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Lake Maggiore (N. Italy) trophic history: fossil diatom, plant pigments, and chironomids, and comparison with long-term limnological data

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Abstract

The availability of long-term series of chemical and biological data and the eutrophication/oligotrophication history of Lake Maggiore allows an attempt to correlate the registered changes with sedimentary records in several sediment cores. Documentary and palaeolimnological data were used to calibrate two important suites of sedimentary indicators of phytoplankton, diatoms and algal pigments.

Diatom assemblages in the sediment cores precisely reflect the pelagic diatom development for approximately the last century. Prediction of total algal biomass from the profile of the ubiquitous β -carotene and some algal groups in certain period of lake development (e.g. diatoms, Cryptophyta, cyanobacteria) was good, whereas the comparison of taxa-specific carotenoids and algal biomass standing stocks (as cell biovolume) in some case revealed poor correspondence. Selective carotenoid losses, taxa production, and mechanisms controlling pigment sedimentation are factors that biased the comparison. However, pigment concentrations and algal biovolumes are different units but equally valid. The use of fossil pigments complements other studies and provides more detailed information on algal development. A sub-fossil chironomid profile agrees well with the general trophic reconstruction as inferred from the pigment and diatom data, adding more details on changes in littoral substratum, water-level fluctuation and flood events.

Models to infer primary productivity and total phosphorus concentration in lake water from sedimentary pigments and diatom assemblages are tested: in the case of the TP reconstruction, reliable results were obtained in this case for the period of high trophic state and for the last decade. During the recovery phase of the 1980s, unexpected high abundance of *Stephanodiscus minutulus* leads to strong overestimation of TP concentrations. Similarly, the reconstructed primary productivity only disagrees with the experimental data for some years in the last decade. Sensitivity of the sedimentary pigment model as well as the relatively reduced sampling dates likely explains this discrepancy.

Similarities are also evident in the temporal diatom assemblage variations of an additional three sub-alpine Italian lakes. As well, the palaeolimnological reconstruction for Lake Maggiore parallels that for Lake Constance, another large sub-alpine lake located north of the Alps.

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1. Introduction

Often, palaeolimnologists are criticized because they rarely analyse duplicate cores and their interpretation of palaeolimnological results is not sufficiently verified and validated against long-term limnological records where

they are available. Studies on diatom-TP transfer functions have been applied to a high-resolution sediment core from lakes in order to reconstruct the recent phosphorus history, and to validate the model by directly comparing the values with the monitored water chemistry data, and by comparing the fossil diatom assemblages with phytoplankton records (Fritz, 1990; Anderson et al., 1993; Fritz et al., 1993; Bennion et al., 1995). Here we present and compare multiproxy

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palaeolimnological data of Lake Maggiore sediments during the 20th century with emphasis on the last 50 years, a period in which the ecosystem underwent several environmental changes (Ruggiu et al., 1998; Jorgensen et al., 2001). This study has developed from a more extensive project on the DDT distribution in several lake compartments (sediments, water, plankton, fish). The palaeolimnological study here presented is a contribution to the IGBP-PAGES Project named LIMPACS (Lake Impact, “Human impacts on lake Ecosystems: the role of palaeolimnology”). The central theme of LIMPACS is “*understanding the past variability of lake ecosystems in order to predict better their future*” (Battarbee, 2000). Future prediction requires process-based dynamic modelling and the models need to be properly validated against high-quality time series that span from years to centuries. It thus requires information on the past states of lakes.

In Italy, there are several lakes with fairly long-term records, and among them Lake Maggiore has the longest limnological data sets, dating back to 1950. This information provides the possibility to investigate how well sediment records (i.e. fossil diatoms, algal pigments) match the archived phytoplankton, benthos and water chemistry data. Lake Maggiore seems ideal for a comparative palaeolimnological vs. limnological analysis.

A range of palaeolimnological records, including plant pigments and biological fossil remains (diatoms, chironomids), are considered and discussed with respect to anthropogenic impacts (eutrophication). For this lake, sediment samples, pelagic phytoplankton and water chemistry data have been compared. Pigment concentrations in lake sediment are directly related to algal standing stock (Leavitt, 1993), and thus they can be used to reconstruct the evolution of phytoplankton assemblages, and to infer total primary productivity and redox conditions (Züllig, 1982; Guilizzoni et al., 1983; Guilizzoni et al., 1992; Ryves et al., 1996). Moreover, the proxy palaeoecological indicators here studied are known to be sensitive to a number of ecosystem responses variations, especially with respect to aquatic productivity and lake catchment surface processes which, if responding synchronously, are likely to reflect regional climatic variations (Sanger, 1988; Smol, 1990a; Bradbury and Dean, 1993; Leavitt et al., 1993). Chironomids, well-known proxy-indicators of lake water-level changes (Hofmann, 1998; Korhola et al., 2000), temperature (Walker et al., 1991, 1997) and trophic conditions (Kansanen, 1985; Quinlan et al., 1998; Brooks et al., 2001), were studied from a littoral core in order to detect changes which could be mainly related to water-level fluctuations, flood events and other human-related disturbances (e.g. aquatic macrophyte removal, bank-protection, dredging).

2. The site

Lake Maggiore is the second largest (212 km²) and deepest (370 m) lake in Italy. It is located at 194 m a.s.l., in a fluvial valley reshaped by glacier activity. Its catchment extends over 6599 km² and is drained by several rivers (e.g. Ticino, Toce, Maggia, Versasca). It receives several inputs from anthropogenic point and diffuse natural sources. Trace elements (e.g. Hg), as well as PCBs, have been extensively studied since the 1970s (Cenci et al., 1991; Galassi et al., 1995). Lake Maggiore has usually undergone a total overturn in wintertime on average every 7 years, but no complete mixing occurred from 1981 to 1999. In the same period deep water temperature was clearly increasing (Ambrosetti and Barbanti, 1999).

The lake sediment is not annually laminated, but clear laminae are however well visible interrupted by bands of variable thickness laid down during flood events (turbidites). Profundal sediments appear undisturbed by mixing or bioturbation.

During the last ca. 50 years, the lake underwent several changes in hydrochemistry, and in the phytoplankton and zooplankton communities. Trends in the mean content of nitric nitrogen, reactive and total phosphorus (TP), and dissolved oxygen in the deepest waters, from 1956 up to present, were published in Calderoni and Mosello (1996), Calderoni et al. (1997), Mosello et al. (1997) and de Bernardi et al. (1999). These data, together with those on the historical trends in algal biomass and zooplankton (Ruggiu, 1989; Manca et al., 1992; Manca and Ruggiu, 1998; Ruggiu et al., 1998), well describe the eutrophication phase of the lake during the period 1965–1970 and a phase of oligotrophication in the 1990s.

3. Materials and methods

In spring and summer 1998, several short cores (up to 84 cm) were collected with a gravity corer (Fig. 1; Table 1), cut lengthwise in the laboratory and photographed. Sectioning was performed at 0.5–1 cm intervals representing ca. 1–3 years per sample. Here, we report the detailed analyses of some selected cores only, i.e. cores 8A, its replicate 8B, 13A, 5C, 3C, 6A and 1E collected at various depth (Table 1), for diatoms and pigments, and the littoral (17 m) core 8B for chironomids.

