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Environmental changes on the Balkans recorded in the sediments from lakes Prespa and Ohrid

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Abstract

Lakes Prespa and Ohrid on the Balkans are considered to be amongst the oldest lakes in Europe. Both lakes are hydraulically connected via karst aquifers. From Lake Ohrid, several up to ca. 15 m long sediment records were studied during the past years. In this study, a first long sediment record from Lake Prespa was studied in order to shed more light on the influence of Lake Prespa on Lake Ohrid and the environmental history of the region. Radiocarbon dating and the occurrence of 3 dated tephra layers provide a good age control and indicate that the 10.5 m long sediment record reaches back to 48 ka. The comparison of the results from this study with those from former studies of the Lake Ohrid cores indicates that Lake Prespa is more susceptible to environmental changes due to its lower volume and water depth. Glacial sedimentation is characterized by low organic matter contents and absence of carbonates in the sediments, which indicate oligotrophic conditions in both lakes. Holocene sedimentation is characterized by particularly high carbonate contents in Lake Ohrid and by particularly high organic matter contents in Lake Prespa, which indicate a shift towards more mesotrophic conditions in the latter. Long-term environmental changes and short-term events, such as the Heinrich events during the Pleistocene or the 8.2 cooling event during the Holocene, are well recorded in both lakes, but partly expressed in different proxies.

1 Introduction

Lakes Prespa and Ohrid on the Balkan peninsula form a hydraulic system, which is considered to have been formed during the early to mid Pliocene, roughly two to five million years ago (Stankovic, 1960; Meybeck, 1995). With such an age, both lakes are presumed to be among the oldest existing lakes in Europe. In the earliest stage of their existence, both lakes probably were part of a much bigger lake group called Dessaretes on the Balkan Peninsula (Stankovic, 1960), which also includes Lake Mikri

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Prespa (Greece, Albania) and Lake Maliq (Albania).

After its formation or separation, Lake Ohrid is supposed to have existed continuously and thus could be the oldest and only European ancient lake (Salemaa, 1994). Lake Prespa, in contrast, is much shallower and thus probably more susceptible to complete desiccation. Their differing geological histories might explain differences in faunal compositions despite their hydrological connection via karst aquifers. Lake Ohrid is famous for its more than 200 endemic species, which make the lake the most diverse lake in the world taken surface area into account (Albrecht and Wilke, 2008). Lake Prespa, in contrast, harbours no endemic species (Albrecht and Wilke, 2008), but the lake is known as an important breeding site for rare water-bird species. The ecological importance of both lakes has been manifested by declaring Lake Ohrid as an UNESCO world heritage site in 1979 and by the establishment of the Prespa National Park in 1999. Increasing population in the lake catchments, increasing eutrophication of the lake waters, and ongoing use of lake water for agriculture jeopardize the ecosystems today. For example, hydrological measurements have shown a gradual lowering of the lake levels during the past decades, which only partly corresponds with increasing temperatures and decreasing precipitation (Popovska and Bonacci, 2007), and is rather caused by irrigation and agriculture. These measurements also revealed that lake level changes are more pronounced in Lake Prespa compared to Lake Ohrid. The larger water depth and volume of Lake Ohrid imply that it reacts less sensitive to environmental changes. However, also Lake Ohrid is very susceptible to environmental changes, since for example temperature changes significantly alter mixis conditions in the lake and thus oxygen conditions in the bottom waters (Matzinger et al., 2007).

The sedimentary records from the lakes were only sparsely used to infer the regional environmental history. Relatively short sediment sequences from both lakes were used to investigate their recent eutrophication and to study the influence of water supply from the today mesotrophic Lake Prespa to the oligotrophic Lake Ohrid (Matzinger et al., 2006a, 2007). Longer sediment sequences were recovered so far only from Lake Ohrid and indicate that this lake sensitively records short- and long-term climatic and environmental changes over the last glacial/interglacial cycle (Roehlofs and Kilham, 1983; Belmecheri et al., 2009; Wagner et al., 2009; Lézine et al., 2010; Vogel et al., 2010a). Moreover, the occurrence of tephras and cryptotephras in these sequences indicates that the lake is a valuable archive for ash dispersal originating from the explosive eruptions of Italian volcanoes during the Late Quaternary (Wagner et al., 2008; Vogel et al., 2010b; Sulpizio et al., 2010).

Comparable long sediment sequences from Lake Prespa did not exist so far. Here, we present a new sediment record from Lake Prespa, which allows a first characterization of the Late Quaternary sedimentation in this lake. A comparison with the sedimentary record from Lake Ohrid will (i) help to better understand the long-term interactions between Lake Prespa and Lake Ohrid, (ii) allow a better discrimination between local and regional environmental changes and their driving forces, (iii) provide a better estimate of the impact of short-term climate events on the Balkans, and (iv) provide more information about ash dispersal on the Balkans.

2 Study sites

Lake Prespa is a transboundary lake shared between the Republics of Macedonia, Albania, and Greece (Fig. 1). The lake is located at 849 m above sea level (a.s.l.), has a surface area of 254 km^2, a catchment area of 1300 km^2, a maximum water depth of 48 m, a mean water depth of 14 m, and a volume of 3.6 km^3. The total inflow is estimated to 16.9 $m^3 s^{-1}$, with 56% originating from river runoff from numerous small streams, 35% from direct precipitation, and 9% from Lake Mikri Prespa to the south (Matzinger et al., 2006a). There is no surface outlet of Lake Prespa. Water loss derives through evaporation (52%), irrigation (2%) and outflow through karst aquifers (46%). The hydraulic residence time in Lake Prespa is about 11 years. A significant lake level decrease of more than 7 m was measured between 1965 and 1996 (Popovska and Bonacci, 2007), and an additional lowering of at least 1 m was observed during the past 9 years. As Lake Prespa is relatively shallow with respect to the large surface

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area, mainly wind-induced mixis leads to a complete destratification of the water column from autumn to spring (Matzinger et al., 2006a). Anoxic bottom waters in summer and an average concentration of 31 mg m^{-3} total phosphorus (TP) in the water column characterize the lake as mesotrophic today. However, short sediment cores and hydrological measurements indicate recent eutrophication (Matzinger et al., 2006a) and imply that Lake Prespa was more oligotrophic in the past.

