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The deglaciation and Holocene sedimentary evolution of southern perialpine Lake Lugano – implications for Alpine paleoclimate

By Frank Niessen[1]) and Kerry Kelts[2])

ABSTRACT

The sedimentary record of Lake Lugano has been examined to provide the framework for correlation of major shifts in paleolimnology between northern and southern perialpine regions. Eight radiocarbon ages were obtained by AMS (2,085 to 13,070 B.P.). For the Late Glacial record paleomagnetic oscillations of declination were shown to be synchronous to those from Lake Zürich, extending the Lugano time scale down to 14,600 B.P. The section can be subdivided into four lithological units. Formation processes of Holocene sapropels (unit 1) vary with time, and are indicative to climatic changes. Two main types of Holocene lake operation can be distinguished: During the climate optimum, the environment is characterized by sluggish water circulation, since production indicators such as authigenic calcite appear to be very low. After 4,600 B.P. sapropel formation is triggered by increased terrestrial runoff and lake-productivity. A remarkably sudden productivity spike at about 3,800 B.P. is evident by high calcite dolomite ratios. The uppermost Late Glacial unit 2 (14,000 to 10,000 B.P.) is dominated by non-glacial detrital muds, bright in color and low in organic carbon, indicative for a well-mixed lake and low production rates. The lowermost recovered section (unit 4, older 14,600 B.P.) is built up entirely by proglacial muds suggesting a proximal distance of the melting Würm glacier at the time of deposition of unit 4. The last pulse of deglaciation is manifested by a transition (unit 3) between the end members from proglacial to non-glacial muds. The content of glacial flour drops to almost zero by 13,900 B.P. However, oxygen isotope evidence from deep water ostracods indicate that the catchment deglaciation continued at least until 13,000 B.P. There is an excellent time correlation of sudden Holocene and Late Glacial shifts (including the deglaciation) in Lake Lugano and Lake Zürich indicative for large-scale climatic changes in Central Europe. Sudden changes occurred at 14,600, 10,000, and 3,800 B.P.

ZUSAMMENFASSUNG

Die Sedimentabfolge des Luganersees wurde untersucht, um die Basis für eine Korrelation von paläolimnologischen Ereignissen zwischen dem nördlichen und südlichen Alpenraum zu verbessern. Acht Radiokarbon-Datierungen wurden mittels AMS bestimmt (2,085 bis 13,070 B.P.). Für den Abschnitt der Spätglazialen Sedimente konnten paläomagnetische Schwankungen der Deklinationswinkel nachgewiesen werden, die sich als synchron mit entsprechenden Mustern aus dem Zürichsee erwiesen haben. Anhand der Deklinationsschwankungen lässt sich die Zeitskala der Luganersee-Ablagerungen bis auf die Marke 14,600 B.P. erweitern. Die gesamte Sequenz umfasst 4 lithologische Einheiten. Sapropele des Holozäns (Einheit 1) sind in verschiedenen Zeitstufen auf unterschiedliche Prozesse zurückzuführen. Dabei sind zwei grundsätzlich gegenläufige Verhaltensweisen des Sees erkennbar: Die Zeit des Klimaoptimums ist durch eine generell schlechte Seezirkulation gekennzeichnet, da Indikatoren für See-Produktivität nur in sehr geringen Mengen nachgewiesen weden konnten. Nach 4,600 B.P. wurde die Bildung der

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Sapropele infolge hoher Erosionsraten im Hinterland durch erhöhte Produktivität kontrolliert. Ein rascher, bemerkenswerter Anstieg der Produktivität um 3,800 B.P. lässt sich anhand von hohen Calcit/Dolomit Verhältnissen nachvollziehen. Die oberste Einheit des Spätglazials (Einheit 2: 14,000 bis 10,000 B.P.) wird durch helle detritische Sedimente mit geringen Gehalten an organischem Kohlenstoff aufgebaut. Sie weisen auf einen gut durchmischten See mit niedriger Primärproduktion hin. Die zu unterst erbohrte Einheit 4 (älter als 14,600 B.P.) enthält ausschliesslich proglaziale Sedimente, die auf eine proximale Distanz des abschmelzenden Würmgletschers zur Zeit der Ablagerung dieser Einheit deuten. Die letzte Phase der Gletscher-Schmelze manifestiert sich in einer Sediment-Übergangszone (Einheit 3), die eine graduelle Sequenz zwischen rein proglazialen und nicht-glazialen Sedimenten enthält. Der Gehalt an Gletscherdetritus geht bis 13,900 auf etwa Null zurück. Es lässt sich jedoch mit Hilfe von Sauerstoff-Isotopenmessungen in benthischen Ostracoden zeigen, dass die Gletscherschmelze im Einzugsgebiet noch mindestens bis 13,000 B.P. andauerte. Insgesamt ist im Luganersee eine ausgezeichnete zeitliche Korrelation zum Zürichsee zu beobachten in Bezug auf rasche Veränderungen während des Holozäns und Spätglazials (Phase der Gletscherschmelze eingeschlossen), die auf grossräumige Klimaänderungen in Mitteleuropa hinweisen. Plötzliche Wechsel treten um 14,600, 10,000 und 3,800 B.P. auf.

CONTENTS

1. Introduction

The recent increase of greenhouse gases in the Earth's atmosphere has focused mankind's interests on forthcoming global climatic changes. Presently, there is a need for more precise climatic computer models and subsequently a growing need for reliable paleoclimatic data (particularly from the Last Glacial and Holocene) with which these models can be checked (e.g. Schneider 1987). For understanding the climate system we require documentation on how the ocean circulation patterns are coupled with climatic conditions on the continent, and how fast systems respond (Broecker 1987). Lake sediments are one of the best archives for the study of the climate response on the continents. A dense net of well-correlated regional paleoclimate information from lakes is therefore needed. The Younger Dryas event offers one critical opportunity for such an interregional comparison of data. This short dramatic cooling, which has been reconstructed from numerous lacustrine records in Europe between 10 and 11 Kyrs B.P., has been interpreted as a result of feedback processes from global deglaciation. The event is thought to be triggered by meltwater input from the Arctic ice cap which caused a sudden breakdown of North Atlantic deep water production (Duplessy et al. 1981, Broecker et al. 1985, Berger et al. 1987).

In Europe a large amount of data from lacustrine environments already exists (see Birks 1986 or Lang 1985 for reviews). Nevertheless, multidisciplinary studies with respect to specific time-windows and good regional correlation of past environmental changes are still rare since precise and efficient dating methods for small samples (e.g.

radiocarbon-dating with AMS) have only recently been available (Wölfli et al. 1983, Lister et al. 1984).

The high-resolution proxy-climate record is still lacking for lakes, in particular from the southern Alpine region. Regional palynological studies are reviewed by Schneider (1985). In contrast, our understanding of the climate history of Late Pleistocene and Holocene is relatively good for the northern perialpine region based on sedimentary and palynological research in various lake basins (Ammann et al. 1983, Lister 1988). The Alps are a key-region since they presently behave as a climate-divide between Central and Southern Europe. In addition, the Alps were covered by an ice cap during the Pleistocene glacial periods which reacted sensitively to global warming at the end of the last Glacial period (Lister 1988), and independent of the Scandinavian ice sheet.

The aim of this paper is to fill an important regional gap in Alpine paleolimnology. We focus on the sedimentary record of the southern perialpine Lake Lugano. The main goals are the description of a lithological and chronological standard profile for a large southern perialpine lake which will provide the framework for paleoclimatological interpretation and regional correlation. For example, one could argue that the timing of the last Alpine deglaciation, as reconstructed by Lister (1986) from northern perialpine Lake Zürich, was a function of local catchment as well as large-scale climatic patterns. Thus, it is necessary to determine whether major changes on both sides of the Alps are synchronous or diachronous. Our specific time-windows of interest are: the last Pleistocene deglaciation, the Pleistocene/Holocene transition (including the Younger Dryas), the early Holocene climate optimum and a possible climate deterioration at mid Holocene time.

This is the first paper of a series of planned publications dealing with various aspects of the sedimentary evolution of Lake Lugano. The interdisciplinary paleolimnological research began in 1982. We present results from chronological, sedimentological and geochemical investigations. The results from pollen analysis from the same standard core are described in a separate publication by Wick (1989).

2. Study area

Lake Lugano is a 35 km long fjord-shaped lake situated along the border between Switzerland and Italy. The catchment of 615 km^2 sits geographically in a triangle between the large southern Alpine drainage systems of Lake Como and Lake Maggiore. Lake Lugano is hydrologically isolated from Lake Como but drains into Lake Maggiore. The lake is surrounded by the Southern Alps, comprising Hercynian gneiss in the northwestern part and Mesozoic carbonates and cherts in the southeastern part of the catchment. The southern end of Lake Lugano cuts into intermediate to acidic volcanic rocks of Permian age that are located in the center of the drainage area.

Seismic data by Niessen (1987) suggest a pre-Pleistocene origin of the Lugano valley system best described as deep fluvial canyons related to the Messinian dessication of the Mediterranean Sea (Hsü et al. 1973, Finckh 1978). However, the present morphology and bathymetry shows an overprint by Pleistocene glaciations. During glacial times the catchment was ice-covered and linked by glacier-transfluencies to the main

