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1 **Holocene evolution and signature of environmental change of the Burullus lagoon (Nile**
2 **Delta) deciphered from a long sediment record**

3

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28 **Abstract**

29 This study presents high-resolution multi-proxy analyses of a well-dated sediment core
30 (BR-1, 19.20 m long) retrieved from the Nile Delta, aiming to reconstruct the Holocene
31 evolution of the Burullus lagoon. In particular, we focus on the morphodynamical processes,
32 sediment provenances and related hydro-climatic changes. The Holocene strata of the lagoon
33 coast comprise Early-Holocene marine transgressive facies and the Mid-Late Holocene
34 retrogressive deltaic facies. Although BR-1 shows no river-channel facies, two peaks of
35 magnetic susceptibility (MS) at ca. 8.0-7.0 ka (also associated with a high sedimentation rate
36 of 50 mm/yr) and 3.5-2.0 ka evoke phases of greater morphodynamic influence of palaeo-Nile
37 branches on the lagoon's development. Both dated peat layers (ca. 13 m and 8 m below MSL)
38 and lagoon muds intercalated in BR-1, together with previously-dated peat strata were
39 benchmarked relatively to MSL for the reconstruction of relative Holocene sea level in the
40 study area. Our results show considerable land lowering on the Burullus coast indicated by a
41 sea-level elevation, ca. 4-1 m lower than the one reconstructed along adjacent coastlines
42 where less land subsidence occurred. The lagoon system began to form after ca. 6.0 ka in
43 response to deceleration in sea-level rise and, being a shallower water body, both macrofauna
44 (*Cerastoderma glaucum* etc.) and ostracods (*Cyprideis torosa*) of brackish-water nature
45 emerged. In addition, geochemical data from BR-1 provide insights into environmental change
46 in association with basin-wide hydro-climate fluctuations. Concomitant peaks in Fe/Al, Ti/Al
47 and Cr/Al ratios (mafic origin), together with higher Zr/Al and Hf/Al ratios (felsic origin) before
48 ca. 8.0 ka suggest sediment provenances derived from the White and the Blue Nile during the
49 main African Humid Period (AHP). Since then, Ti/Al kept slightly ascending core-upwards with
50 two pulses at 7.8-7.3 ka and 3.5-2.0 ka, which was asynchronous to Zr/Al and Hf/Al. This
51 corroborates more sediments of basaltic origin transported to the delta coast after the main
52 AHP due to southerly shift in the position of the ITCZ. The two periods of Ti/Al pulse are
53 consistent with the MS peaks in BR-1, suggesting that palaeo-Nile branches remained active
54 during 8.0-7.0 ka and 3.0-2.0 ka nearby.

55

56 **Keywords:** Sediment provenance; Diagnostic geochemical elements; Source to Sink; Sea-level
57 rise, Sedimentation rate, Paleogeography

58

59

60 **1. Introduction**

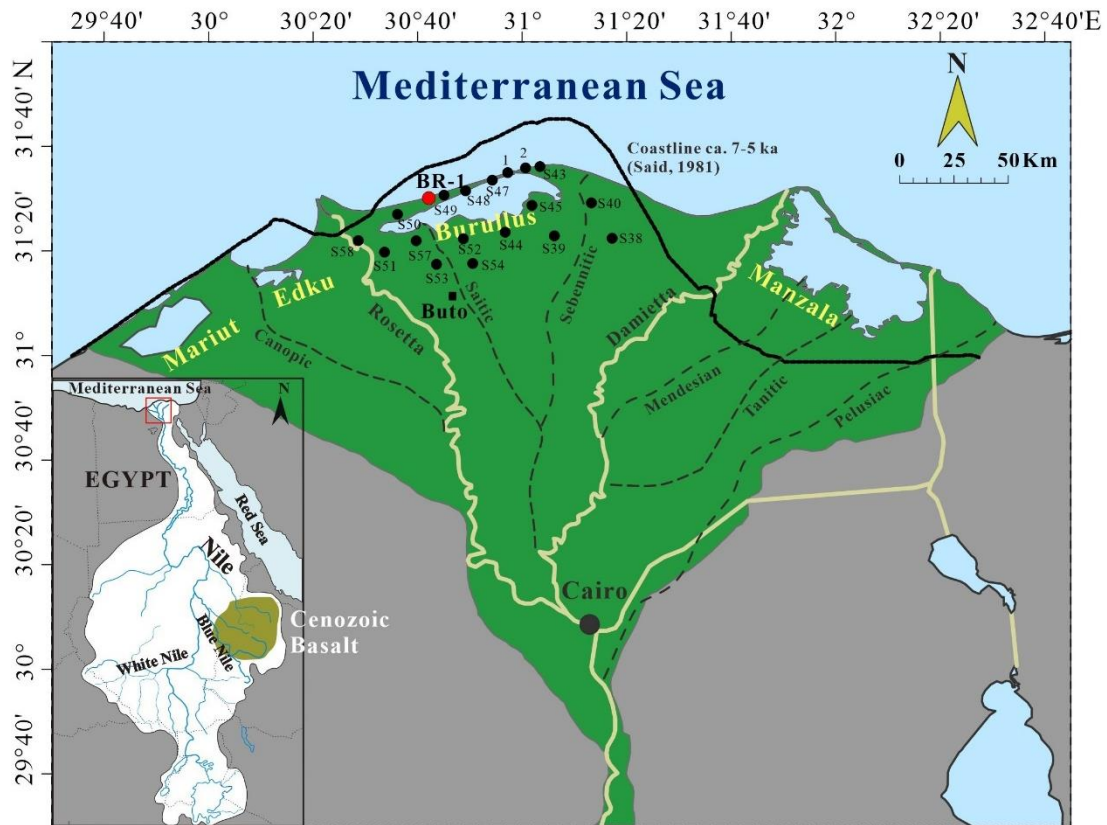
61 Continental rivers and their mega-deltas constitute rich archives of Holocene
62 environmental change and human activities (Törnqvist, 1994; Stanley and Warne, 1997; Krom,
63 et al., 2002; Kennett and Kennett, 2006; Day et al., 2007; Chen et al., 2008; Marriner et al.,
64 2013; Zuo et al., 2016). In recent decades, deltaic coastlines became highly vulnerable,
65 primarily resulting from the rising sea level and the intensification of human activities both on
66 delta plains and in watersheds, leading to a dramatic reduction in sediment supply to deltaic
67 coasts (Syvitski et al., 2009; Renaud et al., 2013; Anthony et al., 2014; Brown and Nicholls,
68 2015; Tessler et al., 2016; Besset et al., 2019).

69 The Nile Delta is a subsiding sedimentary sink that hosts ca. 41% of Egypt's population
70 and 60% of the country's food production (Hereher, 2010). Projected scenarios of relative sea-
71 level rise for the coming decades have sharpened focus on the delta's vulnerability to rapid
72 changes in accommodation space (Frihy et al., 2010; Marriner et al., 2012). The subsidence of
73 its coastal area and the sea-level rise scenarios projected by the Intergovernmental Panel on
74 Climate Change (IPCC), potentially threatens one of Egypt's most valuable economic resources
75 (63% of national agricultural land; Hereher, 2010) and the livelihood of >50 million people
76 (Becker and Sultan, 2009). The vulnerability of the Nile Delta will be exacerbated by the
77 significant increase of population density predicted in the next 25 years (Hzami et al, 2021).
78 Presently, >50% of the Nile Delta's inhabitants live on the coast within the first three meters
79 above the present mean sea level (MSL), with population density exceeding 1000 persons per
80 km² (Warner et al., 2009). Therefore, every future reduction in the delta surface will likely
81 have a very negative impact on Egypt's livelihood and the delta's overall habitability.

82 Although the sedimentary records of the coastal margin of the Nile are numerous, the
83 lack of high-resolution study of paleo-environmental change, including hydro-climatically
84 related sediment provenance is evident. The older deltaic promontories provide the unique
85 opportunity to analyse the sensitivity of these coastal morphological features to long-term
86 changes affected by the variations of Nile sediment supply (Stanley and Warne, 1993; Flaux,
87 et al., 2017). Furthermore, diagnostic geochemical proxies can help comprehend sediment
88 sources that have shaped the coastal topography under the land-sea interface (Arbouille and
89 Stanley, 1991; Krom et al., 2002).

