

Late Glacial and Holocene environmental history of the Pirin Mountains (SW Bulgaria): a paleolimnological study of Lake Dalgoto (2310 m)

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Abstract

Diatoms, Cladocera, and chironomids preserved in the sediments of Lake Dalgoto were studied to reconstruct the history of the lake ecosystem in the context of the vegetation history as represented by the pollen stratigraphy. Younger Dryas silty sediments at the base of the core are characterized by low diversity of aquatic organisms. The transition to the Holocene is indicated by a sharp change from silt to clay-gyttja. The migration and expansion of trees at lower elevations between 10200 and 8500 ¹⁴C-yr BP, along with higher diversities and concentrations of aquatic organisms and the decreased proportion of north-alpine diatoms, point to rapidly rising summer temperatures. After 6500 ¹⁴C-yr BP the expansion of *Pinus mugo* in the catchment coincides with signs of natural eutrophication as recorded by an increase of planktonic diatoms. In the late Holocene (4000–0 ¹⁴C-yr BP) *Pinus peuce* and *Abies* are reduced and *Picea* expands. Cereal grains and disturbance indicators suggest late-Holocene human modification of the vegetation.

Introduction

High-mountain lakes have attracted the interest of limnologists for a long time, mainly because of their extreme climatic and physico-chemical conditions. Only scant information has existed about the algal flora of high-mountain lakes in the Pirin Mountains (Petkoff 1925), but new information will come from the project EVK1-CT-1999-0032 “European Mountain Lake Ecosystems: Regionalization Diagnostics and Socio-Economic Evaluation” (EMERGE), European Commission Framework Programme V. The MOLAR project of the European Union “Measuring and Modelling the Dynamic Response of Remote Mountain Lake Ecosystems to Environmental Change: a Programme of Mountain Lake Research “

is producing results from other mountain areas in Europe (Battarbee et al. 2002)

The Pirin Mountains (Figure 1) are largely composed of Precambrian granite (Boyagjiev 1959), which is cut by numerous glacial cirques now occupied by small lakes (Figure 2). These provide the opportunity to reconstruct the Late Glacial and Holocene vegetation history of the landscape through stratigraphic pollen analysis (Bozilova 1975, 1977; Stefanova and Bozilova 1992, 1995; Stefanova and Oeggl 1993; Panovska et al. 1995; Stefanova 1997, 1998, 1999; Tonkov et al. 2002; Stefanova and Amann 2003; Atanassova and Stefanova 2003). The area is in the eastern part of the Balkan Peninsula, which is considered to have been a refuge for temperate trees during the last glaciation (Bottema 1974;

Beug 1975, 1982; Huntley and Birks 1983; Bennett et al. 1991; Willis 1994). Lake Dalgoto is situated at 2310 m near the top of the sub-alpine belt of *Pinus mugo*. Its sensitivity to environmental change is suggested by distinct features in the Late Glacial and Holocene pollen stratigraphy. Although late migration of conifers to the mountains, as well as long-distance transport of pollen from lower elevations, can be considered as major factors in the interpretation (Stefanova and Ammann 2003), climatic change may also have played an important role. A palaeolimnological approach associated with environmental reconstruction might provide data to evaluate the relative importance of the several factors involved. The project reported here results from an investigation of three additional microfossil components in the sediments of Lake Dalgoto – diatoms, Cladocera, and chironomids.

Setting

Lake Dalgoto (41°40' N, 23°22'E, Figure 2) is about 450 m long and 150 m wide and has a maximum depth of 10 m (Ivanov and Sotirov 1964). Mean annual temperature above 2300 m is below 0°C (Tishkov and Vekilska 1982), and annual precipitation is 800–1250 mm, with a maximum in November–December (Velev 1997).

The vegetation of the subalpine belt (2000–2500 m a.s.l.), where Lake Dalgoto is located at 2310 m, is dominated by communities of *Pinus mugo*, *Juniperus sibirica*, and *Vaccinium myrtillus*. Communities of *Pinus sylvestris*, *Picea abies*, *Pinus peuce*, *P. heldreichii*, and *Abies alba* are present in the coniferous belt between 1500–1600 m and 2000–2200 m. The belt of *Fagus sylvatica* forest (900–1000 to 1500–1600 m a.s.l.) is represented in the northern Pirin Mountains by fragments. Communities of mesophilous and xero-mesophilous *Quercus dalechampii* and *Carpinus betulus* are typical in a belt up to 800–1000 m a.s.l., where communities of *Pinus nigra*, *Ostrya carpinifolia*, and *Corylus avellana* also occur. The belt of xerothermic oak forest (600–700 m a.s.l.) contains communities of *Quercus pubescens*, *Q. frainetto*, and *Carpinus orientalis* (Bondev 1991; Veltshev 1997).

In the study area the upper forest limit, which reaches today only to about 2000–2100 m a.s.l., is formed by communities of *Picea abies* and the Balkan endemic species *Pinus peuce* on siliceous terrain and by communities of the Balkan relict subendemic species *Pinus heldreichii* where calcareous terrain dominates.

The aquatic macrophytes in the lake include *Ranunculus aquatilis*, *Subularia aquatica*, and *Spartanium angustifolium*. The vegetation around the lake includes *Carex nigra*, *Juncus alpinus*, *Silene pusilla*,

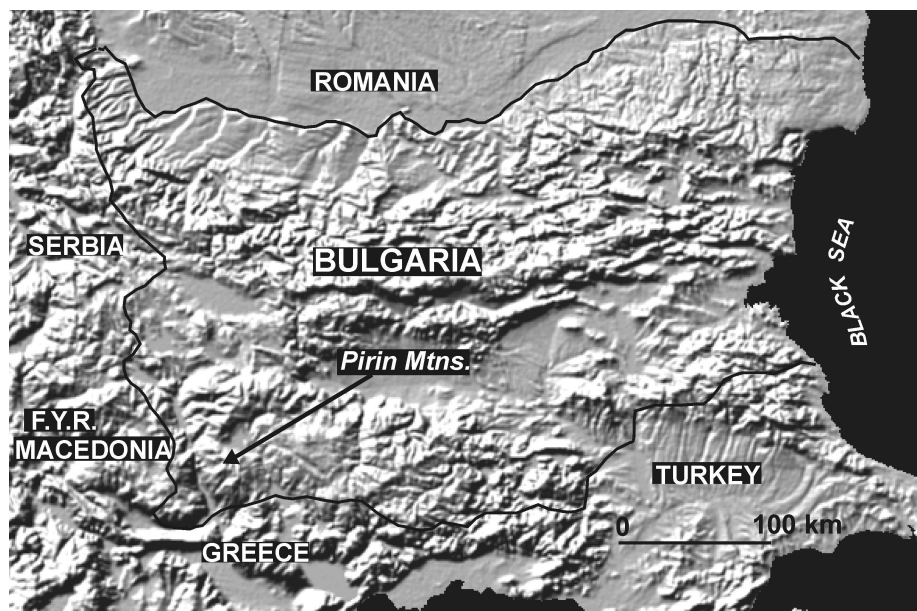


Figure 1. Relief map of the eastern Balkan Peninsula showing location of the Pirin Mountains.

