

Changes in lake level and trophy at Lake Vrana, a large karstic lake on the Island of Cres (Croatia), with respect to palaeoclimate and anthropogenic impacts during the last approx. 16,000 years

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ABSTRACT

A multi-proxy approach study (cladocerans, diatoms, geochemistry, plant macrofossils, pollen), was performed on a sediment core from Lake Vrana (Vransko Jezero), a large and deep karstic lake on the northern Adriatic island of Cres, Croatia. Considerable lake-level changes occurred during the last approx. 16,000 years. The stratigraphic evidence suggests that periods of enhanced precipitation and the post-LGM rise in sea level were the main driving forces. The lake records indicate early human impacts. Sediment echo-sounding indicated that >25 m of lake sediments lies within the site, from which 5 m have been cored. Shallow lake stages occurred from 14.4 ¹⁴C ky BP to early Holocene. Prior to Alleröd, interglacial sediments were redeposited, reflecting the influences of rising sea-level (forming a local groundwater barrier), a temporary increase in precipitation, and lake-level changes. There appears to be a hiatus in the sequence, for no sediments assignable to the Alleröd chronozone could be found. A discordance in the echo profile at the appropriate horizon in the sequence supports this interpretation. Groundwater level increased again at 10.6 ky BP (during Younger Dryas chronozone), a swamp vegetation formed, which gave way to a shallow lake. During the Preboreal chronozone, this freshwater lake persisted with fluctuating levels. The establishment and subsequent persistence of the present deep water lake at about 8.5 ky BP, correspond with findings of a pluvial period at the Dalmatian coast, which lasted from 8.4 to 6 ky BP. First human catchment disturbances were related to settlements of Neolithic or Bronze Age. The increase in summer drought, coupled with forest clearance during Illyrian times, are assumed to be responsible for the change towards present evergreen oak vegetation in the lake catchment. The intensification in land-use during Roman and post-Roman settlements caused a slight increase in the lake trophic level.

Key words: Lake-level variations, Late Pleistocene to Holocene stratigraphy, palaeolimnology, palaeoclimate, anthropogenic impacts

1. INTRODUCTION

Coastal lakes in the Dalmatian Karst area record sensitive responses to changes in climate and sea level. Wunsam *et al.* (1999) investigated two Dalmatian lagoon lakes at 42° south, Malo and Veliko Jezero, and recognized a complex series of pluvial episodes during the Holocene. This pluvial period, which initiated at 8.4 ¹⁴C ky BP, was briefly interrupted by a drier episode from about 7.2 to 7.1 ky BP, and reached its maximum at approximately 7 to 6 ky BP. During 5 to 4 ky BP, respecting the basins thresholds, the oscillating sea level gradually approached the present level. According to Indinger (1999), a temporarily increased freshwater influx into the lagoon Malo Jezero at about 1.7 to 1.3 ky BP (1780±115, 1370±115 ¹⁴C BP), initiated stratification, the onset of a chemocline, and caused sapropel formation. Additionally, nutrient influx from enhanced

catchment runoff was assumed to have increased the epilimnetic primary production. This hypothesis also explains the high pigment concentrations found by Schultze (1988/89) in the sediments of Malo Jezero, as well as shifts in the diatom assemblage composition (Wunsam *et al.* 1999), during the pluvial period 8.4 to 6 ky BP. The onset of this pluvial period corresponds with that of sapropel formation of S1 in the Adriatic (Fontugne *et al.* 1989). Investigations reviewed by Ariztegui *et al.* (2000) from lacustrine (Italian crater lake sediments) and marine sequences from the central Mediterranean region in respect to the formation of sapropel S1 and its palaeoclimate background, suggest a similar duration for the pluvial period, and support the palaeoclimatic conclusions obtained from the lagoon lakes at the eastern Adriatic coast: The sapropel formation lasted from ca. 9.0 to 6.8 cal. ky BP. The sapropel in the study area, however, can be divided into two sub-

phases (S1a and S1b) interrupted by a short-lived episode (*ca* 500 years) of drier conditions. There is evidence for increased stratification and anoxia in the sea-water column during the period of S1 formation. Ariztegui *et al.* (2000) concluded that the key factors of sapropel formation were increased discharge of freshwater into the Mediterranean as a result of a wetter climate. Kallel *et al.* (1996) assumed that enhanced summer rainfall might be responsible for the sapropel formation (S1) in the eastern Mediterranean.

For the Late Pleistocene, Chondrogianni *et al.* (1996) argued for central Italy, that there might have been interactions between Atlantic and Mediterranean climate forces. Late Pleistocene pollen data from Italian Mediterranean sites indicate climate relations with those of northern latitudes (Lowe *et al.* 1996; Oldfield 1996; Watts *et al.* 1996; Huntley *et al.* 1997, 1999; Allen *et al.* 1999). Huntley *et al.* (1999) related *Betula*-rich pollen assemblages found in central Italian crater lake sediments, with a higher moisture availability during an early Lateglacial interstadial. Ramrath *et al.* (1999) suggested that temporarily increase in precipitation in the Mediterranean might be due to North Atlantic jet-stream deviation, which temporarily influenced and extended into the Mediterranean.

Pollen analysis provides climate and anthropogenic impact background data for palaeolimnology. The expansion of the evergreen oak (*Quercus ilex*) forest at the Dalmatian coast at 42° south occurred at 5.5 ¹⁴C ky BP (Jahns 1991; Jahns & van den Bogaard 1998), in central Italy earlier, during early Holocene (Magri & Sadori 1999). According to Beug (1977), at 5 ky BP sub-mediterranean *Quercus* forests predominated in Istria, whereas mediterranean elements were scarce or with limited occurrences along the coast. The Holocene expansion of *Quercus ilex* from south to north in the western Mediterranean were explained by a shift in summer drought (Jalut *et al.* 1997). Human influence on vegetation according to Beug (1977) increased in Istria with Roman colonization (first century BC).

The present investigations are part of a IGBP/PAGES project ("Palaeolimnology of Alpine – Adriatic lakes, PAAL"), with the aims to compare multi proxy data from lake sediments to reconstruct climate change along a north to south transect from the southern Alps to the Adriatic. At the Valun Bay, close to Lake Vrana, ancient lake sediments were detected below the marine sequence (Schmidt *et al.*, submitted). A cold and wet phase rich in pine pollen was related to a cold period observed at Längsee, Carinthia, which was dated by Schmidt *et al.* (1998) between approx. 15.5 to 13.6 ky BP. The Längsee cold period overlaps with the Fontari Stade complex of the central Apennine dated to approx. 16 to 14 ky BP (Giraudi & Frezzotti 1997). The latter was characterized as cold and wet, coupled with high lake levels and increased catchment run-off (Zolitschka & Ramrath 1998).

Lake level changes are an important tool for climate inference. In Lake Vrana they were expected to provide information pertinent to the following questions: Does hydrology of Lake Vrana support the findings of Late Pleistocene oscillations in temperature and moisture in the neighbouring bay of Valun? Is the Holocene pluviale period, observed for the southern Dalmatian lakes, also reflected by lake level change in Lake Vrana? Additionally, what is the anthropogenic impact on changes in the lake environment and lake catchment?

