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Reconstructing Holocene environmental change in Lake Ohrid (Macedonia/Albania) using diatom as proxies

Реконструкција на еколошките промени во Охридското Езеро во текот на Холоцен со употреба на дијатомеите како индикатори

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Lake Ohrid with its Tertiary origin and outstanding biodiversity and endemism represents a unique ecosystem containing valuable data for palaeoenvironmental reconstruction. Investigation of the time sequence of the Last glacial–interglacial transition and the Holocene epoch in the sediment core Co1202 (359–17 cm depth, ca. 14.6–0.3 ka BP) was performed. Diatom proxies were used to reconstruct environmental and climate changes preserved in the investigated time interval. Two major diatom biostratigraphic zones were recognized, comprising DZ 1 (359–158 cm depth, ca. 14.6–3.9 ka) and DZ 2 (158–17 cm depth, ca. 3.9–0.3 ka). Evidence for rapid climate events within these zones was also explored. The diatom response to the colder climate intervals is evidenced by the domination of the hypolimnetic, endemic species *Cyclotella fottii*. Warmer climate conditions are represented by increased dominance of the thermophilic taxon *Cyclotella ocellata*. The analysis is currently made at a relatively low temporal resolution; we also present evidence for short-lived shifts in diatom species assemblage composition which may represent climate disruptions between ca. 9–8 ka BP and ca. 6–5 ka BP, possibly linked to abrupt global climate events. Finally, evidence of increased phosphorus levels compared to the Last Interglacial is suggested by the first appearance during the Holocene of mesotrophic *Stephanodiscus* taxa.

Key words: *Lake Ohrid, diatoms, Holocene, Rapid Climate Change, eutrophication.*

Охридското Езеро со претпоставената Терциерна старост и исклучителниот биодиверзитет и ендемизам кои ги поседува, претставува уникатен екосистем во кој се зачувани податоци, значителни за спроведување на реконструкција палеоеколошките промени. Истражувањето е реализирано на временската секвенца која го опфаќа Последниот глацијален – интерглацијален премин и Холоценската епоха во корот Co1202 (359–17 cm длабочина, 14.6–0.3 ka ПС). Притоа, дијатомеите (*Bacillariophyceae*) се користени како индикатори за реконструкција на еколошките и климатските промени во истражуваниот временски интервал. Во текот на анализите, утврдени се две главни дијатомејски биостратиграфски зони ДЗ 1 (359–158 cm длабочина, 14.6-3.9 ka ПС) и ДЗ 2 (158–17 cm длабочина, 3.9–0.3 ka ПС). Дополнително, во рамки на овие зони е анализирано и евентуално присуство на докази за рапидните климатски промени кои се случувале во истражуваниот период. Одговорот на дијатомејските заедници кон климатските интервали со пониски температури е евидентирано преку доминацијата на хиполимнетичкиот, ендемичен вид *Cyclotella fottii.*Спротивно, климатските интервали со повисоки температури се претставени со зголемена абундантност на термофилниот таксон

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Cyclotella ocellata. Истражувањето е со релативно ниска временска резолуција; дополнително претставени се докази за краткотрајни промени во составот на дијатомејските заедници кои би можеле да претставуваат резултат на климатска нестабилност во временските интервали од 9–8 ka ПС и од 6–5 ka ПС, кои се најверојатно во корелација со рапидните климатски промени на глобално ниво. За крај, зголемено ниво на фосфор во езерото, во споредба со последниот интерглацијален период е индицирано со присуството на мезотрофни таксони од родот *Stephanodiscus,* кои за прв пат се појавуваат во текот на Холоцен.

Клучни зборови: *Охридско Езеро, дијатомеи, Холоцен, рапидни климатски промени, еутрофикација.*

Introduction

The Quaternary geological period, conventionally thought of as the last ca. 2.5 million years, has been dominated by cycles of glaciation with a periodicity of approximately 23 ka, 41 ka and 100 ka (Imbrie et al. 1993). These cycles appear to be largely determined by astronomical forcing, as first proposed by Milankovitch (Coope 2004). 100 ka of orbital eccentricity has dominated the climate variations in the high latitude North Atlantic during the Brunhes magnetic chron (0.000–0.735 Ma BP) and earlier, during the Matuyama chron (0.735–2.400 Ma BP) the climate variations in this region were lower in amplitude and concentrated mainly at a 41 ka rhythm of orbital obliquity (Ruddiman & Raymo 1988). The start of the Last glacial–interglacial transition (LGIT) and the Holocene, as a current epoch within the Quaternary, are dated at approximately 14.7 and 11.7 ka, respectively (Walker et al. 2009).

Initially, the Holocene was thought to be the most complacent epoch, regarding the climate variability, but high resolution research has revealed climatic oscillations, similar to the Dansgaard–Oeschger cycles of climate instability which occurred during the Last interglaciation (Maslin et al. 2001). Evidence for several widespread climate change events have now been recognized in sediment cores from different localities of the Northern and the Southern Hemisphere, for which Mayewski et al. (2004) use the term Rapid Climate Changes ('RCC'). The first event occurs at 8.2 ka and is the most striking and regionally significant cooling event during the Holocene. After that the second event of a sudden and widespread shift to drier or wet conditions happened in the mid–Holocene at approximately 5.5 ka (Maslin et al. 2001). Another event of rapid climate change with decreased temperatures over North America and Eurasia is marked between 4.2–3.8 ka (Mayewski et al. 2004). The most recent Holocene cold event is the Little Ice Age which lasted from the middle of the 18th to the end of the 19th century in temperate NW Europe (Maslin et al. 2001) and follows a warm period in NW Europe termed the Medieval Warm Period. Further on, it is implied that these RCC events had significant effects on ecosystems and humans. For example, the short–lived 1200–1000 cal yr B.P. RCC event coincided with the drought–related collapse of Mayan civilization (Hodell et al. 2001).

