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The Qarun Lake in the Faiyum Oasis (Egypt) provides a unique record of Holocene environmental and climate change in an arid area largely void of fossil proxy records. Multiple lithological, palaeontological. and geochemical proxies and 32 radiocarbon dates from the 26-m long core FA-1 provide a time-series of the lake transformation. Our results confirm that a permanent lake in the Holocene appeared at ~10 cal. ka BP. The finely-laminated lake sediments consist of diatomite, in which diatoms and ostracods together with lower concentrations of ions indicate a freshwater environment at the end of the early and middle Holocene. This was closely associated with regular inflows of the Nile water during flood seasons, when the Intertropical Convergence Zone (ITCZ) migrated northwards in Africa, although it has probably never reached the Faiyum Oasis. Local rainfalls, possibly connected with a northern atmospheric circulation, could have been important during winter. Several phases in the lake evolution are recognized, represented by oscillations between deep open freshwater conditions during more humid climate and shallow fresh to brackish water during drier episodes. After a long freshwater phase, the lake setting has become more brackish since ~6.2 cal. ka BP as indicated by diatoms and increasing contents of evaporite ions in the sediment. This clearly shows that since that time the lake has become occasionally partly desiccated. It resulted from a reduced discharge of the Nile. In the late Holocene the lake was mostly brackish turning gradually into a saline lake. This natural process was interrupted about 2.3 cal. ka BP when a man-made canal facilitated water inflow from the Nile. The examined FA-1 core can be used as the reference age model of climate change in the Holocene and its impact on development and decline of ancient civilisations in north-eastern Africa.

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

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

The dynamics of hydrological and climatic changes in the Nile drainage basin are reflected in the lithological. and geochemical. characteristics of sediments in the Faiyum Oasis where the lake filled a central part of the depression. Because the Faiyum Oasis was located outside the northern extent of the monsoon rainfalls in the Holocene (cf. Williams *et al*. 2000; McCorriston 2006), the lake sediments must have reflected mostly local hydroclimatic conditions. The lake level fluctuations were highly dependent on the frequency of inflows of the Nile water and the Nile discharge was controlled by the intensity of the remote precipitation regime in the Ethiopian Highlands where two main tributaries of the Nile originate i.e. the Blue Nile and the Atbara rivers (Baioumy *et al*. 2010; Hassan *et al*. 2011). During the Holocene the northernmost part of Egypt and the Red Sea have also been influenced by the North Atlantic Circulation, defined also as the Mediterranean Circulation that created winter rainfalls of varying intensity (e.g. Arz *et al*. 2003; Marks *et al*. 2016).

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

Site location and previous studies

The area of the Faiyum Oasis is estimated at some 1270 to 1700 km^2 (Fig. 1). It is located within Eocene and Oligocene rock formations, composed mostly of organodetritic limestones, marls and sandstones of shallow water facies. Oligocene, Late Miocene and Pliocene sedimentary series are overlain by Quaternary sediments, mainly of lacustrine and aeolian origin (Beadnell 1905; Said 1981).

The Faiyum Oasis is one of the most important depressions in the Western Desert of Egypt and the question of its origin has been a subject of numerous disputes and controversies. Its current shape had been controlled by subsidence until the Late Eocene (Dolson *et al.* 2002). A lake could occupy the oasis already in the Pliocene, then it probably dried up in the Pleistocene and intensive deflation occurred, followed by filling with the Nile waters at the beginning of the Holocene (cf. Beadnell 1905; Caton-Thompson & Gardner 1929). On the other hand, Ball (1939) and Said (1979) suggested that the depression was formed by complex tectonic movements and deflation, active since the Pleistocene to the present time (Kusky *et al*. 2011).

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

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

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

Methodology

Drilling, sampling and lithological analysis

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

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

SEM EDS analyses

Samples were dried at room temperature and then analyzed using an electron scanning microscope (HITACHI TM 3000), supplied with an energy dispersion spectrometer (SWIFT ED 3000 Oxford Instruments). Samples were put directly on a carbon band. Surface and point analyses were done with using an accelerating voltage of 15 kV. The analyses were performed at the Research Centre on Innovations, John Paul 2nd State Higher School in Biała Podlaska, Poland.

Ion-geochemistry analysis

10-mg dried samples were put into 20 ml centrifuge tube vials containing 10 mL distilled-deionised water (resistivity of 18 MΩ), placed in ultrasonic water bath for 60 min and then shaken by mechanical shaker for 1h for complete extraction of ionic compounds. The extracts were filtered with 0.45 µm pore size microporous membranes and filtrates were stored at 4°C in a clean tube before further analysis. Three anions (SO_4^{2-}, NO_3^- and Cl^-) and five cations (Na^+, NH_4^+, K^+, Mg^{2+} and Ca^{2+}) were determined in aqueous extracts of the filters, prepared in three steps using ultrapure (18 MΩ) water. Ion chromatography (IC, Dionex 500, Dionex Corporation, Sunnyvale, California, United States) was used for the analysis at the Institute of Earth Environment, Chinese Academy of Sciences (IEECAS). Blank values were subtracted from sample concentrations. One sample in each group of 10 samples was analyzed twice for quality control. Typical precision (percent relative standard deviation) for six pairs of samples was calculated using the equation: $X_i = (C_{i1} – C_{i2})/C_{ia}$, where C_{i1} and C_{i2} were routine and duplicate concentrations, C_{ia} was the mean concentration for the measurement pair i and Xi was the relative difference. The maximum relative precisions were 1.8% for Na^+, 0.9% for NH_4^+, 0.6% for K^+, 4.0% for Ca^{2+}, 1.0% for Mg^{2+}, 1.2% for SO_4^{2-}, 2.6% for NO_3^- and 0.3% for Cl^- (Shen *et al*. 2008).

Diatom analysis

Diatoms were extracted from the studied samples according to the procedure proposed by Zalat (2002) and Zalat & Servant-Vildary (2005, 2007). Diatom identification and statistical studies were done in the Geological. Department of the Tanta University in Egypt with a use of Carl Zeiss light microscope combined with digital camera at normal x100 oil immersion objective. In slides sufficiently rich in diatoms, 1000 diatom valves were counted, whereas at least 200 valves were counted in samples with low-diatom concentrations. Percentage contents of species were calculated for estimation of ecological parameters as life-form groups, pH and salinity. Relative frequencies of every species were calculated as the percentage of total diatom valves (%TDV) in each sample, and identification of ecological. preferences of diatom species was based on previous works (e.g. Hustedt 1930-1966, 1957; Ehrlich 1973; Stoermer *et al.* 1975; Gasse 1986; Kilham *et al.* 1986; Zalat 1991; Wolfe *et al.* 2000; Bradbury *et al.* 2004; Zalat & Servant-Vidary 2007).

Mollusc and ostracod analysis

Standard methods established by Ložek (1986) were applied for mollusc analysis of 6 sediment samples with abundant shells: five were collected at 5 cm intervals at depth of 18.9 – 18.7 m (volume 50 cm^3 each) and a single bulk sample at depth 4.0 – 3.5 m (370 cm^3). Samples were wet-sieved with 0.5 mm mesh. All shells and their identifiable apical fragments were picked from the dried residue, identified under a binocular microscope (magnification up to 64x) with reference to taxonomical keys (Brown 1994; Götting 2008; Welter-Schultes 2012) and counted (Ložek 1986). Ecological preferences of mollusc species were based on Taraschewski & Paperna (1981), Brown (1994), Götting (2008), Ghamizi *et al*. (2010, 2012) and Welter-Schultes (2012).

