Comparison between sedimentary and living diatoms in Lago Maggiore (N. Italy): implications of using transfer functions

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ABSTRACT

We compared the recent history of living planktonic diatom assemblages in Lago Maggiore with the remains found in the topmost section of 14 sediment cores taken from the lake. Sediment samples showed a marked domination of planktonic taxa, but a significant proportion of benthic taxa was found in cores collected close to river mouths. Between-core variability in diatom assemblage and in diatom-inferred total phosphorus concentration was also estimated. The implications of our results for calibration data sets relating environmental variables to diatom assemblages are also discussed.

Key words: diatoms, sediment, plankton, Lago Maggiore

1. INTRODUCTION

Since the last decade, quantitative methods in palaeolimnology have largely relied on the building of calibration data sets. These are used to obtain basic information on the ecological preferences of the species of organisms (e.g. diatoms) used for inferring palaeoenvironmental (e.g. pH, nutrient level) and palaeoclimatic conditions (e.g. temperature).

Calibration data sets are commonly derived from surface sediment samples taken from a number of lakes. A calibration data set generally includes as many lakes as possible, and consequently a single sample is usually taken from each lake, and considered representative of that lake. However, several factors cause differential diatom sedimentation into and re-suspension from lake sediments, and the use of a single surface sediment sample as representative of the lake as a whole should be treated with caution. In spite of its importance for the precision of the palaeoenvironmental inferences, a few papers (e.g. Meriläinen 1971; De Nicola 1986) compare known diatom assemblages with their representation in sediment samples.

In this paper we compare the diatom assemblages found in monthly plankton samples and in 18 surface sediment samples collected in Lago Maggiore, a large and deep lake located in northern Italy, in which the pattern of sediment accumulation is complicated by the complex morphology of the lake bottom, and by the presence of steep slopes, river deltas and a bathymetric step.

We discuss to what extent a random sample of surface sediment may represent the planktonic diatom assemblage. Among-core variability of diatom inferred total phosphorus concentration is also evaluated.

2. STUDY SITE

Lago Maggiore is the second largest (212 km^2) 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 km^2 and is drained by several rivers (Ticino, Toce, Maggia, Verzasca). Several factors contribute to enhancing the accumulation of sediment in the lake: a large bathymetric step joining the lateral Pallanza bay (150 m deep) to the main basin, frequent river floods carrying large amounts of allochthonous material to the lake, and steep slopes causing occasional underwater landslides.

It used to be thought that Lago Maggiore underwent a total overturn in wintertime on average every 7 years, but no complete mixing occurred from 1981 to 1999. In the same period water temperature was clearly increasing (Ambrosetti & Barbanti 1999).

The trophic status of Lago Maggiore shifted from oligotrophy to mesotrophy in the 70s, then back to oligotrophy, which is its present status. Total phosphorus concentration reached 35 µg l^{-1} in 1977, decreasing to less than 10 µg l^{-1} in the 90s (Calderoni & Mosello 1996).

Reliable information on phytoplankton has been available since 1954, when summer plankton was mainly composed of *Cyclotella* spp., *Fragilaria crotonensis*, *Rhizosolenia eriensis*, *Asterionella formosa*, *Tabellaria flocculosa* (at that time misidentified as *T. fenestrata*), *Microcystis aeruginosa*, *Ceratium hirundinella*, *Aphanothece* spp. and *Dinobryon* spp. (Vollenweider 1956).

In the 60s, increasing nutrient input led to the development of *Tabellaria flocculosa*, *Aulacoseira* spp. and a number of cyanobacteria, like *Lyngbya limnetica*, *Os-*
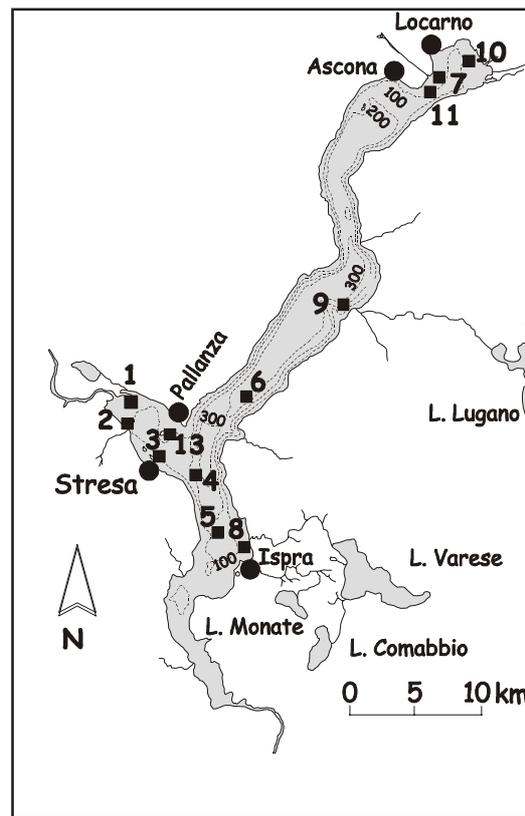
Fig. 1. Sampling sites in Lago Maggiore.