In order to understand the environmental change of the present interglacial, but also to understand their impact on human populations and *vice versa*, the human impact over the environment, we must focus our attention on detailed Holocene palaeoenvironmental reconstruction. In addition to the potential for studying long–term Quaternary environmental change, sediment records recovered from ancient lakes provide enough data for high resolution reconstruction of changes that took place during the Holocene. A prime example for this type of investigations is Lake Baikal (Siberia), as the oldest freshwater lake on the Earth, where beside the number of palaeo-studies focusing the long–term Quaternary changes, there are also proxy studies targeting the post–glacial period (Bradbury et al. 1994, Prokopenko et al. 2007). Selecting the most appropriate biological proxy, the diatoms (single–celled siliceous algae; *Bacillariophyceae*) have proven to be one of the strongest indicator groups used to interpret the Quaternary glacial–interglacial climate change (Edlund & Stoermer 2000; Karabanov et al. 2004; Cherapanova et al. 2007; Felton et al. 2007; Reed *et al.* 2010). They are often well preserved and the most abundant group of fossils in the sediment record. This is due to the presence of the siliceous wall and moreover because of their short life cycle, the diatom assemblages can be considered to respond almost instantaneously to changes in the lacustrine environment (Rioual et al. 2007). Additionally, they are an abundant, diverse and important component of algal assemblages in freshwater lakes that often play an important role in aquatic food web and structure (Hall & Smol 2010). Equally, they are sensitive indicators of many limnological parameters such as salinity, water level fluctuations, pH and nutrient levels (Smol 1988).

During the last few years, a number of palaeo–studies have focused on Lake Ohrid (Macedonia/Albania), not just as the oldest tectonic lake on European territory, but also as one of the most diverse lake ecosystems in the world. Since the first diatom–based palaeolimnological data were generated (Roelofs & Kilham 1983), palaeolimnological investigations of Lake Ohrid were stagnating until the next century, when in the period between 2005 and 2007 several short and one long sediment sequence were recovered from the lake. A number of multi–proxy studies were conducted on these sequences, mostly with a primary aim of investigating long–term Quaternary climate changes (Wagner 2008b, 2009, Vogel et al. 2009, 2010a, 2010b). Directing towards the community response to the glacial–interglacial transitions, Reed et al. (2010) demonstrated again the strong diatom response to climate change.

This paper presents an initial attempt to focus our attention towards the Last glacial–interglacial transition and the Holocene period in Lake Ohrid, using the diatom stratigraphy, in order to explore evidence for environmental change, and the potential for reconstructing RCC events from analysis of the sediment record.

Material and methods

Geographical and limnological setting of Lake Ohrid

Lake Ohrid Basin is the largest of a number of basins in the Dinaride–Alpine mountain belt that stretches along the western shore of the Balkan Peninsula (Hoffmann et al. 2010), located in a tectonically active graben system of the Western Macedonian geotectonic zone. The lake itself (41°01’N, 20°430’E) is part of the Dessarets, a European group consisting of four lakes: Lake Ohrid, Prespa, Mikri Prespa and Lake Maliq, located in Macedonia, Albania and Greece. It is believed that a geological connection existed between these lakes until the late Pliocene or early Pleistocene, when tectonic events occurred which closed the connections (Roelofs & Kilham 1983).

The exact limnological age of the lake is still uncertain; estimates vary between 2 Ma (Cvijic, 1911) to 10 Ma (Sprirkovski et al. 2001). Four hypotheses exist about the limnological origin of the lake, but two of them seem most accurate. The first one supports the theory of “de novo” formation of Lake Ohrid in a dry polje with a spring or river hydrography, and the second hypothesis presumes a palaeogeographical connection of Lake Ohrid with the brackish waters on the Balkan Peninsula (Albrecht & Wilke, 2008). Beside its great age, Lake Ohrid is probably the most diverse lake in the world, taking the surface area into account, with a number of 212 known endemic species (Albrecht & Wilke, 2008).

Topographically, Lake Ohrid is located on the border between Macedonia and Albania at 693 m a. s. l. With an approximate length of 30 km and 15 km width, the surface area of the lake is 358 km^2, the maximum water depth, 289 m, the mean water depth, 155 m, and the total volume of the lake is 55.4 km3. The total watershed of Lake Ohrid is 2610 km^2, when including the catchment area of Lake Prespa, to which it is connected via a major aquifer running below the Galicica Mountain. The hydrological regime of the lake is regulated through the inflow from the carst aquifers, 50 % of which are sublacustrine, and the outflow, through the river Crni Drim (~ 60%) and evaporation (~ 40 %) (Matzinger et al. 2006). The authors calculated water residence time of ~ 70 years. Stankovic (1960) defined Lake Ohrid as an oligomictic lake with occasional complete overturn of the water column at every seventh year.

Lake Ohrid is oligotrophic and phosphorus limited (Allen and Ocevski, 1977), with a Secchi disc depth of 14m (Matzinger et al. 2006). Recent investigations revealed that the mean total phosphorus concentration has risen to 4.5 mg P m^{-3} as a result of the global warming and local anthropogenic impact (Matzinger et al. 2006, 2007). The maintenance of the oligotrophic status of the lake is the basic prerequisite for survival of its unique flora and fauna.

Core recovery and diatom analysis

During autumn 2007, a sediment sequence, core Co1202, was recovered at a coring location in the

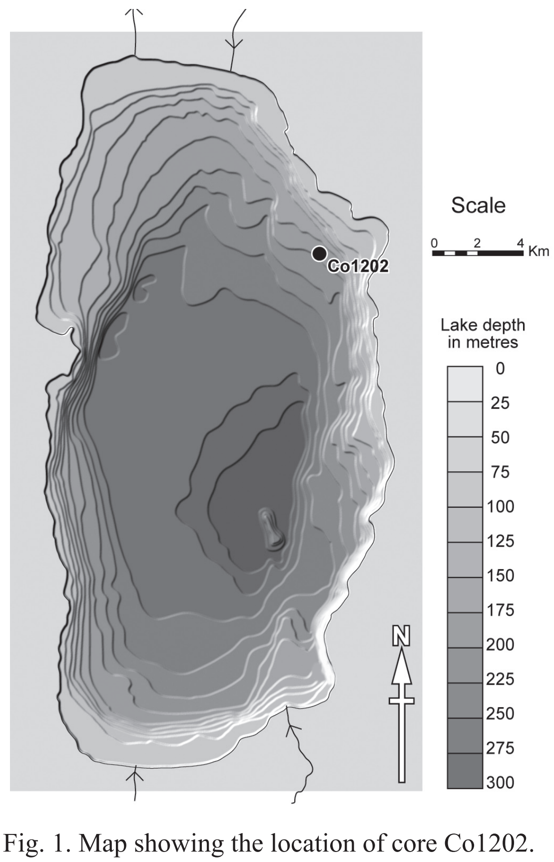

Fig. 1. Map showing the location of core Co1202.

northeastern part of the lake basin, from a water depth of 145 m (Figure 1). The surface sediments and deeper sediments were collected using a 0.6 m gravity corer and a 3 m long percussion piston corer, respectively, both UWITEC Co. (Vogel et al. 2010a). The complete sediment sequence extends from 17 to 1489 cm depth and according the age model adopted from Vogel et al. (2010a) it spans between ca. 135 ka and 0.280 ka BP. Samples for diatom analysis were taken at every ca. 24 cm (ca. 0.6 to >3 ka resolution). For the purpose of this investigation, these samples, stored in small Sterilin tubes, were received from Hull, UK.