2. STUDY SITE

The Island of Cres extends from 44°35' to 45°10' in the northern Adriatic shelf between the peninsula of Istria and the northern Dinarids (Fig. 1). Highly permeable carbonate rocks of Cretaceous age predominate in this locality. Lake Vrana (Vransko Jezero) lies in a northwest-southeast striking tectonic fault where low permeable dolomites occur (Biondić *et al.* 1992). The freshwater lake surface area is 5.75 km², the maximum length is 5.5 km and the maximum width is 1.5 km. The water volume is 220 × 10⁶ m³. The present lake level is 10 to 15 m above mean sea level. The flat lake bottom lies at about 40 m below present sea level. A funnel-shaped depression located at the southern edge of the lake (Fig. 1), penetrates the entire sediment sequence to a maximum depth of 76 m from lake surface. A slight increase in sodium chloride in the depression as observed by Biondić *et al.* (1997), may indicate the position of a freshwater/marine boundary. Small streams subject to occasional torrential flows in the catchment, the dominant water source being groundwater. Different opinions about the hydrology of Lake Vrana exist. Mayer (1873) hypothesised that water may originate from a deeper karstic aquifer connected with the continental karst. Biondić *et al.* (1997) assumed that most groundwater originates from precipitation and the local drainage, though "a small portion could come from the karstified underground". According to Bonacci (1993), the lake water originates solely from a local aquifer with some 25 km² calculated catchment area, and water budget is directly proportional to regional rainfall totals. Reduced lake levels are caused by summer evaporation and possibly by some karst infiltration. Water extraction for water supply during dry summers aggravates the water budget situation. Biondić *et al.* (1992) illustrated lake level fluctuations during 1952 to 1991 within a range of 6.7 m. A general decline in lake level during the second half of the 1980s is explained by lower autumn/winter rainfall and higher summer temperatures (Randić *et al.* 1997). According to Walter & Lieth (1964), summer drought in the northern Kvarner area is less pronounced. On the island of Cres, precipitation increases towards the north (Cres: 1063 mm y⁻¹). This is due to the orographic influences of the higher mountains in the north of the island and the peninsula of Istria. Maximum rainfall occurs during autumn (Cres: 339

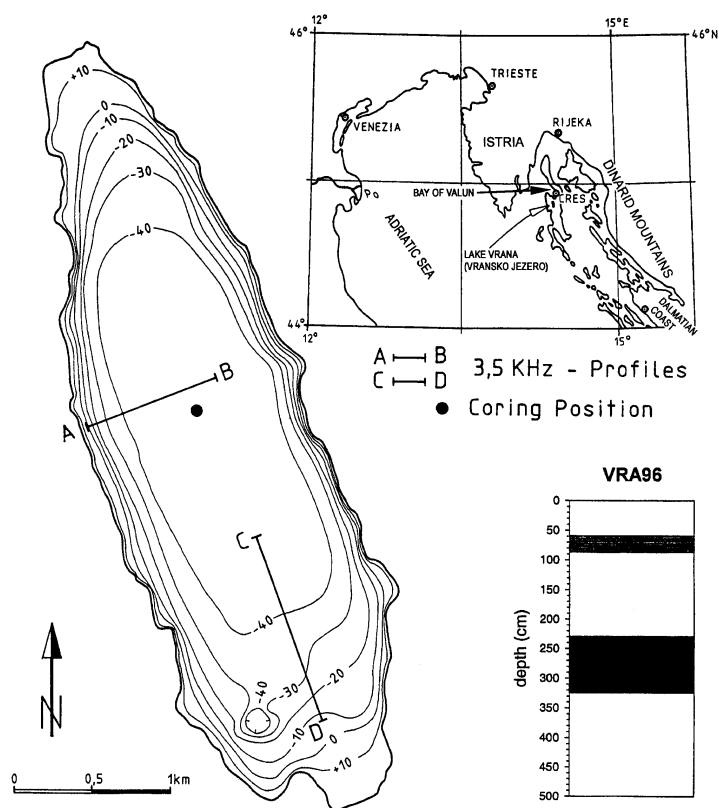


Fig. 1. The site of Lake Vrana. Bathymetric map (in respect to sea level) with location of core (VRA96) and of echo sounding profiles (A - B, C - D). The main features of the VRA96 core are also illustrated: White=sediments rich in carbonates; black=organic detritus; gray=coarse laminated sediments.

mm). The runoff from Lake Vrana was assumed to be associated with submarine karstic springs (vruljas), for example in the bays of Valun, Cres and Lubenice (Biondić *et al.* 1992; Bonacci 1993). The first of these sources maintains a high discharge even during the dry season. For more than 20 years, all interference with the lake, except for public water supply, were forbidden. Lake Vrana, a monomictic hardwater lake ($136 \text{ mg l}^{-1} \text{ CaCO}_3$), has low productivity (the secchi depth in 1989 averaged 10 m; Tomec *et al.* 1996; total phosphorus in the epilimnion averaged $10 \mu\text{g l}^{-1}$) (Biondić *et al.* 1995). Surface water temperature range from 4°C in winter to 25°C in summer. Temperature in the hypolimnion is constant (8.7°C) throughout the year.

Deciduous sub-mediterranean vegetation, similar to that of the Istrian peninsula dominates the northern part of the island, with *Quercus cerris*, *Q. pubescens*, *Carpinus orientalis*, *Ostrya carpinifolia*, and *Castanea sativa* being the dominant taxa. Lake Vrana lies in the transition to the eu-mediterranean *Quercus ilex*-rich zone dominating the south of the island (Mavrović 1994).

3. METHODS

3.1. Echography and coring

Sediment echosounding was performed on transects of Lake Vrana. An ORE-3.5 KHz echosounder was

used. The sediment core (VRA96) of 5 m length was taken with a modified Kullenberg piston corer (Schultze & Niederreiter 1990). The coring equipment consists of plastic tubes (Leiner) of 2 m length and 5.58 mm inside diameter, placed within a steel chamber, and a piston with a hydraulic rubber closing system to avoid sediment losses. Coring was performed from a surface platform at 54 m water depth. The entire 2 m core sections were overlapped when deeper coring. For subsampling, the plastic tubes containing the sediment were cut longitudinally with a saw and divided into halves with the use of two thin metal plates. See figure 1 for locations of the echo profiles, the site of coring, and the main core features.

3.2. Geochemistry and mineralogy

Main constituents of sediments (calcite, dolomite, quartz and layer silicates) were determined by X-ray diffraction applied to 1 cm^3 bulk samples. Organic and inorganic carbon were determined as CO_2 concentrations by IR-spectrometry, following combustion in a LECO furnace. Analysis was done in two steps, separately on two different subsamples. Determination of the total carbon was followed by measuring the organic carbon content after acid leaching (HCL). The inorganic carbon content was calculated as the difference between total and organic carbon concentrations. Quantification

of carbonate constituents was calculated using inorganic carbon in the respective stoichiometric proportions. Quartz content was calculated using peak heights comparison with calcite and considering different mass absorption ratios. The residual (layer silicates) was calculated after including organic carbon as organic matter ($\text{orgC} \times 2.5$).

