Quaternary Depositional Environments in the Vrgoračko Polje Lake, Croatia

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Abstract

In this paper we present our preliminary research on the Quaternary sedimentation in Vrgoračko polje. The Vrgoračko polje is a karst field with the surface area of 37 km² and the altitude between 20 and 28 m above sea level, situated at the southern edge of the Dalmatian Zagora. During the Quaternary the polje was flooded for longer or shorter periods of time and lacustrine environment and sedimentation became dominant. A multidisciplinary study of drilling cores, outcrops and geoelectric measurements was focused on reconstruction of sedimentary facies. Based on the facies research, lacustrine depositional environments during the Holocene are reconstructed and described. Four main sedimentary facies are described: laminated clays, slope sediments, littoral clays and lacustrine characean chalk. Lacustrine lacustrine chalk is dated by the C¹⁴ method and dating shows that entire thickness of the chalk sediment was deposited during the Holocene.

Keywords: karstic field, lacustrine facies, lake sediment, Quaternary, Vrgoračko polje, Croatia

1. Introduction
Karstic fields are extremely important geomorphological features in a cultural sense, but also as a geological phenomenon. Karstic fields, as smaller or larger flat areas in rough karstic relief, are usually places of sediment accumulation. Accumulated sediment can become fertile soil and often the only valuable agricultural zone in the district. Commonly, in some period of geologic past, the karstic fields were flooded and lacustrine environment developed. Lakes in karstic areas and their sediment accumulations are frequently the exclusive record of changes in local and global environment. An excellent example is the Vrgoračko polje. This paper is the first attempt to determine and describe lacustrine depositional environments in Vrgoračko polje. Our intention is that the depositional environments and the systems described here become the basis for the future detailed research and interpretations of the Quaternary lacustrine sediments in Dinaric karst.

2. Geological setting

The research area is situated in Dalmatian Zagora region NE from the Biokovo Mountain (Fig. 1).
The Vrgoračko polje is formed on Upper Cretaceous limnetones and in a smaller extent on Paleocene to Eocene limestone and Eocene flysch (Marinčić et al., 1972) (Fig. 2). Structurally, the area is developed on scale and overturned anticlinal forms. Cretaceous limestones are thrust onto the Eocene flysch. Orientation of the main structures is NW-SE (Dinaric strike) (Herak, 1991, 1986).

During the research for Basic geologic map, the two main sedimentological units; lacustrine chalk and clays were described (Magaš et al., 1972). On the basis of molluscan fauna and
pollen analysis the authors dated lacustrine section as Holocene with probable beginning of the sedimentation in the Pleistocene.

3. Methods

3.1. Field methods

Field investigation and sampling were carried out during the summer 2015 and spring 2016. 119 samples were collected from the drilling cores and outcrops (Fig. 2). Eight micromorphological samples were collected in order to analyse sedimentological and postsedimentation features and to clarify sedimentological processes. On five locations along NE edge of the Vrgoračko polje, cores five to eight meters long with 12 cm diameter were sampled. Surficial 2 cm of the disturbed sediment was removed before the sampling.

Four outcrops were investigated in detail (Plina, Umčani, Plina I and Špila). After removing surficial 20 cm, horizons were defined based on colour, lithological characteristics (composition, structure, and texture) and presence of fossils. Lateral spreading of horizons and contacts between horizons in vertical sections were described in order to reconstruct sedimentation-erosion processes and rates. Samples of about 3 kg were taken at 10 cm intervals in the Plina (Fig. 3) and the Umčani sections, and regarding defined horizons, in the Plina I and Špila outcrops. Some specific sedimentological features are sampled for micromorphological analysis. We were focused on features like nature of border between layers (erosional or bioturbated), resedimented laminated material or SSD features. Colours of the samples were determined on wet sediment by Munsell Soil Color Charts (MUNSELL SOIL COLOR BOOK, 2013).
3.2. Laboratory methods

Complete preparation of samples and their analysis were performed in Croatian Geological Survey, except $^{14}C$ dating that was performed in Radiocarbon dating service DirectAMS, USA.

