Shifting sediment sources in the world’s longest river: A strontium isotope record for the Holocene Nile

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A B S T R A C T

We have reconstructed long-term shifts in catchment sediment sources by analysing, for the first time, the strontium (Sr) and neodymium (Nd) isotope composition of dated floodplain deposits in the Desert Nile. The sediment load of the Nile has been dominated by material from the Ethiopian Highlands for much of the Holocene, but tributary wadis and aeolian sediments in Sudan and Egypt have also made major contributions to valley floor sedimentation. The importance of these sources has shifted dramatically in response to global climate changes. During the African Humid Period, before c. 4.5 ka, when stronger boreal summer insolation produced much higher rainfall across North Africa, the Nile floodplain in northern Sudan shows a tributary wadi input of 40–50%. Thousands of tributary wadis were active at this time along the full length of the Saharan Nile in Egypt and Sudan. As the climate became drier after 4.5 ka, the valley floor shows an abrupt fall in wadi inputs and a stronger Blue Nile/Atbara contribution. In the arid New Kingdom and later periods, in palaeochannel fills on the margins of the valley floor, aeolian sediments replace wadi inputs as the most important secondary contributor to floodplain sedimentation. Our sediment source data do not show a measurable contribution from the White Nile to the floodplain deposits of northern Sudan over the last 8500 years. This can be explained by the distinctive hydrology and sediment delivery dynamics of the upper Nile basin. High strontium isotope ratios observed in delta and offshore records — that were previously ascribed to a stronger White Nile/Atbara input during the African Humid Period — may have to be at least partly reassessed. Our floodplain Sr records also have major implications for bioarchaeologists who carry out Sr isotope-based investigations of ancient human remains in the Nile Valley because the isotopic signature of Nile floodplain deposits has shifted significantly over time.

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1. Introduction

Over the last two decades strontium isotope (87Sr/86Sr) data have made an increasingly important contribution to research projects seeking to better understanding the Quaternary history of the Nile basin. As far as the fluvial record is concerned, it has often been stated that the Nile is well suited to such studies because the upper reaches of the major tributaries lie in markedly contrasting geological and hydrological settings (Gerstenberger et al., 1997; Krom et al., 2002). The headwaters of the White Nile are formed in ancient crystalline shield rocks (with high 87Sr/86Sr ratios) whilst the Blue Nile and Atbara rivers drain the much younger Cenozoic volcanic terrains of the Ethiopian uplands (with much lower 87Sr/86Sr ratios). Downstream of the Blue Nile/White confluence at Khartoum, therefore, the isotopic signature of river sediment in the Desert Nile and delta has commonly been viewed as a weighted average of the end-member isotopic signatures of rocks eroded in these upstream drainage basins (e.g. Krom et al., 2002; Padoan

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et al., 2011). Much less consideration, however, has been given to the supply of sediment from windblown dust and from the many thousands of wadis in Sudan and Egypt along the ~2700 km of the Saharan Nile between Khartoum and the delta. These sources of sediment also have distinctive properties but we know very little about their changing contributions to the suspended sediment load and valley floor deposits of the Saharan Nile during the climate changes of the Holocene.

Four broad areas of Nile basin Quaternary research have made use of strontium isotope data and they may be summarised as follows:

1) Studies seeking to gain a better understanding of the long-term evolution of the drainage network — especially the connections between the equatorial lakes and the White Nile headwaters. The abrupt overflow of Lake Victoria around 14.5 ka, for example, was a very significant event during the Late Pleistocene that has been constrained by Sr isotope data in conjunction with radiocarbon dating (Talbot et al., 2000; Williams et al., 2006).

2) A large corpus of work has used Sr isotope data as an indicator of change in Blue Nile/White Nile suspended sediment source contributions to infer long-term shifts in the hydrological regime of the entire Nile basin. This has mainly involved the study of Pleistocene and/or Holocene sedimentary records preserved in the delta (Krom et al., 2002; Stanley et al., 2003; Flaux et al., 2013) and offshore (Revel et al., 2010, 2015; Box et al., 2011; Blanchet et al., 2013).

3) A deeper understanding of the basin-wide pattern of erosion and sediment delivery in the present-day drainage system has recently been achieved. Padoan et al. (2011) and Garzanti et al. (2015) have compiled the most comprehensive sediment budget for the contemporary Nile river basin using strontium and neodymium isotopes alongside conventional petrological data for fluvial muds and sands.

4) Finally, a developing field of bioarchaeological research in the Desert Nile is using Sr isotope data in the analysis of human skeletal and dental remains from archaeological sites of various ages in Egypt and Sudan. This work aims to tackle a range of questions about human migration within and beyond the Nile Valley with a recent focus on the New Kingdom and later periods (e.g. Buzon et al., 2007; Buzon and Simonetti, 2013).

Despite the success of (1), (2) and (3), there remains a major geographical and temporal gap in our knowledge of the Nile basin because the strontium isotope signature of the Holocene floodplains in the Desert Nile itself, where the great riparian civilizations of Ancient Egypt and Sudan flourished, has not been documented. These data are needed — not only to advance our understanding of how the world's longest river system has responded to global climate change — but also to provide essential reach-specific geological context for (4) since strontium isotope-based investigations of human and animal skeletal remains have typically assumed the 87Sr/86Sr ratio of Holocene Nile alluvium to be fixed within a narrow range. This assumption has not been rigorously tested through direct investigation of the alluvial floodplains of Egypt and Sudan where these people lived, grew their crops, and watered their animals.

Against this background, this paper presents the first strontium (and neodymium) isotope data for the Holocene river sediment record in the Desert Nile. It has three principal aims:

1) To build upon the well-dated Holocene fluvial records in northern Sudan (Woodward et al., 2001; Williams et al., 2010; Spencer et al., 2012; Macklin et al., 2013) to examine the Sr and Nd isotopic signatures of the river sediment record with a particular focus on the period from 8.0 to 1.0 ka that includes profound cultural, climatic and hydrological change.

2) To examine the composition of the alluvial sedimentary record in a range of depositional contexts in northern Sudan to establish the dominant sediment source shifts during the Holocene — to better understand the behaviour of the world’s longest river as the climate shifted from the African Humid Period to the hyper-arid conditions of the last 4500 years.

3) To demonstrate the importance of creating a reference database for the composition of Desert Nile river floodplain deposits for the entire Holocene to facilitate a more meaningful interpretation of the Sr isotopic data obtained from human remains from archaeological excavations in Sudan and Egypt.