All cores were dated using the ²¹⁰Pb and ¹³⁷Cs techniques (Figs. 2 and 3; Langone, 2000) and were correlated using magnetic susceptibility scans (Thompson et al., 1975), Loss on Ignition (LOI), planktonic diatoms and sedimentary markers (e.g. layers originated from known floods, individual laminae, peaks in the concentration of mercury and organochlorine

compounds). Depth–age curves were established for five sampling stations (Figs. 4 and 5), also using well-documented limnological information (e.g. appearance and disappearance of biota, and peaks in pollutant concentrations).

^{210}Pb ($t_{1/2} = 22.26$ years) was determined via alpha counting ^7Be ($t_{1/2} = 53$ d) and ^{137}Cs ($t_{1/2} = 30.2$ years) were counted via gamma spectrometry using an Ortec

GEM (*p*-type) HPGe coaxial intrinsic germanium detector. ^7Be was measured from sediment deposited in front of fluvial inflow (core 1E), where the sediment accumulation rate was thought to be high. A Constant Flux–Constant Sedimentation model was applied to the activity depth profiles of excess ^{210}Pb , except for core 13A where a Constant Rate of Supply model was used. ^{137}Cs peaks were attributed to the Chernobyl accident in 1986 and to maximum global concentration reflecting the tests of atomic bombs (1963).

Water content, organic water (LOI) and carbonate content were determined by drying 5–6 g of wet sediment at a temperature of 80°C, at 550°C and 950°C, respectively. Magnetic susceptibility was measured using a Bartington MS IB instrument.

Photosynthetic pigments were extracted in 90% acetone, overnight in the dark, under nitrogen. The extract obtained was used both to quantify the chlorophylls and their derivatives (Chlorophyll Derivatives Units, CD) and total carotenoids by spectrophotometer (Lami et al., 1994). Individual carotenoids were detected by Reversed Phase High-Performance Liquid Chromatography using a Beckman Gold System (Lami et al., 1994). Carotenoid concentrations were expressed in nanomoles per gram of organic matter ($\text{nmol g}_{\text{OM}}^{-1}$) and chlorophyll derivates in units per gram of organic matter ($\text{U g}_{\text{OM}}^{-1}$).

Diatoms were prepared using standard H_2O_2 –HCl digestion (Renberg, 1990) and mounted in Naphrax. On each slide, a minimum of 500 diatom valves were enumerated by light microscopy, and taxonomical features confirmed by scanning electron microscopy procedures. Diatom abundance was expressed as relative percentages.

For chironomid analysis, 1–3 g of wet sediment were deflocculated in hot 10% KOH for 20 min, then carefully sieved through 200 and 100 μm mesh size. The retained material was transferred to Petri capsules and later hand-sorted using a 25–40 \times magnification Zeiss dissecting microscope. Larval head capsules were mounted in Euparal and then identified under a light microscope. A minimum sample size of 50 HC were counted to ensure the midge percentages were representative. Larvae identifications, mostly to

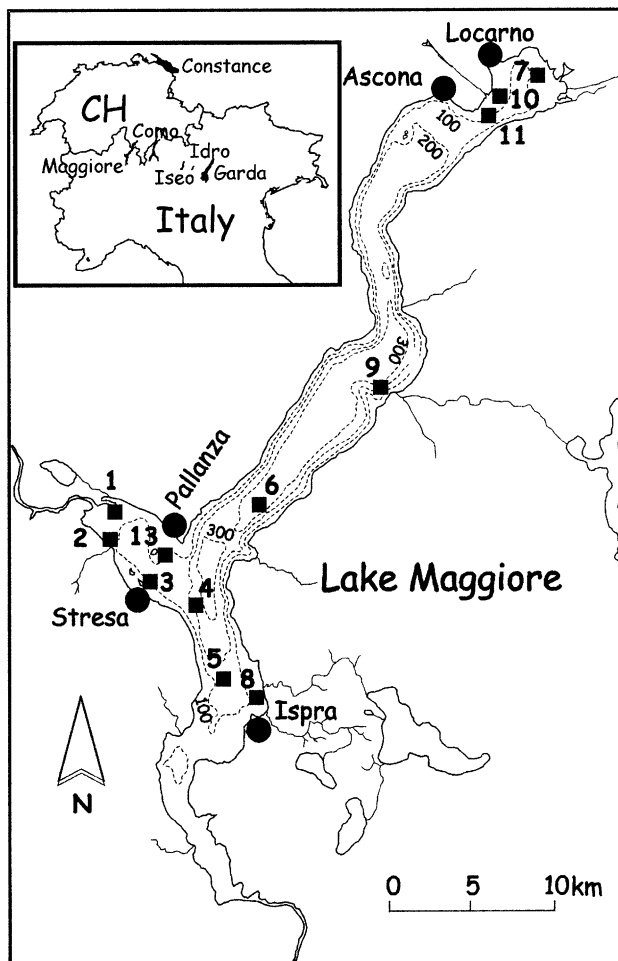


Fig. 1. Bathymetric map of Lake Maggiore showing the core locations (1–11) considered in the DDT Project. In the present study, we only report data on cores from positions 1, 3, 5, 6, 8 and 13.

Table 1
Details about the coring sites and the selected sediment cores

Site	Longitude	Latitude	Coring depth (m)	Core length (cm)	Mean sedimentation rate (cm year^{-1})
LM 98-1E	8° 30' 16"	45° 56' 03"	48	34	1.3
LM 98-3C	8° 32' 38"	45° 53' 35"	153	19	0.54
LM 98-5C	8° 35' 93"	45° 50' 57"	163	84	0.45
LM 98-6A	8° 37' 55"	45° 56' 38"	362	57	0.96
LM 98-8A	8° 37' 07"	45° 50' 11"	17	46	0.33
LM 98-8B	8° 37' 06"	45° 50' 18"	17	34	0.53
LM 98-13A	8° 32' 57"	45° 54' 48"	70	68	0.36

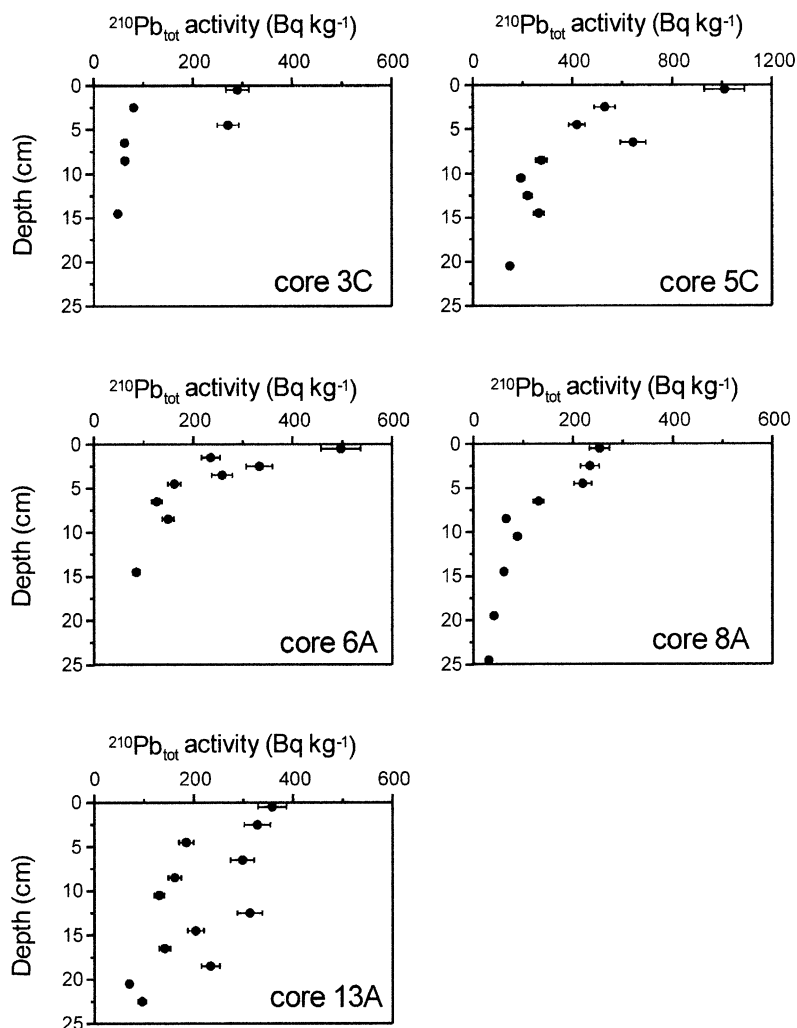


Fig. 2. Activity-depth profiles of total ^{210}Pb of the studied cores.

