A White Nile Megalake during the last interglacial period.

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ABSTRACT

The eastern Sahara Desert is one of the most climatically sensitive areas on Earth, varying from lake-studded savanna woodland to hyper-arid desert over the course of a glacial-interglacial cycle. In presently arid Sudan there is widespread evidence that a very large freshwater lake once filled the White Nile River valley. Here we present the first quantitative estimate for the dimensions of the lake and a direct age for the emplacement of one of the shorelines. Using a profile dating approach with the cosmogenic nuclide ^{10}Be, we estimate an exposure age of 109 ± 8 ka for this megalake, indicating it formed during the last interglacial period. This age is supported by optically stimulated luminescence dating of Blue Nile palaeochannels associated with the lake. Using a high-resolution digital elevation model we estimate that the lake was more than 45,000 km^2 in area, making it comparable to the largest freshwater lakes on Earth today. We attribute the lake’s existence to seasonal flood pulses as a result of local damming of the White Nile by a more southerly position of the Blue Nile and greatly increased precipitation associated with a super monsoon.

INTRODUCTION

The Nile is the longest river in the world and its basin extends over ~3 million km^2 (Figure 1a). Geomorphic records show that the flow of the White Nile has varied dramatically through time as a result of climate change (Williams et al., 2010). These changes in flow have had a profound impact on the environment and the habitability of the lower basin. Since at least the middle Pleistocene the Nile has acted as a corridor for human dispersal and a refuge during periods of aridity (Basell, 2008). The occurrence of warmer, wetter conditions after the last glacial maximum (Gasse, 2000) coincides with the advent of Neolithic farming in the Nile valley and the emergence of one of the world's great urban civilizations in Egypt (Kuper and Kröpelin, 2006).

Sudan was much wetter in the early Holocene than at present, with lakes in the Sahara Desert between ~9500 and 4500 ^{14}C yr BP (Hoelzmann et al., 2000). At this time the Nile flooded up to 5 m above modern river levels forming a lake 20-40 km wide (Williams et al., 2006). Above the Holocene flood level, the presence of a prominent shoreline led Williams et al. (2003) to propose the presence of an even larger lake. In order to maintain a large lake in Sudan, major shifts in regional atmospheric circulation are required (Williams et al., 2003). Attempts have been made to date this White Nile megalake. However, the age remains ambiguous, with estimates ranging from the Holocene back to 400 ka (Williams et al., 2003; Williams et al., 2010).

EXPOSURE DATING AND OPTICALLY STIMULATED LUMINESCENCE

Given the possible maximum age of the shoreline, we chose to exposure date deposition of the shoreline using the cosmogenic nuclide ^{10}Be, which can provide age constraints beyond the limits of radiocarbon and luminescence techniques. Samples for dating were collected from a shoreline on a well-preserved cuspate foreland near Jebelein in south-central Sudan (Site A Fig. 1B; Supplemental Table S1). The shoreline lies ~20 m above the modern Nile River at ~400 m at 12.6 °N. An original survey used the old Alexandria datum and gave an elevation of 386 m for the break in slope at the edge of the shoreline (Williams et al., 2003). The gravel and coarse sand constituting the shoreline is locally derived from weathering of granite inselbergs adjacent to the Nile River, subsequently transported by longshore drift. Wave action has worked the weathered gravel, which is highly rounded (Fig. 2). The shoreline has a typical width of 600 m and only extends about 10 km to the north and south of the inselbergs. We also sampled the summit of the nearest inselberg, Jebel Hawaja, to estimate likely ^{10}Be inheritance in the gravel.

To associate the shoreline formation with contemporary channel development along the Nile, we applied optically stimulated luminescence at three sites further north. A series of former Blue Nile channels radiate northwest across the alluvial plain west of the Blue Nile towards the White Nile and coincide with the northern limit of the lake (Williams, 2009) (Fig. 1B). The first site dated (Site B) is located on a palaeochannel on the east bank of the White Nile. Site C is on the clay floodplain of another channel between a large north-south aligned sand dune and the White Nile. This channel can be traced laterally northwest on aerial photographs until it runs beneath the linear dune on its path towards the White Nile. The site B sands may be part of this same channel complex. Site D is located on the east bank of the current Blue Nile Channel above its current level (Fig. 3).

RESULTS

The ^{10}Be concentration in the depth profile decreases with depth as expected (Fig. 2; Table S2). The exception is the surface sample, which has a lower ^{10}Be concentration than expected because of bioturbation, and the resultant curve fit is poor ($\chi^2/\nu = 2.7$). Excluding the surface sample greatly improves the quality of the fit and the uncertainties are consistent with the curve fit ($\chi^2/\nu = 0.76$). The best-fit age is 109 ± 8 ka. The quality of the fit indicates minimal removal from or addition of sediment to the profile through time.