2. Sediment sources in the Nile basin

The dominant feature of the hydrology of the present-day Nile is the marked spatial and temporal variability in the flux of water and sediment — expressed most vividly by the summer flood (Fig. 1). The suspended sediment load of the modern Desert Nile in Sudan and Egypt is dominated by sediments transported by the Blue Nile (c. 61 ± 5%) and Atbara (c. 35 ± 4%) (Padoan et al., 2011). In a typical year, the White Nile accounts for only a very small proportion (3 ± 2%) of the total sediment load despite draining by far the largest of the main tributary catchments (>1,730,000 km^2). The Blue Nile and Atbara drain catchments of c. 330,000 and 180,000 km^2 respectively (Table 1). It is clear, therefore, that the present-day Nile sediment system is dominated (typically >97%) by fine sediment originating from the Blue Nile and Atbara basins even though, together, they account for just 15% of the total Nile catchment. Much of this sediment load comes from the erodible volcanic highlands of Ethiopia and Eritrea (Fig. 1). During the summer monsoon, these deeply dissected landscapes deliver huge volumes of sediment—charged runoff to the main Nile. The Equatorial headwaters of the White Nile, in contrast, lie in much older and harder rocks, with lower relief, and without marked seasonal fluctuations in vegetation cover and runoff. In addition, a good deal of the sediment load in the White Nile basin is trapped in the lakes region and in the vast wetlands of the Sudd in South Sudan (Fig. 2) (Garzanti et al., 2015; Woodward et al., 2007; Williams et al., 2000). The modern Nile is the world’s longest exotic river — today there are no significant tributary inputs downstream of the confluence with the Atbara in northern Sudan (Fig 2.).

A potentially important — but as yet unquantified — component of the fine-grained sediment load of the main Nile is the input from aeolian activity in the desert reaches of Sudan and Egypt along the c. 3000 km of river channel between Khartoum and the Mediterranean Sea. This contribution is much more difficult to quantify because it involves a range of processes that are diffuse in space and time. The input of windblown dust from the vast desert landscapes surrounding the Nile corridor has commonly been overlooked in considerations of the Holocene Nile sediment budget even though there is a good deal of geomorphological and stratigraphical evidence pointing to its importance. It is well known, for example, that windblown dust from the Sahara forms an important component (up to 90%) of the sediment on the floor of the Mediterranean Sea (krom et al., 1999) and many hundreds of kilometres of river bank in Sudan and Egypt are lined with active aeolian dunes (Fig. 3) (Butzer and Hansen, 1968; Wendorf and Schild, 1976; Said, 1993; Spencer et al., 2012; Vermeersch and Van Neer, 2015). In the vicinity of El-Ugal, for example, in the southern part of the Northern Dongola Reach (Fig. 2), entire dune belts end up in the Nile (Welsby, 2001).
on Foucault and Stanley (1989) but updated with data from Padoan et al. (2011). To what extent is the strontium isotope ratio of sediments and soils in the Desert Nile? Was this modern river sediment system (see Garzanti et al., 2015), important and have influenced by inputs from tributary wadis? Have these inputs changed over the course of the Holocene and how are they influenced by local geomorphological setting?

One way of tackling these problems is to use sediment properties to elucidate the source of deposited sediment (e.g. Foucault and Stanley, 1989; Walling and Woodward, 1995; Stanley and Wingerath, 1996; Krom et al., 2002; Woodward et al., 2008; Box et al., 2011; Garzanti et al., 2015). Studies in the delta have suggested that the contribution from headwater basin sediment sources has fluctuated in response to changes in Holocene climate (see Foucault and Stanley, 1989; Krom et al., 2002). Most attention in this respect has focused on long-term changes in the flood regime and on the contributions of the Blue Nile/Atbara and White Nile catchments and, more recently, on the contribution of aeolian dust to the offshore records (see Box et al., 2011; Revel et al., 2015). There is also a good deal of evidence to suggest that tributary wadi systems of various sizes in Egypt and Sudan may have been significant suppliers of sediment to the main Nile prior to the inception of the modern hyperarid climatic regime. This Desert Nile catchment accounts for almost one third of the total basin area (Table 1). During the African Humid Period of the early Holocene, the Intertropical Convergence Zone lay at least 700 km further north and what is now the Sahara Desert was much wetter with permanent lakes, higher water tables, and extensive vegetation (Ritchie et al., 1985; Hoelzmann et al., 2001; Kuper and Kröpelin, 2006; Blanchet et al., 2015; Williams et al., 2015). Many wadi systems in the Nile Valley that are now strongly ephemeral and very rarely produce channel flows — such as the Wadi el Malik and Wadi Howar in northern Sudan (Pachur and Kröpelin, 1987) — flowed throughout the year at this time forming important tributaries with the main Nile or delivering water and sediment to the margins of the valley floor (Butzer and Hansen, 1968; Butzer et al., 2013). A key aim of this paper is to quantify the contribution of Desert Nile wadis to the sediment load of the Nile during, and after, the African Humid Period.

### 3. Northern Sudan: geomorphological and archaeological setting of the study reaches

The main archaeological periods of northern Sudan discussed in this paper are set out in Table 2. Fig. 2 shows the Desert Nile between the fourth and second cataracts in northern Sudan and the location of the two study reaches discussed in this paper. It also shows the distribution of Kema-age (2400 to c. 1450 BC) sites. The distribution of these sites is a valuable illustration of the changing palaeohydrology of the Holocene Nile in this region because they are closely associated with river channels that flowed throughout the Kerma Period but then dried out when Nile flows fell markedly around 3.3 ka (c. 1300 BC) as the valley floor channel network contracted (see Macklin et al., 2015; Woodward et al., 2016). Many of these palaeochannels are now filled with aeolian sand. At the very end of the Kerma Period, in 1500 BC, the Egyptians invaded this region and the Nile Valley—as far upstream at the fourth cataract — came under Egyptian colonial rule until 1070 BC (Table 2). Much earlier, in the Neolithic (before 3500 BC or 5.5 ka), Nile

![Fig. 1](image-url). The flow regime of the Nile showing the typical contribution from each of the three main tributary basins. Note how the summer flood is dominated by flows from the Blue Nile and Atbara. The other two figures show the typical annual contributions from the main tributary basins to the mean water discharge and sediment load. Original figures based on Foucault and Stanley (1989) but updated with data from Padoan et al. (2011).