3.3. AMS radiocarbon dating

Since the sample (Ua-11253: 493–500 cm) from the core basis contained only a low amount of detritus incorporated in the dominant carbonaceous matrix, a section of 7 cm length was necessary. The sample (Ua-11252) from 315–320 cm consisted of coarser organic detritus and fruits/seeds of water plants (see Fig. 5b). Since not enough terrestrial remains (see chapter 4.4) were found in this sample, the total organic material was used. A further two AMS dates (Ua-13661: 178–180 and Ua-13660: 78–80 cm) were obtained from bulk sediment samples containing dispersed organics in a carbonaceous matrix (compare Fig. 3). All the samples were treated in the same way. Carbonates were dissolved with concentrated HCl. The remaining material was washed in distilled water, dried at 40 °C, and sent to Uppsala University Radiocarbon Laboratory.

3.4. Pollen stratigraphy

For chemical treatment of the samples of 1 cm³ fresh material, a bromide solution (saturated solution of BrNaO₃/HBr 9:1) was used prior to acetolysis treatment. According to Klaus (1975), KOH treatment as used in standard techniques is less suitable to preserve the fine morphological structures which are necessary to differentiate pine pollen grains; instead of KOH he used chloride or bromide solutions, which allow a longer treatment with acetolysis without destroying the exine, however improving light microscopic contrast. Carbonates were removed by HCl, silicates by HF. At least 500 pollen grains per sample were counted for each level with a Leitz Diaplan light microscope, $\times 40$ (plan apo. n.a. 0.75); in the sections pointing evidence for anthropogenic inference in the vegetation (PZ 4 and 5), over 1000 grains were counted per level. Arboreal (AP) and non arboreal pollen (NAP) were summarized in the total sum of 100%. Aquatics and ferns were excluded from the pollen sum. For the biostratigraphic diagrams, the TILIA programme (version 2) was used. In core section 205 to 320 cm, the following *Pinus*-pollentypes were distinguished: *P. mugo*-types were differentiated from *P. sylvestris* according to Klaus (1972, 1977). The Alpine *P. cembra* (Klaus 1975) and the balcanic *P. peuce* (Jäger 1975) could not be differentiated by means of pollen. The name *P. Haploxydon*-type was used for pollen with an intersaccate distal ornamentation and a reticulum as described by Klaus (1975). *P. nigra* (Klaus 1972) and the balcanic *P. heldreichii* (Jäger 1975) display similar features. For pollen with these characters,

the name *P. nigra*-type was used. Identification of mediterranean pollen, Beug (1961a, b), Reille (1992, 1995), and the pollen and spore collection of Drescher-Schneider were used.

3.5. Plant macrofossils

Samples comprising 20 cm³ fresh material were extruded at 10 cm intervals from the core section between 200 and 320 cm, the only section where plant macrofossils were found. The material was washed and sieved (150 μm), and plant macrofossils were selected under the microscope (WILD M3) with low magnification. Recent type material was predominantly used for identification (e. g. University Salzburg, Botanical Institute; Krisai, Braunau).

3.6. Diatom stratigraphy

Diatoms were only preserved in the upper 60 cm of the sequence. Standard preparation were employed, as described by Battarbee (1986). At least 500 valves per sample were counted using a Leitz Diaplan light microscope with $\times 100$ oil immersion objective (n.a. 1.32). Species identification and taxonomy followed Krammer & Lange-Bertalot (1986–1991), Lange-Bertalot & Metzeltin (1996), and Wunsam *et al.* (1995). Total phosphorus (Di-TP) was inferred using the ALPTROPH calibration data set established by Wunsam (1994), Wunsam & Schmidt (1995). On average, 64% (minimum 47%) of the core taxa were represented in the calibration data set.

3.7. Cladoceran stratigraphy

Samples of 1 cm³ fresh material were prepared according to Frey (1986). Carbonates were removed using 10% HCl, after which the sediment was boiled in 10% KOH. The residue was washed and sieved (50 μm), filled to 10 cm³ with distilled water, and stained with safranin. All remains were counted (Ergaval-Zeiss microscope, magnification at least $\times 200$). Absolute numbers were calculated per 1 cm³ fresh material.

4. RESULTS

4.1. Echography (Fig. 2)

Within the central profundal zone (Fig. 2a) where the sediment thickness is around 50 m, several sedimentary units can be recognized. In this flat portion of the lake reflectors can be observed locally down to a depth of >25 m. Sound velocities around 1500 m s⁻¹ are assumed within the sediments. The lowermost unit comprises several faint parallel and continuous reflectors overlain by a ca 5 m thick horizon (Y) displaying no or faint discontinuous internal reflectors. The subsequent upper unit (X) comprises again distinct continuous reflectors with varying degrees of thickness and reflectivity. The uppermost section of this unit (X) is topped by a ca 1 m thick transparent layer ending in a single re-

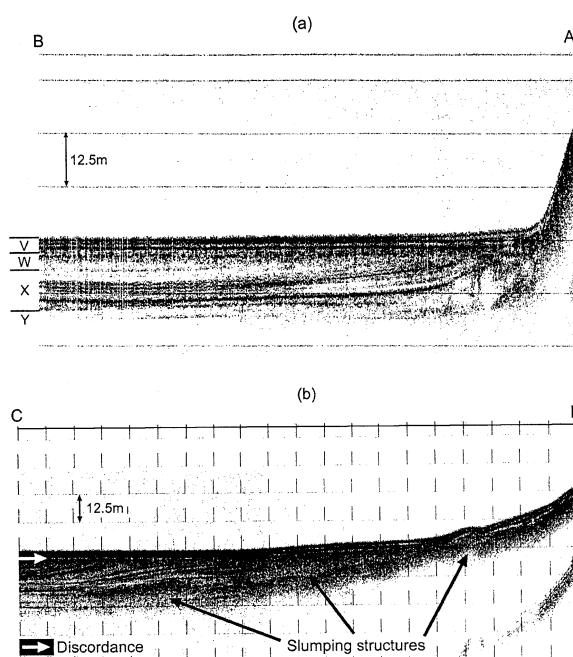


Fig. 2. Examples of 3.5 kHz echosounding profiles with the units V – Y (a), slumping structures and the location of the sediment discordance (b).

flector horizon with changing reflectivity. The uppermost 10 m shows two units. The lower one, *ca* 5 m thick unit (W) displays no or locally faint reflections, in contrast to the uppermost unit (V), which is characterized by several (3 – 5) distinct continuous and parallel reflections.

Profiling the slopes of the lake basin (Fig. 2b), only unit V drapes the lake bottom in a way typical for lake sedimentation originating mainly from vertical settling. On the slopes and at the foot of the slope, numerous structures can be observed, which are best explained as products of slumping. Towards the central basin, slumping structures give way to inclined reflectors, partly as prolongation of the slumping structures. The basis of unit V forms a discordant layer, where former (littoral?) units have been eroded.

4.2. Core stratigraphy, and Geochemistry and Mineralogy (Fig. 3)

The following units and subunits were distinguished by geochemistry and mineralogy:

A (500 – 325 cm)

This unit is characterized by a nearly constant ratio of calcite, dolomite and quartz/clay, and a low content of C_{org} (>1% d.w.). Sediment appeared homogenous and light coloured.

B (325 – 235 cm)

This unit is characterized by a high, but fluctuating content of organic carbon due to the organic detritus, and by a peak of calcite. Three subunits were distinguished: a calcite peak (B2: 290 – 265 cm) divides this

unit into a lower (B1) and upper (B2) sub-unit with higher amounts of silicates and organic carbon. The content of dolomite in the whole unit is lower than in unit A.