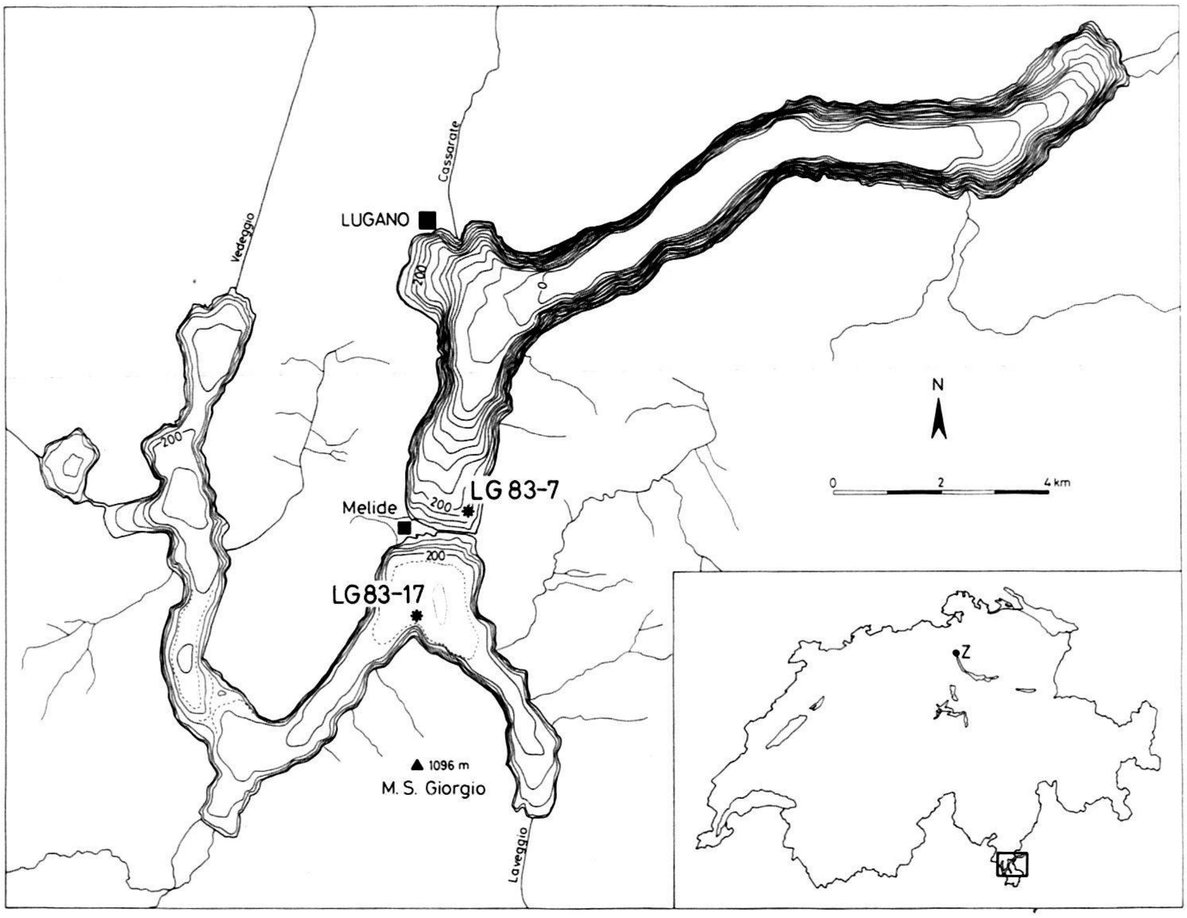

Fig. 1: Lake Lugano: Bathymetry and coring sites. The bathymetric lines are given above sea level. The equidistance is 20 m. The present mean annual lake level is at 271 m above sea level. Note the two subaqueous moraines (east of Melide and 5 km south-west of Melide, respectively) which define the separation of the Lake Lugano 'southern basin'. (The 'Z' in the map of Switzerland marks the location of Zürich).

southern Alpine glacier systems of Lake Como and Lake Maggiore valleys (JÄCKLI 1962, HANTKE 1983).

Lake Lugano is bathymetrically divided into subbasins by two large transversal retreat moraines of the last (= Würm) glaciation (Lecco-Melide stage according to HANTKE 1983). Because the most important streams enter the lake from the north, the moraine ridges function as traps for large detrital input into the southern basin (Melide basin, Fig. 1).

In order to obtain a complete sequence of Late Quaternary sediments, the area with slow sedimentation rates near the Melide-moraine was chosen for piston core analysis (Fig. 1). This paper concentrates on one site (LG 83-17) which functions as the stratigraphic type section for Lake Lugano. NIESSEN (1987) studied 4 piston cores from different localities in the southern basin (including LG 83-17). There is a good lithological correlation among these cores. The thickness of the Holocene sequence varies by only ±7%.

3. Methods

A coring site survey for undisturbed sediments was carried out using an ORE 3.5 KHz sediment-echosounder (NIESSEN 1987). For coring the ETH piston corer system (KELTS et al. 1986) was used. The positioning was done by ship radar. The piston corer over-penetrated into the mud for more than one meter resulting in a gap of unknown thickness. From our coring experience, it is assumed that the gap between the bottom of the short core and the top of the piston core section is about 20 cm (Fig. 4). Prior to core cutting, magnetic measurements of total intensity and declination of the horizontal component were carried out (natural remanent magnetization). The fluxgate of the magnetometer has a resolution of about 5 cm sediment thickness. The core sections were measured in 2-cm intervals. The methodology is described in detail by GIOVANOLI (1979a). For radiocarbon dating, terrestrial organic matter (seeds, leaves, woodpieces) were hand picked after sediment sieving. The organic matter was cleaned, dried, sealed into platinum capsules, and converted to graphite at 10 kbar and 1300 °C (for details see LISTER 1985). The quantitative analysis of radiocarbon isotopes was carried out by the ETH tandem accelerator mass spectrometer (AMS) (WÖLFLI et al. 1983). The results are presented as conventional Libby ^{14}C-dates. The calculation of bulk sedimentation rates is based on the following equation:

bulk acc. rate $= s \cdot p_s \cdot (1 - \Theta)$,

with: s = mean sedimentation rate between two datings; p_s = dry density (data obtained from NIESSEN 1987); Θ = porosity (BERNER 1971).

For the quantification of organic and inorganic carbon a 'coulomat analyzer' (Ströhlein) was used (HERRMANN & KNAKE 1973). The determination of sediment mineralogy was done by x-ray diffraction. The calculation of calcite/dolomite ratios is based on x-ray diffraction intensities (peak height correction according to COOK et al. 1975). Oxygen isotope measurements on hand picked ostracod valves were carried out using a VG Micromass 903 triple-collecting mass spectrometer. The procedure of sample preparation is described by LISTER (1985, 1988).

4. Results and discussion

4.1 Chronology and rates of sedimentation

Radiocarbon, pollen, and geomagnetic chronostratigraphy

The chronology of core LG 83-17 (Melide basin, standard-profile) is based primarily on ^{14}C-dating (see Table 1). Seven conventional radiocarbon ages were obtained by accelerator mass spectrometry (AMS; courtesy of Prof. WÖLFLI and coworkers, Inst. of Mittelenergie-Physik, ETH-Hönggerberg). The youngest radiocarbon age determination is 2,085 ± 95 years B.P. at 179 cm subbottom, the oldest 12,050 ± 130 years B.P. at 800 cm subbottom. When plotted against sediment depth the ^{14}C-dates exhibit a uniform increase with depth. This indicates that the sequence is essentially complete, and there is no major pulse of reworked older material from the slopes.

Six pollen ages, obtained from the same core (LG 83-17) on the basis of correlation with southern Alpine palynological type sections (WICK 1989) were added to the

sample code (1)	lab-no. ETH (2)	depth [cm]	$\delta^{13}C$ [°/oo]	^{14}C-age [yrs BP]	kind of material
17 *1* 59	0488	179	-23.6	2'085 +/- 95	piece of wood
17 *2* 89-95.5	0489	309	-25.5	2'655 +/- 100	80% piece of wood and bark, 20% leaves
17 *4* 10.5-13.5	0490	432.5	-20.6	3'615 +/- 105	twigs (90%) and leaves
17 *5* 7-10	0491	485	-19.0	4'420 +/- 130	50% leaves, 50% pieces of wood and bark
17 *6* 54-57	0492	633	-20.9	7'750 +/- 135	piece of wood (50%),40% leaves, 10% roots
17 7 0-4	0493	680	-25.2	8'980 +/- 130	piece of wood, ca.0.5 cm^3
17 *8* 18	0494	800	-21.6	12'050 +/- 130	twigs
7 *8* 5-7.5	0495	805	-23.0	13'070 +/- 165	90% pieces of wood, 10% seeds and leaves

Table 1: Results of AMS radiocarbon datings (courtesy of Prof. W. Wölfli and coworkers, 'Institut für Mittelenergiephysik', ETH Zürich.

depth-versus-age plot. The pollen ages agree well with interpolations of radiocarbon data. Discrepancies are equal or less than ± 100 years, and generally within the error of the ^{14}C results (Fig. 2).

Below 862 cm subbottom (13,000 years B.P., upper boundary of local pollen zone 2, see Wick 1989 for an interpretation), there is no accurate dating with radiocarbon nor pollen for lack of terrestrial organics. Moreover, Late Glacial southern Alpine pollenstratigraphy is only partly calibrated by ^{14}C (Schneider 1985), and pollen diagrams do not correlate well on a regional scale. Paleomagnetic parameters were thus measured in core LG 83-17 as an aid for regional correlation. Our argument is based on three results from geomagnetic research:

(1) worldwide, high resolution lacustrine records reveal paleomagnetic oscillations of ± 15 degrees for both inclination and declination which are interpreted by westdrift of the earth's non-dipole-field causing continuous clockwise looping of the Earth geomagnetic vector (see Creer & Tucholka 1983 for a review).

(2) declination and inclination features of lacustrine records show large time lags relative to their locations on the different continents but are more or less synchronous on a regional scale (e.g. Central-Europe). Thus, they can be valuable as a dating tool within certain regions (Creer et al. 1976, Thompson & Turner 1979).