### Table 1

<table>
<thead>
<tr>
<th>River basin</th>
<th>Area (km²)</th>
<th>% of basin upstream of Mediterranean</th>
<th>Discharge (km³ per year)</th>
<th>Sediment load (10⁶ tonnes/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nile at the Mediterranean</td>
<td>3,310,000</td>
<td>100</td>
<td>88 ± 5</td>
<td>230 ± 20</td>
</tr>
<tr>
<td>White Nile at Khartoum</td>
<td>1,730,000</td>
<td>52.3</td>
<td>28 ± 3</td>
<td>7</td>
</tr>
<tr>
<td>Blue Nile at Khartoum</td>
<td>330,000</td>
<td>10</td>
<td>48 ± 10</td>
<td>140 ± 40</td>
</tr>
<tr>
<td>Atbara at Nile confluence</td>
<td>180,000</td>
<td>5.4</td>
<td>12 ± 5</td>
<td>82 ± 10</td>
</tr>
<tr>
<td>Desert Nile</td>
<td>1,070,000</td>
<td>32.3</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
discharges were higher, more Nile channels were active, and a much greater proportion of the valley floor was suitable for settlement and agriculture because the local climate was much more humid (Woodward et al., 2001; Welsby et al., 2002; Macklin et al., 2013). Macklin and Woodward have carried out geomorphological fieldwork in the Northern Dongola Reach and at Amara West.
To reconstruct the history of Holocene river behaviour in northern Sudan. This involved collaboration over eight field seasons (between 1995 and 2014) with long-term field surveys and excavations coordinated by archaeologists from the British Museum (see Welsby et al., 2002; Spencer et al., 2012; Woodward et al., 2016).

3.1. The Northern Dongola Reach

Centred on 19°N and including the modern settlement of Dongola and the New Kingdom and Kushite site of Kawa (Fig. 4), this is a low relief landscape with occasional dune fields that extends eastwards to a prominent bedrock plateau, fringed by low-gradient alluvial fans, that marks the eastern limit of the Holocene valley floor. The maximum distance between the modern Nile and this Nubian sandstone plateau is about 18 km. This reach has been described in detail in Woodward et al. (2001) and Welsby (2001). In the mid-1990s, the Northern Dongola Reach Survey led by Derek Welsby recorded all the visible archaeological sites (Neolithic to Medieval) on the eastern valley floor of the Nile over a distance of 80 km north to south. The modern Nile flows close to the western edge of the valley floor throughout most of this reach. Most of the archaeological sites to the east of the present-day Dongola Nile are closely associated with a series of well-preserved palaeochannels. These ancient channels have been mapped using satellite imagery and ground survey. The three main palaeochannels, named the Hawawiya Nile, Alfreda Nile, and Seleim Nile (Fig. 4), have been the focus of detailed study. The ancient alluvial deposits on the margins of these dry channels are utilised by modern farmers who irrigate small holdings using diesel pumps sited in large pits dug into the alluvium. These pits are typically between 2 and 4.5 m deep and provide excellent three dimensional exposures in the Holocene alluvial record — often down to bedrock. We have logged over 40 of these pits and taken samples for OSL, radiocarbon and Sr and Nd analyses. In 2008 we were able to excavate a pit to a depth of more than 2 m in the bed of a particularly well defined palaeochannel on the Alfreda Nile. This is Pit 32 on Fig. 4. We have built up a detailed record of Holocene river history in the Northern Dongola Reach that spans the last c. 8500 years. This period includes marked changes in the hydrological regime of the Nile that were driven by shifts in global climate. In combination with the archaeological survey data, it has been possible to develop a model of long-term human use of this region in the face of profound regional hydrological change and shifts in local climate (see Woodward et al., 2001; Welsby et al., 2002; Macklin et al., 2013).

3.2. Amara West

Amara West is a well preserved late New Kingdom (founded in 1300 BC) town on the left bank of the Nile approximately 190 km downstream of Kawa (Figs. 2 and 3). It has been the focus of a British Museum excavation led by Neal Spencer since 2008. A key element of this project is an exploration of the changing Holocene landscape and river environment because a well-defined palaeochannel lies immediately to the north of the town mound and the town is now covered in windblown sand (Fig. 5). The history of this channel is intimately bound up with the founding and abandonment of the site in the New Kingdom (Spencer et al., 2012; Woodward et al., 2016). Amara West lies downstream of Sai

![Fig. 3. A Landsat image of the Nile Valley in northern Sudan in the vicinity of Amara West that highlights the spatial variation in geomorphological processes and potential sediment source contributions in the Desert Nile. The landscape on the left bank is dominated by dunes and windblown sand from the north whilst the area to the south and east of the river in this reach is marked by a dense network of ephemeral wadis with high drainage densities. Wadis are also present on the opposite side of the river but they are blanketed by windblown sand. All of these wadis would have delivered water and sediment to the main Nile during the African Humid Period.](image-url)
Island in one of the few places in Sudan where the Nile flows from west to east for a significant (>20 km) distance. A steep ramp of dunes lies along the modern left bank of the Nile in this reach (Figs. 3 and 5). A deep pit was dug into the Amara West palaeochannel in January 2011 exposing a series of flood units and fluvially reworked aeolian sands (Fig. 5). The latter were dated using OSL. The flood units were sampled for a range of analyses including Sr and Nd isotopes.

4. Laboratory materials and methods

Thirty seven samples of alluvial sediment (30 from the Northern Dongola Reach and 7 from Amara West) with good dating control were selected for analysis at the UK NERC Isotope Geosciences Laboratory. 150 mg of each sample (<63 μm) was weighed into 15 ml Savillex Teflon beakers and leached in dilute (10%) acetic acid to remove carbonate then spiked with 86Rb, 86Sr and 149Sm-150Nd isotope tracers. Samples were dissolved using standard HF–HNO3 methods, then converted to chloride form prior to separation of Rb, Sr and a bulk REE fraction using Eichrom AG50 cation exchange resin. Sm and Nd were separated using Eichrom LN-Spec ion exchange resin. Sr was loaded on single filaments using a TaO actuator and analysed on a Thermo Scientific Triton thermal ionisation mass spectrometer (TIMS) in multidynamic mode. Data are normalised to 86Sr/88Sr = 0.1194. 25 analyses of the NBS987 standard gave a value of 0.710252 ± 0.000006 (9 ppm, 1-sigma). This is within analytical uncertainty of the preferred value for this standard (0.710250), so no secondary correction of the data was required. Nd fractions were loaded onto one side of an outgassed double Re filament assembly using dilute HCl, and analysed in a Thermo Scientific Triton mass spectrometer in multi-dynamic mode. Data are normalised to 146Nd/144Nd = 0.7219. 15 analyses of the JND-i standard gave a value of 0.512101 ± 0.000008 (16 ppm, 1-sigma). Sample data are quoted relative to a value of 0.512115 for this standard. Rh and Sm concentrations were also analysed on the Triton mass spectrometer. Padoan et al. (2011) have shown that grain size effects on isotopic ratios are not significant in the mud and sand fractions of Nile alluvial sediments. Particle size analysis of the fine-grained flood units from Pit 32 (n = 7) and the Amara West palaeochannel (n = 7) was carried out using a Malvern Laser Granulometer following dispersal in calgon.