Ostracod valves and carapaces were studied in 29 samples according to the method described by Löffler (1986). The core was sampled at every 5 cm at 18.9 – 18.7 and 18.1 – 17.9 m depth. Samples were collected every 1 m at 18.1 – 13.0 m and 8.0 – 5.0 m depth and every 0.5 m at 13.0 – 8.0 m depth. Density of sampling depended on the abundance of fossils. Ten cm^3 of sediment per sample were washed through 0.1 mm mesh sieve. Ostracods were taxonomically determined according to Sywula (1974) and Keatings *et al*. (2010) using a binocular microscope (magnification up to 64x).

Radiocarbon dating

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

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

Results

Lithological characteristics of the core FA-1

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

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

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

Age model and sedimentation rate

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

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

Calcite is present in the laminated deposits and it means that a hard water effect is very likely on the authochonous organic material as well. We have not done any exact estimation of the hard water effect but it seems obvious that it is higher in the lower part of the core, because of intensive redeposition of carbonates from the area around the lake. This effect is considerably smaller in the laminated part of the section, especially as we selected the samples from the organic laminae. In the upper part of the section where the lamination is absent the hard water effect can be higher as the bulk samples were mostly collected for the radiocarbon dating.

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

Sedimentation rate in the lake was estimated based on counting of the laminae, using the high-resolution photographs of the core. Every set of laminae (diatom, mineral and organic mud) was assumed to represent a single year. The reconstructed sedimentation rate was the lowest in the initial phase of the lake, represented by the finest and most regular lamination at 19.8 – 18.9 m depth, with average annual sedimentation rate of 1.4 mm (Fig. 4). Uniform and then slightly rising sedimentation rate of 2.7 – 7.7 mm a^{-1} occurs at 18.4 – 14.1 m depth Sedimentation rate has risen consequently above the depth of 14.1 m and reached maximum of 37.7 mm a^{-1} at 9.08 – 8.5 m, indicating an unstable sedimentary environment. At depth 18.25 – 12.50 m twelve samples were radiocarbon dated, both from organic agglomerations and bulk samples with dispersed organic matter (Table 1). Contents of total organic carbon are the highest and of carbonates are the lowest in this part of the core and all ages are almost in perfect superposition, presumably indicating that neither substantial disturbances in carbon content nor significant redeposition have impacted sedimentation in this part of the core.

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

Lake salinity and geochemical. indicators of climate change

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

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

Phase 2 (19.8 – 13.1 m depth, ~9.8 – 6.2 cal. ka BP): contents of NH_4^+ and NO_3^- increased dramatically upwards but with minor increases for Cl^-, Na^+, Mg^{2+} and Ca^{2+} (Fig. 5), suggesting a relatively strong nitrification due to enhanced productivity of the lake dominated by freshwater setting. Therefore, the freshwater environment implies a hydrological linkage with the Nile, although minor fluctuations in ion contents suggested certain irregularities over time.

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

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

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

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

Diatom phases

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

The diatom spectra are dominated by riverine taxa including *Aulacoseira granulata*, *A. italic*, *A. ambigua* and *Stephanodiscus* spp. Abundant peaks of these taxa are intepreted as an indication of increased discharge of the Nile water into the lake. The diatom assemblage indicative of high stand lake level and increased nutrient availability persisted in the Holocene but lower concentrations or lack of diatom valves at some depths (6.3 – 5.6, 4.95 – 4.8, 4.9, 4.2 – 4.0 m) suggest lower diatom productivity. The upper part of the core (depth 4.0 – 2.0 m) is completely barren of diatom frustules, reflecting marked environmental changes in the lake, connected with transition from freshwater through brackish to saline conditions. Stratigraphic distribution of recorded planktonic taxa samples led to recognition of 5 types of diatom ecozones in the studied core that is *Aulacoseira* spp., *Stephanodiscus* spp., *Aulacoseira*-*Stephanodiscus* spp., *Cyclostephanos dubius* and *Aulacoseira* spp.-*Cyclotella meneghiniana* (Fig. 6).

Aulacoseira spp. assemblage. – This assemblage is recorded 9 times (Fig. 6), being dominated by *Aulacoseira granulata* and accompanied commonly by *A. granulata* var. *angustissima*, *A. ambigua*, *A. italica* and *A. islandica*. There are low contents of other planktonic taxa. *Aulacoseira granulata* was a freshwater planktonic and alkaliphilous species, common in eutrophic water of higher temperature (Hustedt 1957; Ehrlich 1973; Stoermer *et al*. l975). The *Aulacoseira* species indicates high growth requirements for silicon and demanded high silica content in water (Kilham & Kilham 1971), presumably in different combinations of P and light (Kilham *et al*. 1986). However, *Aulacoseira* species are non-competitive, so their wide distribution normally coincided with low concentration of other diatoms (Wolfe *et al*. 2000). *Aulacoseira* taxa are also used as indicators of warmer climate, which may have led to wind-induced mixing in the lake, higher input of humic substances and increased precipitation. They suggest stabilized conditions, remaining wet and windy with increased turbulence and upwelling in the lake, typical of a late phase of the Nile flood cycle (Zalat 1995). *Aulacoseira* species were presumably most dominant in summer and relatively common in spring. Their predominance indicates summers with high silica concentration. Maximum abundances of *Aulacoseira granulata* associated with other *Aulacoseira* species and decreased abundance of *Stephanodiscus* and *Cyclotella* species could reflect a freshwater lake with relatively high level due to nutrient-rich influx from the Nile during a wet warm period.

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

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

Cyclostephanos dubius assemblage. – This assemblage is observed in 3 thin zones (Fig. 6). It is characterised by abundance of *Cyclostephanos dubius* (40-55%), accompanied by *Aulacoseira* spp., which is more abundant than *Stephanodiscus* taxa. Other planktonic taxa as *Cyclotella kützingiana* and *C. ocellata* are distributed frequently. *Cyclostephanos dubius* is a pelagic taxon, common in flowing and stagnant freshwater in a coastal area, of low conductivity and low to medium alkalinity (pH = 7.6-8.9). The diatom assemblage includes common occurrences of *Aulacoseira* spp., *Cyclostephanos dubius* and *Stephanodiscus* taxa, indicating a high stand lake level with clear dominance of eutrophic freshwater conditions and slightly higher salinity and alkalinity in summer.

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

Mollusc and ostracod indicators

Altogether 10 taxa of molluscs (6 snails and 4 bivalves) and 8 taxa of ostracods are recognized in the FA-1 core (Table 2). Molluscs are represented by 735 specimens, but with 1-8 taxa and from 2 to 726 specimens in a single sample. Shells are abundant in the upper part of the core (4.0 – 3.5 m depth) and their assemblage is predominated by brackish species, among which the most numerous is *Hydrobia ventrosa* and *Cerastoderma glaucum*. These species are accompanied by euryhaline snails *Pirenella conica* and *Hinia costulata* and three freshwater snails, the most abundant of which was *Melanoides tuberculata* (Table 2). The lowermost samples (18.9 – 18.7 m depth) contain very scarce shell material with only few specimens of the freshwater endemic snail *Valvata nilotica* and fragments of saline bivalves *Abra ovata* and *Cerastoderma* sp. (Table 2).