90 Therefore, the purpose of the present study is to examine the Holocene environmental
91 evolution of the Burullus lagoon on the northern-central Nile Delta (Figure 1). The goals of the

92 study are: 1) to establish the Holocene stratigraphic framework of the Burullus lagoon using
 93 high-resolution radiocarbon dating; 2) to understand the sedimentary influences of the old
 94 Nile branches on Burullus development through time; and 3) to identify sediment
 95 provenances in relation to basin-wide hydro-climate changes by means of diagnostic sediment
 96 proxies. The result is to fill in our knowledge gap of the study area.



97
 98 **Figure 1:** The Nile Delta, showing: 1) Burullus Lagoon and sediment core site BR-1; 2) paleo-
 99 coastline of ca. 7-5 ka (after Said, 1981); 3) paleo-Nile branches (Said, 1981), and 4)
 100 sediment cores collected from previous studies (Core 1-2 from Sestini, 1989; S-cores from
 101 Arbouille and Stanley, 1991). The basaltic distribution of the Blue Nile was after Revel et
 102 al. (2010). Square in black shows the archaeological site of Buto (discussed in text).

103
 104 **2. Geomorphological setting**

105 The Nile Delta has experienced a dramatic morphological change during the Holocene.
 106 This is reflected by important displacements of the coastline and by the disappearance of
 107 several fluvial branches. Between the Roman annexation of Egypt (1st century BC) and the
 108 early Arab period (7th century AD), the Nile Delta underwent a major reshaping of its

109 hydrology. It evolved from seven major branches to two, namely the current Rosetta (on the
110 west) and Damietta (on the east) branches (Butzer, 1976; Said, 1993; Figure 1). These
111 branches remained active mostly during the Early-Middle Holocene, in transporting fluvial
112 sediment out of gorges at Cairo to the delta coast. Their wax and wane often resulted not only
113 in morphological change of the delta plain, but also large-scale shift of the coastline (Buter,
114 1976). In context of human scale, these changes were a long process. However, on the
115 Holocene scale they happened at a very rapid pace, linking to a period of climate warming,
116 rising sea level, rapid subsidence of the deltaic plain and human interferences (Stanley and
117 Clemente, 2017).

118 The Burullus lagoon is a shallow (depth <2 m; Mohamed et al., 2016) elongated water
119 body separated from the sea by a sand spit through the remobilisation of sediments
120 transported to the coast by the Rosetta branch and the erosion of the Rosetta promontory.
121 The lagoon is presently connected to the sea by an artificially maintained narrow channel at
122 its eastern margin. This lagoon lost 62.5% of its area between 1801 and 1997 (Shaltout and
123 Khalil, 2005) and ca. 43% of its open water area due to severe anthropogenic activities in
124 recent decades (El-Asmar et al., 2013). The sediment core BR-1 was collected on the northern
125 shore of the Burullus lagoon located in the northern-central Nile Delta (Figure 1). Previous
126 studies have highlighted that the Holocene deltaic sedimentary sequence, which covers the
127 marine transgressive sands of Early-Holocene age, is 10-26 m thick. Deltaic deposits are
128 composed of a succession of lagoonal, marshy and fluvial sediments deposited after 8.0-7.5
129 ka. In the northern part of the lagoon, these deposits are covered by a <6 m thick sandy unit,
130 corresponding to the presence of the sand spit since ca. 3-4 ka (Arbouille and Stanley, 1991).

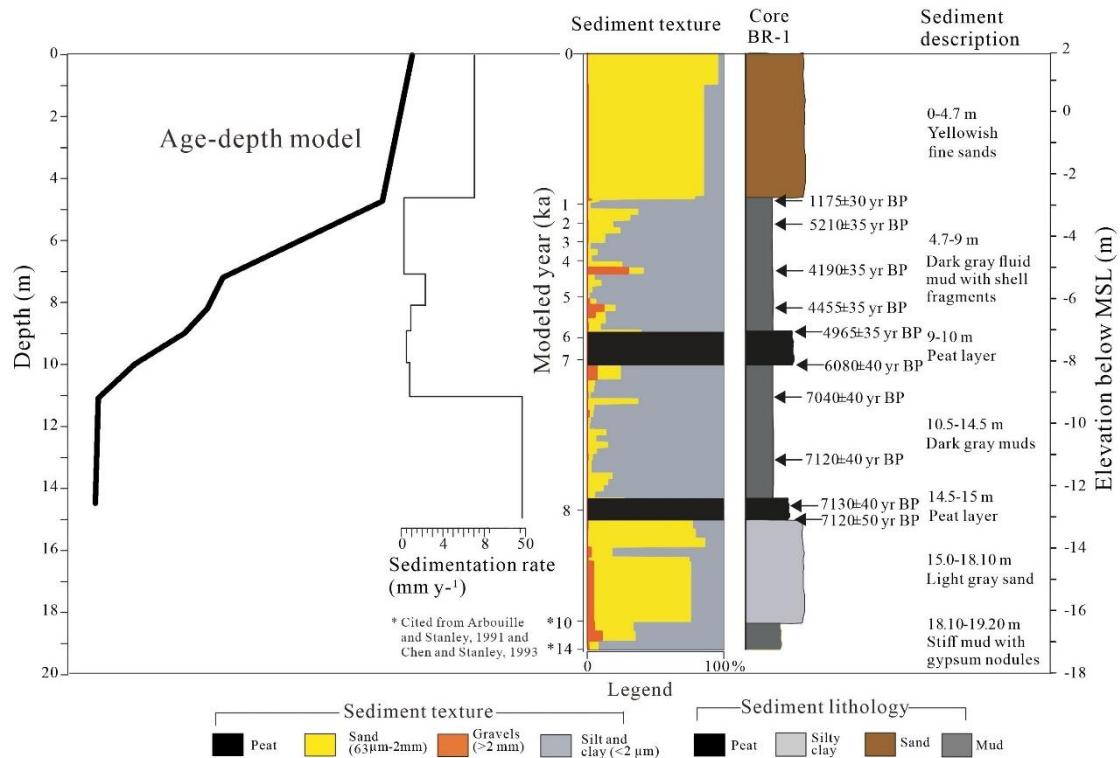
131

132 **3. Material and methods**

133 3.1. Sediment coring, logging and sampling

134 The sedimentary core BR-1 was drilled using a rotary corer (Figures 1 and 2). Sediment
135 was collected continuously by a 1-m long corer with a diameter of 9 cm. BR-1 (19.2 m long:
136 31°28'3.025" N; 30°39'49.662" E; +2 m MSL) was stratigraphically described in the field.
137 Sediment samples were kept in wooden boxes and transported to the laboratory at
138 Kafrelsheikh University (Egypt). The sediment core was split into two halves, one for sampling
139 and the other for archiving. Core sediment was logged for its colour, stratigraphy, water
140 content, biogenic content (complete shells and shell debris) and mineral distribution. In total,

141 65 samples were taken at ca. 30 cm sampling interval. Each sample was divided in two parts,
 142 for bio-sedimentology and geochemistry. Analyses were performed in the Geography and
 143 Archaeology laboratories at Durham University (UK). Samples were freeze-dried and
 144 grounded for magnetic susceptibility, X-ray fluorescence (XRF) and carbon measurements. We
 145 have further compared our analytical results with other data from the Burullus region to
 146 understand the paleo-geographical changes of the lagoon (Wunderlich, 1988; Arbouille and
 147 Stanley, 1991).



148
 149 **Figure 2:** AMS-¹⁴C-dated Holocene sediment sequences of BR-1. The age-depth model was
 150 reconstructed using the dedicated R-code Clam (Blaauw, 2010) and sedimentation rates were
 151 calculated.

152
 153 **3.2. Radiocarbon-dating**

154 Ten (10) AMS-radiocarbon measurements were performed at the Poznan Radiocarbon
 155 Laboratory (Poland) on plant remains, seed, charcoal remains, bulk sediment or articulated
 156 mollusc shell (Table 1). The age obtained from articulated mollusc shell (*Cerastoderma*
 157 *glaucum*), was corrected using a marine reservoir age of 400 years. Using seven ¹⁴C dates
 158 (Table 1; Figure 2), we constructed an age-depth model for BR-1 using the dedicated R-code
 159 Clam (Blaauw, 2010). We did not use three available datings. One was age-inversion at 5.4-5.5

160 m depth for which the age is older than the dating at 7.1-7.2 m depth (Figure 2). Between
 161 12.9-14.9 m depth came with three similar ages from different samples measured. We
 162 rejected two of them; one at 14.9 m depth (7120 ± 50 BP) because the dated sample (seed)
 163 had lower carbon content (0.3 mgC) and another at 13 m depth (7120 ± 40 BP) because of
 164 bulk sediment used.

