum the main Nile flows through the eastern Sahara desert north into the Mediterranean Sea and receives no further inflow below the Atbara confluence until it reaches the sea after a waterless journey of 2,689 km. The inhabitants of northern Sudan and Egypt owe their very existence to the Nile. By the year 2020 over 300 million people will depend upon its waters for their livelihood, so that a clear understanding of the links between present land use, alluvial history and the impacts of climate change on Nile flooding is essential for future planning. This chapter offers a concise summary of our current understanding of Late Quaternary environments in the valleys of the Blue Nile, the White Nile and the Main Nile, while noting gaps in our present knowledge and scope for future research.

2 The Blue Nile

Since its inception some 30 million years ago (McDougall et al., 1974; Pik et al., 2003; Gani et al., 2007), the Blue Nile has incised into its tectonically uplifted volcanic headwaters, depositing part of its load in the form of a large alluvial fan known as the Gezira (Fig. 1c). Gezira is Arabic for island and refers to the land between the Blue and White Nile rivers bounded to the south by the Manaqil Ridge (Fig. 1c). During earlier soil surveys, Williams (1966) mapped a series of former Blue Nile channels. These Late Pleistocene and Early Holocene channels radiated across the Gezira and carried a bed load of sand and fine gravel from the volcanic uplands of Ethiopia. The heavy mineral suite of the source-bordering dunes and sandy point-bars associated with these channels is virtually identical to the heavy mineral assemblage from channel sands collected from the bottom of the Blue Nile gorge in the highlands of Ethiopia (Williams & Adamson, 1973). Incision by the main channel of the Blue Nile beheaded the distributary channels and deprived them progressively of their flood discharge. The abandoned channels show a fining-upwards sequence from medium and coarse quartz sands and fine quartz and carbonate gravels to sandy clays and clays in the upper 50–150 cm. Clay deposition in the back-swamps and flood plains of these channels dwindled and finally ceased about 5,000 years ago, when the seasonally flooded swampy plains gave way first to acacia-tall grass savanna and finally to semi-desert steppe, changes evident in the fossil vertebrate and mollusc fauna (Williams & Nottage, 2006).

The depositional changes evident in the Late Pleistocene and Holocene alluvial record reflect changes in the load/discharge ratio indicative of hydrological/climatic changes in the headwaters. Such changes in river erosion and sedimentation have occurred repeatedly in the past, and are evident in the fining-upwards sequences revealed in scattered bore-logs from the Gezira Formation (Williams & Adamson, 1982).

Williams & Adamson (1980) and Adamson et al. (1980) have discussed possible reasons for the change in the Blue Nile from a Late Pleistocene bed load channel to a Holocene suspension load channel. Quaternary fluctuations in climate, vegetation, soil cover, and geomorphic processes would have repeatedly altered the hydrology and sediment load in the headwaters of every major Nile tributary but only the more recent record is well preserved.

There are extensive periglacial and more limited glacial deposits in the rugged Semien Highlands of Ethiopia close to the headwaters of both the Blue Nile and the Tekezze/Atbara (Fig. 1b) (Williams et al., 1978; Hurni, 1982). The glacial moraines and periglacial solifluction deposits are well mapped but have never been dated although assumed to be of LGM age (Hurni, 1982). It is entirely likely that there may be more than one phase of Late Pleistocene glacial activity in this region, with concomitant impacts on Blue Nile and Atbara discharge and sediment loads.

A coring programme now in progress at Lake Tana (Lamb et al., 2007) and a recently started project involving archaeological excavations in rock shelter sites in the forested uplands of SW Ethiopia are expected to yield new and well dated information about Late Quaternary vegetation history in this region.