C (235 – 190 cm)

This unit is defined by a small peak of calcite and dolomite and a decrease in silicates. The C_{org} content is distinctly lower than in the former section.

D (190 – 85 cm)

It is characterized by the predominance of quartz and clay, and compared with B, low C_{org} . The values are fluctuating in a cyclic (saw-like) way.

E (85 – 0 cm)

Mineral proportions are characterized by a strong increase in calcite forming a marked peak during the subunit E2 (60 – 25 cm). In the subunits E1 (85 – 60 cm) and E3 (25 – 0 cm), C_{org} and dolomite are distinctly higher than in unit D. Between 85 and 60 cm a coarse layering appeared, due to changes in the proportions of C_{org} and calcite.

4.3. Pollen stratigraphy (Figs 4a, b)

The following pollen zones (PZ) were distinguished by CONISS, based on the dataset of AP, NAP, ferns and aquatics:

PZ 1/1 (500 – 415 cm)

This section is characterized by the dominance of *Pinus*. However, also pollen from the mixed oak forest (*Quercus*, *Acer*, *Tilia*, *Ulmus*, *Fraxinus excelsior*) *Carpinus betulus*, *Abies*, *Fagus* occurred. They were ac-

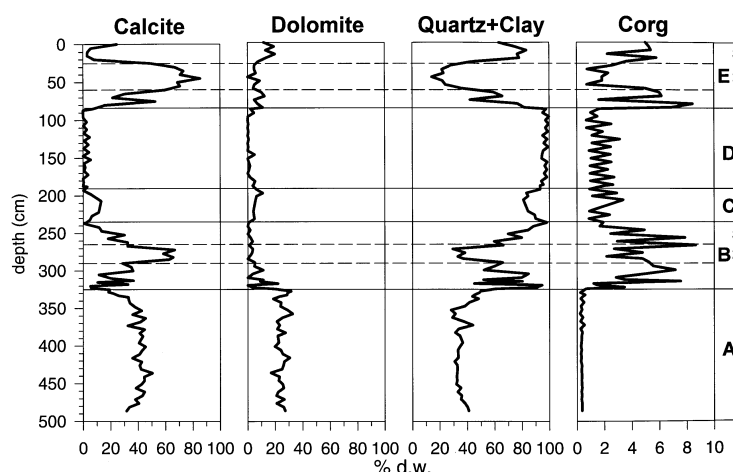


Fig. 3. Proportions of minerogenic components and organic carbon (C_{org}) in the core VRA96. Units A – E are also shown.

accompanied by mediterranean (*Quercus ilex*-type), sub-mediterranean (*Ostrya*-type), and possibly interglacial elements (*Buxus*).

PZ1/2 (415 – 380 cm)

Transition zone between the former pine-rich zone and the following one with increasing *Betula*. Chenopodiaceae, *Plantago*, and *Myriophyllum*, were more frequent than in the former section.

PZ 2/1 (380 – 325 cm)

Betula at the expense of *Pinus* increased. *Juniperus* formed a small peak towards top. *Artemisia* became more abundant. The pollen types of various deciduous trees mentioned for PZ 1 continued, however towards top with decreasing percentages.

PZ 2/2 (325 – 280 cm)

In this section *Pinus* increased again. Elements of the mixed oak forest only occurred in low percentages. The *Quercus ilex*-type and *Buxus* which were present in the former section lack. Poaceae and Cyperaceae reached peaks. *Equisetum*, the *Sparganium*-type and *Potamogeton* became more abundant.

PZ 3 (280 – 210 cm)

This pollen zone is dominated by *Pinus* and *Quercus*. Elements of the mixed oak forest increased in abundance. In low values *Fraxinus ornus* and *Pistacia* occurred.

PZ 4 (210 – 90 cm)

Fagus, *Abies* and *Picea* increased, and *Hedera* occurred. In the lower subzone 4/1 (210 – 155 cm), Chenopodiaceae formed a peak. In the subzone 4/2 (155 – 120 cm), *Pistacia*, *Phillyrea*, Oleaceae, *Ostrya*-type, *Vitis*, and Ericaceae appeared in low percentages. The upper subzone 4/3 (120 – 90 cm) is characterized by a distinct *Juniperus* peak. *Olea* was present sporadically. *Fagus* slightly increased and *Carpinus betulus* appeared. The *Plantago lanceolata*-type and *Cerealia* be-

gan to form continuous curves. Cichoriaceae formed a peak and *Potamogeton* also became more frequent. Charcoal particles were found.

PZ 5/1 (90 – 40 cm)

The *Quercus ilex*-type became abundant. *Phillyrea*, Ericaceae, the *Ostrya*-type, *Fraxinus ornus*, *Carpinus betulus* and *Alnus* expanded. *Castanea* and *Juglans* occurred the first time. *Vitis* and *Olea* slightly increased.

PZ 5/2 (40 – 0 cm)

In this subzone *Juniperus* again reached high abundances. *Pinus* and *Olea* became more frequent. In the core section 320 to 205 cm the following succession with respect to *Pinus* occurred (Fig. 5a): The *P. mugo*-types which dominated in the lower part was followed by a subsection (287.5 – 225 cm) rich in the *P. nigra*-type. The boundary between the Younger Dryas (YD) and the Preboreal (PR) was drawn at the intersection of the *P. mugo*-types curve and the curves of *P. nigra* and *Quercus*.

4.4. Plant macrofossils (Fig. 5b)

Plant remains were only found in the organic rich section 320 to 200 cm. The section was divided into the following zones:

Zone 1: 320 – 280 cm

This zone is characterized by strong short-term fluctuations of the main sediment components, C_{org} , quartz/clay, and calcite. At 320 cm the moss *Calliergon cordifolium/giganteum* (not shown) reached about 5% of the sample volume, and *Spongilla* is abundant. Oospores of *Chara* and *Nitella*, and seeds/fruits of various water plants characterize the following samples of this unit: *Potamogeton pusillus* agg., *P. crispus*, *P. pectinatus*, *P. alpinus*, *P. natans*, *Batrachium*, *Scirpus lacustris*, *Zannichellia*. From the terrestrial vegetation two fruits of *Rumex maritimus* were found.