165 All conventional dates were calibrated using the Calib Rev 8.20 program with the
 166 IntCal20 calibration curve (Stuiver and Reimer, 1993; Reimer et al., 2020). Dates were given
 167 at confidence intervals of 95.4% (2σ) in years before present (cal. yr BP), simply used as ka in
 168 present study.

170 Table 1. Details of AMS- ^{14}C -dating materials of BR-1. ^{14}C dates were expressed in calibrated
 171 years BP at the 95% confidence level (2σ). Accepted ^{14}C dates were used for Age-depth model

Sample No.	Lab. No.	Materials	Sampling depth (m)	Age ^{14}C (yr BP)	Calibrated age (cal. yr BP, 2σ)	Remarks
BR-1 470-473	Poz-107202	Marine shell (<i>Cerastoderma glaucum</i>)	4.70-4.73	1175 ± 30	700 ± 30	Accepted
BR-1 540-550	Poz-107382	Organic material	5.40-5.50	5210 ± 35	5670 ± 222	Rejected (reworked material)
BR-1 710-720	Poz-107238	Plant remains	7.10-7.20	4190 ± 35	4710 ± 130	Accepted
BR-1 810-820	Poz-107239	Charcoal	8.10-8.20	4455 ± 35	5130 ± 155	Accepted
BR-1 890-900	Poz-107384	Peat	8.90-9.00	4965 ± 35	5725 ± 125	Accepted
BR-1 980-1000	Poz-107385	Peat	9.80-10.00	6080 ± 40	6925 ± 225	Accepted
BR-1 1090-1110	Poz-107240	Plant remains	10.90-11.10	7040 ± 40	7612 ± 195	Accepted
BR-1 1290-1300	Poz-107456	Organic sediment	12.90-13.00	7120 ± 40	7688 ± 204	Rejected (bulk sample)
BR-1 1440-1450	Poz-107241	Plant remains	14.40-14.50	7130 ± 40	7945 ± 80	Accepted
BR-1 1480-1490	Poz-107386	Seed	14.80-14.90	7120 ± 50	7690 ± 210	Rejected (0.3 mgC)

172

173

174 3.3. Dated peat and lagoon muds for Holocene sea-level reconstructions

175 Two-¹⁴C dates of peat layers and three ¹⁴C dates of lagoon muds were used to
176 reconstruct the Holocene sea level (Figure 3). Elevation calibration to MSL was performed, i.e.
177 2.0 m subtracted from the core depth of peat layer, accounting for the surface elevation at
178 the core site above MSL; 1.5 m (average water depth of lagoon of the Nile Delta) added to the
179 sampling depth in case of lagoon sample. In addition, 13 ¹⁴C dates of peat layers of the study
180 area were selected from the study by [Arbouille and Stanley \(1991\)](#) for the sea level simulation
181 (Figure 3). The same elevation calibration was also applied to these radiocarbon dates. The
182 sea-level curve was calculated using the best-fit approach.

183

184 3.4. *Bio-sedimentology*

185 The general texture of the sediment, including the gravel (>2 mm), sand (63 µm–2 mm)
186 and silty-clay (<63 µm) fractions, was determined by wet sieving ~50 grams of oven-dried
187 sediments. Ostracods were picked from the >125 µm fraction. Mollusc shells were identified
188 in the gravel fraction according to [D'Angelo and Garguillo \(1978\)](#).

189

190 3.5. *Magnetic parameters*

191 Magnetic susceptibility (MS) measurements were undertaken using a Bartington MS2B
192 magnetic susceptibility meter using a dual frequency sensor. Milled freeze-dried sediments
193 were placed in 10 ml pre-weighted cylindrical plastic containers. MS was measured three
194 times for each sample, both at low (0.465kHz ± 1%) and high frequencies (4.65kHz ± 1%). Mean
195 MS values were corrected to consider mass differences between measured samples and
196 samples used for calibration. Measurements are reported as mass-specific magnetic
197 susceptibility in SI units ($\times 10^{-8} \text{m}^3 \cdot \text{kg}^{-1}$).

198

199 3.6. *Geochemical element analyses*

200 Geochemical elements (Al, Fe, Ti, Cr, Zr, Hf, both major and trace) were measured on
201 ball-milled samples. The homogenised bulk sediment sample 0.6 g was mixed with 6 g of flux
202 (66.67 % Lithium Tetraborate, 32.83 % Lithium Metaborate and 0.50 % Lithium Iodide) and
203 fused to a glass disc using a Claisse LeNeo fusion instrument. Major and trace elements were
204 then determined using a Panalytical Zetium X-Ray Fluorescence Analyser (XRF). We checked
205 the accuracy by international standard reference material and replicates of analyses of

206 selected samples. Fe, Ti and Cr (mafic proxy) were selected considering the nature of basaltic
207 exposures in the Blue Nile watershed (Krom, et al., 2002; Marshall et al., 2011; Chen et al.,
208 2020), and Zr and Hf (felsic proxy) as a tracer of the Precambrian crystalline base of the White
209 Nile (Revel et al., 2010; Gu et al., 2014; Chen 2020). These elements were normalized to Al in
210 order to minimize grain-size effects (Chen et al., 2010). The total bulk sediment elemental
211 composition is presented in the Supplementary data (seeing Supplementary Material). XRF
212 was not measured on peat samples to avoid the possible impact of organic matter on the
213 geochemical composition of the sediments.

214

215 3.7. Carbon content

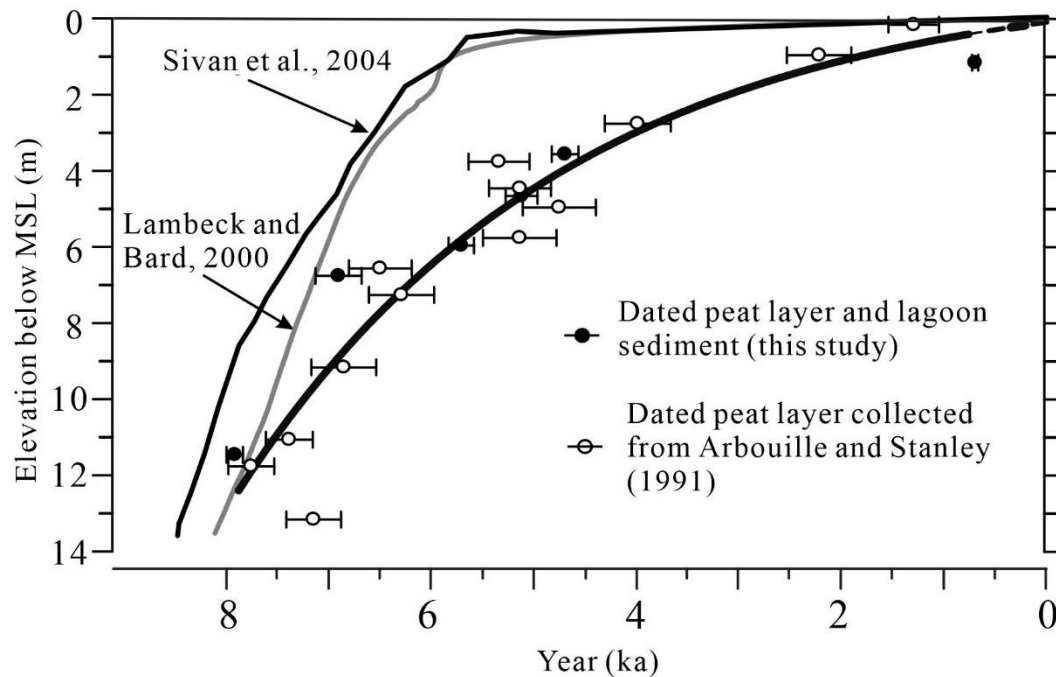
216 Total inorganic carbon (TIC) has been measured using an Analytik Jena Multi EA
217 (Elemental Analyser) 4000. Milled freeze-dried sediments were weighed in ceramic cups and
218 introduced in turn into the instrument via an autosampler. For TC analysis, samples are
219 combusted at 1000 - 1500°C in the presence of oxygen without the use of a catalyst. Samples
220 for TIC analysis were first treated with 40 % Orthophosphoric acid to remove the organic
221 carbon component before being combusted. In both cases the gas generated from the burning
222 of the sample is detected by a NDIR (Non-Dispersive Infrared) detector. TOC is then
223 determined by the instrument from the difference between TC and TIC values.

