



**QUEEN'S
UNIVERSITY
BELFAST**

Holocene lake sediments from the Faiyum Oasis in Egypt: a record of environmental and climate change

Marks, L., Salem, A., Welc, F., Nitychoruk, J., Chen, Z., Blaauw, M., Zalat, A., Majecka, A., Szymanek, M., Chodyka, M., Toloczko-Pasek, A., Sun, Q., Zhao, X., & Jiang, J. (2018). Holocene lake sediments from the Faiyum Oasis in Egypt: a record of environmental and climate change. *Boreas*, 47, 62-79.
<https://doi.org/10.1111/bor.12251>

Published in:
Boreas

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

© 2017 Collegium Boreas. Published by John Wiley & Sons Ltd.

This work is made available online in accordance with the publisher's policies. Please refer to any applicable terms of use of the publisher.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

1 **Holocene lake sediments from the Faiyum Oasis in Egypt: a record of environmental**
2 **and climate change**

3
4 LESZEK MARKS, ALAA SALEM, FABIAN WELC, JERZY NITYCHORUK,
5 ZHONGYUAN CHEN, MAARTEN BLAAUW, ABDELFATTAH ZALAT,
6 ALEKSANDRA MAJECKA, MARCIN SZYMANEK, MARTA CHODYKA, ANNA
7 TOŁOCZKO-PASEK, QIANLI SUN, XIAOSHUANG ZHAO AND JUN JIANG

8
9 Marks, L., Salem, A., Welc, F., Nitychoruk, J., Chen, Z., Blaauw, M., Zalat, A., Majecka, A.,
10 Szymanek, M., Chodyka, M., Tołoczko-Pasek, A., Sun, Q., Zhao, X. & Jiang, J.: Holocene
11 lake sediments from the Faiyum Oasis in Egypt: a record of environmental and climate
12 change.

13
14 The Qarun Lake in the Faiyum Oasis (Egypt) provides a unique record of Holocene
15 environmental and climate change in an arid area largely void of fossil proxy records.
16 Multiple lithological, palaeontological. and geochemical proxies and 32 radiocarbon dates
17 from the 26-m long core FA-1 provide a time-series of the lake transformation. Our results
18 confirm that a permanent lake in the Holocene appeared at ~10 cal. ka BP. The finely-
19 laminated lake sediments consist of diatomite, in which diatoms and ostracods together with
20 lower concentrations of ions indicate a freshwater environment at the end of the early and
21 middle Holocene. This was closely associated with regular inflows of the Nile water during
22 flood seasons, when the Intertropical Convergence Zone (ITCZ) migrated northwards in
23 Africa, although it has probably never reached the Faiyum Oasis. Local rainfalls, possibly
24 connected with a northern atmospheric circulation, could have been important during winter.
25 Several phases in the lake evolution are recognized, represented by oscillations between deep

26 open freshwater conditions during more humid climate and shallow fresh to brackish water
27 during drier episodes. After a long freshwater phase, the lake setting has become more
28 brackish since ~6.2 cal. ka BP as indicated by diatoms and increasing contents of evaporite
29 ions in the sediment. This clearly shows that since that time the lake has become occasionally
30 partly desiccated. It resulted from a reduced discharge of the Nile. In the late Holocene the
31 lake was mostly brackish turning gradually into a saline lake. This natural process was
32 interrupted about 2.3 cal. ka BP when a man-made canal facilitated water inflow from the
33 Nile. The examined FA-1 core can be used as the reference age model of climate change in
34 the Holocene and its impact on development and decline of ancient civilisations in north-
35 eastern Africa.

36

37 *Leszek Marks (leszek.marks@uw.edu.pl), Aleksandra Majecka, Marcin Szymanek and Anna*
38 *Tołoczko-Pasek, University of Warsaw, Faculty of Geology, Warsaw, Poland; Alaa Salem,*
39 *Kafrelsheikh University, Faculty of Science, Kafrelsheikh, Egypt; Fabian Welc, Cardinal*
40 *Stefan Wyszyński University, Institute of Archaeology, Warsaw, Poland; Jerzy Nitychoruk*
41 *and Marta Chodyka, John Paul 2nd State Higher School, Faculty of Economic and*
42 *Technical. Sciences, Białą Podlaska, Poland; Zhongyuan Chen, Qianli Sun, Xiaoshuang*
43 *Zhao and Jun Jiang, East China Normal University, State Key Laboratory of Estuarine and*
44 *Coastal Research, Shanghai, China; Maarten Blaauw, Queen's University Belfast, School of*
45 *Natural and Built Environment, UK; Abdelfattah Zalat, Tanta University, Faculty of Science,*
46 *Tanta, Egypt; received, accepted.....*

47 Palaeoclimatic and geoarchaeological data confirm that transformations of natural
48 environment in north-eastern Africa during the Holocene were caused by climate
49 fluctuations. They stimulated the development and collapse of past human cultures and
50 civilisations in the Nile drainage basin (e.g. Kuper & Kröpelin 2006; Schild & Wendorf
51 2013; Welc & Marks 2014). Long-term south-north migration of the Intertropical
52 Convergence Zone (ITCZ) during early and middle Holocene seems to have been responsible
53 for a major climate change in the northern Nile drainage basin (e.g. Overpeck *et al.* 1996;
54 Abell & Hoelzmann 2000; Arz *et al.* 2003; Hoelzmann *et al.* 2004; Nicoll 2004; Kröpelin *et*
55 *al.* 2008; Welc & Marks 2014).

56 The study area of the Faiyum Oasis is presently located in a desert zone, but this region
57 experienced varying degrees of aridity during the Holocene (cf. Kuper & Kröpelin 2006;
58 Schild & Wendorf 2013). Lake deposits in the Faiyum Oasis are a unique archive of late
59 Quaternary palaeoclimate data for the northern part of the Nile basin (Flower *et al.* 2012;
60 Marks *et al.* 2016). Regular water inflows from the Nile into the Faiyum Oasis in the
61 Holocene resulted from the Indian summer monsoon system in northern Africa that activated
62 seasonal floods in the northern Nile (Weldeab *et al.* 2007; Woodward *et al.* 2007; Revel *et al.*
63 2014). In the centre of the Faiyum Oasis, a vast freshwater reservoir has formed due to
64 seasonal hydrological connection with the Nile (cf. Fig. 1). The relic of this ancient lake
65 survived until the present as the saline and shallow Qarun Lake (Wendorf & Schild 1976;
66 Flower *et al.* 2012, 2013; Zalat 2015; Marks *et al.* 2016).

67 The dynamics of hydrological and climatic changes in the Nile drainage basin are
68 reflected in the lithological. and geochemical. characteristics of sediments in the Faiyum
69 Oasis where the lake filled a central part of the depression. Because the Faiyum Oasis was
70 located outside the northern extent of the monsoon rainfalls in the Holocene (cf. Williams *et*
71 *al.* 2000; McCorrison 2006), the lake sediments must have reflected mostly local

72 hydroclimatic conditions. The lake level fluctuations were highly dependent on the frequency
73 of inflows of the Nile water and the Nile discharge was controlled by the intensity of the
74 remote precipitation regime in the Ethiopian Highlands where two main tributaries of the
75 Nile originate i.e. the Blue Nile and the Atbara rivers (Baïoumy *et al.* 2010; Hassan *et al.*
76 2011). During the Holocene the northernmost part of Egypt and the Red Sea have also been
77 influenced by the North Atlantic Circulation, defined also as the Mediterranean Circulation
78 that created winter rainfalls of varying intensity (e.g. Arz *et al.* 2003; Marks *et al.* 2016).

79 The present contribution is focused on environmental and climate changes recorded in
80 lake sediments of the Faiyum Oasis. It partly follows a postulate of Flower *et al.* (2012) to
81 demonstrate a full potential of the palaeoenvironmental records with a use of a continuous
82 high-resolution analysis of the Holocene sediments in the Faiyum Oasis. Two cores: FA-1
83 (26 m long) and FA-2 (4 m long) were drilled at the south-eastern shore of the Qarun Lake
84 (Fig. 1) in February 2014. They provided complete and undisturbed succession of the
85 Holocene lake sediments (Marks *et al.* 2016). Collected samples were subjected to
86 comprehensive laboratory analyses, the most significant results of these are presented in this
87 paper.

88

89 **Site location and previous studies**

90 The area of the Faiyum Oasis is estimated at some 1270 to 1700 km² (Fig. 1). It is located
91 within Eocene and Oligocene rock formations, composed mostly of organodetritic
92 limestones, marls and sandstones of shallow water facies. Oligocene, Late Miocene and
93 Pliocene sedimentary series are overlain by Quaternary sediments, mainly of lacustrine and
94 aeolian origin (Beadnell 1905; Said 1981).

95 The Faiyum Oasis is one of the most important depressions in the Western Desert of
96 Egypt and the question of its origin has been a subject of numerous disputes and

97 controversies. Its current shape had been controlled by subsidence until the Late Eocene
98 (Dolson *et al.* 2002). A lake could occupy the oasis already in the Pliocene, then it probably
99 dried up in the Pleistocene and intensive deflation occurred, followed by filling with the Nile
100 waters at the beginning of the Holocene (cf. Beadnell 1905; Caton-Thompson & Gardner
101 1929). On the other hand, Ball (1939) and Said (1979) suggested that the depression was
102 formed by complex tectonic movements and deflation, active since the Pleistocene to the
103 present time (Kusky *et al.* 2011).

104 At present, the northern part of the Faiyum Oasis is occupied by the Qarun Lake
105 (location: 29°26'36" – 29°31'15" N and 30°23'52" – 30°49'55" E), which is a relic of the
106 early and middle Holocene freshwater reservoir (cf. Caton-Thompson & Gardner 1934;
107 Wendorf & Schild 1976). The maximum depth of the Qarun Lake is about 8.5 m and its
108 water level is equal to 44 m b.s.l. The reservoir is highly saline ($>30\text{gL}^{-1}$), turbid and devoid
109 of surface outflow, with mean water temperature changing seasonally from 15 to 33°C (El
110 Wakeel 1963; El-Sayed & Guindy 1999; Flower *et al.* 2006, 2013; El-Shabrawy & Dumont
111 2009).

112 The Qarun Lake has been studied intensively since the beginning of the 20th century,
113 particularly along its coastline. Previous investigations focused mainly on terrestrial
114 exposures of diatomite in the north-eastern part of the Faiyum Oasis (Aleem 1958;
115 Przybyłowska-Lange 1976; Schild & Wendorf 1976; Zalat 1991, 1995). This was due to
116 presence of numerous archaeological sites, mainly of Epipalaeolithic and Neolithic age
117 (Caton-Thompson & Gardiner 1929; Wendorf & Schild 1976). These studies resulted in the
118 reconstruction of the main transgressive and regressive phases of the lake, named in turn
119 Paleomoeris, Premoeris, Protomoeris and Moeris (Wendorf & Schild 1976).

120 Recent interdisciplinary research during which several drillings were performed in the
121 lake and along the southern shore of the Qarun Lake provided important data concerning the

122 origin and biostratigraphy of the Holocene lake (Keatings *et al.* 2010; Flower *et al.* 2012,
123 2013). The most important was the 21.4 m long core QARU 9 (Flower *et al.* 2013). However,
124 its location at the south-western lake shore, as with the other cores (Fig. 1), provided a
125 limited record of hydrodynamic and palaeogeographic transformations of the lake during the
126 Holocene (Marks *et al.* 2016). Moreover, its chronology was based on only three radiocarbon
127 dates. Therefore, here we present the new borehole FA-1 (Fig. 2), as likely the longest, best-
128 dated and most complete succession of the Holocene lake sediments in north-eastern Africa
129 (e.g. Pachur *et al.* 1990; Schild & Wendorf 2001; Kröpelin *et al.* 2008; Marshall *et al.* 2009;
130 Baioumy *et al.* 2010; Flower *et al.* 2012).

131

132 **Methodology**

133 *Drilling, sampling and lithological analysis*

134 Drilling was performed with a self-propelled American set Acer with hydraulic rig. The core
135 sections were collected in plastic pipes, each 1 m long and 10 cm in diameter. The most of
136 the subsequent analysis was done at intervals of 5 cm, except where stated otherwise.

137 Preliminary lithological description was based on macroscopic inspection of the core,
138 supplemented with detailed examination of selected fragments using an optical microscope.
139 This general lithological-geochemical analysis of sediments enabled the selection of samples
140 for more detailed analyses.

141

142 *SEM EDS analyses*

143 Samples were dried at room temperature and then analyzed using an electron scanning
144 microscope (HITACHI TM 3000), supplied with an energy dispersion spectrometer (SWIFT
145 ED 3000 Oxford Instruments). Samples were put directly on a carbon band. Surface and
146 point analyses were done with using an accelerating voltage of 15 kV. The analyses were

147 performed at the Research Centre on Innovations, John Paul 2nd State Higher School in Biała
148 Podlaska, Poland.

149

150 *Ion-geochemistry analysis*

151 10-mg dried samples were put into 20 ml centrifuge tube vials containing 10 mL distilled-
152 deionised water (resistivity of 18 MΩ), placed in ultrasonic water bath for 60 min and then
153 shaken by mechanical shaker for 1h for complete extraction of ionic compounds. The extracts
154 were filtered with 0.45 μm pore size microporous membranes and filtrates were stored at 4°C
155 in a clean tube before further analysis. Three anions (SO₄²⁻, NO₃⁻ and Cl⁻) and five cations
156 (Na⁺, NH₄⁺, K⁺, Mg²⁺ and Ca²⁺) were determined in aqueous extracts of the filters, prepared
157 in three steps using ultrapure (18 MΩ) water. Ion chromatography (IC, Dionex 500, Dionex
158 Corporation, Sunnyvale, California, United States) was used for the analysis at the Institute
159 of Earth Environment, Chinese Academy of Sciences (IEECAS). Blank values were
160 subtracted from sample concentrations. One sample in each group of 10 samples was
161 analyzed twice for quality control. Typical precision (percent relative standard deviation) for
162 six pairs of samples was calculated using the equation: $X_i = (C_{i1} - C_{i2})/C_{ia}$, where C_{i1} and C_{i2}
163 were routine and duplicate concentrations, C_{ia} was the mean concentration for the
164 measurement pair i and X_i was the relative difference. The maximum relative precisions were
165 1.8% for Na⁺, 0.9% for NH₄⁺, 0.6% for K⁺, 4.0% for Ca²⁺, 1.0% for Mg²⁺, 1.2% for SO₄²⁻,
166 2.6% for NO₃⁻ and 0.3% for Cl⁻ (Shen *et al.* 2008).

167

168 *Diatom analysis*

169 Diatoms were extracted from the studied samples according to the procedure proposed by
170 Zalat (2002) and Zalat & Servant-Vildary (2005, 2007). Diatom identification and statistical
171 studies were done in the Geological. Department of the Tanta University in Egypt with a use

172 of Carl Zeiss light microscope combined with digital camera at normal x100 oil immersion
173 objective. In slides sufficiently rich in diatoms, 1000 diatom valves were counted, whereas at
174 least 200 valves were counted in samples with low-diatom concentrations. Percentage
175 contents of species were calculated for estimation of ecological parameters as life-form
176 groups, pH and salinity. Relative frequencies of every species were calculated as the
177 percentage of total diatom valves (%TDV) in each sample, and identification of ecological
178 preferences of diatom species was based on previous works (e.g. Hustedt 1930-1966, 1957;
179 Ehrlich 1973; Stoermer *et al.* 1975; Gasse 1986; Kilham *et al.* 1986; Zalat 1991; Wolfe *et al.*
180 2000; Bradbury *et al.* 2004; Zalat & Servant-Vidary 2007).