genus levels, were performed principally using [Wiederholm \(1983\)](#) taxonomic keys. Some of the taxa were lumped to form a single category (e.g. *Cricotopus/Orthocladius*, *Tanytarsus* gr.) because of the lack of taxonomic information. Stratigraphic diagrams were produced using TILIA v.2.1 and TILIA-GRAPH 1.25 ([Grimm, 1991](#)).

4. Results

4.1. Chronology and core-to-core correlations

Short-lived radionuclides (^7Be , ^{137}Cs and ^{210}Pb) were used to obtain sediment accumulation rates on a ca. 50-year time scale (Figs. 2–4). Previous investigations pointed out the very high variability of sediment accumulation rates ([Guzzella et al., 1998](#); [Langone, 2000](#)) and suggested the need to do measurements at

each site where sediments were collected. ^7Be was not found at measurable levels at the top of core 13A, and could not be used as a geochronological tool. In some cases, the ^{137}Cs and ^{210}Pb profiles were not perfect. Hence, the calculated estimates of sediment accumulation rates have a different degree of accuracy. ^{137}Cs was not measured in some cores (e.g. 13A) because the good ^{210}Pb profiles made the analysis unnecessary. Thus, for each station, the radionuclide with the most reliable profile has been chosen. The depth curves shown in [Fig. 4](#) have been also obtained comparing several sources (present work and literature data on mercury and PCBs information; papers quoted in the special volume of the *Memorie dell'Istituto Italiano di Idrobiologia*, 38, 1981; in [Cenci et al., 1991](#); [Galassi et al, 1995](#)). Accumulation rates ranged between 0.03 and 1.5 cm year^{-1} , showing a decreasing trend going toward the deepest stations (cf. [Fig. 1](#)) where the sediments are more porous and finer. In the shallower Pallanza Basin,

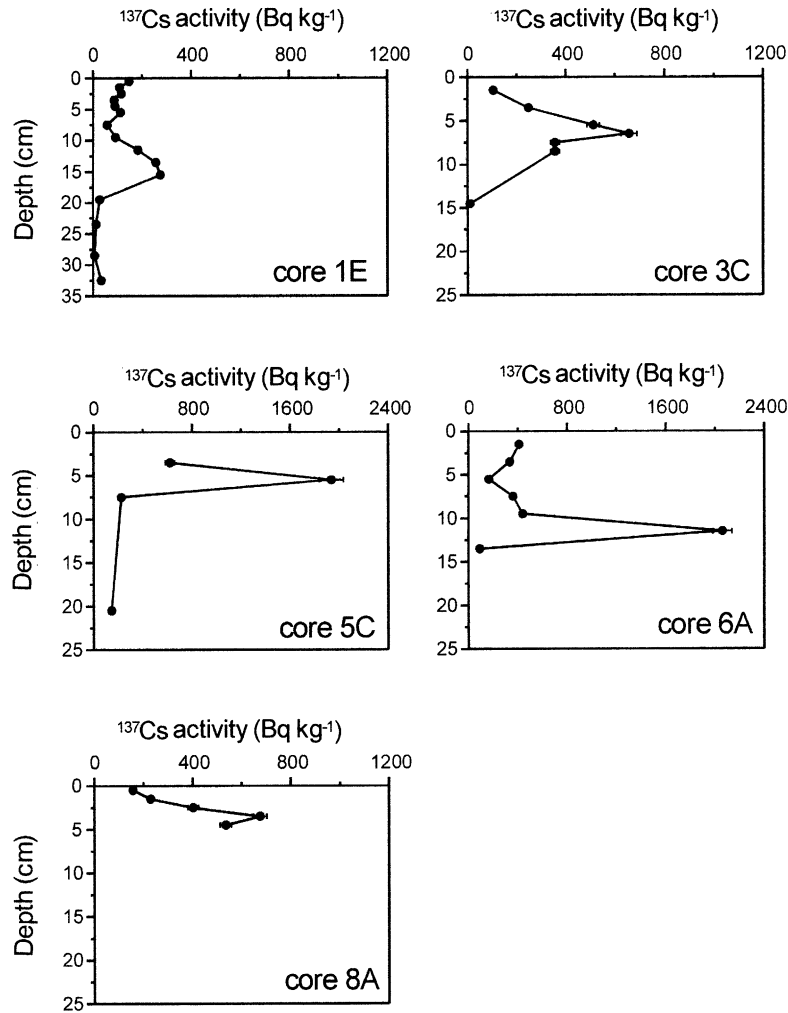


Fig. 3. Downcore plots of ¹³⁷Cs. Peak values were interpreted as the sedimentary record of the Chernobyl accident occurred in April 1986.

higher values were measured (0.07–1.5 cm year⁻¹). These sediment accumulation rates generally agree well with the indirect estimates obtained by diatom and pigment stratigraphies and other documentary information (e.g. origin of Hg and PCBs industrial production and discharge; Figs. 4 and 5).

In general, the cores are very well correlated and included distinct peaks of magnetic susceptibility and LOI. Correlation among cores was also facilitated by lithostratigraphical analysis (Marchetto et al., 1999). Moreover, planktonic diatom assemblage profile showed clear patterns: i.e. the shift from *Cyclotella comensis* to *Stephanodiscus* spp. and vice versa, and the episodic presence of *Tabellaria flocculosa*. This diatom succession was also used for core-to-core correlation (Fig. 5). Correlation between cores LM98-13A (on which most of the data here shown refer to) and LM98-8B, used for the chironomid study, showed mean sedimentation rates of 0.36 and 0.53 cm year⁻¹, respectively (Fig. 5).

4.2. Diatoms

The diatoms identified in the analysed 198 samples belong to 28 genera. In general, the main patterns of planktonic diatom profiles compare well among the independent cores (Fig. 5), but the relative abundance of benthic taxa in cores collected close to river mouths (13–38%) was higher than in cores collected in the deepest parts of the lake bottom (up to 3%). Marchetto and Musazzi (2001) reported a detailed discussion of the between-core variability in diatom abundances.

The planktonic species totalled 34, belonging to 12 genera. Nine species represented ca. 85% of the total planktonic frustules. Sediment samples for the period prior to 1955 were dominated by *C. comensis* (Fig. 6). After 1960, the oligotrophic species *C. comensis* is replaced by *Fragilaria crotonensis*, *T. flocculosa*, *Aulacoseira* spp., *Stephanodiscus minutulus* and *S. hantzschii*. These species of eutrophic waters decline toward the core top with a reappearance of *C. comensis*. The

concentrations of *C. comensis* are lower than those prior to 1950.

