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Quaternary coastline evolution of Lake Ohrid (Macedonia/Albania)

Research article

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Abstract: Lake Ohrid (between FYR of Macedonia and Albania), situated in an active tectonic region of the Balkanides, is characterized by N - S trending active faults. To reconstruct the Holocene shoreline evolution we investigated the coastline using sediment cores and geophysical methods to image sedimentary and tectonic structures. We revealed areas of differing sedimentation regimes. The plains north and south of the lake are dominated by clastic input related to climate variations and uplift/erosion, whereas the steep western and eastern margins are controlled by recent tectonics. Furthermore, no evidence for a much higher lake-level during the Holocene was found in the plains north and south of the lake, except rare temporary floodings. This is supported by mappings of the limestone cliffs around Lake Ohrid, which yielded no evidence for abrasional platforms or notches as indicators for past highstands.

Keywords: Lake Ohrid • neotectonics • normal faults • geophysics

1. Introduction

The Lake Ohrid Basin hosts a cross-boundary lake, which is shared by the Former Yugoslavian Republic of Macedonia (from hereon referred to as Macedonia) and Albania. It is framed by the Galicica Mountain Range with heights of up to 2,250 m to the east and the Mokra Mountain Range with heights up to 2,200 m to the west. While the straight eastern and western shorelines of the lake are determined by neotectonic movements along faults [1, 2], the northern and southern parts of the basin are characterized by plains (fig. 1). They could constitute former parts of Lake Ohrid which have been dried or drained for agricultural use.

The lake is of scientific interest for a number of disciplines. It exhibits the highest endemic diversity for its surface area, which makes it valuable for biologists to study biodiversity, endemism and speciation [3, 4]. Several other authors are working on hydrology [5, 6] and on the relation between the neighbouring Lakes Ohrid and Prespa.

Information on paleoclimate development since the last glacial-interglacial cycle and on coastal evolution was already presented by Vogel et al. and Lindhorst et al.

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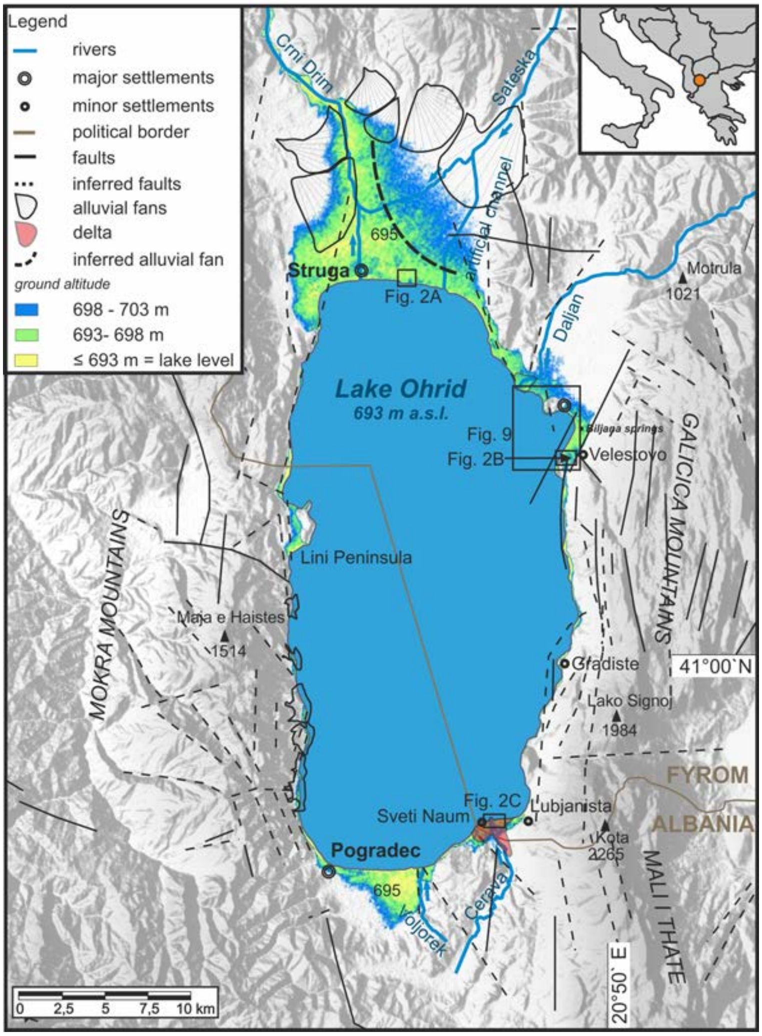

Figure 1. Geographical overview of the Lake Ohrid Area in Macedonia and Albania showing major rivers, alluvial fans, plains and deltas. Locations of investigation are marked with a box. Modelling of the lake-level is based on SRTM data to derive palaeoshorelines. The colored areas do not exceed heights of 10 m above lake-level. Note the normal fault off-shore from the Velestovo site.

[7, 8]. Offshore cores from Lake Ohrid show significant water level lowstands in the Pleistocene, which probably only affected biodiversity in the shallow coastal areas.

We studied the lake-shore and deltaic deposits of the major inflows in order to obtain information on both Holocene lake-level changes and also tectonically induced coastline modifications, which are most likely in this seismic active area [2, 9]. The obtained sediment cores and shallow geophysics (Ground Penetrating Radar and electric resistivity) revealed the large-scale sediment architecture. Grain size and geochemical analyses as well as micropalaeontological investigations supplement the results.

2. Regional setting

The Lake Ohrid Basin lies within the Albanides, which provide the link between the orogenic belts of the Dinarides and Hellenides [10]. It is located within a "basin and range" setting in the extensional back-arc environment of the Northern Hellenic Trench, which is referred to as the Southern Balkan Extensional Regime [11]. This area, especially the intramontane basins of Late Neogene age, forms one of the most active seismic zones in Albania/Macedonia with several moderate earthquakes reported during the last few centuries [12, 13]. Major earthquakes also have occurred during historical times with magnitudes up to M 6.6 [2].

Since the Late Cretaceous three periods of regional extension, separated by periods of compression, affected the area. The last two phases in Eocene/Oligocene and Miocene/Pliocene represent the major periods of extensional deformation [11, 14, 15]. The onset of the formation of the Ohrid and Debar lakes is widely discussed. Trajanovski et al. [16] suggest, on the basis of genetic data of the Lake Ohrid biota, that the lake formed 2-3Ma ago. In contrast, Dumurdzanov et al. [11, 14] places the formation in the Late Miocene in the "Uppermost Meotian to Pontian (5-9Ma ago)", which is referred to as the second major period of extension. This re-established progressive roll-back of the Northern Hellenic Trench after the subduction of the Kruja fragment led then to a WSW - ENE directed extension with NNW trending normal faults [15].

Today, the following geodynamic situation in the Balkans can be observed:

1. ENE - shortening along the Albanian coast, with the formation of NW to NNW striking thrusts and faults [15, 17].

2. E - W extension in eastern Albania and western Macedonia with dominating N striking normal faults [9, 15, 17]. This is also expressed by a series of large, approximately N - S trending grabens bounded by normal and transtensional dextral strike-slip faults [18]. In addition, recent GPS velocities indicate E - W extension with rates of about 2 mm/y across the N - S trending Ohrid and Prespa grabens [18].

3. N - S extension in eastern Macedonia and Bulgaria [14, 15, 19].

The Lake Ohrid Basin holds a fresh-water lake, which covers an area of 360 km^2 with an extent of c. 30 km N-S and c. 15 km E-W. The present lake-level of Lake Ohrid (at 693 m a.s.l.) undergoes annual fluctuations of max. 2 m, reaching its peak value in June and its minimum water level in October/November, while precipitation shows the opposite trend, with a maximum in November and a minimum in July. The reason is that a high portion of this precipitation is snow accumulating in the mountain regions until it starts melting in April [5]. In general, a decrease of 0.67 cm/a for the average water level was observed by Popovska et al. [5].