Lake Ohrid is separated from Lake Prespa by the Galicica mountain range (Fig. 1). Also Lake Ohrid is a transboundary lake, shared by the Republics of Macedonia and Albania. The lake is located at 693 m a.s.l., has a surface area of 358 km^2, a maximum water depth of 289,m, a mean water depth of 155 m, and a volume of 55.4 km^3. The direct catchment area of Lake Ohrid measures 1310 km^2, however, stable isotope measurements and tracer experiments revealed that Lake Ohrid is partly fed by karst aquifers from Lake Prespa (Anovski et al., 1980; Eftimi and Zoto, 1997), which increases the total catchment to 2610 km^2. The total inflow of water can be estimated to 37.9 m^3 s^{-1}, with ca. 25% originating from direct precipitation and 25% from riverine inflow. About 50% of the total inflow derives from karst aquifers, of which ca. 8 m^3 s^{-1} are believed to come from Lake Prespa (Matzinger et al., 2006b). Evaporation (40%) and the main outflow, the river Crn Drim (60%) balance the water budget in Lake Ohrid. The hydraulic residence time in Lake Ohrid is about 70 years. Total decrease of the average lake level between 1965 and 1996 was less than 1 m (Popovska and Bonacci, 2007), however, the water level is artificially regulated since 1962. Mixis of the upper 150 to 200 m of the water column of Lake Ohrid occurs every winter, and complete mixis of the lake can be observed only every few years (Hadzisce, 1966; Matzinger et al., 2006b). The mixis is mainly induced by wind, leading to an anticlockwise current (Fig. 2; see also Vogel et al., 2010c) and upwelling of relatively cold waters mainly in the central northern part of the lake (Stankovic, 1960). Despite the irregular mixis, moderate oxygen saturation in the bottom waters and an average TP concentration of 4.5 mg m^{-3} (Matzinger et al., 2006a) characterize the lake as oligotrophic.

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3 Material and methods

From Lake Ohrid, an 8.85 m long sediment record was recovered in 1973 from the central northern part of the lake (Roehlofs and Kilham, 1983). Two cores measuring about 10 m in length were recovered in 2004 and 2005 from the southwestern (Belmecheri et al., 2009) and the southeastern (Wagner et al., 2009) part of the lake (Fig. 1) using a floating platform, gravity and piston corers (UWITEC Corp. Austria). The longest and best-dated record so far existing is core Co1202 from the northeastern part of the lake (Vogel et al., 2010a). This core is 15 m long and dates back to 136 ka and hence will be mainly used for a comparison with the sediment record from Lake Prespa. The chronology of core Co1202 is well constrained by radiocarbon dating and the occurrence of 10 tephra and cryptotephra layers (Vogel et al., 2010b).

From Lake Prespa, a 10.5 m long sediment sequence was recovered in autumn 2007, also using a floating platform, gravity and piston corers (UWITEC Corp. Austria). The coring location Co1204 is in the northwestern part of the lake (Fig. 1), where a hydroacoustic survey indicated a water depth of 14 m and undisturbed sedimentation. Correlation of the individual up to 3 m long sediment cores to a composite core was based on field measurements, macroscopic core description and physical and geochemical properties of the sediments.

For a better comparison between the sedimentary records of lakes Prespa and Ohrid, we used the same methods as applied to core Co1202 from the northeastern part of Lake Ohrid (see Vogel et al., 2010a, for details). The analytical work focused on high-resolution X-ray fluorescence (XRF) measurements, geochemical measurements, and the determination of the grain-size distribution. XRF scanning was carried out at a resolution of 0.5 mm and an analysis time of 20 s per measurement using an ITRAX core scanner (COX Ltd., Sweden). The obtained count rates were smoothed using a 5-pt running mean. Geochemical measurements were performed in 2 cm intervals on freeze-dried and homogenized subsamples. Concentrations of total carbon (TC), total nitrogen (TN), and total sulphur (TS) were measured with a MICRO CUBE elemental

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analyzer (VARIO Co.). Total organic carbon (TOC) was quantified from the difference between total carbon (TC) and total inorganic carbon (TIC), which were measured with a DIMATOC 200 (DIMATEC Co.). Grain-size analyses were carried out in intervals of between 4 and 8 cm on clastic detritus after removal of $CaCO_3$, finely dispersed iron sulphides, and biogenic silica. The grain-size distribution was measured using a Micromeritics Saturn Digisizer 5200 laser particle analyzer and calculated from the average values of 3 runs.

The chronology of core Co1204 is based on radiocarbon dating (Table 1) and tephrochronology. Radiocarbon dating was performed on macrofossil remains from 15 horizons. Reliable radiocarbon ages were calibrated into calendar years before present (cal. yr BP) using CalPal-2007online and the Cal-Pal2007_HULU calibration curve (Danzeglocke et al., 2008). Three tephra layers at depths of 879.3–863.3 cm (PT0704-3), 767.2–764.2 cm (PT0704-2), and 672.5–667.5 cm (PT0704-1) were identified throughout the core (Sulpizio et al., 2010) and additionally used to establish an age-depth model for core Co1204. As for core Co1202 from Lake Ohrid (cf. Vogel et al., 2010b), the age-depth model for core Co1204 is based on the assumption that the sediment surface represents the year of the coring campaign (2007) and on a linear interpolation between the dated horizons after removal of the tephra layers.