Since the primary aim of this investigation is the Last glacial–interglacial transition and the Holocene period in Lake Ohrid, we focus here on the relevant section of core Co1202 between 17 and 360 cm, which spans the last ca. 14 ka. Samples for the diatom analysis were treated with cold H_2O_2 to oxidize organics and 10% HCl for removing the carbonates (Renberg 1990). Permanent microscope diatom slides were prepared using Naphrax™ as a mountant. Diatom assemblages were analyzed under oil immersion at x1500 magnification with a Nikon Eclipse 80i microscope, and the diatom images were produced using Nikon Coolpix P6000 camera.

A total number of ca. 400 diatom valves were counted per slide, according the standard transect–based method for counting diatom slides (Battarbee 1986). Diatom taxa were identified using standard texts (Krammer and Lange–Bertalot, 1986, 1988, 1991a, b, 2000), and the dedicated Ohrid work of Levkov et al. (2007).

Final counts of diatom taxa were converted to percentage data and displayed using Tilia and TGView v. 2.0.2. (Grimm 1991) and the zone boundaries were defined with Constrained Incremental Sum of Squares cluster analysis (Grimm 1987). Additionally, the preservation status was assessed using the simple F index (Mackay et al. 1998)

Results

Diatom zones

Following the diatom assemblages stratigraphy, the summary diagram reflects the distribution of a total number of 38 taxa in the core sequence (Figure 2). The diatom zone boundaries defined with CONISS are further correlated with the relevant Marine isotope stage boundaries (Imbrie et al. 2007) and the Rapid climate changes (Mayewski et al. 2004).

According the CONISS results the sediment sequence was divided in two diatom zones, consequently marked as Diatom zone 1 (DZ 1) and Diatom zone 2 (DZ 2). The first diatom zone was further divided into two subzones DZ 1a and DZ 1b.

Diatom zone DZ 1 (359–158 cm depth, ca. 14.6–3.9 ka)

This diatom zone is further divided in two subzones DZ 1a (359–230 cm depth, ca. 14.6–6.9 ka) and DZ 1b (230–158 cm depth, ca. 6.9–3.9 ka). The diatom assemblages in the first subzone DZ 1a are completely dominated by the planktonic *Cyclotella fottii* Hustedt, an endemic taxon for Lake Ohrid. Other planktonic taxa present in the lower part of this subzone are *Aulacoseira granulata* (Ehrenberg) Simonsen, *Aulacoseira* sp. Thwaites and *Actinocyclus* sp. Ehrenberg. Further on, the diatom samples at 290 cm depth, ca. 9.8 ka, are marked by the first appearance of *Cyclotella ocellata* Pantocsek and *Stephanodiscus transilvanicus* Pantocsek, both taxa present with a very low relative abundance, e.g. 0.4 and 0.7 %, respectively. The group of benthic taxa is presented with *Cocconeis placentula* var. *euglypta* (Ehrenberg) Grunow and *Pinnularia* sp. Ehrenberg. The facultative planktonic taxa *Fragilaria capucina* Desmazières, *Staurosira construens* Ehrenberg, *Staurosira* sp. Ehrenberg and *Staurosirella pinnata* (Ehrenberg) Williams & Round are present at very low abundance.

The second subzone DZ 1b is marked by a relative increase in *C. ocellata* and *S. transilvanicus,* which are constantly present in the diatom assemblages from this subzone, at the expense of *C. fottii*. Another planktonic taxon present with a low abundance is *Aulacoseira* sp. The proportion of facultative planktonic taxa is also increased in this part of the sequence, and represented by *S. construens* and *S. pinnata.* The second taxon reaches up to 9 % relative abundance at 217 cm depth, ca. 7.4 ka. The group of benthic taxa consists of *Karayevia clevei* (Grunow) Bukhtiyarova, *Amphora pediculus* (Kützing) Grunow, *Amphora* sp. Ehrenberg ex Kützing and *Epithemia ohridana* Levkov & Metzeltin, again present with a low abundance.

Additionally, Vogel et al. (2009) recognized two tephra layers in the part of the sediment sequence which corresponds to DZ 1. The first volcanic ash layer (OTO702–3) is deposited between 277.5 and 269 cm depth and the second one (OTO702–2) was identified between 145.5 and 144 cm depth. The Mercato eruption of the Somma–Vesuvius volcano (8.890±0.090 ka BP) and the FL eruption of Etna volcano (3370±70 cal. yrs BP) are being correlated with the deposition of these tephra layers, respectively (Vogel et al. 2010b).

Diatom zone DZ 2 (158–17 cm depth, ca. 3.9–0.3 ka)

The second diatom zone DZ 2 is again dominated by the group of planktonic taxa in which the endemic *C. fottii* and the cosmopolitan *C. ocellata* predominate over the other taxa. But, it is important to