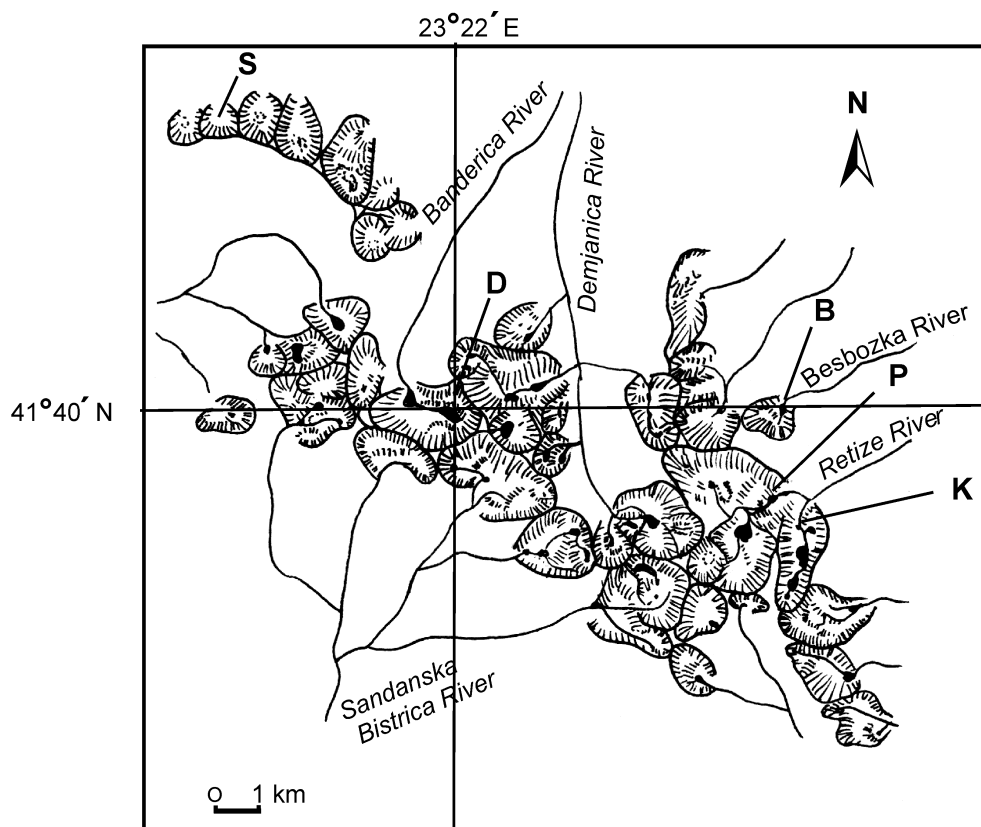


Figure 2. Map of the Pirin Mountains showing the distributions of glacial cirques, many with one or more lakes. B = Besbog, D = Dalgoto, K = Kremensko-5, P = Popovo-6.

Parnassia palustris, *Geum coccineum*, *Plantago gentianoides*, and *Epilobium palustre*.

Nomenclature for vascular plants follows Flora of the Republic of Bulgaria (Jordanov et al. 1963-1995).

Methods

The sediment core was taken in water 6.60 m deep with a square-rod piston corer from a rubber boat (Wright 1991). Gytija and terrestrial macrofossils were separately ^{14}C -dated by accelerator mass spectrometry and were adjusted to the regional chronology (Stefanova and Ammann 2003). Samples for pollen were taken at every 5 cm, and for the other analyses at 10 cm. Pollen samples were prepared according to standard methods (Faegri and Iversen 1975). The percentage pollen diagram is based on total arboreal and non-arboreal pollen and excludes pollen of aquatic plants and Cyperaceae as well as spores of pteridophytes and bryophytes.

Diatom samples were prepared according to the method of Ognjanova-Rumenova (1991). The relative proportion of diatom taxa was determined by the scale of Schrader (1973): 1 - not present; 2 - rare (1–3 specimens per slide 18×18 mm); 3 - frequent (4–40 specimens); 4 - abundant (> 40 specimens), and 5 - “mass” occurrences (>100 specimens). The taxonomic list follows Glezer et al. (1988) and Round et al. (1990). Nomenclature was modified in the light of Abbott and VanLandingham (1971), Krammer and Lange-Bertalot (1986-1991).

The spectra of physico-chemical tolerance based on studies of modern diatoms were used to reconstruct the sedimentary environments (Abbott and VanLandingham 1971). Several techniques based on diatom assemblages have been used to assess trends in acidification and to derive equations for inferring lake-water pH (Nygaard 1956; Renberg and Hellberg 1982; Charles et al. 1989; Ognjanova-Rumenova 2002). In this study index B of Renberg and Hellberg (1982) was used. The percentage ratio of diatom

frustules to chrysophycean stomatocystae was applied as an index of trophic status (Smol 1985).

Cladocera and chironomid samples were prepared by standard methods (Frey 1986), including heating in 10% KOH on a hot-plate stirrer and screening through a 40- μm sieve. The larval head capsules of chironomids were picked from the 200- μm fractions, dehydrated in 96% alcohol, and mounted in Euparal*. For identification the keys by Wiederholm (1983), Kowalyk (1985) were used. *Daphnia ephippia* were counted in the fraction >100 μm under a stereomicroscope at 20x. The chydorids were counted separately in the fractions >100 μm and 40–100 μm . Subsamples in most cases were equivalent to 0.45–1.58 g DW (dry weight). Sample volumes were much greater in the three sandy samples at 770 cm (8.1 g DW), 925 cm (28.3 g DW), and 930 cm (28.1 g DW). Calculation of chydorid fragments follows Frey (1986): Table 32.1). Identification and taxonomy of the chydorids follow Frey (1958, 1959) and Flößner (1972). Species-diversity index follows Lioyad and Ghelardi (1964).

Concerning zonations of all four biostratigraphies, the method of optimal sum-of-squares partitioning was followed, integrating the chord distance as a coefficient and using the program ZONE 1.2 (Juggins 1991) in comparison with the broken-stick model (Bennett 1996) to identify the statistically significant zones (see Figures 2, 3, 5 and 7).

To quantify composition changes in adjacent samples, a preliminary DCA (detrended correspondence analysis, Table 1) showed that the length of the overall gradient is smaller than 2 standard deviations in the pollen and Cladocera stratigraphies and larger than 2 standard deviations in the chironomid stratigraphy. Therefore for pollen and Cladocera a linear response model was used together with PCA, whereas for the chironomids a unimodal response model was assumed and CA (correspondence analysis) was applied.

Results

Lithology

The basal sediments (930–910 cm) consist of silt (Figure 3). After a transitional section (910–880 cm), the rest of the core is fine-grained organic sediment (gyttja).

Pollen

Pollen-percentage data for selected taxa are plotted against depth in Figure 3. Five pollen zones are distinguished, four of them determined as statistically significant by comparison with a broken-stick model (Bennett 1996). The zone PD2/PD3 boundary, shown by dashed line on Figure 3, is ecologically significant.

PAZ PD-1: 930–912.5 cm (11000–10200 ¹⁴C-yr BP)

This zone is characterized by minimum percentages of *Pinus* diploxylon-type (10–25%), whereas *Pinus* haploxylon-type, *Betula*, *Quercus*, *Juniperus*, *Ephedra distachya*-type, and *Ephedra fragillis*-type are only 1–2% each. *Artemisia* reaches 50%, Chenopodiaceae 20%, and Poaceae 5–20%.

The upper boundary of the zone is characterized by increasing values of *Pinus* diploxylon-type, *Quercus*, and *Betula* and by strong decreases of *Artemisia* and Chenopodiaceae.

PAZ PD-2: 912.5–882.5 cm (10200–8500 ¹⁴C-yr BP)

Betula, *Juniperus*, *Pinus* diploxylon-type, *Pinus* haploxylon-type, *Quercus*, *Ulmus*, and *Tilia* increase. *Abies* and *Carpinus orientalis* have their first occurrences in this zone, as well as *Acer*, *Fraxinus excelsior*-type, *Sorbus aucuparia*, *Vitis*, and *Humulus/Cannabis* (not shown in Figure 3). Herb taxa present are Poaceae, *Artemisia*, and Chenopodiaceae.

The upper boundary of the zone is characterized by increasing values of *Quercus*, *Tilia*, *Ulmus*, and *Corylus*.

PAZ PD-3: 882.5–832.5 cm (8500–6500 ¹⁴C-yr BP)

Quercus, *Tilia*, *Ulmus*, and *Corylus* reach maximum values in this zone as *Betula*, *Pinus* diploxylon-type, and *Pinus* haploxylon-type remain unchanged. *Picea* and *Fagus* are characteristic. Poaceae and *Artemisia* dominate.

The upper boundary of the zone is characterized by increasing values of *Pinus* diploxylon-type, *Pinus* haploxylon-type, and *Abies*.