4 Results and discussion

Core Co1204 from Lake Prespa is mainly composed of two lithological units (Fig. 3). The lower unit reaches from the core base at 1050 cm to 314 cm depth and is characterized by greyish colour and absence of lamination in the lower part of the core. Fine-grained clastic matter dominates the sediment composition, which is also reflected in high K and Ti values in the XRF measurements. Sporadic occurrence of sand and gravel grains is interpreted as ice-rafted detritus (IRD). This grain-size composition, which indicates a low energy transport, documents that there is no significant inflow into Lake Prespa close to the coring location. The sporadic occurrence of IRD implies

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that the lake was ice covered at least during winter and that gravel and coarse sand was transported by ice floes during ice break up in spring. Similar observations have been made in glacial sediments from Lake Ohrid (Wagner et al., 2008; Vogel et al., 2010a). Carbonates are absent throughout most of this lithological unit, as it is shown in low TIC values and negligible Ca values in the XRF measurements. The proportion of organic matter is very low and apparently anti-correlates with the K and Ti values. The very low content of carbonates and organic matter implies a very low productivity or a high decomposition during deposition of this lithological unit. In the upper part of this unit, between ca. 600 and 314 cm depth, an increase in lamination can be observed. The lamination is irregular and made by individual dark greyish to black spots, which partly form distinct horizons. As shown by radiography and XRF scanning, the visually dark grey to black horizons are characterized by relatively low density and maxima in Mn and Fe values (Fig. 4) and hence indicate horizons, where concretions have been formed. Concretionary Mn and Fe horizons have also been observed in glacial Lake Ohrid sediments (Vogel et al., 2010a) or in Lake Baikal sediments (Granina et al., 2004) and were related to shifts in the redox conditions of the bottom waters or significant changes in the sedimentation regime. The dark horizons thus likely represent paleo redox fronts, which are partly preserved in the sediment.

Coarser sediments, significantly increased Sr values, and a distinct maximum in Zr values define the occurrence of three tephra horizons in the lower lithological unit. The geochemical composition of the tephras is discussed in detail in Sulpizio et al. (2010) and indicates that tephra PT0704-3 between 879.3–863.3 cm depth corresponds with the Y-5 tephra. Tephra PT0704-02 occurs between 767.2–764.2 cm depth and can tentatively be correlated with the Codola tephra, and tephra PT0704-01 between 672.5–667.5 cm depth correlates with the Y-3 tephra (Fig. 3). The tephrochronological ages are supported by radiocarbon ages from this unit. Sample KIA36356 from 829 cm depth provides an age of 37 990 cal. yr BP, which matches well with its position between the Y-5 and the presumed Codola tephra. Samples KIA36357 and KIA36358 from below the Y-5 tephra have older ages than the Y-5 tephra, but were not taken

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into consideration for establishing the age-depth model, as they are close to or above the limits of radiocarbon dating (Table 1) and a number of extraordinary stratigraphic inconsistencies in radiocarbon ages in samples from above and below the Y-5 tephra have been reported from other sites (e.g., Fedele et al., 2008).

The upper lithological unit reaches from 314 cm depth to the core top and is characterized by olive to greyish colour. The absence of lamination throughout this unit corresponds with some indication of bioturbation. The grain-size composition is again dominated by fine-grained material, but IRD is absent. This implies still relatively calm sedimentation conditions and moderate or no ice cover during winter. The more greenish color in this unit reflects a significantly higher proportion of organic matter, such as indicated in increased TOC values and decreased K and Ti values. The higher content of organic matter likely indicates high productivity in the lake or decreased decomposition. Since TIC and Ca values correlate relatively well with TOC values, it can be assumed that increased productivity led to increased calcite precipitation in the water column or that less decomposition of organic matter at the sediment surface led to less dissolution of precipitated calcite. This pattern was also observed in the interglacial sediments of Lake Ohrid (Wagner et al., 2008; Vogel et al., 2010a). Concretions or concretionary horizons of Mn and Fe compounds, indicating paleo redox fronts in the sediments are widely absent throughout the upper lithological unit (Fig. 3), thus implying relatively stable redox and sedimentation conditions during deposition of this unit. Despite some smaller Sr and Zr peaks, tephras or cryptotephras could not be detected in this upper lithological unit (Sulpizio et al., 2010). The radiocarbon ages indicate that this unit was deposited during the Holocene (Table 1).

Although only three tephras were detected in core Co1204, these tephras can be used as independent tie points to link the sediment records from Lake Prespa with those from Lake Ohrid. The Y-6 tephra, which was observed in the sediment record from Lake Ohrid and was estimated to have an age of 49.2±1.1 ka (Vogel et al., 2010b; Sulpizio et al., 2010), was not found in core Co1204 from Lake Prespa. Tephra PT0704-3 from 879.3–863.3 cm depth in core Co1204, which corresponds with the Y-5 tephra,

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can be used as the lowermost tie point dated to 39.3±0.1 a (^{40}Ar/^{39}Ar dating on sanidine crystals; De Vivo et al., 2001). For establishing an age-depth model on core Co1204, the three tephras and radiocarbon ages with a sufficient amount of carbon were used (Table 1). Linear interpolation between the dated horizons reveals no significant changes in the sedimentation rates, except of slightly higher sedimentation rates during the glacial compared with the Holocene period and some minor changes in the latter. This suggests that the record from Lake Prespa continuously covers the past ca. 48 ka (Fig. 5). The only indication for a potential gap in the record occurs at the Pleistocene/Holocene transition, where a sharp change in lithology and in most of the investigated proxies can be observed (Fig. 3). However, there is no indication for a lake level lowstand with littoral sedimentation, including shell or macrophyte remains, or even a complete desiccation in this part of the core (Fig. 3), and the very shallow bathymetry of the lake argues against significant mass movement processes. Hence, the only reliable explanation would be that wind-driven currents in Lake Prespa were much stronger or had a different location or extent compared to today (Fig. 2) and led to erosion of fine-grained sediments. An indication for stronger aeolian activity around the Pleistocene/Holocene transition in the region does, however, not exist (Vogel et al., 2010a).