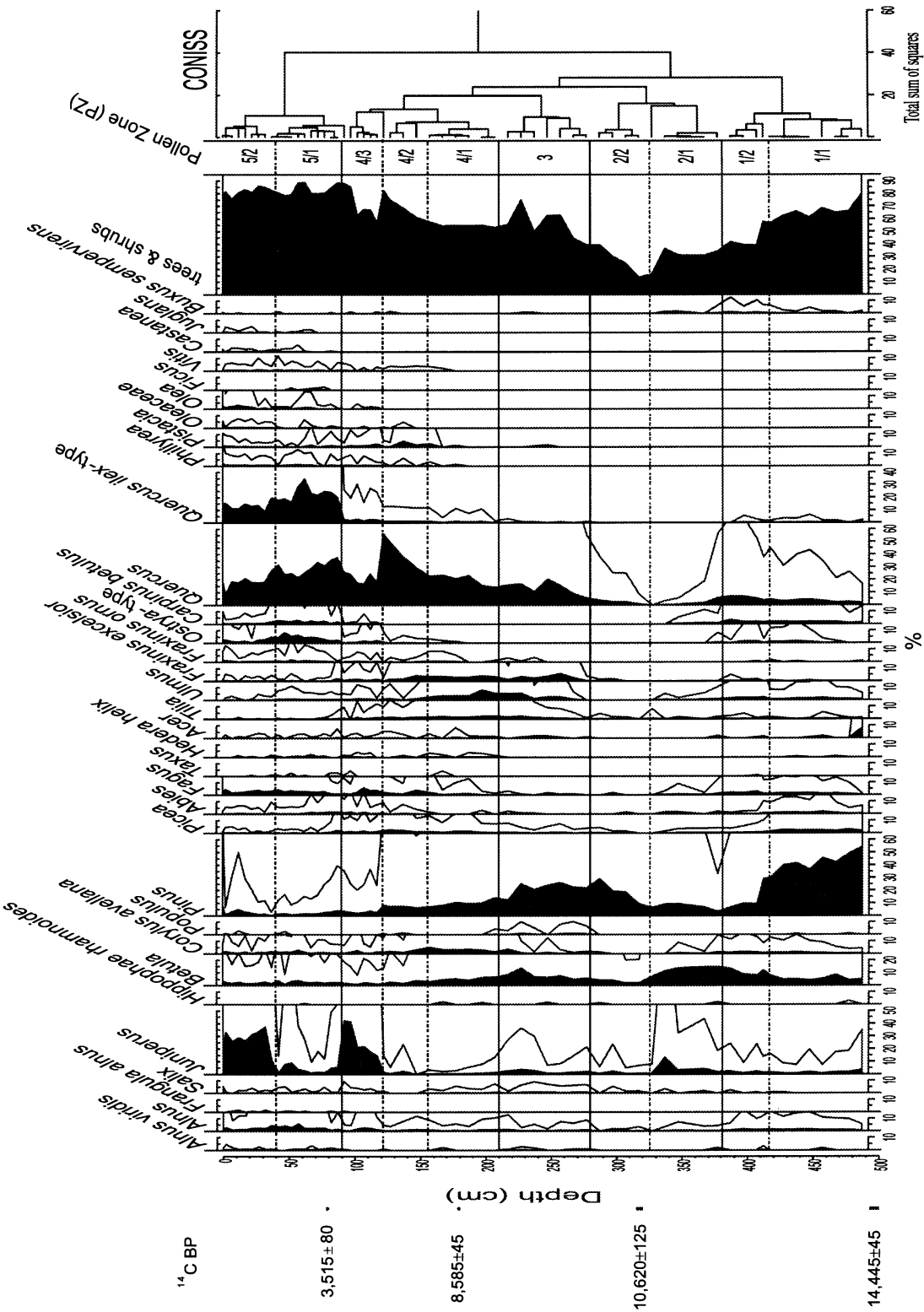
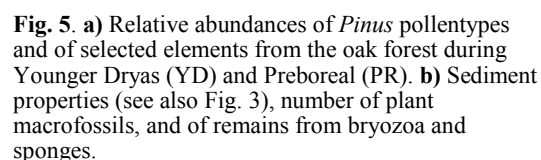


Fig. 4a. Pollen relative abundance diagram of trees and shrubs of the core VRA96 (Exaggeration 10x). Radiocarbon dates (^{14}C) and CONISS zones are added.



Expansion of the *Cyclotella comensis* and the *C. radiosa* complex. *Synedra acus* and *Tabellaria flocculosa* appeared towards the top of this zone in low numbers. *Campylodiscus noricus* was more frequent than in the former zones. *Navicula* cf. *lucinensis* became dominant.

4.6. Cladoceran stratigraphy (Fig. 7)

In the allochthonous sediments below 340 cm depth no cladocerans were found. In the core section 340 cm to 0 cm 4 pelagic and 22 littoral taxa occurred. This section was divided by CONISS, based on all taxa, into the following zones:

CZ 1/1 (340 – 295 cm)

Only littoral species were present, mainly from the genera *Alona* and *Chydorus*. Abundance was low.

CZ 1/2 (295 – 230 cm)

Species diversity and abundances of littoral chydorids increased. Taxa which were not present in the former zone include: *Acroperus harpae*, *Alona guttata*, and the planktic *Daphnia longispina*-group.

CZ 1/3 (230 – 200 cm)

Most of the taxa which were present in the former zone peaked.

CZ 2 (200 – 50 cm)

A marked decrease in total cladocerans occurred, whereas assemblage composition was comparable to the former section. In CZ 2/2 (130 – 50 cm), species composition changed slightly, e. g. *Graptoleberis testudinaria* diminished, and towards the top, *Bosmina* occurred the first time.

CC 3: (50 - 0 cm)

Bosminidae became abundant in the plankton. *Bosmina longispina* and *B. longirostris* occurred together. Values peaked between 40 and 20 cm.

5. DISCUSSION

Because of the limitation of ^{14}C -datable organic material, and the possibility of errors arising from carbonaceous material in a karstic region, for discussion the whole core sequence was divided into five larger time windows: Late Pleistocene > Younger Dryas, Younger Dryas, older, mid, and younger Holocene. An overview of these time windows together with the biostratigraphic and sedimentological units is provided in figure 8.

5.1. Late Pleistocene (core section 500 - 325 cm)

PZ 1/1 was compared with a pine-pollen rich section of the neighbouring site of Valun which was related by Schmidt *et al.* (submitted) to a cold period which ended at about 14 to 13.6 ky BP. This assessment in Lake Vrana is supported by a ^{14}C -date of $14,445 \pm 145$ BP (according to CALIB, 1999, the date lies in the range of approx. 16.8 to 17.8 cal. ky BP). Pollen from deciduous trees as they were found in core VRA96 are missing in Valun. They probably originated from interglacial lake deposits, which is supported by the findings of pollen from *Buxus*. For coastal lake hydrology, the entire sea level is assumed to reduce losses through the karst by forming a local barrier for groundwater. Results from

the Bay of Valun indicate that the sea level during this cold period was about 55 m below present, which is around the basins depth of Lake Vrana; in addition it was a temporarily more wet phase with erosion features. Both together might have been also responsible for an increase in lake level in Lake Vrana. Sediments were redeposited by lake level erosion and slumping as indicated by the echography. Another source for redeposition was assumed the present funnel-shaped hole which penetrates the whole sediment section. Interglacial bottom sediments may have been redeposited by the formation of a karstic spring when groundwater influx increased.

Because of continuing pollen redeposition, PZ 1/2 and 2/1 can not definitely be correlated with the site Valun. However, the higher abundances of *Betula* and *Artemisia*, the lack of cladocerans, and sediments with low organic content and of predominantly allochthonous origin indicate pre-Alleröd time. Huntley *et al.* (1999) related higher *Betula* percentages in Italian crater lakes with a higher moisture availability during an early Lateglacial Interstadial. Since pollen of the *Sparganium*-type, *Myriophyllum*, *Polygonum amphibium*, and *Potamogeton* were found in low numbers in Lake Vrana, a shallow freshwater lake may have prevailed, probably with fluctuating lake level, erosion and redeposition.