PAZ PD-4: 832.5–772.5 cm (6500–4000 ¹⁴C-yr BP)

Pinus diploxylon-type, *Pinus* haploxylon-type, and *Abies* increase, whereas *Quercus*, *Ulmus*, *Tilia*, and

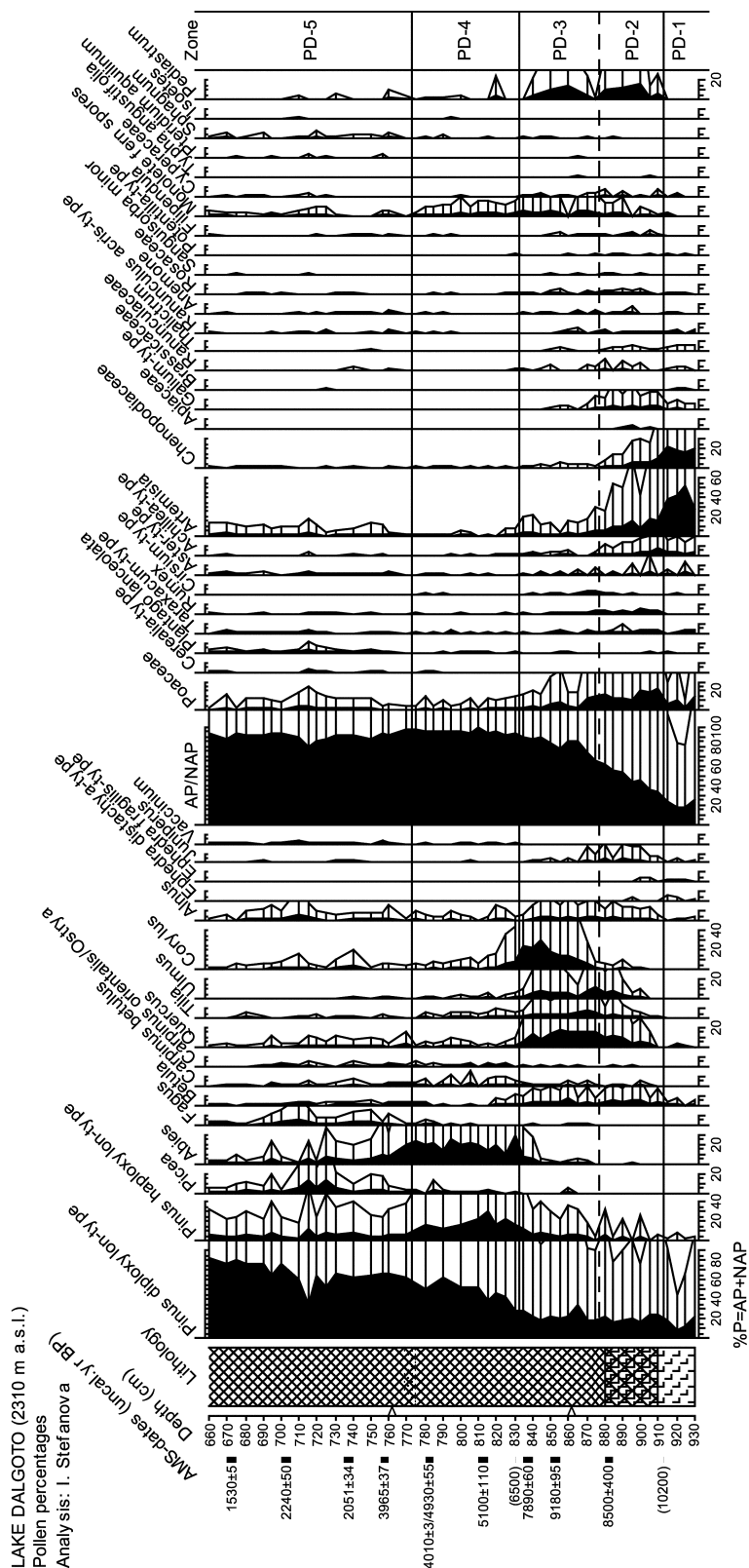


Figure 3. Pollen percentages of selected taxa. Many of the radiocarbon dates presented on the left are based on humic acids and are uncorrected (Stefanova and Ammann 2003). Corrections yield the ages shown in parentheses, supported by the regional chronology.

LAKE DALGOTO (2310 m a.s.l.)
 Diatoms - relative abundance (1-5)
 Analysis: N. Ognjanova-Rumenova

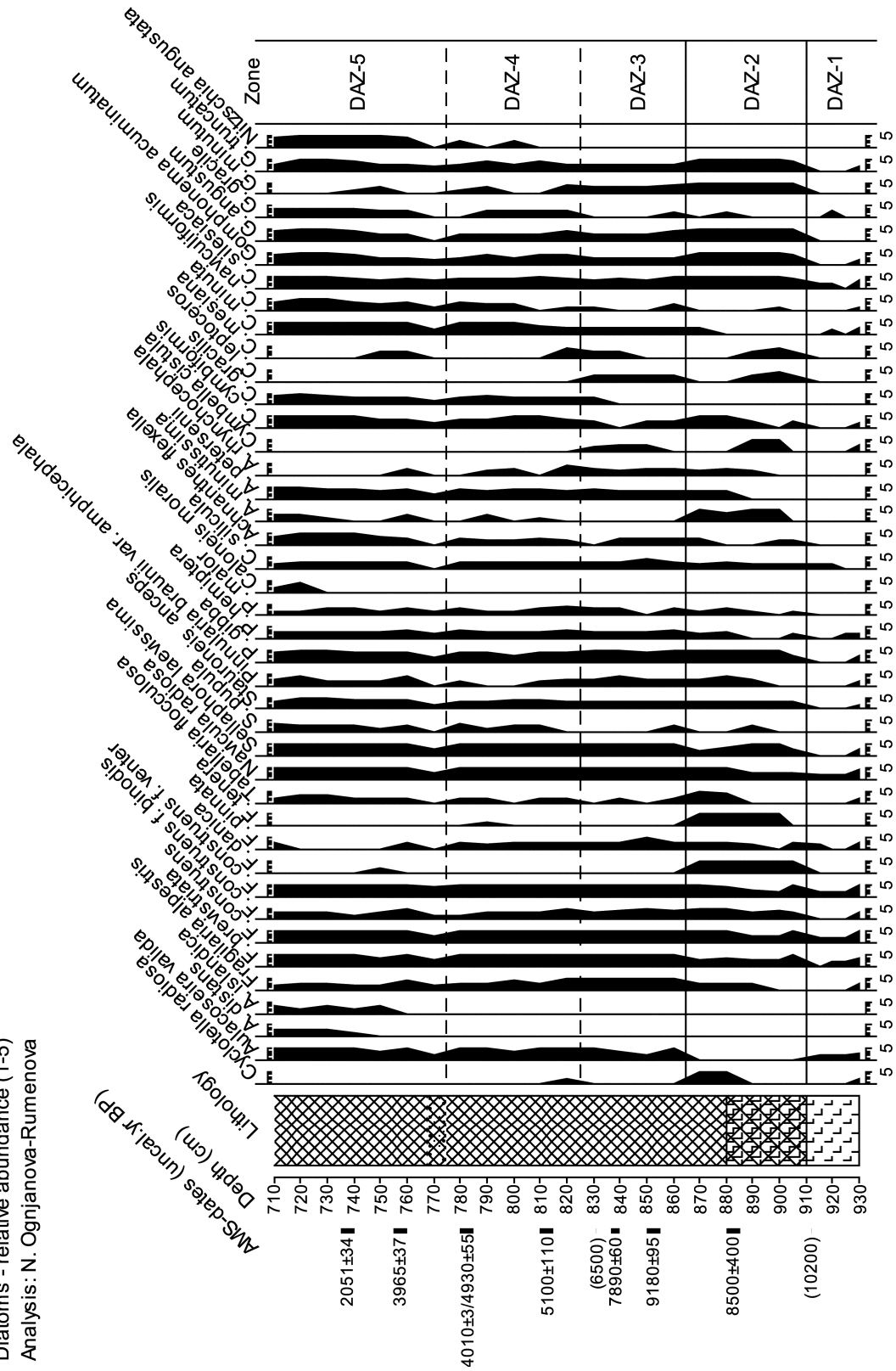


Figure 4. Diatom diagram based on a relative-abundance scale (Schrader 1973).