5. Results

5.1. The Northern Dongola Reach

The Sr isotope ratios for samples of Holocene alluvium from the Northern Dongola Reach and Amara West are plotted against sample age in Fig. 6. For the NDR samples, thirteen (all from pump pit exposures) date to the Neolithic/Pre-Kerma period before c. 4.5 ka. The 87Sr/86Sr ratios of this group range from 0.7058 to 0.7064 with a mean value of 0.7060. Fig. 7 shows a typical exposure in one of the groundwater pump pits on the eastern margin of the Northern Dongola Reach. This is Pit 37 in the northeast sector of the study area close to the alluvial fans that emerge from the wadis draining the bedrock plateau (Fig. 4). This exposure shows two gravel-rich units composed of local wadi flood deposits separated by fine-grained wadi sands mixed with fine alluvial sediments from the main Nile. The upper unit of grey/brown Nile alluvium at this site yielded a ratio of 0.7060. If forms part of the Neolithic/Pre-Kerma sample group plotted on Fig. 6 and it is very close to the mean value for that period.

Eight samples from the Northern Dongola Reach date to the Kerma Period (c. 4.4 to 3.5 ka): their 87Sr/86Sr ratios range from 0.7052 to 0.7057 with a mean value of 0.7055. The Kerma samples are less radiogenic than the Neolithic/Pre-Kerma samples and there is no overlap between these sample groups. Fig. 8 shows a deep (4.75 m) circular exposure in typical grey trunk stream alluvial sediments within the Alfreda Nile palaeochannel (Fig. 4). Four OSL ages (ranging from 3.79 to 3.33 ka) place all of this sequence in Pit 34 in the Kerma Period. Two sediment samples from the upper and lower part of this pit yielded Sr isotope ratios of 0.7056 and 0.7057 respectively. A single sample dating to the period of New Kingdom control (Pit 14) has a 87Sr/86Sr of 0.7061 which is significantly
higher than the Kerma samples. A sample from the Kushite Period (0.7054) falls within the range of the Kerma samples (Fig. 6).

The sedimentary record shown in Fig. 9 was recorded in January 2008 when a 2.3 m pit was dug in the centre of an Alfreda Nile palaeochannel in the Northern Dongola Reach. The location of this site (Pit 32) is shown on Fig. 4. This exposure records a series of major flood events on the main Nile that were large enough to reoccupy this dry channel. Each flood gently reworked the aeolian sands on the bed of the channel to produce a stacked series of flood couplets with distinctive medium-to coarse-grained orange sands capped with grey clayey silts. The exquisite preservation of these thin fine-grained units indicates that they were laid down under low energy conditions. Flood units 1 to 4 show a distinctive size mode <10 μm (fine clay and silt) whilst the lower flood units (5–7) contain more coarse silt and sand. This may indicate a decrease in flood energy over time and/or an increase in the input from windborne dust winnowed from the thick sand units in the upper part of the record (Fig. 9).

Five OSL dates show that the record spans a period of about 1600 years from sometime before 1290 ± 160 BC (3.3 ± 0.16 ka, Flood Unit 7) to just after AD 280 ± 90 (1.73 ± 0.09 ka, Flood Unit 1). In archaeological terms this extends from the period of New Kingdom control in Northern Sudan to the Later Kushite and Post-Meroitic periods (Table 2). Each discrete flood unit was sampled. The thickest of the flood units (Flood Unit 5) contains a much greater proportion of fine sand and this may indicate a slightly higher energy event. The 87Sr/86Sr ratios of the seven flood units in Pit 32 range from 0.7067 to 0.7076 with a mean value of 0.7070. The samples from Pit 32 form a very distinctive group with the highest 87Sr/86Sr ratios so far recorded in the Northern Dongola Reach (Fig. 6). The Sr isotope ratios for these flood units are all significantly higher than the samples collected from the much thicker alluvial units exposed in the groundwater pump pits.

5.2. Amara West palaeochannel fill

A very similar record to that exposed in Pit 32 in the Northern Dongola Reach has been recorded in the palaeochannel at Amara West immediately north of the ancient town mound (Figs. 5 and 10). This channel is much closer to the modern Nile but these
sedi-ments are a product of the same depositional processes described for those in Pit 32 on the Alfreda Nile. The fine-grained components of these Amara West flood units also show elevated \(^{87}\text{Sr}^{86}\text{Sr}\) ratios ranging from 0.7056 to 0.7068 with a mean of 0.7065 (Fig. 10). This group overlaps with the flood units from Pit 32 in the Northern Dongola Reach (Fig. 6). The flood units (A to G) shown in Fig. 10 are generally coarser than those from Pit 32 with a more coarse silt and sand – possibly a reflection of the proximity of this channel to the main Nile or the influx of coarser aeolian sediment from the desert to the north (Fig. 3).

The prevailing wind at Amara West comes from the north and the palaeochannel fill is capped by over 1 m of orange desert sand. This channel dried out around 1300 BC (c. 3.3 ka) shortly after the foundation of the town (Spencer et al., 2012). The OSL ages indicate that flood events A to F took place within a period of about 1100 years. Given the excellent preservation of the alluvial sedimentary records at Pit 32 and in the Amara West palaeochannel, we can be confident that a complete record of exceptionally high Nile floods is recorded for each time interval. When flood flows reoccupied these dry channels they gently reworked the aeolian sands on the channel bed. Any silt and fine sand within these windblown sediments would be mixed with the fluvial suspended sediment from the main Nile before settling out as part of the fine-grained member capping each fine-grained flood unit (Figs. 9 and 10).

6. Discussion: shifting sediment sources in the Holocene

Fig. 11 shows the strontium and neodymium isotope composition of sampled alluvial sediments in the Northern Dongola Reach in relation to two sediment source mixing trends: 1) Ethiopian basalts (Pik et al., 1999) and weathered aeolian dust (Jung et al., 2004) alongside 2) Ethiopian basalts and modern wadi muds draining Mesozoic clastic sediments in the Red Sea Hills (Fielding, 2015). The latter are used here to represent sediment derived from the wadis of the Nile Valley in Egypt and Sudan that drain the Mesozoic rocks such as the Nubian sandstones (Fielding, 2015). The fluvial deposits (<63 μm) from the Northern Dongola Reach are shown by archaeological period and depositional context — they represent a series of mixtures between these end members and they plot in three distinct groups.