The Atbara originates in Ethiopia and flows parallel to the Blue Nile to join the main Nile 320 km north of Khartoum. As noted earlier, the Atbara provides 22% of the peak flow and 25% of the annual sediment load of the Nile, or $82 \pm 10 \times 10^{6}$ t a^{-1} (Garzanti et al., 2006). In contrast to the Blue Nile, which carries more K-feldspar and hornblende from amphibolite-facies basement rocks, the Tekezze-Atbara carries more volcanic rock fragments, brown augite and olivine from basaltic rocks (Garzanti et al., 2006). Given its importance as a seasonal contributor of water and sediment to the Main Nile, it is surprising that the Quaternary depositional history of this river is so poorly documented.

The late Quaternary flood record of the Blue Nile record is still very incomplete. Calibrated radiocarbon ages for high Blue Nile flows indicate very high flood levels towards 13.9-13.2 ka, 8.6 ka, 7.7 ka and 6.3 ka (Williams, in press).

3 The White Nile Headwaters

During the last two decades, major piston-coring campaigns with associated high-resolution seismic surveys on Lakes Edward and Victoria, carried out under the auspices of the International Decade for the East African Lakes (IDEAL) project, have provided detailed insights into the terminal Pleistocene – Holocene history of these waterbodies and their proxy palaeoclimatic records. In addition, new analyses and reinterpretation of the 1971 Lake Albert cores (Harvey, 1976) have greatly refined our understanding of the evolution of this lake over the past ca 33 ka (ages in this section are given in calendar years B.P.). All the studies reveal periods both of prolonged lowstand and inferred high lake levels in the three basins, with obvious consequences for the discharge of the White Nile.

Lake Edward. As a partial consequence of active tectonics within the lake itself, and tectonically induced changes in the upper Semliki valley (see accompanying chapter on the Cenozoic evolution of the Nile basin), the sedimentary record from Lake Edward is complex and locally incomplete. ^{14}C-dating problems provide an additional complication. Lake Edward has a significant old carbon effect, on the order of 3000–4000 years, probably due to the addition of magmatic CO_2 to the basin's DIC reservoir (Lærdal et al., 2002; Beuning & Russell, 2004; Russell et al., 2003). Meticulous sample preparation has therefore been necessary to minimise the influence of old carbon on core chronologies, the most reliable dates coming from hand-picked detrital charcoal fragments (Russell et al., 2003).

Pre-Holocene deposits are to date only known from a displaced slump fragment in one core (Russell et al., 2003), but some insights into the late Pleistocene sedimentary history, albeit poorly constrained chronologically, can be gained from seismic reflection images from the eastern half of the lake (Lærdal & Talbot, 2002; McGlue et al., 2006). These are consistent in indicating lowstand conditions during the late Pleistocene, presumably around or just after the Last Glacial Maximum (LGM; see below), when the lake apparently reached a minimum level of about 37 m below present lake level (McGlue et al., 2006).

The in situ record begins at ca 11 ka (Russell et al., 2003). The sedimentary succession from four cores, taken at depths of 12–60 m, are summarised in Figure 2. As is apparent from these logs, none of the cores sampled the sediment/water interface, three of the cores contain at least one significant hiatus, and the deep-water core, although ca 7 m long, sampled only a relatively short period of the later Holocene. Sediment lithology, organic-matter (OM) composition, authigenic carbonate and biogenic silica contents all point to high lake levels and precipitation:evaporation greater than today during the first half of the Holocene, with generally lower lake levels and a long-term drying trend from about 5400 yr BP, culminating in a phase of particularly arid conditions from ca 2050 to 1850 yr. BP at which time Lake Edward was about 15 m lower than today (Lærdal et al., 2002; Russell et al., 2003; Russell & Johnson, 2005). Both events, and the drying trend, are reflected in the Sr-isotope stratigraphy of Lakes Edward and Albert. The Albert record indicates a progressive decline in the influence of Edward-Semliki discharge on the Sr-isotope budget of the lake (Fig. 3), and in Lake Edward the onset of drier conditions at around 5.4 – 5.0 ka is marked by a fall in 87Sr/86Sr implying a relative increase in runoff from the volcanic rocks (low 87Sr/86Sr) that dominate the Sr budget of the southern part of the basin. A corresponding decrease in the supply of radiogenic Sr (high 87Sr/86Sr) from basement rocks suggests drier conditions in the northern half of the basin. The relatively abrupt transition (Fig. 3) is consistent with other proxy records from northern tropical Africa, and is inferred to have been due to a southward shift in the ITCZ (Gasse, 2000; deMenocal et al., 2001; Russell & Johnson, 2005). Given the dating uncertainties in both lakes, the exceptionally dry interval