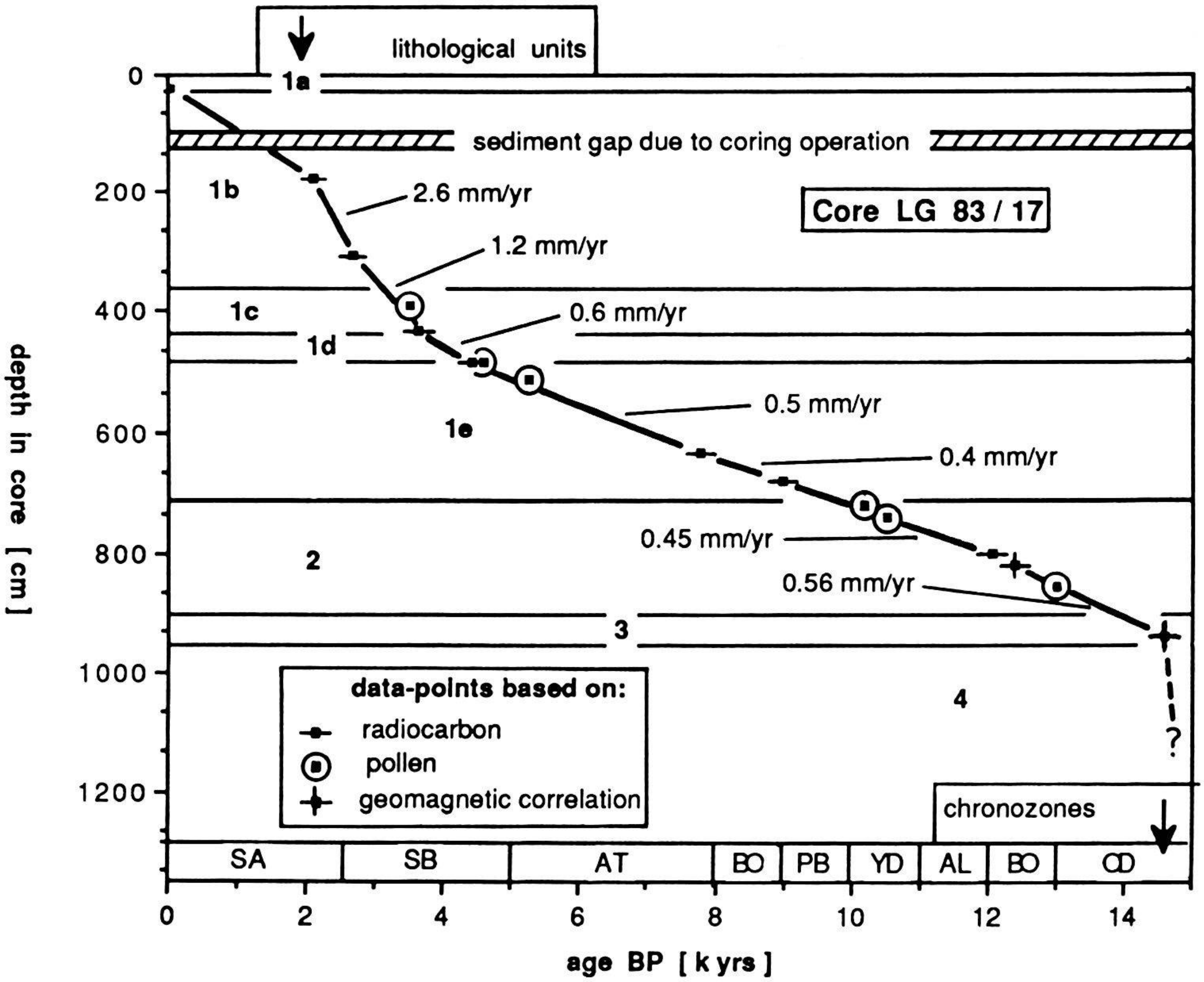

Fig. 2: Radiocarbon, pollen, and geomagnetic ages plotted versus sediment depth. The results of ^{14}C-measurements are listed in Table 1. The pollen results are discussed by Wick (1989), and the paleomagnetic data points are obtained from Figure 3. (Chronozones after Mangerud et al. 1974).

(3) Variations of paleodirections are available from other Swiss lake sequences (Thompson & Kelts 1974, Giovanoli 1979a/b, Creer et al. 1980), and show significant variability between about 14,600 and 10,000 B.P. The early Late Glacial sediments provided ideal preservation of magnetic vectors since there is little dilution of the fine-grained detrital remanent magnetization (DRM) by authigenic carbonates, and there is no significant overprint due to a post-sedimentary chemical remanent magnetization (CRM) from early diagenetic monosulfidic minerals (Giovanoli 1979a, Creer et al. 1980). Moreover, Giovanoli (1979a) has clearly shown from the Late Glacial record of Lake Zürich that the oscillations in declination are stable enough to be reproducable even prior to laboratory cleaning of the chemical component of remanent magnetization.

A distinct record showing declination fluctuations was obtained from the Late Glacial sediments of Lake Lugano core LG 83-17. The results are presented in Figure 3 and 5 and shown in comparison to published declination data from Lake Zürich. According to the results from Giovanoli (1979a) and Creer (1981) there is no doubt that the oscillations in the sedimentary record of Lake Lugano can also be attributed to secular variations of the earth geomagnetic vector, and are therefore synchronous to those from other perialpine lakes because of the relative small lateral distance between northern and southern Switzerland (300–400 km).

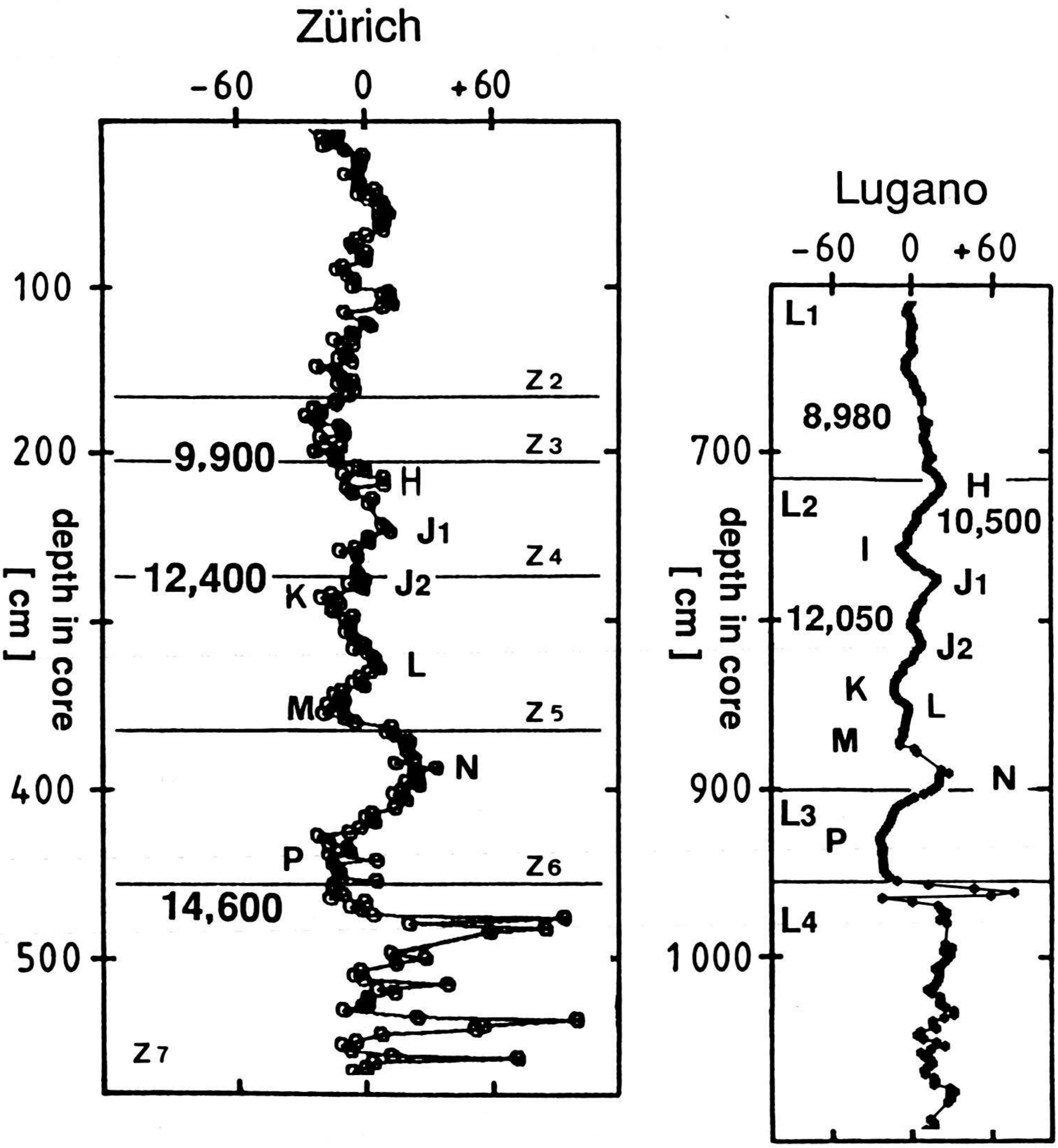

Fig. 3: Correlation of paleomagnetic declination measurements from Lake Zürich (Giovanoli 1979a) and Lake Lugano (this paper, detail from Fig. 5). The lithological changes of the Lake Zürich record were radiocarbon dated (AMS) by Lister (1985).

Consequently, if the ages of specific oscillations are known, and both curves can be linked together with radiocarbon data, then the declination records function as potential dating tools.

The Late Glacial sequence of Lake Zürich was ^{14}C-dated by LISTER (1985, 1988). On the basis of lithological correlation of marker horizons in the sedimentary record of Lake Zürich, GIOVANOLI (pers. comm.) matched the radiocarbon dated sequence and the declination record (Fig. 3). Declination features were labeled according to earlier records from Central European lakes (CREER 1981). As a result, level H in Lake Zürich is somewhat older than 9,900 ± 150 B.P., level J1 has an age of 12,400 ± 250, and level P is about 14,600 ± 250 B.P. old.

The Late Glacial declination fluctuations in the Lake Lugano sequence can be labeled in a similar way (Fig. 3). The number of recognizable levels is correlative with Lake Zürich. Thus, it is assumed that the changes in declination in both lakes are synchronous. This is reasonable because in Lake Lugano the radiocarbon age of 12,000 ± 250 (800 cm subbottom) occurs only a few cm above a positive declination swing suggesting that the underlying oscillation maximum is correlated to level J1 in Lake Zürich (12,400 B.P.). There is strong evidence that this assumption is correct because the youngest observable level in Lake Lugano would then be H (725 cm subbottom), which is, similar to that of Lake Zürich, somewhat older than 8.980 (680 cm subbottom) and somewhat younger than 10.500 (Younger Dryas, 740 cm subbottom, WICK 1989). Consequently, the oldest level P in Lake Lugano is synchronous to level P in Lake Zürich, and thus dated as 14,600 ± 250 B.P. (Fig. 3). This is consistent with the oldest pollen dating (13,000 B.P.) from the Lake Lugano record since the data point on the age versus depth graph lies exactly on the interpolation line between the two magnetic ages (Fig. 2).

Rates of sedimentation

A combination of all chronological data (Fig. 2) indicates four main periods of high or low bulk sedimentation rates with transition zones. The age-versus-depth curve is steep indicating high sedimentation rates between 2,000 and 3,800 B.P. Bulk maximum sedimentation rates range as high as 2.6 mm/yr. Above and below this period, rates are generally lower. The lowest values of 0.45 mm/yr occur between 7,700 and 12,400 B.P. Sediments older than 12,400 B.P. again exhibit higher average rates of about 0.56 mm/yr. The plot of sediment accumulation rates versus depth in core in Figure 5 reveals the same general trend but is corrected for compaction. The decrease in sedimentation rate after 2,000 B.P. remains uncertain because the calculation is based on the assumption that the observed core-gap between short and piston core is not larger than 20 cm (Fig. 4).