Samples from the outcrops and drilling cores and the samples for micromorphological investigations were air-dried for approximately one month period.

Chemical analysis

Although our research was not focused on sediment geochemistry, iron and calcium carbonate content is used to interpret some aspects of the sedimentary environment.
For the chemical analysis of iron and calcium carbonate content, the samples were sieved to the <2 mm fraction to separate larger carbonate and/or Fe-Mn concretions and fossils (mostly gastropods). After sieving, the samples were dried for two days at 110°C in an oven; 100g of the each sample was weighted for the analysis. For the Atomic Absorption Analysis (AAS) of iron the samples were dissolved in 1N HCl. We did not use total digestion procedure to avoid influence of possible detrital silicate minerals containing iron or organic bound iron. HCl digestion dissolved cryptocrystalline and amorphous iron oxides and oxyhydroxides, which are of main interest for our interpretations. Carbonate content was analysed by gas volumetry, measuring the volume of CO$_2$ (VAN LAGEN, 1993) after reaction with HCl ($c$ HCl = 4 mol l$^{-1}$) using Scheibler-instrument.

**Micromorphological observations**

Investigations of polished samples and thin sections were focused on transitional layer between clay silt and clay and lacustrine chalk in order to determine composition and source of analysed sediment and mechanism of sedimentation.

**Radiocarbon dating ($^{14}$C)**

The age of the sediments was determined by radiocarbon dating (AMS method). Gastropod opercula were selected as dating material. *Bythinia tentaculata* opercula are composed of calcite and are excellently well preserved in the lacustrine chalk sediment without any sign of recrystallization. Three samples of opercula were separated from the bottom, the top and the middle of the lacustrine chalk interval on the Plina section (samples VJ10, VJ15 and VJ41). The opercula from the clay underlying lacustrine chalk were completely recrystallized and unsuitable for dating.

**Geophysical investigation**

Geophysical investigations were carried out by the method of specific electrical resistivity – geoelectrical sounding. It was performed using the Schlumberger symmetrical array of current
and potential electrodes with electric range AB/2 up to 200 m. Measuring was made by transistor compensation instrument (TK-24). The measurements were performed on profiles in the central part of the Vrgorac field. Position of the profiles is shown on Fig. 2. Quantitative interpretation of field measured diagrams of geoelectric sounding was based on determination of the value of the electrical resistivity and thickness of the registered geoelectric units. Interpretation of measured diagrams of geoelectric sounding album was performed using two and three layers theoretical diagram. The parameters which are determined by the method of geoelectric sounding are: the specific electrical resistance (ρ), thickness (h) and depth (d) for each geophysical unit.

4. Results

4.1. Description of analysed boreholes and sections

The research results of the boreholes and four sections data are shown in Table 1 and Figures 4 and 5. The C\textsuperscript{14} ages for the opercula from the VJ10, VJ15 and VJ41 samples are respectively 7686, 6836 and 1747 years BP (Fig. 5).

The sections are described below.

<table>
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<tr>
<th>Sample</th>
<th>Drilling cores</th>
<th>Depth from surface (m)</th>
<th>MUNSELL COLOUR (2013)</th>
<th>Sample</th>
<th>Depth from bedrock (m)</th>
<th>MUNSELL COLOUR (2013)</th>
<th>Sample</th>
<th>Depth from bedrock (m)</th>
<th>MUNSELL COLOUR (2013)</th>
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<td>VJ 1</td>
<td>0.0 - 0.1</td>
<td>7.5 YR 4/4 brown</td>
<td>VU 1</td>
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Table 1. List of samples, depths of sampling and colours of analysed horizons (MUNSELL SOIL COLOR BOOK, 2013)
Figure 4. Lithology and carbonate content of boreholes V1-V5.
Figure 5. Lithology, age and carbonate and iron content of sections Plina, Umčani, Plina I and Špila illustrated by photographs of interesting details. Legend in Fig. 4.
4.2. Sediment description