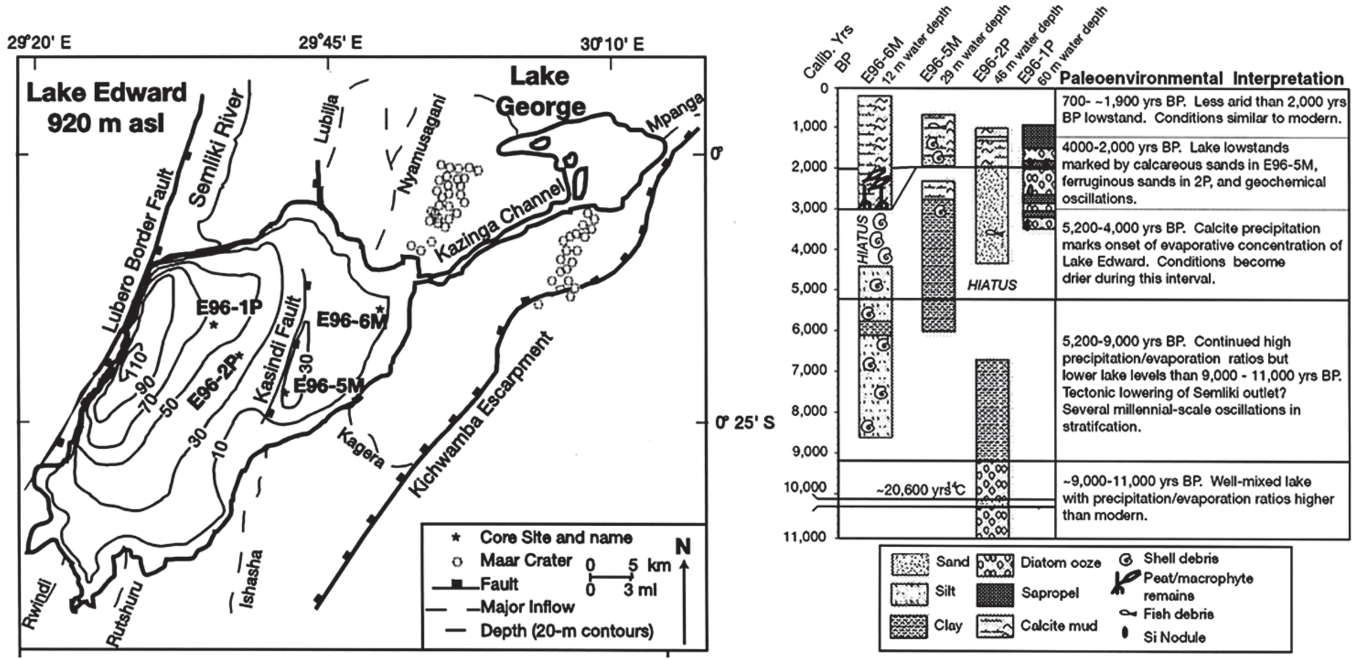

Fig. 2 Lake Edward showing core sites and lithostratigraphy of the IDEAL 1996 cores. Figures reproduced with permission from Russell et al. (2003).

identified in Lake Edward between 2.05 and 1.85 ka is probably represented in the Lake Albert Sr-isotope record by a switch to a Sr-isotope budget dominated by inflow from the Victoria Nile. This drying trend was subsequently reversed, leading to generally wetter conditions over the last 1500 years interrupted by at least two significant drought intervals (Russell & Johnson, 2005). All these droughts are likely to have resulted in greatly reduced or no discharge into the Semliki; Lake Edward's contribution to the flow of the White Nile is thus likely to have been highly variable, especially during the later Holocene.