Tab. 1. List of the cores used in the present study.

Core code	Sampling site (see fig. 1)	Sampling date	Long. E	Lat. N	Sampling depth (m)	Sedimentation rate (cm y^{-1})
LM 98/1E	1	14 May 1998	8°30'16"	45°56'03"	48	1.3
LM 98/2A	2	18 Feb 1998	8°30'08"	45°55'02"	36	1.5
LM 98/3C	3	18 Mar 1998	8°32'38"	45°53'35"	153	0.33
LM 98/4A	4	18 Feb 1998	8°34'02"	45°53'07"	237	0.03
LM 98/5B	5	18 Feb 1998	8°36'17"	45°50'40"	170	-
LM 98/5C	5	5 Mar 1998	8°35'56"	45°50'34"	163	0.4
LM 98/6A	6	18 Mar 1998	8°37'55"	45°56'38"	362	0.96
LM 98/7A	7	4 Mar 1998	8°48'55"	46°08'32"	97	0.2
LM 98/8A	8	14 May 1998	8°37'07"	45°50'11"	17	0.33
LM 98/8B	8	14 May 1998	8°37'04"	45°50'11"	17	-
LM 98/9A	9	7 May 1998	8°43'25"	45°59'54"	31	1.0
LM 98/10B	10	7 May 1998	8°50'50"	46°09'34"	39	0.8
LM 98/11A	11	7 May 1998	8°48'30"	46°08'36"	70	0.2
LM 98/13A	13	14 May 1998	8°32'57"	45°54'48"	89	0.32

cillatoria prolifica and *O. rubescens* (Ravera & Vollenweider 1968). In the 70s, plankton assemblages were dominated by cyanobacteria, diatoms (*Asterionella formosa*, *Fragilaria crotonensis*, *Synedra* spp. and *Stephanodiscus* spp.) and Cryptophyceae, such as *Cryptomonas* spp., *Rhodomonas* spp. and *Ceratium hirundinella* (Ruggiu & Saraceni 1977). Since 1987, recovery from eutrophication has led to the decreasing importance of these species, and the re-appearance of species typical of oligotrophic lakes (Ruggiu *et al*. 1998).

3. MATERIALS AND METHODS

In 1998, 14 short sediment cores (9-84 cm) were taken from 12 sites in Lago Maggiore (Fig. 1 and Tab. 1), using a gravity corer 63.5 mm in diameter. Each core was cut lengthways in the lab, and sliced into 1-cm sections. For each site, one core was dated at the CNR Istituto di Biologia Marina, using either ^{137}Cs or ^{210}Pb (L. Langone, unpublished data).

Diatoms were cleaned following Renberg (1990) and mounted with Naphrax. For each sample, at least

500 valves were identified and enumerated with a light microscope (Zeiss Axiolab). Critical identifications were confirmed using a scanning electron microscope (Philips SEM 505) after filtering the diatom suspension on a 0.45 µm polycarbonate filter and coating the filter using an Edwards S105E sputter coater.

The nomenclature used is that of Krammer & Lange-Bertalot (1986-92), and authorities for quoted species are given in appendix I. The exceptions were *Cyclotella* aff. *gordonensis* Kling & Håkansson 1988, which is described by Wunsam *et al.* (1995), and *Synedra nana* Hustedt 1930 and *Synedra tenera* W. Smith 1856, which were pooled together, as we found intermediate forms.

Diatom profiles were obtained for one core for each sampling site. Further surface sediment samples were analysed, including replicate cores from sites 5 and 8 (for within-site comparison), samples taken from the same sediment section after stirring, and replicate slides of the same sample.