Laminated sediments

Laminated sediments found in the lower sections of the boreholes V1-V5 are composed of alternating submillimetre dark and light laminas (Fig. 4). Light laminas contain yellowish to brownish and black iron and manganese oxide impregnations and micro concretions. Dark laminas contain iron in the magnetite form and occasionally carbonised plant remains. Compositional colour is determined as dark yellowish brown and brown (Table 1). The laminations are very poorly preserved because of the soft sediment deformations, but are still recognizable (Fig. 6a).

Figure 6. A) Contact of laminated sediments and sediments redeposited in a deeper lacustrine facies; B) Contact of sediments redeposited in a deeper lacustrine facies and littoral clays. Cretaceous limestone fragments from surrounding slopes in littoral clays (f), convolution of laminas (c), erosional border (e), water escape (v), redeposited material of lacustrine chalk (k).

Sediments redeposited in a deeper lacustrine facies:
These sediments can be found in boreholes V1-V5 (Fig. 4) as alternating carbonate intercalations in the clay sediments and clay intercalations in the lacustrine chalk sediments (Fig. 6). Colour is determined as yellowish brown (Table 1).

Numerous limestone fragments and gastropod opercula were redeposited in such environment. Gastropod opercula are imbricated following sediment convolution and current direction. Redeposited mud clasts are rounded and plastically deformed, but still containing laminations (Fig. 6b (c)). Laminations inside the clasts are curved and bended following clast outline.

**Slope sediments:**

Slope sediments are present on the South Eastern area of the Vrgoračko polje. They are described on Špila profile (Figs. 5 and 7). Because of disturbed primary position of these sediments, it is not possible to discuss their lateral distribution or sediment body geometry.

Colour varies significantly (dark yellowish, yellowish, reddish, brown and brown), depending of clay content in the matrix (Table 1).

Four sediment types were found:

a) Completely unsorted slope sediment with angular fragments, in the size range from 5 to 70 mm. The sediment is clast supported; interstices between cretaceous limestone fragments are filled with lacustrine chalk (Fig. 7a). The sediment can be described as slope breccia.

b) Breccio-conglomerate, clast supported with partially sorted material.

c) Clast supported sorted conglomerate (Fig. 7b). On some ex situ blocks it is possible to recognize two or three beds of conglomerate, 10 to 40 cm thick. Clasts are 5 to 50 mm in size, well rounded. Clasts are imbricated parallel to the bedding plane. Degree of sorting increases with particle roundness.

d) Gravel, cobbles and boulders, as intercalations in the clay or lacustrine chalk (Figs. 5 and 7). The clasts are matrix supported. The long axes of the clasts are inclined to the bedding
plane. This sediment infill channel form, the channel is only partially preserved; it is about 20 m wide and 1.5 m thick. The channel is incised in the clay with strong erosion border at the base. The clasts are AB-plane imbricated, where is intermediate clast axis oriented in the flow direction and the longest axis is ideally perpendicular to the flow.

![Image](image_url)

**Figure 7.** The slope sediments. A) Unsorted slope sediment with angular fragments, interstices between cretaceous limestone fragments are filled with lacustrine chalk; B) Clast supported sorted conglomerate.

**Littoral clays:**

Littoral clays, found on lower parts of Plina, Umčani and Špila profiles (Fig. 5), are always sedimented on top of Cretaceous limestones, infilling depressions and caverns in karst relief. The clays are intensively bioturbated with massive texture, containing numerous opercula of *Bythinia tentaculata* and Cretaceous limestone fragments (Fig. 6b). In some horizons, especially lower part of the Umčani section (Fig. 5), iron and manganese concretions can be found. Limestone fragments in the clay matrix are mainly corroded and recrystallized, with iron and manganese oxides precipitate on their surface. In the case of recrystallized limestone fragments, Fe and Mn oxides were precipitated inside the fragment, infilling and coating pores and fissures. There is up to 30 % of calcium-carbonate and 20 ppm of iron in the clays (Fig. 5). It is reflected on colour of sediment that is dark brown or brown (Table 1).
Lacustrine chalk:

Lacustrine chalk is the most widespread sediment in Vrgoračko polje, found in upper sections of all profiles and boreholes. Lacustrine chalk can be found on top of Cretaceous limestone as shown on Plina I section (Fig. 5) or overlying laminated sediments like found in boreholes V1-V5 (Fig. 4). At Plina and Umčani sections, the chalk is deposited on top of the littoral clays in erosional and angle discordance (Figs. 2 and 5). Lacustrine chalk is composed almost completely from characean remains. Transitional horizon between littoral clays and lacustrine chalk shows elevated carbonate content and decreased content of iron and is intensively bioturbated.

Characean thalli in the sediments are preserved in the form of tubes up to 3 mm in length (Fig. 8).

There is no mineral infilling of tubes, but on some rare fragments calcite overgrowth can be noticed. Thalli calcification is very porous, but this is their primary characteristic. Despite porosity, there is no visible dissolution or corrosion of carbonate fragments. Authigenic characean carbonate material is present up to 97% in the sediment; the rest is siliciclastic clay.
fraction. The sediment colour varies from yellowish brown to light grey depending of clay and iron content (Table 1).

**Geophysical investigation**

Four lithologic members are separated: 1. the values of natural resistivity for the uppermost unit are over 25 Ohmm; 2. the values of natural resistivity are under 20 Ohmm; 3. the values of natural resistivity are between 50 and 150 Ohmm; 4. the values of natural resistivity are over 150 Ohmm. The first lithologic unit corresponds to the lacustrine chalk, second unit shows natural resistivity of the clay, third unit has geoelectric features of the limestone breccia with clay matrix, and fourth unit represent limestone. On Fig. 9 is shown lithology reconstructed on from the geoelectric profiles. Position of the profiles is shown on Fig.2.

![Geophysical investigation](image)

Figure 9. Lithological profiles S21-S24 and S1-S6 reconstructed from the geoelectric resistivity measurements.

**Discussion**

On the basis of our research we determined existence of the four main depositional environments. In these environments five sedimentary facies can be recognized (Fig. 10).

**Deeper water depositional environment:**
In which can be recognized: 1. Facies of laminated sediments, 2. Facies of sediments redeposited in a deeper lacustrine facies

**Lacustrine littoral depositional environment**


**Slope depositional environment**

**Deposition environment of periodically desiccated lake**

![Figure 10. Reconstruction of the depositional environments in the Vrgoračko polje lake.](image)

**Deeper water depositional environment**

1. **Facies of laminated sediments**

In deeper lake zones, laminated sediments were deposited. According to interpretation of geoelectric profiles and borehole data; laminated clay thickness on NE area of the polje exceeds 60 meters (Fig. 4. and 9.). With the high degree of certainty this sediment can be
recognised as varve. Varve sedimentation reflects seasonal changes in the environment (O’SULLIVAN, 1983; ANDERSON & DEAN, 1988).

Lighter laminas were sedimented in more oxic conditions and iron is in more oxidised form, colouring lamina in yellowish and reddish colours. Enhanced water aeration and the end of water stratification are usually connected with the rainy season (ANDREW, 2003). Intensive water flow is also evidenced with increased input of millimetre and sub millimetre limestone fragments from the shore zone.

Occasionally, in lighter laminas it is possible to find gastropod opercula, which were redeposited from the shallow water environment. There is no preserved plant remains because oxic conditions were favourable for organic matter decomposition.

After inflow of oxygenated water was stopped, and stratification of water column established, the oxygen was consumed by organic matter decay and iron and manganese oxidation. In such conditions dark laminas were sedimented. They are coloured by finely dispersed magnetite and organic matter, preserved in oxygen depleted environment.