Lake Victoria. As its principal source of water (ca 90% of the total flow), Lake Victoria is the key to the discharge history of the White Nile. Instrumental records of variations in the level of the lake are cl.

The lower White Nile flows across the floor of an ancient lake that existed ~400,000 years ago (Williams et al., 2003). This may also be the time when Lake Victoria first originated and began to overflow to the north. As a result, the White Nile unregulated flood gradient is a remarkably gentle 1 cm per km during peak flow. Owing to the very gentle slope of the flood plain, the depositional record is unusually well preserved, unlike the main Nile and Blue Nile where phases of erosion have destroyed segments of the sedimentary record. Millennial-scale evidence for at least the past 15,000 years shows that times of high flow in the Blue Nile and main Nile were essentially synchronous with those in the White Nile, so that the use of the White Nile flood record as a general surrogate for the Nile basin seems justified when other evidence is not available (Williams et al., 2006).

Owing to its very gentle flood gradient, the White Nile has been spared from major erosion so that it has a relatively well-preserved record of terminal Pleistocene and Holocene floods. A modest number of calibrated radiocarbon ages on White Nile gastropod shells indicate that White Nile levels were high around 14.7–13.1, 9.7–9.0, 7.9–7.6, 6.3 and 3.2–2.8 ka (Williams, 2008, in press).

The Khor Abu Habl (KAH) mega-fan (Fig. 1c) adjoins the White Nile west bank near the town of Kosti and contains a high-resolution record of depositional events linked to *local* climatic changes. The distributary channels on the fan range from long abandoned to still active but have never been dated. The KAH alluvium interfingers with at least one generation of N-S aligned desert dunes. Preliminary OSL ages obtained by us from the upper 2 m of one such dune reveal discrete phases of dune activity that seem to correlate with three of the six periods of rapid Holocene climate change identified by Mayewski et al. (2004) based on the results from 50 global Holocene records. There were six significant periods of rapid climate change during 9–8, 6–5, 4.2–3.8, 1.2–1.0 and 0.6–0.15 ka, the first five of which coincided with polar cooling and tropical aridity. The intervals in between were wetter in the tropics and, allowing for dating errors, tally reasonably well with the intervals of high White Nile floods identified here.

Small lakes occupied hollows between dunes at En Nahud in Kordofan towards 7.6 ka and in the Wadi Mansurab basin west of Jebel Aulia at intervals between 9.4–7.8 ka (Williams et al., 1974; Ayliffe et al., 1996). These were times of high flow in the White Nile and of stronger summer monsoon. We turn now to the sedimentary record in the main Nile.