Climatic conditions are continental and strongly influenced by the water bodies of Lakes Ohrid and Prespa, which reduce temperature extremes. An average rainfall for the Lake Ohrid watershed of 907 mm has been determined by Popovska et al. [5].

The lake is presently drained by the Crni Drim River at the northern end of the basin. Today the outflow is regulated to stabilize the water level. It has been suggested that draining had already started in the Lower Pleistocene, as evidenced by deeply incised channels [14]. Major fluvial inflows are from the rivers Daljan, Sateska, Cerava and Voljorek (fig. 1) with their distinct deltas. Also, high inflow is observed from multiple karstic springs (sublacustrine and subaerial; [3, 5]). The basin, with a total depth of roughly 1,000 m below the present lake level preserves c. 700 m of sediments [2, 8]. The watershed of Lake Ohrid extends fairly over 2,393 km^2 including Lake Prespa and its tributaries [5]. Because of the large extent of the karst system and the hydrological connection with Lake Prespa, the exact spatial distribution of the Lake Ohrid drainage basin is hard to determine.

Geological formations around the Lake Ohrid Basin mainly comprise low to medium-grade metamorphosed Paleozoic sedimentary rocks and Triassic limestones of the Galicica and Mali i Thate Mountains [9, 14]. The western shoreline is characterized by Jurassic ophiolites of the Mirdita Zone, mainly consisting of lherzolites, gabbros and minor harzburgites. Syn- and post-orogenic Oligocene-Miocene molasse sediments are present only west and south of Lake Ohrid [9].

3. Methods

In order to delineate the Holocene-Late Pleistocene shoreline evolution and lake-level fluctuations, we studied coastal environments around Lake Ohrid with shallow subsurface geophysics to obtain sedimentary and deformational structures [2]. We applied Ground Penetrating Radar (GPR) and geoelectrical (resistivity) measurements as non-invasive methods for subsurface investigations. An SIR 3000 GPR system by GSSI with 270 MHz and 100 MHz antennas was used to cover penetration depths of 3 - 20 m with a maximal vertical resolution of 7 cm. The data were processed with ReflexW software (version 5.6 by Sandmeier [20]). We applied DC-resistivity measurements with the "4-Punkt light" geoelectrics system from Lippmann Geophysikalische Messgeräte; inversions were computed with RES2DINV v. 3.58 by Geotomo software. Due to the limits of the software version, only three inversion steps could be calculated. Since the errors were relatively small, they did not affect the interpretation.

We used a Klein 3000 dual frequency Sidescan-sonar with 100 kHz and 500 kHz transducers connected to a lightweight cable for investigations of the lake floor morphology. The entire area of Ohrid Bay was mapped up to 100 m water depth, with profiles covering widths of 150 or 200 m. Data were then processed with the mosaicking

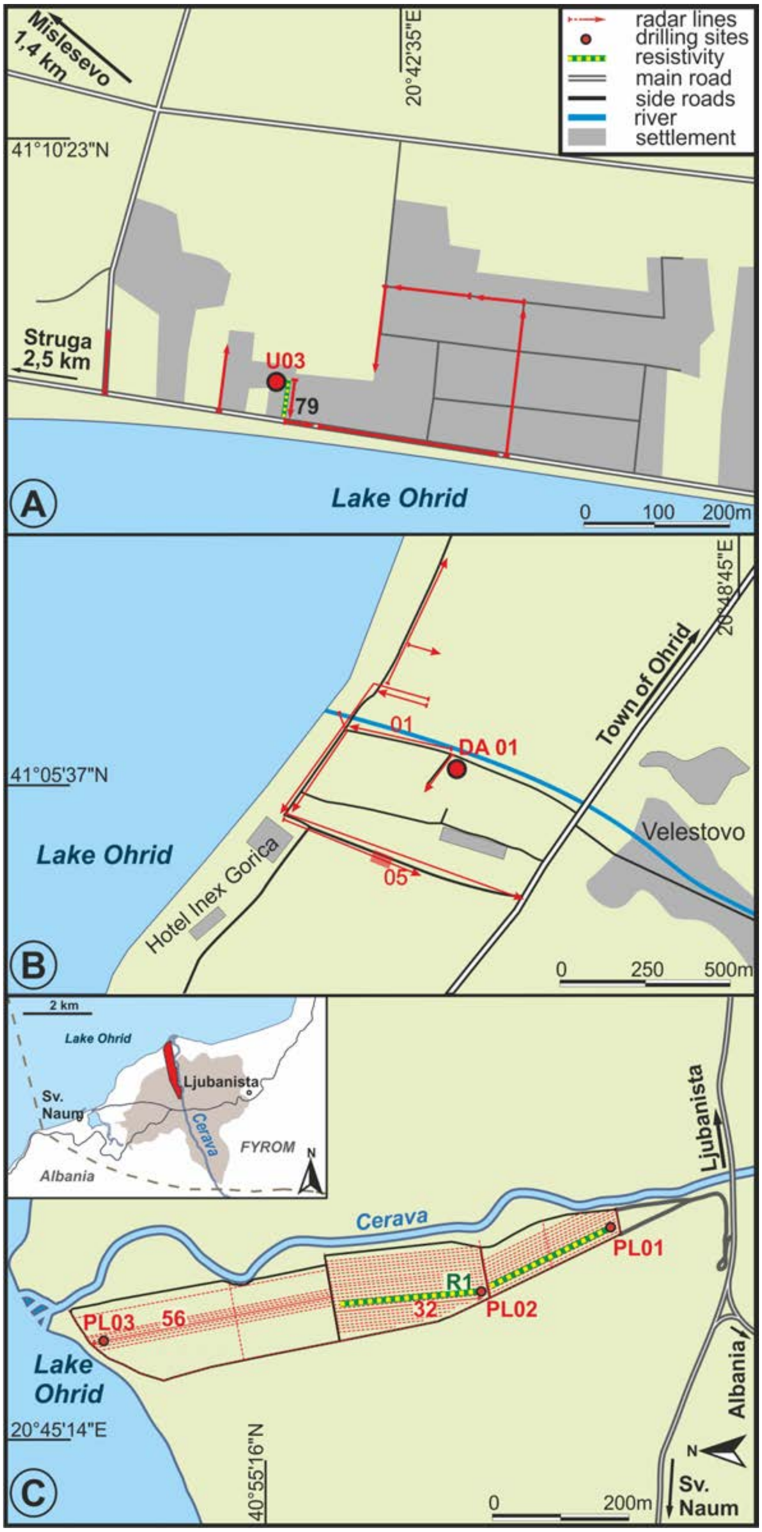

Figure 2. Map locations are shown in fig. 1. A: Sketch map of the study area near Struga. Electric resistivity measurements were carried out parallel to radar line 79 (see fig. 5). U03 marks the drilling site; the core log is illustrated in fig. 3. B: Radar and drilling localities at the Velestovo site. For core log of DA01 see fig. 6. The red box shows the segment of GPR line 05 displayed in fig. 8. C: Sketch map of the investigation site at Sveti Naum/Ljubanista. Core PL03 is plotted in fig. 10. Radar reflection lines (no. 32 and 56) are displayed in fig. 11 and fig. 12A). Electric resistivity measurement R1 is illustrated in fig. 12B).

software SonarWiz and we used a georeferenced image with 0.5 m resolution for further analysis.

In addition to the geophysical survey, a detailed sediment analysis of shortcores was performed and the microfaunal content, the composition of sediments, and their architecture were studied. Sample aliquots were wet sieved on a 0.063 mm mesh and oven dried. Macro and microfossils were sorted and identified for palaeoenvironmental analysis. The ostracods were identified by the works of Klie and Petovski [21–30].