Numerous soft sediment deformation textures indicate periodic and very intensive input of material from the shore or shallower lake zones. Cretaceous limestone fragments deposited on still soft laminated sediment disturbed laminated structure in the form of convolution or water escape textures (PATRICK, 1983; MALTMAN, 1984).

2. Facies of sediments redeposited in a deeper lacustrine facies

This facies differs from the facies of laminated sediments, where the sedimentation from the suspended material was dominant. Here, redeposited sediments were carried by water current or mud flow, and their movement was probably initiated by slope movement and/or rain flash flow.

Alternations of carbonate intercalations in the clay sediments and clay intercalations in the lacustrine chalk sediments were deposited due to extensive erosion of the clay and lacustrine
chalk. General transport directions are from the North West of the Vrgoračko polje and locally from shallow to deeper environment. Numerous Cretaceous limestone fragments were washed from colluvial sediments on shore, but also from littoral clays.

Plastically deformed clasts and curved laminations inside the clast indicate underwater erosion. Mud clasts were striped from the lake bottom by strong water current, rounded and deposited in deeper environment. This is visible on Fig. 6b where laminated clays with SSD structures floating in lacustrine chalk matrix. Clay clasts and lacustrine chalk were eroded by strong flow and redeposited on top of deeper water laminated sediment. Later, littoral clays with limestone fragments were redeposited on top of this section.

**Lacustrine littoral depositional environment:**

3. **Slope sediment facies**

The whole perimeter of the Vrgorac polje is defined by strong fault systems (Fig. 2) and many of them are neotectonic and still active (CVIJANOVIĆ et al. 1981; BOŽIČEVIĆ & BENČEK, 1983; HERAK et al. 1995, 1996; BLAŠKOVIĆ, 1998; DRAGIČEVIĆ et al. 1999). Especially active zone is South Eastern part, where recent colluvial conical forms protruding into the polje. Whole group of sediments connected with slope processes (see chapter 4.2. Sediment description) can be explained by similar mechanism.

Unsorted slope sediment with angular fragments is colluvial material that prograded into ancient lake.

Angular clasts of colluvial material were more or less rounded in dynamic environment of the lake shore. This material has been reworked by stream and flash flow and resedimented as alluvium, probably in a fan form. It is preserved as clast supported, sorted conglomerate. A-axis clast imbrication, with longer clast axis parallel to the stream flow is typical for a fast-decreasing suspended flow (POTTER & PETTIJOHN, 1977; REINECK & SINGH, 1980), which transported material from the lake shore.
Different sedimentation process is recorded in the gravel, cobble and boulder channel infill inside the clays or lacustrine chalk.

Matrix supported, unsorted, poorly rounded or angular clasts in the size range from gravel to boulders with AB-plane imbrication, are the result of very dynamic event, which can be described as debris or mud bed flow. Debris or mud flow probably started from colluvial sediments accumulated on top of littoral clays. Colluvium weight and some initiating event, like rain or earthquake, could start debris flow. After debris mixing with littoral clay, the material continued moving as mud flow. The flow incised the channel in the clays and lacustrine chalk. Lake carbonate sedimentation continued.

4. Facies of Littoral clays:

In vicinity of clastic (colluvial wedges) intake, the clays contain numerous Cretaceous limestone fragments. Corroded and recrystallized limestone fragments point to elevated environment acidity in which calcite dissolves. Iron and manganese-oxide concretions and impregnations imply that cations of these metals were mobile during the early diagenesis, or even during the sedimentation. Cations of Fe and Mn are mobile in aqueous solution with low oxygen levels (EMERSON, 1976; LANGMUIR, 1997). Corroded limestone fragments and mobile iron and manganese ions are indicators of acidified low oxygen environment. Contrary, numerous remains of gastropod Bithynia tentaculata and intensive bioturbation indicate oxic environment with intensive benthic life. There are two possible scenarios: a) periodic deoxygenation and acidification of the littoral environment, and b) shallow oxygenation of the sediment column. It is very likely that both scenarios were significant. During the season of lower input of oxygenated water, oxygen can be faster consumed by living organisms and decaying organic matter, than can be replaced. Decaying organic matter consume oxygen and at the same time increase water acidity.
Anoxic acidic period in littoral environment corresponds to the period of dark lamina formation in deep water laminated clays.