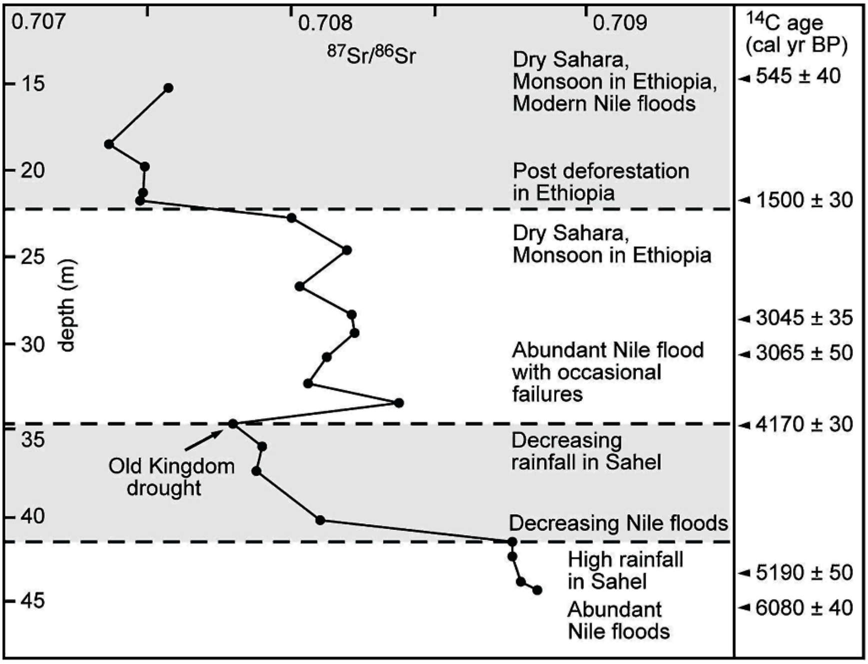

Fig. 3 Depth profile of $^{87}Sr/^{86}Sr$ from core S21 in the Nile Delta (Stanley et al., 2003)

4 Main Nile

Earlier efforts to reconstruct and interpret Late Quaternary Nile flood history using alluvial deposits along the main (or Saharan) Nile failed to take adequate account of the very different hydrological responses to climate change of the major tributaries. Williams and Adamson (1980) and Adamson et al. (1980) confronted this problem and their depositional model has since been widely accepted (Woodward et al., 2007). However, the model they put forward was perforce general and assumed that the Last Glacial Maximum (LGM) was uniformly cold and dry in the Blue and White Nile headwaters, resulting in bare, unstable slopes, highly seasonal Blue Nile flow and a seasonal influx of coarse bed-load sediment. More recent evidence from tropical Africa indicates that the LGM and ensuing postglacial climates were far more variable than previously supposed (Sylvestre et al., 2007) so that in future years we might expect that a more complex alluvial history will be unravelled.

Butzer (1980) has provided a clear overview of the main phases of Nile sedimentation in Egypt indicating very high floods towards 12.0–14.5 ka, with episodes of Nile alluviation between 12.9–13.5 and 8.4–9.0 ka and again towards 8.0 ka, coeval with Sapropel S1 in the eastern Mediterranean (Rossignol-Strick et al., 1982; Freydier et al., 2001). These intervals were times of high flow in the Blue and White Nile rivers, suggesting that the more complete White Nile depositional record can be used as a surrogate for times of high flow in the main Nile when the alluvial record in these rivers is incomplete.

Working under the auspices of the Sudan Archaeological Research Society, a team of archaeologists and geomorphologists affiliated with the British Museum has conducted detailed surveys of archaeological sites and stratigraphic sections east of the Nile in northern Sudan. This team has mapped a large number of archaeological sites and three former Nile palaeochannels and associated floodplains, for which they have obtained ten OSL ages and two radiocarbon ages that range from 7.5 to 0.5 ka (Woodward et al., 2001; Welsby et al., 2002). The sites cluster along certain palaeochannel belts and cover the cultural sequence from Neolithic (7.5–5.7 ka) through Kerma (4.5–3.5 ka), New Kingdom/Kushite (3.1–2.8 ka) to Meroitic and Post-Meroitic (0.5 ka).

Sites belonging to the Kerma Period (4.5–3.5 ka) were concentrated along the margins of the former Nile channel belts, some of them located more then 15 km from the present river. Two major palaeochannels (the Hawawiya and the Alfreda) converge downstream into the present-day Seleim Basin. The Kerma sites on the Hawawiya palaeochannel contain no pottery later than the Classic Kerma Period (1750–1580 BC), interpreted as suggesting that the Hawawiya Nile ceased to flow during or soon after this period (Woodward et al., 2001; Welsby et al., 2002). The youngest OSL ages show that both the Alfreda and the Seleim Nile palaeochannels were active until at least 800 BC and possibly on occasion until about AD 500. This work has once again shown the close relationship between former human settlement and the Nile.