Magnetic susceptibility, X-ray fluorescence analysis (XRF) and radiocarbon dating were additionally used where applicable. For magnetic susceptibility measurements the Bartington MS2 system was used with the MS2K sensor in our lab. The response volume for the MS2K of the sample is on the order of 0.2 cm^3. The sample interval was between 1 cm and 2.5 cm. Radiocarbon dates from organic material such as leaves and roots in core DA01 were measured at the Keck Carbon Cycle AMS Laboratory of the UC Irvine and calibrated into calendar years before present (cal. a BP) using the CalPal2007HULU calibration curve [31].

4. Locations

Three locations were chosen close to the shoreline of Lake Ohrid in order to study sedimentary evidence of past lake-level fluctuations and of the evolution of the plains (fig. 1). At each location, radar lines, drilling/coring, and resistivity measurements were applied. The location "Struga" (fig. 2A) is situated east of the town of Struga (41°10′14″N, 20°42′28″E) in the northern plain of the basin near the outlet of Lake Ohrid and close to the river Sateska. The sedimentation here is mainly controlled by alluvial processes and large fan complexes. Formerly swampy wetlands in the lower areas have been drained for agricultural use.

The second location is south of the town of Ohrid (41°05′38″N, 20°48′18″E), on the eastern shore of the lake, close to the village Velestovo (fig. 2B). Here, the fault-related steep slopes of the Galicica Mountains [9] generate a high relief and supply the water for a relatively small swampy area with a minor alluvial channel and fan. This site should provide insight into the fault mechanisms driving basin development and give evidence for the interaction between lake-level fluctuations and basin extension.

The third site is located in the southern part of Lake Ohrid near the monastery of Sveti Naum (40° 55′23″N, 20° 45′ 19″E) and east of the Macedonia/Albanian border in the

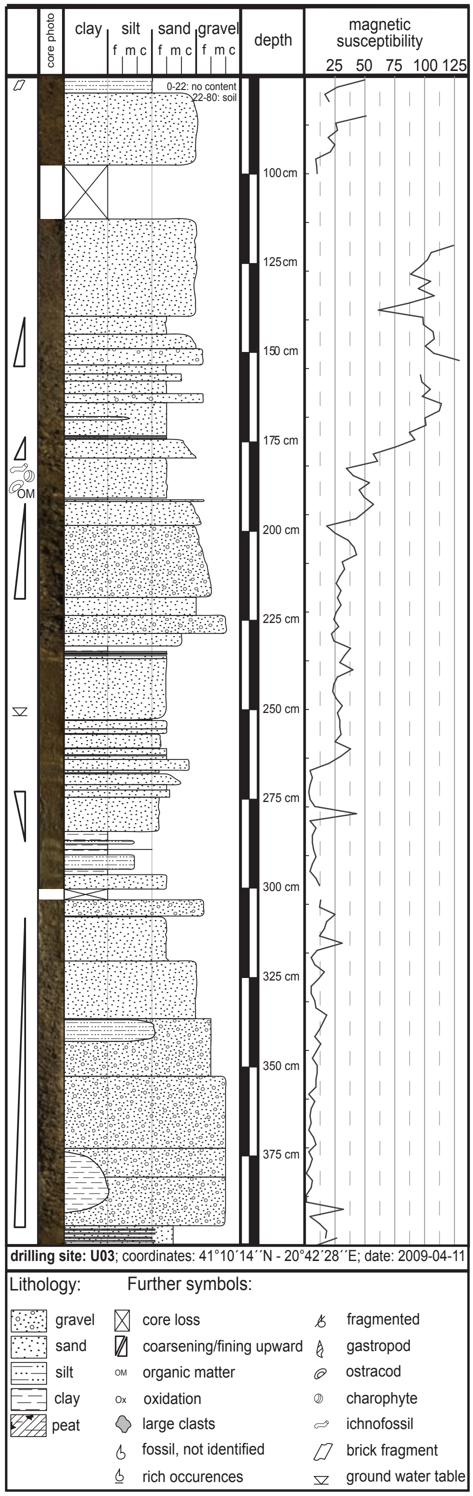

Figure 3. Core U03 at the Struga site with a total length of 400 cm. Grain size, fossil content and magnetic susceptibility are displayed. The first 75 cm are not illustrated because of loss of core material. The ground water table can be observed at about 250 cm by a sudden increase of water content in the sediment.

village of Lubjanista (fig. 2C). In this area, many subaerial karstic springs feed Lake Ohrid [4], and the Cerava River discharges into the lake via a delta. Together with the Struga site, this area is suitable to study the plain's evolution.

5. Results and interpretation

5.1. Struga

5.1.1. Drilling and core logging

The core recovered close to Struga has a total length of 400 cm (fig. 3). The water table was encountered at approximately 2.50 m depth, which corresponds to the present-day lake-level. In general, we can summarize the lithology of core U03 in 4 stratigraphical and sedimentological intervals; the facies points to deltaic sediments.

(1) 400 - 275 cm: Mixed clastic sequence ranging from gravels to clays. Sieve residues of this interval yield a significant lacustrine fossil content, consisting mainly of remains of charophyte algae (carbonate-coated stems and oogonia), tubes of tubifids, and ostracod valves. The latter taphocoenosis is fairly diverse and contains juveniles and adults (fig. 4).

(2) 275 - 175 cm: Deltaic mixed clastic-lacustrine sediments as evidenced by *Chara oogonia* and ostracod assemblage. Clayey and silty layers are intercalated with fine-grained sands between 275 and 233 cm. Above 233 cm, sand and gravel layers with fining-upward sequences follow.

(3) 175 - 80.5 cm: Fluvial sediments made up of sand to fine-grained gravel with fining-upward sequences. The coarser components show an oval shape, indicative of a longer fluvial transportation distance.

(4) Anthropogenic filling from 80.5 - 0 cm containing fragments of bricks (at 58.5 cm, 56 cm and 37.5 cm).

The subdivision is also mirrored in the results of magnetic susceptibility (MS) measurements (fig. 3). From the bottom to the top of the core the MS signal generally gets stronger, and, remarkably so at the sedimentary interval changes. The signal remains almost stable within each of the four sedimentary units.

The ostracod fauna in the core material of U03 is diverse and dominated by Candonidae (e.g., *Cypria obliqua, C. ophtalmica, Candona parvula, C. lychnitis, C. trapeziformis* and *C. hartmanni*, fig. 4), associated with *Paralimnocythere slavei, P. karamani* and *Amnicythere (Leptocythere) karamani*. Characeae remains and fragmented aquatic shells complement the findings.

5.1.2. Geophysical investigations

A total of 24 radar profiles were made in the Struga area (fig. 2A). Radarline 79 has a total length of 47 m and depicts the subsurface architecture of sedimentary intervals (fig. 5A). The upper interval to a depth of maximum 180 cm is characterized by diffuse horizontal to subhorizontal reflectors caused by diffraction hyperbolae of larger clasts. Based on our drilling results we ascribe the interval from 0 - 80 cm to the anthropogenic layer (e.g. a buried tube at horizontal 19.5 m) and the following 80 - 175 cm to the interval influenced by fluvial processes. Below this horizon a set of S - dipping reflectors at up to 300 cm depth were found along the entire length of the profile. The dip angle of the reflections varies between 5 and 10°. Below 300 cm depth (which corresponds to 60 ns) the radar signal diminishes and no interpretable data were obtained. The extinction of electromagnetic waves may be due to the ground water level (lake-level).

The resistivity profile (fig. 5B), which runs parallel to radarline 79, does not show as comparably high resolution as the GPR. However, it also shows a change around 300 cm depth to very weak resistivity. This could be the result of sedimentary change, but a high water table is the more likely explanation. Additionally, a gentle dip to the S can be observed along the entire profile, which might be related to the aforementioned orientation of the foresets.