181

182 *Mollusc and ostracod analysis*

183 Standard methods established by Ložek (1986) were applied for mollusc analysis of 6
184 sediment samples with abundant shells: five were collected at 5 cm intervals at depth of 18.9
185 – 18.7 m (volume 50 cm³ each) and a single bulk sample at depth 4.0 – 3.5 m (370 cm³).
186 Samples were wet-sieved with 0.5 mm mesh. All shells and their identifiable apical
187 fragments were picked from the dried residue, identified under a binocular microscope
188 (magnification up to 64x) with reference to taxonomical keys (Brown 1994; Götting 2008;
189 Welter-Schultes 2012) and counted (Ložek 1986). Ecological preferences of mollusc species
190 were based on Taraschewski & Paperna (1981), Brown (1994), Götting (2008), Ghamizi *et*
191 *al.* (2010, 2012) and Welter-Schultes (2012).

192 Ostracod valves and carapaces were studied in 29 samples according to the method
193 described by Löffler (1986). The core was sampled at every 5 cm at 18.9 – 18.7 and 18.1 –
194 17.9 m depth. Samples were collected every 1 m at 18.1 – 13.0 m and 8.0 – 5.0 m depth and
195 every 0.5 m at 13.0 – 8.0 m depth. Density of sampling depended on the abundance of fossils.
196 Ten cm³ of sediment per sample were washed through 0.1 mm mesh sieve. Ostracods were

197 taxonomically determined according to Sywula (1974) and Keatings *et al.* (2010) using a
198 binocular microscope (magnification up to 64x).

199

200 *Radiocarbon dating*

201 From layers with organic-rich mud or mud with dispersed organic matter, samples were
202 selected for radiocarbon dating. The organic matter could have been produced within the lake
203 itself but also partly derived from external terrestrial sources (for example through inwash
204 from local heavy rainfall or periodical floods of the Nile). AMS dating was done at the
205 Poznań Radiocarbon Laboratory in Poland using graphite targets (Goslar *et al.* 2004).
206 Conventional ^{14}C ages were calculated using corrections for isotopic fractionation according
207 to Stuiver & Polach (1977). The $\delta^{13}\text{C}$ values cannot be used for palaeoecological
208 reconstructions, because they were measured in the graphite prepared from the samples, and
209 the graphitisation process introduces significant isotopic fractionation. The second point is
210 that the AMS spectrometer introduces fractionation, too. The $\delta^{13}\text{C}$ values reflect therefore the
211 original isotopic composition in the sample very roughly only. Nevertheless, this $\delta^{13}\text{C}$
212 measurement is fully suitable for fractionation correction of $^{14}\text{C}/^{12}\text{C}$ ratios.

213 Calibration of ^{14}C age was performed (Fig. 3), using OxCal ver. 4.2 software
214 (<http://c14.arch.ox.ac.uk>) and the northern hemisphere terrestrial calibration curve IntCal13
215 (Reimer *et al.* 2013). An age-depth model was produced using the Bayesian software Bacon
216 (Blaauw & Christen 2011), which assumed a piece-wise linear accumulation of the lake
217 sediment constrained by prior information on the lake's accumulation rate and its variability
218 between neighbouring depths.

219

220 **Results**

221 *Lithological characteristics of the core FA-1*

222 The basal succession of the core FA-1 (Fig. 2) is composed of massive carbonate clayey
223 eluvium (26.0 – 20.8 m depth). This is overlain by coarse sand at 20.8 – 19.8 m depth,
224 followed by thinly and rhythmically-laminated silt and clay, interrupted at 15.53 – 15.45 m
225 depth by a sand layer. The clayey and silty material is probably fluvial in origin and indicates
226 inflow of the Nile water during the summer floods, whereas sandy and carbonate material
227 could be derived by local heavy rainfalls from the vicinity of the lake (cf. Flower *et al.* 2012).
228 The thinly laminated part of the core (19.76 – 13.05 m depth) is composed of carbonate,
229 diatomite and clayey laminae. Light laminae contain almost exclusively planktonic diatoms
230 of the genera *Stephanodiscus* and *Aulacoseira* (relative abundance of 60-90%). There are also
231 very thin (~0.5 mm) layers of amorphous organic matter.

232 A considerable lithological change occurs at 13.1 m depth (Fig. 2). Rhythmites are
233 replaced by massive silt and clay with irregular, thick diatomite and ferruginous interbeds. At
234 12.8 – 10.0 m depth, the core is composed mostly of silty clay with white-grey interbeds, 1-5
235 mm thick, containing predominantly *Aulacoseira granulata* and *Stephanodiscus* diatoms (90-
236 95%). Starting from depths of ~8 m upwards, the core is composed of massive silty clay with
237 sandy interbeds at ~7.6 m and 7.2 m. At 6.9 – 6.3 m they are replaced by silty clay with
238 dispersed organic matter and irregular crystals of gypsum.

239 Steel-gray silty clay is characteristic at depth 6.0 – 5.6 m and it is occasionally
240 interbedded with organic and white-gray laminae (Fig. 2). At depth 5.5 – 4.0 m the core is
241 composed of massive gray-brown silty clay. Above, at 4.0 – 3.4 m there is a loose shell
242 sediment with pieces of malacofauna mixed with gray sludge silt. This deposit resembles
243 modern shell accumulations on the present beach. The overlying sediments at 3.4 – 1.9 m
244 depth are composed of massive gray-brown silty clay with gravel grains, several mm in
245 diameter (depth 2.57 – 2.65 m). At 2.2 m depth silt is predominated by angular grains of
246 quartz.

247

248 *Age model and sedimentation rate*

249 Most samples for radiocarbon dating were collected from layers rich in organic matter, except
250 for the lowermost part (Table 1). In the lower part of the core (depth 18.5 – 13.0 m) there are
251 regular and very thin laminae of dark brown amorphous organic matter intercalated with
252 diatom and calcite laminae. Other fragments of the core contain laminated deposits separated
253 by either sandy-silty massive or deformed series (cf. Fig. 2). Several successive laminae could
254 be deposited in a single year (cf. Marks *et al.* 2016).

255 Organic material, usually associated with calcite layers, indicates a predominance of
256 inner-lake biological processes including a high algal productivity (cf. Flower *et al.* 2012). In
257 the upper 13.0 – 2.0 m, less regular (see Marks *et al.* 2016), bulk samples were collected for
258 radiocarbon dating, composed of silty clay with varied admixture of organic matter. We
259 assumed that this organic matter was produced by both biogenic production within the lake
260 and delivery of allochthonous material, both alluvial from the Nile during summer floods and
261 terrestrial material eroded during occasional heavy rainfall in winter (see Flower *et al.* 2012).
262 Such significant redeposition could result in a hard water effect and incorporation of old
263 carbonates and other carbon sources. We note that the radiocarbon dates show a considerable
264 spread at this section of the core (Fig. 3), whereas they appear much more coherent within the
265 other sections.

266 Calcite is present in the laminated deposits and it means that a hard water effect is very
267 likely on the authochonous organic material as well. We have not done any exact estimation
268 of the hard water effect but it seems obvious that it is higher in the lower part of the core,
269 because of intensive redeposition of carbonates from the area around the lake. This effect is
270 considerably smaller in the laminated part of the section, especially as we selected the
271 samples from the organic laminae. In the upper part of the section where the lamination is

272 absent the hard water effect can be higher as the bulk samples were mostly collected for the
273 radiocarbon dating.

274 Construction of the age-depth model of the lake sediments required an assessment of
275 several agents that could disturb constant accumulation of deposits. Disturbances could result
276 both from sedimentary and post-sedimentary processes, including varying rates of deposition,
277 erosional and omission surfaces, progressive or varied compaction and impacts of
278 bioturbation. In the examined core some of these factors could be ignored such as effects of
279 compaction (because of highly homogeneous sediment in the analyzed section) and
280 bioturbation (no benthic organisms were detected) (e.g. Björck & Wohlfarth 2001). A
281 potentially important factor was a varied influx of sediment to the lake from the adjacent area
282 and by the Nile. We therefore used Bacon (Blaauw & Christen 2011), a flexible age-depth
283 routine which explicitly models the accumulation rate and its variability, and which uses
284 student-t distributions with wide tails to accommodate dating scatter. We used all the default
285 settings, except for the section thickness which was set at 20 cm given the length of this core.
286 Bacon used the IntCal13 curve (Reimer *et al.* 2013) to calibrate the radiocarbon dates.

287 Sedimentation rate in the lake was estimated based on counting of the laminae, using the
288 high-resolution photographs of the core. Every set of laminae (diatom, mineral and organic
289 mud) was assumed to represent a single year. The reconstructed sedimentation rate was the
290 lowest in the initial phase of the lake, represented by the finest and most regular lamination at
291 19.8 – 18.9 m depth, with average annual sedimentation rate of 1.4 mm (Fig. 4). Uniform and
292 then slightly rising sedimentation rate of 2.7 – 7.7 mm a⁻¹ occurs at 18.4 – 14.1 m depth
293 Sedimentation rate has risen consequently above the depth of 14.1 m and reached maximum
294 of 37.7 mm a⁻¹ at 9.08 – 8.5 m, indicating an unstable sedimentary environment. At depth
295 18.25 – 12.50 m twelve samples were radiocarbon dated, both from organic agglomerations
296 and bulk samples with dispersed organic matter (Table 1). Contents of total organic carbon

297 are the highest and of carbonates are the lowest in this part of the core and all ages are almost
298 in perfect superposition, presumably indicating that neither substantial disturbances in carbon
299 content nor significant redeposition have impacted sedimentation in this part of the core.

300 Taking into account the above considerations and other data, tentative chronological.
301 boundaries were determined for the core FA-1 (Fig. 3). Very low contents of total organic
302 carbon below 19.7 m depth and much inorganic carbonate between 19.5 and 19.0 m depth
303 made the age model tentative for these parts of the core.

304

305 *Lake salinity and geochemical indicators of climate change*

306 Variations of salinity in the lake could directly reflect incoming water sources and
307 evaporation. Among the former the most important were intermittent inflows of the Nile
308 water, because impermeable bedrock and small annual precipitation made eventual feeding
309 by groundwater doubtful (Flower *et al.* 2012). Palaeosalinity of the lake was determined *via*
310 measurement of contents of water-soluble ions in the sediment. The lake water was found to
311 have evolved generally from freshwater to saltwater setting but it was not a straightforward
312 change. This went through several important stages of sedimentation: from carbonate to
313 sodium, to sulphur and then to the final desiccated lake basin. Analytical results from the
314 core FA-1 sediments indicate at least 6 phases (Fig. 5), based on varying contents of ions in
315 the sediments:

316 Phase 1 (>19.8 m depth, >9.8 cal. ka BP): except of NH_4^+ which was derived mainly from a
317 soil release, the lowest values of all anions were due to drier climate and indicated a
318 desiccated lake basin.

319 Phase 2 (19.8 – 13.1 m depth, ~9.8 – 6.2 cal. ka BP): contents of NH_4^+ and NO_3^- increased
320 dramatically upwards but with minor increases for Cl^- , Na^+ , Mg^{2+} and Ca^{2+} (Fig. 5),
321 suggesting a relatively strong nitrification due to enhanced productivity of the lake

322 dominated by freshwater setting. Therefore, the freshwater environment implies a
323 hydrological linkage with the Nile, although minor fluctuations in ion contents
324 suggested certain irregularities over time.

325 Phase 3 (13.1 – 12.4 m depth, 6.2 – 5.9 cal. ka BP): sharp increases of Cl^- , Mg^{2+} , Ca^{2+} and
326 Na^+ indicated rapid rise in lake water salinity (Fig. 5). This implies a dry
327 environment setting and notably a restricted hydrological connection with the Nile.

328 Phase 4 (12.4 – 7.9 m depth, 5.9 – 4.4 cal. ka BP) – ion contents were kept almost stable.
329 This implies slight salinization resulting from moderate connection to the Nile.

330 Phase 5 (7.9 – 4.0 m depth, 4.4 – 1.5 cal. ka BP): evident increase of all ion contents at the
331 beginning (Fig. 5) indicates enhanced salinization due to lack of precipitation and/or
332 input from the Nile.

333 Phase 6 (4.0 – 1.9 m depth, <1.5 cal. ka BP): all anions contents were kept lower than
334 previously. This suggests a sound connection of the lake to the Nile.

335

336 *Diatom phases*

337 Diatoms are abundant and moderately to well-preserved throughout the core FA-1 from a
338 depth 19.8 to 6.5 m, and relatively frequent toward the top but with some samples containing
339 poorly preserved sporadic diatoms (depths: 6.3 – 5.9, 5.7 – 5.6, 4.9 – 4.8 and 4.2 – 4.0 m). A
340 low diversity with 112 species is recognized. Planktonic taxa are the most abundant, reaching
341 to 98% of the total assemblage, while benthic and epiphytic forms are very rare and sparsely
342 distributed. *Aulacoseira* with 11 species, followed by *Stephanodiscus* with 9 species are the
343 most dominant planktonic genera, with *Cyclostephanos* and *Cyclotella* species distributed
344 frequently (Fig. 6).

345 The diatom spectra are dominated by riverine taxa including *Aulacoseira granulata*, *A.*
346 *italic*, *A. ambigua* and *Stephanodiscus* spp. Abundant peaks of these taxa are interpreted as an

347 indication of increased discharge of the Nile water into the lake. The diatom assemblage
348 indicative of high stand lake level and increased nutrient availability persisted in the
349 Holocene but lower concentrations or lack of diatom valves at some depths (6.3 – 5.6, 4.95 –
350 4.8, 4.9, 4.2 – 4.0 m) suggest lower diatom productivity. The upper part of the core (depth 4.0
351 – 2.0 m) is completely barren of diatom frustules, reflecting marked environmental changes
352 in the lake, connected with transition from freshwater through brackish to saline conditions.
353 Stratigraphic distribution of recorded planktonic taxa samples led to recognition of 5 types of
354 diatom ecozones in the studied core that is *Aulacoseira* spp., *Stephanodiscus* spp.,
355 *Aulacoseira-Stephanodiscus* spp., *Cyclostephanos dubius* and *Aulacoseira* spp.-*Cyclotella*
356 *meneghiniana* (Fig. 6).

