

## Diatom assemblage variations in the Aral Sea core C2/2004 over the past two millennia

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**Abstract:** This study assesses changes in the environmental conditions in Chernyshov Bay (northern part of Aral Sea Western Basin) during the last ~2 ky from geochemical and diatom analyses of sediment core C2/2004. Comparison of fossil assemblages with the contemporary distribution of diatoms in the Aral Sea suggests that considerable changes occurred in water level as well as salinity. Deposits with high diatom concentrations and dominance of the marine species *Actinocyclus octonarius* EHRENBURG are interpreted as periods of high water level, whereas replacement by *Tryblionella compressa* (BAILEY) BOYER is considered to indicate lake level fall. On the other hand sediments with low diatom concentration represent higher freshwater input and therefore salinity decrease. This interpretation is supported by estimates of siliciclastic and chemogenic sediment components. A chronology of major lake stages is derived and roughly agrees with recent findings from other studies.

**Key words:** *Actinocyclus octonarius*, arid region, CEC, central Asia, lake level changes, multi-proxy reconstruction

### Introduction

The water level of endorheic lakes such as Aral Sea strongly depends on the riverine inflow. As the lake level rises and falls, many changes occur in both biological (lake productivity, species diversity and assemblages) and inorganic (salinity, presence/absence of precipitates, amount of allochthonous particles including clay minerals and nutrients) characteristics of the water column that are traceable later-on in the sedimentary record. Changes in the level of Aral Sea have been estimated from sedimentary cores (LE CALLONEC et al. 2005, SORREL et al. 2006), archaeological excavations (BOROFFKA et al. 2006), morphological features (REINHARDT et al. 2008), and historical documents (BOOMER et al. 2000). The lake regression in the last 50 years is well documented: the lake level has fallen by more than 23 m (ZAVIALOV 2005) and salinity increased from 10 ‰ (MIRABDULLAYEV et al. 2004)

to more than 100 ‰ (SAPOZHNIKOV et al. 2009) in the Western Basin. At least from 1853 until 1961, the Aral Sea had been a relatively stable water body with secular variations of the water level less than 3 m (KAWABATA et al. 1997). Studies of earlier lake-level changes generally agree on 3–4 major regression phases in the last 2 ky (BOOMER et al. 2009). Among others, variable reworking of carbon complicates age-model construction, thus contributing to considerable chronological uncertainty.

Several studies on recent diatom assemblages from various parts of Aral Sea have been published. Most authors (e.g., KAWABATA et al. 1997, MIRABDULLAYEV et al. 2004) merely related diatom assemblage composition to salinity as the principle steering variable. According to MIRABDULLAYEV et al. (2004) species diversity and productivity of the biological communities decreased at the transition from oligosaline to hypersaline conditions. So far, SAPOZHNIKOV

et al. (2009) provide the most comprehensive study, including a comparison of water column and sediment samples from many sites. They have found discrepancies between published salinity demands of certain diatom species and their abundance in hypersaline conditions. In addition, they illustrate the importance of water depth for the composition of diatom communities. These studies allow us to understand better what happened during the last lake regression as well as in the more remote past. However, current analogues for transgressive phases or a stable lake level are not available.

The only study on fossil diatom assemblages in the Aral Sea of the last 1.6 ky was reported by AUSTIN et al. (2007). Using a salinity training set derived from the European Diatom Database, they obtained a paleoconductivity reconstruction for a core from Chernyshov Bay about 25 km NW from C2/2004. Their results were reconsidered soon after publication (BOOMER et al. 2009) their salinity reconstruction was confounded by changes in basin morphology with falling level. BOOMER et al. (2009) reviewed most data from Aral Sea and concluded in four major regressive phases in Aral Sea over the past 2000 years correlative with climate signals occurring at approximately: AD 0–400, AD 900–1350, AD 1500–1650 and AD 1800 to today.

We aim to trace the main diatom-assemblage changes during the last 2 ky in this part of the Aral Sea from an additional sediment core, and in combination with geochemical data, reconstruct lake-level variations in the light of observations from the last 50 years.

## Materials and methods

### Core C2/2004

The core C2/2004 from Chernyshov Bay, northern part of western Aral Sea, was retrieved from water depth of ~ 3 m (NOURGALIEV et al. 2007). It consists of 4.3 m of rather homogenous clayey sediment with some variation in organic content and laminae of organic matter, and chemogenic precipitates (Fig. 4). Laminations are absent in the organic-poor intervals at depths of 87–104 cm and 210–305 cm. Mollusc shells (mostly *Cerastoderma* spp., *Caspihydrobia* spp., and *Dreissena* spp.) and algal remains are confined to organic-rich layers.