Gastropod *Bithynia tentaculata* lives in the lakes and ponds with standing or low-velocity water circulation. This gastropod can be found up to five meters deep in littoral zone, grazing on the bottom or on aquatic plants. It is interesting to point up that *Bithynia* can also feed by filtering water, this allow high population density to survive in eutrophic and shallow water (CLARKE, 1979; DILLON, 2000). High number of *Bithynia tentaculata* opercula found in littoral clays indicates high population density. From sedimentological data we know that the lake water level periodically decreased and in some parts completely dried up. In this case eutrophic conditions can appear, and this is limiting condition for significant mollusc diversity to occur. Because of that, almost monospecific gastropod fauna existed in the lake. Rarely, characean gyrogonites can be found, up to 30 per kg of the clay.

5. **Lacustrine chalk facies:**

Almost the whole area of Vrgoračko polje is covered by the chalk sediment, it can be found on top of all other sedimentary facies found in the lake (Fig. 4) Depositional environment of the lacustrine chalk was the last stage of the lake life cycle. Characeae grows in littoral zone usually up to 10 or 15 meters deep (SOULIE-MARSCH & GARCIA, 2015), with maximum recorded depth of 30 meters (BEILBY & CASANOVA, 2014). This type of intensive carbonate production is primary confined to the littoral zone, but significant amount of resedimentation in deeper environment can occur. At the Plina section there is 3.8 meters of characean carbonate deposit. Transitional horizon between the clays and lacustrine chalk is erosional and intensively bioturbated, this can explain elevated iron content in this horizon (Fig. 4).

Characean algae assimilate CO$_2$ from bicarbonate ion during photosynthesis. As a result calcium-carbonate encrustation precipitates on the thalli surface (BEILBY & CASANOVA,
Charophytes are extremely successful in calcite precipitation and are usually the most important factor in carbonate precipitation in littoral zone. PENTECOST (1984) found that some species of characea can produce up to 1100 g of calcium-carbonate per square meter, but the average value of precipitated calcite for different species is more than 400 gm$^2$ (PELECHATY et al., 2013; APOLINARSKA et al. 2011).

Rate of sedimentation:

Based on the C$^{14}$ dates from the three horizons in characean carbonate from the Plina section, we calculated average sedimentation rate in the lake. The sediment thickness between the oldest date of 7686 years and the middle date of 6836 is 500 mm (Fig. 5). This data gives sedimentation rate of 0.58 mm/y. Between the middle and the youngest date is 5087 years and 2600 mm of sediment, with sedimentation rate of 0.51 mm/y. Based on measured specific mass of the sediment and the sediment volume, we calculated carbonate production of 1050 gm$^2$/y. Calculated carbonate mass is in the range measured for recent characea by earlier cited researchers. Constant sedimentation rate indicate constant rate of the characean carbonate production, as the result of well balanced and constant lake ecosystem. Generally the sediment is not much changed by diagenesis. Water pH in the lake was elevated and probably buffered to relatively constant value by excess of easily soluble calcium-carbonate material.

**Depositional environment of periodically desiccated lake:**

The lake has been periodically, partially or completely desiccated. During that time, erosion became the main sedimentological process in the lake basin. Material was resedimented from the emerged areas in the deeper parts of the basin. Lacustrine chalk is easily erodible material, but, after water level drop, the sediment surface stays protected under the cover of aqueous algae remains. During decaying time of algal remains, the new growth of terrestrial grass is
formed and the sediment is protected from the erosion. If stronger stream locally remove protective vegetation cover, erosion channel is formed immediately. Widening and deepening of the channel is extremely fast. When the channel network is formed, individual channels intersect, merge and separate their flows. The result is indented, irregular relief with steep slopes. In the Vrgorac lake such erosional areas occurs on very narrow area, but are very intensive.