4.2. Lithological units, paleolimnological implications, and paleoclimate

The 12.80 m long core LG 83-17 was subdivided into 4 main units primarily on the basis of sedimentologic characteristics. In addition, the unit boundaries can be identified by geochemical parameters, such as: organic/inorganic carbon, water content, geomagnetic features (horizontal component of intensity and declination). The litho-

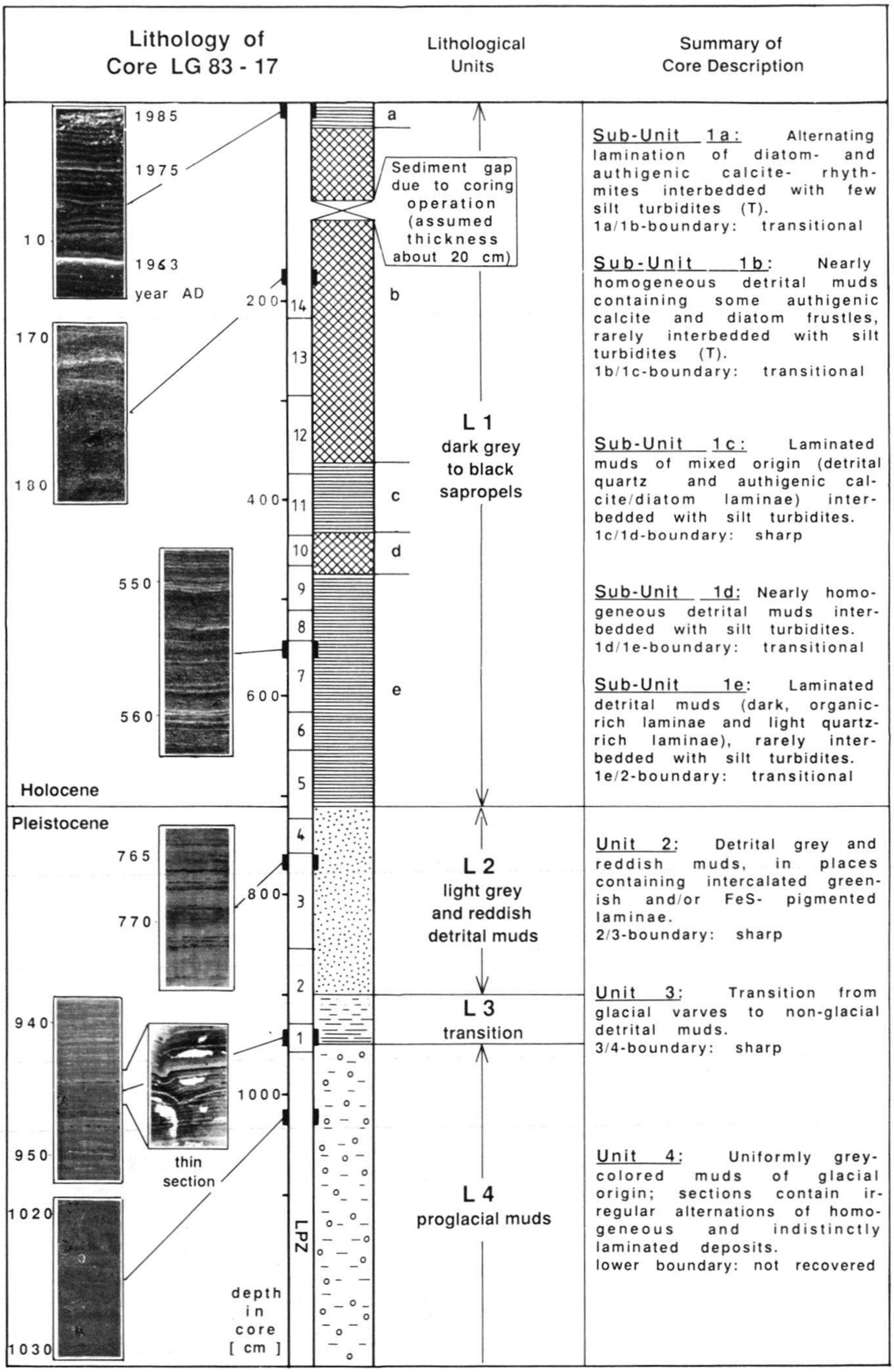

Fig. 4: Summary of core description (LG 83-17, southern basin). Local pollen zones (LPZ) are described by Wick (1989).

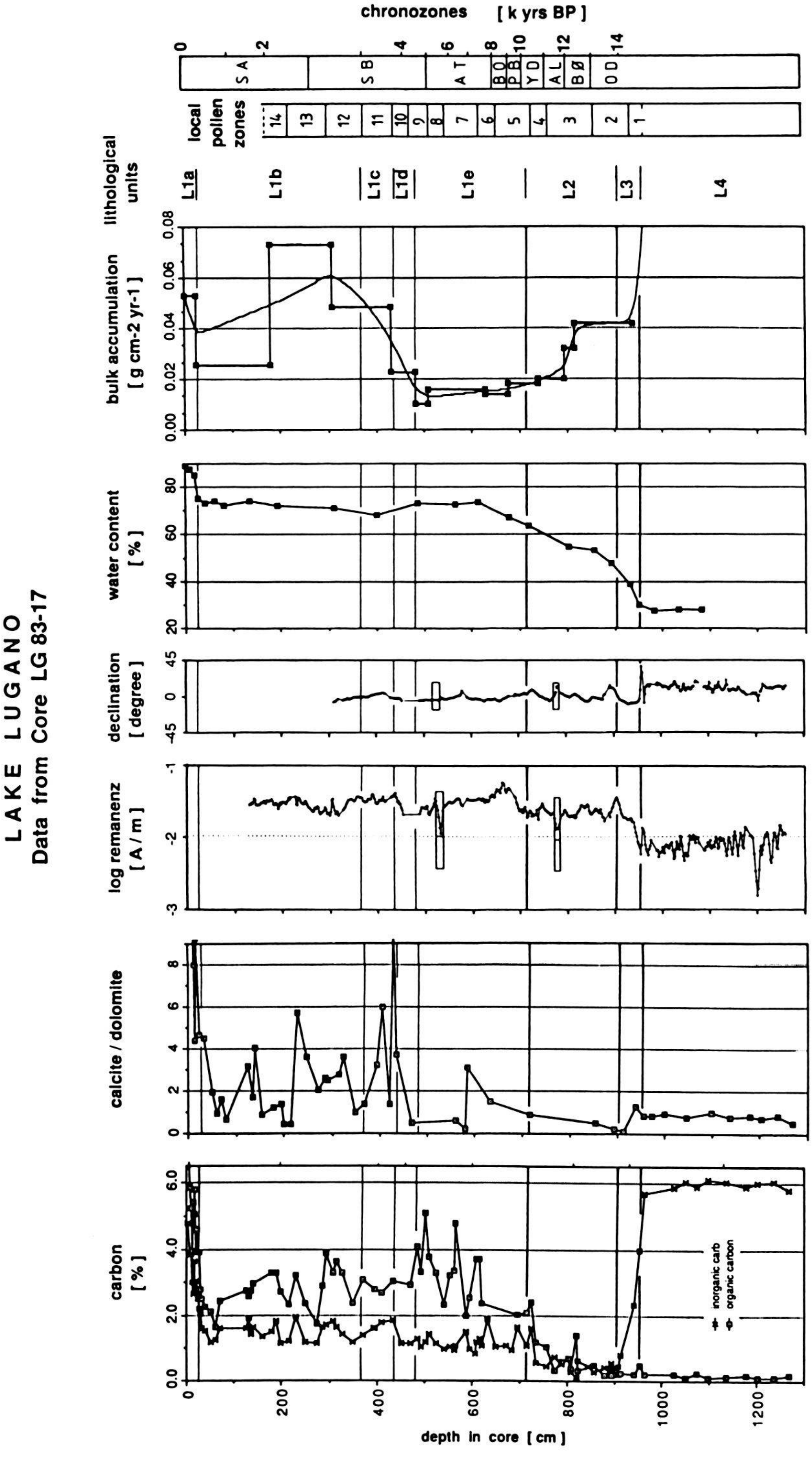

Fig. 5: Results of sediment parameter measured in core LG 83-17. (Local pollen zones after Wick 1989; chronozones are after Mangerud et al. 1974 and based on interpolation of data points in Fig. 2). The rectangles in the records of remanence and declination mark positions with major turbidite deposits.

logical description is summarized in Figure 4. The results of quantitative sediment analyses are plotted in Figure 5.

Unit 1: Laminated and homogenous sapropels

Characteristics: The upper part of the core down to 713 cm subbottom consist of intensively FeS-pigmented, dark grey to black organic rich sediments with average organic carbon contents of 2–3% interbedded with scattered mm- to cm-thick quartz turbidites. The lower boundary of this unit can be dated on the basis of interpolation of radiocarbon and pollen data (Fig. 2) to approximately 10,000 B.P. (beginning of the Holocene). The sequence is characterized on the basis of color and organic carbon content (> 2%) as sapropels (unit 1).

In detail, unit 1 shows cyclic changes in bedding structure somewhere between the two end-members 'homogenous' and 'laminated' (Fig. 4). Moreover, the dating information revealed minimum bulk sedimentation rates in the lower part and maximum rates in the middle part. The high-resolution character of unit 1 (and subsequently the Holocene paleolimnology) is complex and needs a more detailed examination. Based on the lamination patterns, unit 1 can be further subdivided into 5 subunits 'a' to 'e'. The character of Holocene sapropels is summarized in Table 2. In terms of unit thicknesses, unit 1e and unit 1b dominate the Holocene sequence (Figs. 4, 5). The other units are notably thinner and have more the character of transition zones.

The uppermost *subunit 1a* (0–35 cm, 0–55 yrs B.P.) differs from the rest of the Holocene sequence. The sediments are rhythmically laminated with 55 authochtonous diatom/calcite varve-couplets intercalated with 4 quartzose turbidites. Organic carbon contents range up to 8.2% and calcite/dolomite ratios up to 23.7. The inorganic carbon content averages about 5%, which indicates about 42% of mainly authigenic calcite.

The *subunit 1b* (35–365 cm, 55–3,000 B.P.) is more homogenous than laminated. The sediments are petrographically dominated by detrital muds as indicated by an abundance of quartz, low average inorganic carbon contents of 1.5% (ca. 12% carbonate content) and reduced calcite/dolomite ratios (2–6). Visual inspection of organic matter indicates a mixed origin of terrestrial- and planctic-derived input. Most notable in subunit 1b is the relative high sedimentation rate of up to 2.6 mm/yr. According to the mineral composition of the sediments, the input of settling particles is mainly from allochthonous sources.

Subunit 1c (365–435 cm, 3,000–3,800 B.P.) shows similarities to 1a, particulary to the lower part of subunit 1a near the transition to 1b. The subunit 1c is laminated although not as perfectly as 1a. Despite the dominance of detrital muds in 1c, autochthonous components are more common than in other Holocene units (except the upper part of 1a) as indicated by relatively high calcite/dolomite ratios. Chronostratigraphic data shows a gradient in bulk sedimentation rates from low (subunit 1d) to high (subunit 1b).

Subunit 1d (435–480 cm, 3800–4300 B.P.) is again more homogeneous and similar to subunit 1b. It differs from 1b by the slightly lower calcite/dolomite ratios and a lower bulk sedimentation rate indicating lower input rates of autochthonous sediments.

The lowermost Holocene *subunit 1e* (480–713 cm, 4,300–10,000 B.P.) is again laminated and thus comparable with subunit 1a. In terms of all other parameters, however, the two subunits differ significantly. In contrast to subunit 1a, subunit 1e is characterized by low calice dolomite ratios (<1) and minimum sedimentation rates indicating low bulk sediment input combined with low proportions of authigenic calcite in the sediments. The organic matter composition is visually dominated by allochthonous debris.