The age model is based on 8  $^{14}\text{C}$  dates obtained by accelerator mass spectrometry in Poznań Radiocarbon Laboratory, Poland (Table 1). Most of the dates are from mollusc shell carbonate; those from 204 and 290–298

cm depth originate from mechanically separated algal filaments. The  $^{14}\text{C}$  ages were converted to conventional calendar ages using OxCal4.0 (BRONK RAMSEY 2005). All data points are almost linearly distributed between the top and ~305 cm, where a sedimentary discontinuity and/or reworked sediments occur. Our age model (Fig. 4) was constructed by linear interpolation with forced value at the year 2000 AD at the core top. Only one  $^{14}\text{C}$  point of the inverted date obtained from a carbon fragment of unknown origin at the depth 254–256 cm was discarded. The total error of ages in our age model should be below 200 years. ( $3\sigma$  radiocarbon data error plus regression uncertainties).

### Diatom analysis

0.1 g of sediment sampled at 0.5–4 cm intervals was stirred with distilled water and on average 350  $\mu\text{l}$  of divinylbenzene microspheres (mean concentration  $6.18 \times 10^6$  g/l) were added to calculate diatom valve concentration (GRYGAR et al. 2006, 2007). Samples were settled onto coverslips and allowed to dry before mounting on slides using Naphrax<sup>TM</sup>. Diatom species were counted at 1000x magnification using an Olympus BX40 optical microscope. We counted 300 valves per sample if the preservation of frustules was high enough; otherwise we scanned the 2 cm line 3 times in different levels resulting in some cases in only 50 counted valves. Small *Cyclotella* species were not separated. The percentage of the less abundant or unidentified species was less than 12 % of the total counted diatoms. Identification was based on publications of KRAMMER & LANGE-BERTALOT (1986–1991), ÇELEKLI (2006), and YIM & LI (2000), considering the species listed by AUSTIN et al. (2007) (Fig. 1). Salinity preferences are according to the KOLBE (1927)–HUSTEDT (1937–39) salinity system taken from SCHRADER & GERSONDE (1978) (Fig. 3).

Table 1. Radiocarbon ages of the core. C2/2004, Chernyshov Bay.

Depth [cm]	$^{14}\text{C}$ Age [years BP]	Calibrated age [AD]	Funding
7.5	112.8 [pMC]	modern	EU-INTAS
112–115	775 $\pm$ 30	1215 to 1281	GA AS CR
125–126	915 $\pm$ 30	1031 to 1206	GA AS CR
204	1400 $\pm$ 30	590 to 670	GA AS CR
207–208	1415 $\pm$ 30	584 to 663	GA AS CR
254–256	3080 $\pm$ 70	–1496 to –1136	GA AS CR
290–298	1820 $\pm$ 40	85 to 323	GA AS CR
316–318	4875 $\pm$ 35	–3750 to –3538	GA AS CR

### Chemical analysis

The proxy of the content of the siliciclastic component was estimated by measuring cation exchange capacity using  $[\text{Cu}(\text{trien})]^{2+}$  (MEIER & KAHR 1999, GRYGAR et al. 2005, GRYGAR et al. 2009). The method gives a quantitative estimate of expandable clay mineral structures, water soluble components, particularly gypsum and part of the calcium carbonates. The analysis was performed by extraction of a subsample of dried and ground sediment by aqueous solution of  $[\text{Cu}(\text{trien})]^{2+}$  complex (trien: 1,4,7,10-tetraazadecane) and analysis of Cu cations remaining after sorption by expandable cations and Ca and Mg cations evolved to solution by ion exchange and by plain dissolution. Cu and Mg concentration was determined by atomic absorption spectroscopy and Ca by atomic emission spectroscopy using AAS3 spectrometer (Zeiss Jena, Germany).