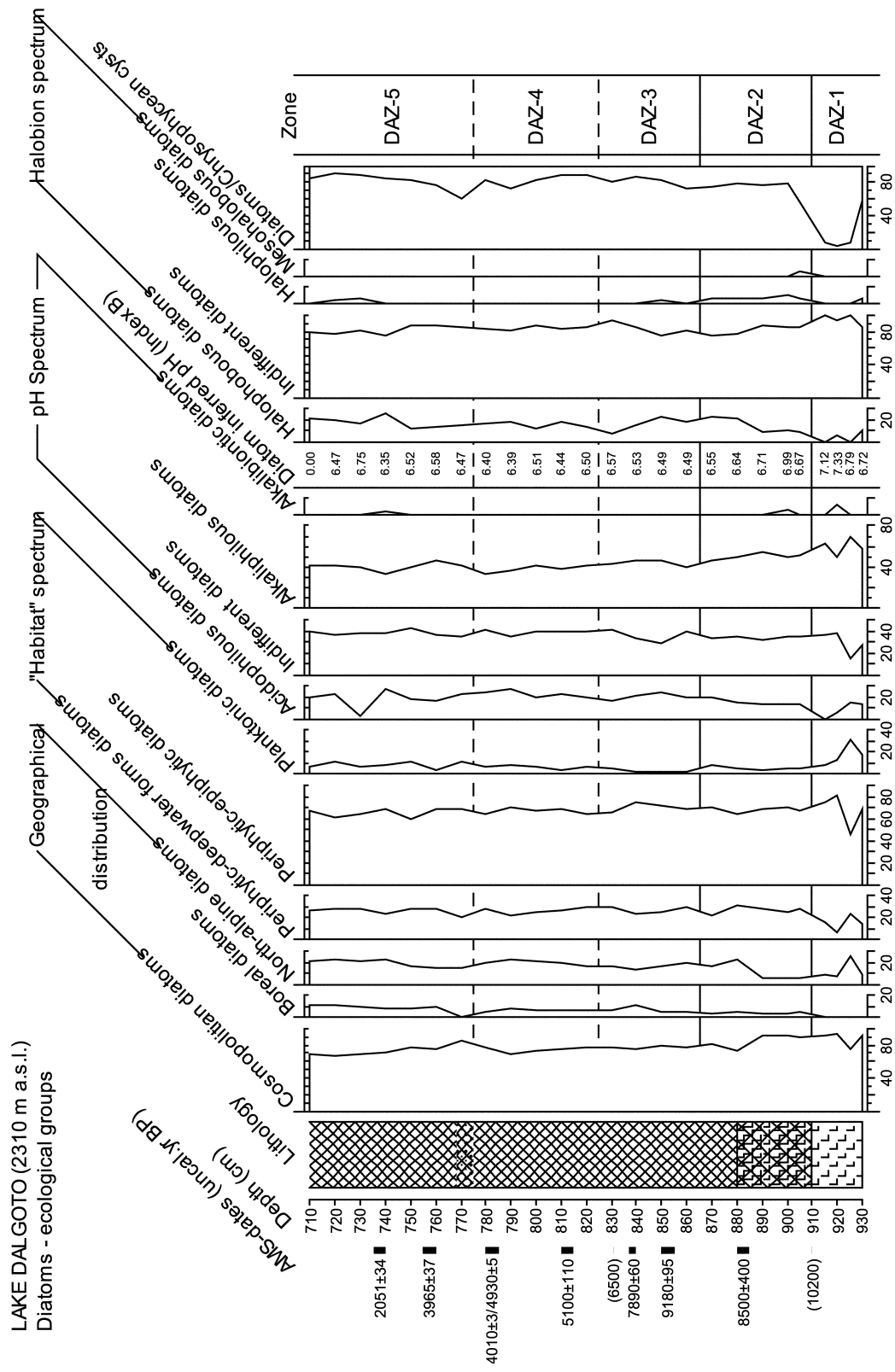


Figure 5. Diagram illustrating the different diatom ecological groups.

LAKEDALGOTO (2310 m.a.s.l.)
 Cladocera
 Analysis: W. Hofmann

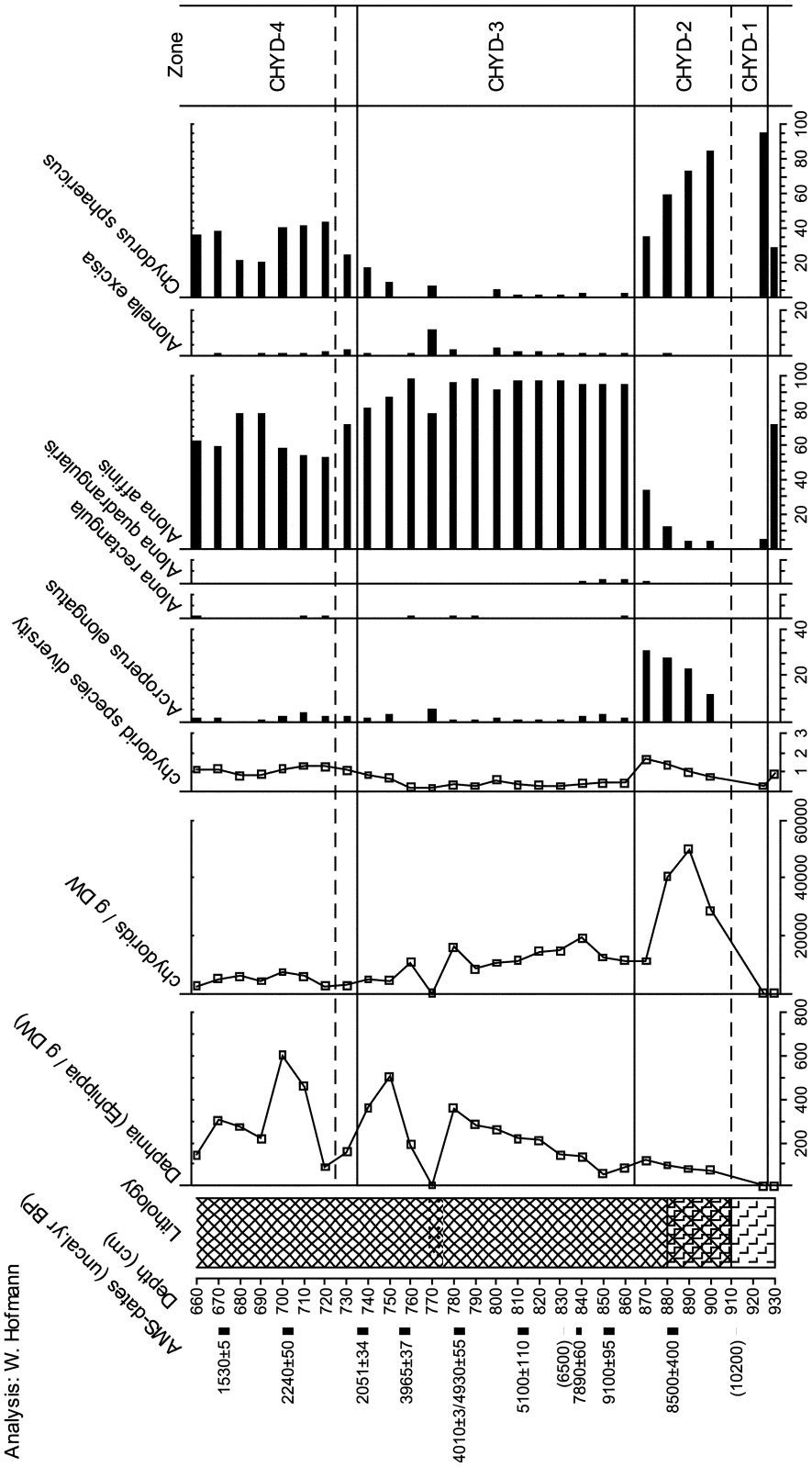


Figure 6. Cladocera: density of *Daphnia* ephippia, density of chydorid remains, chydorid species diversity Hs, and percentages of species. CHYD1 to CHYD4 indicate faunal zones delineated by optimal partitioning and broken-stick.