In summary, the characteristics of unit 1 sapropels show, depite a relative uniform high organic carbon content, a distinct cyclicity among subunits. The complexities within unit 1 document shifts in processes of Holocene sapropel formation in Lake Lugano.

sapropel subunits	sediment texture	autochthonous compounds	calcite / dolomite ratios	bioturbation, bottom water oxygen	lake productivity	paleolimnology oxygen	approximate age (yrs BP)	bulk accumulation rates
1a	laminated	dominant	very high	very low or absent	very high (2nd production maximum)	anthropogenic eutrophication	55 to present	medium
1b	homogeneous	minor, but notable	medium	increased	medium	increased lake circulation ?	3,000 to 55	high
1c	laminated	increased	high	low, nearly absent	increased, sudden change at 1c/1d boundary (1st production max.)	accelerated nutrient input due to hinterland erosion	3,800 to 3,000	medium
1d	homogeneous	minor, but notable	medium	increased	low	increased lake circulation, cooler	4,400 to 3,800	low
1e	laminarted	nearly absent, only traces	low	low, nearly absent	very low	reduced circulation "stagnant bottom water"	10,000 to 4,400	very low

Table 2: Summary of characteristics of Holocene sapropels (unit L1, 10,000 B.P. to present).

Interpretation: Undisturbed laminations in sapropelic sediments are commonly an indicator of limited sediment bioturbation which in turn is mainly controlled by low oxygen concentration in bottom waters. In contrast, higher bottom water oxygen leads to homogenization of sediments by bottom dwellers (e.g. Rhodes 1974). According to this model, the cyclic changes in the Holocene of Lake Lugano can be explained by long-term variations in bottom water oxygen. Consequently, the period with laminated sediments from early Holocene until 4,300 B.P. represents a low-oxygen deep-water environment. Younger periods of the Holocene were generally characterized by higher bottom-water oxygen concentrations with bioturbation in subunits 1b and 1d. The latter trend is interrupted by two relatively short periods with more intensively laminated sediments between 3,000 and 3,800 B.P. and the last 55 years. These are interpreted as shifts to increased bottom-water anoxia.

Low oxygen content in deep waters can result from either a high primary production rate and subsequent increased oxygen utilization due to decay of organic matter below the thermocline or from limited current circulation and subsequently slow renewal rates for oxygen in bottom waters (Demaison & Moore 1980). Which one controlled the cyclic changes in bottom-water oxygen in Holocene Lake Lugano?

The diatom/calcite laminae of subunit 1a are typical deposits in eutrophic lakes as described by Kelts & Hsü (1978) or Niessen & Sturm (1987). Since Lake Lugano is presently a highly productive lake (primary production of 460 g C m^{-2} yr^{-1}, Ruffli 1982) with one annual turn over, the subunit 1a sediments provide a modern model for sapropel formation due to high productivity in a monomictic lake. The high productivity is recorded in the sediments by high calcite/dolomite ratios as well as organic carbon contents. High production rate cause more calcite to precipitate in surface waters, followed by increased sedimentation of authigenic calcite which dilutes detrital dolomite in the sediments.

From this, it appears that the productivity was generally lower in earlier Holocene times than at present because none of the subunits 1b–e exhibit high values for calcite/dolomite and organic carbon. On the other hand, it seems likely that those earlier laminated sapropels with notably increased calcite/dolomite ratios, such as in subunit 1c and partly 1b, were deposited under conditions with greater productivity compared with the average production level during the entire Holocene. In contrast, when laminated sediments are low in autochthonous compounds (such as the early Holocene subunit 1e) then they are more characteristic for a very low productivity environment with physically stagnant bottom waters.

It has to be pointed out that the interpretation of paleoproductivity is based on the assumption that calcite/dolomite ratios in the sediments are mainly controlled by authigenic calcite fluxes relative to allochthonous dolomite input. However, Finger et al. (1984) argued that low calcite/dolomite ratios may also be caused by carbonate dissolution at the lake bottom if sedimentation rates are low. Their conclusion, drawn from very low calcite/dolomite ratios in the Late Glacial FeS-pigmented sediments from Lake Zürich, is that the input of organic matter enriched the deep water environment in biogenic CO_2, and subsequently caused a selective dissolution of authigenic calcite. In fact, the Holocene sediments of Lake Lugano are rich in organic matter. Calcite dissolution is likely. Nevertheless, it is evident from subunit 1a, that the input of organic matter shows a positive correlation with calcite/dolomite ratios. Preservation of authigenic calcite is possible, despite a high input of organic matter into the deep water environment. We conclude that the main process controlling calcite/dolomite ratios in the Holocene record of Lake Lugano is the productivity-induced flux of authigenic calcite to the lake bottom. Carbonate dissolution may occur, but seems to be minor compared with effects of changing productivity. This is consistent with NIESSEN's (1987) results which show a positive correlation between calcite/dolomite ratios and the content of diatom silica and algae pigments in all sediment-units of Lake Lugano.

Implications for paleoclimate: The Holocene paleolimnological evolution of Lake Lugano is characterized by two main features: First, based on sedimentary structures, there is a general tendency from low bottom water oxygen conditions in earlier Holocene (10,000 to 4,300 B.P.) towards a more oxygenated environment in younger Holocene times, interrupted by the relatively short periods of subunit 1c (3,800 to 3,000 B.P.) and the uppermost part of subunit 1a. Secondly there is a general trend from low bulk sedimentation rates to higher input rates of both allochthonous and autochthonous materials in younger Holocene time (from about 4,300 B.P. on).

The changes in sedimentation rates are mainly due to increased detrital input since inorganic carbon remains low for the whole Holocene indicating a minor input of calcite. However, if the increased sediment input after 4,300 B.P. derived entirely from allochtonous sources, a decrease in the calcite/dolomite ratios should be expected in younger sediments due to sediment dilution of authigenic calcite by detrital material. The opposite is observed, which is an indication for at least a small shift towards more autochthonous compounds along with higher input rates from terrestrial sources after 4,300 B.P. One possible explanation could be described in a scenario where higher productivity in the aqueous environment follows as a response to increased runoff rates in the hinterland. The reason for accelerated catchment erosion could be either deforestation by neolithic to bronze age settlers or by changes in rainfall rates due to climatic shifts.

It seems contradictory that a general increase in productivity after 4,300 B.P. parallels an increase in bottom water oxygen as concluded from sediment structures in subunits 1d and 1b. One explanation could be, that declining annual heat input from the atmosphere to the lake could have favoured a more vigorous lake-water circulation or higher seasonal wind stress. Subsequently, this would inject oxygen to the deepest zone of the basin as a compensation for the higher oxygen demand in bottom waters derived from the increased productivity. Productivity could have been increased as a result of climatic changes and/or by early human modifications in the catchment. We have no conclusive evidence but the increased bottom water oxygen tends to support a theory of a cooling since 4,300 B.P., because anthropogenic influences may have changed the nutrient budget of the lake but less likely the wind-driven circulation.

With respect to the present situation in Lake Lugano, the two relatively short periods with laminations and high autochthonous compounds since 4,300 B.P. (subunits 1a and 1c) are caused by productivity and respiration levels too high for an efficient oxygen supply to the bottom water. The backshifts to anoxia at the lake bottom demonstrates the sensitivity of the Lake Lugano environment, which clearly responsed even relatively small changes in nutrient input.

In summary, the cyclicity in Lake Lugano Holocene sapropels is interpreted as productivity and circulation shifts controlled by subtle climate variation. The laminations in subunit 1e (10,000 to 4,300 B.P.) are due to sluggisch water circulation rather than productivity. This is consistent with other patterns for the Holocene climate optimum interval. Southern Alpine glacier fluctuations indicate summer temperatures up to 4 degrees higher during the Atlanticum compared with present day conditions (PORTER & OROMBELLI 1985). The Lake Lugano record demonstrates that a warmer climate with lower terrestrial run-off rates results in lower lake-productivity levels.

At the beginning of subunit 1d, the change to more bioturbation, higher bulk sedimentation rates and increased autochthonous sediments reflects a cooling in climate as well as soil erosion and higher lake productivity. The latter changes are perhaps the result of an increase of heavy rainfall and wind events. In subunit 1c (3,800–3,000 B.P.) the laminations are most likely productivity-induced since autochthonous compounds reach levels similar to those of the recent eutrophication level. During this period, bulk sedimentation rates and productivity tracers indicate a very high input from terrestrial runoff for both dissolved nutrients and debris. Thus, subunit 1c indicates a mid Hololcene production spike that occurred shortly after 3,800 B.P. After 3,000 B.P. (subunit 1b) homogeneous structures reflect increased bioturbation which is linked either to a further cooling of climate and more vigorous circulation or by a slight decrease in productivity as suggested by fewer autochthonous components in comparison with subunit 1c. Finally, laminations in subunit 1a are caused exclusively by anthropogenic eutrophication because the lake circulation has not changed significantly during this century.

Unit 2: Colored non-glacial muds (grey, reddish, greenish and FeS-laminae)

Characteristics: Unit L2 sediments consist almost entirely of detrital muds deposited between about 14,000 and 10,000 B.P. (Oldest Dryas to Younger Dryas). The unit comprises a uniform alternation of grey, reddish, greenish and FeS-pigmented laminae intercalated by a few cm-thick silt turbidites. At 870 cm subbottom, a 1 cm diameter dropstone was found in the mud-matrix. By interpolation of ages, the stone was deposited at about 13,200 B.P. The mineralogy of unit 2 sediments is dominated by quartz, feldspars, layered silicates and goethite. The carbonate content is very low (average inorganic carbon content of only 0.5 to 1%). The sediments in unit 2 differ from the Holocene sapropels by their generally brighter color (punctuated by the FeS-laminae), by significantly lower organic carbon contents (averaging 0.5% in comparison to 2–3% in the sapropels) and by lower magnetic intensities.

Interpretation: The laminations in unit 2 are mainly the result of sediment input from different local runoff sources. Reddish and greenish colors are typical for Permian Rhyolites surrounding part of the southern Lake Lugano basin and/or soil weathering in the catchment. Grey may be derived from Liassic cherty limestone and the few black-pigmented laminae derive from unstable sulfides associated with short intervals with more organic rich laminae (from visual inspection dominated by mostly allochthonous organic debris). The sediments have non-glacial origins because they lack carbonate-rich (dolomite and calcite) components which characterize the glacial clays and silts of the underlying units 3 and 4. Nevertheless, the occurrence of a dropstone is evidence for local or occasional freezing of lake water and drifting ice.