## Results

### Mineral composition

Chemical analysis produced estimation of the allochthonous clay minerals, which are “diluted” by two types of autochthonous sediment fractions: chemogenic (gypsum and part of calcium carbonates) and biogenic (major part of calcite and aragonite, mostly mollusc and ostracod shells, and organic matter, mostly various algae). Because the large distance of any river mouth and low sedimentation rate we expect that amount of allochthonous organic matter is insignificant. The cation exchange capacity (CEC) depth profile (Fig. 4) traces the most important changes in bulk sediment composition. Highest CEC values occur at 72–108 cm, 155–265 cm and 320–340 cm depth. Gypsum layers, indicating periods of lake level fall, are present at 0–17, 149–153, 354, 368, 388, and 420–424 cm.

### Diatom concentration and organic remains

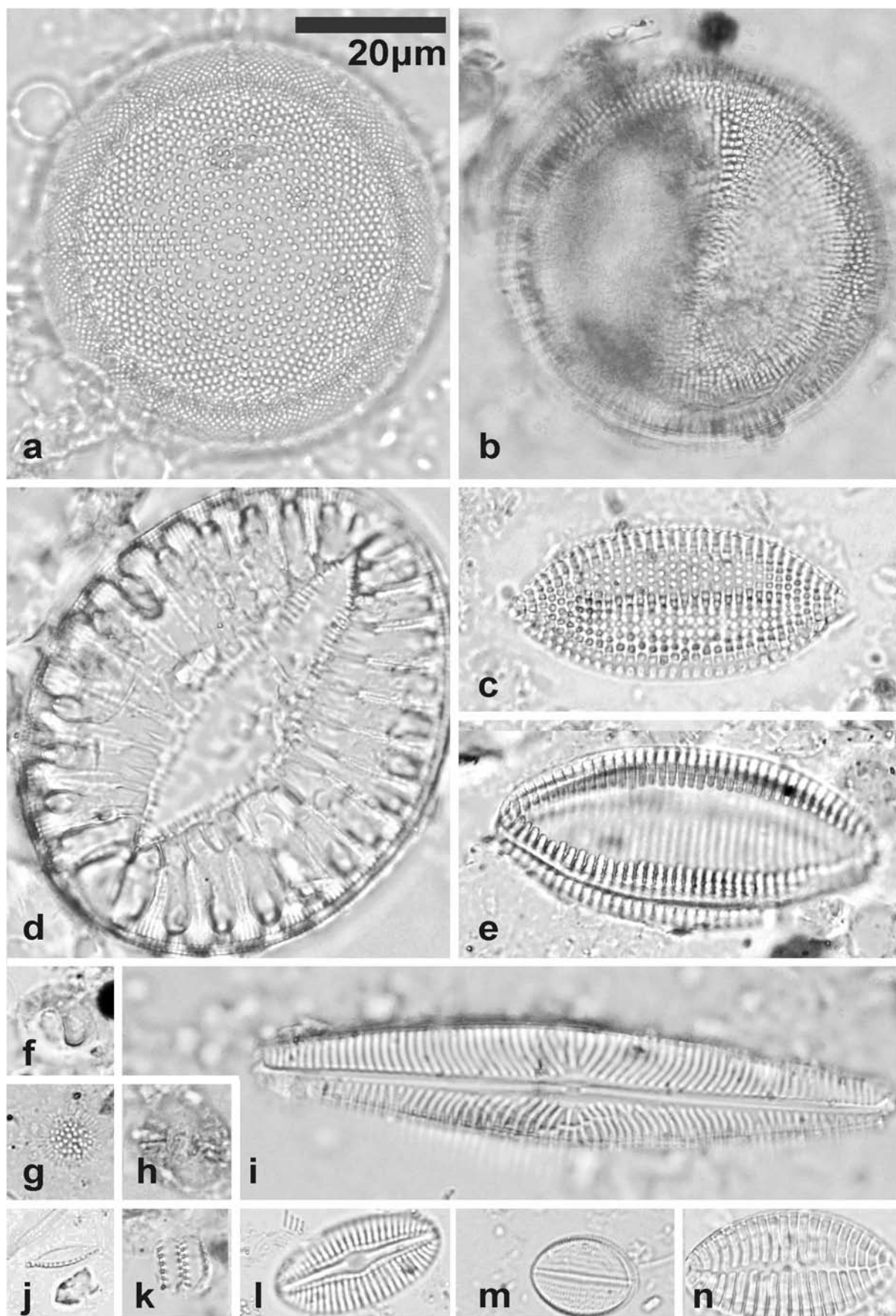
We distinguished 11 diatom assemblage zones (DAZ) according to the total diatom concentration changes and major changes in the diatom species composition (Fig. 3). Lowered diatom concentrations ( $<2 \times 10^6/\text{g}$ ), absence of water plant remains and few mollusc shells are observed at the top of the core (0–15 cm), and at 52–98, 125–150 and 220–300 cm depth. This corresponds roughly to DAZ 1, 3, 5, 8, and 9 (Fig. 3). Importantly, sediment lamination is absent (DAZ 3, 8, and 9) or only faintly visible (DAZ 1, and 5). This may be due to increased bioturbation by nematodes, which are nowadays most common in deeper,