4.3. Pigments

A general increase in pigment concentration indicates a rise in phytoplankton biomass during the last decades of the 20th century (Fig. 7). Chlorophyll and most carotenoids reach levels about 20–30 times higher than in the deeper section of the core, while the increase in β -carotene is even stronger (ca. 100 times). Carotenoids typical of cyanobacteria were present during the whole history of the lake, but their relative abundance sharply increases during the 1970s. By contrast, the relative

abundance of alloxanthin was higher in the oligotrophic period. Recent lake recovery is mainly shown by decreasing concentrations of cyanobacteria carotenoids and of β -carotene. In good agreement with diatom data, the uppermost part of pigment profiles differs from the bottom part of the core, prior to lake eutrophication, showing that the lake has still not reached its pre-1950s trophic status. However, depth profiles of fossil pigments show a higher variability than diatoms, indicating more variability in production/preservation conditions in this large lake.

4.4. Chironomids

A total of 34 chironomid taxa were recovered from a littoral core from Lake Maggiore (core 8B). The dominant taxa along the sequence were *Cricotopus/Orthocladius* (hereafter cited as *Cricotopus*) representing 40% of the total relative abundance, followed by *Tanytarsus* group, *Polypedilum* and *Chironomus* with values close to 20%.

The chironomid profile shows a clear succession (Fig. 8). Some of the taxa present in the lower part of the core disappear or decrease towards the top, being replaced by new ones. Other taxa are always present, but their abundance shows fluctuations along the core.

From the bottom to 18 cm (1963 AD) the dominant taxa are *Cricotopus*, *Tanytarsus* gr. and *Polypedilum*. Towards the end of this section, *Dicrotendipes*, *Paratendipes*, and the oligotrophic genera *Psectrocladius*, *Parakiefferiella*, *Heterotrissocladius* and *Parorthocladius* disappear. An important increase of Diamesinae is recorded at 18 cm.

From 18 to 13 cm (~1975 AD) the number of taxa recovers. This zone is characterized by the increase of *Chironomus* and *Micropsectra*, the appearance of *Paracladopelma* and the gradual decrease of *Polypedilum*. At the end of the zone, the decline of *Tanytarsus* gr. is coincident with the appearance of *Cryptochironomus*, *Parachironomus* and *Limmophyes*.

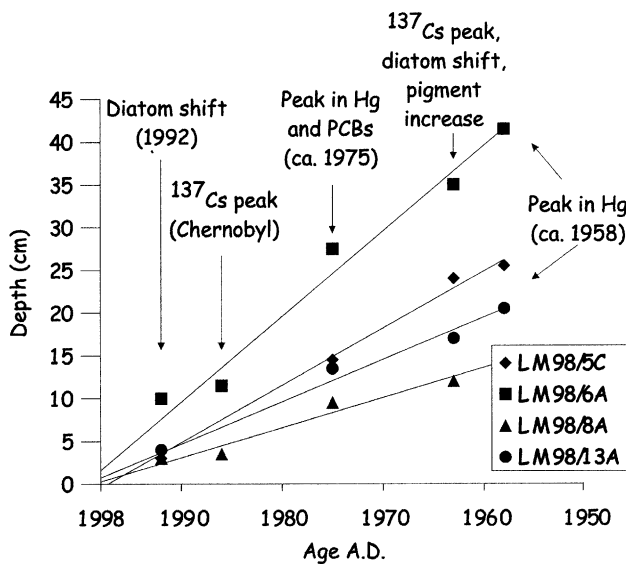


Fig. 4. Depth–age curves for the last ca. 50 years for some selected cores of Lake Maggiore (5C, 6A, 8A and 13A). Lines were drawn combining several information sources like diatom assemblage shifts (cf. Fig. 5), ^{137}Cs profiles, mercury and PCBs concentration peaks (literature data), and fossil pigment increase caused by the eutrophication process (see text).

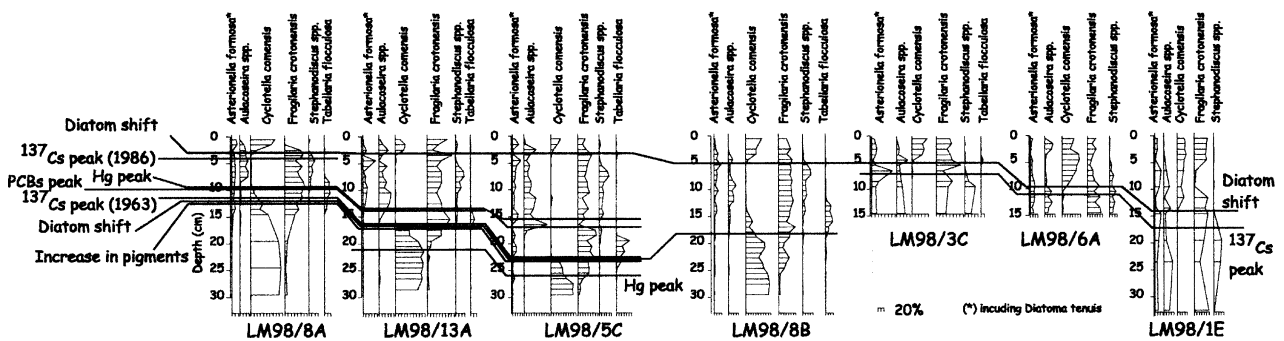


Fig. 5. Profiles of sub-fossil diatom remains in six sediment cores from Lake Maggiore. Correlation lines rely on biostratigraphic shifts (mainly diatom assemblages and fossil pigments, cf. Figs. 6 and 7), peaks in ^{137}Cs activity and documentary information (Hg and PCBs concentration peaks).

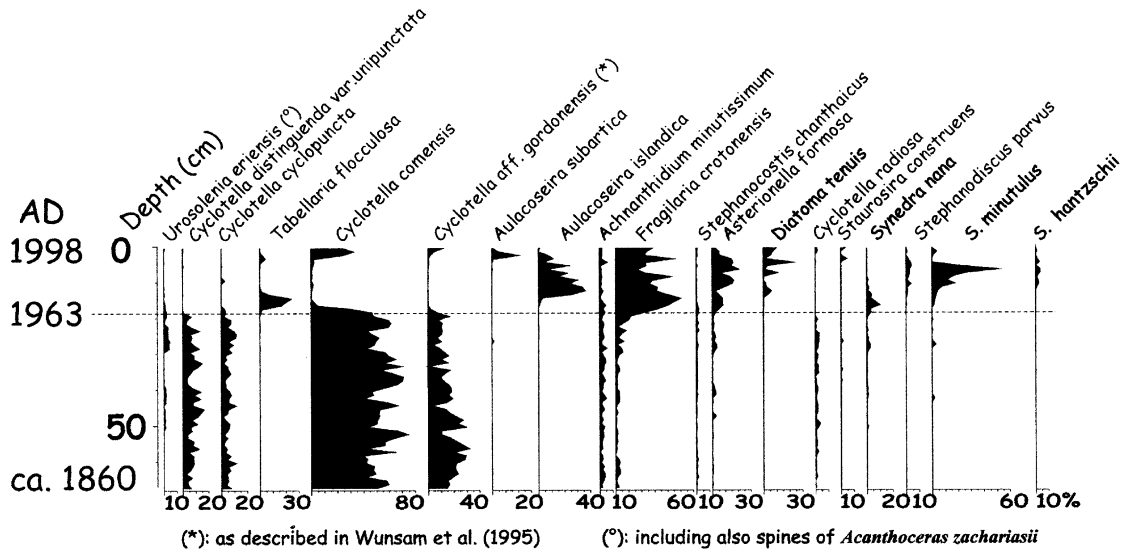


Fig. 6. Profiles of diatom percent abundances along core LM98-13A. Abrupt shift from oligotrophic to eutrophic conditions has been found contemporary to the ¹³⁷Cs peak dated 1963 (dashed line).