5.2. Younger Dryas (core section 325 – 287.5 cm)

Compared with the results from Valun, the expansion of *Quercus* and mixed oak forest indicating the distinct climate amelioration during Alleröd is missing. Hence, a hiatus was interpreted for the chronozone of Alleröd at Lake Vrana, separating the sediment sections A and B. One of the reflectors of the echo-unit V may indicate this discordance. Based on the ^{14}C -date ($10,620 \pm 125$ BP), and the dominance of the *P. mugo*-type, the lower part of sediment section B and PZ 2/2 from 325 to 287.5 cm (see Fig. 5a) were correlated with the Younger Dryas. An increase in precipitation was probably responsible for catchment erosion (high amounts of spores, quartz and clay), and the onset of a swamp vegetation when groundwater level increased again. In the pollen diagram, peaks of Poaceae, Cyperaceae, *Sparganium*-type and *Equisetum* occurred; macrofossils of *Scirpus lacustris* and *Rumex maritimus* were found; the latter at present occurs far away from the sea (see Adler *et al.* 1994). The high organic detritus content is reflected by peaks of C_{org} . A shallow lake is indicated by the high abundance of macrofossils of *Chara* and *Nitella*, *Batrachium* and *Potamogeton* taxa; e. g. *P. natans* only occurs in water up to 2 m depth. *P. alpinus* requires slightly cooler conditions than the other frequent *Potamogeton* taxa, *P. natans*, *P. pectinatus*, and *P. pusillus* (Oberdorfer 1990). Pollen of *Potamogeton* increased in relative abundance in the upper part of this section.

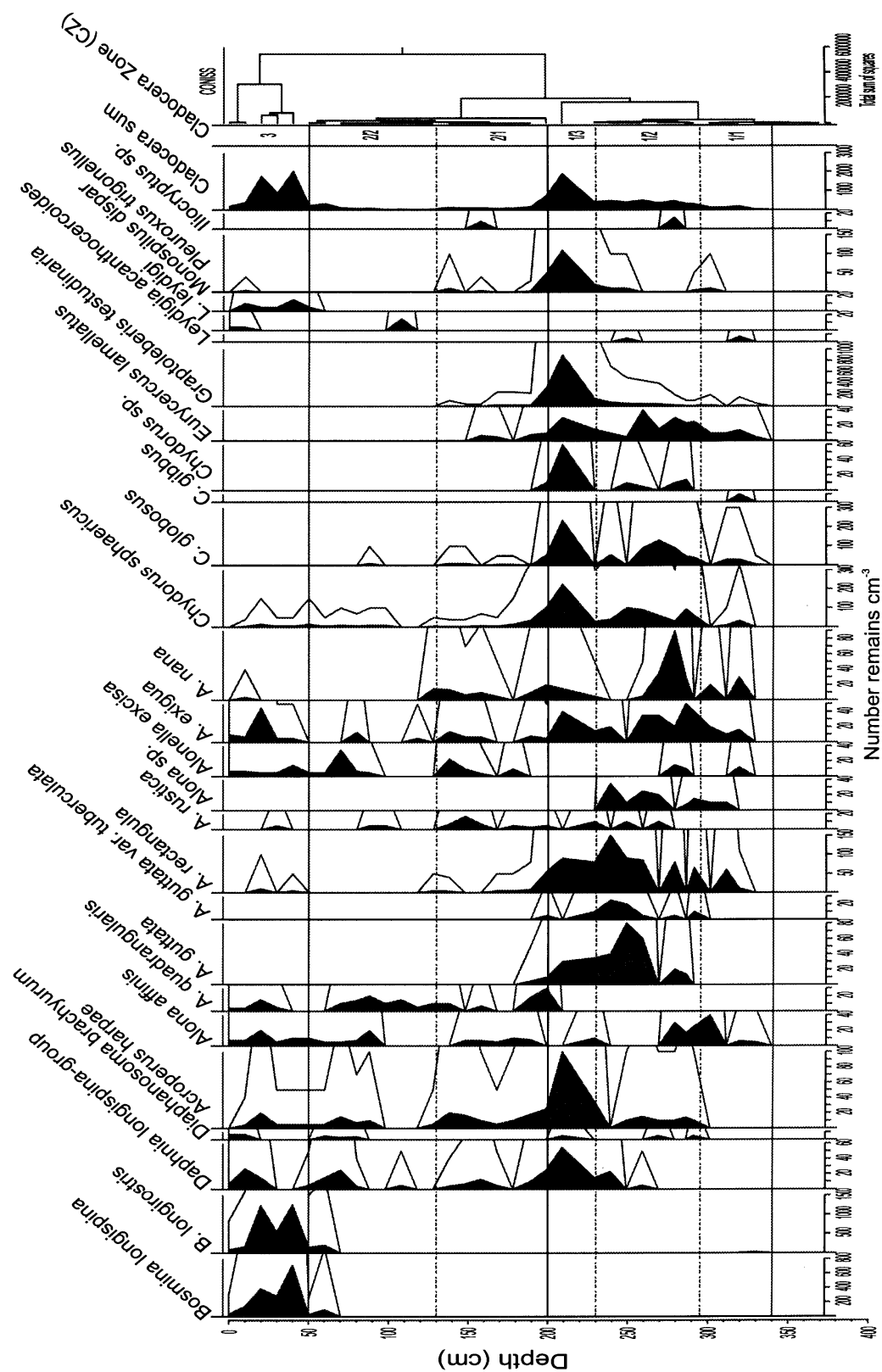


Fig. 7. Absolute numbers of cladocerans in the core VRA96.

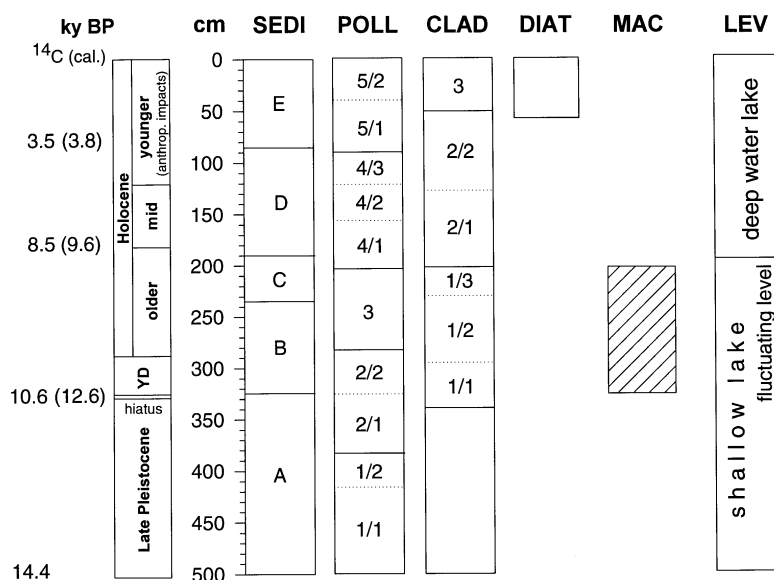


Fig. 8. Overview of time windows (approx. kiloyears ¹⁴C before present, ky BP, and calibrated kyears in brackets), sedimentological units (SEDI=Sediment), biostratigraphic zones (CLAD=Cladocerans; DIAT=Diatoms; MAC=Plant macrofossils; POLL=Pollen), and lake stages (LEV) in core VRA96.