moderately oxic bottom environments (MOKIEVSKY 2009) or by increased water turbidity.

Periods of high biological activity appears to be reflected at depths of 16–51, 99–124, 151–219, and 301–432 cm, corresponding to DAZ 2, 4, 7, 10, and 11 as evidenced by a gradually increasing diatom concentrations, appearance of mollusc shells, and increased amounts of water plant fragments, forming distinct laminae. The highest concentration of diatoms ( $\sim 9 \times 10^6/\text{g}$ ) is observed in DAZ 4 and coincides with massive accumulation of mollusc and ostracod shells.

### Diatom assemblage changes

In total we counted diatom assemblages of 141 samples, 110 diatom intraspecific taxa has been recognized. Most of the observed species are alkaliphilous and eutraphentic according to VAN DAM et al. (1994). However, the species composition differs markedly between DAZ 1–10 and DAZ 11 (Figs 3–4). In the upper 3 m of the core, planktonic diatoms preferring higher salinities, mainly *Actinocyclus octonarius* EHRENB. (Fig. 1a) and *Cyclotella* spp., are dominant whereas in the lower part of the core smaller, mainly tychoplanktonic sessile and bottom-dwelling species (*Cocconeis placentula* EHRENB. (Fig. 1m), *Nitzschia sigma* (KÜTZ.) GRUNOV, *Nitzschia fonticola* GRUNOV (Fig. 1j), *Opephora krumbeinii* WITKOWSKI (Fig. 1k) with mixed salinity demands prevail (Fig. 3). Diatoms that are generally considered to be oligohalobous (*C. placentula*, *N. fonticola*) and are frequently used as indicators of low salinity presently occur in the Aral Sea at salinities exceeding 100 ‰ (SAPOZHNIKOV et al. 2009). Therefore, their abundance may be controlled by factors other than salinity. According to VAN DAM et al. (1994), *N. fonticola*, which is common in DAZ 11 indicates well oxygenated water ( $>75\%$  saturation) and lower nutrient levels. DAZ 10 (298–315 cm) is the only one dominated by *Grammatophora marina* LYNGBYE (Fig. 2o), which indicates warm and highly saline shallow water with low nutrient availability (MUNDA 2005, RESENDE et al. 2007). In DAZ 9, *G. marina* is replaced by a *Diploneis smithii* (BRÉB.) CLEVE (Fig. 1l) which has a lower salinity tolerance (SCHRADER & GERSONDE 1978) and the mesohalobous plankton diatom *Thalassiosira lacustris* (GRUNOV) HASLE (Fig. 1b). The other zones with higher diatom concentration (DAZ 2, 4, 7) show a dominance of *A. octonarius*. The salinity range of this species is wide, e.g. its reported optimum varies from