Monthly diatom abundance data were provided by Morabito, Ruggiu & Panzani (unpublished data) and refer to integrated plankton samples collected between 0 and 50 m depth and counted following Utermöhl (1958). Comparable plankton sample were obtained taking into consideration the time period spanned by each sediment sample. For each taxon, a mean absolute abundance (in cell ml^{-1}) was obtained as the time-weighted mean of the abundance of that taxon in all the plankton samples collected in this period. Finally, relative abundance was calculated on the basis of planktonic species only. The sporadic presence of re-suspended benthic diatoms (mainly *Achnanthes minutissima* and *Cymbella* spp.) was not considered in the sum of diatoms.

4. RESULTS AND DISCUSSION

4.1. Diatom abundance in surface sediment samples

Selected diatom taxa found in surface sediment samples are reported in table 2. In some cores (LM98/3C, LM98/4A, LM98/5C, LM98/5B, LM98/6A and LM98/13A) more than 97% of the valves belonged to planktonic species (Tab. 3). In sediment cores taken closer to river mouths, planktonic species accounted for 65-83% of the diatom abundance. The occurrence of the most common benthic taxa is related to the location of the sampling sites; they are *Achnanthes minutissima* (core LM98/7A, LM98/10B and LM98/11A), *Nitzschia* spp. (cores LM98/1E and LM98/2A), *Fragilaria construens* and *F. pinnata* (cores LM98/8A and LM98/8B) and *Cocconeis placentula* (core LM98/9A). In contrast, the relative abundance of benthic species (Tab. 3) is not related to the depth at which each core was taken.

According to Meriläinen (1971), the high proportion of planktonic taxa in deep sediment is due to the steepness of the slopes and to the long periods of lake stratification, since settled planktonic diatoms are more likely to be transported than are the attached periphytic taxa, when turbulence is low.

The diatom assemblage found in core LM98/4A is completely different from those found in all the other cores, being heavily dominated by *Cyclotella comensis*. This pattern is found in older sediment sections in other cores (cf. section 4.2), and might be due to the very low sediment accumulation rate at this sampling site, or to the loss of recently deposited sediment, or a hiatus in sediment deposition.

Besides the patterns described before, cluster analysis (Fig. 2) also shows that subsamples taken from the same core (such as 5B, 5B-1 and 5B-2 or 8B-1 and 8B-2) lie in subclusters with very small Euclidean distance. The high homogeneity among subsamples taken from the same core slice is due to sediment stirring before subsampling. However, different cores taken at the same site (as 8A and 8B, or 5B and 5C) are classified in different subclusters, and the distance between them is comparable to the distance between two cores at different sites. This means that we can consider a single sample as representative of the whole of Lago Maggiore and use planktonic diatoms for core correlation. In fact, cores taken in different areas of the lake bottom were unexpectedly similar in diatom composition, in spite of the elongated, somewhat branched shape of the lake and the complex morphology of the lake bottom.

Diatom-inferred total phosphorus concentrations, calculated following the equation given by Wunsam & Schmidt (1995), are also reported in table 3. Their mean value is 9.7 µg l^{-1} with a standard deviation (SD) of 1.5 µg l^{-1}. Similar results are obtained when only planktonic taxa are used (9.5 µg l^{-1} ± 1.6 µg l^{-1}). In both cases, the difference between the values obtained in cores taken from the same location (ranging between 1.3 and 3.1 µg l^{-1}) are similar to the differences between cores taken from different parts of the lake. In 1997-98, mean annual TP concentration measured in the lake water ranged between 6 and 11 µg l^{-1} with a mean value of 8.45 µg l^{-1}. Within the core, SD of diatom inferred TP is very low, on average 0.14 µg l^{-1}, and comparable to the SD of slides obtained from the same digested sample (0.07) and of repeated counts of the same slide (0.04).

Our results agree with the findings of Charles *et al.* (1991) that the variability associated to subsampling, processing and counting is far smaller than between-core variability, and that the inferred values are relatively unaffected by the small differences between diatom assemblages collected in different cores. They also found that the relative importance of littoral *vs* planktonic forms was the most significant cause of variability between cores in the 70-m deep Big Moose Lake.

In contrast, in shallow Loch Fleet, Anderson (1990) found a significant variability between cores, both in diatom assemblages and in inferred pH values. In common with our study, he also found a core with atypical diatom assemblage.

Tab. 2. Percent relative abundance of selected diatom taxa in surface sediment samples. Only taxa with relative abundance higher than 2% in any sample are shown. bis: replicate count of the same slide, rep: replicate slide of the same subsample, −1 and −2: replicate subsamples of the same core.