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

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

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

Development of the Faiyum Lake in the Holocene

Multi-proxy investigations of the core FA-1 (Figs 4-6, Table 2) and comparison of their results with other cores in the Qarun Lake area (cf. Baioumy *et al*. 2010, 2011; Flower *et al*. 2012, 2013) supplied with high-resolution palaeoclimate data indicate several phases of the Faiyum Lake development during the Holocene (Fig. 7). The lake was initially a freshwater lake, but then went through brackish to saline conditions. These changes were accompanied by a fluctuating water level in the lake (interpreted from shifts of lake shore and varying salinity), strictly combined with more intensive or reduced annual influx from the Nile.

>10.0 cal. ka BP: pre-lake deposition

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

10.0 – 9.8 cal ka. BP: initial lake

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

Termination of this phase is represented by a greenish-gray sandy mud intercalated with bedded sand with taxa of *Chara* that indicate shallow (0.5 –4.0 m), fresh to slightly brackish lake and increased evaporation during drier periods (Zalat 1995, 2015). Regular inflows of the Nile water in late spring and early summer are evidenced by predominant diatoms of the *Aulacoseira* spp. assemblage zone (Fig. 6). They were blooming in summer, what could result in strong nitrification and high primary productivity in the lake. The lake was freshwater, slightly alkaline (pH = 7-8) and eutrophic, and due to increasing primary productivity – with more silica in late spring and summer.

9.8 – 8.6 cal ka. BP: freshwater deep lake

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

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

The laminae of clayey silt (depth 18.1 – 17.7 m) are strongly deformed, presumably due to unstable sedimentary environment. It was a short episode of increased salinity indicated by higher contents of Na^+, Ca^{2+}, Mg^{2+} and Cl^- (Fig. 5) and high frequency of Cy*prideis torosa* (Table 2), accompanied by a drop of water level. Regular inflows of the Nile water in late spring and early summer are evidenced by predominant diatoms of the *Aulacoseira* spp. assemblage (Fig. 6), blooming in summer. A distinct rise in contents of NH_4^+ occurred at the end, indicating input of washing-out from soils in the surroundings of the lake.

8.4 – 6.2 cal. ka BP: freshwater deep lake

This phase is expressed by thinly laminated clayey silts (depth 17.7 – 13.1 m), reflecting varied seasonal sediment input to the lake. Dark laminae represent winter deposition, mostly of terrigenous derivation and white laminae reflect high diatom productivity in summer (Flower *et al*. 2012; cf. Marks *et al*. 2016). Thin (0.5 mm) layers of amorphous organic matter could be deposited either during floods of the Nile or due to intensive biogenic production in the lake. An increased influx of sand from the surroundings is recorded at about 8.2 cal. ka BP (17.4 m depth) and 7.2 cal. ka BP (15.45 – 15.53 m depth). The former could reflect a climate crisis connected roughly with the 8.2 ka BP event (cf. Rohling & Pälike 2005). The sedimentation rate had been slightly rising from 2.7 to 3.7 mm a^{-1} at the beginning and reached 6.9 mm a^{-1} at the end (Fig. 4). An enhanced nutrient availability in the lake indicates regular inflows of the Nile water in late spring and early summer. Peaks of NO_3^- and NH_4^+ are due to increased content of organic matter, presumably washed into the lake from the surroundings. Diatoms of the *Aulacoseira* spp. assemblage (Fig. 6) bloomed in summer, which could result in strong nitrification, enhanced silica content and high primary productivity in the lake. The lake was slightly alkaline (pH = 7-8) and eutrophic, with a high water level. Archaeological. sites of the Neolithic Faiyum A Culture located along the shoreline prove that the lake reached its maximum extension (Fig. 8) and depth, with its water level at about 20 m a.s.l. (Wendorf & Schild 1976; Wenke *et al*. 1988). Cl^- and Na^+ were slightly decreasing in the second part of the phase (Fig. 5), suggesting a rising water level. FeS_2 formed occasionally, presumably indicating reductive conditions, but the accompanying strong nitrification allowed for high productivity in the lake.

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

Abrupt rise of Cl^-, Na^+, Mg^{2+} and Ca^{2+} and less regular lamination of lake sediments (13.1 – 11.7 m depth) indicate restricted hydrological connection with the Nile. The lake had been periodically brackish (Fig. 5) and the water level dropped significantly (cf. Baioumy *et al*. 2011). The reservoir became smaller and shallower, with predominance of *Aulacoseira* spp. assemblage (Fig. 6) but sporadic thick diatom layers in the sediments could indicate extremely huge occasional floods. Intensive influx of material from the surroundings (also from exposed older lake deposits) as is indicated by interbeds of sand and silt, slightly higher contents of NO_3^- and SO_4^{2-}, with local concentration of Fe compounds due to drying of the peripheral area. The sedimentation rate was 9.6 mm a^{-1} (Fig. 4). Human settlements in the Faiyum Oasis had disappeared but the Pharaonic civilization developed in the Nile valley in Egypt (Wendorf & Schild 1976; Hassan *et al*. 2012).

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

At the very beginning and at the end of this phase the littoral zone of the lake became restricted as mostly pelagic and oligosaprobic (mesosaprobic) *Cyclostephanos dubius* diatoms occurred (Fig. 6). Deposition of grey-brown clayey silt (11.7 – 7.9 m depth) with irregular, thick (1-5 mm) diatomite prevailed, combined with few organic laminae and ferruginous interbeds (Fig. 2). Rapid increase of terrestrial material is noted around 5.0 – 4.8 cal. ka BP. The sedimentation rate was 16.9 – 17.0 mm a^{-1} at the beginning and then rapidly increased to the maximum of 37.7 mm a^{-1} (Fig. 4), presumably due to increasing supply of material from the surroundings and the Nile. During most of this time interval (5.6 – 4.6 cal. ka BP) the lake was slightly alkaline (pH = 7-8) and eutrophic, with higher water level and wind-induced water mixing in winter. *Aulacoseira* and *Stephanodiscus* assemblages dominated, indicating intensive seasonal water circulation, enhanced nutrient availability with much P and seasonal influx of the Nile water. There was a short and weak brackish episode at about 5.1 cal. ka BP, indicated by small rises of Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, NH_4^{+}, NO_3^{-} and Cl^{-} (Fig. 5).

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

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

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

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

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

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

<1.2 cal. ka BP: shallow saline lake

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

Conclusions

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

The Faiyum Oasis has been outside the Intertropical Convergence Zone (ITCZ) in the Holocene and therefore, its lake could survive due to inflows of the Nile water during flood seasons. The latter were most regular from 9.8 to 6.2 cal. ka BP when in a deep freshwater lake, a succession of fine-laminated sediments was formed, composed mostly of diatomite, mineral and organic silt, clearly indicating a seasonal change of lake productivity. This was significantly associated with regular inflows of the Nile water during flood seasons. Southward migration of ITCZ in northeastern Africa resulted in less regular inflows of the Nile water into the Faiyum Oasis. From 6.2 to 4.4 cal. ka BP the lake deposits were less regularly laminated, the water level dropped considerably and there were gradually more frequent brackish episodes. From 4.4 to 3.0 cal. ka BP the lake was brackish and considerably less extensive, with water level at about -20 m a.s.l., the sediments were massive but with occasional inputs of sandy material washed from the surroundings due to local winter rainfalls. The episode 3.0 to 1.5 cal. ka BP was a return to occasional freshwater conditions in the lake, mostly due to a man-made canal dug at about 2.3 cal. ka BP that renewed a hydrological connection with the Nile. Then the lake was gradually turned into a brackish and finally, saline lake.