Implications for paleoclimate: The predominance of bright sediment colors and the stability of goethite indicates a generally oxidizing environment on the lake bottom (e.g. Berner 1981). This suggests a well mixed lake and/or very low fluxes of organic matter to the lake bottom during the Late Glacial. Because productivity indicators such as calcite/dolomite ratios differ little from the oldest Holocene subunit 1e, the primary production rate is assumed to be as low as that of early Holocene. In addition to low input of authigenic calcite through the water column, a further reduction of the content of inorganic carbon in the sediments by selective dissolution of calcite at the sediment surface is likely. Vigorous lake mixing before 10,000 B.P. was probably the result of longer winters or stronger winds which maintained a continuously oxic deep water environment most of the time.

The deposition of reddish muds and the occurrence of goethite in unit 2 may indicate semi-arid weathering conditions over the catchment similar to modern Mediterranean terrains with typical 'terra-rossa' soils. Thus, the indicators for both, warm and cold conditions during the Late Glacial may be a result of local climate with a larger seasonality signal. This is consistent with the pollen record that indicates both widespread pine forests in the Bölling-Alleröd, and pollen of some conifer species, such as *ephedra,* typical for cooler temperatures than present (Wick 1989).

The sporadic intervals of increased anoxia, indicated by mm-thin FeS-pigmented laminae may be the result of periods with slightly higher organic matter fluxes (mostly allochthonous from visual inspection) or a reduced lake circulation similar to that of the early Holocene climate optimum situation (subunit 1e).

In spite of pollen indicators which clearly show a sudden cooling during the Younger Dryas (core LG 83-17, 740 cm subbottom, Wick 1989, there is no sedimentological evidence for a climate deterioration at the end of the Late Glacial period. It seems reasonable to assume that the depositional environment of Lake Lugano before 10,000 B.P. was not sensitive enough to record the Younger Dryas climatic shift. On the other hand, the beginning of sapropel deposition in Lake Lugano at 10,000 B.P. can be taken as evidence for a sudden and rapid warming of the climate at the end of the Younger Dryas period (beginning of the Holocene).

Unit 3: Transition from glacial to non-glacial muds

Characteristics: This sequence comprises bright yellowish to reddish detrital muds with regular and irregular rhythmic laminations. The lowermost part of unit 3 is built up of a rhythmic alternation of distinctive silt laminae with overlying dark grey clay laminae (Fig. 4). These are similar to varves in modern proglacial lakes. There are sharp transitions within one varve-cycle for both the contact between silt and clay and vice versa. A total number of 85 couplets with variable thicknesses between 0.2 and 1.5 mm were counted in the lowermost 15 cm of unit 3.

Thicknesses of rhythmic laminations decrease rapidly above 938 cm subbottom. The lithology changes with a transition to a muddy matrix interrupted by a few mm-thick silt turbidites in the upper part of unit 3. The first occurrence of a FeS-pigmented laminae at 904 cm subbottom marks the boundary to unit 2. The upward thinning of varve laminae in unit 3 is accompanied by a significant decrease in inorganic carbon (calcite/dolomite ratio: 1) from 5% to 0.5% and an increase in magnetic intensity (Fig. 5).

Interpretation: Unit 3 forms a transitional sequence from endmember proglacial muds (about 14,600 B.P.) to purely non-glacial muds derived from local catchment runoff sources (about 13,900 B.P.). The content of carbonates can be taken as an indication for the amount of glacial flour in the sediments. This is so because the eastern Würm-glacier eroded preferentially into Mesozoic carbonate rocks in the eastern part of the catchment. Consequently, glacial silt contains a higher amount of calcite and dolomite compared with sediments derived from local catchment runoff in the southern basin. This is documented by an average inorganic carbon content of 6% (equivalent to about 48% carbonate) in the purely glacial sediments of the underlying unit 4 (Fig. 5). Thus, the content of 5% inorganic carbon at the basis of unit 3 indicates a glacial mud content of about 80%. Glacially-derived laminae decline upwards to almost nil in the lower part of unit 3. Any selective dissolution of calcite can be ruled out because the calcite/dolomite ratios remain uniform throughout units 3 and 4.

In addition, the laminae couplets in the lowermost part of unit 3 are texturally identical to glacial varves described from modern proglacial lakes (e.g. Leonard 1986). According to an interpretation by Zhao et al. (1983) or Leonard (1986), the repetition of the darker clay layer indicates a regular break in the input of coarser sediment that occurs during winter time when the lake is frozen. Thus, the regular occurrence of clay laminae interbedded with silt layers can be taken as evidence for both, annual winter freezing of the lake and subsequently annual repetition of laminae couplets (classical glacial varves as described by de Geer 1912). Varve counting for the lower part of unit 3 give a mean sedimentation rate of about 1.7 mm per year (equivalent to a bulk accumulation of 1.6 g cm^{-2} yr^{-1}, Fig. 5). This is about a factor of 4 higher than the average accumulation rate in the lower part of the overlying unit 2.

Implications for paleoclimate: The transition character of unit 3 is the result of the rapid deglaciation of the Lake Lugano catchment. The sedimentary record provides two controls of Late Glacial paleoclimate models. Firstly, the decrease in glacial mud from nearly 100% to almost zero lasted 700 years (14,600 to 13,900 B.P.). Within that interval, glaciers must have retreated rapidly to at least the northern margin of the basin. Almost no glacial muds were deposited in the southern basin after 13,900 B.P. Secondly, the occurrence of glacial varves in the lower part of unit 3 indicate cold winters with an annual freeze-over of the lake until about 14,500 B.P. Thereafter, only selective freezes occurred until about 13,200 B.P. as indicated by a dropstone in unit 2. Since then, there is no further sedimentary evidence for the lake freezing. Both, deglaciation and decrease of winter lake freezes suggest a rapid warming completed by the Oldest Dryas/Bölling boundary (13,000 B.P.).

Unit 4: Irregular proglacial muds

Characteristics: Unit 4 is the lowermost cored unit of Lake Lugano. The cores contain about 4 m of this sequence but the total thickness is about 35 m based on seismic interpretation by Niessen (1987).

The sediments comprise massive, uniform, colored muds of glacial origin. The content of clay-sized particles is over 30% (Niessen 1987). The sediment concentration of inorganic carbon is about 6%, and the calcite/dolomite ratios are about 1 (Fig. 5), both with little variation downcore. Texturally, unit 4 is irregular, built up by homogeneous sections interbedded in mm to cm scale with indistinctly laminated sections and sand turbidites. In contrast to the glacial varves of unit 3, there is no basin-wide correlation of particular textural features in unit 4 possible (NIESSEN 1987).

Interpretation: Unit 4 sediments are interpreted as glacial muds based on the sediment structure, lack of organic carbon and high carbonate contents (see discussion above). A precise image of the depositional environment of unit 4 is difficult to assess. The general absence of distinct clay rich winter-laminae as described in the overlying unit 3 precludes any determination of annual sediment input or rates of sedimentation. Nevertheless, it is reasonable to assume that the glacier position relative to the southern basin was more proximal compared to the situation recorded in the overlying unit 3 possibly resulting in higher sedimentation rates and stronger bottom currents at the time of deposition of unit 4. This idea is supported by the lack of any regular oscillations in declination features below 953 cm subbottom (Fig. 3, 5). Since bioturbation and overprint by CRM is absent in unit 4, it is likely that the irregular pattern of unit 4 DRM is controlled by forced allignment of magnetic particles rather than long-term geomagnetic variations of the geomagnetic field. In such a scenario it is possible that thin clay-rich winter laminae were deposited, but then eroded and reworked during sommer melting periods with intensive sediment input and turbid bottom waters. Hence, the structures of unit 4 are interpreted as a result of strong, irregular pulses of summer meltwater input in combination with local bottom water currents in a proximal proglacial lake environment.

In terms of analogy to modern systems, the interpretation of the change in lithology between Lake Lugano units 3 and 4 as a function of distance to the glacier is in agreement with observations from a Canadian glacier lake system. LEONARD (1986) describes irregular structures and high sedimentation rates in the more proximal part, and preservation of typical varves in the more distal part of a glacio-lacustrine environment.

Implications for paleoclimate: There are two important paleoclimatic conclusions that can be drawn from the lithology of unit 4. (1) The distinct end of unit 4 shortly before 14,600 B.P. marks a rapid change in the deglaciation regime and a sudden retreat of the glacier towards the upper end of the Lake Lugano catchment. The changes occurred within a few decades or even less. (2) The absence of dropstones and deformation structures indicates that the location of the glacier was somewhere in the northern basin of Lake Lugano at time of deposition of unit 4. This suggest that the deglaciation of the whole lake basin was already well under way before 14,600 B.P.

4.3 Discussion of deglaciation chronology

The deglaciation of a whole Alpine lake catchment is difficult to assess from only lithological parameters. This is particularly the case for lakes and catchments with several lake-basins upstream that could function as trap basins for meltwater sediments. Thus, the end of input of glacial derived meltwater sediments into the southern basin of Lake Lugano at about 13,900 B.P. may not be synchronous with the end of the whole catchment deglaciation because the northern basin could have trapped glacial flour for an uncertain period of time.

In order to evaluate the end of whole catchment deglaciation of Lake Zürich, LISTER (1985, 1988 and 1989) used a stable oxygen isotope record from the shell material of Late Glacial benthic ostacods and pelecypods as a geochemical tracer. His evidence is based on two arguments.

(1) $\delta^{18}O$ in deep water carbonate shells (below the thermocline) sensitively reflect changes in lake water composition and hence catchment runoff. No temperature dependant isotope fractionation occurs on the lake bottom due to uniform temperatures (4 °C = highest density of water).

(2) According to global as well as regional $\delta^{18}O$-values measured in precipitation (DANSGAARD 1964, SIEGENTHALER & OESCHGER 1980), glacial meltwater from the last glaciation must be isotopically lighter due to regional altitude and global climate patterns in comparison to the Late Glacial and Holocene precipitation in the catchment. LISTER (1988) recognized a sudden shift in the carbonate shells of nearly 4‰ between 12,800 and 12,400 B.P. and interpreted the isotope results as evidence for the completed deglaciation of the whole Lake Zürich catchment.

core/depth	unit type	ages BP	ostracod species	$\delta^{18}O$ (PDB)
17/ 38	1b	233*	Candona candida	-3.8
17/ 58	1b	500*	""	-3.8
17/ 68	1b	633*	""	-4.1
17/ 78	1b	733*	""	-3.5
17/143	1b	1.633*	""	-3.8
17/170	1b	2.000*	""	-3.8
17/214	1b	2.267*	""	-3.7
17/247	1b	2.413*	""	-4.0
17/286.5	1b	2.587*	""	-3.9
17/314	1b	2.655*	""	-3.9
17/348.5	1b	2.967*	""	-3.9
17/369.5	1c	3.133*	""	-3.8
17/434	1c	3.615*	""	-3.6
17/442.5	1d	3.800*	""	-3.8
17/633	1e	7.750*	""	-4.2
7/798	2	13.040 +/- 160	Limnocythere inopinata	-6.6
7/799	2	13.120@	""	-7.2
7/800.5	2	13.200@	""	-7.0

* interpolation (Fig.2)
@ extrapolation (estimated on the basis of constant mean sedimentation rates)
Water depth at coring site LG 83-17 and LG 83-7 is 87m and 42m, respectively.