224

225 4. Results

226 4.1. Chronology, sedimentation rate and Holocene sea level curve

227 The 7 AMS-datings of BR-1 provide a chronological framework from ca. 8.0 to ca. 0.7
228 ka BP (Table 1, Figure 2). In addition, considering absence of ¹⁴C dating at the basal section of
229 the core, we inferred an age of ca. 10 ka for the Holocene bottom sediment section, and ca.
230 14 ka for the Late Pleistocene stiff muds (Figure 2,4,5), according to the substantial
231 chronostratigraphic data produced by previous studies (Arbouille and Stanley, 1991; Chen et
232 al., 1992; Chen and Stanley 1993). ¹⁴C datings were used to calculate the sedimentation rate
233 of BR-1, showing an extraordinarily high rate (50 mm/yr) between the core depth 14.5-11 m,
234 and the lower rate (0.6-2.3 mm/yr) between 11-4.7 m, and higher rate (7.2 mm/yr) between
235 4.7-0 m (Figure 2). The reconstructed Holocene sea-level curve of the study area indicates that
236 the sea level was 14 m below MSL at 8 ka, and then quickly rose to 4 m below MSL at 6 ka,
237 before approaching the present MSL (Figure 3).

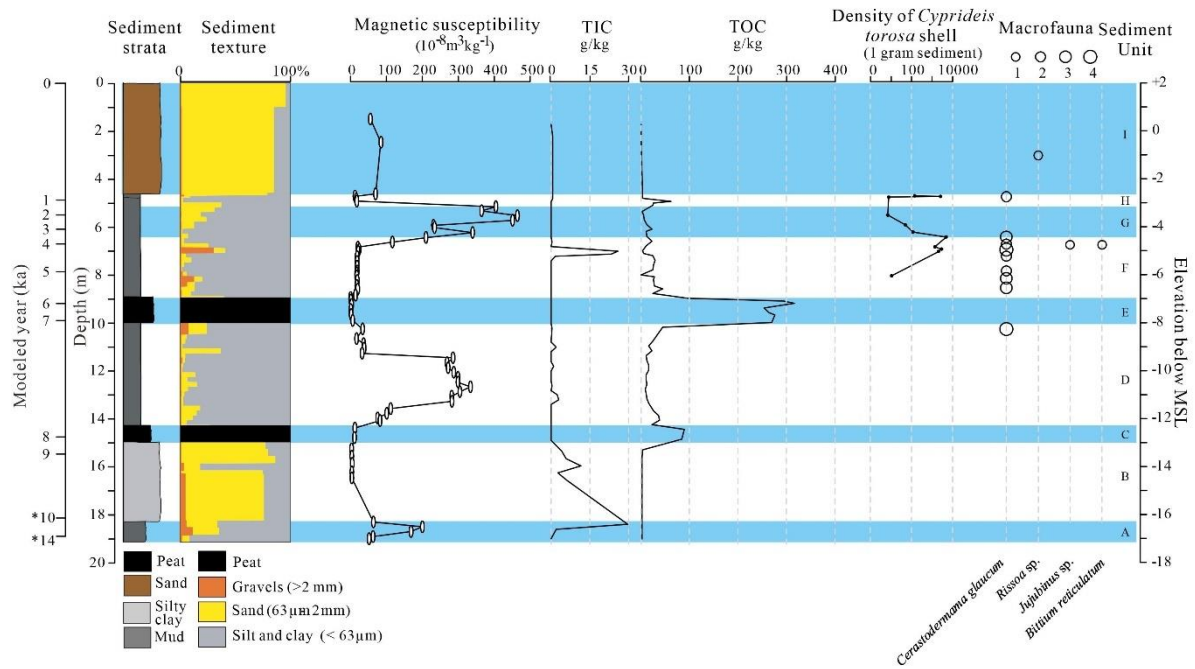


238
 239 Figure 3. Reconstructed relative sea level of Burrulus coast, using both dated peat layers and
 240 lagoon muds from this study and dated peat layers from Arbouille and Stanley (1991).

241
 242 4.2. Bio-sedimentology of core BR-1

243 The sedimentary sequence of core BR-1 constitutes a classic transgressive-
 244 retrogressive sequence (Reineck and Singh, 1975; Figure 2). The sequence broadly displays
 245 three main sedimentary textures; silty-clay between 19.2-18.8 m, between 14.5-10 m and
 246 then between 8.8-4.7 m; from fine-to-medium sands between 18.8-15 m and then between
 247 4.7-0 m. Two organic-rich peat layers are intercalated in the sequence (between 15.0-14.3 m
 248 and between 10.0-8.8 m).

249 Most of the sediment samples are devoid of fauna. Only valves of the ostracod
 250 *Cyprideis torosa* were found in variable quantity in the upper section of the core (7-4.6 m;
 251 Figure 4). Molluscs were also found in nine samples of the upper core sediment (Figure 4),
 252 represented by lagoonal *Cerastoderma glaucum* shells (n=8). The upper part of the core also
 253 shows the presence of shells living in infralittoral environments such as *Bittium reticulatum*
 254 (n=1), *Jujubinus* sp. (n=1) and *Rissoa* sp. (n=1).



255
 256 **Figure 4:** Distribution of sediment magnetic susceptibility (MS), TIC, TOC, macro-fauna and
 257 ostracod of core BR-1. Our data were used to define nine sedimentary units (A-I). * - age cited
 258 from Arbouille and Stanley (1991) and Chen and Stanley (1993)
 259

260 4.3. Magnetic susceptibility

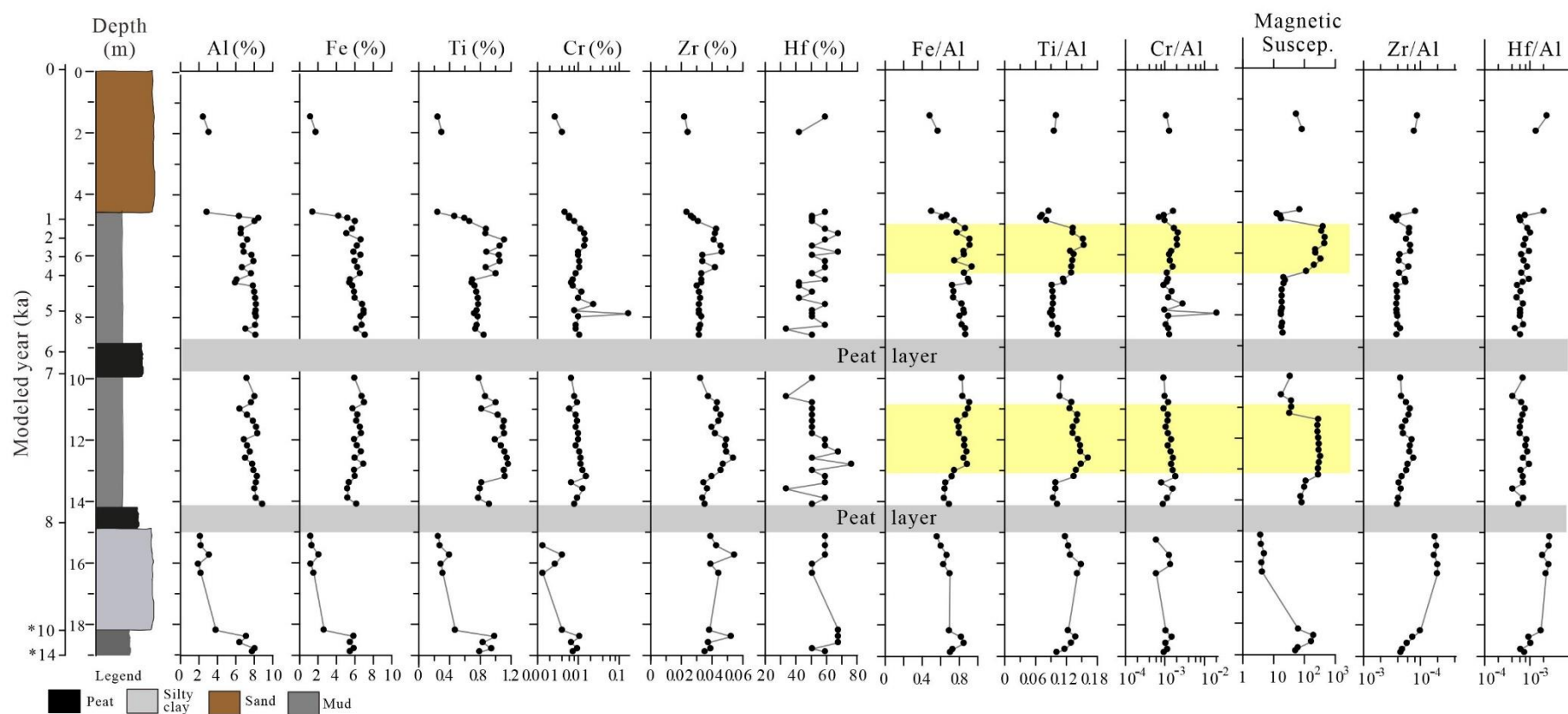
261 Magnetic susceptibility (MS) values are non-uniform along the sedimentary profile and
 262 vary from $1 \cdot 10^{-8} \text{m}^3 / \text{kg}^{-1}$ to $468 \cdot 10^{-8} \text{m}^3 / \text{kg}^{-1}$. Two MS peaks ($14 \cdot 10^{-8} \text{m}^3 / \text{kg}^{-1}$ to $468 \cdot 10^{-8} \text{m}^3 / \text{kg}^{-1}$
 263 at 11.4-13.3 m and $233-468 \cdot 10^{-8} \text{m}^3 / \text{kg}^{-1}$ at 6.3-5.2 m) occurred in the Holocene muddy
 264 sediment section (Figure 4), separated by the markedly low MS throughout. MS variations can
 265 often be subject to sediment provenances from the mother rocks of river basin, nevertheless
 266 post-sedimentary diagenesis is also possible.