5 Interpretation

The general sedimentation pattern of Lake Prespa matches well with the sedimentation pattern in Lake Ohrid.

Only marginal variations in sediment composition during the glacial period indicate a relatively stable low productivity environment in both lakes. Sporadic occurrence of IRD, absence or very low contents of TIC, and very low TOC contents characterize glacial sedimentation (Fig. 6). The occurrence of IRD indicates that both lakes had significantly more ice cover during the glacial period than today, when the lakes remain mostly ice-free during winter. Cold conditions with a typical steppe biome, such as also reported from other records in the region (e.g., Allen et al., 2000; Matrat et al., 2004), and ice cover during winter likely led to dimictic conditions in Lake Ohrid during this period (Wagner et al., 2009; Vogel et al., 2010a). Restricted productivity in the lake and increased mixis led to low organic matter accumulation and enhanced decomposition of organic matter. Similar conditions and processes apparently prevailed in Lake Prespa, since similar TOC and TIC contents (Fig. 6) suggest that this lake was also oligotrophic during the glacial period. However, there is a slight difference between both lakes at the end of Marine Isotope stage (MIS) 3, between ca. 44 and 32 ka. This period is inferred to have experienced slightly warmer climate (e.g., Geraga et al., 2005), shows a maximum in arboreal pollen in the Lake Ohrid records (Wagner et al., 2009; Fig. 7), and is characterized by slightly higher amounts of organic matter in both lakes. During this period, TOC contents in Lake Prespa are somewhat higher than those in Lake Ohrid (Fig. 6). It can hence be assumed that even relatively moderate changes in the environmental conditions are more pronounced in Lake Prespa.

Lowest organic matter contents and numerous concretionary horizons, as expressed by extremely high fluctuations in Mn counts (Fig. 7), can be found during the MIS 2 between ca. 30 and 15 ka. This period corresponds to the maximum of Late Weichselian glaciation, when local ice caps were widespread and also likely covered Galicica Mountains down to ca. 1500 m a.s.l. (Hughes et al., 2006; Kuhlemann et al., 2008). The core from Lake Prespa does not indicate a glaciation down to the shore of Lake Prespa, such as proposed by Belmecheri et al. (2009). However, very cold conditions during the Last Glacial Maximum, with 6–9 °C lower temperatures compared to today (Peyron et al., 1998; Hayes et al., 2005), are likely correlated with oligotrophic conditions in the lake, reduced supply and replenishment of nutrients and Ca^{2+} and HCO^{3-} ions, and fostered decomposition of OM and dissolution of calcite by a well oxygenated water column and surface sediment, as it was also reported from Lake Ohrid (Vogel et al., 2010a).

Despite the only marginal variations in long-term sedimentation conditions in both lakes during the Pleistocene, there are some distinct short-term fluctuations. These

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short-term fluctuations are best indicated in distinct carbonate peaks and maxima in Mn concretionary horizons in the Lake Prespa record and by maxima in the Zr/Ti ratio and the sand content in the Lake Ohrid record (Fig. 7). Although expressed in different proxies, these short-term events occur almost simultaneously in both lakes, as evidenced by the occurrence of the tephra horizons providing a good age control during the Pleistocene. The only exceptions are the peaks in the Lake Ohrid record beyond ca. 48 ka, where the age control is a bit vague (cf. Vogel et al., 2010b). It can be excluded that tephra deposition in the lakes or in their catchments caused the significant short-term events, since the tephras were subtracted from the records and the events are located above, below or even far away from the respective tephra horizons. Tentatively, the short-term events can be correlated with the Heinrich events H1-H6 as identified in from several marine records from the North Atlantic (e.g., Bond et al., 1993; McManus et al., 1999; de Abreu et al., 2003; Fig. 7). The distinct carbonate peaks and maxima in Mn concretionary horizons in the Lake Prespa record indicate that the Heinrich events in the North Atlantic can be correlated with a lake level drop and increased ion concentration and mixis in the water column of Lake Prespa. Weakest environmental impact apparently occurred during H4. However, it has been shown that there are some overlaps between this event and the Campanian Ignimbrite eruption (Fedele et al., 2008) and the environmental signal may at least partly have been deleted by subtracting the Y-5 tephra from the Prespa record (Fig. 7). The maxima in the Zr/Ti ratio and the sand content in the Lake Ohrid record indicate higher aeolian activity, whilst the minima in arboreal pollen indicate lower temperatures during the Heinrich events (cf. Wagner et al., 2008; Vogel et al., 2010a). Cold and dry conditions in response to Heinrich events are also recorded in other Mediterranean records (e.g., Roberts et al., 2008; Wohlfarth et al., 2008; Stein et al., 2009; Castañeda et al., 2010). The records from lakes Prespa and Ohrid indicate that similar conditions also existed on the Balkans.

The Pleistocene/Holocene transition is relatively sharp in Lake Prespa and apparently more pronounced than in Lake Ohrid (Fig. 6). Although a gap in the record from Lake Prespa cannot be completely excluded, the sharp transition could also be caused

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by a delay of full interglacial conditions compared to other palaeoclimate reconstructions (Allen et al., 1999; Martrat et al., 2004; Lawson et al., 2004; Kotthoff et al., 2008; Bordon et al., 2009). Such a delay was already observed at Lake Ohrid and was attributed to prevailing cold winters with at least partial ice cover in the early Holocene (Vogel et al., 2010a). Similar conditions might have also affected Lake Prespa.