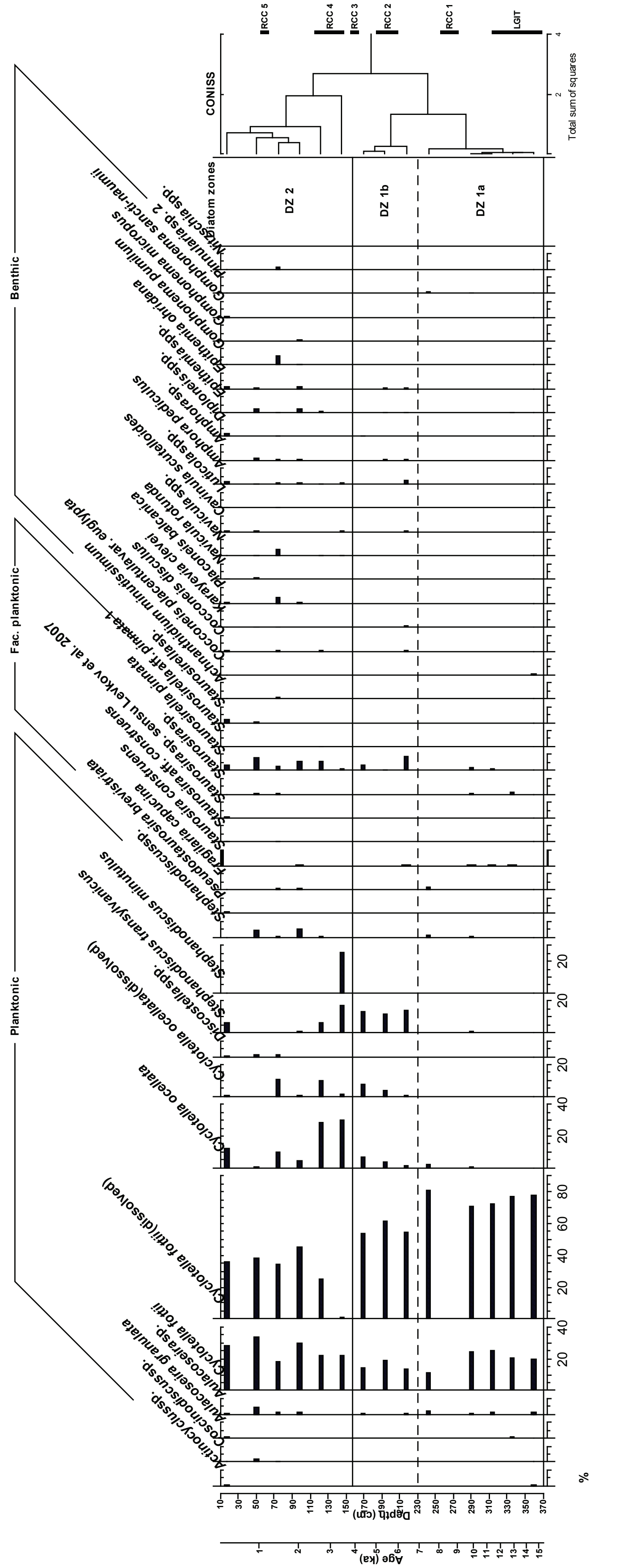

Fig. 2. Stratigraphic diagram of diatom taxa present in core Co1202, displaying the diatom zones (DZ) defined with CONISS and the time intervals for the RCC events according to Mayewski et al. 2004.

note that *C. ocellata* in this part of the sediment sequence is constantly present and reaches up to 30 % relative abundance. Also, the relative proportions of *S. transilvanicus* increases and reaches a maximum of 16 % abundance at 145.5 cm depth, ca. 3.4 ka. Another interesting remark for the same sample (145.5 cm depth, ca. 3.4 ka) is the appearance of the more mesotrophic taxon, *S. minutulus* (Kützing) Cleve & Möller, which with an abundance of 24.6 % is present only in this part of the sequence. The group of facultative planktonic taxa increases in diversity and abundance and it's represented with *Pseudostaurosira brevistriata* (Grunow) Williams & Round, *F. capucina*, *S. construens*, *Staurosira* sp., *Staurosirella pinnata* and *Staurosirella* sp. Although with a low relative abundance, the group of benthic taxa is also more diverse and consists of *Achnanthidium minutissimum* (Kützing) Czarnecki, *Cocconeis disculus* (Schumann) Cleve, *K. clevei*, *Placoneis balcanica* (Hustedt) Lange–Bertalot, Metzeltin & Levkov, *Navicula* spp. Bory, *N. rotunda* Hustedt, *Cavinula scutelloides* (W. Smith) Lange–Bertalot, *Luticola* spp. Mann, *A. pediculus*, *Diploneis* spp. (Ehrenberg) Cleve, *Epithemia* spp. Kutzing, *Gomphonema pumilum* (Grunow) Reichardt & Lange–Bertalot, *G. micropus* Kützing and *Nitzschia* spp. Hassall.

Additionally, Vogel et al. (2009) identified one tephra layer in this part of the sequence, marked as OTO702–1, between 77.5–74.5 cm depth, and supposed to originate from two distinct eruptions of the Somma–Vesuvius volcano.

Tracing nutrient levels and evidence for Rapid climate changes (RCC)

In the following section diatom assemblages are represented in order to assess evidence for the six periods of major climate variations during the Holocene period, after the Last glacial–interglacial transition. The dates of the Rapid Climate Changes are according to Mayewski et al. (2004).

The Last glacial–interglacial transition (14.6–11.5 ka) is presented by diatom assemblages dominated by planktonic taxa, the facultative planktonic species are present with very low diversity and abundance and the benthic taxa are almost absent in the samples. The diatom samples are dominated by the endemic, oligotrophic species *C. fottii,* which reaches a relative abundance of ~ 20%, while the dissolved category is present with ~ 80 %. However, the further interpretation of this period is influenced by the possible compromising of the relevant part of the sediment sequence.

The first rapid climate change during the Holocene (ca. 9–8 ka BP), also named as "Glacial Aftermath" (Mayewski et al. 2004) cannot be assessed due to the current low resolution of diatom sample analysis which does not include diatom samples from this period. However, the first appearance of the more thermophilic taxa including *C. ocellata* and *S. transylvanicus* is recorded in the diatom samples after this period of climate cooling.

The second event of climate disruption (ca. 6–5 ka BP) in Ohrid Lake sediment record is represented with a single diatom sample. Compared with the previous phase, the planktonic *C. fottii* increases in abundance, while the abundance of *S. transylvanucus* decreases. *C. ocellata* is also present in the section, and together with the first two taxa comprises the major proportion of the diatom community. The benthic taxa are almost absent in the sample, and represented only with the low abundant *Epithemia* sp.

A less widespread climate event of severe cooling occurred between ca. 4.2 and 3.8 ka BP (Mayevski et al. 2004), but, again, cannot yet be assessed in full. However, in the diatom sample analysed representing the period between this and the next RCC event which occurred between ca. 2.5 and 3.5 ka BP, the relative abundance of the more thermophilic planktonic taxa increases (*C. ocellata, S. transilvanicus*) at the expense of the decreased proportion of *C. fottii*. Another planktonic, more mesotrophic species which occurs only in this sample is *S. minutulus.* The benthic diatom community is also more diverse compared to the previous section. The RCC event between ca. 2. 5 and 3.5 ka BP is characterized by a very slight decrease in the relative abundance of *C. ocellata*, and also a decrease of the proportion of the mesotrophic *S. transilvanicus*, while *S. minutulus* is absent in the diatom samples from this point forward. Again, *C. fottii* increases its abundance, such as the facultative planktonic taxon *S. pinnata*. After this event of cooler climate conditions, the diatom samples from the sediment record became more diverse. Although, *C. fottii* and *C. ocellata* remain dominant in the planktonic diatom community, other taxa such as *Aulacoseira* sp., *Discostella* sp. and *Stephanodiscus* sp. appear in the samples. The community of facultative planktonic taxa is also more diverse, such as the benthic community in which dominates the group of Naviculoid taxa.