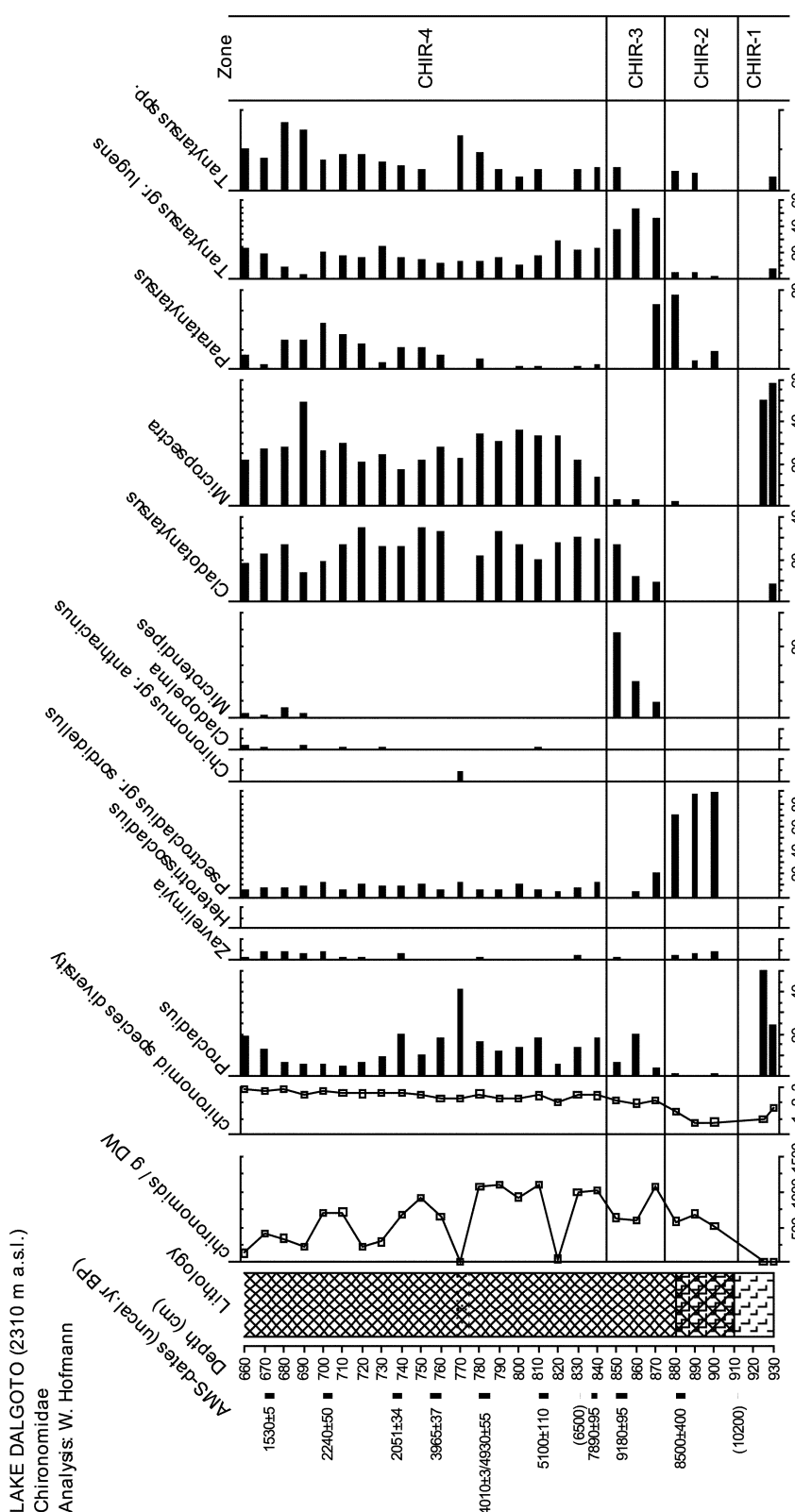


Figure 7. Chironomid density, species diversity, and percentages of most frequent taxa. CHIR1 to CHIR4 indicate faunal zones separated by optimal partitioning and broken-stick.

Table 1. To quantify the changes in species composition between adjacent samples in the three biostratigraphies two steps were necessary: (1) to estimate the gradient length of the overall changes by detrended correspondence analysis (DCA, preliminary), and (2) the appropriate ordination technique (final), i.e. principal component analysis (PCA), if the gradient length in DCA is smaller than 2 standard deviations (as in pollen and Cladocera), and correspondence analysis (CA) if it is larger than 2 (Chironomidae).

| | Pollen | Chironomidae | Cladocera |
|---------------------------------|--------|--------------|-----------|
| Preliminary DCA Gradient length | 1.853 | 2.494 | 1.399 |
| Inertia | 0.987 | 0.515 | 0.356 |
| % axis 1 | 24.4 | 36.8 | 58.4 |
| Final | PCA | CA | PCA |
| Axis 1 | 42.3 | 36.8 | 83.4 |
| Axis 2 | 21.1 | 26.0 | 10.1 |

Corylus decrease. Herb taxa (NAP) amount to less than 10%.

The upper boundary of the zone is marked by decreasing values of *Pinus* haploxylon-type and *Abies*.

PAZ PD-5: 772.5–660 cm (4000–0 ¹⁴C-yr BP)

Pinus haploxylon-type and *Abies* decrease, in contrast to *Pinus* diploxylon-type, which is dominant. *Picea* and *Fagus* are common. Herb taxa increase to 20%, and Poaceae is 2–3%. Regular presence of anthropophytes such as *Plantago lanceolata* is characteristic.

Diatoms

A detailed taxonomic review of the diatom flora was published previously (Ognjanova-Rumenova 2001). In total, 135 diatom taxa were distinguished. The stratigraphic distributions of the most abundant taxa are presented in Figure 4, which includes all species, varieties, and forms with a relative abundance of 4–5 according to the 5-point scale of Schrader (1973). The diatom flora is composed entirely of modern species. The environmental variables known to affect dynamics and community structure of diatoms are habitat, halobity, pH, nutrients, temperature, and geographic distribution. The results of ecological analysis show the following proportions (Figure 5).

Periphytic species predominate, with epiphytic species ranging between 46 and 81% and benthic and deep-water forms between 6 and 28%. Planktonic species range between 2 and 31%, but some are more numerous in the lowest part of the core, e.g. *Aulacoseira valida* and *Fragilaria danica*. A peak occurs at 925 cm in planktonic species and benthic deep-water forms, within the silty sediments of the Younger Dryas cold interval. Subsequent variations in the percentages of these groups are slight.

According to the halobion system, the indifferent

oligohalobous taxa predominate, ranging from 76 to 100%, with halophobous taxa 0 to 22%.

Alkaliphilic species predominate (34 to 69%), followed by indifferent (15 to 40%) and acidophilic (0 to 22%, Figure 5).

Concerning geographical distribution the cosmopolitan group is the most abundant (67 to 93%), followed by north-alpine (5 to 25%) and boreal diatoms (0 to 11%). A peak in north-alpine species (25%) occurs at 925 cm at the Younger Dryas level (Figure 5).

pH reconstruction by index B

Near the bottom of the sediments the inferred pH values of the lake water range between 6.7 and 7.3 (Figure 5). Along the rest of the core the values are generally lower and variable, probably because of changes in the vegetation around the lake and the progressive pedogenesis in the catchment area (Lotter and Hölzer 1994). Very small changes in the salinity could result from abiotic and biotic factors.

Relative proportions of diatom frustules and chrysophycean stomatocysts

Chrysophycean stomatocysts are very abundant near the base of the core, coinciding with the low taxonomic diversity of the diatom assemblage (Figure 5). In other intervals of the core, diatoms are dominant, and the relative proportion in the algal assemblages is relatively constant. On the basis of species composition and relation among ecological groups, five diatom assemblage zones are distinguished.