5.1.3. Interpretation

The sediment core from the Struga site shows a typical channelized fluvial facies in the upper part. In the lower part a change into deltaic sediments with fining-up and alternating coarse- and fine-grained layers at up to 300 cm depth, including littoral faunal and floral evidence, is recorded. The identified ostracod fauna consists of a rich littoral species assemblage (fig. 4). Remains of *Chara sp.* are also generally found in water depths of between 3 and 20 m in Lake Ohrid [3]. Today, Characeae normally occur at not deeper than 12 m. Therefore, the faunal and floral remains at approx. 200 cm depth in the core are interpreted as a lake-level high stand. According to the results of GPR and drilling, the lakeward dipping reflectors are interpreted as delta foresets of the mixed fluvial-lacustrine layer.

The shallow topography of the northern Struga plain can be taken as an indicator of a wider extent for the lake during past times. Later, the plain was exposed by lake-level drop, or, alternately, it represents an area of lower subsidence and higher sedimentation rates, as evidenced by the large alluvial fans (fig. 1).

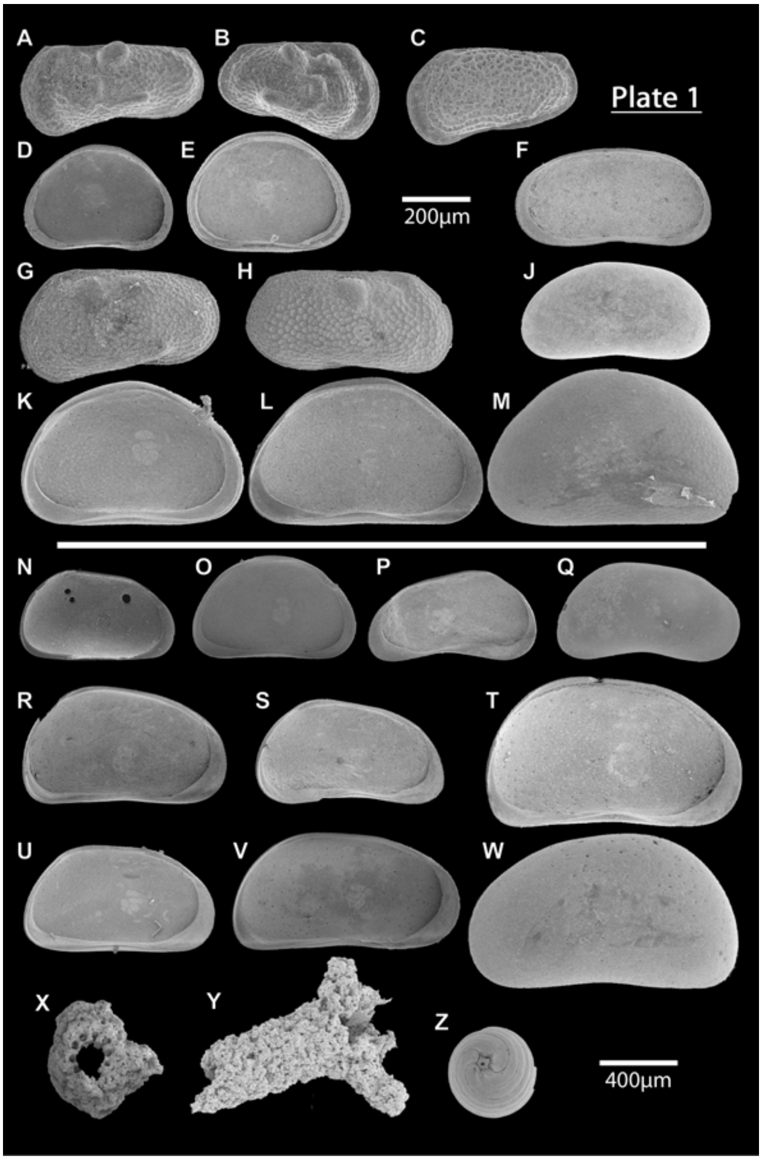

Figure 4. Fossil ostracods. A- *Paralimnocythere karmani* [26] (male), LV, extern., U02 (182 - 187.5 cm), 560 µm; B- *Paralimnocythere karmani* [26] (female), RV, extern., U02 (182 - 187.5 cm), 480 µm; C- *Leptocythere karamani* [22], LV, extern., U02 (182 - 187.5 cm), 500 µm; D- *Paralimnocythere slavei* [28] (female), LV, extern., DA01 (885 - 890 cm), 610 µm; E- *Paralimnocythere slavei* [28] (male), RV, extern., DA01 (880 - 885 cm), 610 µm; F- *Cypria ophtalmica* (Jurine, 1820), LV, intern., U02 (182 - 187.5 cm), 435 µm; G- *Cypria oblique* [21], LV, intern., U02 (182 - 187.5 cm), 475 µm; H- *Candona parvula* Mikulic, 1961, RV, intern., U02 (182 - 187.5 cm), 580 µm; J- *Candona goricensis* Mikulic, 1961 (male), LV, intern., DA01 (880 - 885 cm), 840 µm; K- *Candona lychnitis* [29], RV, extern., DA01 (880 - 885 cm), 985 µm; L- *Candona hartmanni* [29], LV, intern., U02 (182 - 187.5 cm), 1020 µm; M- *Candona trapeziformis* [23], LV, intern., U02 (182 - 187.5 cm), 1000 µm; N- *Candona formosa* Mikulic, 1961, LV, intern., DA01 (880 - 885 cm), 1240 µm; O- "Characeae" stem, planar, U02 (182 - 187.5 cm); P- "Characeae" stem, lateral, U02 (182 - 187.5 cm); Q- "Characeae" oogonia, U02 (182 - 187.5 cm); R- *Candona lychnitis* [29], LV, intern., DA01 (880 - 885 cm), 1435 µm.

5.2. Velestovo

5.2.1. Drilling and core logging

The core drilled at the Velestovo site (fig. 6) has a total length of 900 cm. The ground water level was encountered at approximately 3.7 m depth. Four main stratigraphic sequences are apparent:

(1) 900 – 700 cm: Gray-yellowish-whitish marly open-lacustrine deposits, partly laminated, with a record of littoral faunal and floral remains (e.g. shell fragments of gastropods, tubes of tubifids, ostracod valves and oogonia of *Chara sp.*; fig. 4). The high carbonate content

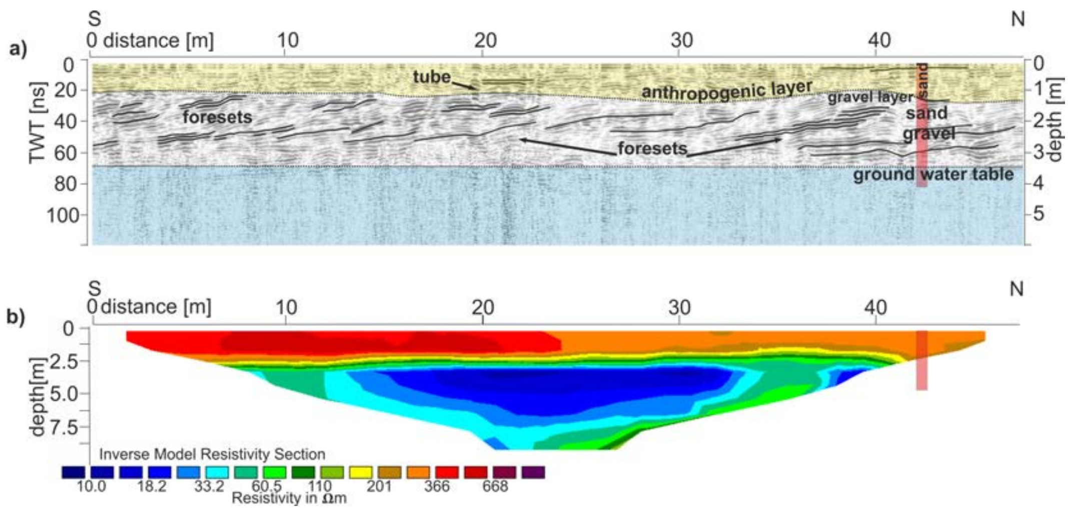

Figure 5. a) Interpreted N-S oriented GPR line no. 79 (270 MHz antenna) at the Struga site with a total length of 47 m. Core U03 and lithologies are projected into the profile. Vertical exaggeration 1.5. b) Resistivity measurement in Wenner array with an electrode spacing of 1.25 m and a maximum depth of 8.28 m. Three iterations were applied for inversion with a final error in the model of 2.0%. The red column shows the projected position of core U03. Sudden drop of resistivity values at an approximate depth of 3 m is interpreted as the water table.