Under the assumption of steady state erosion, the three analyses from Jebel Hawaja indicate that it is lowering at a rate of 1-5 m/Ma (Table 2), typical of desert inselbergs (e.g. (Bierman and Caffee, 2002)). The range in these values is likely to be due to the varying degrees of exfoliation observed across the summit. Sediment derived from this surface is therefore likely to have a significant ^{10}Be inheritance. The ^{10}Be concentrations represent a maximum for sediment being generated from the inselberg; the steep, shielded, higher surface area flanks will contain lower concentrations of ^{10}Be. The inherited component from the curve fit in the section is 303,500 atoms/g, consistent with weathering from the Jebel once the steep shielded flanks are taken into account.

The OSL ages on channel sands at site B indicate a prolonged phase of fluvial sand entrainment and deposition in this area between about 100 and 70 ka ago (Fig. 3; Table S3). At site C the floodplain clays were deposited in the late Pleistocene and early Holocene after the resumption of the African Monsoon (Williams et al., 2006). The underlying well-sorted fluvial sand was deposited during the last interglacial period at the same time as the sand at the base of Site B. Site D has an age similar to the base of the other two sections and indicates high-energy flow at 104 ka at the site of the modern Blue Nile Channel.

Based on SRTM90 data, the White Nile Megalake at its maximum level would have extended as far north as 15º N with a length of 650 km, a maximum width of 80 km, an average depth of 6 m, and an area of 45,000 km^2 (see also supplemental methods). This lake area is likely to be a minimum because of progradation by the extensive Khor Abu Habl alluvial fan and encroachment of the linear dunes of the Sahara Desert formed before and during the last glacial maximum, both of which have partially blocked the valley. The maximum depth above the Holocene floodplain in the middle of the lake is ~12 m, which does not take into account Holocene sedimentation. The lake extends 150 km further south than proposed by Williams et al. (2003) and the volume would have been ~270 km^3, which is more than twice the amount previously estimated by Williams et al. (2003).

DISCUSSION

The age of the White Nile Megalake shoreline dates the origin of the White Nile River back to at least the last interglacial period. The reconstructed dimensions of the 'lake' would make the White Nile at that time the widest river on Earth, and would currently rank it one of the four largest lakes by area. The presence of a significant shoreline only on the eastern side of the White Nile suggests that the lake was only full during the summer months of the monsoon when southwesterly winds delivered rain from inner Africa and there was much greater flow into the White Nile from the Ugandan lakes. The optical ages indicate at least two channels of the Blue Nile were active at the same time, delivering large volumes of discharge.

The setting for such a large lake occupying a broad and shallow river valley without an obvious dam is highly unusual on Earth today. The lack of a prominent shoreline north of Esh Shawal (13° 30' N) corresponds to three important morphological features which could contribute to the damming of a lake. First, the major linear dune field from the west impinges on the river from ~13-14° N (Figure 1b) and was probably present in some form before the last glacial maximum. This sheet of sand partially fills the eastern side of the valley and forces the White Nile up against the Managil Ridge. Second, the White Nile valley narrows north of 14° N, which acts to constrict the flow of the river. Third, the Blue Nile joins the White Nile at 15° 36'

N. When the unregulated Blue Nile was in flood in modern times, the flood pulse of the Blue Nile resulted in damming of the White Nile for 300 km up the valley to create a lake up to 3 km wide near its northern end (Willcocks, 1904). With completion in 1935 of the Jebel Aulia dam (Fig. 1b) on the White Nile 35 km upstream of Khartoum, the reservoir when full also produces a body of slack water that extends ~300 km upstream.

Our dating of the Blue Nile palaeochannels indicates that the third factor was much more significant during the last interglacial period than at present. A major late Pleistocene palaeochannel of the Blue Nile joined the White Nile near Naima and El Geteina (Fig. 1b), 120 km and 80 km south of the modern confluence, respectively (Williams, 2009) and our dating demonstrates that the channel development and flooding were contemporaneous. Given enhanced flow from both the Blue and the White Nile at this time, it is likely that the Blue Nile floods could have acted to dam the White Nile to an elevation of 400 m. Much higher flow than present is suggested by the age at Site D, indicating a distributary was also active (probably during peak flooding) at this time near the site of the present Blue Nile.