267
 268 4.4. Carbon content

269 Both total inorganic carbon (TIC) and organic carbon (TOC) values are not consistent
 270 along the core profile (Figure 4). TIC values are typically <3 g/kg with some exceptions in the
 271 basal core sediment and around 7 m depth (Figure 4). TOC values are also markedly low (10-
 272 15 g/kg) in BR-1 sediments, except the peat layers (60-300 g/kg).

273
 274 4.5. Geochemical element distribution

275 The results of the XRF analysis of diagnostic geochemical elements (Al, Fe, Ti, Cr, Zr, Hf)
276 used in the study were shown in Figure 4 ([seeing raw data in Supplementary Material](#)). Almost
277 all elements had kept their distribution pattern with Al ([Figure 5](#)), apparently due to grain-size
278 effect ([Chen et al., 2020](#)). Fe, Ti, Cr and Hf showed decreasing values from 14- 8 ka, while Zr
279 shows a minor increase ([Figure 5](#)). After this, all elemental values rose until ca. 2 ka, in addition
280 to Hf, which had kept its fluctuations in the same time. Interestingly, after normalization to Al
281 ([Figure 5](#)), Fe/Al and Ti/Al show similar trends throughout the Holocene, while Cr/Al is also
282 lightly correlated with the pattern. In general, Fe/Al, Ti/Al and Cr/Al show higher values after
283 8 ka with two co-highs to MS during ca. 7.8-7.3 ka and 3.5-2.0 ka ([Figure 5](#)). In comparison,
284 Zr/Al and Hf/Al were markedly high before 8 ka, before being superseded by Fe/Al and Ti/Al
285 from 8.0-2.0 ka ([Figure 5](#)). Since then, Zr/Al and Hf/Al were lower. Geochemical results of the
286 sandy section of the core top (<2.0 ka) are not discussed here.
287



289

290 **Figure 5:** Diagnostic geochemical elements (Al, Fe, Ti, Cr, Zr, Hf) and their normalized values (to Al) of core BR-1 (data from the peat layers are
 291 not included). Magnetic susceptibility (MS) is listed for comparison. * - age cited from Arbouille and Stanley (1991) and Chen and Stanley
 292 (1993)

293 5. Discussion

294 Using multiple proxies from sediment cores to reconstruct the paleo-environmental
295 change can serve as a robust approach to enhance understanding of the Holocene evolution
296 of deltas (Coleman et al., 1998; Reitz et al., 2015). Our well-dated BR-1 sediment data attests
297 to this.

298

299 5.1. Coastal paleo-environmental changes: transgressive and retrogressive sequences

300 The nine paleo-environmental units of BR-1 (A to I) can be identified (Figure 2,4),
301 namely units A-D the transgressive sequence, and units E-I the retrogressive sequence. These
302 units, from core-bottom to top, highlight the morphodynamic evolution of Burullus lagoon
303 during the Holocene.

304

305 5.1.1. Unit A – over bank deposits: 19.2-18.2 m (14-12 ka)

306 This unit is composed of brownish stiff muds of Late Pleistocene age (Figure 4; Chen
307 and Stanley, 1993). MS values vary from 53 SI to 202 SI (Figure 4). Calcareous nodules and
308 higher TIC (30 g/kg) are observed, both reflecting the evaporation setting of the Late
309 Pleistocene in the NE Africa (Chen and Stanley, 1993). Previous works (Elliott, 1974; Arbouille
310 and Stanley, 1991; Chen and Stanley, 1993) have associated similar deposits formed by the
311 Nile channel overbank processes in the area, dating to ca. 14-10 ka (Stanley and Warne, 1993),
312 when the sea level was much lower than today.

313

314 5.1.2. Unit B - marine/estuarine transgression: 18.2-15 m (before 8.0 ka)

315 A 3.2 m thick sandy unit overlies the overbank deposits. This unit is homogeneous,
316 mainly composed of greyish fine sand (80-86%). The gravel fraction (<4 %) consists of small
317 calcareous nodules and marine shell fragments. MS values are lower in this unit (4-5 SI) (Figure
318 4). Two ¹⁴C dates obtained from the peat sediment on the top demonstrate that the sandy
319 section developed before ca. 8 ka (Figure 2). This section was the reworked product of the
320 earlier marine and shallow-marine shelf sediments, which were mostly deposited between
321 12.0-7.5 ka in the Burullus area (Arbouille and Stanley; 1991). Flaux et al. (2017) interpreted a
322 similar deposit in the nearby Abukir Bay (west of the Rosetta promontory) and found this
323 environment consistent with a euryhaline estuarine/coastal setting before ca. 7.0 ka. Unit B

324 usually represents the maximum marine transgression of the Early Holocene in the study area,
325 and the coastline was further south of the coring site (Arbouille and Stanley, 1991).

326

327 5.1.3. Unit C - salt-marshland: 15-14.3 m (ca. 8 ka)

328 Unit C is composed of peat sediment rich in organic matter and with lower MS values
329 (11-12 SI) (Figure 2, 4). The unit is dated to ca. 8 ka (age-depth model; Figure 2), corresponding
330 to the development of a costal marshland when sea-level rise began to stabilize. It developed
331 at an elevation of 13 m below MSL (Figure 2). Coastal marshland was widely developed on the
332 back of central-west of Burullus lagoon, which enables to be used for the Holocene sea-level
333 reconstruction (Figure 3; discussed below) (Arbouille and Stanley, 1991).

334

335 5.1.4. Unit D - open bay with higher fluvial inputs: 14.3-10.0 m (ca. 8.0-7.0 ka)

336 Unit D comprises brownish grey muds (63-99%) and is devoid of fauna. Higher MS
337 values (271-336 SI) were recorded in the middle of this unit (Figure 4). Flaux et al. (2017) have
338 described high MS for the nearby Edku lagoon, and associated them with high fluvial inputs
339 referring to the similar range of MS values measured in the Late-Holocene floodplain muds of
340 the Nile (100-470 SI) (Ghilardi and Boraik, 2011). In addition, higher mica content seen under
341 binocular microscope is in accordance with the composition of modern fluvial samples
342 (Stanley and Chen, 1991). Unit D can be interpreted as an open bay before sea level reached
343 its maximum level. The markedly high sedimentation rate (50 mm/yr, Figure 2) of the unit
344 translates an episode of high deposition, most likely affected by the paleo-branches of the
345 Nile that prevailed on the Burullus coast in the Early-Middle Holocene (Buzter, 1976).

346

347 5.1.5. Unit E - salt-marshland: ca. 10.0-8.9 m (ca. 7.0-5.7 ka)

348 Like unit C, unit E consists of peat sediments rich in organic matter, indicating a
349 deceleration of sea-level rise during the Early-Middle Holocene (Figures 2, 4). The formation
350 of this peat layer translates the seaward position of the coastline at ca. 7-5.7 ka (Figure 2).
351 Wunderlich (1988) has described a marshy area, dated from 6 to 4.5 ka, which extended
352 further inland around the archaeological site of Buto, ca. 30 km south of the coring site. The
353 development of a marshy environment in this area can be linked to a decrease in sediment
354 inputs from the river or a channel avulsion. Revel et al. (2015) show that the decrease in Nile
355 terrigenous inputs to the western pro-delta occurred during the first half of the 7th millennium

356 BP. The base of this peat layer dated to ca. 7 ka at 8 m below MSL was used to reconstruct the
357 sea-level rise history of the study area (Figure 3; discussed below).