Table 1. Radiocarbon dates of core DA01. Radiocarbon concentrations are given as fractions of the modern standard, D^{14C}, conventional radiocarbon age, following [32], and calibrated radiocarbon age after [31]. Sedimentation rates were calculated from the 14C ages assuming that the differing compaction of several lithofacies is neglectable.

	DA01-1	DA01-2	DA01-3
depth [cm]	373 - 381	656 - 662	800 - 820
14C conventional [aBP]	1765 ± 15	3540 ± 15	6520 ± 20
14C calibrated [cal. aBP]	1674 ± 34	3825 ± 37	7440 ± 9
sedimentation rates [mm/a]	2.28	1.31	0.44

hints to a possible influence by carbonate influx of the karstic springs of Biljana (fig. 1). Noteworthy is the sediment section between 830 and 800 cm composed of clayey marls (high proportion of carbonate) with a high content of organic material and gravel (clasts up to 2 cm). This part contains organic remains such as particles of roots and leaves, coaly fragments and seeds, as well as ostracods, oogonia and the calcified stems of *Chara sp.*

(2) 700 - 300 cm: Swamp development in a coastal lagoonal environment influenced by occasional fluvial terrigenous input. Several peat sequences are intermitted by silts and sands including fining-upward sequences (e.g. 520 - 502 cm). At 304 cm, a 4 cm thick debris flow layer, with a silty matrix containing gastropods and gravel, occurs.

(3) 300 - 178 cm: Silty and sandy section of terrigenous material containing organic matter and fragmented carbonate shells, possibly originating from a close-by fluvial channel, and representing distal fine-grained deposits.

(4) 178 - 0 cm: Anthropogenically modified horizon, with grain sizes between silt and gravel. The entire sequence contains large clasts up to 20 mm in diameter, brick fragments, charcoal and roots. At a depth of 173 - 150 cm aquatic and terrestrial gastropods have been encountered.

The MS signal (fig. 6) also reflects the four stratigraphic intervals described above and correlates well with the sequences. However, major positive excursions are observed in the peaty sections. Almost no MS signal is given in the marls of the lowest part (700 - 900 cm) with deviations between 830 and 800 cm, where values increase.

The core material of DA01 is less diverse in its ostracod fauna than core U03 (*Candona formosa, C. goricensis, C. lychnitis, Paralimnocythere karamani* and *P. slavei*) and less well preserved, but Characeae remains and fragmented aquatic gastropod shells are also present.

XRF data were obtained for the lower 2 m (900 - 700 cm) of the Velestovo core. The elements K, Ca, Ti, Fe, Sr and Zr/Ti were plotted in figure 7. It is obvious that this part of the core is relatively uniform apart from the sequence between 830 cm and 800 cm, where the values in

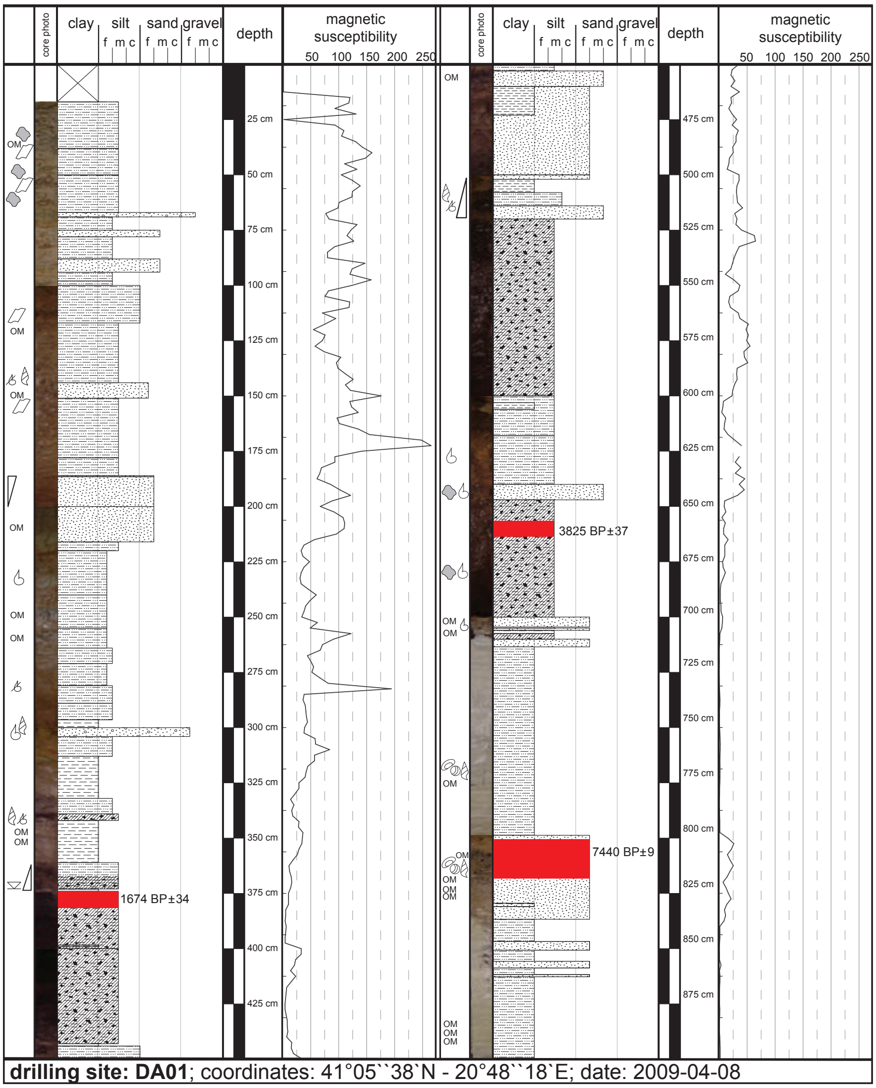

Figure 6. Core DA01 with a total length of 9 m. Grain size, fossil content, and magnetic susceptibility are displayed. The red signature shows the location and calibrated age of the 14^{C} samples.

all plotted elements vary distinctively. These observations correlate well with the MS data.

The radiocarbon ages for three samples taken at 820 cm, 662 cm and 381 cm depths are displayed in Table 1. DA01-3 (7440 cal. a BP ± 9) was sampled from the section 830 - 800 cm, which is described in detail above. Samples DA01-2 (3825 cal. a BP ± 37) and DA01-1 (1674 cal. a BP ± 34) were taken in peat sequences containing high portions of roots and wood.