	1E	2A	3C	4A	5B	5B bis	5B-1 rep.	5B-2	5C	6A	7A	8A	8B	8B bis	8B rep.	8B-1	8B-2	9A	10B	11A	13A	13A bis
Achnanthes minutissima	6.3	9.9	1.5	3.0	1.7	1.6	1.2	1.5	0.9	1.2	15.5	1.0	2.1	3.3	4.1	0.9	2.4	6.6	12.4	14.0	2.1	2.5
Asterionella formosa	9.9	1.4	3.2	1.9	2.5	1.6	2.1	1.5	4.2	2.6	6.6	2.9	9.2	9.5	8.5	8.0	6.3	6.3	3.3	14.0	2.2	2.3
Aulacoseira islandica	1.4	1.2	1.1	0.0	5.5	3.6	3.3	1.9	3.1	5.4	0.0	0.5	1.5	1.8	1.0	1.7	1.6	2.8	2.4	1.7	1.1	1.6
Aulacoseira subarctica	0.0	0.0	0.0	0.4	1.1	1.4	1.1	1.1	0.9	2.8	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0	0.0	0.8	0.5
Cocconeis placentula	0.1	1.0	0.4	0.4	0.0	0.0	0.2	0.0	0.0	0.2	0.3	0.6	0.0	0.4	0.2	0.2	0.7	2.5	3.1	1.5	0.1	0.0
Cyclotella aff gordonensis	9.8	6.6	8.8	3.6	8.7	10.9	13.7	14.2	9.5	8.5	9.3	7.1	12.7	13.0	9.5	9.5	6.7	6.0	4.9	5.0	11.4	11.9
Cyclotella comensis	22.5	20.0	37.6	79.9	41.9	42.7	40.8	36.9	31.5	30.0	25.0	26.9	34.3	30.5	34.7	34.0	38.5	21.3	8.4	27.2	27.4	33.7
Diatoma tenuis	7.8	14.3	15.7	0.0	6.2	7.8	7.4	9.1	5.8	8.5	10.5	9.8	4.7	3.9	4.4	3.2	3.6	2.7	0.0	0.1	10.1	9.8
Fragilaria brevistriata	0.0	0.4	0.0	0.0	4.4	4.0	0.0	0.7	0.0	0.0	0.2	0.3	0.0	3.0	2.3	5.8	2.6	0.6	0.2	0.0	0.0	0.0
Fragilaria capucina	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.4	0.2	0.5	0.0	0.2	0.0	2.1	0.4	0.5	0.4	0.8	0.4	0.2	0.1	0.1
Fragilaria construens	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	1.5	1.9	3.9	0.0	0.0	0.0	0.0	0.0	0.0	2.1	3.4	0.0
Fragilaria crotonensis	25.7	16.3	24.0	5.3	19.1	19.3	18.8	23.5	35.8	26.3	7.0	30.5	18.2	20.6	20.8	24.8	20.4	18.3	38.2	20.5	28.9	30.9
Fragilaria spp.	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	2.0	3.1	1.9	0.0	0.8	0.0	2.0	0.6	0.0	0.0	0.0	0.0
Gomphonema spp.	0.5	0.6	0.0	1.2	0.0	0.3	0.0	0.6	0.0	0.3	1.7	0.3	0.4	0.0	0.0	0.0	0.4	1.5	3.4	0.7	0.4	0.4
Nitzschia spp.	4.8	11.2	1.1	0.0	2.1	2.1	2.8	2.8	0.9	1.2	1.8	0.6	1.0	1.9	0.7	1.2	1.4	10.5	4.7	1.6	0.9	0.8
Stephanocostis chanthaicus	0.3	0.4	0.0	0.2	0.3	0.0	0.9	0.3	1.9	0.2	0.5	0.0	1.1	0.4	1.2	0.7	0.8	0.7	0.0	0.2	0.0	0.4
Stephanodiscus parvus	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	1.3	0.0	0.5	0.0	0.4	0.2	0.0	0.0	3.2	0.0	0.0	0.2	0.2

Tab. 3. Percent of planktonic diatoms in the top sample of each core, and diatom-inferred total phosphorus concentration (TP), based on the calibration model provided by Wunsam & Schmidt (1995).