The Ethiopian basalt end member represents sediment inputs from the Blue Nile and Atbara rivers. The Ethiopian basalt/wadi mud mixing curve shows a significant shift in the mean isotopic values of floodplain sediment (n = 13) in the Neolithic/Pre-Kerma period in comparison to the succeeding Kerma Period. Kerma floodplain samples (n = 8) show a stronger Blue Nile/Atbara component (c. 55–70%) with a mean value of 60%. There is a clear separation between these groups — the Neolithic floodplain samples generally show a greater contribution (40 to >50%) from wadi sediments with a mean value of 45%.

The samples from the Neolithic-age floodplain show high Sr ratios and Nd values that can only be explained by large-scale inputs from wadi floods. It can be argued that they are representative of the sediment load of the main Nile at this time because we see the same isotope signal at sites located many kilometres away from the bedrock plateau. Five of the samples that show the highest wadi component are located in the northeastern sector of the Northern Dongola Reach (sites 37, 38, 40, Fig. 4), away from the Alfreda Nile and close to the alluvial fans of the bedrock plateau where we have observed wadi sediments interbedded with main Nile alluvium (Fig. 7). Several Neolithic sites have been recorded in this part of the reach (Fig. 12). It is important to note that several pits (33, 34, 35) that also show a strong wadi signal are located away from the eastern edge of the valley floor on the western side of the Alfreda Nile and site 33 near Kawa is close to the modern Nile (Fig. 4). The two samples from Kawa have strong wadi input signals (0.7059 and 0.7064) and one of these is the highest \(^{87}\text{Sr}^{86}\text{Sr}\) ratio so far obtained for a Neolithic floodplain sample in the Northern Dongola Reach. This location cannot be reached by local tributary wadis — these isotopic signatures indicate important contributions to the load of the main Nile from wadis upstream.

It is not possible to differentiate between the sediment contribution from local wadis in the Northern Dongola Reach and the inputs from all of the active wadis that fed the main Nile upstream of this reach. The latter must be a substantial part of this signal. It is also important to appreciate that the Atbara and Blue Nile also provide large volumes of non-volcanic material to the main Nile derived from tributaries in their middle and lower reaches. Indeed, modern bed sediment samples from the Blue Nile catchment published by Padoan et al. (2011) overlap with the Kerma group presented here. It is also important to appreciate that three very large river systems — the Wadi Howar, Wadi el Malik and Wadi
Muqaddam — that formed important tributaries of the Sudanese Nile in the early Holocene — join the main Nile immediately upstream in the reach between Jebel Barkal and Mulwad (Fig. 2). This ‘Desert Nile’ catchment is discussed more fully below.

The seven flood unit samples (Pit 32) from the dried out palaeochannel associated with periodic infilling with aeolian sediments plot in a distinctive group on the mixing trend with a weathered aeolian dust end member (Fig. 11). These sediments have higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than the samples of alluvium collected from the much thicker alluvial units that were then reworked by Nile floods and incorporated into the fluvial sediment load. Any aeolian inputs from the desert landscape upstream of the Northern Dongola Reach would add to the aeolian signal that we see in the mixing relationships shown in Fig. 11.

The Sr and Nd isotopic data produce a clear differentiation between the three main sample groups and reveal remarkable consistency for these periods when one considers that they integrate a wide range of geomorphological processes in the upstream basin of one of the world’s largest and most diverse river basins — as well as those taking place more locally in the Northern Dongola Reach. It follows, therefore, that one would expect to see a progressive increase in the contribution from wadis moving downstream through the Desert Nile of Sudan and Egypt during the African Humid Period. Indeed, this may help to explain the elevated Sr isotope ratios recorded in the delta and offshore for the earlier part of the Holocene that have been interpreted as a stronger While Nile signal (e.g. Krom et al., 2002; Box et al., 2011). Fig. 11 highlights the
importance of using more than one parameter to identify catch- 
ment sediment sources (Walling and Woodward, 1995).

7. Palaeogeography of the Northern Dongola Reach

The sediment source data for the Northern Dongola Reach reflect major shifts in global climate that are expressed in distinctive reach-scale geomorphological and archaeological contexts. The presence of active wadis along the length of the Northern Dongola Reach helps to explain the distribution of Neolithic sites in this part of the Nile valley as, in marked contrast to later periods, many of them are not associated with the main channels of the Nile that were active at that time (Fig. 12). The local climate was much wetter during the Neolithic. As the African Humid Period came to an end around 4.5 ka, the local wadis of the Northern Dongola Reach — that drained catchments on the eastern bedrock plateau — ceased to flow on a regular basis and become strongly ephemeral (Fig. 12). At the same time, under a drier regional climate, flows in the main Nile fell and the channel network contracted (Woodward et al., 2001; Macklin et al., 2013, 2015). The channel belts of the Nile provided the only reliable source of running water after this time. All of the Kerma sites are situated along these channels (Fig. 12). The composition of the Kerma-age floodplain alluvium shows a significant drop in the contribution from tributary wadis. We have not observed Kerma-age Nile sediments interbedded with wadi sediment anywhere in the Northern Dongola Reach.

As the regional climate became drier, the transport of aeolian sediments (dune sands and fine dust) became much more important. The flood units in Pit 32 now show a rather different character with no evidence of wadi inputs — their composition can be largely explained by a mixture of Blue Nile/Atbara sediment and inputs of weathered aeolian dust (Fig. 11). Again, it is important to point out that the windblown component can enter the Northern Dongola Reach as part of the sediment load of the main Nile (i.e. material that was blown or washed in upstream) and as direct dust input to the valley floor of the Northern Dongola Reach. Rather like the wadi sediment inputs during the African Humid Period, the aeolian signal in the main Nile would be expected to increase downstream after c. 4.5 ka. These ideas need to be tested further with a more wide ranging sampling programme that also includes the Holocene floodplains of Egypt.