After the establishment of full interglacial Holocene conditions, absence of IRD and high amounts of TIC and TOC with some significant fluctuations characterize the sedimentation in both lakes (Fig. 6). Although the sedimentation pattern in both lakes is similar during the Holocene, organic matter content is much higher and carbonate contents are much lower in Lake Prespa compared to Lake Ohrid. These differences are most likely due to the differences in the catchment and the hydrology of both lakes (cf. Leng et al., 2010). Whilst Lake Ohrid is mainly fed by water from karst aquifers (Matzinger et al., 2006b), which provides sufficient Ca^{2+} ions to the lake, Lake Prespa is mainly fed by river runoff from numerous small streams (Matzinger et al., 2006a) from the granitoid and Ca^{2+} ion depleted eastern part of the catchment. The overall higher contents of organic matter in Lake Prespa compared to Lake Ohrid are likely the result of the lower water depths of Lake Prespa, thus leading to higher water temperatures and enhanced productivity in summer. In addition, these conditions likely promoted oxygen depletion of the bottom waters during summer, and could have led to decreased decomposition of organic matter. At present, the prevailance of anoxic bottom water conditions during summer in Lake Prespa is indicated by intense release of methane bubbles all over the lake. The distinct decline in carbonate contents of Lake Prespa at 4 ka could be caused by a significant increase in lake level, as it is reported from Lake Maliq nearby (Fouache et al., 2010). However, there is a discrepancy between increasing lake levels at Lake Prespa and Lake Maliq (Fouache et al., 2010) and increasing aridification inferred from stable isotope studies from lakes Prespa and Ohrid (Leng et al., 2010) and also reported from several other studies (e.g., Roberts et al., 2008) around this period. The mid to late Holocene climatic and particularly hydrological history in the northern Mediterranean apparently is characterized by

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several short-term fluctuations, and increasing anthropogenic influence, forest clearance, and/or tectonic activity probably led to local particularities. The mid Holocene general shift in environmental conditions seems to be less pronounced in the sediment sequences from Lake Ohrid (Fig. 6), probably because the concentration of Ca^{2+} ions in the water of Lake Ohrid was less affected due to the larger volume of this lake and the ongoing ion supply from karst aquifers. The relatively high carbonate concentrations in Lake Ohrid until about 2.5 ka, when anthropogenic influence led to a decrease in arboreal pollen and probably to increased erosion in the catchment of Lake Ohrid (Wagner et al., 2009), correspond well with increased organic matter contents in Lake Prespa (Fig. 6). A similar correspondence can be observed during the late Holocene. This suggests similar environmental and anthropogenic impacts on both lakes, which are however expressed in different parameters.

Short-term events during the Holocene, such as the 8.2 cooling event or a period of inferred wetter conditions between 4200 and 4000 yr BP with a significant lake level highstand in Lake Maliq (Fouache et al., 2010), are recorded in lakes Prespa and Ohrid by a distinct decrease of carbonate and organic matter content (cf. Wagner et al., 2009). As shown by biomarker measurements, particularly the 8.2 cooling event is characterized at Lake Ohrid by relatively dry conditions (Holtvoeth et al., 2010).

6 Conclusions

The study of a sediment record from Lake Prespa and the comparison of the results with those derived from former studies of Lake Ohrid revealed similar sedimentation patterns in both lakes during the last ca. 48 ka. The occurrence of tephra layers in both lakes and radiocarbon dates provide reliable chronological constraints for the sediment successions.

During the last ca. 48 ka, there is no indication for distinctly lower levels of Lake Prespa compared to today, although the relatively low volume and low water depth make the lake very sensitive to changes in precipitation and evaporation. We cannot

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exclude that the level of Lake Prespa was much higher in the past and that the recent level is close to its minimum.

The Pleistocene records from lakes Prespa and Ohrid indicate relatively stable sedimentation conditions. At least partial ice-cover on the lakes during winter, a well-mixed water column and oligotrophic conditions with a marginal increase of lake productivity at the end of MIS 3 characterize the lakes. Coldest conditions during MIS 2 are documented by lowest organic matter contents in both lakes and the highest abundance of concretionary horizons in Prespa, thus indicating a well mixed water column.

The Pleistocene/Holocene transition in both lakes is relatively sharp and delayed compared to other climate records from the region. The Holocene sediments are characterized by high contents of organic matter, particularly in Lake Prespa, and high contents of carbonate, particularly in Lake Ohrid. The differences between both lakes indicate that Lake Prespa had rather mesotrophic conditions during this period, since the lake water warms up faster in spring and summer. Lake Ohrid in contrast, with a larger volume and water depth, remained oligotrophic during the Holocene.

Short-term events are well documented during the Pleistocene and the Holocene. The most prominent short-term events during the Pleistocene are tentatively correlated with the Heinrich events, which are characterized by increased aeolian activity, lower temperatures and/or increased aridity on the Balkans. During the Holocene, the 8.2 cooling event and a period of inferred wetter conditions between 4200 and 4000 yr BP is well recorded in both lakes. Anthropogenic impact superimposed the climatic and environmental changes during the past ca. 2500 yr BP.

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Interactive Discussion

Table 1. Radiocarbon age determinations from Lake Prespa core Co1204. The depth values in brackets in samples KIA36356–KIA36358 indicate depths after subtraction of tephra thicknesses.