Core code	Sampling depth (m)	Planktonic diatoms (%)	Diatom inferred TP	
			All species	Planktonic only
LM 98/1E	48	83.4	10.1	10.1
LM 98/2A	36	70.0	9.2	8.7
LM 98/3C	153	95.5	7.7	7.7
LM 98/4A	237	94.2	-	-
LM 98/5B	170	90.7	7.7	7.6
LM 98/5C	163	97.2	9.0	9.0
LM 98/6A	362	93.7	10.3	10.2
LM 98/7A	97	69.6	8.2	7.5
LM 98/8A	17	86.9	11.4	11.3
LM 98/8B	17	85.2	9.0	8.2
LM 98/9A	31	71.1	11.9	11.8
LM 98/10B	39	65.5	11.9	12.0
LM 98/11A	70	75.5	9.4	9.2
LM 98/13A	89	92.4	10.4	9.7
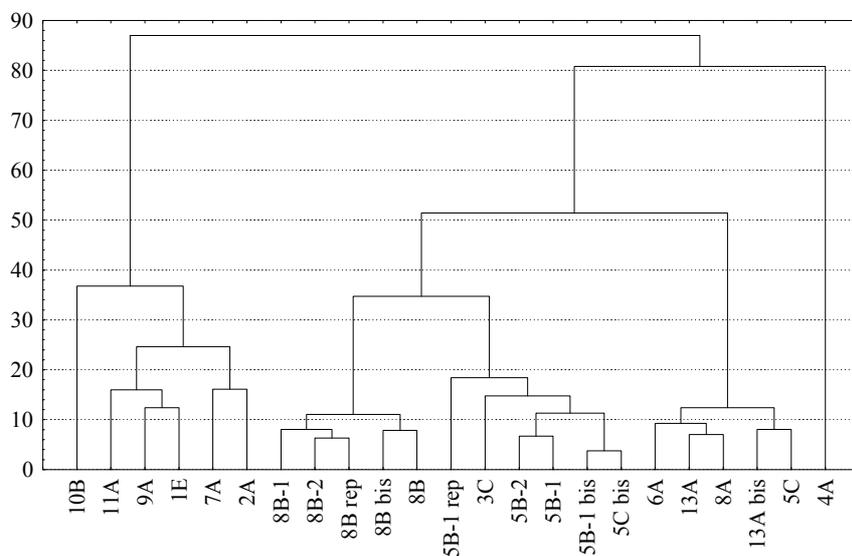
Fig. 2. Cluster diagram (Ward's method) of the Euclidean distance among surface sediment samples. bis: replicate count of the same slide, rep: replicate slide of the same subsample, -1 and –2: replicate subsample of the same core.

4.2. Diatom profiles of cores LM98/13A and LM98/5C

The diatom profile of core LM98/13A may be divided into three zones (Fig. 3): (i) in the deepest part of the core (below 20 cm), the diatom assemblage shows the marked dominance of *Cyclotella* species, mainly *C. comensis*, a species typical of oligotrophic lakes (Reynolds 1984); (ii) the zone between 20 and 7 cm (*ca* 1935-63 A.D.) is characterised by an initial increase in the abundance of *Fragilaria crotonensis*, followed by the sequential appearance of meso- and eutrophic species, such as *Tabellaria flocculosa*, *Aulacoseira islandica*, *A. ambigua*, and finally *Stephanodiscus minutulus*, *S. hantzschii* and *Diatoma tenuis*; (iii) in the topmost 7 cm there is a decline in eutrophic species, which are re-

placed by *Asterionella formosa* and by *Cyclotella comensis*, whose relative abundance however does not reach the values found in the deepest part of the core.

The diatom profiles of cores LM98/5C and LM98/13A are very similar, apart from the very high abundance (85%) of *Aulacoseira islandica* found at 17 cm (*ca* 1956) in core LM98/5C, probably related to a local crowding of colonies at the sampling point.

Sedimentary diatom abundance compares well with historical reports of changes in diatom assemblages. The first description of Lago Maggiore phytoplankton (Vollenweider 1956) reports high abundance of *Fragilaria crotonensis* and *Asterionella formosa*, and also the dominance of "small Cyclotellas" and of *Rhizosolenia eriensis*, though there is practically no record of the latter species in the lake sediment.