Compared with a modern data set from the Swiss Alps (Lotter *et al.* 1997), Cladocera have occurred which are currently more frequent in the Alps at altitudes above 1500 m (*Alona affinis*, *Alonella excisa*, *Chydorus sphaericus*). Most of the cladoceran taxa found are also known from the Lateglacial time from Lake Gościaz in Poland (Szeroczyńska 1998).

5.3. Older Holocene (287.5 – 180 cm)

The decrease of the *Pinus mugo*-types and the increase of the *P. nigra*-type and *Quercus* indicate climate amelioration, and therefore the transition from Younger Dryas to Preboreal (see Fig. 5a). This is supported by the change from an allochthonous (quartz/clay, dolomite) to an autochthonous sediment rich in calcite. Occurrences of pollen from *Nymphaea*, *Nuphar*, and between 260 – 280 cm, macrofossils of *Najas minor*, indicate an increase in water temperature. The latter according to Oberdorfer (1990) is a plant of warm, base-rich mesotrophic lakes and grows at water depths of 30 – 200 cm. Among the Cladocera, littoral chydorids increased in species diversity (*Acroperus harpae*, *Alona guttata*, *A. guttata* var. *tuberculata*, *A. rustica*) and abundance. This was probably due to both increase in temperature and the presence of macrophytes.

At the transition Younger Dryas/Preboreal the sediment properties indicate fluctuating water level. The increase of quartz and clay at the expense of calcite forming a peak at 237.5 cm core depth was interpreted as an indication of a rise in lake level. This is supported by the increase of the *Daphnia longispina*-group in the plankton, corresponding with the increase in abundance of *Spongilla* and Bryozoa. Sediment proportions at the

core level 237.5 cm are comparable to sediment unit D, with a change to the silicate fraction. The rise in lake level corresponds with a temporary decrease of *Quercus*.

In the overlying sediment section C calcite slightly increased. The ratio between calcite and dolomite indicates allochthonous influence when compared with section A. The high numbers of littoral macrophytes indicate a lowering of the lake level compared with before. The following gastropods/molluscs were found in the sample 200 – 210 cm: *Bithynia* sp., *Gyraulus albus*, *G. cristata*, *Hippeutis complanatus*, *Pisidium* sp., *Valvata cristata*. They are also indicators of low water level. There is little change in species composition of cladocera compared to the former section (B). Since several taxa form distinct peaks in abundance, total number reaches the maximum recorded. The high values of the *Graptoleberis testudinaria* are remarkable; this species has been recorded in lakes with higher temperatures (Goulden 1964; Mezquita & Miracle 1997), and it also was found by Brancelj *et al.* (1997) in an eutrophic lake rich in macrophytes. The lake level lowering in Lake Vrana may correlate with Preboreal sediment gaps found in several Apennine sites (Cruise 1990; Lowe & Watson 1993).

In the terrestrial vegetation, *Fraxinus ornus* appeared in low relative pollen abundances. Together with increasing percentages of *Quercus* at the expense of the *Pinus nigra*-type, it may indicate an increase in temperature. At present *P. nigra* ssp. *dalmatica* occurs in the submediterranean belt of the coastal mountain range of the Dinarids (Domac 1965). The amounts of *P. Haploxydon*-type indicate that during Younger

Dryas/Preboreal a pine of this section was present in the northern Dinarid mountains. At present there is a gap between the areal of the Alpine *P. cembra* and the southern *P. peuce* which has in the southern Dinarids its northern borderline (Fukarek 1970).

5.4. Mid-Holocene (core section 180 - 120 cm)

The boundary between the chronozones of Preboreal and Boreal is not dated. Increasing percentages of *Fagus* pollen indicate the formation of the present beech-rich belt at about 8.5 ky BP, which dominates the mountain ranges in Istria and the Dinarids. It fits to the Boreal expansion of *Fagus* in Slovenia mentioned by Šercelj (1963). First occurrences of *Hedera* indicate mild winter conditions. In addition, *Abies* was present in low percentages, and ferns increased. The expansion of *Fagus*, which avoids areas with dry summers and severe cold winters, correlate with the onset of a pluvial period at the Dalmatian coast, which according to Wunsam *et al.* (1999), initiated at 8.4 C ky BP. At this time, the karstic basins of Malo and Veliko Jezero, Isle of Mljet, were filled with freshwater, and the Lake Vrana may have reached its present depth. There is little change in the cladoceran assemblage composition when compared with the shallow lake stages of the older Holocene. However, the distinct decrease in absolute number marks the onset of the present deep water lake during the Boreal. The mineral proportions over the whole unit D were nearly constant. They are dominated by quartz and clay. To explain these proportions, there are two possibilities; calcite dissolution and/or erosion from laterite soils. Since ostracod shells were lacking, calcite dissolution possibly by CO₂ enriched cold waters was assumed. Because of calcite dissolution and less productivity, sedimentation rates decreased when compared with the shallow lake phases of older Holocene (from 0.9 to about 0.2 mm per year). Diatom valves also are missing. Diatom dissolution commonly occurs in oligotrophic hardwater lakes (Klee *et al.* 1993).

There is a distinct increase of *Chenopodiaceae* with the onset of the deep Lake Vrana. Since this contradicts the climate setting, the lake may have been attractive for mesolithic men, whose presence on the island is recorded by artefacts found in caves (see Mavrović 1994). In this case, the *Chenopodiaceae* are interpreted as weeds resulting from human occupation of the lake shore.

In the upper part of this section (PZ 4/2) slightly increased values of *Pistacia* and *Phillyrea* indicate expansion of mediterranean elements.

5.5. Younger Holocene with anthropogenic impacts (core section 120 – 0 cm)

From pollen assemblage, three stages were observed which differ in land-use, and impact on vegetation and lake environment.

a) Core section 120 – 90 cm

The change in vegetation caused by anthropogenic impact at Lake Vrana commenced with a marked *Juniperus* pollen peak at 120 cm core depth. At the same time the continuous *Cerealia*, *Plantago*, *Olea* and *Carpinus betulus* pollen curves begin. The degradation of the *Quercus* dominated forests in the catchment is supported by the expansion of heliophilous plants (e. g. *Anthericum*). Charcoal particles indicate forest clearing by the use of fire. A linear extrapolation of the ¹⁴C date of 3518 ± 80 BP at 80 cm core depth indicates Bronze or even Neolithic settlement.

b) Core section 90 – 40 cm

During this section the present terrestrial vegetation formed; *Quercus ilex*, *Ostrya/Carpinus orientalis*, *Carpinus betulus*, *Fraxinus ornus* expanded. The advantage in competition of the evergreen over the deciduous oaks (Freitag 1975) may have been increased by forest clearance, coupled with an increase in summer drought. This may explain the sudden increase of *Quercus ilex* as extrapolated for 4.2 ky BP, and subsequent occurrences of *Ficus* pollen combined with a peak of the *Quercus ilex*-type.

At 90 cm core depth, the lake environment changed. In the sediment a coarse layering occurred. Organic matter and dolomite increased, probably due to increased allochthonous influx from human catchment disturbances. The calibrated (CALIB 1999) ¹⁴C-date at 80 cm core depth lies within the range of about 1900 to 1700 BC. In this case, the catchment disturbances were related to Illyrian settlement.