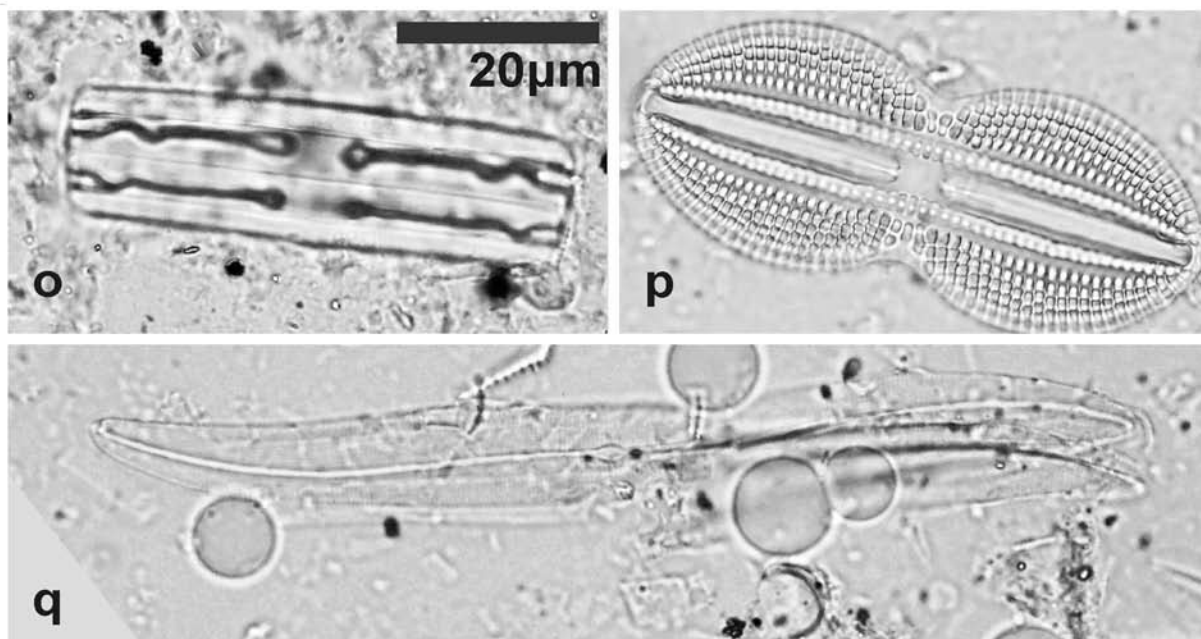


Fig. 2. (o) *Grammatophora marina*; (p) *Diploneis bombus*; (q) *Pleurosigma salinarum*.

Fig. 1. Images of the most common diatom species in our core from optical microscopy: (a) *Actinocyclus octonarius*; (b) *Thalassiosira lacustris*; (c) *Tryblionella compressa*; (d) *Surirella fastuosa*; (e) *Nitzschia navicularis*; (f) *Cyclotella choctawhatcheeana*; (g, h) *Cyclotella* sp.; (i) *Navicula digitoradiata*; (j) *Nitzschia fonticola*; (k) *Opephora krumbeinii*; (l) *Diploneis smithii*; (m) *Cocconeis placentula*; (n) *Nitzschia cocconeiformis*.

36 ‰ (WOOD 1973) to ~ 100 ‰ (SAPOZHNIKOV et al. 2009). *A. octonarius* is also typical in other regions for autumn bloom (WASMUNDL et al. 1996; GROMISZ & SZYMELFENIG 2005), higher amount of nitrates (RESENDE et al. 2007) and low temperature optimum (~13.5 °C) (RESENDE et al. 2007; SAPOZHNIKOV et al. 2009). High abundances of *Navicula digitoradiata* (GREGORY) RALFS (Fig. 1i) and *Diploneis bombus* (KÜTZ.) CLEVE (Fig. 2p) are observed in DAZ 2 and DAZ 7. These species are common in salt marshes along many marine coasts (e.g. SAWAI et al. 2004, WILSON et al. 2005).