8. The Desert Nile

We have estimated the size of the Desert Nile catchment to be well over 1 million km² which amounts to almost one third of the total area of the Nile drainage basin (Table 1). This is the catchment area upstream of the Mediterranean Sea but downstream of Khartoum and not including the Atbara River (Fig. 13). This sector of the basin is currently arid or hyperarid and drained by innumerable ephemeral wadis — it is more than twice the size of the Blue Nile and Atbara basins combined (Table 1). Many of the largest wadis in
the Eastern Desert have supplied sediment from the Red Sea Hills to the main Nile. The wadis Shait, Natash and Kharit (that have a combined drainage area of 24,900 km²) converge on the Kom Ombo Plain just north of Aswan. These were studied by Butzer and Hansen (1968) as part of the UNESCO campaign to salvage the archaeology of Nubia during the construction of the Aswan High Dam. Each wadi contains deeply incised bedrock reaches and thick Pleistocene and Holocene fluvially reworked aeolian sand and Rip-up clasts. They were clearly capable of supplying large volumes of sediment to the main Nile in the recent past under more humid climatic conditions (Butzer and Hansen, 1968). All of the wadis draining from the Red Sea Hills to the Nile would have generated high sediment yields under more humid climatic conditions rather like many of the semi-arid upland basins around the Mediterranean that drain erodible clastic lithologies (Macklin and Woodward, 2009; Thornes et al., 2009; Woodward, 1995, 2009). More recent work on the Lower Nile in Egypt has explored the complex interaction between wadi floods, aeolian deposits, and main Nile sedimentation in the urban complex of Giza (Butzer et al., 2013). Apart from sporadic wadi floods related to more local precipitation events, the ‘Desert Nile catchment’ as defined here (Fig. 13 and Table 1) is largely dormant under the present-day arid climate and has made only a minimal contribution to the total

Fig. 10. The seven late Holocene flood units exposed in the deep pit dug into the Amara West town palaeochannel in 2011. The local geomorphological context is shown in Fig. 5. Strontium isotope and particle size data relate to the fine-grained dark grey clayey silts that form the upper part of each flood unit. The three OSL ages are shown.
sediment load of the main Nile over the last 4000 years or so. Yet we have shown that it was a major supplier of sediment in the Holocene before c. 4.5 ka and this was very likely to have also been the case during earlier humid phases of the Quaternary when the tropical rainfall belts extended further north under conditions of enhanced boreal summer insolation (Hamdan and Brook, 2015), when the summer monsoon was more intense, and sapropels formed in the eastern Mediterranean (Williams et al., 2015).

9. White Nile sediment delivery dynamics

The Sr and Nd isotope data presented in this paper do not show a measurable White Nile contribution to the Holocene floodplain sediments of the Northern Dongola Reach. There are good reasons to suggest that this is also the case for the rest of the Desert Nile. Several factors combine to limit sediment delivery from the White Nile basin. Sediment yields from the hard shield rocks of the White Nile headwaters are already very low by global standards (Milliman and Syvitski, 1992; Garzanti et al., 2015) and there are major physical barriers that trap sediment in the upper White Nile basin. Material is deposited in the equatorial lakes and in the vast swamps of one of the world’s largest wetlands (the Sudd) that swells to over 125,000 km² between Juba and Malakal during times of highest river flows. Padoan et al. (2011) have shown that sediments from the Sobat River — that drains the southern Ethiopian uplands and enters the lower White Nile just upstream of Malakal (Fig. 2) — are progressively homogenized in South Sudan, following conveyance losses in the Machar marshes and dilution with more local sources. Further downstream, when the Blue Nile is in flood, the lower White Nile backs up to form a vast seasonal lake upstream of Khartoum that is several hundred kilometres long (Barrows et al., 2014). Any sediment that escapes the Sudd is therefore held up in the lower reaches of the White Nile at the very time when the sediment loads of the Blue Nile and Atbara rivers are at their greatest. In consequence, as the summer floodwaters rise along the desert Nile in August and September, and the annual inundation of the floodplains of Sudan and Egypt takes place, any contribution from the White Nile is below levels of detection. Our data indicate that this has been the case for at least the last 6500 years and perhaps also for the last 8500 years (Figs. 6 and 11).

It is important to recognise that when the floodplains of Egypt and Sudan are inundated by the summer flood, the main Nile is overwhelmingly dominated by suspended sediment from the Blue Nile and Atbara rivers. With a peak to low flow ratio of 40:1, and typical mean June and August suspended sediment concentrations of 100 and 4000 mg l⁻¹ respectively, the Blue Nile can transport up to 1600 times more sediment during the summer floods than at the end of the dry season (Williams et al., 1982: 119; Woodward et al., 2007). About 98% of the annual fluvial suspended sediment load of the main Nile is transported during the summer flood season from July to October.

In common with its water discharge (Fig. 1), the suspended sediment load of the White Nile is fairly evenly distributed throughout the year (Woodward et al., 2007) so that the greater part of any White Nile load is transported through the Desert Nile from November to June when the much reduced discharges of the main Nile are confined within the main channel zone. The monthly sediment load of the present-day White Nile may account for as little as 0.25% of the total load of the Desert Nile. The crucial point here is that any suspended sediment from the White Nile that reaches the Desert Nile (which is already meagre, Fig. 1) does not take part in overbank flows because it is transported between...
November and June. This material is not deposited on the floodplains of Sudan and Egypt. This sediment delivery pattern may, in fact, contribute to the stronger ‘White Nile signal’ reported from Holocene lagoonal records in the delta (see Krom et al., 2002; Flaux et al., 2013), and offshore in the Eastern Mediterranean (Box et al., 2011). As most of the White Nile sediment load is transported under low flow conditions it effectively bypasses the alluvial floodplains of Sudan and Egypt because the main channel is typically deeply incised within the floodplain (Fig. 5). Our results highlight that it is important to avoid using strontium isotopes in isolation in the Nile basin to allow better discrimination between all potential upstream sediment sources (see Garzanti et al., 2015). Table 4 compares the Holocene sediment source estimates from this study for the Neolithic and Kerma Nile with those of the modern river from Padoan et al. (2011).

10. Strontium isotopes and ancient human populations in the Nile Valley

Buzon et al. (2007) have analysed human tooth enamel from skeletal remains excavated from the site of Tombos in northern Sudan to explore the feasibility of using strontium isotopes to identify first generation immigrants to this New Kingdom period Egyptian colonial town. Tombos is located on the east bank of the Nile immediately downstream of the Third Cataract (Fig. 2). Lying between our study reaches — downstream of the Northern Dongola Reach and upstream of Amara West — it provides a unique opportunity to compare the strontium isotope composition of dated Holocene floodplain deposits with human skeletal remains from the same sector of the Nile Valley for the first time.

Buzon et al. (2007) have set out the principles that underpin this approach. The strontium isotope ratio of tooth enamel will reflect the strontium isotope composition of water and foodstuffs consumed by an individual when that tooth was forming — the tooth enamel of permanent adult teeth forms during early childhood. Because an individual’s diet provides a link with the local environment and because strontium present in soils and groundwater (and irrigation water) is incorporated into local plants and animals — the strontium isotope composition of tooth enamel should mirror that of the environment in which the person lived in childhood. This is the basis of attempts to track the movement of people.