There are no diatom samples representing the most recent RCC event (ca. 1.2–1 ka BP), but the intriguing feature of the diatom sample correlated with the period afterwards is the total predomination of *C. fottii*, while *C. ocellata* is present at very low relative abundance, even less than 0.5 %. It's also interesting to note that the proportion of *Aulacoseira* sp. is highest in this sample compared with its presence in the other diatom samples from the sequence. Although with a smaller number of taxa, the benthic diatom community seems to preserve its diversity.

Additionally, in order to access the preservation status of the diatom assemblages, we adopted the simple F index (Mackay et al. 1998) of counting the dissolved valves of the dominant planktonic taxa in the sequence. The obtained results marked the last glacial–interglacial transition as a zone with low preservation and high percent of dissolved *C. fottii* valves. Better preservation follows during the warmer Holocene period.

Disscusion

Last glacial–interglacial transition (ca. 14.6–11.5 ka BP) and the "Glacial Aftermath" (ca. 9–8 ka BP)

The first diatom subzone DZ 1a (359–230 cm depth, ca. 14.6–6.9 ka) correlates with the period of the last glacial–interglacial transition and the first rapid climate change which occurred during the Holocene. The complete domination of planktonic diatom taxa and the low abundance of benthic taxa suggest deep, oligotrophic water conditions. The dominant planktonic species, *Cyclotella fottii* is an oligotrophic, hypolimnetic taxon. In recent diatom samples this taxon reaches maximum abundance at 30 m water depth, although its relatively high abundance is maintained down to 200 m depth (Stankovic 1960). The diatom profile is well in accordance to the geochemical record (Vogel et al. 2010) and the indication that the period between 14.7 and 11 ka is distinguished by cold winters and partial ice cover. Although, the Younger Dryas cooling between 12.7 and 11.6 ka was not clearly inferred from the calcite profile of Co1202, we could speculate here that the diatom profile and the domination of the hypolimnetic *C. fottii* reflects decreased productivity and low temperatures during this time interval. The time interval (ca. 9–8 ka BP) of the first Holocene climate deterioration is probably one of the most striking events during the present interglacial. During that time the Aegean Sea was exposed to more frequent polar north–west outbreaks (Mayewski et al. 2004). Although, we could not refer to this climate event since the lack of diatom samples from this part of the sequence, we could hypothesize about the possible effect of this RCC on Lake Ohrid. The first appearance of *Cyclotella ocellata* and *Stephanodiscus transilvanicus* although with a very low abundance is before this RCC event (e. g. at ca. 9.8 ka) and again the increased relative abundance, especially of *S. transylvanicus* occurs much latter (at ca. 6.9 ka BP), after the termination of this event. Similar pattern is observed in Lake Ioannina (Greece), where the Pleistocene–Holocene boundary is dominated by *Cyclotella* spp. (Wilson et al. 2008). *C. ocellata* is a more thermophilic species occurring in oligotrophic to eutrophic waters (Cremer et al. 2005) and *S. transylvanicus* is also more termophilic taxon. According to Jurilj (1954), *Stephanodiscus* taxa inhabit the littoral and the sublittoral zone of the lake and they are often considered as higher nutrient level indicators that become dominant in low light conditions and increased phosphorus concentrations (Kilham et al. 1986). Based on this, we hypothesize that the RCC event between ca. 9–8 ka BP had probably affected the lake, and the increase in the relative abundance of the more termophilic taxa reflects more stable and warmer climate conditions afterwards. Additionally, the presence of *S. transylvanicus* and its increased proportion probably reflects increased nutrient level and production of the lake. The 8.2 ka cooling event was recognized in another core from Lake Ohrid (Lz1120) by the decreased carbonate concentration (Wagner et al. 2009). Beside the lower temperatures, the authors suggest decreased nutrient loads in the lake, more arid climate and additionally significantly lower level of Lake Prespa. Reed et al. (2010) considered that probably the sediments in the core sequence in the period of the Last Glacial warming were mixed and that was reflected in the low diatom response towards the increased temperatures. However, at this point we can only speculate about a possible RCC diatom response, but this hypothesis needs future testing when high resolution diatom samples will be obtained for the relevant sequence.

Holocene period and the RCC events (8–0.3 ka BP)

The second diatom subzone DZ 1b (230–158 cm depth, ca. 6.9–3.9 ka) and diatom zone DZ 2 (158–17 cm depth, ca. 3.9–0.3 ka) correlate with the Holocene period after ca. 6.9 ka and four climate change events, although only two of these periods are represented directly by diatom samples.

The continuous presence of *C. ocellata* starting at DZ 1b (ca. 6.9 ka BP) reflects the complete transition towards the warmer Holocene temperatures. Additionally, the higher abundance of taxa belonging to the group of facultative planktonics could possibly reflect increased annual temperatures. The peak abundance of *S. pinnata* at the beginning of diatom subzone DZ 1b could be a possible explanation for ice cover melting and increased temperatures. According to Schmidt et al. (2004) the distribution of taxa belonging to the group of Fragilariaceae appears to be highly sensitive to climate–driven variables, mainly the duration of ice cover and the mean summer water temperature. When taking into account the distribution of *S. pinnata*, which is described as a littoral and sublittoral species occurring in waters with higher pH Schmidt et al. (2004), the diatom profile in this part of the sequence matches well with the other proxies which suggested increased temperatures, lower effective moisture and ice–free winters from ca. 7.5 ka to present (Vogel et al. 2010b).

The single sample correlated to the RCC event between ca. 6 and 5 ka could lead us to an assumption of a possible diatom response caused by this event, indicated by the increased abundance of the hypolimnetic *C. fottii* and its dissolved category at the expense of the decreased proportion of *S. transilvanicus*, *C. ocellata* and additionally the absence of benthic taxa. However, a single sample is not enough to support our assumptions, since the other proxies (Wagner et al. 2009, Vogel et al. 2010b) suggest warm, stable temperatures for the period between ca. 6.4 and 2.4 ka BP.

The second diatom zone DZ 2 (158–17 cm depth, ca. 3.9–0.3 ka) corresponds to the period following another RCC event (4.2–3.8 ka BP), but since there are no diatom samples which directly correspond to the event the possible effect of this event on diatom communities in Lake Ohrid sediment sequence cannot be assessed here. However the presence of the more thermophilic taxa *C. ocellata* and *S. transilvanicus*, and additionally the higher abundance and diversity of facultative planktonic and benthic species compared with the two previous sections reflects stable warm conditions.