The climate must have been significantly more humid during the last interglacial period in order for such a large lake to persist in the White Nile valley. Sudan is presently arid, with mean annual rainfall decreasing northwards from 780 mm at Malakal in the south to 140 mm at Khartoum (Hijmans et al., 2005), reflecting limited transport of moisture northward during the modern southwest monsoon. Pan evaporation rates increase northwards from 2000 mm/yr at Malakal to nearly 4000 mm/yr at Khartoum (Shahin, 1985). Modern evaporation rates on a lake of 45,000 km^2 would amount to a total of 63,-95,000 km^3/yr on a lake with a volume of only 270 km^3. Modern day flow is only ~27 km^3/yr at the southern end of the lake (Williams et al., 2003) and modern precipitation on the lake would be ~ 21 km^3/yr, indicating that it would not be possible to form the lake under conditions similar to the present. Ignoring lake outflow, flow would need to triple or have a major contribution from the Blue Nile flood pulse, and on-lake precipitation increase by 50% just to start filling the lake, provided increased cloudiness and humidity led to a concomitant drop in evaporation to levels characteristic of the humid south of Sudan.

The presence of a White Nile Megalake adds to an emerging picture that during the last interglacial period the Sahara Desert was an oasis-studded savanna hosting Middle Paleolithic hunter-gatherers (Wendorf et al., 1993). Identifying large lakes present during this period has been hampered by difficulties in dating (Geyh and Thiedig, 2008). (Armitage et al., 2007) have determined a possible high lake phase in the middle of the last interglacial period at 100 – 110 ka for Lake Megafazzan in the Libyan Desert based on OSL ages from coquinas. A slightly later age of 95ka has been suggested as representing a humid phase in the western Sahara Desert, based on uranium-series dating of lake sediments (Causse et al., 1988). Deep sea cores taken off the west coast of Africa show that during the last interglacial period the climate was more humid in North Africa because there were low inputs from dust (Moreno et al., 2001) and high river flow (Weldeab et al., 2007).

Further confirmation of high fluvial flow comes from deep sea cores collected from the floor of the eastern Mediterranean which show a repetitive sequence of alternating calcareous muds with a significant content of Saharan wind-blown dust, and dark organic-rich sediments, termed sapropels (Ducassou et al., 2008; Larrasoaña et al., 2003). These sapropel units are thought to have accumulated during times of enhanced freshwater inflow from the Nile and now inactive Saharan rivers (Osborne et al., 2008; Scrivner et al., 2004; Wehausen and Brumsack, 1998). The White Nile Megalake probably formed during Sapropel Unit 5 (S5) (Kroon et al., 1998; Lourens et al., 1996). Based on these sapropel units, (Rohling et al., 2002) have suggested that the Intertropical Convergence Zone (ITCZ) penetrated seasonally approximately 21ºN during the last interglacial period. Global Circulation Models (GCMs) support this finding (Kutzbach and Liu, 1997). The Indian Ocean monsoonal rainfall reached as far north as northern Sudan during the Holocene pluvial phase (Rodrigues et al., 2000), which is thought to have been of lesser magnitude than during the last interglacial (de Noblet et al., 1996).

The only feasible way to maintain a lake the size of the White Nile Megalake in south-central Sudan is though intensification of the African Monsoon and its increased penetration into northern Africa. The last interglacial period coincided with a very strong northern hemisphere solar insolation maximum, which greatly enhanced the intensity of the summer monsoon in the northern hemisphere (Rossignol-Strick, 1983). This super monsoon occurred at a time when sea level likely exceeded 8 m higher than present (Rohling et al., 2008) and mean temperatures were up to 2 °C higher than present. The accompanying increased precipitation was capable of transforming this section of the Sahara into a wet, vegetated landscape.

ACKNOWLEDGEMENTS

We thank three anonymous reviewers of an earlier draft for their constructive suggestions. We thank the Australian Research Council for financial support (grant DP0878058 to MAJW) and the Geological Research Authority of the Sudan for logistical support. Sayed Nagi Abdalla Mohamed, Field Manager, Danfodia Company for Contracting Roads and Bridges, Jebelein, generously allowed the use of a bulldozer for excavating the trench at site A.

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FIGURES

Figure 1

a) The catchment of the Nile River, b) reconstruction of the White Nile Megalake in Sudan, and c) a section of the eastern shoreline showing the sample location and cuspate forelands.

Figure 2

a) Section log of the sampled profile at Site A. Soil development was strong on the section and the colour was dark brown at the surface, grading to orange red below 1.3 m, b) Approximate breakdown of size classes for the sediment. Note the low concentration of very fine sediment in the soil, and c) ^{10}Be concentrations in the measured samples together with least squares fit to the data, excluding the surface sample. Note the asymptotic decline of the curve indicating a significant inherited component.

Figure 3

Section logs at Sites B-D. At site D, the sands contained abundant fossils, including a probable rhinoceros femur, three broken pieces of a tree trunk 0.6 to 1.0 m in diameter and 4.05 m long, entirely replaced by crystalline calcite, abundant silicified fragmentary mammal bones, horn cores, and Nile oyster shells (*Etheria elliptica*). The gravel forms a low terrace flooded during the Blue Nile floods, preserved from erosion because of carbonate cement.