In the absence of a strontium isotope database for the Holocene fluvial record in the Desert Nile, Buzon et al. (2007) compared their Tombos data to the record from Manzala Lagoon in the eastern part of the Nile Delta published by Krom et al. (2002). Buzon et al. (2007) report $^{87}$Sr/$^{86}$Sr ratios for 49 samples of human teeth enamel from individuals buried at Tombos — these span a wide range from 0.7071 to 0.7091 (Fig. 14). They also cite a value for the New Kingdom River Nile (from the delta record of Krom et al., 2002) of 0.7075 which falls within the range of their archaeological samples. All of the Tombos tooth enamel values are much higher than all of the samples (Neolithic, Kerma, New Kingdom and Kushite) from thick Nile flood deposits exposed in pump pits in the Northern Dongola Reach. They are also higher than the 7 palaeo-channel flood units from Amara West, but they do overlap with the

![Fig. 12. Geomorphological and cultural changes in the Northern Dongola Reach from the Neolithic to the end of the Kushite period from before 3500 BC to the end of the 4th century AD (before 5.5 ka to c. 1.6 ka). The prevailing wind at the present day is from the northeast. Modern dune systems move from NE to SW across the Northern Dongola Reach (Welsby, 2001). Archaeological sites to the west of the modern Dongola Nile were mapped between 1996 and 1998 by a team led by Stuart Tyson Smith from the University of California, Santa Barbara.](image-url)
Sr isotope ratios for the palaeochannel flood units from Pit 32 on the Alfreda Nile which span the New Kingdom to Later Kushite periods (Fig. 14). It has been suggested that the high variability and generally high Sr isotope values in the Tombos data signal the presence in the local population of New Kingdom immigrants from Egypt. This may well be the case, but it is now clear that the teeth data from Tombos are not representative of typical overbank floodplain deposits for the Kerma and later periods, but they do overlap with valley floor sediments in northern Sudan that contain a significant proportion of windblown dust. We would therefore argue that these tooth data should not be used as the sole basis for the identification of immigrants to northern Sudan. It is much more likely that the enhanced ratios reported by Buzon et al. (2007) simply reflect a population who lived in an environment strongly affected by windborne dust and who farmed alluvial deposits that contained a significant proportion of aeolian material (Fig. 14). Indeed, this conclusion receives support from Buzon’s own research on dental disease in the Nile Valley that has identified an unusually high degree of tooth wear in the Tombos people which Buzon and Bombak (2010) attribute to high amounts of sand in their food.

It is now clear that the local geomorphological context in the Nile Valley must be taken into consideration because the Sr isotope signatures of Desert Nile alluvium have shifted significantly during the Holocene. As the climate became drier in the Kerma and later periods (Fig. 14), the discharge of each sub-catchment.

<table>
<thead>
<tr>
<th>Pit number</th>
<th>OSL age (ka)</th>
<th>Cultural period</th>
<th>87Sr/86Sr</th>
<th>Nd</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>4.73 ± 0.29</td>
<td>Neolithic/Pre Kerma</td>
<td>0.70600</td>
<td>0.59</td>
</tr>
<tr>
<td>36</td>
<td>4.14 ± 0.15</td>
<td>Kerma</td>
<td>0.70560</td>
<td>-0.17</td>
</tr>
<tr>
<td>34</td>
<td>3.79 ± 0.18</td>
<td>Kerma</td>
<td>0.70570</td>
<td>0.65</td>
</tr>
<tr>
<td>26</td>
<td>3.83 ± 0.05**</td>
<td>Kerma</td>
<td>0.70569</td>
<td>0.76</td>
</tr>
<tr>
<td>25</td>
<td>3.83 ± 0.05**</td>
<td>Kerma</td>
<td>0.70555</td>
<td>0.27</td>
</tr>
<tr>
<td>18</td>
<td>4.50 ± 0.30</td>
<td>Kerma</td>
<td>0.70517</td>
<td>1.11</td>
</tr>
<tr>
<td>17</td>
<td>5.10 ± 0.08**</td>
<td>Neolithic/Pre Kerma</td>
<td>0.70575</td>
<td>-0.25</td>
</tr>
<tr>
<td>07</td>
<td>5.17 ± 0.53</td>
<td>Neolithic/Pre Kerma</td>
<td>0.70597</td>
<td>-0.27</td>
</tr>
<tr>
<td>06</td>
<td>6.41 ± 0.27</td>
<td>New Kingdom</td>
<td>0.70612</td>
<td>-0.54</td>
</tr>
<tr>
<td>05</td>
<td>7.29 ± 0.10</td>
<td>Early Kushite</td>
<td>0.70535</td>
<td>0.80</td>
</tr>
<tr>
<td>04</td>
<td>8.00 ± 0.15</td>
<td>Kerma</td>
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<tr>
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<td>8.79 ± 0.18</td>
<td>Kerma</td>
<td>0.70570</td>
<td>0.65</td>
</tr>
<tr>
<td>02</td>
<td>9.33 ± 0.27</td>
<td>Kerma</td>
<td>0.70559</td>
<td>0.39</td>
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<tr>
<td>01</td>
<td>10.83 ± 0.05**</td>
<td>Kerma</td>
<td>0.70569</td>
<td>0.76</td>
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<td>18</td>
<td>14.50 ± 0.30</td>
<td>Kerma</td>
<td>0.70517</td>
<td>1.11</td>
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<tr>
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<td>Kerma</td>
<td>0.70548</td>
<td>0.35</td>
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<td>16</td>
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<td>New Kingdom</td>
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<td>16.29 ± 0.10</td>
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<td>0.70535</td>
<td>0.80</td>
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<td>17.03 ± 0.09</td>
<td>Later Kushite</td>
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<td>-0.84</td>
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<td>13</td>
<td>18.05 ± 0.10</td>
<td>Later Kushite</td>
<td>0.70763</td>
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<td>12</td>
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<td>Later Kushite</td>
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<td>11</td>
<td>20.74 ± 0.15</td>
<td>Early Kushite</td>
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<td>21.27 ± 0.13</td>
<td>Early Kushite</td>
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<td>-1.29</td>
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<td>09</td>
<td>22.30 ± 0.13</td>
<td>Early Kushite</td>
<td>0.70676</td>
<td>-0.98</td>
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<td>23.30 ± 0.16</td>
<td>New Kingdom</td>
<td>0.70664</td>
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<td>07</td>
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<td>Later Kushite</td>
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<td>06</td>
<td>25.22 ± 0.18</td>
<td>Later Kushite</td>
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<td>0.70640</td>
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<tr>
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<td>27.42 ± 0.34</td>
<td>Early Kushite</td>
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</tr>
<tr>
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<td>28.42 ± 0.34</td>
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<td>30.28 ± 0.22</td>
<td>New Kingdom</td>
<td>0.70656</td>
<td>No data</td>
</tr>
</tbody>
</table>

Table 3
Strontium and neodymium isotope data and ages for alluvial sediments in the Northern Dongola Reach and Amara West. Further information on the OSL and radiocarbon dates can be found in Woodward et al. (2001) and Macklin et al. (2013, 2015).