A slight decrease in the relative abundance of *C. ocellata* and *S. transilvanicus* and increased abundance of poorly preserved *C. fottii* valves corresponds with the RCC event between ca. 2.5 and 3.5 ka BP. A similar zone of poor diatom preservation and abrupt decrease in the carbonate concentration was recorded in core Lz 1120 around ca. 2.4 ka BP (Wagner et al. 2009) and correlated with a possible human–induced erosion. In core Co1202 the decreased calcite and organic matter concentrations recorded in the period between ca. 4.3 and 3.0 ka BP were interpreted as an indication of lower productivity as a result of lower temperatures (Vogel et al. 2010), while in the period between 3.0 and 2.4 ka the calcite concentrations increased, but the organic content remained relatively low (Vogel et al. 2010). Although the diatom data after 2.5 ka indicates increased productivity, at this point one may only speculate about the possible effect of this climate event. A further study with higher resolution is necessary to determinate the diatom response and the possible effect of the rapid climate changes on Lake Ohrid.

A second aspect in the diatom response is the appearance of the mesotrophic *Stephanodiscus* species in the assemblages. The first appearance of *S. transilvanicus* with higher abundance occurs in the diatom sample at 158 cm depth, ca. 6.9 ka BP. Although it is well in accord with the start of more stable diatom–inferred temperatures, its appearance in the sediment record also reflects increased nutrient and especially phosphorus input in the lake. Another interesting feature is the occurrence and at the same time the domination of another mesotrophic taxon *S. minutulus* in a single sample at 145.5 cm depth, ca. 3.4 ka BP. To become dominant in the diatom communities, *Stephanodiscus* species need high concentration levels of phosphorus and additionally they need low light conditions and Si concentrations for successful growth, as for example *S. minutulus* which is considered as a good competitor on Si (Kilham et al. 1986). Therefore, the appearance of *Stephanodiscus* species can be interpreted as a result of nutrient enrichment of Lake Ohrid, with peak phosphorus concentrations which probably occurred around ca. 3.4 ka. The explanation about the single occurrence of *S. minutulus* may be additionally correlated with the volcanic eruption events of the Somma–Vesuvius and Etna volcano and consequently the deposition of a tephra layer between 145.5 and 144 cm depth. The lowered solar radiation and the increased input of aerosols in the lake have probably influenced the development of a diatom flora dominated by good competitor species in low light conditions, such as *S. minutulus.* However, a further more detailed study on a longer time scale is needed in order to investigate other possible occurrences of this taxon in the sediment record of Lake Ohrid.

Finally, the indication for nutrient enrichment of the lake can be correlated with the human influence during the last 5.5 ka. Similar indication for human disturbance was evidenced in the pollen record in core Lz1120 (Wagner et al. 2009) which started at ca. 5 ka BP and distinctly increased after ca. 2.5 ka BP. The first human populations around Lake Ohrid appeared in the early Holocene, even before the abrupt climatic event at 8.2 ka, e.g. according to Holvoeth et al. (2010) there is an indication of early human populations development at ca. 8.5 ka BP. Today, the number of inhabitants only in the city of Ohrid is estimated at approximately 200 000, and even more during the summer season, when the number of tourists is added. Thus the human induced eutrophication, together with the change of the water balance and the global warming, is among the three main factors that nowadays affect the ecological balance of the lake. Concerns over the possible anthropogenically–induced eutrophication of Lake Ohrid have already been raised in several studies (Allen & Ocevski 1977, Ocevski & Allen 1977, Mitic 1985, Watzin et al. 2002). Most convincingly, the process of recent eutrophication of the lake has been argued for in a study of short (<1m depth) gravity cores (Matzinger et al. 2007). The linear model of P concentration demonstrated increased values, from historic, 1.3 mg m^{-3} to current, 4.5 mg m^{-3} P. The authors state that the eutrophication is relatively slow but there is evidence for its onset 0.15 to 0.20 ka ago, with acceleration since the late 1940s.

Although, a value of 4.5 mg m^{-3} P is low compared to the measured average concentration of 31 mg P/m^3 in its sister lake Prespa, (Matzinger et al. 2006), and Lake Ohrid is still classified as oligotrophic freshwater ecosystem, the main problem emerging with the accelerating human pressure is the possible loss of the oligotrophic status of the lake, which is the main factor dictating its high level of diversity and endemism. Thus, the maintenance of lower nutrient levels and human pressure control are the basic steps towards preventing the possible loss of the many endemic and relict species in Lake Ohrid.

Finally, this study is only an initial attempt for recognizing climate and other environmental changes that took place during the Holocene epoch. A further, more detailed, high resolution study is necessary to better understand the effects of the rapid climate changes and investigate the history of the anthropogenic influence, not only on this extraordinary ecosystem, but also its sister Lake Prespa in order to recognize the possible interconnections between both lakes.

Conclusions

Because of the lack of higher temporal resolution of diatom samples, the investigated Holocene section and the last glacial–interglacial transition in core Co1202 provided only basic data about the diatom response for the reconstructed time interval in Lake Ohrid.

In regard to diatom stratigraphy, diatom samples dominated by the endemic *Cyclotella fottii* are inferred to represent lower temperatures and colder climate conditions. At the opposite extreme, the domination of *C. ocellata* represents higher temperatures and warmer climate intervals. Additionally, *Stephanodiscus* taxa are considered to represent increased productivity intervals and consequently higher nutrient levels. Thus, their presence and even more increased relative abundance in the samples are considered as an indication for a possible process of eutrophication.

Although the onset of the Holocene is marked at ca. 11.5 ka, the diatom profile does not indicate warmer temperatures and stable interglacial conditions until ca. 6.9 ka. A possible explanation about the low diatom response is sediment mixing in that part of the sequence as it is also stated by Reed et al. (2010). Another aspect is the events of climate disruption during the Holocene. Although the time resolution of the diatom samples is not enough for a detailed reconstruction; a preliminary hypothesis is that some of the RCC events affected the diatom community in Lake Ohrid. The increased relative abundance of *C. fottii* after the time intervals between ca. 9–8 ka BP and ca. 6–5 ka BP is interpreted as a possible indication for colder climate conditions e.g. the RCC events in these time intervals. However, a more detailed study is necessary to confirm our hypothesis and further investigate the climate change events in Lake Ohrid.