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

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Captions to the figures and tables

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

Fig. 2. Lithology of core FA-1.

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

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

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

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

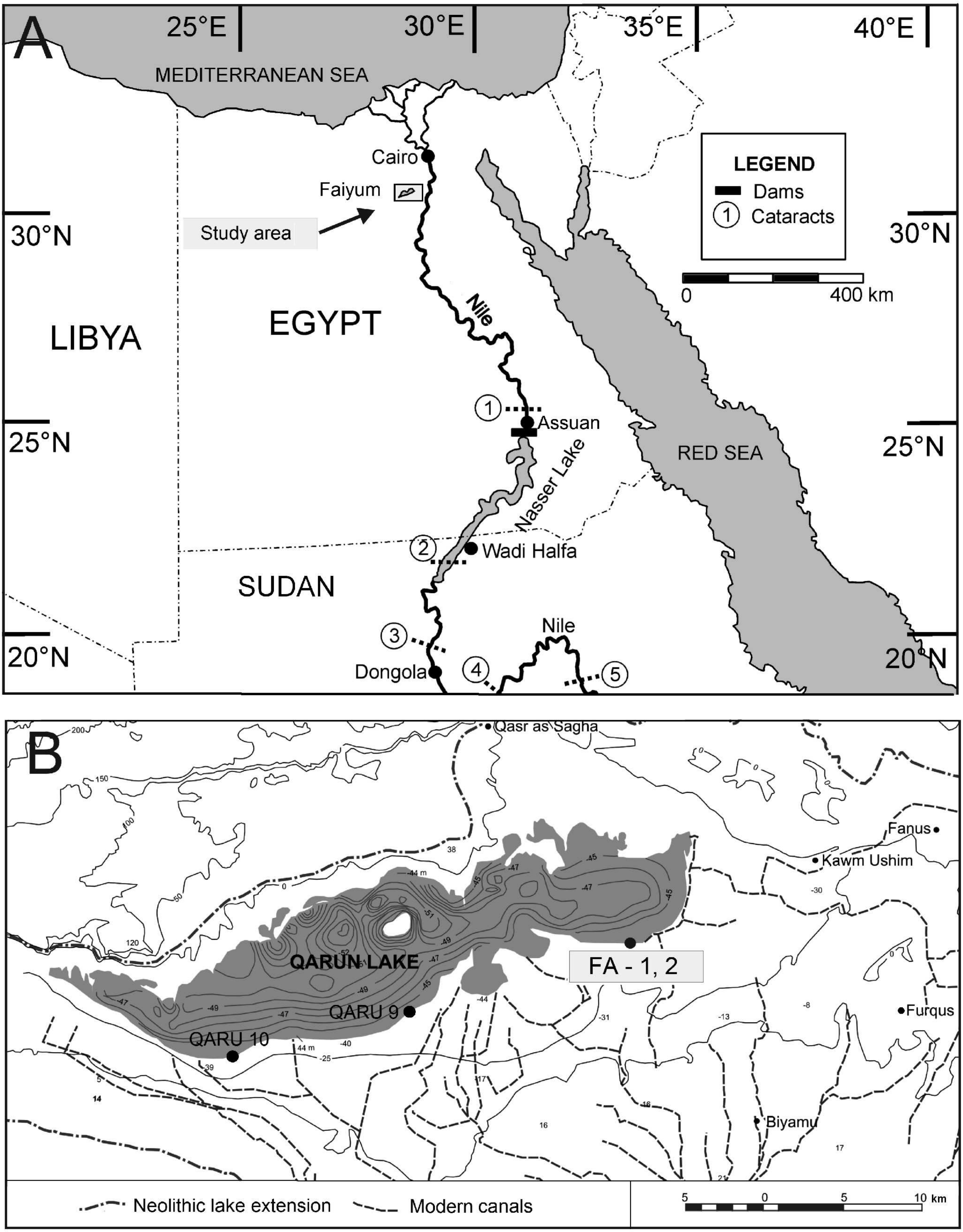
Fig. 7. Main phases of the Qarun Lake development indicated in core FA-1; for lithological description see Fig. 2.

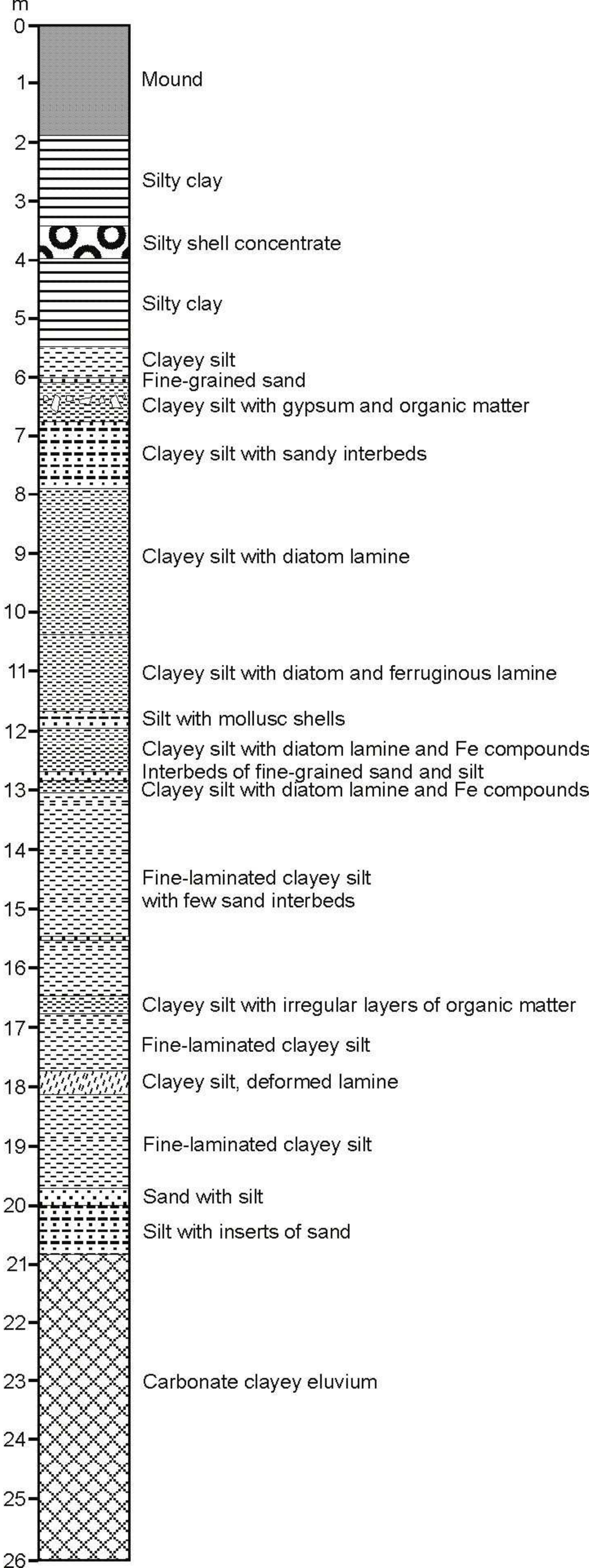
Fig. 8. Palaeogeography of the Faiyum Oasis in the Holocene with past lake extents (in dark gray); indicated are the present lakes (in black), the area above 50 m a.s.l. (in light gray) and contour lines at 0 m and -25 m b.s.l.