5.2.2. Geophysical investigations

The GPR profile 05 at the Velestovo site has a total length of 350 m (see fig. 2B). Generally weak and mainly parallel reflections are observed, with a representative 35 m of the entire profile shown (fig. 8). The topmost 50 cm show parallel reflectors and anthropogenic modifications (e.g., a tube at horizontal 260 m with road construction). A rugged pattern points to gravel horizons with concave-up reflectors, which are interpreted as a channel structure (at horizontal 237 - 243 m). Below that, a slight inclination of the strata towards the lake (W) is observed (fig. 8). At about 75 ns TWT, corresponding to 370 cm depth,

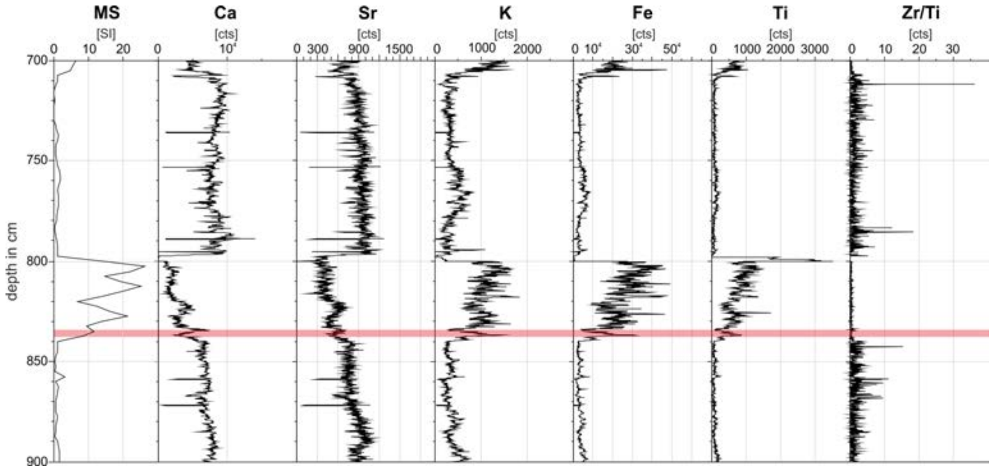

Figure 7. Magnetic susceptibility and XRF-measurements from the depth 900 - 700 cm of core DA01. Element intensities of Ca, Sr, K, Fe, Ti and Zr/Ti are displayed as counts (cnts). The red signature refers to the sample at 836 cm depth which is described in section 5.2.3. The analysis was carried out at the Institute of Geology and Mineralogy at the University of Cologne using an ITRAX core scanner (COX Ltd.). Scanning resolution was set to 1 mm with an analysis time of 10 s per measurement. The relative concentrations of the elements were derived as an equivalent to the count rates.

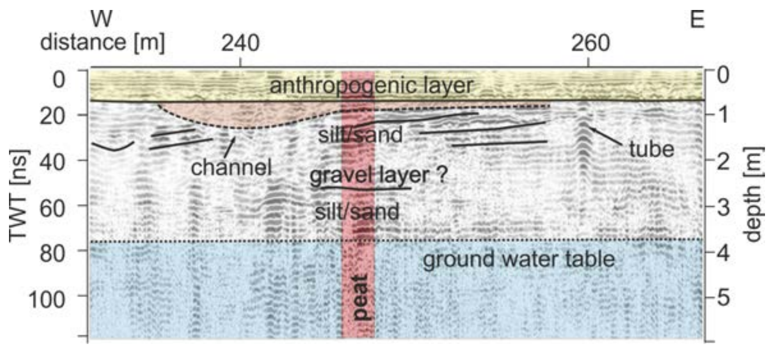

Figure 8. Segment 230 - 265 m in W-E orientation of GPR line 05 (270 MHz antenna; total length 346 m) including interpretation. The red signature shows the projected position of core DA01 including lithology. Vertical exaggeration 2.6.

the radar signal vanishes. No interpretable data were obtained below, most likely due to the action of the ground water table.

5.2.3. Interpretation

The Velestovo site exhibits a sudden change of sedimentary regime along the Lake Ohrid coast. The formation of the carbonate-rich marly lake sediments of the lowest section (900 - 700 cm) can probably be related to input from the karstic springs of Biljana [4]. As proposed by Lézine et al. [33], the origin of the calcareous sediments are limestone outcrops, where the carbonates are dissolved by rain water and soil acids and transported into the lake as run-off or by the karstic aquifers. In contrast, the organic and clastic rich interval between 830 and 800 cm testifies to a high clastic input in times of high precipitation. This hypothesis is supported by the geochemical data, where highs in the Ti content are interpreted as fluvial clastic input [7]. The lamination observed in core DA01 needs a relatively calm depositional environment, which does presently not exist, as the Velestovo site is situated along the east coast of Lake Ohrid, which is generally affected by western wind and wave action. But the geomorphology at this stretch of coast could possibly have built a local lagoon in Holocene times, which would have provided such a depositional environment, protected from strong winds and waves. A sedimentation rate of 0.44 mm/a for this site was calculated from the radiocarbon ages and correlates well with the data of Vogel et al. and Leng et al. [34, 35] who show a sedimentation rate of 0.5 mm/a for the Late Holocene in core Co1202 (located offshore, NW of Velestovo). In Lake Ohrid, a significant hard water effect on 14^C dates was observed by Wagner et al.[1, 36] where a sample from surface sediments was

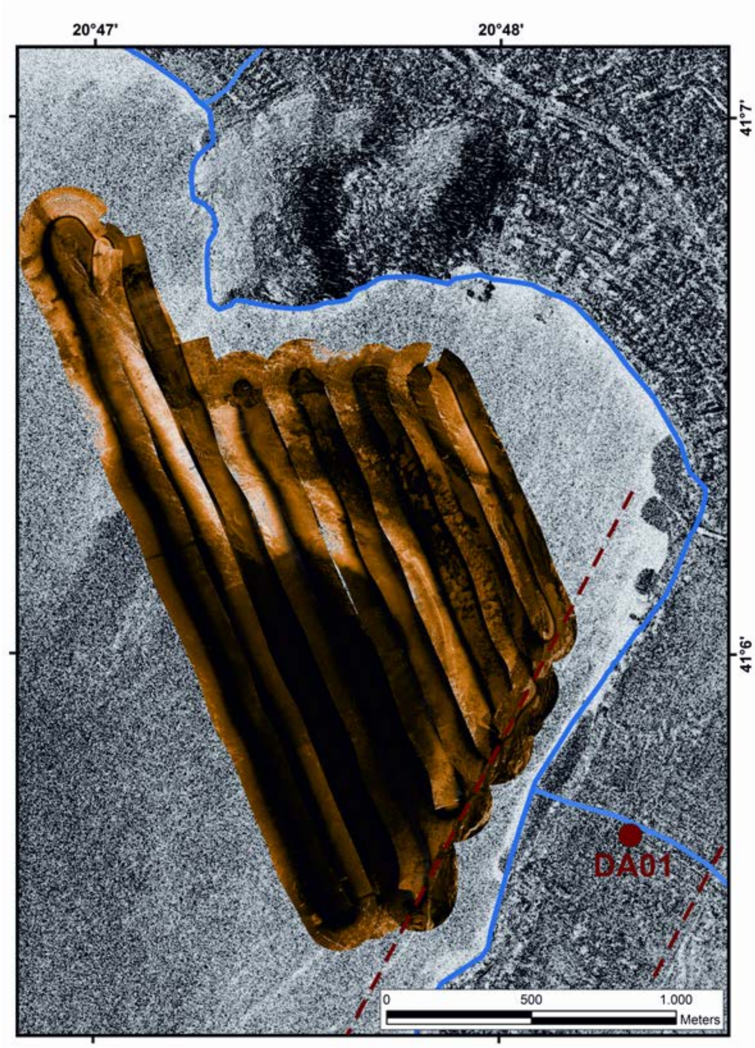

Figure 9. Sidescan sonar data from Ohrid Bay showing fault trace indicated by the red dashed line. Core DA01 is projected into the graphic.

dated 1560 14C BP. An effect like this in sample DA01-3 would lower the sedimentation rate to approximately 0.3 mm/a in this section. Notwithstanding, as the dated material was only wood, roots and leaves, the hard water effect can probably be neglected.