a) core LM 98/5C
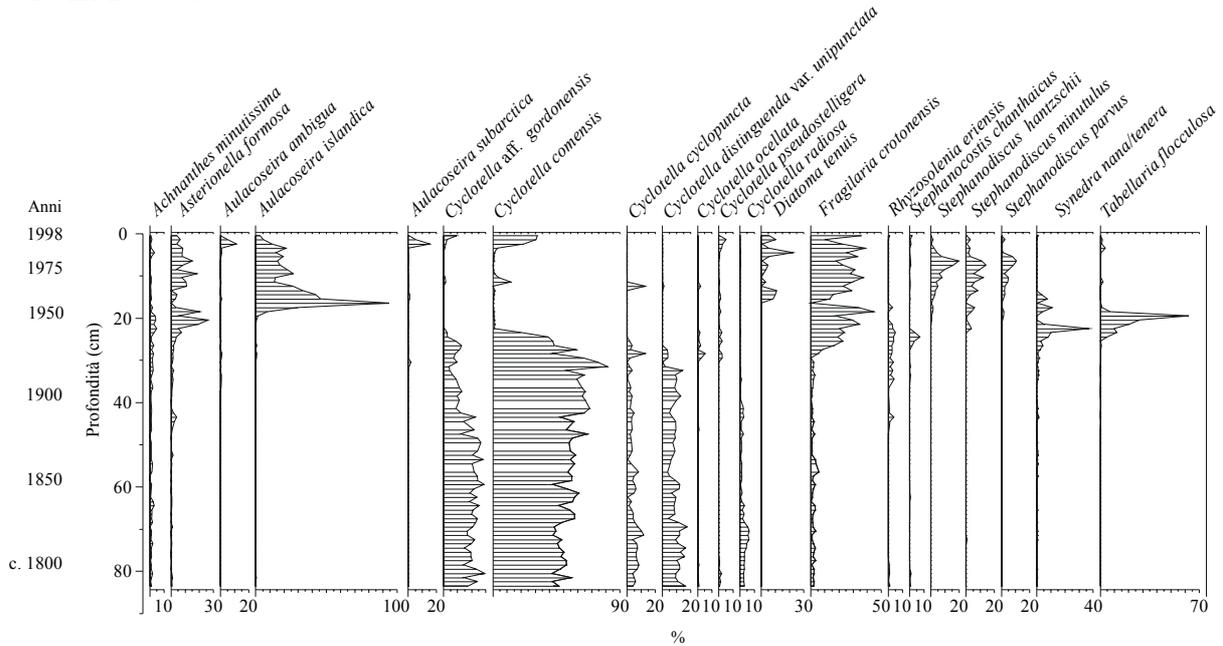
b) core LM98/13A
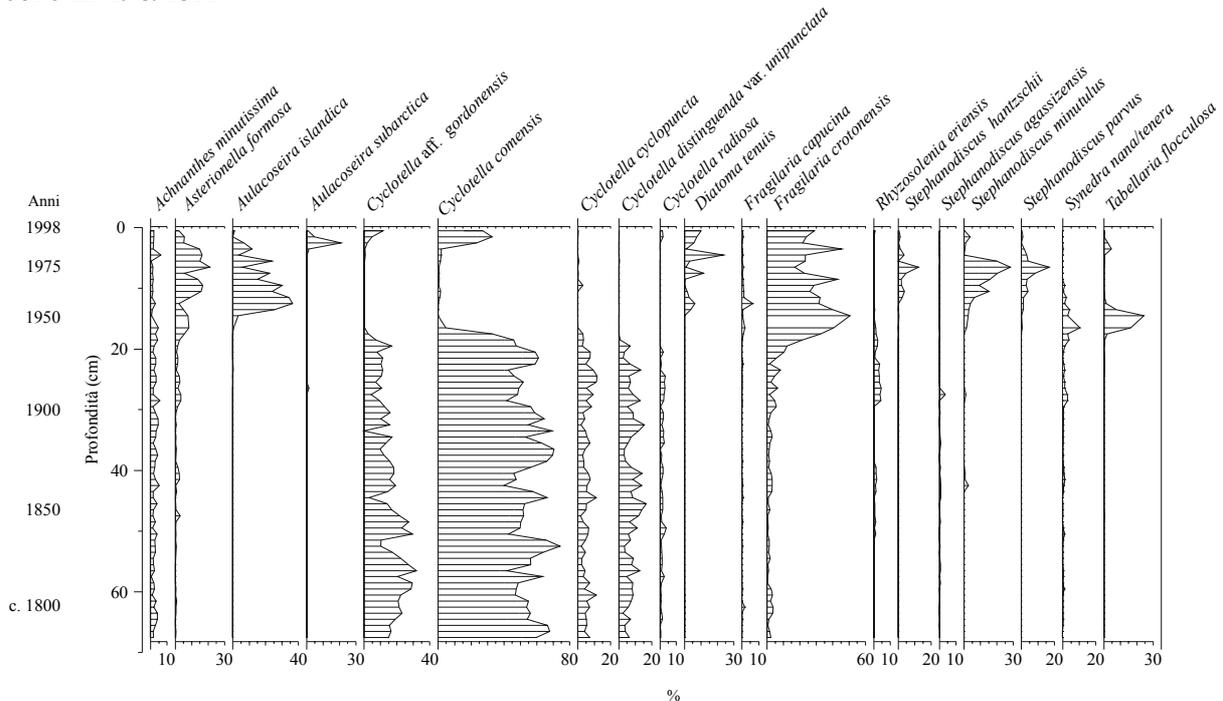
Fig. 3. Profiles of the relative abundance of some selected diatom taxa along cores LM98/5C and LM98/13A.