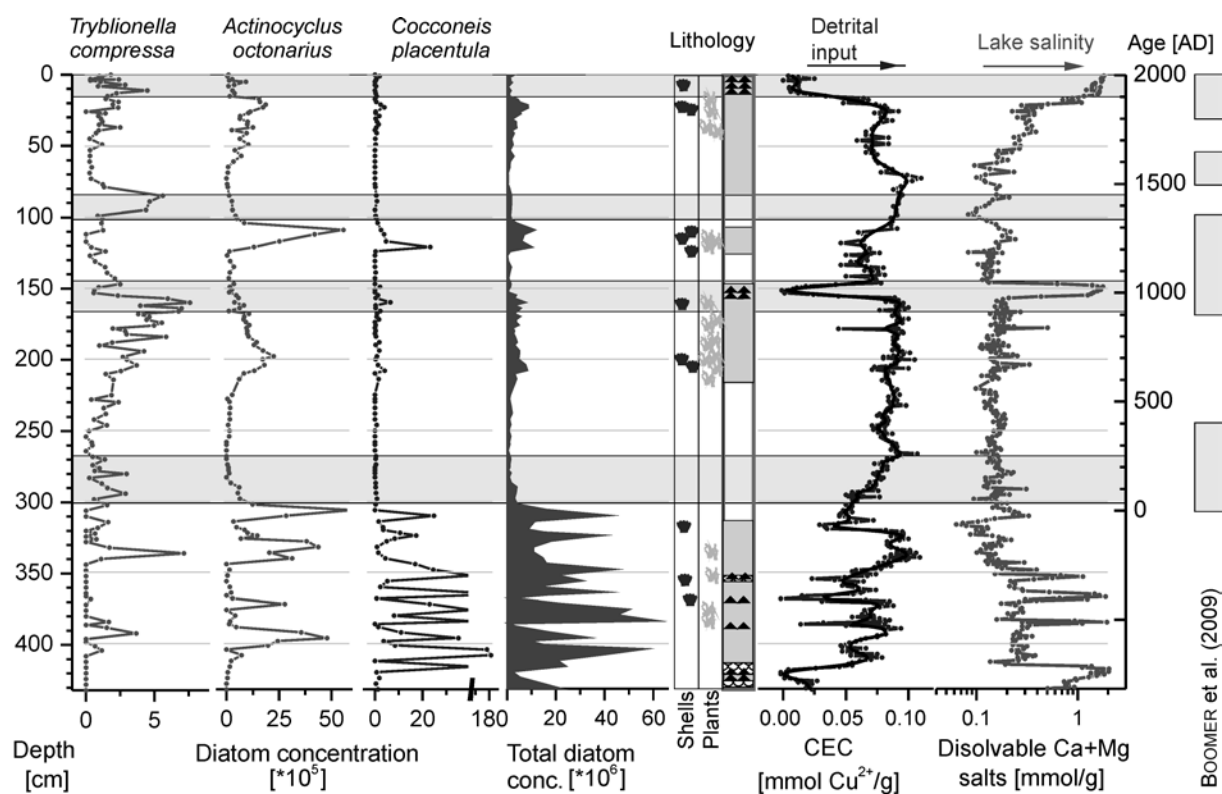
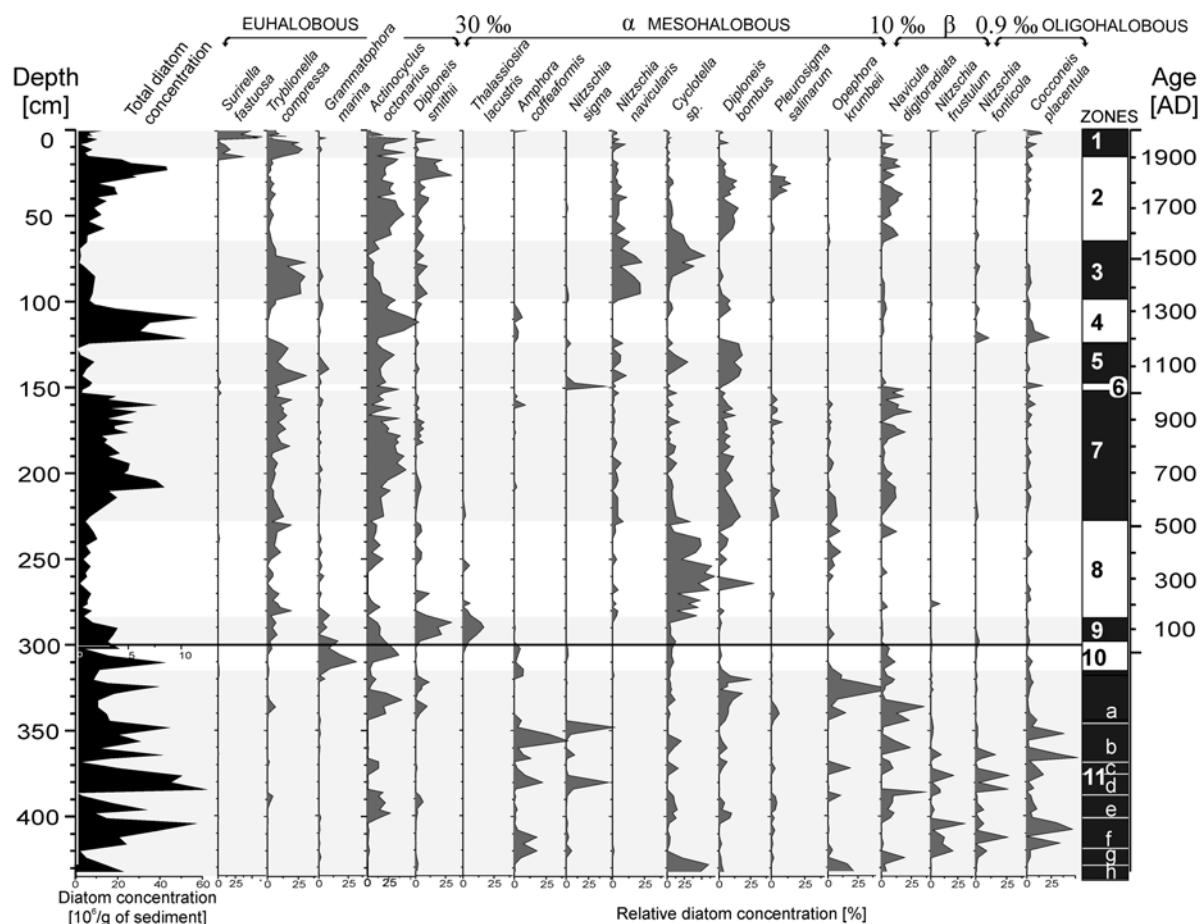
DAZ 1, 3, 5, 6, and 8 present low diatom concentrations, often agreeing with a high relative abundance of *Cyclotella* spp. (DAZ 3, 5, 8). The concentration of these species remains almost the same throughout the core, therefore their dominance points rather to selective dissolution of less resistant diatom frustules or environmental conditions which are unfavourable for growth or deposition of other taxa. In the lower part of DAZ3 there is high abundance of *Tryblionella compressa* (BAILEY) BOYER (Fig. 1c) and *Nitzschia navicularis* (BRÉB. ex KÜTZ.) GRUNOW (Fig. 1e), which are both common in contemporary tidal