Between the lacustrine marls and the peat deposits, no transitional sediments (e.g., beach sands and gravels) are developed. We interpret the remarkable change from littoral conditions to a coastal swamp as a sudden lake-level drop of several meters within the Holocene. Such a change can either be caused by climatic or tectonic influences. A coast-parallel, large normal fault (N30E) stretches off-shore along the wetland plain and causes a steep relief within the lake [1]. High-resolution seismic data [8] suggest very recent activity along that fault. In addition, the Ohrid area is characterized by frequent normal faulting connected to moderate seismicity [2, 9]. Therefore, we interpret the dramatic environmental change as fault-induced footwall uplift rather than climatic lake-level fluctuations. Lindhorst et al. [8] also show that environmental conditions have not undergone a significant change since the mid-Holocene. For the formation of this part of the coastline we propose the following model of lagoon development. During movement along a normal fault, which means a downthrow of the hanging wall block, we observe, also, significant coseismic uplift within the footwall of the fault during an earthquake. The recent L'Aquila earthquake (6th April 2009) demonstrated that the ratio of the footwall uplift versus the hanging wall subsidence is around 0.3 [37]. Therefore, ongoing faulting and the de-

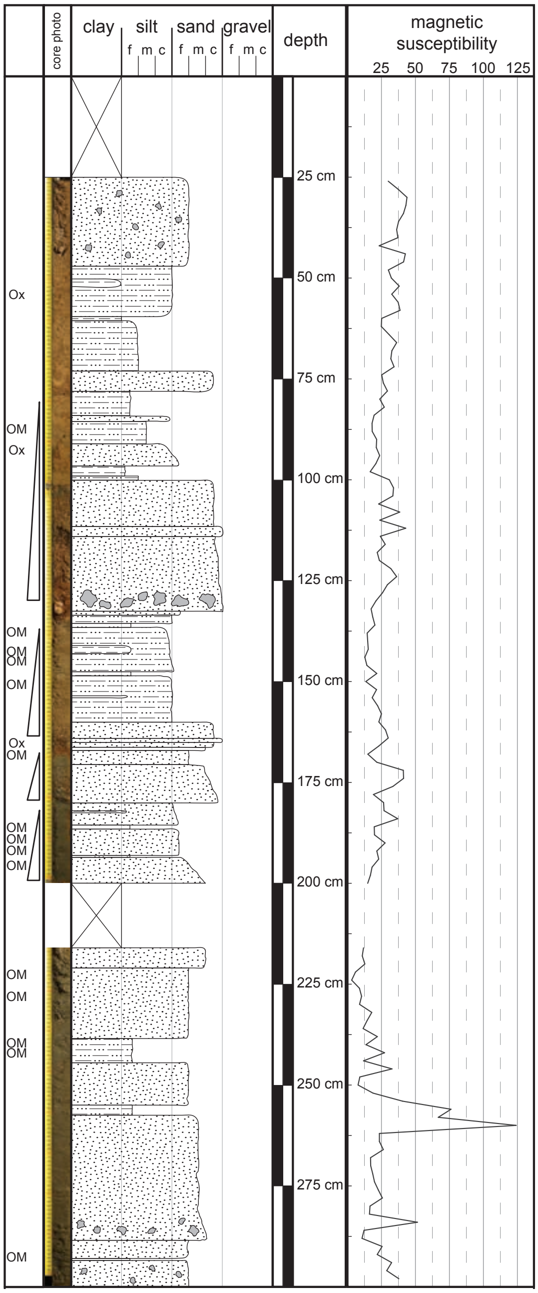

Figure 10. Core PL03 with a total length of 300 cm. Grain size, and magnetic susceptibility are displayed.

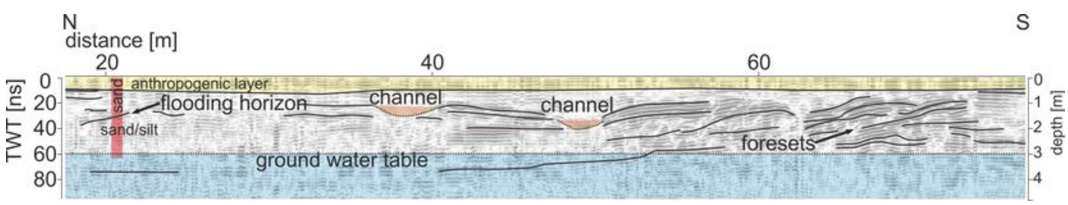

Figure 11. GPR line 56 (270 MHz antenna) at Sv. Naum with a total length of 351 m. Only the segment 18 - 79 m in NS orientation is displayed with its interpretation. The profile has been flipped in the x-direction for better interpretation. The red column shows the approximate position of core PL03 (fig. 10) with projected lithologies. Vertical exaggeration 1.5.

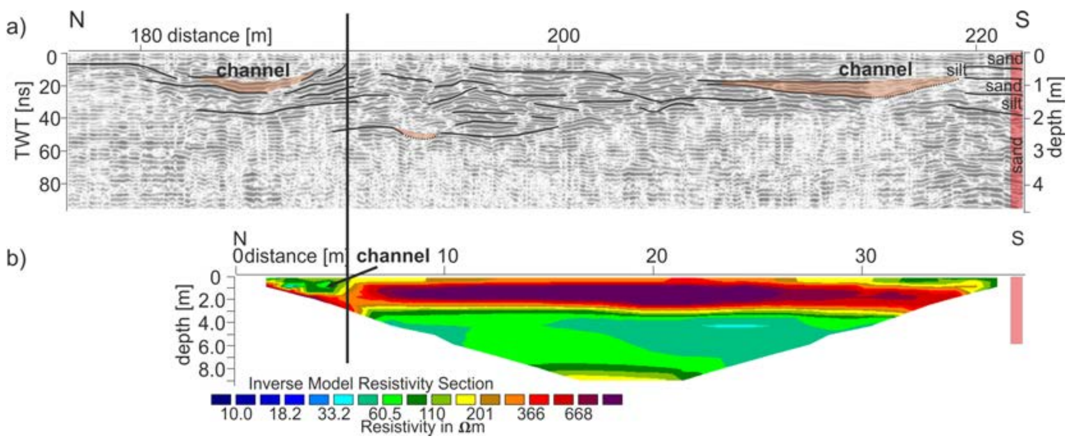

Figure 12. a) Interpretation of segment 178 - 222 m of GPR line 32 (270 MHz antenna; total length 224 m). The red column shows the position of core PL02 (see fig. 2C) with projected lithology. Orientation of the profile is N-S. Vertical exaggeration 1.5. A black line marks the beginning of a channel structure in both profiles. b): Resistivity line R1 in Dipole-Dipole array with an electrode spacing of 1.00 m and a maximum depth of 9 m. The red column shows the projected drilling site PL02. Three iterations were applied for inversion with a final error of the model of 5.50%.

velopment of listric normal faults has led to a tilted block, which partly separated a stretch of water, in a lagoon-like setting, from the lake. This would create the fitting shallow environment for the deposition of the marls. Later, further development of the basin and the propagation of faults towards the basin center would have created a new fault, located further west. Due to coseismic hangingwall-uplift, the lagoon also would have been lifted up, resulting in swamp formation. Even later, the levels would have eroded so that today only parts of it are still preserved at the hill of the Inex Gorica Hotel (see fig. 2B). The peaty interval hearkens to periodic wetland formation (lagoon) in the plain south of Ohrid city, probably related to a change of weather conditions and therefore a change of input. Sandy-silty deposits of terrigenous origin below, are interpreted as distal alluvial fan deposits of the Velestovo creek and include periodic flood sediments (debris flows). However, today neither an alluvial fan nor a delta from this little creek are active and the coastline is linear. Besides that, the Velestovo creek is artificially channelized as soon as it enters the plain. The upper portion is ascribed to agricultural land, and includes buried tubes for irrigation.