Sample	Core section	Corr. depth (cm)	Material	C (mg)	^{13}C (‰)	^{14}C age (yr BP)	Calendar age (cal. yr BP)
ETH39603	Co1204-1	9	shell remain		−7.30	−955±35	–[a]
ETH39604	Co1204-3	43	fish scale		−34.70	1070±50	1000±90
KIA36347	Co1204-1	53	plant remains	0.3	−27.51	235±50	–[b]
ETH39605	Co1204-3	96	plant remains		−26.70	3665±40	3990±100
KIA36348	Co1204-3	119	plant remains	1.1	−29.33	3745±30	4090±60
KIA36349	Co1204-3	166–172	plant remains	0.1	−24.48	6135±480	–[b]
ETH39606	Co1204-3	175	plant remains		−27.00	5265±40	6055±125
KIA36351	Co1204-3	186	plant remains	0.1	−23.71	6536±275	–[b]
KIA36352	Co1204-3	216	plant remains	1.7	−25.72	6230±40	7140±85
KIA36353	Co1204-3	239	plant remains	1.9	−27.80	6970±40	7800±50
KIA36354	Co1204-4	308	plant remains	1.1	−26.36	9075±55	10 250±50
KIA36355	Co1204-4	314	fish remains	0.2	−21.47	10 386±265	–[b]
KIA36356	Co1204-6	829 (821)	plant remains	1.9	−27.40	33 270±540	37 99 ±1130
KIA36357	Co1204-7	887 (863)	plant remains	3.3	−27.01	37 960±570	–[c]
KIA36358	Co1204-7	1001 (977)	plant remains	2.0	−27.14	>45 680	–[c]

[a] sample was not calibrated and used for age-depth model due to influence of bomb ^{14}C
[b] samples were not calibrated and used for age-depth model due to very low C contents
[c] samples were not used for age-depth model as they are close to or above the limits of radiocarbon dating

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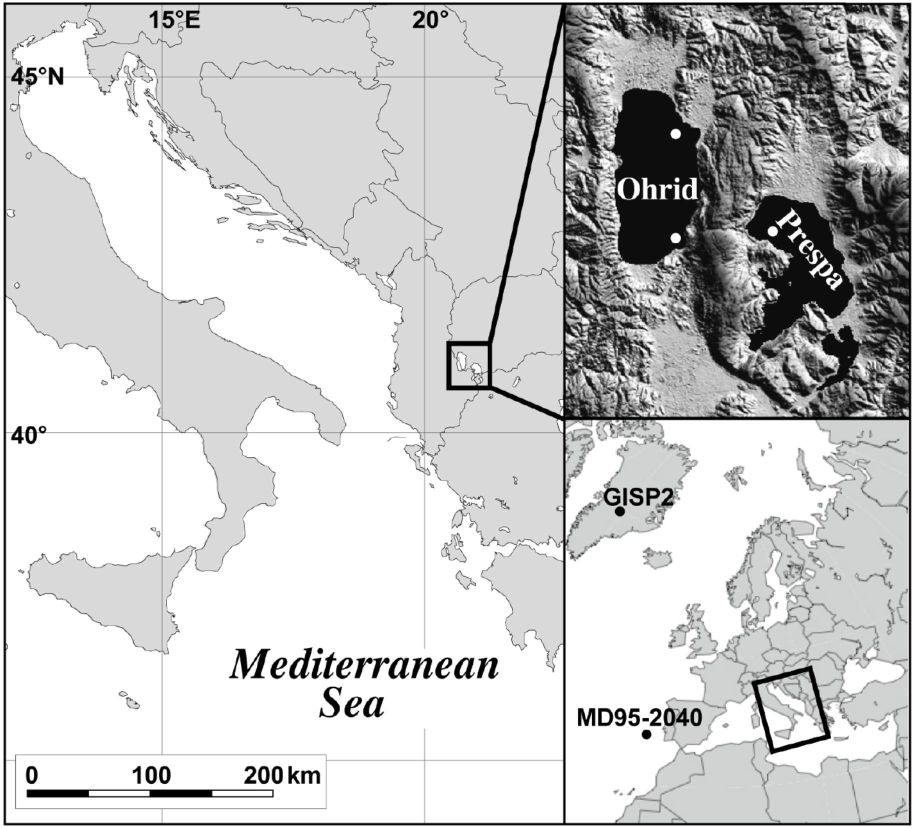

Fig. 1. Map of the northern Mediterranean region showing the location of Lakes Ohrid and Prespa. White dots indicate coring locations Lz1120 in the southeastern part of Lake Ohrid, Co1202 in the northeastern part of Lake Ohrid and Co1204 in the northwestern part of Lake Prespa. The insert at the right (bottom) shows the locations of the marine sediment core MD95-2040 from the western Iberian margin and the GISP2 ice core from Greenland.

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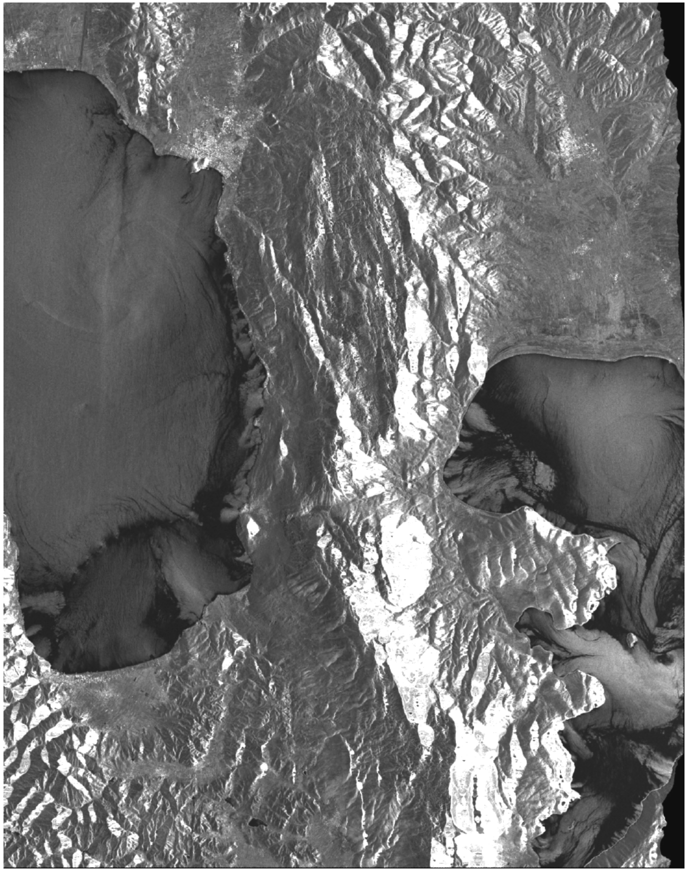

Fig. 2. Satellite radar image taken on 30 September 2009 (© DLR 2009) showing anti-clockwise surface currents in lakes Ohrid and Prespa.