Finally, changes in diatom communities are an indirect reflection of climate change. It is not temperature per se which drives change–it is limnological change influenced by climate. This could include pH, physical habitat restructuring and productivity and we still need to disentangle human–induced change from this package. Thus, the increased proportion of mesotrophic taxa since ca. 6.9 ka BP and more over their domination at ca. 3.4 ka BP, followed with the appearance of *Stephanodiscus minutulus*, is indicated as nutrient level increase. Finally, it is necessary to point out the need of a higher temporal palaeoenvironmental study in order to closely reconstruct Holocene environment and determinate the human pressure in Lake Ohrid.

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References

Albrecht, C. & Wilke, T. (2008). Ancient Lake Ohrid: Biodiversity and evolution. *Hydrobiologia,* **615**: 103–140.

Allen, H. L. & Ocevski, B. T. (1977). Limnological studies in a large, deep, oligotrophic lake (Lake Ohrid, Yugoslavia). *Arch. Hydrobiol*., **53(1)**: 1–21.

Battarbee, R. W. (1986). Diatom analysis, in: Handbook of Holocene Palaeoecology and Palaeohydrology, edited by: Berglund, B. E., Wiley, Chichester, 527–570.

Bradbury, J.P., Bezrukova, V.Y, Chernyeaeva, P.G. et al. (1994). A synthesis of post–glacial diatom records from Lake Baikal. *Journal of Paleolimnology*, **10**: 213–252.

Cherapanova, V. M., Snyder, A. J. & Brigham–Grette, J. (2007). Diatom stratigraphy of the last 250 ka at Lake El'gygytgyn, northeast Siberia. *J. Paleolimnol*, **37**: 155–162.

Coope, R. (2004). Quaternary climatic changes–what can we learn from history? *ESS Bulletin*, **2 (2)**: 57–75.

Cremer, H., Wagner, B., Juschus, O. & Melles, M. (2005). A microscopical study of diatom phytoplankton in deep crater Lake El'gygytgyn, Northeast Siberia. *Algological Studies,* **116**: 147–169.

Cvijic, J. (1911). Fundamentals of geography and geology of Macedonia and Old Serbia. Book III, *Serbian Academy of Sciences, Special Edition*, Beograd (in Serbian).

Edlund, B. M. & Stoermer E. F. (2000). A 200.000–year, high-resolution record of diatom productivity and community makeup from Lake Baikal shows high correspondence to the marine oxygen–isotope record of climate change. *Limnol. Oceanogr.*, **45(4)**: 948–962.

Felton A. A., Russell M. J., Cohen, S. A., et al. (2007). Paleolimnological evidence for the onset and termination of glacial aridity from Lake Tanganyika, Tropical East Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **252**: 405–423.

Grimm, E. C. (1987). CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences*, **13**: 13–35.

Grimm, E. C. (1991). TILIA and TILIA–GRAPH. Illinois State Museum, Springfield, USA.

Hall, I. R. & Smol, J. P. (2010). Diatoms as indicators of lake eutrophication. In: *The Diatoms: Applications for the Environmental and Earth Sciences.* Cambridge University Press, **2**: 122–151.

Hodell, D. A., Brenner, M., Curtis, H. J. & Guilderson, T. (2001). Solar forcing of Drought Frequency in the Maya Lowlands. *Science*, **292**: 1367–1370.

Hoffmann N., Reicherter K., Ferńandez–Steeger T. & Grützner C. (2010). Evolution of ancient Lake Ohrid: a tectonic perspective. *Biogeosciences Discuss*., **7**: 4641–4664.

Holtvoeth, J., Vogel, H., Wagner, B. & Wolff, G. A. (2010). Lipid biomarkers in Holocene and glacial sediments from ancient Lake Ohrid (Macedonia, Albania). *Biogeosciences*, **7**: 4607–4640.

Imbrie, J, Berger, A., Boyle, E. A., et al. (1993). On the structure and origin of major glaciation cycles 2. The 100,000-year cycle, *Paleoceanography*, **8(6)**: 699–735,

Imbrie, J., Hays, J. D., Martinson, D. G., et al. (2007). The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record, in: Milankovitch and Climate (Pt. 1), edited by: Berger, A. L., Imbrie, J., Hays, J. D., Kukla, G., and Saltzman, B.: Dordrecht, Reidel, 269–305.

Jurilj, A. (1954). Flora i vegetacija dijatomeja Ohridskog Jezera. *Prirodolsovna Istrazivanja*, **26**, Zagreb, 99–190.

Karabanov E., Williams D., Kuzmin M., et al. (2004). Ecological collapse of Lake Baikal and Lake Hövsgöl ecosystems during the Last Glacial and consequences for aquatic species diversity. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **209**: 227– 243.

Kilham, P., Kilham, S. S. & Hecky, E. R. (1986). Hypothesized resource relationships among African planktonic diatoms. *Limnology and Oceanography*., **31(6)**: 1169–l181.

Krammer, K. & Lange–Bertalot, H. (1986). Süsswasserflora von Mitteleuropa. Bacillariophyceae. 1. Teil: Naviculaceae, Gustav Fischer Verlag, Stuttgart, Vol. 2/1.

Krammer, K. & Lange–Bertalot, H. (1988). Süsswasserflora von Mitteleuropa. Bacillariophyceae. 2. Teil: Epithemiaceae, Bacillariaceae, Surirellaceae, Gustav Fischer Verlag, Stuttgart, Vol. 2/2.

Krammer, K. & Lange–Bertalot, H. (1991a). Süsswasserflora von Mitteleuropa. Bacillariophyceae. 3. Teil: Centrales, 5 Fragilariaceae, Eunotiaceae, Gustav Fischer Verlag, Stuttgart, Vol. 2/3.

Krammer, K. & Lange–Bertalot, H. (1991b). Süsswasserflora von Mitteleuropa. Bacillariophyceae. 4. Teil: Achnanthaceae, Gustav Fischer Verlag, Stuttgart, Vol. 2/4.

Krammer, K. & Lange–Bertalot, H. (2000). Süsswasserflora von Mitteleuropa. Bacillariophyceae. 5. Teil: English and French translation of the keys. Spectrum Akademischer Verlag GmbH Heidelberg, Berlin, Vol. 2/5.

Levkov, Z., Krstic, S., Metzeltin, D. & Nakov, T. (2007). Diatoms of Lakes Prespa and Ohrid. About 500 taxa from ancient lake system. Iconographia Diatomologica Vol. **16**: 1–603. ARG Gartner Verlag.