If the sediment stay exposed above the water level long enough, pedogenetic processes can occur. Soil is intensively bioturbated and bioturbations are infilled with overlaying sediment. After water level rise, the soil and the freshly deposited sediment are in erosional and usually angle discordance. Desiccation cracks in the sediment immediately bellow the erosional events are also excellent indicator of the lake desiccation (Fig.11.)

Figure 11. Desiccation cracks infilled with overlying sediment. White bar is 20 cm.

Occasional lake shallowing and partial desiccation events can be reflected in decrease of biogenic carbonate content in the sediment. There are two possible explanations; older clay sediments were eroded and resedimented in to the deeper lake areas and, at the same time, production of biogenic (characean) carbonate was decreased or stopped.
Decrease of characean carbonate content and increase of detrital component is always followed by appearance of numerous *Bithynia tentaculata* opercula. This is very important to notice, because, spreading of Bithynia population is consequence of shallow littoral zone widening. Shallow littoral zone is the environment where *Bithynia tentaculata* population flourished.

Lake shallowing in two ways affects iron content and oxidation state. With shallowing, clay content increase, and this is reflected as iron increase. Increased clay content decreases sediment pore water circulation and promotes more anoxic environment. In low oxygen conditions, yellowish and reddish iron-oxyhydroxides reduce in black and grey magnetite phase (VANCE, 1994; LANGMUIR, 1997).

The entire lacustrine chalk interval is radiocarbon dated to Holocene. Although underlying clay sediment were not dated because of unsuitable material, with the high degree of certainty it might be stated that laminated and littoral clays were sedimented during the Pleistocene. The oldest dated sample from the first 10 cm interval of the lacustrine chalk (7686 yr BP) on the Plina section is sedimented during the Middle Holocene according to subdivision of WALKER et al. 2012. Underlying littoral clays on some locations can be 10 meter thick. Umčani section is composed of 2 meters of underlying clays and 1 meter of lacustrine chalk. Sedimentation of the lacustrine characean chalk was very fast, as shown before. Underlying clay sedimentation should be much slower. If we compare thickness of the chalk with the clay thickness it can be concluded that the clay interval was sedimented during the longer time span than the chalk interval. According to geoelectric profiles, laminated clays are be more than 60 meters thick. Submillimetre varve structure and sedimentation mechanism from the suspended material indicate slow sedimentation rate and consequently longer time interval of
their formation. We can suppose that the littoral clay and laminated clay were sedimented completely or partially during the Pleistocene.

More intensive neotectonic movements on North-East edge of the Vrgoračko polje caused faster bottom subsidence in that area. In such deeper environment, laminated sediments were sedimented. Active neotectonics initiated formation of colluvial material, flush washed and slided in to the lake, today found as canal infilling or different alluvial fan forms.

South-West area of Vrgoračko polje is characterized with more shallow sedimentation environment and slight inclined wide littoral zone, where littoral clays were sedimented. With the climate change during the Holocene, environment conditions become favourable for characean algae intensive growth. Characean algae with their mass carbonate production significantly accelerated lake shallowing. As a consequence, emersions of the wider shore areas were more frequent. Intensive erosion and resedimentation into deeper lake zones took place.

Conclusion

Quaternary sediments of the Vrgoračko polje represent complete record of the environments which existed in the area during the Holocene, with probable beginning of sedimentation during the Pleistocene. Four main deposition environments were found and described: Littoral, deeper water, slope and desiccated lake environment. Each environment has defined corresponding typical sedimentary facies, which is easily recognizable and typical for their depositional environment. Depositional environments and sediment facies found and described in Vrgoračko polje can be used as a typical for Quaternary lacustrine sedimentation in karstic poljes.
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