357

358 *Aulacoseira* spp. assemblage. – This assemblage is recorded 9 times (Fig. 6), being
359 dominated by *Aulacoseira granulata* and accompanied commonly by *A. granulata* var.
360 *angustissima*, *A. ambigua*, *A. italica* and *A. islandica*. There are low contents of other
361 planktonic taxa. *Aulacoseira granulata* was a freshwater planktonic and alkaliphilous
362 species, common in eutrophic water of higher temperature (Hustedt 1957; Ehrlich 1973;
363 Stoermer *et al.* 1975). The *Aulacoseira* species indicates high growth requirements for silicon
364 and demanded high silica content in water (Kilham & Kilham 1971), presumably in different
365 combinations of P and light (Kilham *et al.* 1986). However, *Aulacoseira* species are non-
366 competitive, so their wide distribution normally coincided with low concentration of other
367 diatoms (Wolfe *et al.* 2000). *Aulacoseira* taxa are also used as indicators of warmer climate,
368 which may have led to wind-induced mixing in the lake, higher input of humic substances
369 and increased precipitation. They suggest stabilized conditions, remaining wet and windy
370 with increased turbulence and upwelling in the lake, typical of a late phase of the Nile flood
371 cycle (Zalat 1995). *Aulacoseira* species were presumably most dominant in summer and
372 relatively common in spring. Their predominance indicates summers with high silica
373 concentration. Maximum abundances of *Aulacoseira granulata* associated with other
374 *Aulacoseira* species and decreased abundance of *Stephanodiscus* and *Cyclotella* species
375 could reflect a freshwater lake with relatively high level due to nutrient-rich influx from the
376 Nile during a wet warm period.

377

378 Stephanodiscus spp. assemblage. – Seven such assemblages are recorded (Fig. 6). They have
379 the highest abundance of planktonic freshwater *Stephanodiscus* species (60-83%), including
380 *S. rotula*, *S. agassizensis*, *S. minutulus*, *S. aegyptiacus*, *S. neoastreae*, *S. alpinus*, *S. hantzschii*
381 and *S. niagarae*. Other planktonic taxa are rare. *Stephanodiscus* species are known to occupy
382 slightly alkaline and eutrophic freshwater with low silica content (Gasse 1986; Kilham *et al.*
383 1986; Zalat & Servant-Vildary 2007). *Stephanodiscus* taxa were dominant in winter and
384 spring when increased turbulence could suspend these relatively heavy diatoms, therefore
385 they could denote moist winters and springs with active circulation (Bradbury 1992;
386 Bradbury *et al.* 2004). Dominance of small and intermediate-sized *Stephanodiscus* species (*S.*
387 *minutulus*, *S. hantzschii*, and *S. agassizensis*) characterized spring bloom when nutrient
388 loading was related to spring runoff, along with *Aulacoseira granulata*. The increased
389 abundance of planktonic *Stephanodiscus* species reflects a high lake level and increased
390 nutrient loading to the lake with low Si and high P supply rates prevailing at time of
391 deposition (Zalat 2015).

392
393 Aulacoseira-Stephanodiscus spp. assemblage. – This assemblage is recorded three times in
394 the core FA-1 (Fig. 6) and is characterized by common occurrence of *Aulacoseira* spp. and
395 *Stephanodiscus* spp. (80-90%). Other planktonic taxa are distributed sporadically. This
396 diatom assemblage is indicative of a high stand lake level with enhanced nutrient availability
397 by repeated inflows of the Nile to the lake at the transition from spring to summer.

398
399 Cyclostephanos dubius assemblage. – This assemblage is observed in 3 thin zones (Fig. 6). It
400 is characterised by abundance of *Cyclostephanos dubius* (40-55%), accompanied by
401 *Aulacoseira* spp., which is more abundant than *Stephanodiscus* taxa. Other planktonic taxa as
402 *Cyclotella kützingiana* and *C. ocellata* are distributed frequently. *Cyclostephanos dubius* is a

403 pelagic taxon, common in flowing and stagnant freshwater in a coastal area, of low
404 conductivity and low to medium alkalinity (pH = 7.6-8.9). The diatom assemblage includes
405 common occurrences of *Aulacoseira* spp., *Cyclostephanos dubius* and *Stephanodiscus* taxa,
406 indicating a high stand lake level with clear dominance of eutrophic freshwater conditions
407 and slightly higher salinity and alkalinity in summer.

408

409 *Aulacoseira* spp. – *Cyclotella meneghiniana* assemblage. – The zone was recorded only once,
410 with a thickness of about 0.5 m (Fig. 6) and is characterised by high abundance of
411 *Aulacoseira* spp. and *Cyclotella meneghiniana*. Other planktonic taxa including
412 *Stephanodiscus* spp. and *Cyclotella* spp. are rare. *Cyclotella meneghiniana* is a facultative
413 planktonic taxon typical for moderately alkaline conditions (Hecky & Kilham 1973;
414 Richardson *et al.* 1978), in coastal and estuarine locations with water of varied chemistry
415 (Trigueros & Orive 2000; Tibby & Reid 2004). Its most favourable development occurs at
416 ~20°C but it is eurythermal (Gasse 1986). This species was reported from slightly brackish
417 water of coastal Egyptian lakes, being dominant in spring and at the beginning of summer at
418 water temperatures of 29-31°C (Zalat & Servant-Vildary 2007). Common occurrence of
419 *Cyclotella meneghiniana* with high abundances of *Aulacoseira* species and frequently to low
420 amounts of *Stephanodiscus* taxa reflect warm eutrophic freshwater conditions with slight
421 increased salinity and alkalinity.

422

423 *Mollusc and ostracod indicators*

424 Altogether 10 taxa of molluscs (6 snails and 4 bivalves) and 8 taxa of ostracods are
425 recognized in the FA-1 core (Table 2). Molluscs are represented by 735 specimens, but with
426 1-8 taxa and from 2 to 726 specimens in a single sample. Shells are abundant in the upper
427 part of the core (4.0 – 3.5 m depth) and their assemblage is predominated by brackish species,

428 among which the most numerous is *Hydrobia ventrosa* and *Cerastoderma glaucum*. These
429 species are accompanied by euryhaline snails *Pirenella conica* and *Hinia costulata* and three
430 freshwater snails, the most abundant of which was *Melanooides tuberculata* (Table 2). The
431 lowermost samples (18.9 – 18.7 m depth) contain very scarce shell material with only few
432 specimens of the freshwater endemic snail *Valvata nilotica* and fragments of saline bivalves
433 *Abra ovata* and *Cerastoderma* sp. (Table 2).

434 Ostracods with 8 taxa and 2872 specimens are more abundant than molluscs. There are
435 1-6 taxa and from 2 to 626 specimens in a single sample, with the lowest number at depths of
436 18.05, 17.95 – 17.9 and 17.0 – 6.0 m (Table 2). Most ostracod species have wide ecological
437 tolerance (Sywula 1974; Park & Martens 2001; Keatings *et al.* 2010). Samples from 18.9 –
438 18.7 m depth are dominated by *Herpetocypris* sp. (juveniles and damaged valves) and
439 *Gomphocythere* sp., most common and characteristic for a sublittoral zone of a freshwater
440 lake (e.g. Park & Martens 2001; Boomer & Gearey 2010; Cohen *et al.* 2013). Numerous
441 *Candona neglecta* and *Limnocythere inopinata* tolerate both fresh and salty waters, and
442 various depth conditions. *Cyprideis torosa* dominate at 18.0 m and 4.0 – 3.5 m depth. It is the
443 most frequent in calm, near-shore zones of a brackish water body (cf. Sywula 1974; Neale
444 1988). The valves of this species are all without the nodes (cf. Keatings *et al.* 2010). It seems
445 that most ostracods represent a near-shore zone and they were common at depths when a
446 coastline was near the drilling site.

447 The occurrence of *Valvata nilotica* and *Gomphocythere* sp. at 18.9 – 18.7 m depth
448 indicates a freshwater environment. Single fragments of shells of salt-water taxa *Abra ovata*
449 and *Cerastoderma* sp. were probably redeposited during drilling from the uppermost part of
450 the core. Scarce molluscs and abundant ostracods with *Gomphocythere* sp., *Candona*
451 *neglecta* and *Limnocythere inopinata* could provide evidence for somewhat deeper part of the
452 lake in the lower part of the succession. A small number of complete carapaces (2.4 – 28.0%)

453 point out to presumably high-energy conditions (cf. Keatings *et al.* 2010). Variable relations
454 of *Cyprideis torosa* and *Limnocythere inopinata* at 18.0, 5.0 and 4.0 – 3.5 m depth could be
455 connected with changes of water chemistry in the Qarun Lake (cf. Keatings *et al.* 2010). The
456 isolated high count of *C. torosa* at 18 m depth (Table 2) is especially worth noting, as it
457 implies very short, probably decadal scale episode with higher salinity. *C. torosa*
458 predominate in waters with Na⁺ and Cl⁻ ions, whereas *L. inopinata* prefer carbonate-
459 bicarbonate rich waters with Na⁺ and low content of Ca²⁺. These changes can be connected
460 with farming in the region and/or changes of the Nile supply (cf. Keatings *et al.* 2010).
461 Abundant *Cyprideis torosa* and expansion of molluscs typical of saline waters at 4.0 – 3.5 m
462 could reflect an increased salinity and shallow-water conditions in the lake. Distinct
463 predominance of *Hydrobia ventrosa* and *Cyprides torosa* indicate a drop of water level and
464 salinity of 14-25‰ as no noded valves of *C. torosa* occur (e.g. Neale 1988; Keyser &
465 Aladin 2004; Götting 2008; Welter-Schultes 2012). A considerable amount of complete
466 ostracod carapaces (45%) and occurrence of *Pirenella conica* support steady sedimentation in
467 a shallow lake (Taraschewski & Paperna 1981; Boomer *et al.* 2003; Keatings *et al.* 2010). An
468 admixture of freshwater species could suggest some shell mixing, but most of these species
469 co-occurred with brackish taxa in other Egyptian lakes. *Melanoides tuberculata* and
470 *Cleopatra bulimoides* were even listed amongst brackish snails (e.g. Sattmann & Kinzelbah
471 1988).

472

473 **Development of the Faiyum Lake in the Holocene**

474 Multi-proxy investigations of the core FA-1 (Figs 4-6, Table 2) and comparison of their
475 results with other cores in the Qarun Lake area (cf. Baioumy *et al.* 2010, 2011; Flower *et al.*
476 2012, 2013) supplied with high-resolution palaeoclimate data indicate several phases of the
477 Faiyum Lake development during the Holocene (Fig. 7). The lake was initially a freshwater

478 lake, but then went through brackish to saline conditions. These changes were accompanied
479 by a fluctuating water level in the lake (interpreted from shifts of lake shore and varying
480 salinity), strictly combined with more intensive or reduced annual influx from the Nile.

481

482 *>10.0 cal. ka BP: pre-lake deposition*

483 Weathered mantle of the Late Eocene marls and limestones from the adjacent area were the
484 main source of yellow-brown massive carbonate clay (depth 26.00 – 20.8 m) that could be
485 redeposited by occasional sheet-floods to the central part of the basin. These deposits contain
486 inserts and concentrations of clayey silt, sand, gravel and dispersed organic matter, indicating
487 influx of mineral material in a semi-dry climate from the surroundings. There was no
488 hydrological connection with the Nile, because of lack of any, even ephemeral lake
489 sediments.

490

491 *10.0 – 9.8 cal ka. BP: initial lake*

492 A freshwater lake appeared in the Faiyum Oasis at about 10.0 cal. ka BP (cf. Fig. 7),
493 confirming the earlier suggestion of Flower *et al.* (2012). The lake had presumably a quasi-
494 permanent seasonal connection with the Nile at 17 m a.s.l. (Hassan *et al.* 2011) as indicated
495 by deposition of gray silt (20.8 – 19.8 m depth). Intermittent influx of terrestrial sandy
496 material as well as gradually decreasing and varied contents of NH_4^+ , NO_3^- , Mg^{2+} and Ca^{2+}
497 suggests erosion and redeposition of covering deposits and soils in the surroundings (Fig. 5).

498 Termination of this phase is represented by a greenish-gray sandy mud intercalated with
499 bedded sand with taxa of *Chara* that indicate shallow (0.5 –4.0 m), fresh to slightly brackish
500 lake and increased evaporation during drier periods (Zalat 1995, 2015). Regular inflows of the
501 Nile water in late spring and early summer are evidenced by predominant diatoms of the
502 *Aulacoseira* spp. assemblage zone (Fig. 6). They were blooming in summer, what could result

503 in strong nitrification and high primary productivity in the lake. The lake was freshwater,
504 slightly alkaline (pH = 7-8) and eutrophic, and due to increasing primary productivity – with
505 more silica in late spring and summer.

506

507 *9.8 – 8.6 cal ka. BP: freshwater deep lake*

508 A regularly laminated part of the core (depth 19.8 – 18.1 m) indicates a stabilized
509 environment of the lake (Figs 4, 7). Organic-rich clayey silt laminae reflect varied seasonal
510 sediment input to the lake. Thin (0.5 mm) layers of amorphous organic matter could be due
511 either floods of the Nile or a high biogenic production in the lake. Dark laminae are deposited
512 in winter and white laminae reflect high diatom productivity during summer (cf. Flower *et al.*
513 2012; cf. Marks *et al.* 2016). This phase of lake development started with a rapid replacement
514 of the planktonic *Aulacoseira* by the *Stephanodiscus* diatoms. The latter indicates increased
515 winter and spring wind-induced water turbulence and diatom blooming in spring (cf.
516 Bradbury 1975, 1988). Much P, peaks of Ca^{2+} and NO_3^- are recorded (Figs 5, 6). The lake was
517 generally freshwater, eutrophic and slightly alkaline, with a high water level. The
518 sedimentation rate doubled from 1.4 to 2.8 mm a^{-1} (Fig. 4). Enhanced nutrient availability
519 resulted in strong nitrification and high productivity. Silica content was high in spring and
520 summer (Fig. 6). Peaks of K^+ and NH_4^+ contents, rapid rises of Na^+ and Mg^{2+} are recorded,
521 indicating salted lake water occasionally happening (Fig. 5).

522

523 *8.6 – 8.4 cal ka. BP: slightly brackish shallow lake*

524 The laminae of clayey silt (depth 18.1 – 17.7 m) are strongly deformed, presumably due to
525 unstable sedimentary environment. It was a short episode of increased salinity indicated by
526 higher contents of Na^+ , Ca^{2+} , Mg^{2+} and Cl^- (Fig. 5) and high frequency of *Cyprideis torosa*
527 (Table 2), accompanied by a drop of water level. Regular inflows of the Nile water in late

528 spring and early summer are evidenced by predominant diatoms of the *Aulacoseira* spp.
529 assemblage (Fig. 6), blooming in summer. A distinct rise in contents of NH_4^+ occurred at the
530 end, indicating input of washing-out from soils in the surroundings of the lake.