flats (e.g. SAWAI et al. 2004; WILSON et al. 2005). RESENDE et al. (2007) found that in Portugal coastal waters these species differ by salinity and temperature optima. *Cyclotella* spp. are dominant only in the upper half of the zone. DAZ 6 is a very short period of the high abundance of *N. sigma* and *C. placentula*. DAZ 1 has exceptionally high concentration of *Surirella fastuosa* EHRENB. (Fig. 1d) which is recently dominant in Western Basin at salinities exceeding 130 ‰ (SAPOZHNIKOV et al. 2009). *D. smithii*, *T. compressa*, and *S. fastuosa* represent an assemblage common on tidal flats (e.g. SAWAI et al. 2004).

## Discussion

### Sediment chemistry

Periods of strongest siliciclastic input, as indicated by the highest CEC values, are likely to correspond with increased influx of river water and stronger dilution of lake water preventing preservation of carbonate shells, or to highstand preventing deposition of shells in the study site. If lake bioproductivity was high and siliciclastic input – relatively low, CEC of the sediment



decreases due to the increased concentration of calcium carbonates and organic material. This appears to have been the case during DAZ 2 and 4. CEC is in its minimal values whenever dissolved Ca+Mg cations are maximal as gypsum starts to precipitate. Such events in last 2 ky are dated at 1900–2000, and 970–1050 AD. The third most remarkable CEC minimum corresponding to apt. 0–250 AD has not been explained by gypsum or organic matter but some other yet unestablished chemogenic precipitate is probably present.

### Interpretation of the diatom record

In deposits corresponding to the last 1.6 ky we found much lower diatom concentrations and substantially different assemblages from those reported by AUSTIN et al. (2007). They described a dominance of small benthic species (*Amphora pediculus* (KÜTZ) GRUNOW, *N. fonticola*, *Karayeva clevei* GRUNOW) which occur rarely in DAZ 1–10 of C2/2004. However, similarities exist between both records with regard to the abundance of large planktonic species (*A. octonarius*, and *Thalassiosira* sp.). The most remarkable correlation feature of these two cores is the maximum of *A. octonarius* concentration centred at the 109 cm, dated at 1290 AD, which correlates with a single maximum of this species shown by AUSTIN et al. (2007) at 490 cm (1310 AD according to their chronology). Less evident is the correlation of a high abundance of *Thalassiosira* spp. in their core centered at 420 AD and at 115 AD in ours. Nevertheless, given the dating uncertainty these peaks may well be coeval, as well.