AWP — Amara West palaeochannel.
* Age interpolated from OSL ages above and below.
** = Radiocarbon date.

Table 4
Changing sediment source contributions to the main Nile from the main sub-catchments (Fig. 14) for the Neolithic and Kerma periods in northern Sudan (this study) and for the modern Nile (after Padoan et al., 2013). The White Nile value of 3 ± 2 is likely to be an overestimate of the load of the modern Nile because the samples were collected at low flow from the channel zone. See text for further discussion. See Table 2 for the time range of the archaeological periods.

<table>
<thead>
<tr>
<th>Time period</th>
<th>Sediment source contributions to the main Nile (%)</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>White Nile</td>
</tr>
<tr>
<td>Neolithic floodplain</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Kerma floodplain</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Present day Nile</td>
<td>3 ± 2</td>
</tr>
</tbody>
</table>

Fig. 13. The major tributary basins of the River Nile. The Desert Nile accounts for almost one third of the Nile basin. See Table 1 for information on the area and discharge of each sub-catchment.
soils. We have shown in this paper how post-Kerma flood units in ephemeral channels become much more radiogenic. If such marginal locations with significant inputs of dust were utilised for seasonal irrigation agriculture, their soils would have an elevated Sr isotope signal. It seems clear from our data that as the Sahara became drier after 4.5 ka, the flux of windblown dust became the most important secondary addition to the alluvial deposits on the floodplain surface as the contribution from tributary wadis fell significantly (Figs. 6 and 11).

Whilst we need more samples to fully establish the composition of the New Kingdom and later floodplain deposits (Figs. 6 and 14) in northern Sudan, it is very likely that any tooth enamel values >0.7065 for Kerma and New Kingdom graves come from individuals exposed to significant quantities of wind-borne sediment since the climate in northern Sudan and Egypt was much drier at this time in comparison to the Neolithic of the African Humid Period. It follows, therefore, that the Sr isotope analysis of older human skeletal remains from the Neolithic must be calibrated against the composition of the valley floor deposits from that time when wadi inputs were much more important throughout the length of the Desert Nile and wind-borne dust was much reduced or absent.

Price et al. (2002) have shown that many factors need to be considered when interpreting Sr isotope data from ancient human remains. The interpretation of such datasets is not straightforward. If we consider the present-day small holdings along the Alfreda Nile palaeochannel in the NDR, for example, these farmers make use of fossil groundwater (of unknown age) to cultivate crops in alluvial deposits of Kerma age, that receive regular inputs of modern aeolian sand (see Fig. 8). Any meaningful interpretation of strontium isotope data from human remains in the Nile Valley must be rooted within an understanding of the strontium isotope composition of the alluvial sediments of that period in a given reach. We have shown that the distinctive sediment delivery dynamics of the Nile catchment mean that the records in the delta are not appropriate for this particular task.

11. Conclusions

This paper has addressed a major geographical and temporal gap in our knowledge of the Holocene Nile through an analysis of the isotopic composition of securely dated floodplain deposits in northern Sudan. The sediment load of the River Nile has been dominated by material from the Ethiopian Highlands (via the Blue Nile and Atbara rivers) for much of the Holocene, but two other sources — tributary wadi sediments and aeolian dust — have also made very significant contributions to valley floor sedimentation and floodplain soils. The importance of these tributary wadis and aeolian sources has shifted dramatically as the various sectors of the Nile basin responded to global climate changes. During the African Humid Period before c. 4.5 ka, floodplains in northern Sudan show a wadi input of around 45% (Neolithic/Pre-Kerma). As the climate became much drier after 4.5 ka, the Kerma floodplain shows a fall in wadi inputs and a stronger Blue Nile/Atbara contribution (60 ± 5%) (Table 4). In the New Kingdom and later periods, in palaeochannel fills on the margins of the valley floor, aeolian sediments replace wadi inputs as the most important secondary contributor. Palaeochannel fills in the Northern Dongola Reach contain multiple fine-grained flood units with an aeolian component of between 40 and 50%.

Our sediment source data do not show a contribution from the White Nile to the floodplains of northern Sudan over the last 6500 years and this may have been the case for the last 8500 years (Fig. 6). This can be explained by the distinctive sediment delivery dynamics of the Nile basin. The very small White Nile inputs to the main Nile presently bypass the floodplains of Egypt and Sudan because they are mainly transported out of the summer flood season when main Nile discharges are confined to the channel zone. We need more samples for the period before 6.5 ka to fully test this idea for the early Holocene since there is substantial geomorphological evidence for higher White Nile flows and more active channels at this time (Williams et al., 2000). Having said that, high strontium isotope ratios in the delta records that have previously been ascribed to a stronger White Nile input during the African Humid Period may have to be at least partly reassessed because thousands of tributary wadis were active at this time along the full length of the main Nile in Sudan and Egypt.

In addition to revising our understanding of long-term sediment delivery dynamics in the Nile basin, these findings have important implications for the interpretation of the strontium isotope-based investigation of ancient human populations in Sudan and Egypt because the strontium isotope signature of the Holocene floodplains and soils in the Nile Valley has shifted significantly over time. We now have an opportunity to obtain a more nuanced interpretation of the bioarchaeological strontium data from the Holocene Desert Nile and one that is grounded in the reality of a highly dynamic river basin sediment system.

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(Adelaide) and Jean-Luc Schweningen (Oxford) for OSL analyses. Andy Hardy kindly provided the Landsat image in Fig. 3. Special thanks to Nick Scare (Cartographic Unit in Geography at The University of Manchester) for his skill and patience in drawing all the diagrams. Our fieldwork in Sudan would not be possible without the permission and support of the National Corporation of Antiquities and Museums in Khartoum. Finally, we thank the three QSR reviewers and Michaela Binder for helpful feedback on this paper.

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