358

359 5.1.6. Unit F - lagoon environment: 8.90-6.30 m (ca. 5.7-3.2 ka)

360 Unit F is dated to ca. 5.7-3.2 ka (Figure 2). This unit is characterized by lower and
361 homogenous MS values (15-24 SI). In the unit, a high abundance of *Cyprideis torosa* (up to
362 2680 individual/1-g sediments) is observed. They are associated with lagoonal molluscs
363 (*Cerastoderma glaucum*) and some marine species (*Jujubinus* sp. and *Bittium reticulatum*).
364 This demonstrates that the former transgressive and open marine setting (unit D) was
365 transformed to an open lagoon environment after ca. 5.7 ka, as part of retrogressive process.
366 Previous work has shown the same succession, with a lagoonal environment covering a salt-
367 marshy layer in the Burullus and Edku coast (Wunderlich, 1988; Arbouille and Stanley, 1991;
368 Chen et al. 1992; Flaux et al., 2017). The lower sedimentation rate of this unit indicates less
369 fluvial input to the lagoon during this time period (Figure 2).

370

371 5.1.7. Unit G - fluviially-affected lagoon: 6.3- 5.15 m (ca. 3.2-1.5 ka)

372 Unit G is the same sediment texture as unit F. It is dated to 3.2- 1.5 ka (Figure 2).
373 However, this unit presents higher MS values (234-410 SI) consistent with the presence of
374 mica in the sand fraction. Lagoonal fauna disappear, along with a decrease in the density of
375 the ostracod *Cyprideis torosa*. Nevertheless, the persistence of the ostracod demonstrates
376 that the lagoon was still partially connected to the sea. In this unit, we observed an inverted
377 date at core depth 5.4 m (Table 1), which may be consistent with the deposition of reworked
378 older organic matter via river transport. Probably, a negative sedimentary budget leading to
379 a marine intrusion into the Canopic promontory was identified between 3.5-2.0 ka (Flaux et
380 al., 2017). While a lowering of Nile flow during this period was widely documented (Marriner
381 et al., 2012), the negative sedimentary budget identified in the area of the Canopic branch
382 may result in from the partial the shift of the river branch towards the east of the Burullus
383 area.

384

385 5.1.8. Unit H - closing lagoon: 5.15-4.70 m (ca. 1.5-0.7 ka)

386 Unit H highlights the brief development of a lagoon, but much more isolated from the
387 sea because of the growing sand spit (Figure 2). Increasing ostracod (*Cyprideis torosa*) density

388 (132-2300 individual/1-g sediment) is observed (Figure 2, 4), perhaps due to more saline water
389 under reduced Nile flow during the post-AHP climate aridification (Zhao et al., 2020).

390

391 5.1.9. Unit I - sand spit: 4.70 – 0 m (0.7 – 0 ka)

392 Unit I consists of thicker sand section on the top of BR-1 (Figure 2), with small
393 calcareous gravels in the lower part of this unit. This unit corresponds to the development of
394 the sand spit along Burullus coast as of ca. 3-4 ka (Arbouille and Stanley, 1991). The sand spit
395 formed because of reworking of sediments via coastal currents, as the water and sediment
396 supply from the upper basin dramatically decreased under the drying climate in the Late
397 Holocene (Marriner et al., 2013; Zhao et al., 2020).

398

399 **5.2. Palaeoenvironmental evolution of Burullus lagoon: multi-proxy implications**

400 The multiple sediment proxies of BR-1 used in this study can help comprehend the
401 Holocene environmental change of the Nile Delta, including hydroclimate-related sediment
402 provenances, sea-level rise and coastal morphodynamical processes.

403

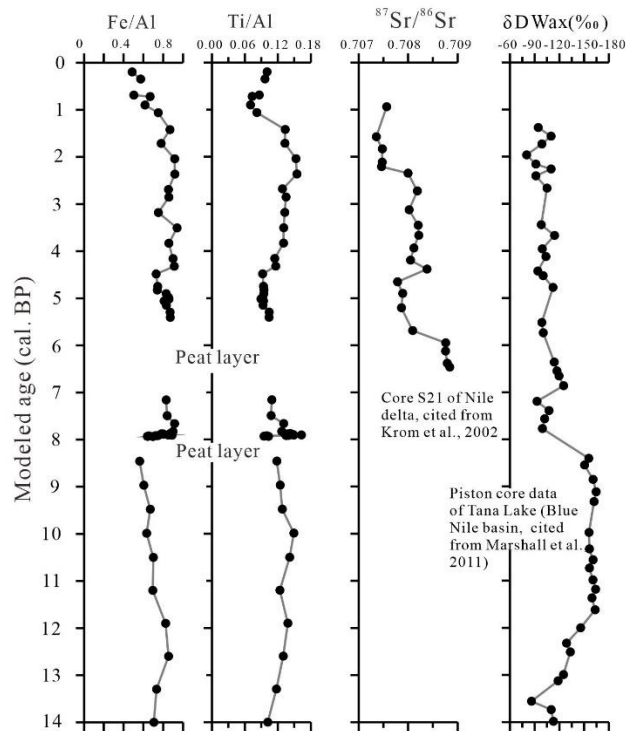
404 5.2.1. Sediment provenances and sedimentation rate: hydroclimate implications

405 Diagnostic geochemical elements of BR-1 selected in this study are meaningful in
406 reflecting sediment provenances of mother rocks of the Nile River basin (Figure 5). Ti and Cr
407 (mafic origin) can be used to trace sediment provenance from the Blue Nile where basaltic
408 exposures are dominant (Krom et al., 2002; Revel et al., 2010; Gu et al., 2014). High Fe content
409 was also linked to the Blue Nile source (Krom et al., 2002). Zr and Hf can commonly refer to
410 the felsic nature of a sediment source (Gu et al., 2014; Chen et al., 2020), and thus can be
411 linked to the White Nile, where Precambrian crystalline bedrock prevails (Revel et al., 2010).
412 Of note, this source-sink inter-correlation using same diagnostic geochemical elements as this
413 study has been established in the Changjiang River catchment and on the southeast China
414 coast, recently (Gu et al., 2014; Chen et al., 2020).

415 As mentioned before, the elemental values of bulk samples are inevitably affected by
416 the proportion of fine grain size (Figure 5). However, after normalization to Al (grain-size
417 proxy), our results show the coherent interlinkage of source-sink (Figure 5).

418 The synchronous increase in Fe/Al, Ti/Al, Zr/Al, Hf/Al in the sediment profile of BR-1
419 before ca. 8 ka (Figure 5) indicates sediment provenance both derived from the White Nile

420 and the Blue Nile during the main AHP. Since then, Fe/Al and Ti/Al (Cr/Al is also lightly
 421 correlated), had kept their ascending values up the core with two increases. This was
 422 asynchronous to non-fluctuated Zr/Al and Hf/Al in BR-1 (Figure 5). The higher Fe/Al, Ti/Al and
 423 Cr/Al can be attributed to the increasing sediment source from Blue Nile, since a less
 424 vegetated basaltic surface suffered from intensive erosion due to the southerly shifting ITCZ
 425 (Krom and Stanley, 2002; Revel et al., 2010). Our Fe/Al and Ti/Al vs. reduced $^{87}\text{Sr}/^{86}\text{Sr}$ value
 426 measured in sediment core S21 of the Nile Delta reflects the long-term climate aridification
 427 and the concomitant increase in sediment flux from the Blue Nile since 6 ka (Figure 6) (Krom
 428 et al., 2002). Also, the lowering level of lake Tana in the Blue Nile basin (Ethiopia Plateau) has
 429 been evidenced since 8 ka through analysis of $\delta\text{D}_{\text{Wax}}$ (lake level proxy), confirming the post
 430 AHP drying climate, with the similar context of Fe/Al and Ti/Al (Figure 6) (Marshall et al., 2011).