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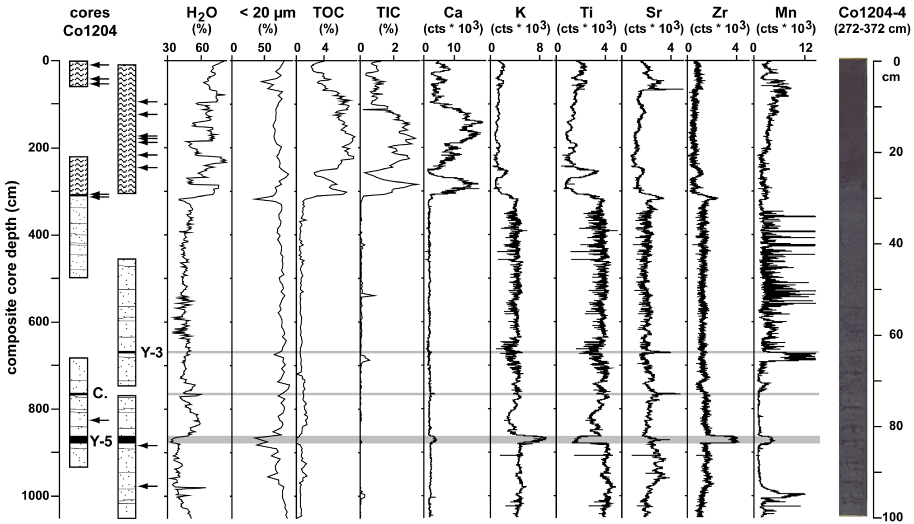

Fig. 3. Lithology, water content, amount of fine-grained particles, total organic carbon (TOC), total inorganic carbon (TIC), and calcium (Ca), potassium (K), titanium (Ti), strontium (Sr), zirconium (Zr) and manganese (Mn) counts of composite core Co1204 from Lake Prespa. Individual core segments are indicated to the left. Arrows indicate horizons, which were used for radiocarbon dating. Black bars in the lithology mark tephra horizons. The line scan photo to the right is from core segment Co1204-4, 272–372 cm field depth. This segment contains the transition from greyish Pleistocene sedimentation (bottom) to olive to greyish Holocene sedimentation (top).

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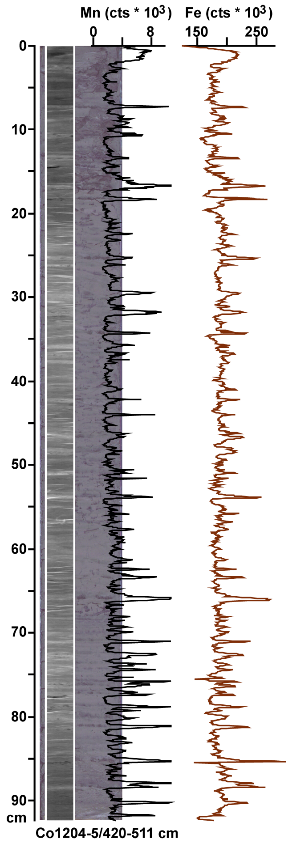

Fig. 4. Manganese (Mn) and iron (Fe) counts from XRF scanning in core segment Co1204-5 from 420–511 cm field depth. Maxima in Mn and Fe counts are correlated with dark grey spots or black horizons in the line scan photo and with light horizons in the radiography (overlain on the left side of the line scan photo) and indicate concretionary spots or horizons.

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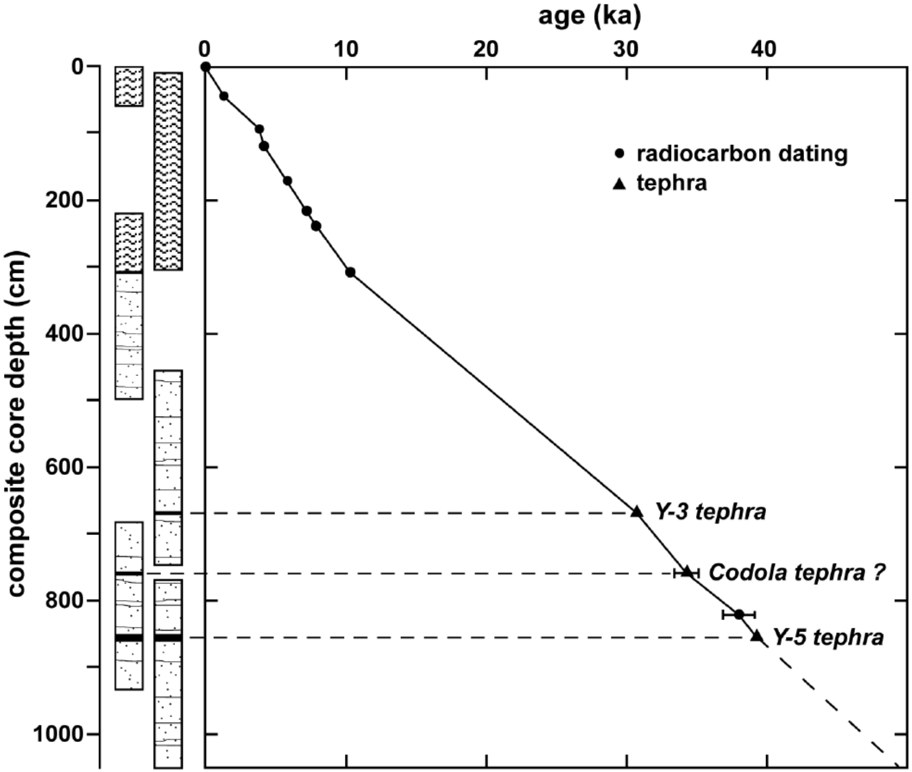