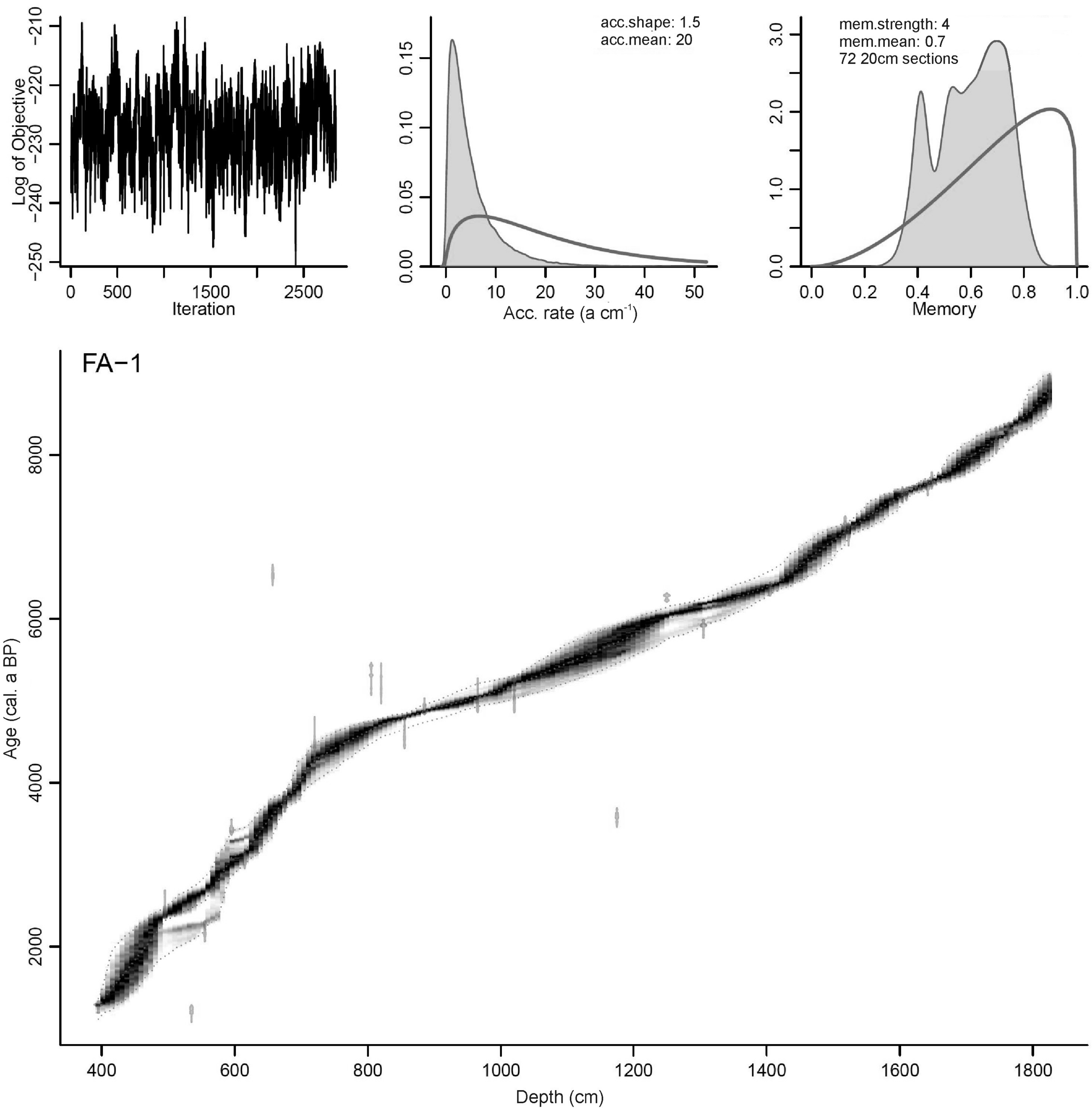
Table 1. List of radiocarbon dates in core FA-1; concentrations of organic matter are indicated but dispersed organic matter occurred in every sample. Calibrated ranges are based on Oxcal 2016 with 95.4% probability; AMS $\delta^{13}C$ values are for correcting measurement-induced fractionation and should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

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

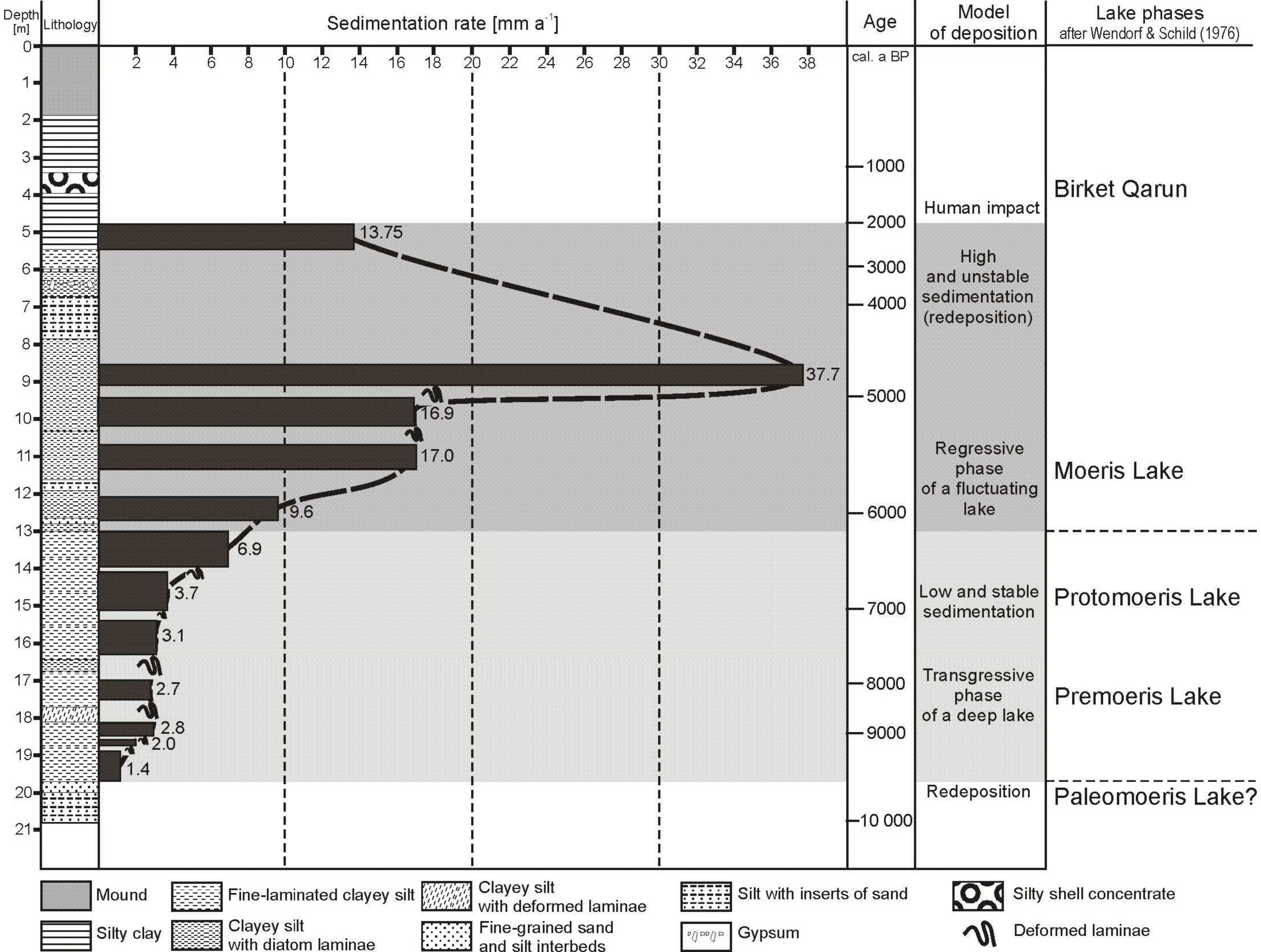
F – freshwater: *s* – stagnant water, *f* – flowing water; Sa – saltwater: *br* – brackish; *d* – shell detritus, *fr* – few fragments of shell, 2-6 – phases of the lake based on sedimentary sequence; for bivalves and ostracods a number of valves is given