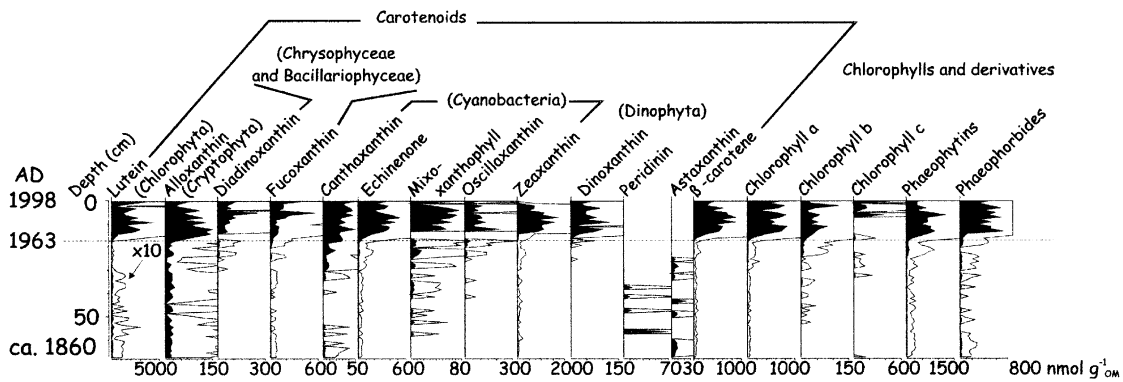


Fig. 7. Concentrations of algal pigments (chlorophylls and carotenoids, nanomoles per gram organic matter) of some specific algal groups for the core LM-13A. β -carotene and Chl *a* = all plants; Chl *c* = Chrysophyceae, Bacillariophyceae; Chl *b* = Chlorophyceae, tracheophytes; Phaeophytin = chlorophyll derivatives (general); Phaeophorbides = chlorophyll derivatives (herbivores grazing).

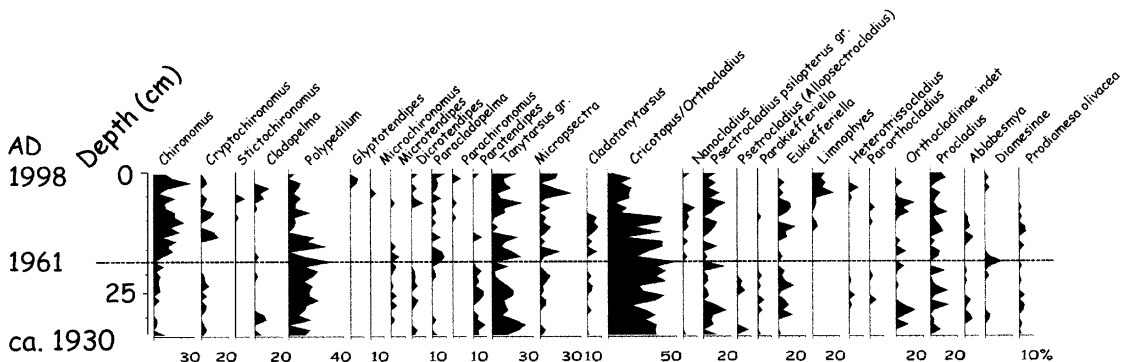


Fig. 8. Profile of the percent abundance of sub-fossil chironomids along core LM 98-8B. The AD 1963 oligotrophy/eutrophy change in diatom assemblage (cf. Fig. 6) is also shown (dashed line).

In the brief period between 13 and 9 cm (~1980 AD), the decline of *Polypedilum* and *Tanytarsus* gr. abundance, the increase of *Chironomus* and the appearance of *Limnophyes*, a typical littoral taxa

(Hofmann, 1998; Brooks, personal observations) take place. The upper zone boundary is characterized by a sharp change in *Cricotopus* abundance which decrease below 25%.

Finally, from 9 cm to the top (1998), the number of taxa reaches the maximum values. This zone is dominated by *Chironomus*, *Micropsectra*, *Limnophyes* and *Cricotopus*, although this taxon reaches the minimum values during this period. Some littoral taxa like *Glyptotendipes*, *Parachironomus*, *Microchironomus* and *Stictochironomus* appear for the first time along the sequence. Towards the end of the zone, *Cladotanytarsus*, *Ablabesmya* and *Prodiamesa olivacea* disappear.

5. Discussion

5.1. Diatoms

A comparison of sedimentary diatom results with the documentary data on phytoplankton (Ruggiu et al., 1998) and hydrochemistry (Mosello et al., 1997) shows a high level of coherence as regards the timing and relative abundance of the species. Despite changing sampling techniques (e.g. plankton net or bottle sampler) and laboratory methods, the displacement of “small *Cyclotella* species” by more mesoeutrophic species (e.g. *T. flocculosa*) was also reported by Vollenweider (1956) and Goldman et al. (1968). In addition, the inferred transition from oligotrophic conditions to a more

productive phase, occurring around the beginning of the 1960s (Figs. 5 and 6), is well documented in the phosphorus trend during the last ca. 45 years (Mosello et al., 1997). Similarly, the inferred oligotrophication phase of the lake of the 1990s is well described by phytoplankton analyses (Ruggiu et al., 1998). Plankton samples have been taken at least monthly from Lake Maggiore since 1981. In Fig. 9, we compare diatom assemblages found in the topmost sediment slices of core LM98/13A (which integrate 2–4 years) with biannual time-weighted averages of abundance of diatoms found in plankton samples. This data homogenization was accomplished for a more reliable comparison between the two data sets as it reduces the impact of single year peaks. The abundances observed in sediment and plankton samples generally agree, but the agreement is better for species more frequent in plankton samples, such as *Asterionella Formosa*, *Cyclotella* spp., *Diatoma tenuis* and *F. crotonensis*, than for fast-growing bloom-forming *Stephanodiscus* spp., the abundance of which is difficult to evaluate using monthly samplings. In the case of *Aulacoseira subartica*, the high relative abundance in some sediment slices conflicts with its virtual absence in plankton samples. In wintertime, this species suddenly develops large aggregates that quickly settle, and probably were not caught during plankton sampling.