DAZ-1 (930–910 cm, corresponding to PAZ PD-1, 11000–10200 ¹⁴C-yr BP)

During the Younger Dryas the open vegetation favoured active soil erosion in the Lake Dalgoto catchment, producing more terrigenous material in the

lake sediments. The high abundance of chrysophycean stomatocysts could be attributed to longer ice cover on the lake (Douglas and Smol 1995). The diatoms have very low species diversity, dominated mainly by *Fragilaria construens*, *F. construens* f. *venter*, and *F. brevistriata*. The low abundance of *Aulacoseira valida* suggests low diatom productivity. The water was neutral to slightly alkaline (6.7–7.3), and the percentage of acidophilous species is relatively low (Figure 5). During this stage the higher values for north-alpine species indicates a comparatively low lake-water temperature (Figure 5).

DAZ-2 (910–865 cm, corresponding to PAZ PD-2, 10200–8500 ¹⁴C-yr BP)

The diatom flora is very rich and diverse. Large amounts of *Fragilaria tenera* and *F. danica* are present. The great abundance of the planktonic species *Cyclotella radiosa*, *Tabellaria flocculosa*, and *F. danica* indicates high but fluctuating diatom productivity. A small rise in the lake-water temperature is suggested by the low percentages of north-alpine forms. The reconstructed pH was 6.65–6.71, with a slight increase in the quantity of acidophilous species (Figure 5).

DAZ-3 (865–825 cm, corresponding to PAZ PD-3, 8500–6500 ¹⁴C-yr BP)

Alkaliphilous species decrease and acidophilous diatoms increase as base cations continue to be leached from the soils. Reconstructed pH is 6.69–6.57. The appearance of considerable quantities of *Aulacoseira valida* may be connected with an increase in diatom phytoplankton production and the beginning of natural eutrophication in the lake (Marciniak 1998). The increase of boreal diatom taxa suggests climatic warming during this period, influencing the process of eutrophication (Figures 4 and 5).

DAZ-4 (825–775 cm, corresponding to PAZ PD-4, 6500–4000 ¹⁴C-yr BP)

Abundant *Aulacoseira valida* indicates continued eutrophication. Many alkaline diatoms are replaced by indifferent forms, perhaps related to the proportion of nutrients and to the primary productivity in the lake (Figures 4 and 5). The further increase in acidophilous forms may reflect the accumulation of acid organic humus from conifer litter, as well as waterlogging of soils. The pH is reconstructed to 6.39 and 6.51.

DAZ-5 (775–710 cm, corresponding to PAZ PD-5, 4000–0 ¹⁴C yr BP)

After 4000 ¹⁴C-yr BP the lake-water conditions were favourable for the development of *Aulacoseira valida*, the most abundant planktonic species. The pH is 6.35–6.75. North-alpine and boreal species also increase, suggesting a decrease in lake-water temperature, which could explain the change in the relative proportions of diatom frustules and chrysophycean stomatocysts (Figure 5). Important changes include the appearance and development of *Aulacoseira islandica* and *A. distans*, as well as the increasing quantity of the acidophilous species *Achnanthes flexella* and the north-alpine *A. petersenii* (Figure 4).

Cladocera

All chydorid species in the Cladocera found in the sediment from Lake Dalgoto have been reported from sites above 2000 m a.s.l. in the Rila and Pirin Mountains (Naidenov 1975). Other species found in subfossil material at this altitude are *Eurycerus lamellatus*, *Camptocercus restirostris*, *Alona rustica*, and *Alonella nana*. With the exception of *Acroperus elongatus*, the subfossil chydorids from Lake Dalgoto have been found in surface sediments from Swiss Alpine lakes above 2000 m (Lotter et al. 1997). In this data set of 68 lakes from 334 m to 2339 m a.s.l., *Acroperus elongatus* was present in only one site at 1058 m. The frequency distribution of the species in the core from Lake Dalgoto, i.e. strong predominance of either *Alona affinis* or *Chydorus sphaericus*, is almost identical with the early-Holocene chydorid assemblages from the Swiss Alpine site Heremence at 2290 m (Hofmann 2000).

The 27 faunal samples examined represent a span of 11000 years, with a time interval between samples of about 400 years. Therefore the discussion of climatic reconstruction is confined to the major stratigraphic patterns.

The frequency distribution of the species divides the core into four faunal zones (Figure 6). Concentrations of *Daphnia ephippia* are extremely low in CHYD-1 (930–910 cm, Figure 6). In CHYD-2 (910–865 cm) they increase gradually upward. Above 770 cm in CHYD-3 (865–725 cm) and in CHYD-4 (725–660 cm) densities fluctuate greatly. Chydorid concentrations are also extremely low in CHYD-1, whereas maximum values occur in CHYD-2. In CHYD-3 the concentrations regularly decrease.

The subfossil chydorid material consists of six species: *Acroperus elongatus*, *Alona rectangula*,

Alona quadrangularis, *Alona affinis*, *Alonella excisa*, and *Chydorus sphaericus*. In CHYD-1 only two species are found, i.e. *Alona affinis* and *Chydorus sphaericus*. CHYD-2 is characterized by a predominance of *Chydorus sphaericus* and fairly high percentages of *Acroperus elongatus*. The latter prefers oligotrophic to moderate eutrophic sites. Its occurrences in high-altitude lakes (Alps: 2000 m; Bulgaria: 2300 m a.s.l.) (Flöbner 1972) and during the Younger Dryas in the Swiss Alpine sites of Gerzensee (603 m a.s.l.) and Regenmoos (1260 m a.s.l.) (Hofmann 2000) indicate cold-tolerance, although Harmsworth (1968) classified the species as south-temperate. On the basis of these general characteristics we are not able to give a reasonable explanation for the specific ecological situation that resulted in the high frequencies of *Acroperus elongatus* during CHYD-2. During this period frequencies of *Alona affinis* are relatively low compared to CHYD-3, in which *Alona affinis* strongly dominates. In CHYD-4 frequencies of *Chydorus sphaericus* distinctly increase at the expense of *Alona affinis*. In total, the subfossil chydorid assemblages from Lake Dalgoto are characterized by a strong predominance of *Alona affinis* and *Chydorus sphaericus*. In spite of higher frequencies of *Acroperus elongatus* in CHYD-2, the remaining four species are extremely rare.

The major shift within the chydorid fauna resulted from changing percentages in two euryoecious species, *Alona affinis* and *Chydorus sphaericus*. Korhola (1999) found *Alona affinis* as the most frequent species in all 36 subarctic Fennoscandian lakes examined. The species showed no significant correlations with any of the lake variables studied, thus indicating a very wide ecological tolerance. Similarly, Korhola (1999) found *Chydorus sphaericus* rather evenly distributed among the sites and mentioned that this species is known to occur under various ecological conditions.

The species-diversity index H_s is low because of the predominance of *Alona affinis* and *Chydorus sphaericus*.

Chironomids

Sampling resolution for chironomids is equal to that for Cladocera (about every 400 years a sample). The species composition of the subfossil chironomid fauna in Lake Dalgoto basically corresponds to the fauna in Alpine lakes from altitudes above 2000 m (Lotter et al. 1997), especially for the most common taxa, such as *Micropsectra*, *Tanytarsus gr. lugens*, *Psectro-*

cladus gr. sordidellus, *Procladius*, and *Paratanytarsus*. However, *Cladotanytarsus*, which was quite frequent in Lake Dalgoto, was not found in surface sediments of the thirteen Alpine lakes located above 1850 m. This taxon occurred in 14 of 32 sites below 1060 m and less frequently in 4 of 13 sites from 1120 m to 1830 m. On the other hand, Brooks (2000) reported this taxon from the late-glacial of the Alpine site Heremence (2290 m a.s.l.).

The number of chironomid head capsules per sample ranged from 22 to 361 per g DW (average 136). In most of the samples the concentration ranged from 222 to 1096 head capsules (average 700) (Figure 7). In total, 21 taxa were distinguished. The following rare taxa are not shown in Figure 7: *Ablabesmyia* (1 specimen), *Apsectrotanypus* (3), *Diamesa* (1), *Pseudodiamesa* (2.5), *Cricotopus* (3), *Psectrocladius* (1.5), *Synorthocladius* (3), Orthoclaadiinae indet. (2), and *Paracladopelma* (1).