In 1965, Goldman *et al.* (1968) found phytoplankton very rich in diatoms, mainly *Tabellaria flocculosa*, a peak of which is evident in both cores. In 1972-73, *T. flocculosa* was declining, while *Fragilaria crotonensis* and *Asterionella formosa* were increasing and *Stephanodiscus* spp. appeared (Ruggiu & Saraceni 1977). Finally, in close agreement with the sediment profiles, Ruggiu *et al.* (1993) reported the reappearance of *T.*

flocculosa in 1990, and *C. comensis* increased greatly in abundance in 1992.

4.3. Comparison between sediment samples and counts of living plankton

Plankton samples have been taken at least monthly from Lago Maggiore since 1981. In figure 4 we compare planktonic diatom assemblages found in sediment
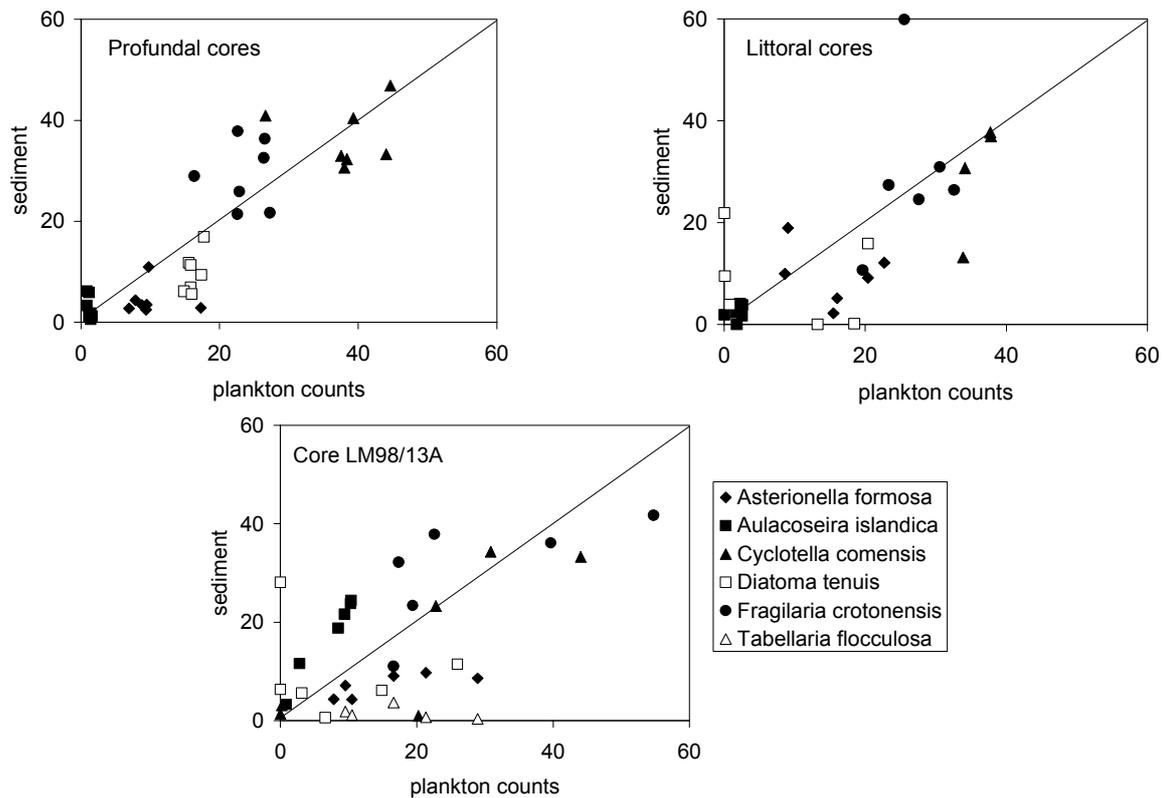
Fig. 4. Percent abundance of some selected planktonic diatom taxa in surface sediment sample, excluding core LM98/4A (**a**, **b**), and along core LM98/13A (**c**) plotted *vs* time-weighted average plankton samples. Abundances were calculated on the total of planktonic diatoms, omitting benthic species, and differ from the values reported in table 2. Profundal and littoral cores are defined on the basis of the results of cluster analysis (Fig. 2).