Since the onset of *Juglans* and *Castanea sativa*, according to Beug (1977), are good markers for the change from the Illyrian to the Roman influence in the Northern Adriatic during the first century BC, the core section 65 to 70 cm may be related to this time of Illyrian/Roman transition. The increase in *Olea* and *Vitis* also probably indicates cultivation. However, if this is the case, the ¹⁴C-date at 80 cm core depth may indicate that the accumulation rate was not linear or the date obtained is too old. Diatoms were only preserved in the uppermost 60 cm, indicating also a change in the lake environment. The slightly increase in the diatom inferred total phosphorus culminating at 40 cm core depth (14.2 µg l⁻¹, Fig. 9) primarily is caused by the occurrence of *Aulacoseira ambigua*, which has a optimum of 52.4 µg l⁻¹ TP in the data set established by Wunsam & Schmidt (1995), at the expense of *Cyclotella comensis* morphotypes (MT). *Cyclotella* spp. dominate at present (Tomec *et al.* 1996). The high abundances of *Fragilaria*-taxa may be related to seasonal lake level and water temperature change (Wunsam 1994). Since the calcite peak between 60 and 25 cm (sediment unit E 2) correlates with the peak in Di-TP (Fig. 9), increase in nutrients starting with Roman settlement is likely to have enhanced phytoplankton development and hence biogenic calcite precipitation. Increase in phytoplankton

forced the onset of Bosminidae in the plankton. Both, *B. longirostris* and *B. longispina* co-occurred, whereas in present water samples by Bukvić *et al.* (1997) only *B. longirostris* was mentioned. In Lake Albano Manca *et al.* (1996) observed an increase of *Bosmina* sp. during the time of human impact from the Bronze age to present.

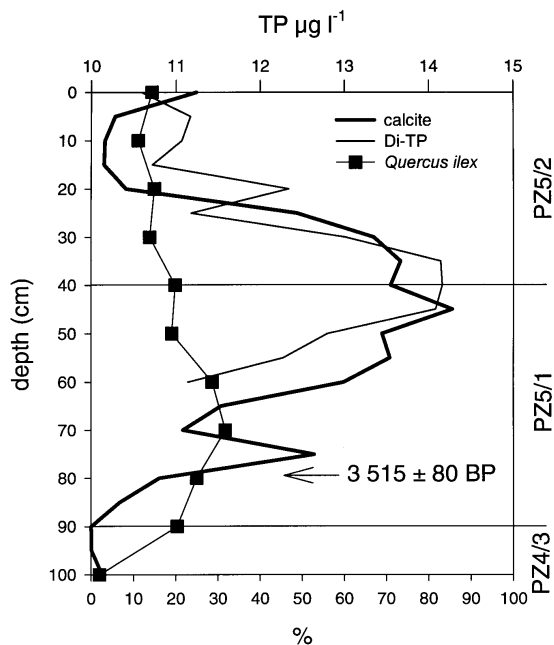


Fig. 9. Calcite accumulation in the core section 0 - 100 cm of VRA96 (see also Fig. 3) in relation with diatom inferred total phosphorus (Di-TP), and with a pollen temperature biomarker (*Quercus ilex*). Pollen zones and a ^{14}C date are added.

c) Core section 40 – 0 cm

A younger *Juniperus* peak began at 40 cm. It probably indicates clearance for pastures. Since also pollen of *Olea* increased, *Olea* cultivation may have been intensified. According to Beug (1977), during Middle Ages there was a strong development of *Juniperus* heaths in Istria. The change in land use and probability that settlements moved away from the catchment towards sea may explain the following onset of re-oligotrophication in Lake Vrana.

6. CONCLUSIONS

Analyses of the upper 5 m of sediments from a sediment filling of at least 25 m thickness indicate considerable lake level and environmental changes since 14.4 ky BP (16.8 to 17.8 cal. ky BP). A shallow lake with fluctuating levels occurred during Late Pleistocene and early Holocene. In the section prior to Alleröd, pollen was reworked from interglacial sediments. Possible sources were erosion by lake level increase, slumping, and redeposition by a karstic spring penetrating older lake sediments. These findings support the wet

character for a Late Pleistocene cold period, as observed for the neighbouring site Valun. The ^{14}C date of about 14.4 ky BP obtained at Lake Vrana is in accordance with the assumed age of this cold period of 16 to 14 ky BP. Infiltration losses into the karst probably were reduced by the post-LGM sea-level rise up to the basins depth, forming a local groundwater barrier. Results in Lake Vrana support the inference of a moist and relatively moderate summer temperate phase following the cold period of Lake Valun, when compared with Alleröd. There appears to be a hiatus in the succession of Lake Vrana, for no sediments assignable to Alleröd chronozone as observed at Valun could be found; a discordance in the echo profile was related to this gap. During the Younger Dryas, groundwater level increased again. A swamp vegetation formed followed by a shallow freshwater lake. YD appeared more humid when compared with other Mediterranean sites. During the Preboreal the shallow freshwater lake prevailed and was rich in macrophytes and littoral chydorides. Because of increased in-lake production and hence accumulation rate, episodes of environmental changes were observed. The section was divided into a phase of rapid fluctuating lake level at the Younger Dryas/Preboreal transition, followed by a lake level increase and a subsequent lowering. These findings correspond with indications of low lake levels from sites in northern Italy.

After a transition stage in lake level, probably lasting several hundred years, the present deep water lake established at about 8.5 ky BP (about 9.6 cal. ky BP). It correlates with the change in terrestrial vegetation indicating an increase in humidity. Both were related to an pluvial period, which at the Dalmatian coast initiated at about 8.4 ky BP. In the deep Lake Vrana no environmental changes until the time of anthropogenic impact were detected. Calcite dissolution, possibly by influx of CO_2 enriched cold waters, and low productivity, caused low accumulation rates and change in the sediment proportion towards the silicate fraction. The interval of approx. 6 to 4 ky BP is characterized by a transition stage between deciduous oak forests and northwards expanding mediterranean elements. The sudden *Quercus ilex* expansion at about 4.2 ky BP was related to a period with drier summers, coupled with forest clearance. However, with the exclusion of this period, which probably lasted until the Illyrian/Roman transition, it was assumed that present autumn/winter rain maxima coupled with less summer drought, are the primary causes that allowed deep Lake Vrana to persist until present.

The following stages of anthropogenic impact were detected. Weeds indicate an early (mesolithic?) anthropogenic impact. Distinct catchment disturbances by the use of fire started during Neolithic or Bronze Age settlement. The main features of the present terrestrial vegetation formed during Illyrian and Roman time. During the latter the lake trophic level slightly in-

creased. It culminated during a younger stage of forest clearance (not dated) for intensification of *Olea* cultivation and pastures. When land use changed and the focus of human interest moved away from the lake, re-oligotrophication occurred. The oligotrophic stage was conserved by recent lake protection.

In conclusion, the multi proxy approach supports models which relate the water budget of Lake Vrana to climate. Climate patterns were observed which fit to a larger Adriatic scale. The freshwater lake has been attractive for human settlers at least since the time when the present deep lake formed (about 9.6 cal. ky BP).

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