531

532 *8.4 – 6.2 cal. ka BP: freshwater deep lake*

533 This phase is expressed by thinly laminated clayey silts (depth 17.7 – 13.1 m), reflecting
534 varied seasonal sediment input to the lake. Dark laminae represent winter deposition, mostly
535 of terrigenous derivation and white laminae reflect high diatom productivity in summer
536 (Flower *et al.* 2012; cf. Marks *et al.* 2016). Thin (0.5 mm) layers of amorphous organic matter
537 could be deposited either during floods of the Nile or due to intensive biogenic production in
538 the lake. An increased influx of sand from the surroundings is recorded at about 8.2 cal. ka BP
539 (17.4 m depth) and 7.2 cal. ka BP (15.45 – 15.53 m depth). The former could reflect a climate
540 crisis connected roughly with the 8.2 ka BP event (cf. Rohling & Pälike 2005). The
541 sedimentation rate had been slightly rising from 2.7 to 3.7 mm a^{-1} at the beginning and
542 reached 6.9 mm a^{-1} at the end (Fig. 4). An enhanced nutrient availability in the lake indicates
543 regular inflows of the Nile water in late spring and early summer. Peaks of NO_3^- and NH_4^+ are
544 due to increased content of organic matter, presumably washed into the lake from the
545 surroundings. Diatoms of the *Aulacoseira* spp. assemblage (Fig. 6) bloomed in summer,
546 which could result in strong nitrification, enhanced silica content and high primary
547 productivity in the lake. The lake was slightly alkaline (pH = 7-8) and eutrophic, with a high
548 water level. Archaeological sites of the Neolithic Faiyum A Culture located along the
549 shoreline prove that the lake reached its maximum extension (Fig. 8) and depth, with its
550 water level at about 20 m a.s.l. (Wendorf & Schild 1976; Wenke *et al.* 1988). Cl^- and Na^+
551 were slightly decreasing in the second part of the phase (Fig. 5), suggesting a rising water

552 level. FeS₂ formed occasionally, presumably indicating reductive conditions, but the
553 accompanying strong nitrification allowed for high productivity in the lake.

554

555 *6.2 – 5.7 cal. ka BP: shallow brackish to freshwater lake*

556 Abrupt rise of Cl⁻, Na⁺, Mg²⁺ and Ca²⁺ and less regular lamination of lake sediments (13.1 –
557 11.7 m depth) indicate restricted hydrological connection with the Nile. The lake had been
558 periodically brackish (Fig. 5) and the water level dropped significantly (cf. Baioumy *et al.*
559 2011). The reservoir became smaller and shallower, with predominance of *Aulacoseira* spp.
560 assemblage (Fig. 6) but sporadic thick diatom layers in the sediments could indicate
561 extremely huge occasional floods. Intensive influx of material from the surroundings (also
562 from exposed older lake deposits) as is indicated by interbeds of sand and silt, slightly higher
563 contents of NO₃⁻ and SO₄²⁻, with local concentration of Fe compounds due to drying of the
564 peripheral area. The sedimentation rate was 9.6 mm a⁻¹ (Fig. 4). Human settlements in the
565 Faiyum Oasis had disappeared but the Pharaonic civilization developed in the Nile valley in
566 Egypt (Wendorf & Schild 1976; Hassan *et al.* 2012).

567

568 *5.7 – 4.4 cal. ka BP: shallow freshwater lake with brackish episodes*

569 At the very beginning and at the end of this phase the littoral zone of the lake became
570 restricted as mostly pelagic and oligosaprobic (mesosaprobic) *Cyclostephanos dubius* diatoms
571 occurred (Fig. 6). Deposition of grey-brown clayey silt (11.7 – 7.9 m depth) with irregular,
572 thick (1-5 mm) diatomite prevailed, combined with few organic laminae and ferruginous
573 interbeds (Fig. 2). Rapid increase of terrestrial material is noted around 5.0 – 4.8 cal. ka BP.
574 The sedimentation rate was 16.9 – 17.0 mm a⁻¹ at the beginning and then rapidly increased to
575 the maximum of 37.7 mm a⁻¹ (Fig. 4), presumably due to increasing supply of material from
576 the surroundings and the Nile. During most of this time interval (5.6 – 4.6 cal. ka BP) the lake

577 was slightly alkaline (pH = 7-8) and eutrophic, with higher water level and wind-induced
578 water mixing in winter. *Aulacoseira* and *Stephanodiscus* assemblages dominated, indicating
579 intensive seasonal water circulation, enhanced nutrient availability with much P and seasonal
580 influx of the Nile water. There was a short and weak brackish episode at about 5.1 cal. ka BP,
581 indicated by small rises of Ca^{2+} , Mg^{2+} , Na^+ , K^+ , SO_4^{2-} , NH_4^+ , NO_3^- and Cl^- (Fig. 5).

582

583 *4.4 – 3.0 cal. ka BP: shallow brackish and partly desiccated lake*

584 The deposition in the lake became considerably varied (7.9 – 6.0 m depth): at first, with
585 significant input of sand, presumably by sheet floods caused by occasional heavy rainfalls in
586 the surroundings (Welc & Marks 2014). Intensive wind-induced water mixing in winter could
587 have resulted in maximum abundance of *Stephanodiscus* species (>70% of the total diatom
588 assemblage) (Fig. 6). It reflects a presence of a slightly alkaline (pH = 7-8) and eutrophic lake
589 with water level rise to about 12 m a.s.l. (Fig. 8) and low contents of Na^+ , K^+ , Cl^- and NO_3^-
590 but enhanced nutrient availability, much P and low silica. The lake was basically cut-off from
591 the Nile but deposition of clayey silt suggests that rare inflows were possible, presumably as
592 suggested by common planktonic *Aulacoseira* diatoms that bloomed in summer. The first part
593 of this phase was generally dry and it was expressed by progressing desiccation of shallower
594 parts of the lake as indicated by rising contents of Mg^{2+} , Ca^{2+} and SO_4^{2-} (Fig. 5) and
595 admixture of gypsum in lake sediments. The lake level could be dramatically low at that time
596 (Baïoumy *et al.* 2010). Such unfavourable regional climate and environmental conditions at
597 the beginning of this phase could be referred to the 4.2 ka event that resulted in a collapse of
598 the Egyptian Old Kingdom (Hassan 2007). At the termination of this phase at about 3.2 cal.
599 ka BP, the lake sediments were completely devoid of diatoms and dominated by sand from
600 the surroundings (Fig. 6).

601

602 *3.0 – 1.5 cal. ka BP: brackish to freshwater lake*

603 A more regular seasonal water supply from the Nile returned presumably at the beginning of
604 this phase when the lake contained much silica and planktonic *Aulacoseira* were common in
605 spring (Fig. 6). The sedimentary environment became more stable with deposition of silt (6.0
606 – 4.0 m depth), locally interbedded with organic and diatomite laminae, sandy layers and
607 dispersed organic matter. Admixture of pyrite indicates a reducing environment and possibly,
608 also a deeper lake. The sedimentation rate was 13.75 mm a^{-1} (Fig. 4). However, the following
609 very low diatom content or even lack of diatoms in the sediments were combined with lower
610 productivity in the lake itself (Fig. 6). The lake had been occasionally brackish as indicated by
611 dominance of *Aulacoseira* spp. – *Cyclotella meneghiniana* assemblage, characteristic of
612 warm, eutrophic and slightly brackish water conditions (Fig. 6) what is indicated by rising
613 contents of Cl^- , NO_3^- , SO_4^{2-} , Na^+ , K^+ , Mg^{2+} and Ca^{2+} (Fig. 5). Contents of Ca^{2+} , Mg^{2+} , Na^+ ,
614 SO_4^{2-} , Cl^- and NO_3^- were decreasing at 2.3 – 1.8 cal. ka BP (Fig. 5), showing desalinizing lake
615 water, presumably due to higher water supply from the Nile *via* the man-made channel in the
616 Ptolemaic Period (Garbrecht 1994). The lake water level was at about the sea level (Fig. 8).
617 Increased nutrients in the lake and probably wind as well induced winter circulation favoured
618 blooming of *Stephanodiscus* in spring but diatoms completely disappeared at the termination
619 of this phase.

620

621 *1.5 – 1.2 cal. ka BP: shallow brackish-saline lake*

622 Deposition of beach loose shell sediment occurred (4.0 – 3.4 m depth), mixed with grey
623 sludge silt (Fig. 2). Gastropod and ostracod assemblages indicate a drop of water level and
624 salinity of 14-25‰, with carbonate-bicarbonate rich water, seemingly due to farming and
625 changes in water supply from the Nile.

626

627 <1.2 cal. ka BP: shallow saline lake

628 There was a deposition of massive grey-brown clayey silt (3.4 – 1.9 m depth) with admixture
629 of gravel and angular quartz grains, typical of a shallow and near-shore environment. Lower
630 contents of Mg^{2+} , Ca^{2+} , Na^+ and Cl^- , and rise of K^+ are recorded (Fig. 5). Recent
631 environmental transformations of the lake were presented by Flower *et al.* (2006).

632

633 **Conclusions**

634 The core FA-1 from a beach of the Qarun Lake in the Faiyum Oasis with fine-laminated lake
635 sediments supplied a continuous high-resolution record of environmental and climate changes
636 through the Holocene. We demonstrated at least partly a palaeoenvironmental record of the
637 Qarun Lake sediments, a potential of which was already estimated by Flower *et al.* (2012). A
638 multi-proxies analysis enabled us to establish the age model and transformation of the lake in
639 the Holocene. Our results confirm that a permanent lake in this area appeared at about 10 cal.
640 ka BP but then its evolution went through several freshwater and brackish phases, starting
641 from carbonate-dominant through Cl^- and SO_4^{2-} sedimentation, but it has never come to a total
642 desiccation of the lake.

643 The Faiyum Oasis has been outside the Intertropical Convergence Zone (ITCZ) in the
644 Holocene and therefore, its lake could survive due to inflows of the Nile water during flood
645 seasons. The latter were most regular from 9.8 to 6.2 cal. ka BP when in a deep freshwater
646 lake, a succession of fine-laminated sediments was formed, composed mostly of diatomite,
647 mineral and organic silt, clearly indicating a seasonal change of lake productivity. This was
648 significantly associated with regular inflows of the Nile water during flood seasons.
649 Southward migration of ITCZ in northeastern Africa resulted in less regular inflows of the
650 Nile water into the Faiyum Oasis. From 6.2 to 4.4 cal. ka BP the lake deposits were less
651 regularly laminated, the water level dropped considerably and there were gradually more

652 frequent brackish episodes. From 4.4 to 3.0 cal. ka BP the lake was brackish and considerably
653 less extensive, with water level at about -20 m a.s.l., the sediments were massive but with
654 occasional inputs of sandy material washed from the surroundings due to local winter
655 rainfalls. The episode 3.0 to 1.5 cal. ka BP was a return to occasional freshwater conditions in
656 the lake, mostly due to a man-made canal dug at about 2.3 cal. ka BP that renewed a
657 hydrological connection with the Nile. Then the lake was gradually turned into a brackish and
658 finally, saline lake.

659 The examined FA-1 core created the reference age model of the Holocene climate
660 change in north-eastern Africa and its impact on development and decline of ancient
661 civilisations in Egypt.

662

663 Acknowledgements. – The authors are grateful to the reviewer Paula J. Reimer and the
664 anonymous reviewers for their insightful and helpful comments that greatly improved a
665 previous version of the manuscript. The Editor-in-Chief Jan A. Piotrowski is thanked for his
666 patience, thorough and constructive comments of the revised version. The project was
667 implemented jointly by the Faculty of Geology of the University of Warsaw and the Institute
668 of Archaeology of Cardinal Stefan Wyszyński University in Warsaw (Poland), Faculty of
669 Science of the Kafr-el-Sheikh University (Egypt) and East China Normal University in
670 Shanghai (China). The data were collected within the Nile Climate Change Project (NCCP)
671 that was funded by the Polish National Science Centre in 2013-2016 (decision no. DEC-
672 2012/05/B/ST10/00558). The National Natural Sciences Foundation of China (NSFC, grant
673 No. 41272194) supported financially a part of the geochemical. analyses. The authors are
674 grateful to the authorities of the Kafrelsheikh University in Egypt for assistance in sampling
675 and providing access to laboratory investigation. We thank to Dr. Zbigniew Szafranski from

676 the Centre of Mediterranean Archaeology of the University of Warsaw for a logistic support
677 during fieldwork in Egypt.

678

679 **References**

680 Abell, P. I. & Hoelzmann, P. 2000: Holocene palaeoclimates in northwestern Sudan: stable
681 isotope studies on molluscs. *Global and Planetary Change* 26, 1-12.

682 Abu-Zied, R. H., Keatings, K. W. & Flower, R. J. 2007: Environmental controls on
683 foraminifera in lake Qarun, Egypt. *Journal of Foraminiferal Research* 37, 136–149.

684 Aleem, A. A. 1958: A taxonomic and palaeoecological investigation of the diatom flora of
685 the extinct Faiyum Lake (Upper Egypt). *University of Alexandria Bulletin* 2, 217–44.

686 Arz, H. W., Lamy, F., Patzold, J., Muller, P. J. & Prins, M. 2003: Mediterranean moisture
687 source for an Early-Holocene humid period in the northern Red Sea. *Science* 300, 118-
688 121.

689 Baioumy, H., Kayanne, H. & Tada, R. 2010: Reconstruction of lake-level and climate
690 changes in Lake Qarun, Egypt, during the last 7000 years. *Journal of Great Lakes*
691 *Research* 36, 318-327.

692 Baioumy, H., Kayanne, H. & Tada, R. 2011: Record of Holocene aridification (6000-7000
693 BP) in Egypt (NE Africa): authigenic carbonate minerals from laminated sediments in
694 Lake Qarun. *Quaternary International* 245, 170-177.

695 Ball, J. 1939: *Contributions to the Geography of Egypt*. 308 pp. Egyptian Survey and Mines
696 Department, Cairo.

697 Beadnell, H. J. L. 1905: *The Topography and Geology of the Fayum Province of Egypt*. 101
698 pp. Survey Department, Cairo.

699 Björck, S. & Wohlfarth, B. 2001: ¹⁴C chronostratigraphic techniques in paleolimnology. In
700 Last, W. M. & Smol J. P. (eds.): *Tracking Environmental Change Using Lake Sediments*,

- 701 *Basin Analysis, Coring and Chronological. Techniques. Developments in*
702 *Palaeoenvironmental Research 1*, 205–245. Kluwer, Dordrecht.
- 703 Blaauw, M. & Christen, J. A. 2011: Flexible paleoclimate age-depth models using an
704 autoregressive gamma process. *Bayesian Analysis 6*, 457-474.
- 705 Blaauw, M., van Geel, B., Kristen, I., Plessen, B., Lyaruu, A., Engstrom, D. R., van der
706 Plicht, J. & Verschuren, D. 2011: High-resolution ^{14}C dating of a 25,000-year lake-
707 sediment record from equatorial East Africa. *Quaternary Science Reviews 30*, 3043-3059.
- 708 Boomer, I. & Gearey, B. 2010: The occurrence of a new species of *Gomphocythere*
709 (Ostracoda, Limnocytheridae) in the Holocene of SE Turkey: the northernmost record for
710 the genus. *Journal of Micropalaeontology 29*, 115–118.
- 711 Boomer, I., Horne, D. J. & Slipper, I. J. 2003: The use of ostracods in palaeoenvironmental
712 studies, or what can you do with an ostracod shell? In Park, L. E. & Smith, A. J. (eds.):
713 *Bridging the Gap: Trends in the Ostracode Biological. and Geological. Sciences. The*
714 *Palaeontological. Society Papers 9*, 153–179.
- 715 Bradbury, J. P. 1975: Diatom stratigraphy and human settlement in Minnesota. *Geological.*
716 *Society of America, Special Paper 171*, 1–74.
- 717 Bradbury, J. P. 1988: A climate-limnological model of diatom succession for
718 palaeolimnological. interpretation of varved sediments in Elk Lake. *Journal of*
719 *Palaeolimnology 1*, 115-131.
- 720 Bradbury, J. P. 1992: Late Cenozoic lacustrine and climatic environments at Tule Lake,
721 northern Great Basin, USA. *Climate Dynamics 6*, 275-284.
- 722 Bradbury, J. P., Colman, S. M. & Dean, W. E. 2004: Limnological and climatic environments
723 at Upper Klamath Lake, Oregon during the past 45,000 years. *Journal of Palaeolimnology*
724 *31*, 167–188.