Crucial for understanding of the diatom assemblage is the interpretation of the *A. octonarius* abundance. This species is mainly abundant when the sediment contains a very high diatom concentration that point to a relatively

low dissolution rate of the frustules within the water column. Although *A. octonarius* is a marine diatom it was a dominant species in the Aral Sea in 1960 (MIRABDULLAYEV et al. 2004). SAPOZHNIKOV et al. (2009) pointed to the dependence of diatom assemblage composition on water depth. They observed that *A. octonarius* is abundant in the Western Basin today, but that it does not occur where water depth is less than 10 m and reaches its highest abundance in sediments in a depth of 20 m. Similar observation were published by WOOD (1973), who reported preferred *A. octonarius* depth range of 20–130 m. With abundance of *A. octonarius* should also correlate low oxygen periods which are apparently influenced by mixing dynamics because recently it has been found to survive anoxia (SAPOZHNIKOV et al. 2009). Based on the observations of SAPOZHNIKOV et al. (2009) we interpret the replacement of *A. octonarius* by *T. compressa* repeated in DAZ 1–2, 3–4, and 7 as a lake level fall. This interpretation is supported by gypsum layers that occur in DAZ 1 and *T. compressa* is then followed by the reduction of diatom concentration and a relatively high abundance of *Cyclotella* spp. (DAZ 3 and 5) and *S. fastuosa* (DAZ 1). The bloom of *S. fastuosa*, which we captured in DAZ 1, was reported by SAPOZHNIKOV et al. (2009) in the last decade. This observation confirms that the topmost part of our core represents the most recent period of sedimentation.

### Past lake level changes

In DAZ 1 corresponding to ~1900–2000 AD (error max. 200 years) and representing the latest phase of regression (last 50 years), we observed high abundances of *T. compressa* as the end of the succession described above and later dominance of *S. fastuosa* connected with a low total diatom concentration accompanied by a high concentration of gypsum. Similar conditions within the core were dated 1330–1450 AD and 910–1060 AD (error max. 200 years) although a gypsum layer was only formed during the latter period. During 0–250 AD was probably other lake level regression phase because of minimal CEC values.

A stable lake level between 1960 and at least the beginning of the 19<sup>th</sup> century is reflected by the highest diatom concentrations (*A. octonarius* dominance), laminated sediments, and variable amount of chemogenic precipitates, mainly carbonates. Therefore high total diatom

Fig. 3. Diatom concentrations and relative abundance of euhalobous, mesohalobous ( $\alpha$ ,  $\beta$ ), and oligohalobous species that occurred with an abundance of > 20% in more than one sample, as well as *Pleurosigma salinarum* and *Thalassiosira lacustris*. Note the change in scale of total diatom concentration at 300 cm.

Fig. 4. Total diatom concentrations, concentrations of *Tryblionella compressa*, *Actinocyclus octonarius* and *Cocconeis placentula*, simplified core lithology (dark triangles = gypsum layers, white rectangles = absence of laminations) and CEC results plotted against depth and age. Low lake-level periods are shaded and for comparison see on the right side the chronology of regression phases by BOOMER et al. (2009).



concentrations at 1600–1900, 1200–1330, and 525–910 AD (error max. 200 years) are likely to represent high lake-level stages.

The phases with low diatom concentrations are more difficult to interpret. Prevalence of *Cyclotella* spp. coinciding with low biological productivity could prove a low nutrient availability and/or turbidity increase. During these periods formation of autochthonous precipitates was minimal and consequently CEC high so we can assume that these stages represent more or less intensive transgressive phase when salinity decreased. According to this interpretation transgression phases occurred in the following periods: 1450–1600, 1060–1200, and 250–525 AD (error max. 200 years). These lake level phases are in general agreement with a recent review of the evidence on Aral Sea lake-level changes by BOOMER et al. (2009) (Fig. 4).

#### Acknowledgements

We are grateful to anonymous reviewer for his constructive comments and English corrections. We would like to thank Danis K. Nourgaliev from Kazan State University, Kazan, Tatarstan, Russia for providing core C2/2004 with a Mackereth (MACKERETH 1958) type hydraulic corer. We are very grateful to Vladimír Piška for his excellent database which facilitated the evaluation of the diatom results. CEC analyses were performed by Jana Dörflöová and Petr Vorm. Funding of the work by the Grant Agency of Academy of Sciences of the Czech Republic (KJB300320901) is kindly acknowledged. One  $^{14}\text{C}$  analyses were funded by EU–INTAS (CLIMAN project).

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*Received April 25, 2009*

*Accepted May 25, 2009*