A
25°E
30°E
35°E
40°E
MEDITERRANEAN SEA
Cairo
Faiyum
Study area
30°N
LEGEND
Dams
1 Cataracts
0
400 km
Nile
LIBYA
EGYPT
Assuan
25°N
RED SEA
Nasser Lake
Wadi Halfa
SUDAN
20°N
Nile
Dongola
B
Qasr as Sagha
Fanus
Kawm Ushim
QARUN LAKE
FA - 1, 2
QARU 9
QARU 10
Furqus
Biyamu
Neolithic lake extension
Modern canals
5
0
5
10 km

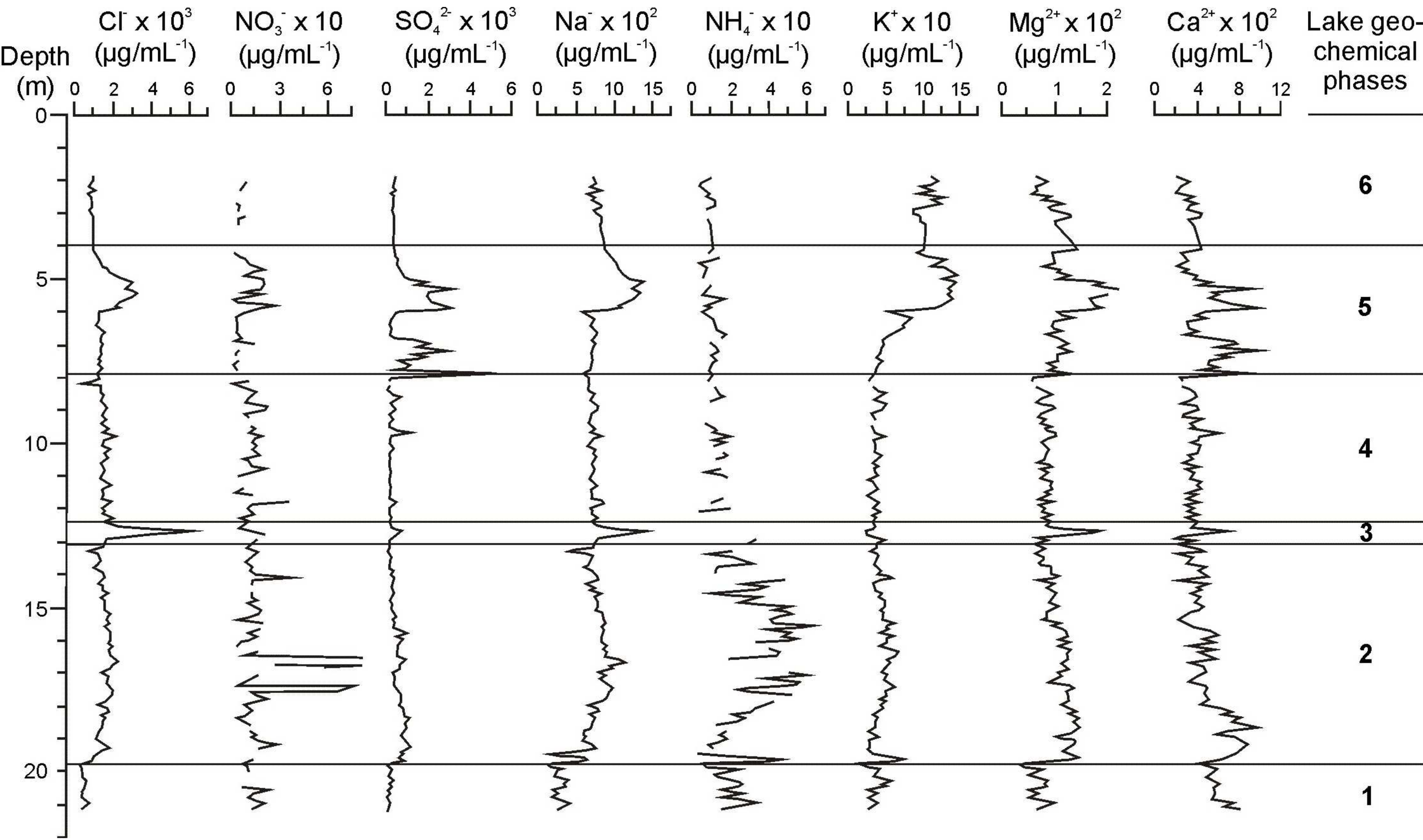

m
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
Mound
Silty clay
Silty shell concentrate
Silty clay
Clayey silt
Fine-grained sand
Clayey silt with gypsum and organic matter
Clayey silt with sandy interbeds
Clayey silt with diatom lamine
Clayey silt with diatom and ferruginous lamine
Silt with mollusc shells
Clayey silt with diatom lamine and Fe compounds
Interbeds of fine-grained sand and silt
Clayey silt with diatom lamine and Fe compounds
Fine-laminated clayey silt
with few sand interbeds
Clayey silt with irregular layers of organic matter
Fine-laminated clayey silt
Clayey silt, deformed lamine
Fine-laminated clayey silt
Sand with silt
Silt with inserts of sand
Carbonate clayey eluvium