431
 432 **Figure 6:** Comparison of Fe/Al and Ti/Al of this study to $^{87}\text{Sr}/^{86}\text{Sr}$ of core S21 (Nile Delta) and
 433 water level proxy ($\delta\text{D}_{\text{Wax}}$ ‰) of the Blue Nile basin

434
 435 The two pulses of higher Fe/Al and Ti/Al that were also coeval in distribution to the
 436 higher MS recorded in BR-1 profile during ca. 7.8-7.3 ka and 3.5-2.0 ka (Figures 4, 5),
 437 suggesting more mafic sediment fluxes to be flooded from the Blue Nile to lagoon coast via
 438 paleo-Nile branches prevailed at those times. Ti content is a good indicator for Blue Nile inputs,

439 since its catchment is characterised by a volcanic (basaltic) nature, especially when it varies
440 synchronously with changes in the magnetic mineralogy (volcanic rocks being enriched in Ti-
441 magnetite) (Marshall et al., 2011).

442 The lowering sedimentation rate from the previous 50 mm/yr before 8 ka to ca. 1-2
443 mm/yr between 8-1 ka (Figure 2) was associated to the drying climate setting after the main
444 AHP (Shanahan et al., 2015; Tierney et al., 2017). Virtually, the high sedimentation rate (ca.
445 7.0 mm/yr) of thicker sand layer on the top BR-1 manifested the intensifying aeolian processes
446 coupled with weakening fluvial sedimentation during the Late-Holocene drying climate
447 condition (Figure 2).

448

449 5.2.2. Reconstructed relative sea-level: insights from dated peat layers and lagoon muds

450 Saltmarshes (peat layer) are often used for reconstructing the Holocene sea level
451 because they form at an elevation corresponding to the contemporary position of mean sea
452 level (Chen and Stanley, 1998; González and Törnqvist, 2009; Wilson, et al., 2020). Our dated
453 peat layers, together with dated lagoon muds can highlight more precisely the sea-level
454 positions of the central Nile coast during the Holocene (Figure 3).

455 We noted that all reconstructed Holocene sea levels of delta coast are relative ones
456 due to eustatic and isostatic movements. Through comparison, it is demonstrated that our
457 reconstructed sea level that lies -14 m below MSL at 8 ka, and -4 m below MSL at 6.0 ka before
458 gradually approaching the present MSL is similar to that of the Mississippi delta, where higher
459 tectonic subsidence predominates (Törnqvist et al., 2004). Also, our reconstructed sea level
460 curve lies ca. 4-1 m below the relative sea-level curve established for the Mediterranean coast
461 of France and Israel (Figure 3), where tectonic subsidence is thought to be minor (Lambeck
462 and Bard, 2000; Morhange et al., 2001; Sivan et al., 2004, Vacchi et al., 2018). This comparison
463 highlights the considerable land surface lowering that occurred in the central Nile Delta during
464 the Holocene. The compaction rate measured in different part of the Nile Delta are clearly
465 related to the thickness of the Holocene sedimentary sequence mainly formed by fine
466 lagoonal and marsh deposits. Stanley and Clemente (2017) reported subsidence rate of ca. 7.7
467 mm/yr in the central Nile Delta during the Holocene that can be explained by the thicker
468 lagoonal deposits (>15 m). Higher subsidence rates have been measured in the NE Nile delta
469 where the Holocene sedimentary sequence is 20-40 m thick (Stanley and Clemente, 2017).

470

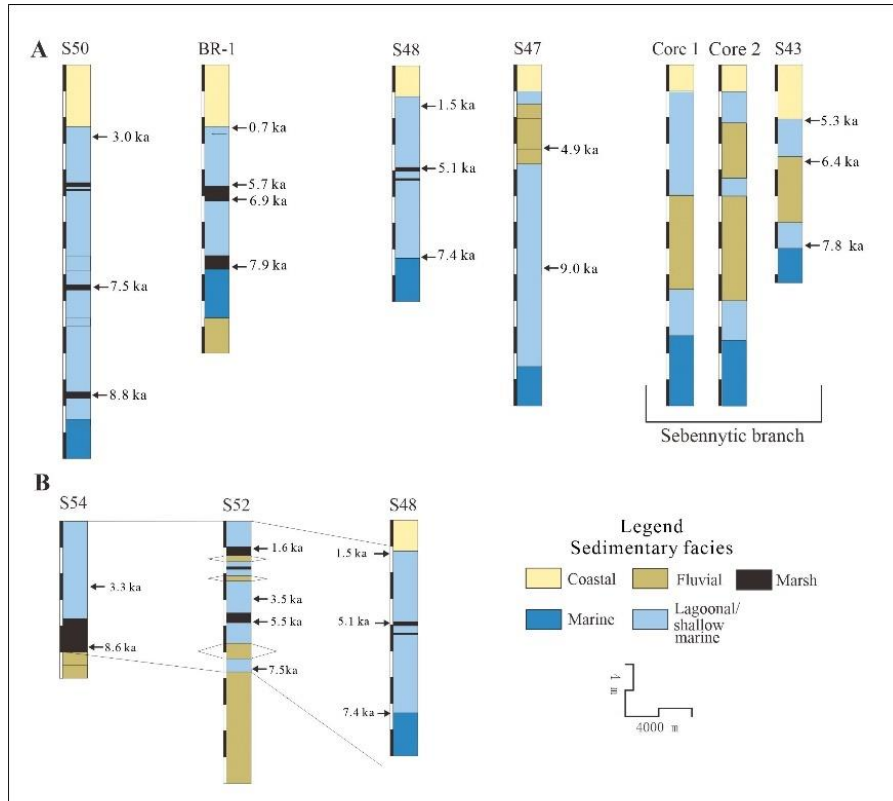
471 5.2.3. Morphodynamic impact of the former Nile branches on Burullus lagoon

472 In the Holocene, there were many paleo-Nile branches flowing through the Nile Delta
473 into the Mediterranean Sea (Figure 1) (Butzer, 1976). The Sebennytic and Saitic branches were
474 the two major branches developed on the eastern and western sides of Burullus lagoon in the
475 Early Holocene (Tousson, 1922; Arbouille and Stanley, 1991). Rapid fluvial sedimentation
476 made the central Nile coast a large-scale promontory-like topography (Figure 1). The coast
477 subsequently suffered from intensive erosion as the branches shifted and diminished during
478 Late Holocene (UNDP/UNESCO, 1978).

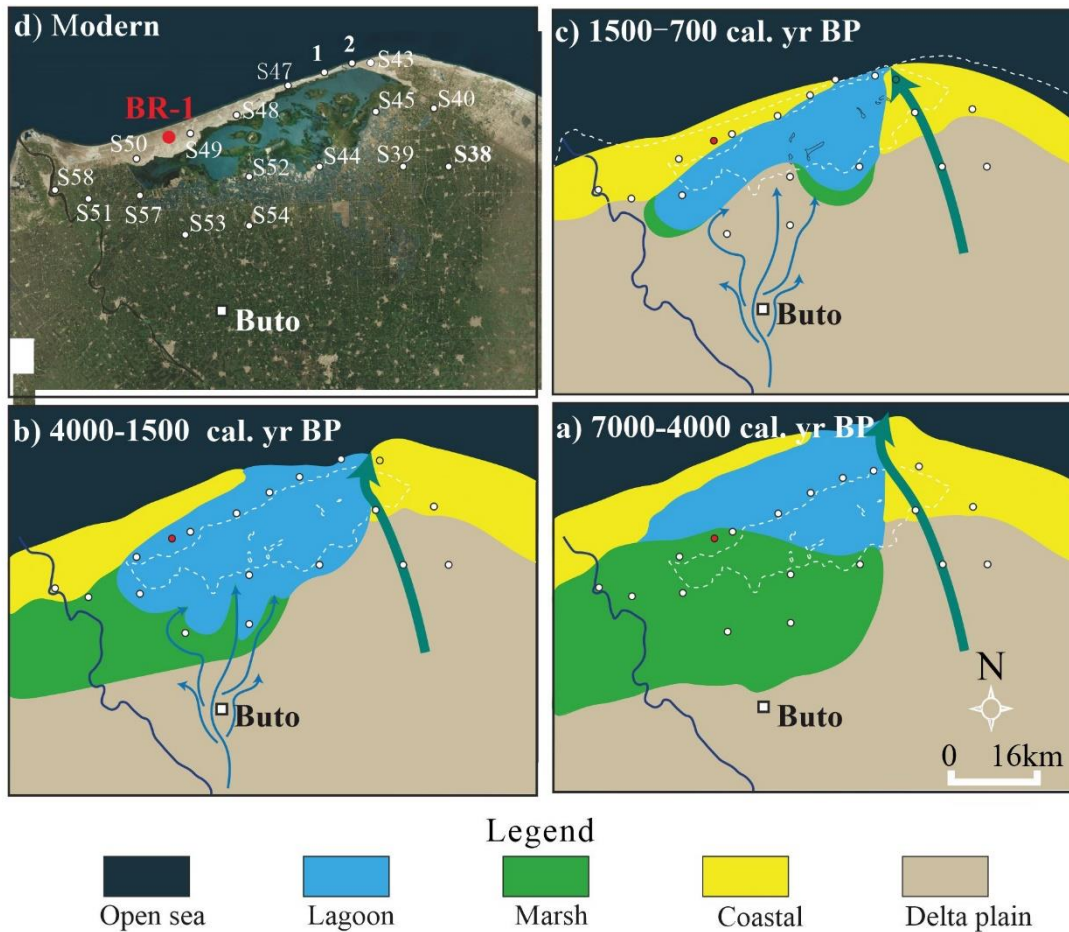
479 BR-1 highlights two major periods with higher fluvial inputs to the Burullus lagoon-
480 coast around 8-7 ka and 3.5-1.5 ka (Units D and G; Figure 4), characterized by the markedly
481 high MS recorded in BR-1 sediment. It is widely acknowledged that fluvial sediment usually
482 contains higher MS derived from soil erosion from river basins (Thompson and Oldfield, 1986),
483 although post-sedimentary diagenesis could be attributable. Here, we would interpret the
484 high MS values of BR-1 as being linked to the stronger fluvial processes of old Nile branches
485 present in the region, in particular, the unit D showing a high sedimentation rate of 50 mm/yr
486 at 8-7 ka (Figure 2, 4). Also, Bernhardt et al. (2012) using terrestrial vegetation identified that
487 high Nile flow occurred before ca. 6.5 ka, as indicated by an increase in Cyperaceae (with
488 *Cladium*) pollen in a core drilled on the southern margin of the Burullus. On the contrary, a
489 reduction in Nile flow and regional precipitation is attested by the decrease in Cyperaceae
490 pollen between ca. 5.2 and 3.5 ka. This period corresponds to an open-lagoonal environment
491 according to the results of the bio-sedimentological study of BR-1.