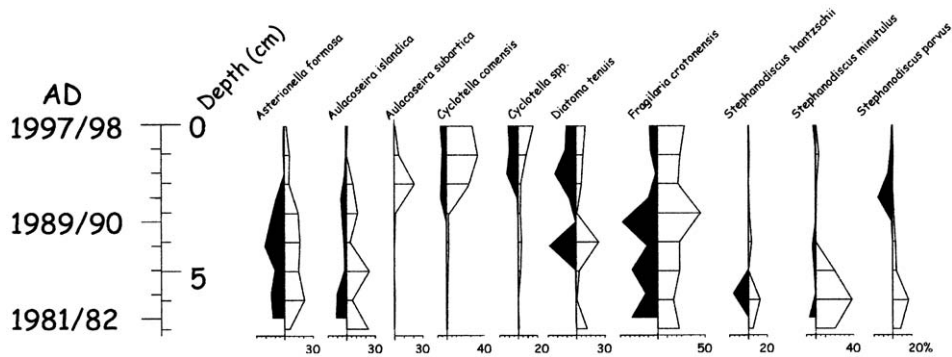


Fig. 9. Comparison between percent composition of sedimentary diatom assemblages (core 13A; on the right) and bi-annual time-weighted averages of diatom percent abundances in plankton samples (on the left), for the last ca. 20 years.

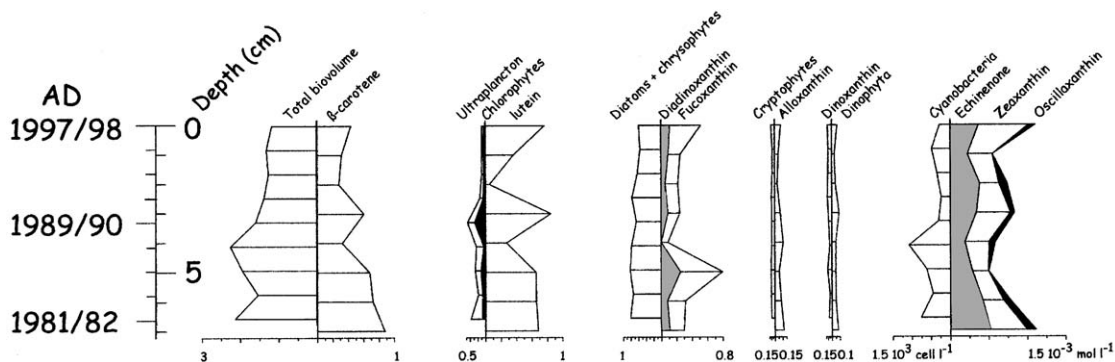


Fig. 10. Comparison between concentration of specific carotenoid in the sediment (core 13A; on the right) and bi-annual weighed average of the biovolume of the algal groups in phytoplankton (on the left) for the last ca. 20 years.

5.2. Pigments vs. algal biovolumes

The profile for specific carotenoids along core LM98/13A is compared with the biannual time-weighted average of algal biovolume in Fig. 10. The profile of the concentration of β -carotene agrees roughly with total algal biovolume. In contrast, the concentration of lutein is very high compared to the abundance of chlorophytes. As shown in other lakes (Leavitt, 1993), this is due to the contribution of allochthonous sources (very high during the flood events) and aquatic macrophytes containing high concentration of undegraded lutein (Bianchi et al., 1991). The maximum peak of chlorophytes is matched, however, by the sedimentary lutein (Fig. 10).

Among cyanobacteria, the dominant species belong to the genus *Oscillatoria* spp., but their abundance is not paralleled by a comparable concentration of oscillaxanthin. The main cyanobacteria pigments in sediment samples are echinenone and zeaxanthin, whose profiles reveal a decreasing trend during the 1980s, roughly following the decrease in cyanobacteria biomass and relative abundance, while the high concentration in the topmost slice (1 cm) may reflect rapid diagenesis in this critical oxidized microzone, leading to continual diagenesis of pigments. Consequently, signals occurring in the upper few cm of sediment should be viewed with extreme caution (Leavitt, 1993).

5.3. Quantitative inference of total phosphorus and phytoplankton primary productivity

Phosphorus is the limiting nutrient in Lake Maggiore, and for a reconstruction of its trophic state changes we have used the inferred TP profile obtained from a regional weighted-averaging transfer function based on diatoms of surface sediment from 86 lakes in the Alpine region (Wunsam and Schmidt, 1995; Wunsam et al., 1995). This model has been selected because the data set is based on many deep lakes located around the Alps (including Lake Maggiore itself) and includes most of the diatom species found in our cores. Modelled and measured values agree very well during the period of highest trophic status and in the last decade whereas during the 80s unexpected high abundance of *S. minutulus*, which has a high TP optimum of $36 \mu\text{g l}^{-1}$, leads to strong overestimation of the TP level ($62 \mu\text{g l}^{-1}$ against $27 \mu\text{g l}^{-1}$, Fig. 11). A similar discrepancy in the monitored water chemistry and the actual values of TP inferred by the model was found in an Austrian pre-alpine lake (Lake Mondsee) (Bennion et al., 1995).

To reconstruct primary productivity, a regression curve between primary production and CDs in 19 sediment samples taken from 12 lakes in the Alpine region was used (Guilizzoni et al., 1982, 1983). The

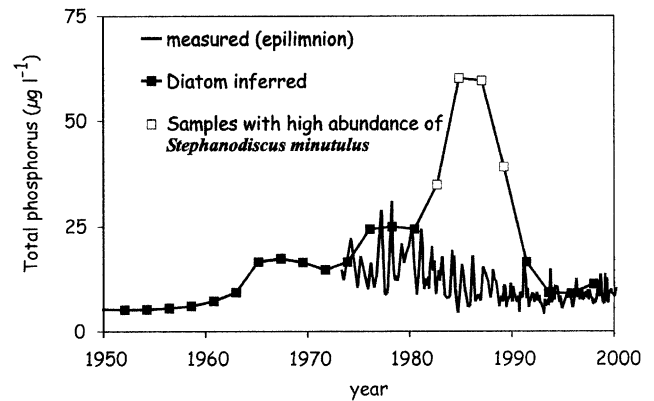


Fig. 11. Diatom-inferred total epilimnetic phosphorus compared with long-term trend of measured P in Lake Maggiore epilimnion (monthly values).

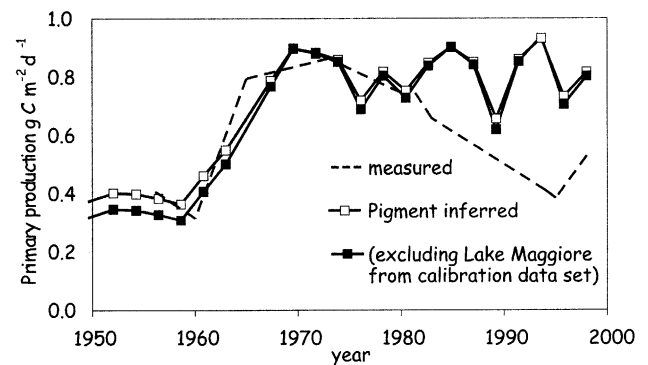


Fig. 12. Sedimentary pigment-inferred primary productivity compared with the long-term trend in measured annual primary productivity (^{14}C technique) data.

calibration data set used for this model included Lake Maggiore. Reconstruction obtained by a revised model excluding this lake (solid squares, Fig. 12) does not significantly differ from the reconstruction of the original model (empty squares). This model successfully infers the increase in primary productivity between the 1950s and the 1980s. However, a discrepancy is observed in that the measured lower values in the 1990s are not paralleled by a decrease in sedimentary pigment concentration (Fig. 12). Sensitivity of this model as well as the relatively scarce sampling dates (Circa monthly) could primarily explain this disagreement. Recent study on deep water warming in Lake Maggiore as well as in other Italian deep lakes, particularly during the 90s, has demonstrated a progressive increase in the heat content of deep waters (Ambrosetti and Barbanti, 1999). This phenomenon is likely to interfere with pigment deposition and losses through its potential effect on residence times, mixing, hypolimnetic oxygen status and species composition.