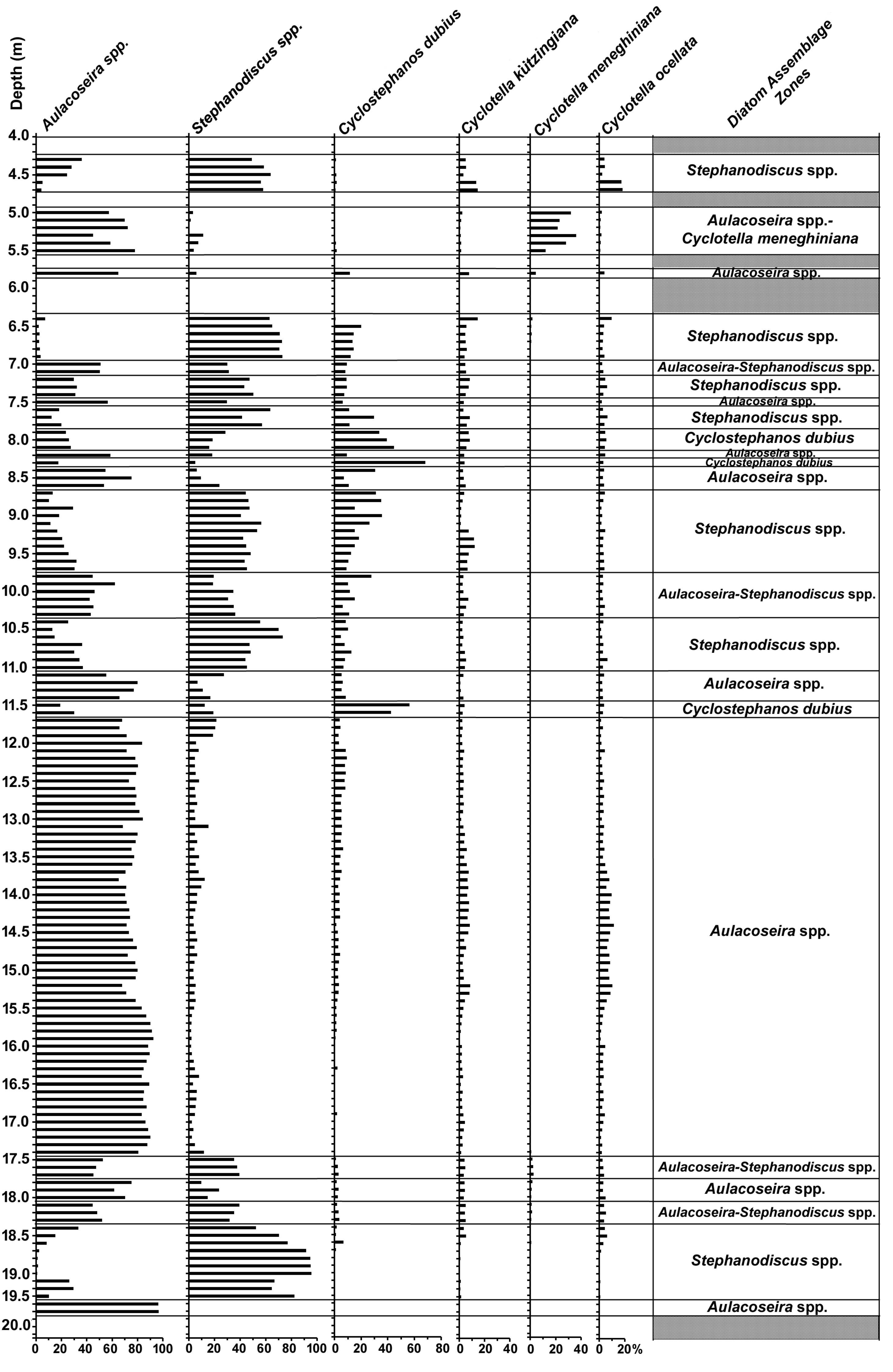
Log of Objective
Iteration
acc.shape: 1.5
acc.mean: 20
Acc. rate (a cm^{-1})
mem.strength: 4
mem.mean: 0.7
72 20cm sections
Memory
FA−1
Age (cal. a BP)
Depth (cm)



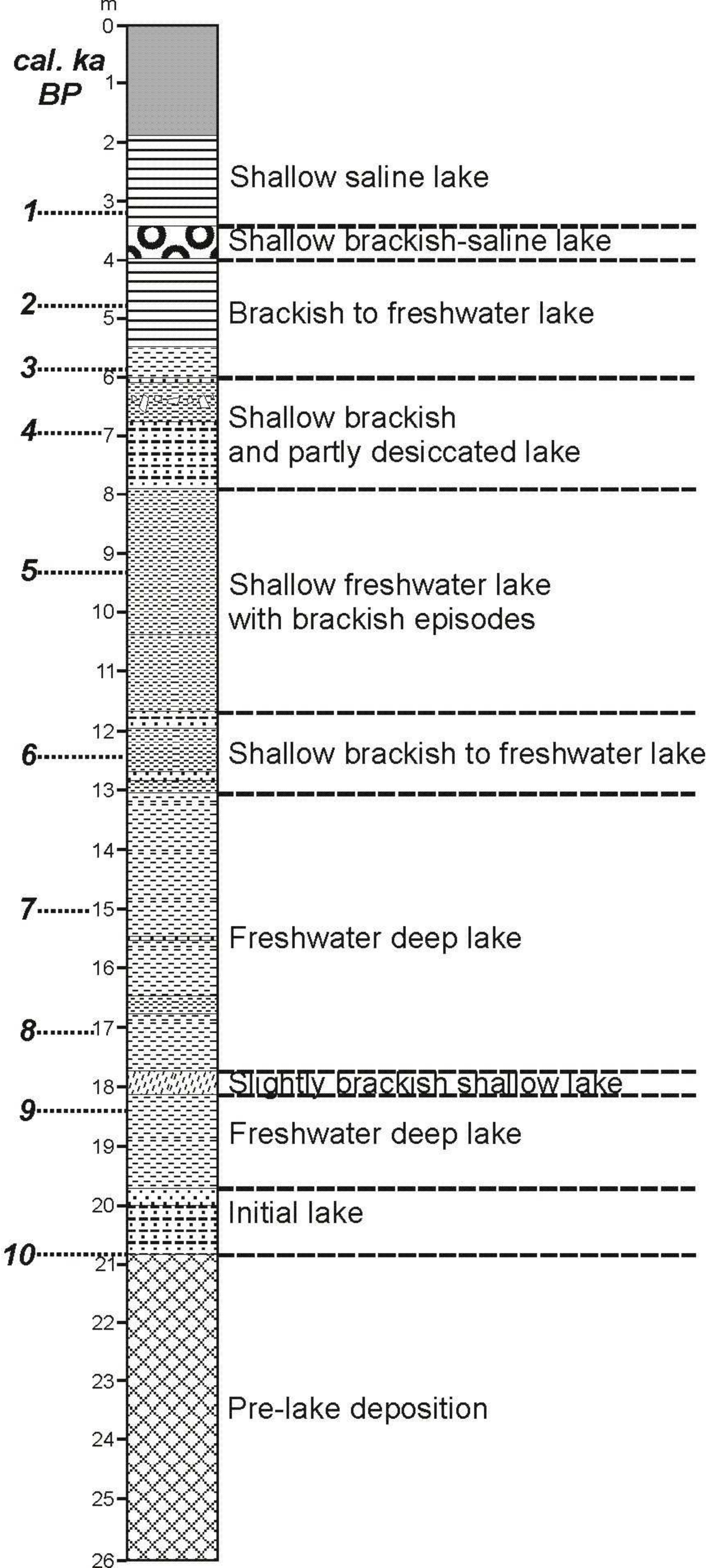
Depth [m]
Lithology
Sedimentation rate [mm a-1]
Age
cal. a BP
Model of deposition
Lake phases after Wendorf & Schild (1976)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
13.75
37.7
16.9
17.0
9.6
6.9
3.7
3.1
2.7
2.8
2.0
1.4
1000
2000
3000
4000
5000
6000
7000
8000
9000
10 000
Human impact
High and unstable sedimentation (redeposition)
Regressive phase of a fluctuating lake
Low and stable sedimentation
Transgressive phase of a deep lake
Redeposition
Birket Qarun
Moeris Lake
Protomoeris Lake
Premoeris Lake
Paleomoeris Lake?
Mound
Silty clay
Fine-laminated clayey silt
Clayey silt with diatom laminae
Clayey silt with deformed laminae
Fine-grained sand and silt interbeds
Silt with inserts of sand
Gypsum
Silty shell concentrate
Deformed laminae