492 Marshland was well developed on the central-west Burullus coast (including BR-1 core
493 site) between ca. 8- 4 ka, indicating lower fluvial inputs in the region as identified at both W-
494 E and S-N Holocene sediment transects (Figure 7A,B). During that period, the eastern lagoon
495 coast was deeply incised with fluvial sediment facies via paleo Sebennitic branch
496 sedimentation (Figure 1), as recorded in many sediment cores (Figure 7A) (Sestini, 1989;
497 Arbouille and Stanley; 1991). Subsequently, the established marshland and lagoonal
498 environments were subjected to progressive infilling and reduction in their surface areas
499 (Figure 7A,B; Figure 8a), due to the deposition of fluvial and marine sediments and by the
500 southward displacement of the sand spit. This perhaps was prone to the early human
501 occupation at site of Buto (Tell el-Fara'in), an early cultural center (6 ka, Pre-Dynastic) of Egypt
502 (Ginau et al., 2020), ca. 30 km south to the lagoon coast (Figure 1, 8). The infilling seems to

503 have been particularly important ca. 3.5-1.5 ka in relation to the presence of several Nile
 504 branches flowing into the western area of the lagoon (Figure 8b, c) (Wunderlich, 1988; Wilson,
 505 2012, 2018). In recent time, human activities have made the lagoonal largely shrunk (Figure
 506 8a).



507
 508 **Figure 7:** Holocene sediment core transect of Burullus lagoon-coast: A) along-coast; B)
 509 perpendicular to coast. Fluvial sediment facies prevail on the eastern lagoon coast, and
 510 marshland on the central-west lagoon coast. Holocene sediment core (1-2) and S-cores were
 511 collected from Sestini (1989); and Arbouille and Stanley (1991).



512

513

Figure 8 sketch map, showing the Holocene evolution of Burullus lagoon

514

515 6. Conclusions

516 The coastal lagoon of the Nile Delta is an excellent sediment recorder to explore basin-
 517 wide hydroclimate change, sea-level rise, source-to-sink sediment transfers, and the history
 518 of early cultural development. Our high-resolution study of core BR-1 allows us to make the
 519 following conclusions:

- 520 1) The Holocene strata of the Burullus lagoon consists of a typical transgressive-retrogressive
 521 deltaic sequence, characterized by a marine-estuarine facies (ca. 10-8.0 ka), an open bay
 522 facies (ca. 8.0-7.0 ka), a lagoon facies (ca 6.0 ka) and an aeolian facies formed after ca. 1
 523 ka.
- 524 2) Two units showing high sediment magnetic susceptibility values are dated to 7.8-7.3 ka
 525 and 3.5-2.0 ka in BR-1 show the timing of the main fluvial impact on the lagoon formation.

- 526 3) Diagnostic elemental ratios (Fe/Al, Ti/Al, Zr/Al, Hf/Al) showed a synchronous rise before
527 8.0 ka (the main phase of the AHP), indicating sediment provenances both derived from
528 the White and the Blue Nile watershed. During ca. 8.0-2.0 ka, Fe/Al, Ti/Al, Zr/Al (mafic
529 proxy) maintained an increasing trend with two major fluctuations vs. lightly-fluctuating
530 Zr/Al and Hf/Al (felsic proxy) up the core. This implies more sediment fluxes from the Blue
531 Nile, in relation to the withdrawal of the ITCZ during the post-AHP.
- 532 4) Two peat layers (saltwater marsh), dated to ca. 8.0 ka and 7.0-5.7 ka are intercalated with
533 marine-bay and lagoon sediments. Both dated peat and lagoon sediments, along with data
534 collected during previous studies, allowed us to reconstruct the RSL history of the study
535 area. The reconstructed local sea level curve shows that the evaluation of sea level was
536 ca. 4-1 m lower than the reconstructed analogues on tectonically stable coasts during the
537 Holocene, implying an important effect of land surface lowering (most likely sediment
538 compaction) on relative sea level changes.

539

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544

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550

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751 **Figure and table captions**

752 **Figure 1:** The Nile Delta, showing: 1) Burullus Lagoon and sediment core site BR-1; 2) paleo-
753 coastline of ca. 7-5 ka (after Said, 1981); 3) paleo-Nile branches (Said, 1981), and 4)
754 sediment cores collected from previous studies (Core 1-2 from Sestini, 1989; S-cores from
755 Arbouille and Stanley, 1991). The basaltic distribution of the Blue Nile was after Revel et
756 al. (2010). Square in black shows the archaeological site of Buto (discussed in text).

757

758 **Figure 2:** AMS-¹⁴C-dated Holocene sediment sequences of BR-1. The age-depth model was
759 reconstructed using the dedicated R-code Clam (Blaauw, 2010) and sedimentation rates
760 were calculated.

761

762 **Figure 3.** Reconstructed relative sea level of Burrulus coast, using both dated peat layers and
763 lagoon muds from this study and dated peat layers from Arbouille and Stanley (1991).4.2.
764 Bio-sedimentology of core BR-1

765

766 **Figure 4.** Distribution of sediment magnetic susceptibility (MS), TIC, TOC, macro-fauna and
767 ostracod of core BR-1. Our data were used to define nine sedimentary units (A-I). * - age
768 cited from Arbouille and Stanley (1991) and Chen and Stanley (1993)

769

770 **Figure 5.** Diagnostic geochemical elements (Al, Fe, Ti, Cr, Zr, Hf) and their normalized values
771 (to Al) of core BR-1 (data from the peat layers are not included). Magnetic susceptibility

772 (MS) is listed for comparison. * - age cited from Arbouille and Stanley (1991) and Chen
773 and Stanley (1993).

774

775 **Figure 6.** Comparison of Fe/Al and Ti/Al of this study to $^{87}\text{Sr}/^{86}\text{Sr}$ of core S21 (Nile Delta) and
776 water level proxy ($\delta\text{DWax } \text{‰}$) of the Blue Nile basin

777

778 **Figure 7.** Holocene sediment core transect of Burullus lagoon-coast: A) along-coast; B)
779 perpendicular to coast. Fluvial sediment facies prevail on the eastern lagoon coast, and
780 marshland on the central-west lagoon coast. Holocene sediment core (1-2) and S-cores
781 were collected from Sestini (1989); and Arbouille and Stanley (1991).

782

783 **Figure 8.** Sketch map, showing the Holocene evolution of Burullus lagoon

784

785 **Table 1.** Details of AMS- ^{14}C -dating materials of BR-1. ^{14}C dates were expressed in calibrated
786 years BP at the 95% confidence level (2σ). Accepted ^{14}C dates were used for Age-depth model.

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