Mackay, A.W., Flower, R. J., Kuzmina, A. E., et al. (1998). Diatom succession trends in recent sediments from Lake Baikal and their relationship to atmospheric pollution and to climate change. *Philosophical Transactions of the Royal Society of London*, **353**: 1011–1055.

Mackay, A. (2007). The paleoclimatology of Lake Baikal: a diatom synthesis and prospectus. *Earth Sci. Rev*., **82**: 181–215.

Maslin, M., Seidov, D. & Lowe, J. (2001). Synthesis of the Nature and Causes of Rapid Climate Transitions During the Quaternary. *The Oceans and Rapid Climate Change: Past, Present and Future Geophysical Monograph*, **126**: 9–52.

Matzinger, A., Schmid, M., Veljanoska–Sarafiloska, E., et al. (2007). Eutrophication of ancient Lake Ohrid: Global warming amplifies detrimental effects of increased nutrient inputs. *Limnol. Oceanogr.*, **52(1)**: 338–353.

Matzinger, A., Spirkovski, Z., Patceva, S. & Wüest, A. (2006b). Sensitivity of ancient Lake Ohrid to local anthropogenic impacts and global warming. *J. Great Lakes Res.*, **32**: 158–179.

Mayewski, P. A., Rohling, E. E., Stager, J. C. et al.

(2004). Holocene climate variability. *Quaternary Research*, **62**: 243–255.

Mitic, V. (1985). Vlijanieto na antropogeniot faktor vrz promenite na fitoplanktonot vo Oridskoto ezero. (In Macedonian). Macedonian academy of sciences and arts, 51–54.

Ocevski, B. T. & Allen, H. L. (1977). Limnological studies in a large deep, oligotrophic lake (lake Ohrid, Yugoslavia). Seasonal and annual primary production dynamics of the pelagial phytoplankton. *Arch. Hydrobiol.* , **79(4)**: 429–440.1–916.

Prokopenko A. A., Khursevich K. G., Bezrukova V. E., et al. (2007). Paleoenvironmental proxy records from Lake Hövsgöl, Mongolia, and a synthesis of Holocene climate change in the Lake Baikal watershed. *Quaternary Research*, **68**: 2–17.

Reed, J. M., Cvetkoska, A., Levkov, Z., et al. (2010). The last glacial–interglacial cycle in Lake Ohrid (Macedonia/Albania): testing diatom response to climate. *Biogeosciences*, **7**: 3083–3094.

Renberg, I. (1990). A procedure for preparing large sets of diatom slides from sediment cores. *Journal of Paleolimnology*, **4**: 87–90.

Rioual, P., Andrieu–Ponel, V., De Beaulieu, J–L., et al. (2007). Diatom responses to limnological and climatic changes at Ribains Maar (French Massif Central) during the Eemian and Early Würm. *Quarternary Science Reviews*, **26**: 1557–1609.

Roelofs, A. K. & Kilham, P. (1983). The Diatom stratigraphy and paleoecology of Lake Ohrid, Yugoslavia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **42**: 225–245.

Ruddiman, W. F. & Raymo, M. E. (1988). Northern Hemisphere climate regimes during the past 3 Ma: possible tectonic connections. *Phil. Trans. R. Soc. Lond.*, **B 318**: 411–430.

Schmidt, R., Kamenik, C., Lange–Bertalot, H. & Klee, R. (2004). *Fragilaria* and *Staurosira* (Bacillariophyceae) from sediment surfaces of 40 lakes in the Austrian Alps in relation to environmental variables, and their potential for palaeoclimatology. *J. Limnol.*, **63(2)**: 171–189.

Smol, J. P. (1988). Paleoclimate proxy data from freshwater arctic diatoms. *Verh. Internat. Verein. Limnol.*, **23**: 837–844.

Spirkovski, Z., Avramovski, O. & Kodzoman, A. (2001). Watershed management in the Lake Ohrid region of Albania and Macedonia. *Lake Reserv. Manag*., **6**: 237–242.

Stankovic, S. (1960). The Balkan Lake Ohrid and its living world. *Monographiae Biologicae,* IX. Uitgeverij Dr. W. Junk, Den Haag, Netherlands.

Vogel, H., Wessels, M., Albrecht, C., Stich, B. H. & Wagner, B. (2010a). Spatial variability of recent sedimentation in Lake Ohrid (Albania/Macedonia) – a complex interplay of natural and anthropogenic factors and their possible impact on biodiversity patterns. *Biogeosciences*, 3333–3342.

Vogel, H., Wagner, B., Zanchetta G., et al. (2010b). A paleoclimate record with tephrochronological age control for the last glacial–interglacial cycle from Lake Ohrid, Albania and Macedonia. *Journal of Paleolimnology*, **44**: 295–310.

Vogel, H., Zanchetta, G., Sulpizio, R., et al. (2009). A tephrostratigraphic record for the last glacial–interglacial cycle from Lake Ohrid, Albania and Macedonia. *J. Quarternary Science*, **25**: 320–328.

Wagner, B., Lotter, A. F., Nowaczyk, N., et al. (2009). A 40.000–year record of environmental change from ancient Lake Ohrid (Albania and Macedonia). *J. Paleolimnol,* **41**: 407–430.

Wagner, B., Reicherter, K., Daut, G., et al. (2008b). The potential of Lake Ohrid for long–term palaeoenvironmental reconstructions. *Palaeogeography, Palaeoclimatology, Palaeoecology,* **259**: 341–356.

Wagner, B., Vogel, H., Zanchetta, G. & Sulpizio, R. (2010). Environmental changes on the Balkans recorded in the sediments from lakes Prespa and Ohrid. *Biogeosciences*, **7**: 3365–3392.

Walker, M., Johnsen, S., Rasmussen. O. S., et al. (2009). Formal definition and dating of the GSSP (Global Stratotype Section and Point) for the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. *Journal of Quaternary Science*, **24(1)**: 3–17.

Watzin, M. C., Puka, V. & Naumoski, B. T. (2002). Lake Ohrid and its watershed, state of the environment report. Lake Ohrid Conservation Project. Tirana, Albania and Ohrid, Macedonia.

Wilson, G. P., Reed, J. M., Lawson, I. T., Frogley, M. R., Preece, R. C., & Tzedakis, P. C. (2008). Diatom response to the last glacial–interglacial transition in the Ioannina basin, northwest Greece: implications for Mediterranean palaeoclimate reconstruction, *Quaternary Science Reviews*, **27**: 428–440.