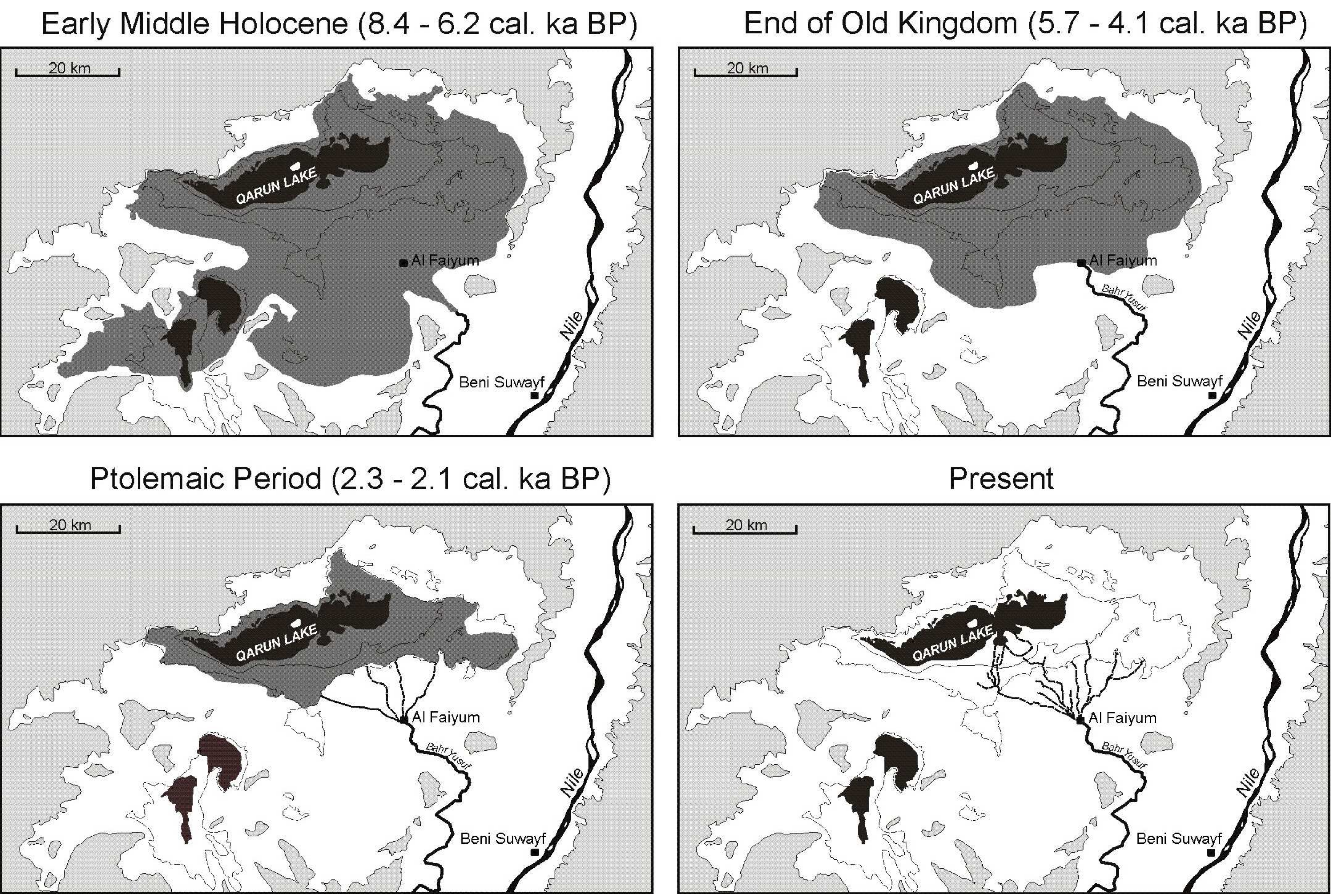


Depth (m)
0
5
10
15
20
Cl- x 10^3 (µg/mL-1)
0 2 4 6
NO3- x 10 (µg/mL-1)
0 3 6
SO4 2- x 10^3 (µg/mL-1)
0 2 4 6
Na- x 10^2 (µg/mL-1)
0 5 10 15
NH4- x 10 (µg/mL-1)
0 2 4 6
K+ x 10 (µg/mL-1)
0 5 10 15
Mg2+ x 10^2 (µg/mL-1)
0 1 2
Ca2+ x 10^2 (µg/mL-1)
0 4 8 12
Lake geo-chemical phases
6
5
4
3
2
1



Depth (m)
Aulacoseira spp.
Stephanodiscus spp.
Cyclostephanos dubius
Cyclotella kützingiana
Cyclotella meneghiniana
Cyclotella ocellata
Diatom Assemblage Zones
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0
12.5
13.0
13.5
14.0
14.5
15.0
15.5
16.0
16.5
17.0
17.5
18.0
18.5
19.0
19.5
20.0
Stephanodiscus spp.
Aulacoseira spp.-
Cyclotella meneghiniana
Aulacoseira spp.
Stephanodiscus spp.
Aulacoseira-Stephanodiscus spp.
Stephanodiscus spp.
Aulacoseira spp.
Stephanodiscus spp.
Cyclostephanos dubius
Aulacoseira spp.
Cyclostephanos dubius
Aulacoseira spp.
Stephanodiscus spp.
Aulacoseira-Stephanodiscus spp.
Stephanodiscus spp.
Aulacoseira spp.
Cyclostephanos dubius
Aulacoseira spp.
Aulacoseira-Stephanodiscus spp.
Aulacoseira spp.
Aulacoseira-Stephanodiscus spp.
Stephanodiscus spp.
Aulacoseira spp.
0 20 40 60 80 100
0 20 40 60 80 100
0 20 40 60 80
0 20 40
0 20 40
0 20%


m
cal. ka BP
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
1
2
3
4
5
6
7
8
9
10
Shallow saline lake
Shallow brackish-saline lake
Brackish to freshwater lake
Shallow brackish
and partly desiccated lake
Shallow freshwater lake
with brackish episodes
Shallow brackish to freshwater lake
Freshwater deep lake
Slightly brackish shallow lake
Freshwater deep lake
Initial lake
Pre-lake deposition


Early Middle Holocene (8.4 - 6.2 cal. ka BP)
20 km
QARUN LAKE
Al Faiyum
Beni Suwayf
Nile
End of Old Kingdom (5.7 - 4.1 cal. ka BP)
20 km
QARUN LAKE
Al Faiyum
Bahr Yusuf
Beni Suwayf
Nile
Ptolemaic Period (2.3 - 2.1 cal. ka BP)
20 km
QARUN LAKE
Al Faiyum
Bahr Yusuf
Beni Suwayf
Nile
Present
20 km
QARUN LAKE
Al Faiyum
Bahr Yusuf
Beni Suwayf
Nile