- 725 Brown, D. S. 1994: *Freshwater Snails of Africa and their Medical Importance*. 608 pp.
726 Taylor & Francis, London.
- 727 Caton-Thompson, G. & Gardner, E. W. 1929: Recent work on the problem of Lake Moeris.
728 *Geographical. Journal* 73, 20-60.
- 729 Caton-Thompson, G. & Gardner, E. W. 1934: The Desert Faiyum. Vols I & II. Royal
730 Anthropological. Institute, London.
- 731 Cohen, A. S., van Bocxlaer, B., Todd J. A., McGlue, M., Michel, E., Nkotagu, H. H., Grove,
732 A. T. & Delvaux, D. 2013: Quaternary ostracodes and molluscs from the Rukwa Basin
733 (Tanzania) and their evolutionary and palaeobiogeographic implications.
734 *Palaeogeography, Palaeoclimatology, Palaeoecology* 392, 79–97.
- 735 Dolson, J., El Barkooky, A., Wehr, F., Gingerich, P.D., Prochazka, N. & Shann, M. (2002):
736 The Eocene and Oligocene Paleo-Ecology and Paleo-Geography of Whale Valley and the
737 Fayoum Basins: Implication for Hydrocarbon Exploration in the Nile Delta and Eco-
738 Tourism in the Greater Fayoum Basin. *AAPG/EPEX/SEG/EGS/EAGE Field Trip-*
739 *guidebook No. 7*, 1-79. Cairo.
- 740 Ehrlich, A. 1973: Quaternary diatoms of the Hula Basin (northern Israel). *Geological Survey*
741 *of Israel bulletin* 58, 1-39.
- 742 El Wakeel, S. K. 1963: A study of the bottom deposits of Lake Qarun. Egypt, 1, Mechanical.
743 analysis. *Bulletin of Faculty of Science of the Alexandria University* 5, 33 – 60.
- 744 El-Sayed, E. & Guindy, K. A. 1999: Hydrochemical investigations of El Fayium locality with
745 special reference to the sulphate enrichment phenomenon in Lake Qarun. *Bulletin of the*
746 *Faculty of Science, Mansoura University* 26, 1–21.
- 747 El-Shabrawy, G. M. & Dumont, H. J. 2009: The Fayum Depression and its Lakes.
748 *Monographiae Biologicae* 89, 95-124.

- 749 Flower, R. J., Keatings, K., Hamdan, M. A. & Hassan, F. A. 2013: *Stephanodiscus* Her.
750 Species from Holocene sediments in the Faiyum Depression (Middle Egypt). *Phytotaxa*
751 127, 66-80.
- 752 Flower, R. J., Keatings, K., Hamdan, M., Hassan, F. A., Boyle, J. F., Yamada, K. & Yasuda,
753 Y. 2012: The structure and significance of early Holocene laminated lake sediments in the
754 Faiyum Depression (Egypt) with special reference to diatoms. *Diatom Research* 27, 127–
755 140.
- 756 Flower, R. J., Stickley, C., Rose, N. L., Peglar, S., Fathi, A. A. & Appleby, P. G. 2006:
757 Environmental changes at the desert margin: an assessment of recent paleolimnological
758 records in Lake Qarun, Middle Egypt. *Journal of Paleolimnology* 34, 1-24.
- 759 Garbrecht, G. 1994: Historical water storage for irrigation in the Fayum Depression (Egypt).
760 In Fahlbusch, H. (ed.): *Historical Dams: Foundation of the Future Rest on the*
761 *Achievements of the Past*. International Commission on Irrigation and Drainage, New
762 Delhi, 19-47.
- 763 Gasse, F. 1986: East African diatoms, taxonomy, ecological distribution. *Bibliotheca*
764 *Diatomologica* 2, 1-201.
- 765 Ghamizi, M., Jørgensen, A., Kristensen, T. K., Lange, C., Stensgaard, A.-S. & Van Damme,
766 D. 2012: *Cleopatra bulimoides*. *The IUCN Red List of Threatened Species*. Version
767 2014.2. <www.iucnredlist.org>, accessed on 15 October 2014.
- 768 Ghamizi, M., Kristensen, T. K., Stensgaard, A.-S. & Van Damme, D. 2010: *Musculium*
769 *hartmanni*. *The IUCN Red List of Threatened Species*. Version 2014.3.
770 <www.iucnredlist.org>, accessed on 17 November 2014.
- 771 Goslar, T., Czernik, J. & Goslar, E. 2004: Low-energy ¹⁴C AMS in Poznań Radiocarbon
772 Laboratory, Poland. *Nuclear instruments and methods in physics research section B:*
773 *Beam Interactions with Materials and Atoms* 223–224, 5-11.

- 774 Götting, K.-J. 2008: Meeres-Gehäuseschnecken Deutschlands. Bestimmungsschlüssel,
775 Lebensweise, Verbreitung. *Die Tierwelt Deutschlands* 80, 1-170. ConchBooks,
776 Hackenheim.
- 777 Hassan, F. 2007: Droughts, famine and the collapse of the Old Kingdom: Re-Reading Ipuwer.
778 In Hawass, Z. & Richards, J. (eds.): *Archaeology and Art of Ancient Egypt. Essays in*
779 *Honor of David B. O. Connor 1*, 357-377.
- 780 Hassan, F. A., Hamdan, M. A., Flower, R. J. & Keatings, K. 2012: The oxygen and carbon
781 isotopic records in Holocene freshwater mollusc shells from the Faiyum palaeolakes,
782 Egypt: Their palaeoenvironmental and palaeoclimatic implications. *Quaternary*
783 *International* 266, 175-187
- 784 Hassan, F., Hamdan, M., Flower, R. & Tassie, G. 2011: Holocene geoarchaeology and water
785 history of the Faiyum, Egypt. In Pirelli, R. (ed.): *Natural and cultural landscapes in the*
786 *Faiyum*, 116-133. UNESCO, Cairo.
- 787 Hecky, R.E. & Kilham, P. 1973: Diatoms in alkaline, saline lakes: ecology and geochemical.
788 significance. *Limnology and Oceanography* 18, 53–71.
- 789 Hoelzmann, P., Gasse, F., Dupont, L. M., Salzmann, U., Staubwasser, M., Leuschner, D. C. &
790 Sirocko, F. 2004: Palaeoenvironmental changes in the arid and subarid-belt (Sahara-Sahel-
791 Arabian Peninsula) from 150 ka to present. In Battarbee, R. W., Gasse, F. & Stickley, C.
792 E. (eds.): *Past Climate Variability Through Europe and Africa. Developments in*
793 *Paleoenvironmental Research* 6, 219-256.
- 794 Hustedt, F. 1930-1966: Die Kieselalgen. In L. Rabenhorst (ed.): *Kryptogamenflora von*
795 *Deutschland, Oesterreich und der Schweiz, Akademische Verlagsgesellschaft, Leipzig, 1:*
796 *1-920, 2: 1-845, 3: 1-816.*
- 797 Hustedt, F. 1957: Die Diatomeenflora des Fluss-systems der Weser im Gebiet der Hansestadt
798 Bremen. *Abhandlungen der Naturwissenschaftlichen Verein zu Bremen* 34, 181-440.

- 799 Keatings, K., Holmes, J. A., Flower, R. J., Horne, D., Whittiker, J. E. & Abu-Zied, R. H.
800 2010: Ostracods and the Holocene palaeolimnology of Lake Qarun, with special reference
801 to past human-environment interactions in the Faiyum (Egypt). *Hydrobiologia* 654, 155 –
802 176.
- 803 Keyser, D. & Aladin, N. 2004: Noding in *Cyprideis torosa* and its causes. *Studia Quaternaria*
804 21, 19–24.
- 805 Kilham, P. & Kilham, S. S. 1971: *Melosira granulata* (Ehr.) Ralfs: morphology and ecology
806 of a cosmopolitan freshwater diatom. *Verhandlungen der Internationalen Vereinigung*
807 *Limnologie* 19, 2716-2721.
- 808 Kilham, P., Kilham, S. S. & Hecky, R. E. 1986: Hypothesized resource relationships among
809 African planktonic diatoms. *Limnology and Oceanography* 31, 1169-1181.
- 810 Kröpelin, S., Verschuren, D., Lezine, A.-M., Eggermont, H., Cocquyt, C., Francus, P., Cazet,
811 J.-P., Fagot, M., Rumes, B., Russell, J. M., Darius, F., Conley, D. J., Schuster, M.,
812 Suchodoletz, H. & Engstrom, D. R. 2008: Climate-driven ecosystem succession in the
813 Sahara: the past 6000 years. *Science* 320, 765-768.
- 814 Kuper, R. & Kröpelein, S. 2006: Climate-controlled Holocene occupation in the Sahara:
815 motor of African evolution. *Science* 313, 803–807.
- 816 Kusky, T. M., Ramadan, T. M., Massaan, M. M. & Gabr, S. 2011: Structural and Tectonic
817 Evolution of El – Faiyum Depression, North Western Desert, Egypt based on analysis of
818 Landsat ETM+ and SRTM data. *Journal of Earth Science* 22, 75-100.
- 819 Löffler, H. W. 1986: Ostracod analysis. In Berglund, B. E. (ed.): *Handbook of Holocene*
820 *Palaeoecology and Palaeohydrology*, 693–702. Wiley & Sons, Chichester.
- 821 Ložek, V. 1986: Mollusca Analysis. In Berglund, B. E. (ed.): *Handbook of Holocene*
822 *Palaeoecology and Palaeohydrology*, 729–740. Wiley & Sons, Chichester.

- 823 Marks, L., Salem, A., Welc, F., Nitychoruk, J., Chen, Z., Zalat, A., Majecka, A., Chodyka,
824 M., Szymanek, M. & Tołoczko-Pasek, A. 2016: Preliminary report on unique laminated
825 Holocene sediments from the Qarun Lake in Egypt. *Studia Quaternaria* 33, 35-46.
- 826 Marshall, M, H., Lamb, H. F., Davies, S. J., Leng, M, J., Umer, M., Bryant, Ch. & Kubsa, Z.
827 2009: Climatic change in northern Ethiopia during the past 17,000 years: A diatom and
828 stable isotope record from Lake Ashenge. *Palaeogeography, Palaeoclimatology,*
829 *Palaeoecology* 279, 114–127.
- 830 McCorriston, J. 2006: Breaking the rain barrier and the tropical. spread of near eastern
831 agriculture into southern Arabia. In Kennett, D. J. & Winterhalder, B. (eds.): *Behavioral*
832 *Ecology and the Transition to Agriculture*, 217-236. University of California Press,
833 Berkeley.
- 834 Neale, J. V. 1988: Ostracods and palaeosalinity reconstruction. In De Deckker, P., Colin, J. P.
835 & Peypouquet, J. P. (eds.): *Ostracoda in the Earth Sciences*, 125–155. Elsevier,
836 Amsterdam.
- 837 Nicoll, K. 2004: Recent environmental change and prehistoric human activity in Egypt and
838 northern Sudan. *Quaternary Science Reviews* 23, 561–580.
- 839 Overpeck, J., Anderson, D., Trumbore, S. & Prell, W. 1996: The southwest Indian Monsoon
840 over the last 18,000 yrs. *Climate Dynamics* 12, 213–225.
- 841 Pachur, H. J., Kröpelin, S., Hoelzmann, P., Goschin, M. & Altmann, N. 1990. Late
842 Quaternary fluvio-lacustrine environments of western Nubia. *Research in Egypt and*
843 *Sudan* 120, 203–260.
- 844 Park, L. E. & Martens, K. 2001: Four new species of *Gomphocythere* (Crustacea, Ostracoda)
845 from Lake Tanganyika, East Africa. *Hydrobiologia* 450, 129–147.

- 846 Przybyłowska-Lange, W. 1976: Diatoms from the site E71K14, area 1, trench 1, upper
847 diatomaceous silt. In Wendorf, F. & Schild, R. (eds.): *Prehistory of the Nile Valley*, 321 –
848 323. Academic Press, New York.
- 849 Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck,
850 C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Guilderson, T. P.,
851 Hafliðason, H., Hajdas, I., Hatté, C., Heaton, T. J., Hoffmann, D. L., Hogg, A. G.,
852 Hughen, K. A., Kaiser, K. F., Kromer, B., Manning, S. W., Niu, M., Reimer, R. W.,
853 Richards, D. A., Scott, E. M., Southon, J. R., Staff, R. A., Turney, C. S. M. & van der
854 Plicht, J. 2013: IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years
855 cal. BP. *Radiocarbon* 55,1869–1887.
- 856 Revel, M., Colin, C., Bernasconi, S., Combourieu-Nebout, N. C., Ducassou, E., Grousset, F.
857 F., Rolland, Y., Migeon, S., Bosch, D., Brunet, P., Zhao, Y. & Mascle, J. 2014: 21,000
858 Years of Ethiopian African monsoon variability recorded in sediments of the western Nile
859 deep-sea fan. *Regional Environmental Change* 14, 1685–169.
- 860 Richardson, J. L., Harvey, T. J. & Holdship, S. A., 1978: Diatoms in the history of shallow
861 East African lakes. *Polskie Archiwum Hydrobiologii* 25, 341-343.
- 862 Rohling, E. & Pälike, H. 2005: Centennial-scale climate cooling with a sudden cold event
863 around 8,200 years ago. *Nature* 434, 975–979.
- 864 Said, R. 1979: The Messinian in Egypt. Proceedings of the International Congress on
865 Mediterranean Neogene, Athens. *Annales Geologiques des Pays Helleniques III*, 1083–
866 1090.
- 867 Said, R. 1981: *The Geologic Evolution of the River Nile*. 151 pp. Springer, New York.
- 868 Sattmann, H. & Kinzelbah, R. 1988: Notes on inland water molluscs from Egypt (Mollusca:
869 Gastropoda, Bivalvia). *Zoology in the Middle East* 2, 72–78.