and plankton water samples. The relative abundance of plankton in sediment samples was recalculated discarding all benthic species, so that their values differ from those reported in table 2.

If we look at the cores with higher abundances of planktonic species (Fig. 4a), there is a general agreement between the abundances observed in sediment and plankton samples. However, most species show slightly higher relative abundance in the plankton samples, while *Fragilaria crotonensis* is relatively more abundant in the sediment samples. This pattern is probably due to the different seasonal development of this species, which is found in most samples, compared to other species which peak suddenly.

If we extend the comparison to the other cores (Fig. 4b), dispersion around the expected 1:1 ratio increases, and large differences between the relative species abundance in sediment and plankton are found in particular for core LM98/10B and for *Diatoma tenuis*. However, we should stress that in cores taken close to river mouths, such as LM98/10B, accumulation rates are very variable, and the use of the mean accumulation rate for defining the time window spanned by the surface sediment is questionable.

On the contrary, if we compare the diatom assemblage in the topmost 5 samples of core LM98/13A and

the mean plankton composition in the corresponding periods (Fig. 4c), there is good agreement for most species, apart from *Diatoma tenuis* and *Tabellaria flocculosa*.

5. CONCLUSIONS

In spite of the large size and complex bottom morphology and sedimentary processes of Lago Maggiore, the diatom assemblage derived from a single surface sediment sample can be regarded as being representative of the lake. Cores taken in different sites and at different depths give very similar results in terms of relative abundance of diatom and of diatom-inferred nutrient level (cf. Tab. 3). Even cores taken close to river mouths only differ in so far as they contain a higher fraction of benthic species, which can be easily discarded during data processing. However, the diatom assemblage in one core (LM98/4A) was completely different from those found in the others, and would have heavily biased any calibration data set if included. This stresses the importance of having multiple sampling sites in each lake if the calibration data set includes a small number of lakes.

In data sets including a large number of lakes sampled once, it is possible to perform specific tests to de-

tect "rogues", i.e. samples in which there is an anomalous relationship between environmental variables and diatom assemblages, as described, for example, by Birks *et al.* (1990). If obvious outliers are discarded, our results suggest that even in deep lakes, single surface sediment can be regarded as being representative of the planktonic diatom community.

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Appendix I List of quoted species with authorities

Achnanthes minutissima Kützing 1833	*Fragilaria capucina* Desmaziéres 1925
Asterionella formosa Hassall 1850	*Fragilaria construens* (Ehrenberg) Hustedt 1957
Aulacoseira ambigua (Grunow) Simonsen 1979	*Fragilaria crotonensis* Kitton 1869
Aulacoseira islandica (O. Müller) Simonsen 1979	*Fragilaria pinnata* Ehrenberg 1843
Aulacoseira subartica (O. Müller) Haworth 1988	*Rhyzosolenia eriensis* H. L. Smith 1872
Cocconeis placentula Ehrenberg 1838	*Stephanocostis chanthaicus* Genkal & Kuzmin 1985
Cyclotella cyclopuncta Håkansson & Carter 1990	*Stephanodiscus agassizensis* Håkansson & Kling 1989
Cyclotella distinguenda var. *unipunctata* (Hustedt) Håkansson & Carter 1990	*Stephanodiscus hantzschii* Grunow 1880
Cyclotella aff. *gordonensis* Kling & Håkansson 1988	*Stephanodiscus minutulus* (Kützing) Cleve & Möller 1878
Cyclotella ocellata Pantocsek 1901	*Stephanodiscus parvus* Stoermer & Håkansson 1984
Cyclotella pseudostelligera Hustedt 1939	*Synedra nana* Hustedt 1930
Cyclotella radiosa (Grunow) Lemmermann 1900	*Synedra tenera* W. Smith 1856
Diatoma tenuis Agardh 1812	*Tabellaria flocculosa* (Roth) Kützing 1844