Quaternary Science Reviews 130 (2015) 189–199

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

Integral view of Holocene precipitation and vegetation changes in the Nile catchment area as inferred from its delta sediments

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A R T I C L E I N F O

Article history:
Received 1 December 2014
Received in revised form
21 May 2015
Accepted 29 May 2015
Available online 6 June 2015

Keywords:
Nile discharge
Nile delta
Vegetation
Precipitation
Sedimentation
Sapropel S1
Geochemistry
Pollen

A B S T R A C T

We compare geochemical and pollen data of several well-dated, high-resolution cores to provide an integral Holocene overview of Nile outflow, sedimentation, and vegetation in and around the Nile delta. We show that the focus point of the Nile plume varied considerably, as indicated by planktonic foraminifer *Globigerinoides ruber* oxygen isotopes tracing Nile discharge differences in an east–west delta transect. At 13–11.5 cal kyr BP, Nile discharge was low and runoff was predominantly directed to the western part of the delta. Sediment arriving in the delta during that period was dominated by Ethiopian Highland (~Blue Nile) material, shown by high Ti/Al values of the bulk sediment, indicating dry conditions in the source area of the Blue Nile. Nile discharge increased from ~11.5 cal kyr BP, and was high across the whole delta from ~10–6.5 cal kyr BP. During this time, the Ti/Al values decreased within most Nile-delta sediments, suggesting that the relative contribution of Blue-Nile sediment decreased. This was likely due to an increased vegetation cover causing diminished erosion in the Ethiopian Highlands. Nile discharge gradually decreased from ~6.5 cal kyr BP to present. This decrease was more abrupt in the Western Province of the delta and became more gradual towards the east as the shrinking Nile runoff was directed there. The gradual decrease in precipitation in the Nile catchment area seems not to be matched by a gradual response in vegetation growing around the river plain in the lower Nile catchment. Our findings suggest a nonlinear response of northeast African vegetation to precipitation from the middle to late Holocene.

1. Introduction

The Nile River traverses the entire northeast African continent (Fig. 1a). Nile delta sediments ought to play, therefore, a key role for reconstructions of northeast African climate. They record the catchment-wide effects of variability in the position of Intertropical Convergence Zone (ITCZ) and its associated precipitation (e.g. Stanley and Warne, 1993; Fontugne et al., 1994; Cheddadi and Rossignol-Strick, 1995; Almogi-Labin et al., 2009; Blanchet et al., 2013; Hennekam et al., 2014; Revel et al., 2014; Weldeab et al., 2014). These reconstructions of the climatic change in the catchment have been based on sediments from the Western, Central, and Eastern Provinces in the Nile delta. The consistency of these records has not been verified.

Deep-sea fan deposits show that the activity of Nile channel systems and related sediment deposition may have considerably varied over the course of the Holocene (Ducassou et al., 2009). Most Nile sediment is presently deposited in the southeast corner of the Levantine basin as the material is directed there by prevailing counterclockwise-moving surface currents (Krom et al., 1999) (Fig. 1b). This was probably similar in the early to middle Holocene as Nile discharge seemed also directed towards the same area then (Fontugne et al., 1994). These southeast Levantine sediments allowed, therefore, continuous, high-resolution reconstructions of Nile sedimentation and discharge during the Holocene (Hamann et al., 2008; Hennekam et al., 2014; Weldeab et al., 2014). Sediments from the western side of the Nile delta were also used to

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http://dx.doi.org/10.1016/j.quascirev.2015.05.031
0277-3791/

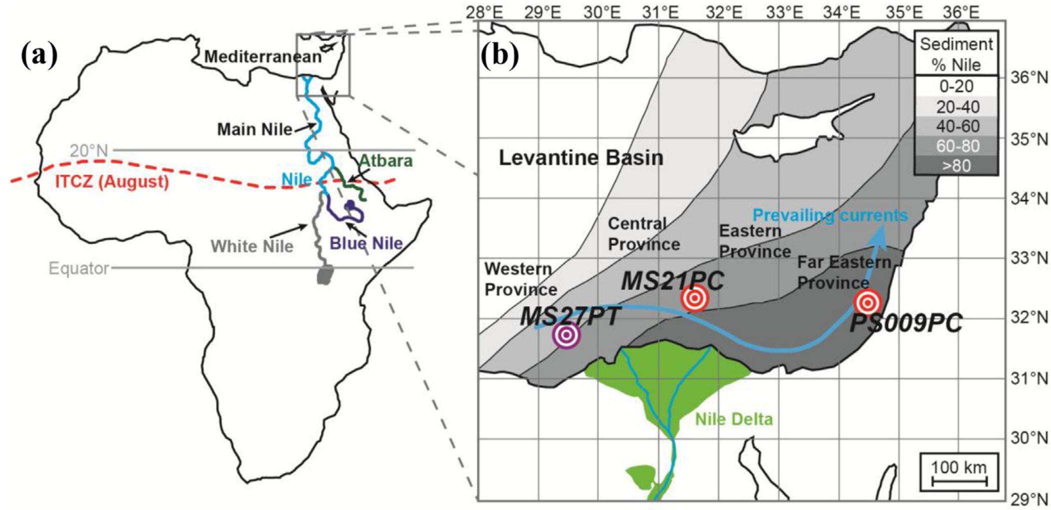

Fig. 1. Location of studied cores. (a) Map of Africa showing the Nile River. (b) Nile delta and the cores of interest. Core MS27PT was studied in Revel et al. (2010, 2014). Also shown are the prevailing current direction, delta provinces, and Sr-isotopes-based percentages of Nile particulate matter in the Levantine surface sediments (from Krom et al., 1999).

make detailed reconstructions of especially the early to middle Holocene history when high sedimentation rates were present in that area (Revel et al., 2010, 2014; Blanchet et al., 2013). Nile sedimentation at sea, and by inference associated discharge, varied spatially during the Holocene. Our aim is to study this spatial variability across the Nile delta by looking at a west-east transect of a selection of high-resolution Holocene records, and assess the consistency of the climatic and depositional history of Nile delta and catchment throughout the Holocene.