Fig. 5. Age-depth model of core Co1204 based on linear interpolation between dated horizons. Ages from tephras and cryptotephras are based on Sulpizio et al. (2010) and indicated by triangles. Ages (in calendar yr BP) from radiocarbon dating of macrofossils are indicated by black dots.

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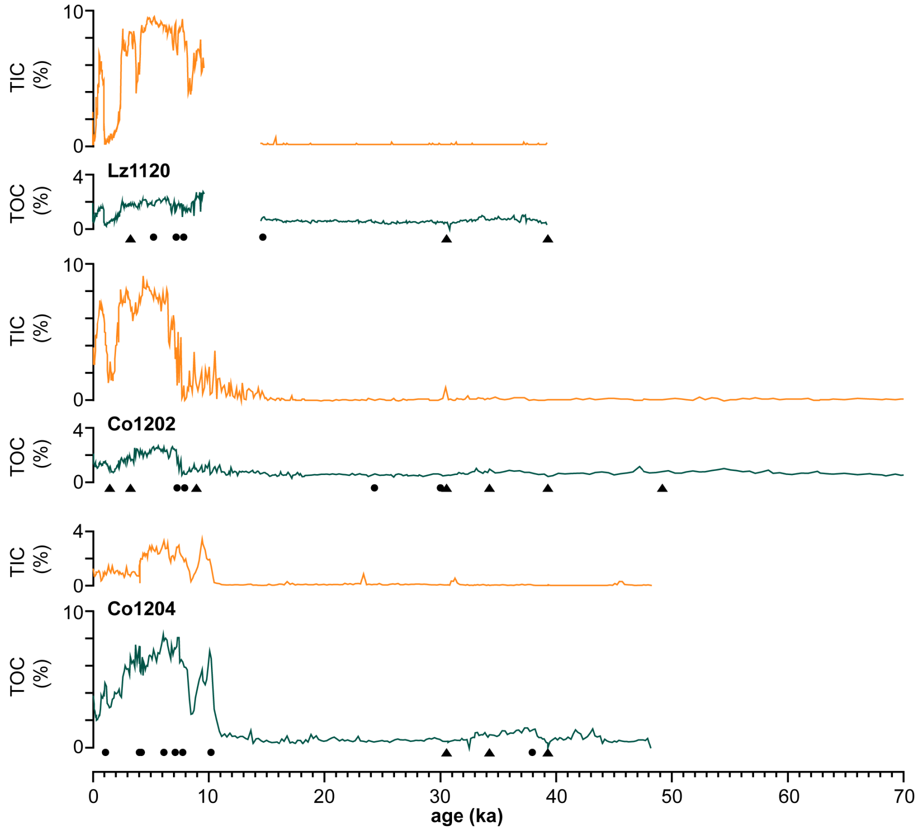

Fig. 6. Comparison of total organic carbon (TOC) and total inorganic carbon (TIC) contents in cores from Lake Prespa (Co1204) and Lake Ohrid (Co1202 and Lz1120). For location of the cores see Fig. 1.

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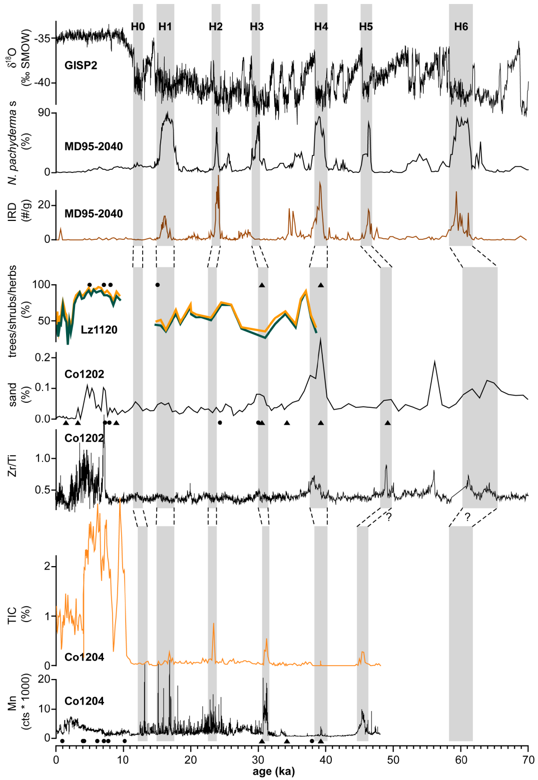

Fig. 7. Palaeoenvironmental records from Lake Prespa (core Co1204) and Lake Ohrid (cores Lz1120 and Co1202; Wagner et al., 2009; Vogel et al., 2010a) compared with the number of IRD grains and the cold water thriving foraminifera *N. pachyderma* from the western Iberian margin (Fig. 1; MD95-2040; de Abreu et al., 2003) and with the d^{18}O record from the GISP2 ice core (Grootes et al., 1993). Black dots and triangles in the cores from lakes Prespa and Ohrid indicate horizons, which were used for radiocarbon dating and tephrochronology. The timing and thickness of Heinrich events H1-H6 is according to de Abreu et al. (2003).

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