- 870 Schild, R., Wendorf, F. 2001. Geoarchaeology of the Holocene Climatic Optimum at Nabta
871 Playa, Southwestern Desert, Egypt. *Geoarchaeology* 16, 7–28.
- 872 Schild, R. & Wendorf, F. 2013: Early and Middle Holocene palaeoclimates in the
873 Southwestern Desert of Egypt – the world before unification. *Studia Quaternaria* 30, 125
874 – 133.
- 875 Shen, Z. X., Arimoto, R., Okuda, T., Cao, J. J., Zhang, R. J., Li, X. X., Du, N., Nakao, S. &
876 Tanaka, S. 2008: Seasonal variations and evidence for the effectiveness of pollution
877 controls on water-soluble inorganic species in total suspended particulates and fine
878 particulate matter from Xi'an, China. *Journal of Air Waste Management Association* 58:
879 1560-1570.
- 880 Stoermer, E. F., Bowman, M., Kingston, J. C. V. & Schaedel, A. L. 1975: Phytoplankton
881 composition and abundance in Lake Ontario during IFYGL. U.S. Environmental
882 Protection Agency. Report No. EPA-660/3-75-004. February 1975, Corvallis, Oregon.
- 883 Stuiver, M. & Polach, H. A. 1977: Discussion reporting of C14 data. *Radiocarbon* 19, 355-
884 363.
- 885 Sywula, T. 1974: *Małżoraczki (Ostracoda)*. *Fauna słodkowodna Polski* 24. 315 pp.
886 Państwowe Wydawnictwo Naukowe, Poznań.
- 887 Taraschewski, H. & Paperna, I. 1981: Distribution of the snail *Pirenellaconica* in Sinai and
888 Israel and its infection by Heterophyidae and other Trematodes. *Marine Ecology –*
889 *Progress Series* 5, 193–205.
- 890 Tibby, J. & Reid, M. 2004: A model for inferring past conductivity in low salinity waters
891 derived from Murray River diatom plankton. *Marine and Freshwater Research* 55, 587-
892 607.
- 893 Trigueros, M. & Orive, E. 2000: Tidally driven distribution of phytoplankton blooms in a
894 shallow, macrotidal estuary. *Journal of Plankton Research* 22, 969-986.

- 895 Welc, F. & Marks, L. 2014: Climate change at the end of the Old Kingdom in Egypt around
896 4200 BP: New geoarcheological evidence. *Quaternary International* 324, 124-133.
- 897 Weldeab, S., Lea, D. W., Schneider, R. E. & Andersen, N. 2007: 155,000 years of West
898 African monsoon and ocean thermal evolution. *Science* 316, 1303–1307.
- 899 Welter-Schultes, F. 2012: *European Non-Marine Molluscs, a Guide for Species*
900 *Identification*. 76 pp. Planet Poster Editions, Goettingen.
- 901 Wendorf, F. & Schild, R. 1976: *The Prehistory of the Nile Valley*. 404 pp. Academic Press,
902 New York.
- 903 Wenke, R. J., Long, J. E. & Buck, P. E. 1988: Epipalaeolithic and Neolithic subsistence and
904 settlement in the Faiyum Oasis in Egypt. *Journal of Field Archaeology* 15, 29-51.
- 905 Williams, M. A. J., Adamson, D., Cock, B. & McEvedy, R. 2000: Late Quaternary
906 environments in the White Nile region, Sudan. *Global and Planetary Change* 26, 305-316.
- 907 Wolfe, A. P., Fréchette, B., Richard, P. J. H., Miller, G. H. & Forman, S. L. 2000:
908 Palaeoecological assessment of a 90,000-year lacustrine sequence from Fog Lake, Baffin
909 Island, Arctic Canada. *Quaternary Science Reviews* 19, 1677-1699.
- 910 Woodward, J. C., Macklin, M. G., Krom, M. D. & Williams, M. A. J. 2007: The Nile:
911 evolution, Quaternary river environments and material fluxes. In Gupta, A. (ed.): *Large*
912 *Rivers: Geomorphology and Management*, 262 – 292. Wiley & Sons, London.
- 913 Zalat, A. A. 1991: *Paleontological. studies on the Quaternary diatomite of the Fayoum*
914 *Depression, Western Desert, Egypt. Ph.D. thesis*, Tanta University, 329 pp.
- 915 Zalat, A. A. 1995: Calcareous nannoplankton and diatoms from the Eocene/Pliocene
916 sediments, Fayoum depression, Egypt. *Journal of African Earth Sciences* 20, 227-244.
- 917 Zalat, A. A. 2002: Distribution and origin of diatoms in the bottom sediments of the Suez
918 canal lakes and adjacent areas, Egypt. *Diatom Research* 17, 243-266.

919 Zalut, A. A. 2015: Holocene diatom assemblages and their palaeoenvironmental
920 interpretations in Fayoum Depression, Western Desert, Egypt. *Quaternary International*
921 369, 86-98.

922 Zalut, A. A. & Servant-Vildary S. 2005: Distribution of diatom assemblages and their
923 relationship to environmental variables in the surface sediments of three northern Egyptian
924 lakes. *Journal of Palaeolimnology* 34, 159-174.

925 Zalut, A. A. & Servant-Vildary S. 2007: Environmental change in northern Egyptian Delta
926 lakes during the late Holocene, based on diatom analysis. *Journal of Paleolimnology* 37,
927 273-299.

928 **Captions to the figures and tables**

929 Fig. 1. Location sketch; A – after Woodward *et al.* (2007), modified; B – based on broad
930 compilation, bathymetry of the lake is after Abu-Zied *et al.* (2007).

931 Fig. 2. Lithology of core FA-1.

932 Fig. 3. Age-depth model of the core FA-1. Top panels reflect: the MCMC process (left), the
933 prior and posterior distributions for the deposition time (middle) and its variability between
934 depths (right). The main panel shows the calibrated radiocarbon dates and the age-depth
935 model (grey-scale, with darker areas indicating more secure sections). Stippled curves
936 indicate 95% range and curve between them indicates a mean. Depths are in cm.

937 Fig. 4. Sedimentation rate and model of deposition in the lake.

938 Fig. 5. Variation of water soluble ions in sediments of core FA-1.

939 Fig. 6. Percentage diagram of selected diatoms in the FA-1; sediment without diatoms is
940 indicated in gray.

941 Fig. 7. Main phases of the Qarun Lake development indicated in core FA-1; for lithological
942 description see Fig. 2.

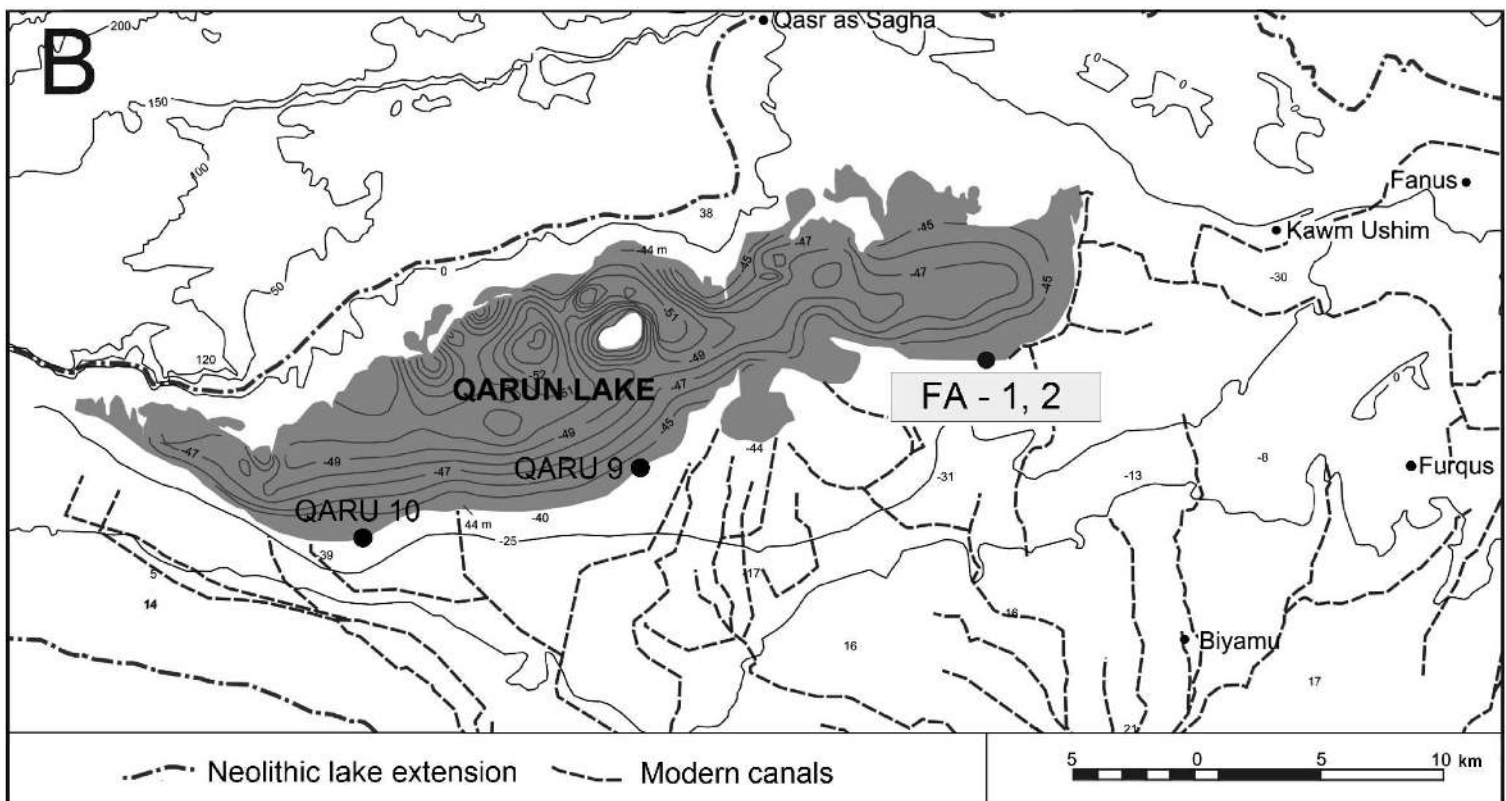
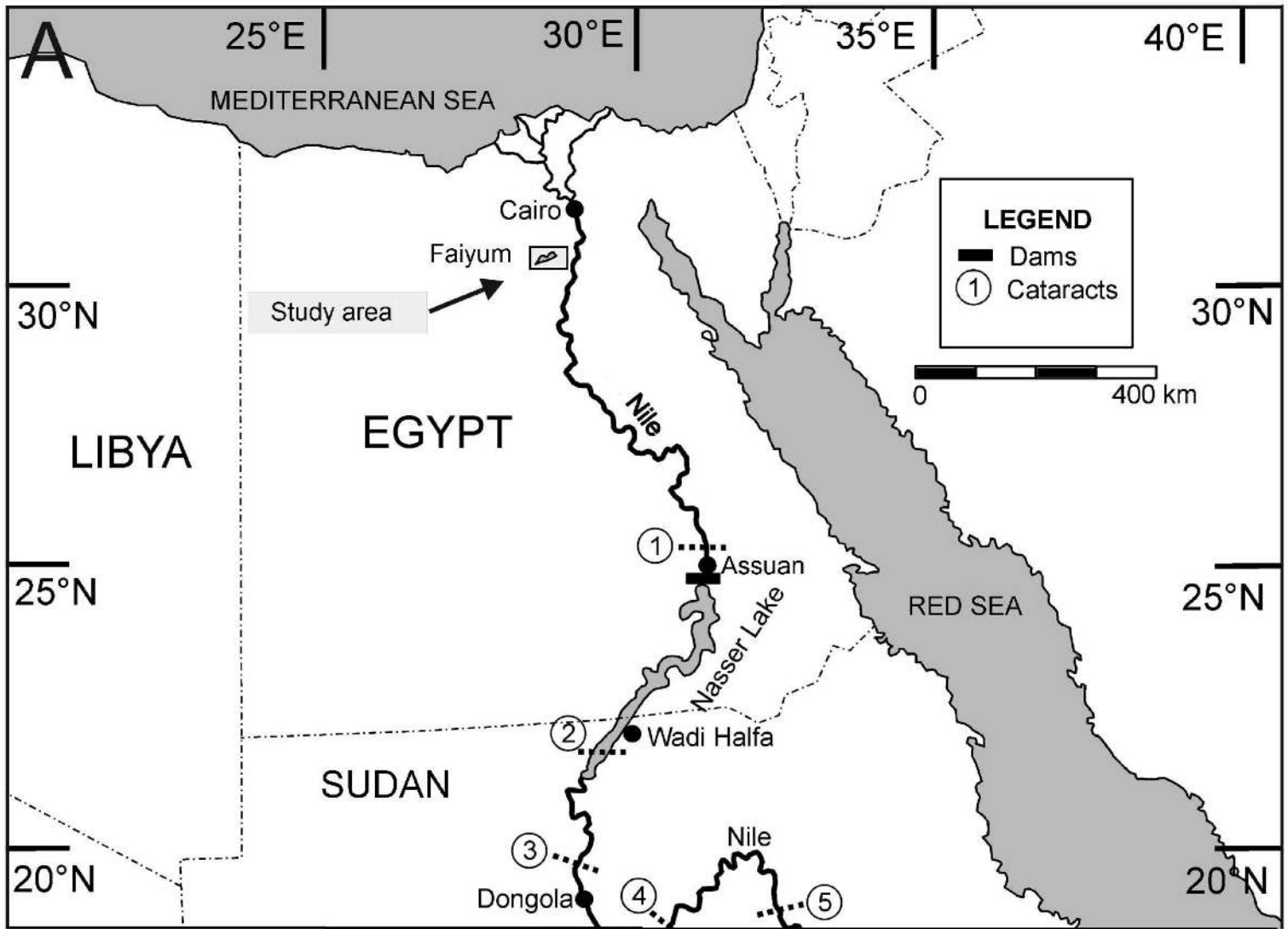
943 Fig. 8. Palaeogeography of the Faiyum Oasis in the Holocene with past lake extents (in dark
944 gray); indicated are the present lakes (in black), the area above 50 m a.s.l. (in light gray)
945 and contour lines at 0 m and -25 m b.s.l.