Table 3: Results of stable isotope mass spectrometry on ostracod valves from Lake Lugano cores LG 83-7 and LG 83-17.

In Lake Lugano carbonate shells from benthic deep water ostracods were obtained from two cores LG 83-7 and LG 83-17 (Fig. 1). Depth in core, age of samples, ostracod species, and $\delta^{18}O$ results from the shells are summarized in Table 3. The total number of $\delta^{18}O$ results from both cores are plotted versus age in order to present a preliminary deep water isotope stratigraphy from a southern perialpine lake (Fig. 6). However, the Lugano record has one serious problem arising from the fact that there are very few well-preserved carbonate shells in the sediments, particularly in the Late Glacial and early Holocene part of the sequence. Thus, only 4 ostracod samples have yet been isotopically analyzed for the whole time span between 13,000 and 4,000 B.P., and because of these large gaps the isotope data may be taken only as a reflection of conditions in different time windows.

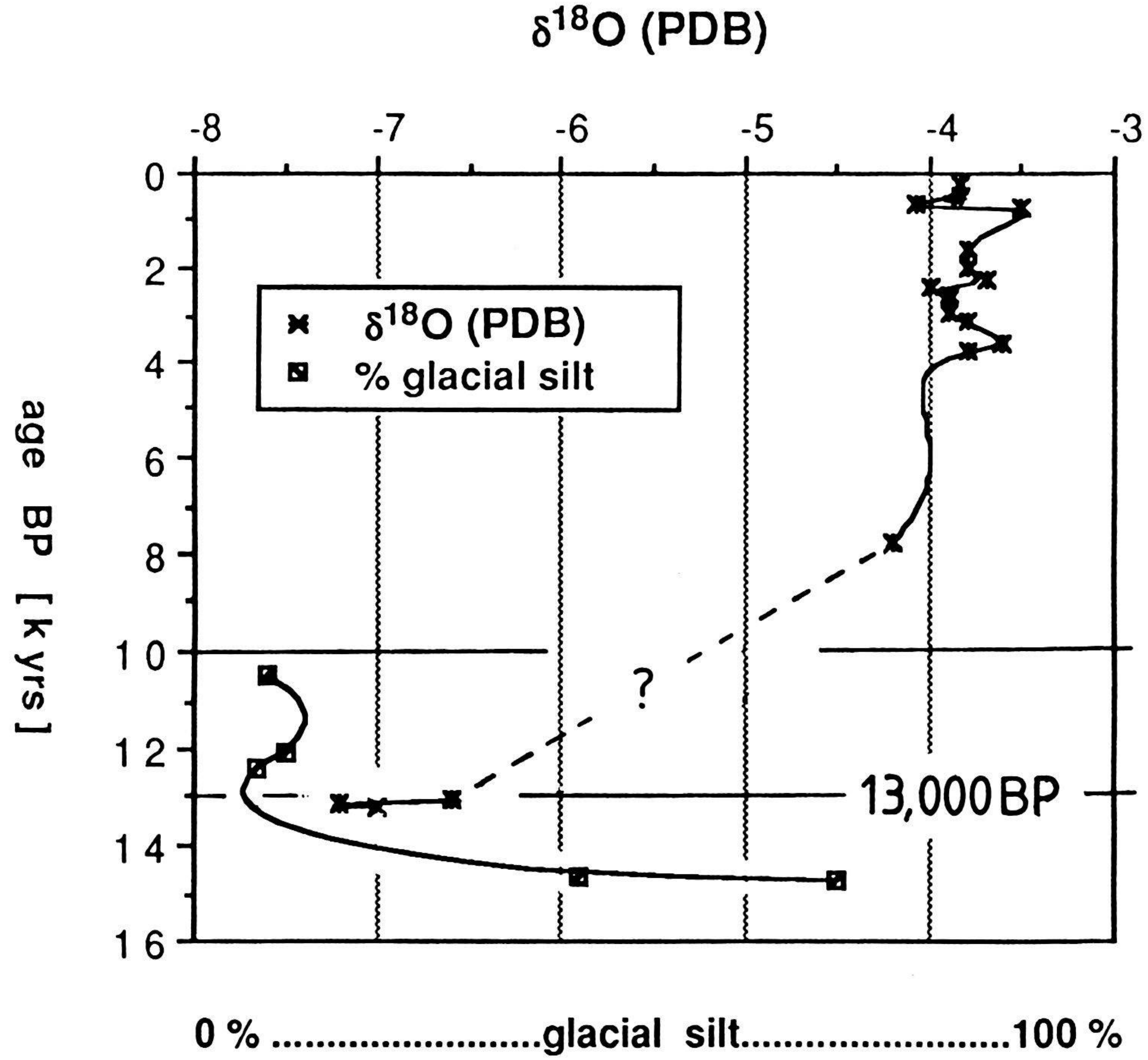

Fig. 6: Oxygen isotope results from benthic deep water ostracods (cores LG 83-7 and LG 83-17) plotted versus time (details are listed in Table 3). The isotope stratigraphy is compared to the amount of glacial silt in bulk samples which was estimated from calcite and dolomite contents. Note that the two gradients of glacial silt and $\delta^{18}O$ are displaced by at least 900 years.

Nonetheless, the $\delta^{18}O$-stratigraphy shows a clear difference of 3‰ between samples from 13,000 B.P. in comparison to the Holocene (Fig. 6). This large shift is interpreted as a change in isotope composition of the water since oxygen isotope fractionation between benthic carbonate shells takes place in isotopic equilibrium with the surrounding water (e.g. FRITZ & POPLAWSKY 1974). It is assumed that any temperature-dependent isotopic fractionation can be neglected for the deep water species from cores LG 83-7 and 83-17. For the whole of the Late Glacial and Holocene the sediment surface at both core localities was characterized by deep water temperatures around 5 °C.

Thus, the most probable interpretation is that a change in isotopic composition of inflow waters produced the 3‰-shift in the oxygen isotope record of Lake Lugano. This is consistent with the interpretation from Lake Zürich by LISTER (1988) who explained the more negative $\delta^{18}O$ values of the Late Glacial ostracods as a meltwater signal from deglaciation in the catchment. This indicates that in Lake Lugano, the catchment deglaciation was still in progress around 13,000 B.P. The final decrease of glacial silt in the southern basin of Lake Lugano as traced by inorganic carbon content and calcite/dolomite ratios, (Fig. 5, 6) began about 900 years earlier. Thus, trapping of glacial sediments occurred in upstream basins (Northern basin) until about 13,000 B.P.

The same scenario was described by LISTER (1988). The main drop in glacial flour-content in Lake Zürich occurred between about 14,000 and 12,800 B.P. whereas the end of catchments glaciation took place between 12,800 and 12,400 B.P. based on stable isotope results. This comparison suggests that deglaciation was synchronous across the Alps. Unfortunately, the precise end of catchment deglaciation has not yet been documented in Lake Lugano due to the lack of ostracod shells in the critical interval. Nevertheless, distinct similarities between Lake Zürich and Lake Lugano suggest that the final retreat of the glacier from the Lake Lugano catchment after 13,000 B.P. did not last more than a few hundred years (Fig. 6).

4.4 Correlation of major changes in Lake Lugano with regional and global climate patterns

The implications of the major changes within the sedimentary record of Lake Lugano are shown in Table 3 with comparative results from northern perialpine Lake Zürich and the global ocean. One important aspect of this comparison is the fact that the timing of major changes of all records under discussion is based on high precision ^{14}C dating by AMS. There appears a surprisingly good time-correlation between the two regional (north-south) counterparts of the perialpine lakes. There is also a clear correlation between the continental pattern and the ocean record. Some notable differences are discussed below.

One important feature that both lake records have in common is the dominance of their stepwise rather than gradual evolution. These steps determine the intervals for specific time windows where major changes occurred:

(1) Alpine deglaciation (> 15,000 to 12,000 B.P.): The observed synchronous deglaciation from different perialpine lake catchments (Table 4) is taken as further evidence for rapid changes in the whole Alpine region. The causes of such changes are probably linked to general Late Glacial climate development in Central Europe rather than to local conditions in the each Alpine region. Consequently, as argued earlier by

LISTER (1988), Alpine deglaciation was well under way before 15,000 B.P. and finished at about 12,400 B.P.

In comparison with the timing of the global deglaciation, as recorded in marine sediments (Table 4), the signals of rapid Alpine deglaciation appear notably earlier. Changes in modal ocean circulation at the last glacial/interglacial transition are considered causes for distinct positive feedback on the timing and mechanisms of global deglaciation (DUPLESSY et al. 1981, BROECKER et al. 1985). BARD et al. (1987) suggests that the first rapid deglaciation of polar ice (termination I A) occurred after 15,000 B.P. which is in time correspondence to a rapid warming of the North Atlantic (BROECKER 1987, Table 4). The temperature of the North Atlantic has a large influence on the European climate (BROECKER et al. 1985) and provides an expected feedback of ocean processes on Alpine deglaciation.

The rapid change in lithology that occurred in Lake Lugano and Lake Zürich at 14,600 (and interpreted as the begin of the last rapid deglaciation pulse) may be the response to such ocean circulation changes. The smaller size of the Alpine ice cap would make it more responsive to changes than the massive northern European ice sheets. It is interesting to note that the Alpine glacier responded to impulses within only few decades. This is further evidence for BROECKER's suggestion (1987) that the dynamics of the ocean atmosphere interactions give rise to sudden, rather than gradual climatic changes. It remains however obscure which mechanisms led to the early signals of Alpine deglaciation before 15,000 B.P., because the ocean circulation was, at that time, apparently still in its glacial mode of operation (eg. BARD et al. 1987; LISTER 1988).

(2) The Pleistocene/Holocene transition (11,000–7,000 B.P.): The sedimentary records on both sides of the alps reveal evidence for a series of climate oscillations at the transition from Pleistocene to Holocene (Table 4). The most remarkable change is that of a cooler period between 11,000 and 10,000 (Younger Dryas) which is also recorded in the pollen record of Lake Lugano (WICK 1989). This sudden cooling event has been reconstructed from many European lacustrine records (although not yet from Lake Zürich) and provides evidence for a strong interaction between ocean circulation and continental climate (BROECKER 1987). The Younger Dryas is one important key time period for the understanding of the global climate system. BROECKER et al. (1985) and BERGER et al. (1987) suggested similar scenarios of a sudden breakdown of North Atlantic deep water production as a feedback from rapid input of freshwater from the melting of North Atlantic ice after termination I A. As a result, less heat was transported in surface waters of the Atlantic to higher latitudes, and that in turn triggered a rapid cooling mainly on the European continent.