The percentage distribution of the taxa indicates distinct changes in the composition of the chironomid fauna in the sediment section below 850 cm. In CHIR-1 (910–930 cm) *Micropsectra* and *Procladius* dominate. In CHIR-2 (875–910 cm) these taxa almost completely disappear and are replaced by *Psectrocladius gr. sordidellus*. However, we cannot give a sound ecological explanation for the predominance of the littoral chironomid *Psectrocladius gr. sordidellus* from 10200 to 8500 BP (CHIR-2). In CHIR-3 (835–875) *Tanytarsus gr. lugens* becomes dominant together with *Microtendipes* and *Cladotanytarsus*. In CHIR-4 (above 835 cm) a uniform assemblage is established in which the following six taxa show more or less constant percentages: *Micropsectra*, *Cladotanytarsus*, *Tanytarsus gr. lugens*, *Procladius*, *Psectrocladius gr. sordidellus*, and *Tanytarsus* spp.

Chironomid species diversity increases towards the top of the core. The diversity index is particularly low ($H_s = 1.067$) in the two lowest zones, with high percentages of only a few taxa. In zone CHIR-3 it increases to $H_s = 1.931$. Mean values increase to $H_s = 2.360$ in the lower part of zone CHIR-4 and to $H_s = 2.675$ in the upper part.

Discussion

Environmental history of the lake Dalgoto and its catchment

The compositional changes extracted from the data of Figures 3, 4, 6 and 7 are shown in Figure 8. The

continuous lines mean statistically significant zone boundaries, and dashed lines mean that they are statistically not significant. The first axes of a PCA (pollen, Cladocera) or CA (chironomids) are a measure of the dissimilarity between neighbouring samples. The amount of change in all groups is greater before 5000 ^{14}C -yr BP than after.

Climatic interpretation can encounter difficulties when based on various biostratigraphies. In pollen records of terrestrial vegetation migrational lags may cause disequilibrium between climate and vegetation (Ammann 2000). Aquatic organisms are thought to be less vulnerable to this problem because of their higher mobility and thus migration rate. However, for the two invertebrate groups studied here difficulties arise related to altitude, low taxonomic resolution, and poorly known autecology. Because of the high elevation the site was only occupied during the Holocene by cold-tolerant taxa, similar to Late-Glacial records in the lowland. Therefore a shift from oligothermal to eu/mesothermal is unlikely to occur. Furthermore, the temperature tolerance of most of the taxa involved cannot be specified, because only genera or species groups are known among the chironomids, and the chydorid species have relatively wide ecological tolerances. Climate indirectly controls limnological processes indirectly through lake-level fluctuations. Climatic changes may also favor the rapid development of a dense forest cover, leading to the formation of forest soils in which nitrogen accumulates, providing nutrients to the lake by runoff. Planktonic diatoms are favored by nutrient input, and north-alpine forms imply decreased temperatures.

The Younger Dryas (11000–10200 ^{14}C -yr BP, biozones PD-1, DAZ-1, CHIR-1, CHYD-1, see Figures 3 to 8 to 8) is characterized by low diversity in all four biostratigraphies. The terrestrial vegetation was marked by *Artemisia*-Chenopodiaceae mountain steppe. Although arboreal pollen reaches 30%, influx is low, and tree pollen may have been transported from lower elevations (Stefanova and Ammann 2003). Tree density must have been low even at lower elevations, as suggested by the fact that in surface samples near the lake tree pollen derived from closed forest at lower elevations reaches 90%. Erosion of open ground resulted in deposition of silt in the lake. The high proportion of chrysophycean stomatocysts compared to diatoms may reflect a more extensive ice cover on the lake. The high abundance of north-alpine species indicates relatively low water temperatures. Among chironomids and chydorids, however, neither group contained oligothermal elements restricted to

this period, for all the taxa found occurred quite frequently during the entire Holocene

The early Holocene (10200– ca 8500 ^{14}C -yr BP, biozones PD-2, DAZ-2, CHIR-2, CHYD-2) is characterized by a climatic warming indicated in several records. The lithology shows increasing proportions of organic matter (silty gyttja). Diversity in three biostratigraphic groups increased (pollen, diatoms, and Cladocera), but diversity in chironomids decreased due to the strong predominance of *Psectrocladius* gr. *sordidellus*. In the pollen record the *Artemisia*-Chenopodiaceae assemblage was replaced by grasses and *Juniperus*, with percentages and influx of *Betula* as high as those at Lake Popovo-6 (2180 m a.s.l., Figure 2), where macrofossils indicate the local presence of birch. Around Lake Dalgoto vegetation became denser, pedogenesis started, and minerogenic inwash into the lake decreased. Decreasing proportions of Chrysophyceae cysts also indicate less extensive ice cover on the lake.

The chironomid and chydorid faunas of the Younger Dryas were characterized by extremely low species diversity. However, particular oligothermal taxa that disappeared in the following “warmer” periods were not present. Nevertheless, the appearance of additional taxa in both animal groups in the early Holocene is likely related to climatic warming. Both animal groups show unique assemblages never repeated during the rest of the Holocene.

In the early mid-Holocene (8500–6500 ^{14}C -yr BP, biozones PD-3, DAZ-3, CHIR-3 plus the two lowest samples of CHIR-4 and first part of CHYD-3) the sediment is a pure fine-detritus gyttja. Species diversities are relatively high, except for Cladocera. *Betula* pollen is common, as are temperate deciduous taxa (*Quercus*, *Ulmus*, *Tilia*, and *Alnus*), all of which could have been blown up from a closed deciduous forest at lower elevations, for local pollen production from herbs in the sparsely wooded alpine zone around the lake was still low. On the other hand, modern surface samples from the area contain only a few percent of such deciduous taxa, blown from the modern closed mixed deciduous forests at 600 to 1100 m a.s.l. (Stefanova and Ammann 2003). Macrofossils of *Betula pendula* were found at Praso mire (1900 m in the next valley) as well as single macrofossils of *Acer* and *Quercus* and high pollen percentages of *Quercus* (36%) and *Tilia* (25%). The pollen-source area (related to basin site, Jacobson and Bradshaw (1981) for the Praso mire (diameter 25 m) should be local and extra-local. Thus mixed deciduous forest of *Quercus*, *Acer* (with macroremains), and *Tilia* grew