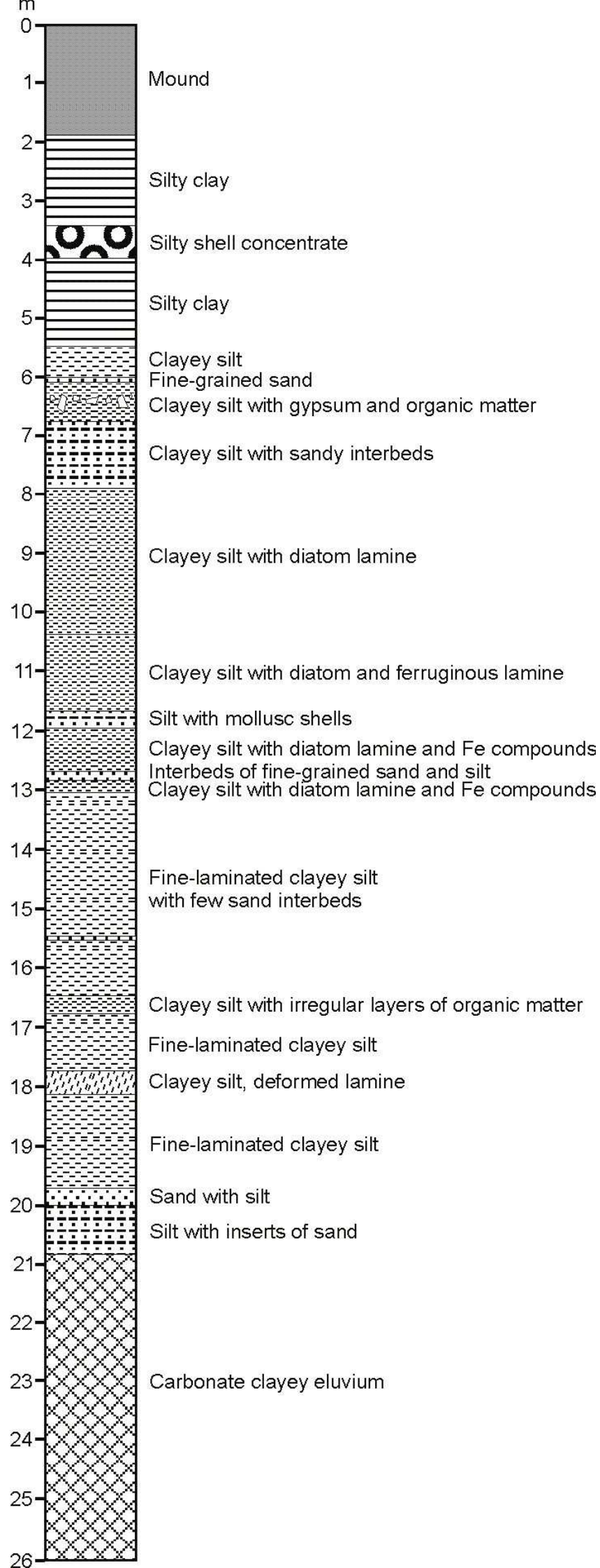
946

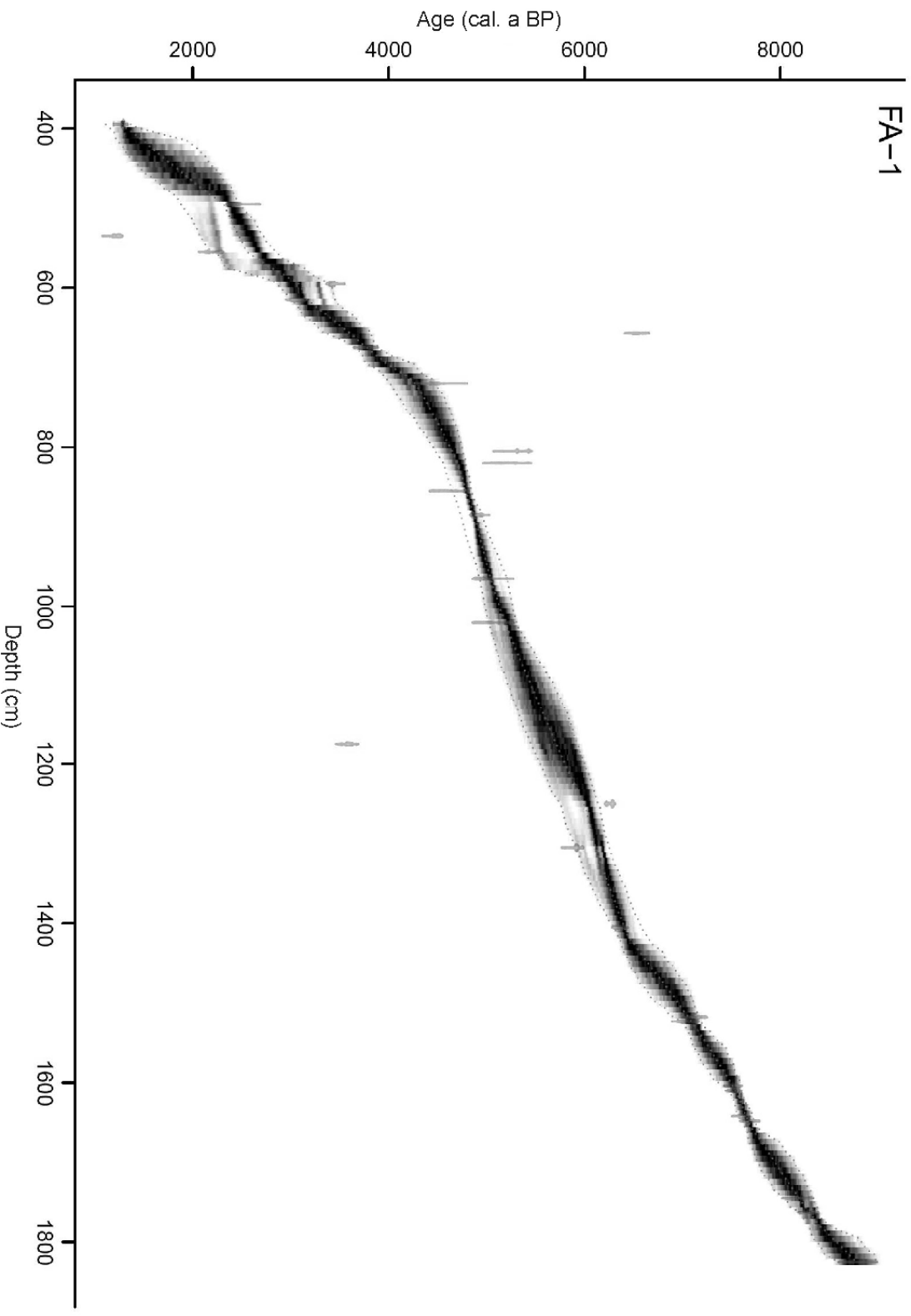
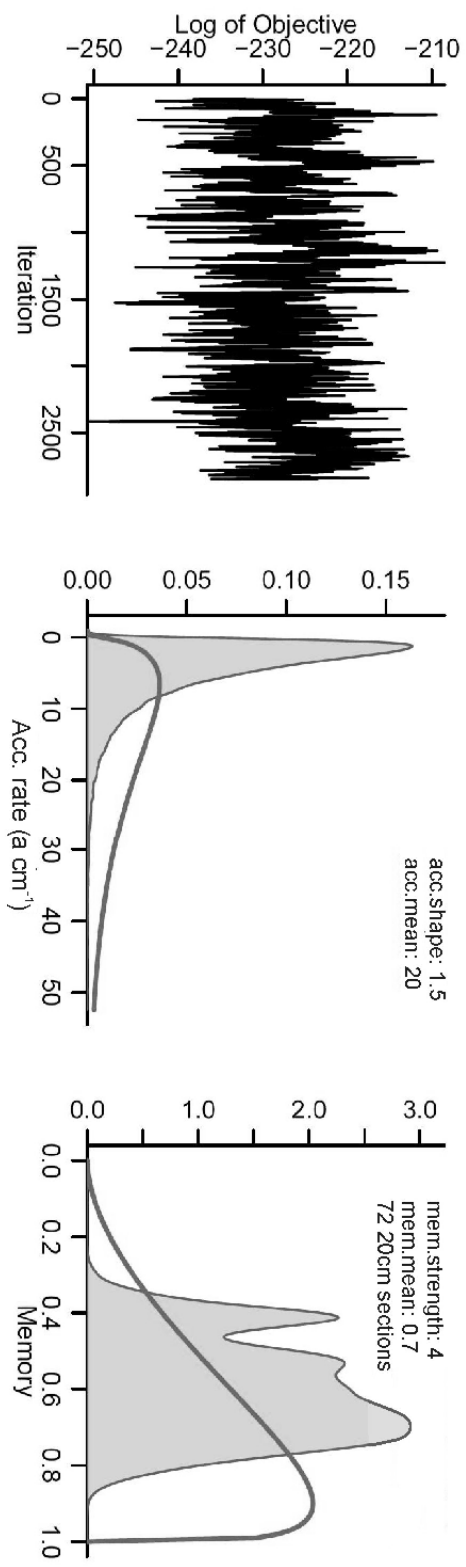
947 Table 1. List of radiocarbon dates in core FA-1; concentrations of organic matter are indicated
948 but dispersed organic matter occurred in every sample. Calibrated ranges are based on
949 Oxcal 2016 with 95.4% probability; AMS $\delta^{13}\text{C}$ values are for correcting measurement-
950 induced fractionation and should not be interpreted ecologically.

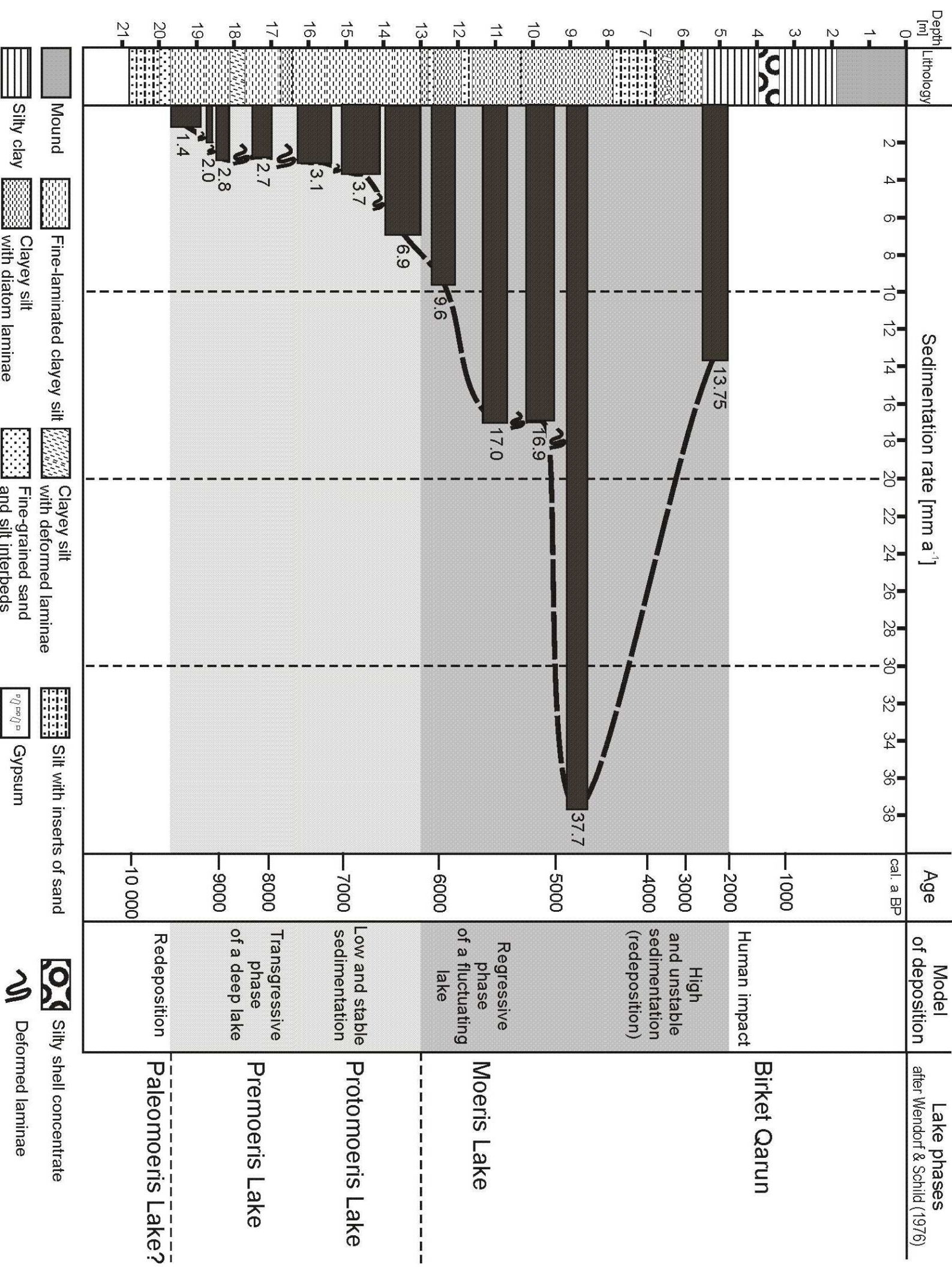
951 Table 2. Molluscs and ostracods of core FA-1.

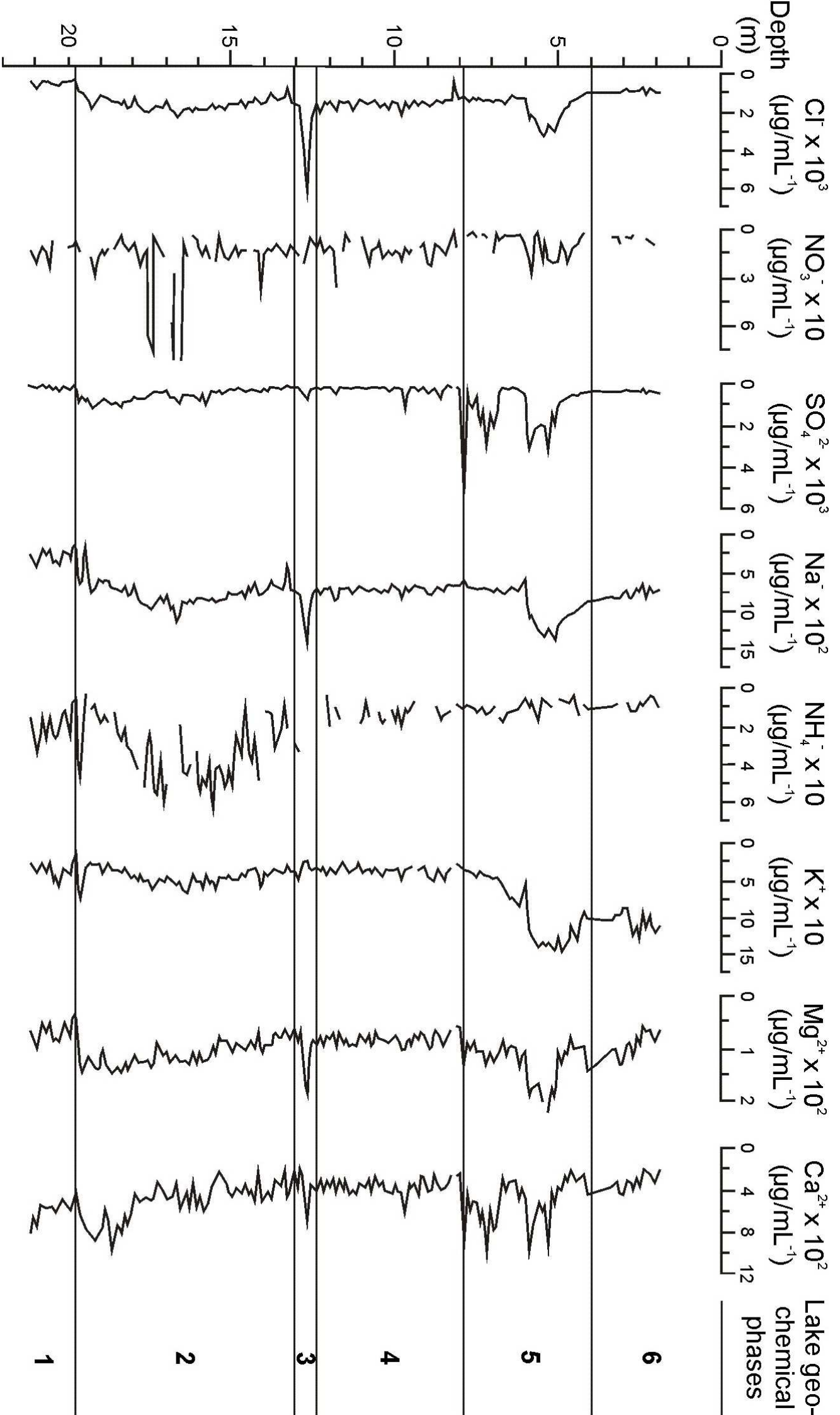
952 F – freshwater: *s* – stagnant water, *f* – flowing water; Sa – saltwater: *br* – brackish; *d* –
953 shell detritus, *fr* – few fragments of shell, 2-6 – phases of the lake based on sedimentary
954 sequence; for bivalves and ostracods a number of valves is given