Apart from clear evidence for the Younger Dryas event from many perialpine lakes, the records from Lakes Zürich and Lugano (Table 4) also reveal similar short (but weaker) climatic deteriorations in early Holocene time that are superimposed on the trend of rapid warming. Although not dated precisely, there seems to be a time correspondence of one or two short periods with cooler conditions at 9,000 and 8,000 B.P. as detected by pollen results in Lake Lugano (and other lakes in Northern Italy, see WICK 1989 for a discussion) and stable isotope results from Lake Zürich (LISTER 1988, Table 4).

The evidence from Alpine lakes may open up new questions and problems for the understanding of climate history. In spite of an excellent time correlation of the lithological changes in Lake Lugano and Lake Zürich at 10,000 B.P. (Table 4) there is a notable difference in environmental changes that occurred on both sides of the Alps since the Younger Dryas. During Late Glacial nearly-synchronous lithological units (unit 4 in Lake Zürich and unit 2 in Lake Lugano) were deposited in both lakes dominated by detrital muds interbedded with a few anoxic laminae and no indication for a high lake productivity.

In contrast, the Holocene development appears to differ. After 10,000 B.P. the sequence from 87 m deep Lake Lugano (south basin) is characterized by laminated sapropels whereas in 135 m deep Lake Zürich autochthonous homogenous light-colored carbonate muds are found (Kelts & Hsü 1978). Lister (1988) proposed a 5-fold increase in productivity in Lake Zürich at 10,000 B.P. In contrast, our results suggest low primary production rates for early Holocene Lake Lugano in combination with a climatically-induced, thermally stratified water column.

The differences are interpreted by changes in local climate patterns at 10,000 B.P. For the Late Glacial period between about 12,000 and 10,000 B.P. the differences in temperature and/or wind intensity on both sides of the Alps were probably less than at present. After 10,000 B.P. the two regions split climatically. One explanation is that the gradient in climate between northern and southern perialpine regions has changed. North of the Alps the winter period was obviously cold enough for homothermic lake circulation so that the deep water environment of lake Zürich was oxic throughout the year. The opposite occurred in the southern Alpine region. Warmer winter temperatures than present could have resulted in sluggish water circulation and subsequently the lack of oxygen at the bottom of Lake Lugano.

Perhaps the climate divide of the Alps became more prominent at the beginning of the Holocene. This is consistent with conclusions from paleolimnological results from Central Europe which suggest the end of a period of intensified continentality at the Late Glacial/Holocene boundary (see Birks 1986 for a review). Bearing in mind that the mode of ocean circulation was supposed to be similar at 12,000 B.P. and after 10,000 B.P., the relatively sudden change in the European climate at 10,000 B.P. is puzzling. Broecker et al. (1985) suggested that the oceanic transport of heat to the North Atlantic is greatest during times with an interglacial mode of ocean circulation (at about 12,000 and after 10,000 B.P.) which in turn influences to a large extent the temperatures on the adjacent continents, in particular Europe.

The perialpine lake records reflect relatively large differences between the Late Glacial and Holocene. Perhaps, an interpretation of a dominance of the European climate by the ocean circulation pattern may be too simple. Other aspects such as an interaction of increased levels of atmospheric CO_2, reduced land ice, changes in vegetation, and land surface albedo may have contributed to a large extent to the rapid changes at the Pleistocene/Holocene boundary.

(3) The end of the Holocene climate optimum (4,000–3,800 B.P.): A subdivision of the Holocene into two major time intervals is evidend from lithological changes in the perialpine lakes between 4,600 and 3,800 B.P. (Table 4). These changes may be attributed to the end of a Holocene climate optimum. However, in Europe there are many uncertainties in the understanding of timing and mechanisms for the climatic amelioration during mid Holocene time. As Birks (1986) notes, dates for the end of the optimum scatter over a time span between 5,000 and 2,500 B.P. depending on lo-

Time window (yrs BP)	Lake Lugano record	Lake Zürich record	Ocean Record
3,800 to 3,600	Sudden increase in productivity increased terrestrial runoff evidence: accumulation rates, high calcite/dolomite ratios [1]	Sudden increase in productivity increased terrestrial runoff evidence: change in lithology (end of lake chalk unit), carbon isotopes [4], [5]	
4,400	increase in lake circulation end of climate optimum, cooler evidence: more bioturbation [1]		
6,000	low productivity, stagnation of bottom water evidence: laminations, authochtonous sediment compounds nearly absent [1]	low terrestrial runoff evidence: high content of authigenic calcite [4], [5]	end of deglaciation, climate optimum evidence: oxigen isotopes in benthic foraminifera [6], [7]
9,000 - 7,000	climatic temperature fluctuations (not well dated yet) evidence: pollen record [3]	climatic temperature fluctuations cooler at 9,000 and 8,000 BP, warmer at 8,500 evidence: oxygen isotopes, [4], [5]	possible 2nd meltwater spike evidence: climatic modeling, [6] decrease in North Atlantic surface water temperature evidence: oxygen isotopes, [8]
10,000	rapid warming, decrease in lake circulation evidence: pollen, sapropel formation, laminations [1], [3]	increase in production evidence: high content of authigenic calcite [4], [5]	2nd rapid deglaciation (termination I B) evidence: oxygen isotopes [6] mode of ocean circulation: interglacial [9]
10,800 - 10,500	sudden cooling (Younger Dryas) evidence: pollen, [3]		sudden cooling of North Atlantic surface waters evidence: oxygen isotopes [8] mode of ocean circulation: glacial [9]
13,000 - 12,400	end of catchment deglaciation evidence: content of glacial silt, oxygen isotopes [1]	end of catchment deglaciation (12,400) evidence: oxygen isotopes, [4], [5]	slow down of 1st rapid deglaciation evidence: oxygen isotopes [6] mode of ocean circulation: interglacial, [9]
14,600	begin of the last rapid deglaciation pulse evidence: sudden decrease in glacial silt [1]	begin of the last rapid deglaciation pulse evidence: decrease in glacial silt, [5]	(after 15,000) start of 1st rapid deglaciation (termination I A), evidence: oxygen isotopes [6]
15,000	earlier rapid catchment deglaciation evidence: seismic stratigraphy [2]	deglaciation in the Alpine Region well under way evidence: lithology, [5]	sudden warming of the North Atlantic region evidence: oxygen isotopes [8] mode of ocean circulation: interglacial ?
17,000			glacial maximum evidence: oxygen isotopes, [6]

Table 4: Comparison of major changes in the sedimentary records (Latest Glacial and Holocene) of Lake Lugano, Lake Zürich, and world oceans. References: [1] Niessen this paper, [2] Niessen 1987, [3] Wick 1989, [4] Lister 1988, [5] Lister 1985, [6] Bart et al. 1987, [7] Berger et al. 1987, [8] Broecker 1987, [9] Broecker et al. 1985.

calities in Europe. Moreover, there is no ocean record to which the continental signals could be clearly correlated (Table 4) although BERGER et al. (1987) have recently argued that North Atlantic deep water production might have increased in the Holocene after 6,000 B.P.

Since about 5,000 B.P., the growing influence of early human activities on terrestrial ecosystems has been felt in Central Europe (see BIRKS 1986 for a review). For the paleolimnology of many lakes, such as Lake Lugano, it is often difficult or even impossible to distinguish between anthropogenic influences and changes due to climate (NIESSEN 1987, WICK 1989).

Isotopic evidence from Lake Zürich suggests a sudden increase in productivity without any indication for a change in climate between 3,800 and 3,600 B.P. (LISTER 1988). This change was interpreted as a result of deforestation by neolithic settlers. In Lake Lugano an increase of bioturbation occurring since 4,600 B.P. is interpreted as evidence of more vigorous winter circulation of the lake water. This suggests a gradual cooling of climate between 4,400 and 3,600 B.P. rather than increased anthropogenic overprint.

Moreover, there is a good correlation of a sudden rise in lake productivity occurring between 3,800 and 3,600 B.P. on both sides of the Alps (Table 4). It remains moot whether this can be attributed to anthropogenic activities alone? It can not be ruled out that a further sudden climatic change, such as an increase in heavy rainfall events, influenced catchment erosion and lake production since 3,800 B.P. More detailed investigation in the Alpine region will be necessary to distinguish between human and climate influences.

5. Conclusions

(1) Lithological changes in the sedimentary record of Lake Lugano occurred rapidly. These indicate rapid climatic shifts and responses in the southern Alpine region in the order of 10^1 to 10^2 years. The shifts define contacts between relatively uniform states lasting millenia. Major rapid shifts occurred at 14,600, 10,000 and 3,800 B.P.

(2) Holocene sapropels in Lake Lugano are highly sensitive indicators for paleoclimate. Thermally induced stagnation of bottom water in combination with low productivity is a feature of the early Holocene climate optimum (about 10,000 to 4,400 B.P.). The younger Holocene is characterized by a different environment with higher levels of productivity and deep water turnover rates linked to a cooler climate and higher terrestrial runoff rates. The full potential of the sequence as a high-resolution record of short-term variability between the two different modes of operation is not yet fully explored.

(3) Major changes for southern and northern perialpine lake sequences appear synchronous as demonstrated by a comparison between Lake Lugano and Lake Zürich. These indicate synchronous climatic shifts on a European rather than local scale. Several shifts match well with marine records (at 14,600, 10,500, 10,000 B.P.). These provide further evidence for the influence of circulation patterns in the North Atlantic on climate over the European continent.

(4) For the Late Glacial period (14,600–10,000 B.P.) there is a strong indication for synchronous paleomagnetic features in southern and northern Alpine lake sedi-

ments. These support an application of declination curves from perialpine lakes as high resolution correlation tools. A paleomagnetic correlation of the Late Glacial records from Lake Zürich and Lake Lugano demonstrate that the last rapid deglaciation pulse of the Pleistocene was essentially synchronous and lasted from 14,600 B.P. to 12,400 B.P.

(5) Parallels and divergences between southern and northern Alpine lake environments change with time. These define variations in the climatically-induced gradient along a south to north Alpine transect for Late Glacial to present. Paleolimnology indicates a very low gradient (which means distinct similarities) prior to 10,000 B.P., followed by a larger gradient during the climate optimum (about 9,000 to 4,400 B.P.) and a shift back to a lower gradient starting at 4,400 B.P. The latter change may be due either to climatic and/or early human influences. These results underline the rearrangement of continental climate patterns in Europe at the end of the Pleistocene and to some extent around 4,400 B.P. More detailed investigation is required in order to explain the causes, and to quantify the magnitude of such gradients.

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