5.4. Chironomids

In the case of chironomid fauna, the comparison between core samples and documentary records is made difficult by the high spatial variability found in benthic assemblages among different sampling stations. However, some general features described in the limnological literature can be found in core profiles. Although studies of benthic fauna from Lake Maggiore started at the beginning of the 20th century (Bretscher, 1900; De Marchi, 1910), the first data of insect larvae were presented by Lundbeck (1936) and were related to the northern Swiss basin. In that paper, Lake Maggiore was characterized as an oligotrophic lake dominated by the genera *Orthocladius* and *Tanytarsus* community with an important presence of Tanypodinae. Some years later, Lenz (1949) described Lake Maggiore as an *Orthocladius/Tanytarsus* lake but he noted an important increase of the *Chironomini Polypedilum* and the *Pseudochironomini pseudochironomus* as well. Similar chironomid composition was found in the bottom of the core LM98/8A.

In 1961, Nocentini (1963) still observed the same chironomid assemblages in Lake Maggiore. In this study, Orthoclaadiinae is the dominant sub-family (*Trichocladius*, *Paratrachocladus* and *Cricotopus*), but an important increase of *Cryptochironomus* was recorded in the littoral sample sites. A high proportion of Diamesinae was recorded in Monvalle station, close to the sampling site of LM98/8B sediment core. This peak at around 1961 AD is well represented in the core profile (Fig. 8), indicating the high comparability between documentary and sedimentary data and the good correlation among midges, diatoms and radiochemical chronology.

Unfortunately, no data are available until the beginning of the 1980s. At that time, dominant chironomid fauna, on the western part of the lake, was composed mainly by the genera *Chironomus*, *Cryptochironomus* and *Procladius* (Nocentini, 1988, 1989). Although a direct comparison between historical data and the core LM98/8A is difficult, the literature reported an increase in *Chironomus* and *Cryptochironomus* abundances after 1961, which is also evident at the same time in our core.

The chironomid results along the littoral core LM98/8B also agree with the documentary records of water-level fluctuations in Lake Maggiore (Ambrosetti et al., 1994). In fact, the Diamesinae peak at 18 cm (1961 AD) is coincident with an important water-level increase recorded by that time. Both, the increase of Diamesinae and the sharp drop in the number of taxa could be interpreted as the effect of increased input of allochthonous material from the catchment area, during the flood which caused the change in water level.

The effect of lake eutrophication in the 1960s–1970s, clearly evident in the diatom and pigment data, is not recorded by sharp changes in the chironomid assemblages. Later on, at around 1975 AD (ca. 13 cm), the increase of *Chironomus* together with the decline of *Tanytarsus* gr. and *Polypedilum* may be linked with the first episode of oxygen deficit due to the increase in lake productivity and with the oligomictic regime of Lake Maggiore, (i.e. a complete overturn occurs only occasionally). Further peaks in *Chironomus* abundance at 6 and 2 cm may be related to oxygen depletion recorded in 1889–90 and 1994–96 (Fig. 8).

However, these changes may also be related to water fluctuations as during this interval of time, the lake overflowed three times. In addition, in 1980 a large change was recorded in the littoral macrophyte community. By that time, a massive macrophyte cutting and dredging occurred in the littoral zone which may have an important impact on the chironomid composition.

Hofmann (1998) and Korhola et al. (2000) demonstrated that water depth is one of the main factors influencing the littoral communities. Lake-level fluctuations affect the littoral habitat changing sediment composition and the zonation of littoral vegetation. Thus, littoral fauna responds indirectly to water-level fluctuations as they changed due to these new habitat conditions (Hofmann, 1998).

In conclusion, the comparison between neolimnological (*sensu* Smol, 1990b) and palaeolimnological data in this case is affected by the high spatial variability of the benthic fauna. Because of a lack of historical data from the area of the coring sites, the comparison is limited to most widespread events (e.g. the clear increase of *Chironomus* abundance during eutrophication). Conversely, when the documentary data and the sediment core come from the same area, local events such the peak of Diamesinae in 1961, can be traced through sediment analysis. Our results demonstrate that lake eutrophication did not have a clear and immediate response to the chironomid composition. Instead, water-level changes seemed to affect more the littoral chironomid assemblages as all the sharp changes recorded in the sediment sequence are coincident with major fluctuations of the Lake Maggiore lake level. It is, however, difficult to isolate a clear chironomid response to any particular environmental factor as many other variables, as macrophyte manipulation, lake area, lake trophy, fish introduction occurred during the time span represented in the analysed core, have also affected chironomid composition in some way. The multivariate approach (e.g. CCA) applied to the data (not shown) also demonstrated that faunal variations are linked to a complex of varying physical conditions which affect in different ways the structure and zonation of the littoral community.