Here, we focus on cores that have good age control, comparable high-resolution datasets, and which are representative of a specific Nile Delta Province. Data are presented for cores PS009PC (Hennekam et al., 2014) and MS21PC (this study), representing respectively the (Far-)Eastern Province and Central Province of the Nile prodelta (Fig. 1b). To capture variability in the Western Province of the delta, we use geochemical data from core MS27PT of Revel et al. (2010; Fig. 1b), using their latest age model (Revel et al., 2014). Hence, we will also briefly discuss the data of MS27PT in our results to provide a complete overview of the Holocene Nile delta development from west to east.

We use several proxies to reconstruct the paleoenvironmental conditions at sea. Oxygen isotopes of the planktonic foraminifer *Globigerinoides ruber* ($\delta^{18}O_{ruber}$) are used to indicate differences in Nile outflow across the Nile delta. Ti/Al of bulk sediment, along with sedimentation rates, are used to define sources of fluvial sediment material and to observe sedimentation variability in the Nile delta. Total organic carbon (C_{org}), organic carbon isotopes ($\delta^{13}C_{org}$) of the bulk sediment, $\delta^{13}C$ of *G. ruber* ($\delta^{13}C_{ruber}$), and pollen are studied to investigate the effects of variability in Nile discharge on productivity in the Mediterranean, and variability in precipitation on terrestrial vegetation in and around the Nile River.

2. Materials and methods

Piston core MS21PC (32°20.7′N, 31°39.0′E; 1022 m water depth; 752 cm in length) was recovered from the Central Province of the Nile delta during the MIMES cruise with R/V *Pelagia* in 2004 (Fig. 1b). The top ~138 cm of the core was sliced at 0.5-cm intervals, which comprises the last ~13 kyr of deposition, for further geochemical and palynological analyses. The data of core PS009PC (552 m water depth; 32°07.7′N, 34°24.4′E) were partly published elsewhere (Hennekam et al., 2014; Mojtahid et al., 2015; Van Helmond et al., 2015) and we have added $\delta^{13}C_{org}$ data to this extensive dataset. We focus on the top ~278 cm in core PS009PC, representing ~13 kyr.

The chronological frameworks for cores MS21PC and PS009PC are based on Accelerator Mass Spectrometry ^{14}C measurements of mixed planktonic foraminifer material done at the Poznań Radiocarbon Laboratory in Poland (Table 1). All samples were chemically pretreated following the standard guidelines of this laboratory (http://radiocarbon.pl). The calibrated ages for MS21PC and PS009PC are calculated against the marine calibration curves in respectively the Calib 7.0.2 (Stuiver and Reimer, 1993) and OxCal 4.1.7 (Ramsey, 2009) programs, using a local reservoir correction of 21 ± 63 year based on measurements of recent mollusk shell material in the eastern Levantine basin (Reimer and McCormac, 2002; Boaretto et al., 2010). The final age model of core MS21PC is constructed by using a linear fit of the top 18.5 cm and a third-order polynomial fit for the deeper samples (18.5–143 cm; Fig. 2). The final age model of core PS009PC is based on a second-order polynomial fit for the top samples (0–190 cm) and a linear fit in the deeper part (191–323 cm; Fig. 2) (Hennekam et al., 2014).

Stable isotope analyses on *G. ruber* carbonate tests were done for MS21PC and PS009PC (Hennekam et al., 2014; Mojtahid et al., 2015). Approximately 20–30 tests were picked from the 250–300 μm size range. For PS009PC, a 212–300 μm size range was used for the interval from 173 cm (≈5.1 cal kyr BP) to the top to have a sufficient amount of *G. ruber* in that interval. Approximately 20–60 μg of sample was analyzed with a Kiel-III carbonate preparation device connected to a Finnigan MAT-253 mass spectrometer at Utrecht University, after cleaning (with H_2O_2 and CH_3OH) and crushing of the tests. The average standard deviation was 0.04‰ and 0.06‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively, based on regular measurement of the NBS-19 standard. All $\delta^{13}C_{ruber}$ and $\delta^{18}O_{ruber}$ values are reported relative to the Vienna PeeDee Belemnite (VPDB). The MS27PT $\delta^{18}O_{ruber}$ data were taken from Revel et al. (2010, i.e. Table 2 of that publication), measured similarly as in our study.

MS21PC bulk geochemistry was measured by Inductively Coupled Plasma-Optical Emission Spectroscopy at Utrecht University after a routine total digestion (in an acid mixture of 2.5 ml 3:2 $HClO_4$(60%)-HNO_3(65%) and 2.5 ml HF (40%)) of the sediment samples. The inorganic geochemistry for PS009PC sediments was done by X-Ray Fluorescence on fused glass beads at the Institute of