5.3. Sveti Naum

5.3.1. *Drilling and core logging*

The recent delta of the Cerava River to the south of Lake Ohrid is characterized by a flat delta plain incised with the meandering river and includes several ox-bows. We drilled three cores in a transect perpendicular to the coastline (fig. 2C). Core PL 03, with a total length of 300 cm (fig. 10), is described here in detail.

(1) 300 - 200 cm: Sandy sediments containing quartz grains, mica and organic material. The occurrence of white mica is related to the content of organic matter; both are enriched downsection.

(2) 200 - 132 cm: Fining-up sequences. Three fining-up sequences can be described (200 - 180 cm, 180 - 170 cm and 160 - 132 cm); all are sandy to silty with clay clasts, organic material and white mica. At 162 cm a 3.5 cm thick oxidation horizon occurs in between two of the sequences. Towards the base of the whole interval (200 cm) the silt fraction decreases, whereas the content of organic material increases.

(3) 132 - 0 cm: Silty to clayey material with no organic remains; in the lower part the grain size decreases from cobbles of quartzite and quartz with diameters up to 35 mm in the basal layer to sand/silt. The uppermost 47 cm contain recent soil with roots and a mixed interval of sand and gravel (grain size up to 15 mm in diameter).

The PL02 and PL01 open window samples were drilled at 600 m (900 m) distance (fig. 2C) to the shoreline and about 7 m (10 m) above lake-level. Both reach a total depth of 600 cm. Lithologies of both comprise a sedimentary composition comparable to core PL03, with fine to medium-grained sands, silts and occasional gravels.

5.3.2. *Geophysical investigations*

A series of 52 radar profiles and resistivity sections were carried out at the Cerava delta (fig. 2C); here, only two are described. Profile 56 (fig. 11) has a total length of 351 m and is displayed only partly. Horizontal reflectors up to a depth of about 100 cm are underlain by northward dipping reflectors (between 50 and 75 m at a depth of 100 - 300 cm) and several concave-up patterns (35 - 40 m and 48 - 52 m at a depth of 100 - 200 cm). These structures can be traced in almost all the N - S trending radar profiles (fig. 2C) and are interpreted as channels.

Profile 32 (fig. 12A) shows horizontal reflectors that can be traced over several tens of meters down to about 20 ns. A well-detectable channel occurs between 180 and 190 m at a depth of about 100 cm.

The related electric resistivity profile R1 (fig. 12B) shows a significant drop in resistivity values at a depth of approximately 300 cm with a slight dip to the south that correlates with the dipping of reflectors in the radargram. In the very N of the resistivity profile, a concave structure may be recognized, which correlates well with the concave structure in the radargram.

5.3.3. Interpretation

Drillings at the Cerava delta provide evidence that the delta is dominated by alluvial plain deposits. These are characterized by coarse to fine-grained clastics with occasional soil development (paleosols). N-ward dipping reflectors are interpreted as shallow deltaic foresets. Abundant mica and granitic pebbles testify to a provenance of either basement rock, which outcrops to the south along the Greek/Albanian border, or more likely, of conglomerates of the Mirdita Zone [9], which are exposed to the south and west of Pogradec (see fig. 1). The correlation between the occurrence of mica and organic material is interpreted as the influence of high precipitation on the transportation capacity of the Cerava River. The Cerava delta plain is used agriculturally and has been incised by the meandering Cerava River, leaving several channels of different ages. Because no remains of *Chara sp.* or ostracods were encountered in the core, we do not have any evidence for lacustrine sediments in that part of the lake during the Holocene.

6. Discussion and Conclusions

Shallow drillings and geophysical investigations from three different positions at Lake Ohrid provide insight into the Holocene coastal evolution of the lake. In general, we can distinguish two main geomorphological systems with different mechanisms driving the sedimentation. These are, on the one hand, the plains to the north and south of Lake Ohrid and, on the other hand, the steep hillslopes to the east and west along the Mountains of Galicica, Mali I Thate and Mokra.

The northern part around Struga is characterized by an extensive shallow plain with large, but very shallow, alluvial fans (fig. 1). Their source areas are the calcareous mountain ranges to the west and east of the plain. Today, these alluvial fans are mainly inactive. At a depth of two meters, we have clear evidence of diverse lacustrine fauna and flora, represented by shell fragments of gastropods, ostracod valves and oogonia of *Chara sp.*, testifying to a lake setting. Findings of charophyte oogonia are not suitable for inferring the exact water depth from sediment archives, as they are dispersal agents and the charophyte communities are highly dynamic [38]. Thus, the so-called Chara-belt [3] in modern Lake Ohrid in 3 - 20 m water depth does not necessarily serve as a modern analogy for past lake-level conditions. Shallow, lake-ward dipping foresets in the lower part and typical fluvial facies in the upper part suggest a southward sediment transport by a former inflow. The Sateska river, today, is in parts channelized (since 1962) and dewaters partly into the Crni Drim and partly into Lake Ohrid. It acts as the only possible northern inflow. According to Jordanoski et al. [39] the original inflow of the Sateska River used to be east of Mislesevo (fig. 2A). Since the 18th century the area around Lake Ohrid was successively deforested. The increasing sediment load of the Sateska River led over time to a backfilling of the river bed and to a change of the river course. Remnants of the old river bed and land use patterns are indications for the former location of the Sateska, but are today superimposed by agricultural use and new settlements. In general, the plain is dominated by clastic input, which, however, varies over time and is influenced by climatic variations [36].

The Velestovo site, in contrast, shows a coastal marsh/lagoon environment during the Holocene, weakly influenced by clastic input from the Velestovo creek. The clastic interbedded sequences are interpreted as periodic flood sediments. The most striking observation at the site is that marly lake sediments are overlain by a thick package of peat, suggesting a sudden change in the depositional environment. Causes may be a rapid lake-level drop or neotectonic activity of a nearby active normal fault, which runs parallel to the coast.

However, where the ostracod remains are present (U03 and DA01), they clearly indicate a lacustrine assemblage in the shallow littoral of a lake system [40]. The Characeae and gastropod fragments support this scenario.

The Cerava plain constitutes a typical delta plain depositional environment at the southern part of Lake Ohrid, including a meandering fluvial system with incised channels. Albrecht and Wilke [8] describe several prograding delta deposits detected in offshore multichannel seismic data. Indeed, we can conclude that this inflow was stable at least during Holocene.

From this we suggest that the northern and southern shores of Lake Ohrid are dominated by sedimentary input. Alluvial fans and deltas are interpreted to be climatically driven, whereas the eastern and western shores (Velestovo and Lini Peninsula, fig. 1) clearly show the influence of active tectonics on the depositional system. On the other hand, the annual periodic lake-level fluctuations of Lake Ohrid do not exceed 1 m (amplitude; i.e. ± 50 cm, [5, 6]). Several high stands with coastal flooding have been reported during the last century (e.g. in 1936 and 1956 [41]). Those short-term flood events cover the coastal areas and form intermittent "lagoons" (fig. 1). They do not reach 695 m a.s.l. The Struga Plain and the Pogradec Plain have been filled up with sediment during the Holocene (fig. 1).

In conclusion, based on sedimentological and paleontological investigations and supported by shallow geophysics, we are able to distinguish the northern and southern plains of Lake Ohrid which are dominated by fluvial clastic input, and the eastern and western shores, which are controlled by active normal faulting. The rapid changes from open lacustrine to swampy areas are attributed to syntectonic footwall uplift, possibly induced by a paleoseismic event.

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