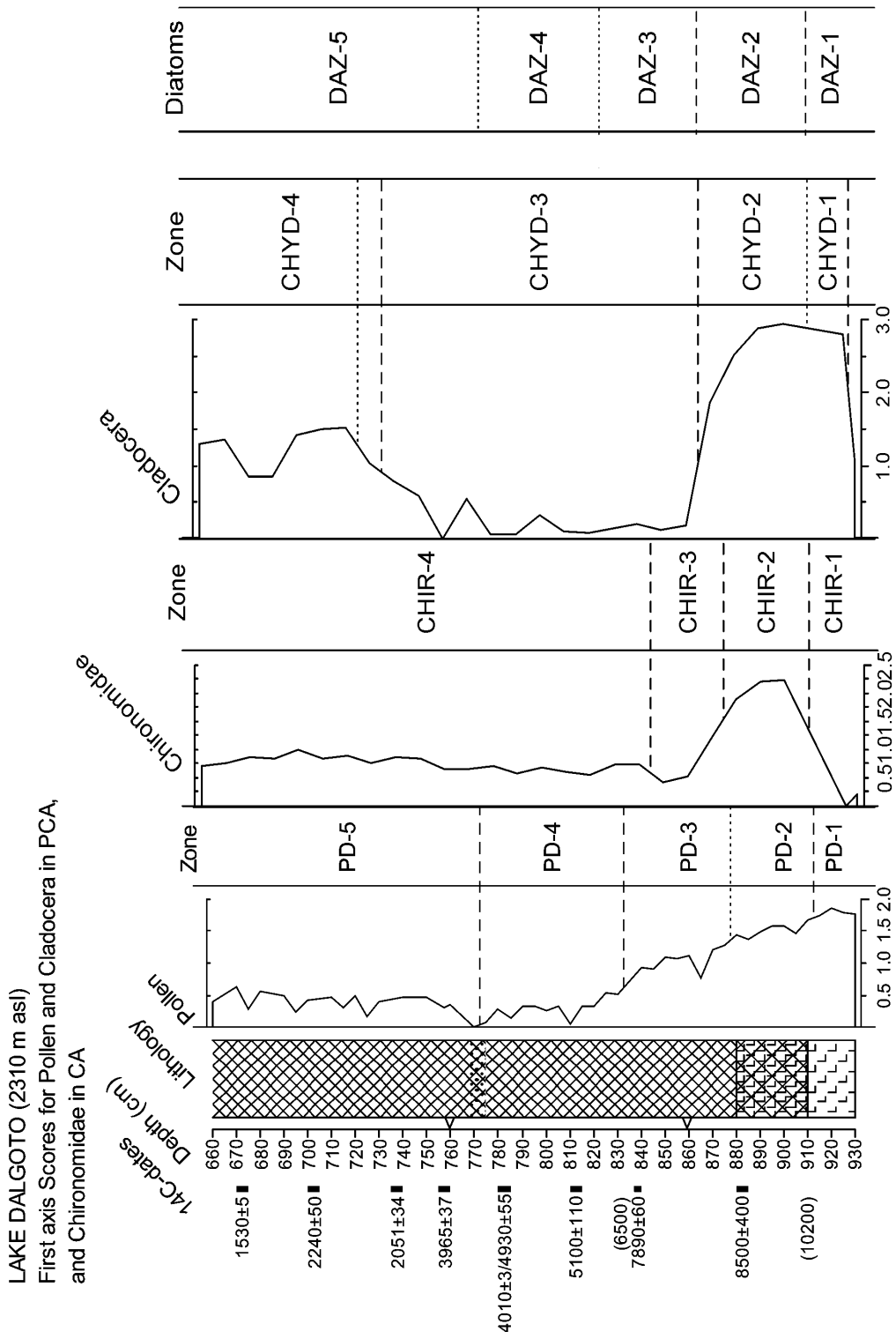


Figure 8. Synthesis of the data analysis at Lake Dalgoto (Pirin Mountains, Bulgaria). First-axis scores of PCA for pollen and Cladocera and of CA for chironomids are plotted on three scales to enhance comparison. In addition, lithostratigraphy, radiocarbon ages, and limits of biostratigraphic zones are presented. Continuous lines indicate the statistically significant zone boundaries, and long dashes show the non-significant zone boundaries. A strong synchronism of changes in upland vegetation (recorded in pollen) and aquatic organisms becomes obvious at around 10200 ¹⁴C yr BP (in lithology, pollen, diatoms, and chironomids) and at around 8500 ¹⁴C yr BP (in lithology, diatoms, chydorids, and chironomids). Less sharp are the also remarkably synchronous changes around 6500 ¹⁴C yr BP (pollen, diatoms, and chironomids), and at around 4200 ¹⁴C yr BP (pollen and diatoms). A sand layer is present at 770 cm.

close to the upper forest limit at 1900 m, which was formed by communities of *Betula pendula* between 7200 and 6500 BP (Stefanova and Oeggl 1993; Stefanova 1999). Thus deciduous forest occurred as much as 800 m higher than today's limit at 1100 m, high enough to provide 60% of the total pollen at Lake Dalgoto, which is above the treeline at 2310 m. Local vegetation was relatively dense, and erosional inwash into the lake was unimportant.

Among the aquatic organisms a slight decrease in inferred pH and a beginning of natural eutrophication are indicated by changes in the diatom assemblages. The reasons for the change among the chironomids is unknown. The increase of *Micropsectra* at the expense of *Tanytarsus* gr. *lugens* at the CHIR-3/CHIR-4 boundary concerned two oligothermal, euoxyphilous, eurybathic taxa of the *Tanytarsus* gr. *lugens* community. The members of this community frequently occur in high-elevation lakes in the Swiss Alps (Lotter et al. 1997).

The younger mid-Holocene (6500–4000 ¹⁴C-yr BP, biozones PD-4, DAZ-4, part of CHIR-4, part of CHYD-3) is recorded in an unstructured fine-detritus gyttja with species diversities little changed. Vegetation changes are characterized by the abrupt expansion of *Pinus peuce*, *P. sylvestris*/*P. mugo*, and *Abies* around 6500 ¹⁴C-yr BP at the higher elevations. These conifers are better adapted to such conditions than *Betula* and temperate trees. The latter were thereby forced to lower elevations by competition. Macrofossil evidence from other sites suggests that *Pinus peuce* was then dominant at the tree line at 2200 m.

The arrival of *Pinus mugo* in the catchment coincides with signs of natural eutrophication as recorded by the increase of planktonic diatoms. Pedogenesis even at the altitude of over 2300 m may have been a factor.

The late Holocene (4000–0 ¹⁴C-yr BP, biozones PD-5, DAZ-5, younger part of CHIR-4, younger part of CHYD-3 and CHYD-4): At about 4000 ¹⁴C-yr BP *Pinus peuce* and *Abies* were reduced. *Picea* and *Fagus* were later added to the mix of conifer pollen in the subalpine belt. The late arrival of *Picea* might be a result of the great distance from its glacial refuge. A slight increase in pollen percentages of *Fagus* marks an expansion of its communities and the formation of a fragmented belt in the mountain (today between 900–1000 and 1500–1600 m a.s.l.). *Pinus mugo* is the most prominent conifer in the Dalgoto area today. Cereal grains and disturbance indicators suggest modification of the vegetation by humans.

Conclusions

Synchrony of changes in terrestrial and aquatic ecosystems

The question about whether organisms with various life histories (especially concerning the duration of a generation) respond differently to climatic changes can be answered only if the temporal resolution in all biostratigraphies involved is identical. However, at Lake Dalgoto we have about 200 years in time between pollen samples and about 400-year intervals for diatoms, Cladocera, and chironomids. Within this comparably low temporal resolution, we observe a surprisingly high degree of contemporary change. This is especially true for changes at two levels (see Figure 8):

(1) At the beginning of the Holocene around 10200 ¹⁴C-yr BP (910 cm) the main lithological shift from silt to clay-gyttja jointly occurs with statistically significant boundaries in pollen, diatoms, and chironomids, as well as an ecologically important (but not statistically significant) limit in the chydorid Cladocera.

(2) At around 8500 ¹⁴C yr BP (about 880 cm) the clay-gyttja changes to gyttja, and shifts are observed in the aquatic assemblages perhaps in response to changes in the sediment: chironomids change most strongly at 875 cm and diatom and chydorids at 865 cm. At nearly the same level *Corylus* pollen increases and *Juniperus* decreases.

Two less pronounced but also synchronous changes are:

(3) At 6500 ¹⁴C-yr BP (830 cm) conifers become established in the catchment, but less distinct changes are evident in the aquatics, although a zone boundary is selected numerically for diatoms and chironomids.

(4) At 4000 ¹⁴C-yr BP (770 cm), when *Abies* and *Pinus peuce* decline, a slight change is evident in the diatom profiles but little in the two faunal groups.

Possible causes for synchronism/asynchronism: climate vs. migration and catchment processes

With their different life histories, it is interesting that long-lived plants (including trees) and short-lived algae or zooplankton responded synchronously to environmental change. Climatic forcing on biological change may be important when climatic variables (e.g. summer temperature) shift either with a high

amplitude and rapidity, or more gradually but passing a threshold significant for the biota involved. The transition from the Younger Dryas to the Holocene (around 10200 ¹⁴C-yr BP) may illustrate the first case. Individual responses of taxa to minor or gradual climatic changes may not be obvious, unless the sites are close to biogeographical limits (range limits). Population expansions and declines, as found in all biostratigraphic groups, can illustrate such individual responses, e.g. to warming in the early Holocene.

Catchment processes such as increasing vegetation cover and pedogenesis may cause changes in the trophic state of a lake, as recorded at Lake Dalgoto around 10200 ¹⁴C-yr BP and 8500 ¹⁴C-yr BP by the lithology and by all four biostratigraphies (Figure 7). Similarly the establishment of conifers in the catchment coincides with a change in the diatom assemblages (around 6500 ¹⁴C-yr BP).

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