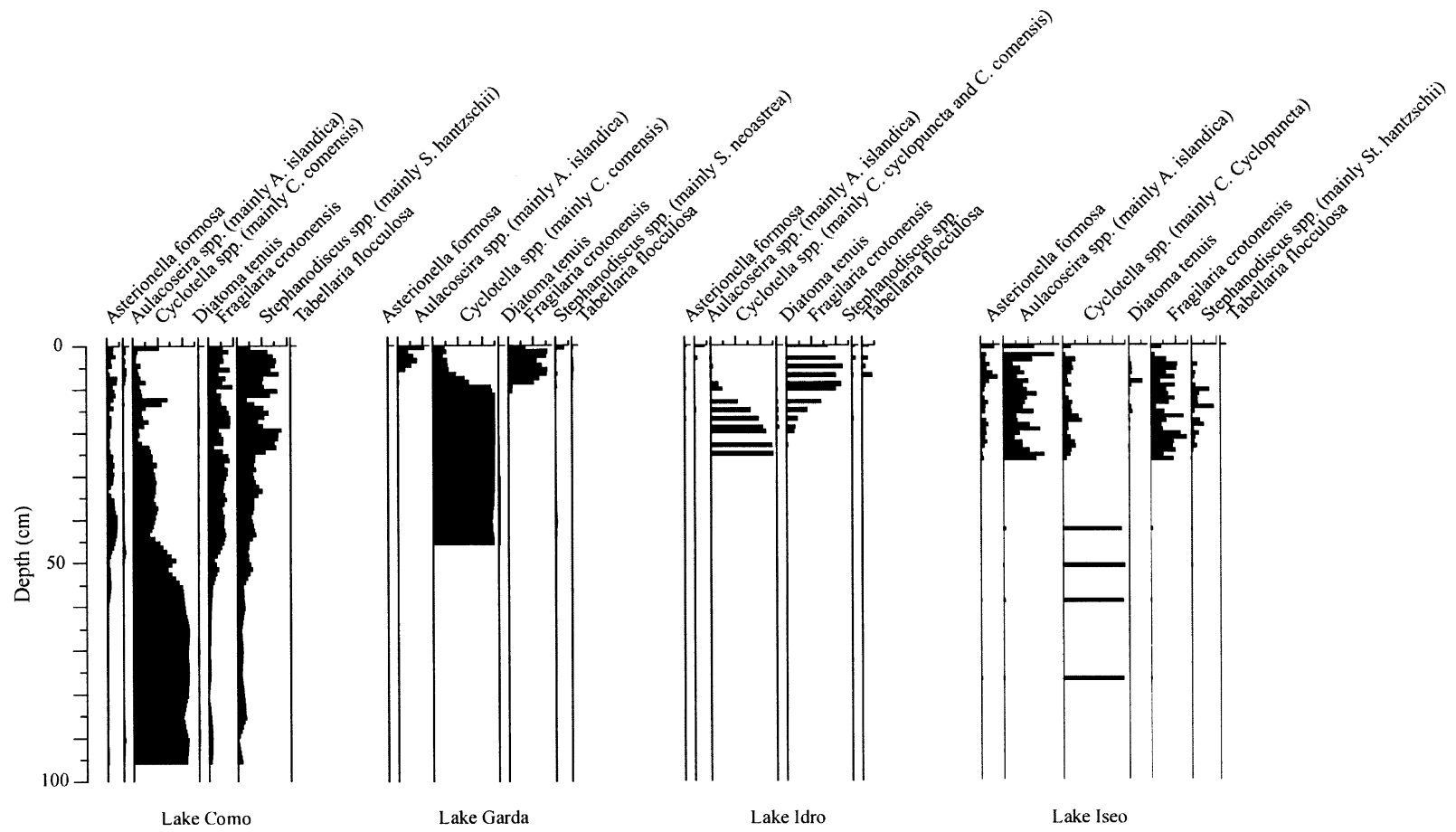


Fig. 13. Vertical variation of the diatom remains, as percent of total abundance, along sediment cores of four sub-alpine Italian lakes.

6. Comparison with other lakes

6.1. Italian sub-alpine lakes

Three major Italian sub-alpine lakes, Como, Iseo and Garda and the nearby small Lake Idro were in the past the subject of fossil diatom investigation, aimed to assessing their trophic evolution during the last ca. 100 years (Marchetto and Bettinetti, 1995; Marchetto, unpublished data). On the basis of long-term data on nutrient inputs, in-lake nutrient concentration, production and algal biomass, the lakes are classified along a trophic range (from eutrophic to mesotrophic): Como \cong Iseo > Idro > Garda (Mosello and Giussani, 1997). In general, this classification is also confirmed by fossil diatom analyses, from which it is also evident that the community structure differs somewhat among lakes. In contrast, similar sharp modifications (very pronounced in Lake Garda) and species succession are observed (Fig. 13). Also, in these lakes *Cyclotella* spp. is the dominant taxa in the oldest sediments and it is replaced during the eutrophic phase by more eutrophic and mesotrophic taxa such as *Stephanodiscus* spp., *F. crotonensis*, *T. flocculosa*, *A. Formosa* and *Aulacoseira islandica*. We conclude that the trophic histories of these lakes as reconstructed by the diatom remains is basically the same like in Lake Maggiore, except that no recent sign of recovery is shown, likely because the data refer to cores collected 4–7 years earlier so that the recent story is lacking.

6.2. Lake Constance

Lakes Constance and Maggiore, located at the opposite edges of the Alps, underwent a similar trophic development: their trophic status increased in 1950–1980 and then decreased after the construction of wastewater treatment plants and the ban of detergents containing phosphorus compounds. However, their present trophic status is still higher than in the first decades of the 20th century.

Although eutrophication in Lake Constance started earlier than in Lake Maggiore and was more marked (Wessels et al., 1999), their diatom communities developed following similar patterns (Fig. 14). Pigment concentrations were subject to similar increasing trends during this period: in both lakes, total pigment concentration increased by a factor of 20–25 between 1917–1924 and 1970–1990. Lake recovery, indicated by the shift from eutrophic species back to oligotrophic taxa, is shown by both lakes, but is more advanced in Lake Maggiore, where *C. comensis* is presently abundant. In both lakes, decreasing concentrations of TP during the 1980s were not immediately paralleled by a decline of eutrophic *Stephanodiscus* species, which maintained high abundances up to the end of the 1980s.

7. Conclusions

Data on several cores from the large and deep Lake Maggiore illustrate the need for limnological information to interpret properly the chronology and the significance of the past 3–4 decades of the eutrophication and the recent (last decade) oligotrophication phase. The first evidence of eutrophication was detected in sediments from the mid-1950s and in the 1960s. Since the early mid-1990s, there was a clear sign of lake recovery with the reoccurrence of the pre-1950 diatoms species. In conclusion, the succession of diatoms, pigments and chironomids in the sediment cores follows the documented historical trophic and environmental changes.

The sedimentary diatom records are consistent with the water diatom samples. Most species showed an almost linear relationship between their relative abundance in the sediments and that in the plankton.

Prediction of total algal biomass from the ubiquitous β -carotene concentration was generally good whereas single indicator carotenoids were rarely correlated with the documented biovolume of single algal groups. Carotenoid measurements monitor different features of

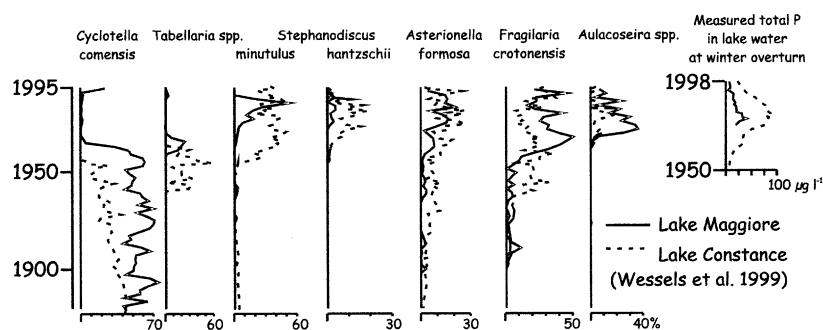


Fig. 14. Profiles of percent abundance of some selected diatoms along cores of Lake Maggiore and Lake Constance (Switzerland, Wessels et al., 1999). Inferred TP during spring overturn in both lakes is also shown.

algal population than do biovolume estimates of algal standing crop. Errors in methodology in long-term studies, changes in abundance of individual species, succession taxa, light intensity, mechanism controlling pigment decomposition and sedimentation, are the main factor that bias the comparison. Although pigment and biovolumes are different, they are nevertheless equally valid and complementary in limnological and palaeolimnological studies (Leavitt et al., 1993). Clearly, further experimental studies would be useful to determine the various processes and interactions between algal deposition and food web interaction.

The diatom-phosphorus weighted-averaging transfer function, derived from a training set from range of eutrophic and oligotrophic lakes (Wunsam and Schmidt, 1995), compares well with the limnological TP data except for a period 1983–1988 in which extraordinary blooms of a species (*S. minutulus*) lead the model to overestimate by a factor of 3 the epilimnetic P concentration.

Similar conclusions can be drawn from the primary productivity and fossil algal pigment concentrations. Despite the natural intra- and interannual variability of these measurements and the recent global warming that could interfere with the pigment sedimentary process and preservation, the model seems quite accurate. It is interesting to note that the trophic reconstruction of Lake Maggiore, as based on diatom analyses, is very similar to the recent evolution of Lake South and North of the Alps (Como, Iseo, Garda, Idro, Constance).

As regard Lake Maggiore and Constance for which a good comparison is possible because reliable chronological control has been possible, we can conclude that, apart from the difference in some diatoms species between the two lakes, the eutrophication of Lake Constance started about 30 years earlier (ca. 1930) attaining with time a much higher trophic state than Lake Maggiore (e.g. higher P water content). The 1990s recovery is common to both lakes.

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