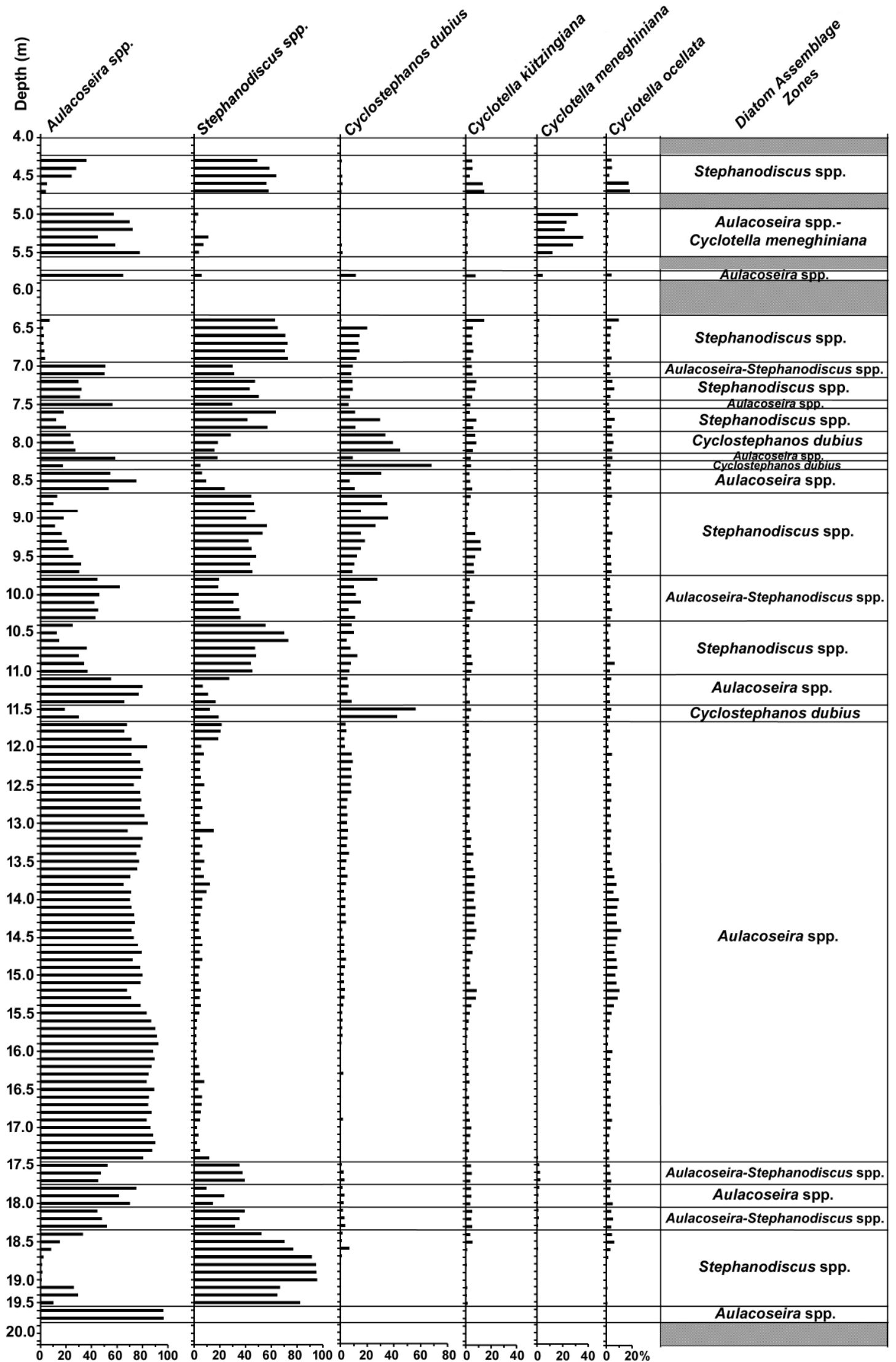


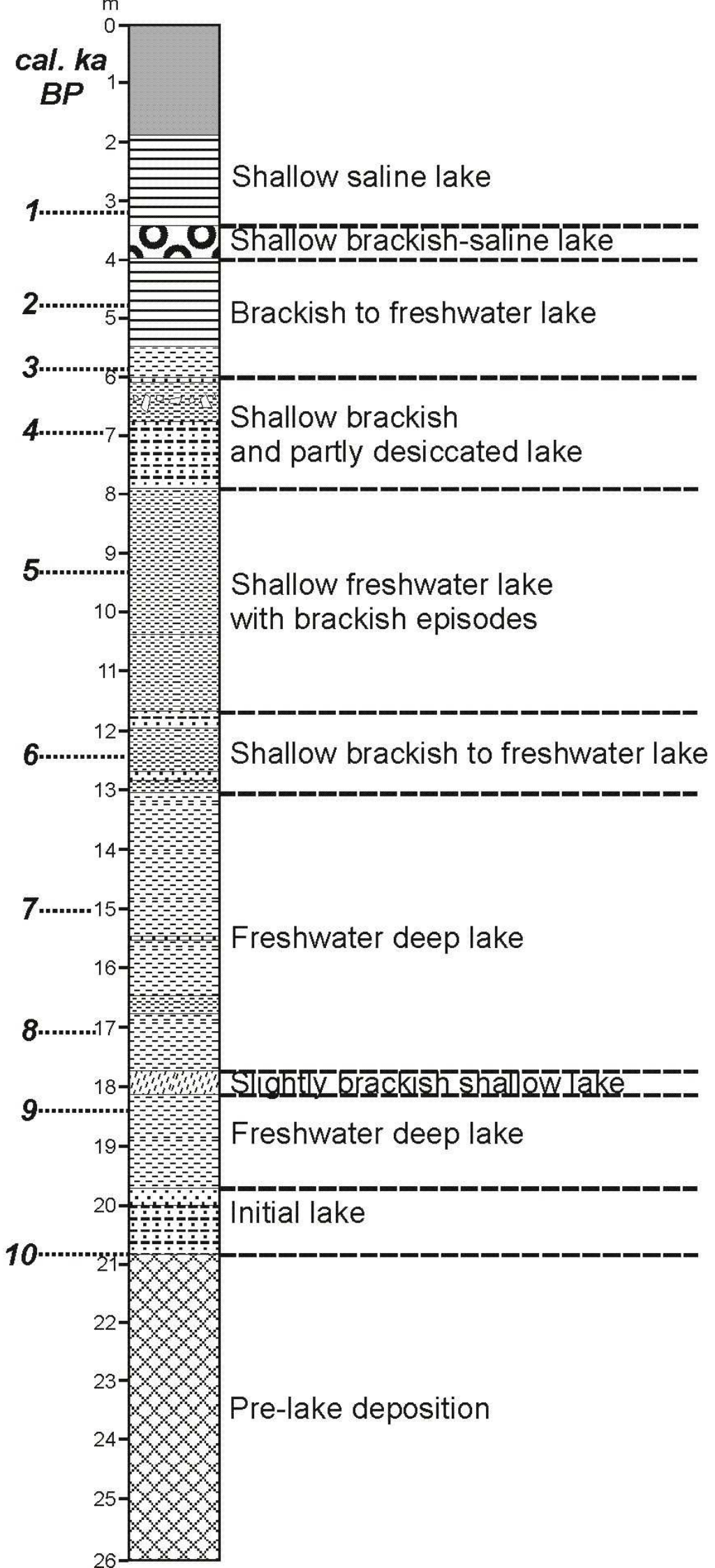




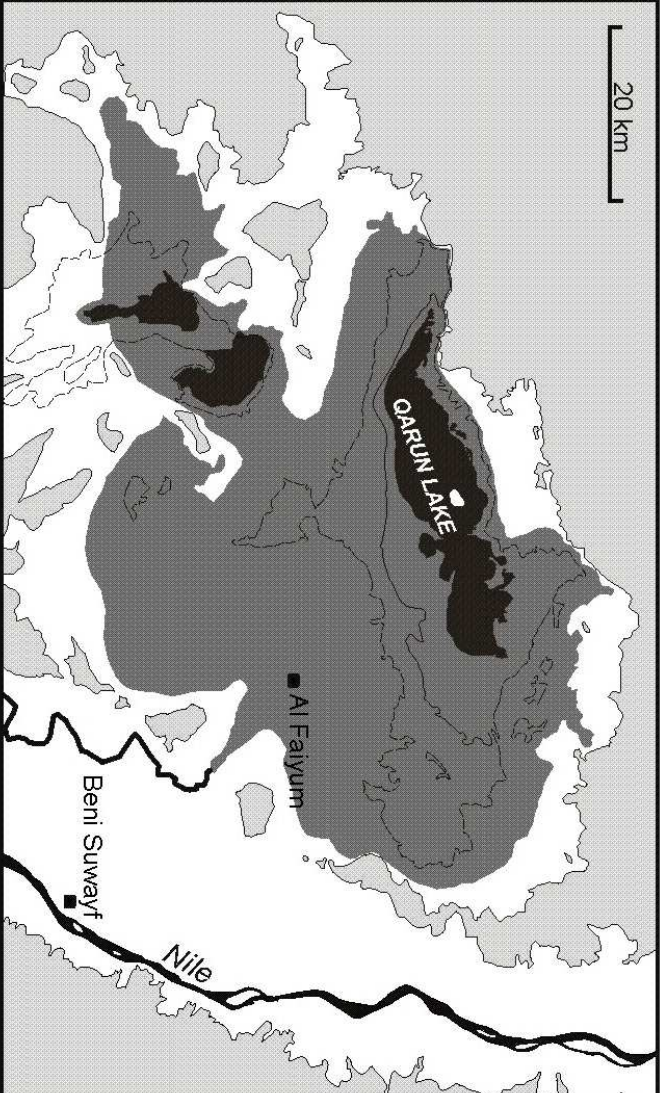




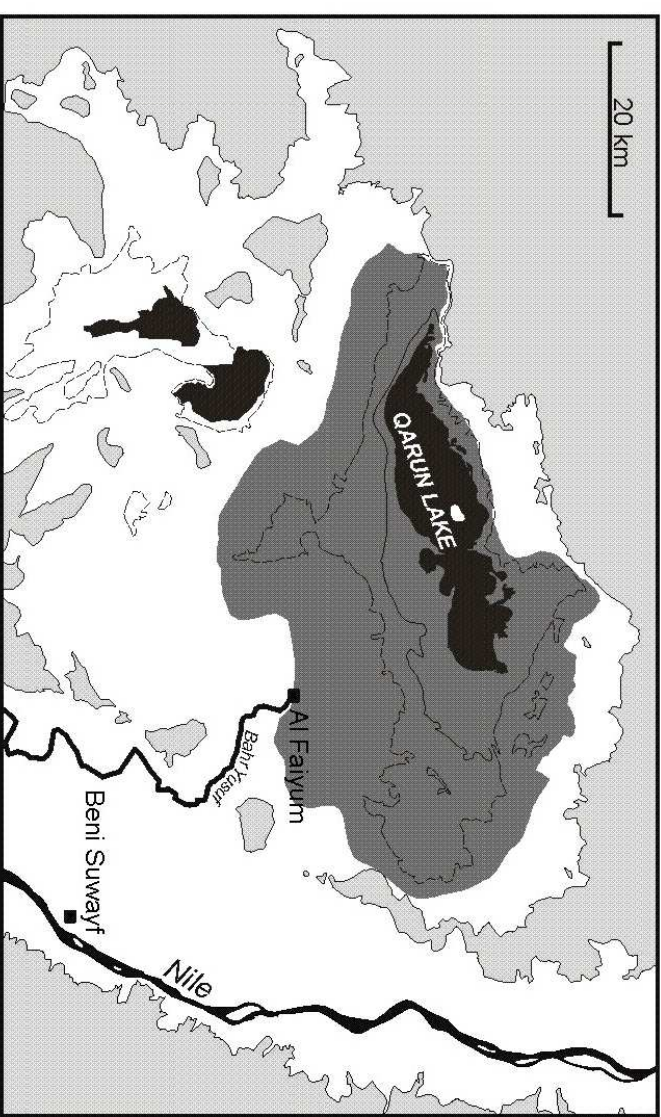




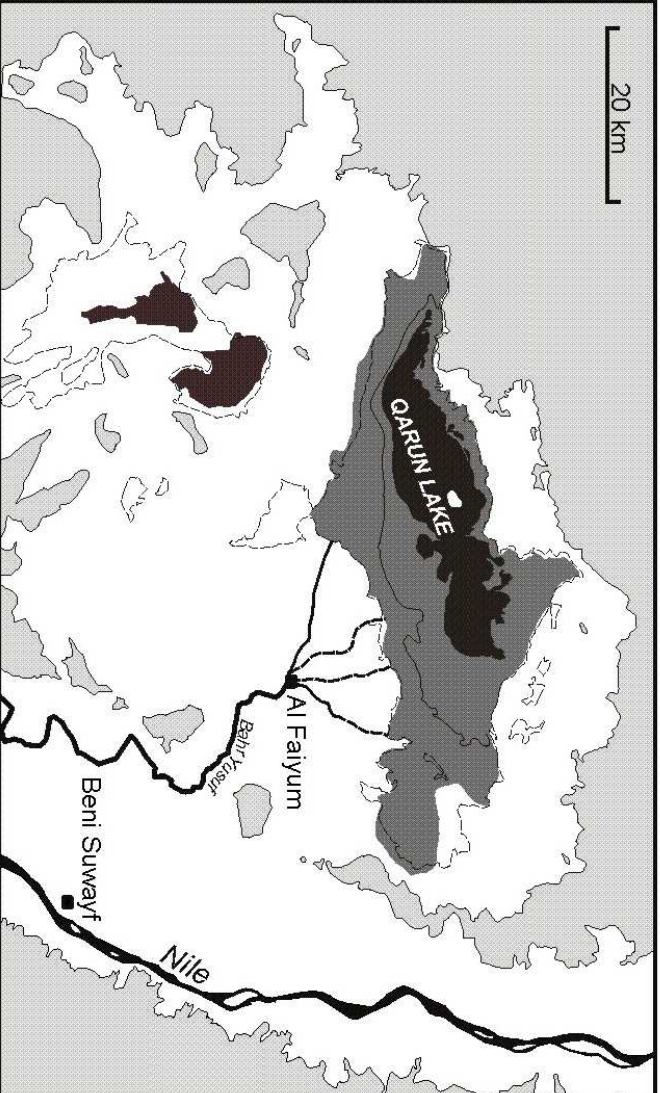
Early Middle Holocene (8.4 - 6.2 cal. ka BP)



End of Old Kingdom (5.7 - 4.1 cal. ka BP)



Ptolemaic Period (2.3 - 2.1 cal. ka BP)



Present