5 The Nile Delta

Nearly 2,000 km downstream, in the Nile delta, Krom et al. (2002) and Stanley et al. (2003) have analysed the strontium isotopic and petrological composition of Nile sediments (Fig. 3). Changes in the strontium isotope ratios at a coastal site in the Nile delta east of the Suez Canal (Fig. 3) have shown a major hydrological change towards 4.2–4.0 ka, when there was a sharp decline in the proportion of sediments derived from the White Nile basin (Stanley et al., 2003). This major reduction in the low season flow of the river Nile might have been in part responsible for the collapse of the Old Kingdom.

6 The Record from the Eastern Mediterranean

Marine sediment cores collected from the floor of the eastern Mediterranean show a repetitive depositional sequence of alternating dark, organic rich sediments (known as sapropels) and calcareous muds with a significant content of Saharan wind-blown dust (Krom et al., 2002). The sapropel units are thought to reflect accumulation in anoxic bottom waters during times of enhanced freshwater flow into the Mediterranean from now inactive Saharan rivers and from the Nile (Rossignol-Strick et al., 1982; Rossignol-Strick, 1985). The influence of the summer monsoon over northern Africa was apparently stronger, and Nile floods more extreme, during intervals of sapropel accumulation (Freydier et al., 2001; Larrasoaňa et al., 2003; Scrivner et al., 2004) and there is some evidence of enhanced winter rainfall over northern Africa at these times. Many of these inferences about former Nile floods are based on indirect and often circumstantial evidence, as are the inferences about variations in winter rainfall and in the summer monsoon regime (Claussen et al., 1998). Future work will need to test the marine depositional models (and derived climate models) against the terrestrial archives provided by the big Nile tributaries upstream in order to provide independent insights into the climatic changes in the northeast quadrant of Africa. The rich archives of fluvial, aeolian and lacustrine sedimentary sequences and landforms preserved in the Nile basin (Williams & Faure, 1980) augur well for this important task.

7 Conclusion

The Greek historian Herodotus (ca 485–425 BC) was puzzled by the hundred days of annual Nile floods during the time of the summer solstice when no rain fell in Egypt, correctly interpreting the cause as heavy precipitation in the Nile headwaters during this time of year. The question then arises as to when the present hydrological regime of the Nile originated. In a successful effort to resolve this same issue, Talbot et al. (2000) analysed the strontium isotope ratios in the shells of freshwater mollusca collected from every major tributary throughout the Nile basin. The strontium isotopic composition of present day lakes and rivers in the Nile basin varies with catchment geology, and is reflected in the composition of the shells of mollusca living in those waters. The results demonstrated that the present flow regime of the Nile was re-established ~15,000 years ago, when the abrupt return of the summer monsoon precipitated the overflow of Lakes Albert and Victoria in the Ugandan headwaters of the White Nile (Fig. 2a). The technique has been used with success in the Nile Delta to define times of much reduced sediment inputs from the White Nile (Fig. 2b).

Calibrated radiocarbon dates obtained on freshwater shells within White Nile flood deposits indicate that White Nile levels were high around 14.7–13.1, 9.7–9.0, 7.9–7.6, 6.3 and 3.2–2.8 ka. The Blue Nile record is more fragmentary and that of the main Nile even more so except for the Holocene Nile delta. Calibrated radiocarbon ages for high Blue Nile flows indicate very high flood levels towards 13.9–13.2, 8.6, 7.7 and 6.3 ka.

Ongoing research in the Nile basin will provide the fine-resolution depositional history needed to test climatic models relating to the waxing and waning of the summer monsoon (Claussen et al., 1998; Chylek et al., 2001; Kuper & Kröpelin, 2006). In particular, it would be useful to build upon the pioneering research of Abell and Hoelzmann (2000) and Rodrigues et al. (2000) into past changes in rainfall seasonality inferred from changes in the stable oxygen isotopic composition in Nile oyster and Nile gastropod shells.

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