Table 8.6. Area, depth and volume of lakes and deposits (after Lencewicz 1928, Glazik 1978, Więckowski 1993, Churski, Chapter 3.3, compiled by Starkel and Więckowski).

Lake	Area in ha			Max. depth in m		Volume in $10^3 m^3$	Thickness of deposits in m		Volume of lacustrine deposits in $10^3 m^3$	% of filling of depressions
	1928	1963	1994	1928	1994		max.	min		
Gościąż	46.9	44.4	41.7	25.8	24.5	2073–2700	19.6	8	2960	58%
Wierzchoń	15.3	14.0		1.6		130–160	12.5	7	1050	<90%
Brzózka	3.1	2.4		1.4		18–20	11.5	7	190	>90%
Mielec	6.9	3.5		1.0		35–39	15.0	8	280	>90%
Other valley segments		ca 30–35				–	–	5	1500	100%
Total		95–100				2250–2300	–	6	ca 6020	>72%

In the case of a 1 m water-level rise in the early Subatlantic, the water volume increased by ca. 6×10^5 m^3, i.e. by more than 20%. A similar rise or drop at the beginning of the Holocene was connected with a twice greater change in water storage. Considering these relations the curve of lake-water storage during the last 12,000 yr BP was constructed (Fig. 8.32). It shows a distinct declining tendency. In this context we cannot evaluate the role of other factors such as deepening of the Ruda channel, which, before the construction of the weir, drained the surplus of water after heavy rains or snow melting. But simultaneous overgrowing of narrow and shallow parts of the valley, especially downstream of Lake Mielec, made the water outflow and deepening of channel more difficult. Therefore from one side the fluctuations of water level were controlled by the most dynamic factor (the inflow of groundwater), but from the other side these fluctuations could not be too high, because the extremes were regulated by the river outflow. This means that the distinct transgressions at ca. 8300–8000 and 2500–2300 ^{14}C BP were undoubtedly related to humid phases when over decades and centuries the increased inflow could not be levelled by outflow. The second of these phases coincided with the famous transgression of Lake Biskupin, for which one of the first calculations of the water budget was made (Skarżyńska 1965). In case of Lake Gościąż such full reconstruction would need the reconstruction of the input and output of both the groundwater and surficial water.

On the contrary, the lowerings of the water level caused by the drop in annual precipitation or by higher evaporation were reflected not only in the decrease of water storage but also in overgrowing of littoral zones and shallow parts of the longitudinal lake-valley depression. This led to the more and more restricted water storage during subsequent lake-level rises.

The water storage of the Na Jazach lake system is continuously declining. This causes the acceleration in the surficial runoff, which results in a quicker levelling of the groundwater surplus. In the last millennia the water cycle was more controlled by deforestation and changes in the fertility of the forest habitats.

8.6. OXYGEN AND CARBON ISOTOPE COMPOSITION OF AUTHIGENIC CARBONATES IN THE HOLOCENE PART OF THE LAKE GOŚCIĄŻ SEDIMENTS

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Factors controlling isotope composition of precipitated carbonates

Numerous isotopic studies of lacustrine sediments performed to date have demonstrated the usefulness of stable isotopes as a powerful tool in reconstructing past climatic and environmental changes on the continents (e.g. Siegenthaler et al. 1984, Gasse et al. 1990, Talbot 1990, von Grafenstein et al. 1992, Dean & Stuiver 1993, Gasse & Van Campo 1994). Lake sediments often contain authigenic carbonates and fossil shells whose carbon and oxygen isotopic composition is governed by climatically controlled properties of the given lacustrine system and its surroundings.

Oxygen-isotopic composition of authigenic carbonate is controlled by two physical properties of the lake in which calcite is being precipitated: the oxygen-18 content and the temperature of the lake water. The temperature dependence of oxygen-18 equilibrium fractionation factor between water and precipitated calcite amounts to -0.25‰ per ^{o}C for the temperature range and δ^{18}O values of water typical for Lake Gościąż (O'Neil et al. 1969). Possible kinetic fractionation effects during rapid growth of calcite crystals are thought to be associated mainly with the dehydration reaction induced by fast withdrawal of CO_2 from the epilimnion during periods of algal blooms (Clark & Lauriol 1992). They may lead to an additional enrichment in oxygen-18 of the precipitated calcite.

For open lakes with fast water turnover, the oxygen-18 isotope composition of the lake water is closely re-

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lated to the annual weighted mean isotopic composition of precipitation over the catchment area of the lake. Under temperate climatic conditions, there is a strong link between isotopic composition of precipitation and the surface air temperature, both on a seasonal and inter-annual basis (Różański et al. 1992). Consequently, $\delta^{18}O$ of authigenic calcite deposited in a lake should respond mainly to changes in oxygen-18 isotopic composition of precipitation, induced by fluctuations of climate.

Carbon-13 isotope composition of authigenic calcite is determined by the isotopic composition of bicarbonate (HCO_3^-) and by the extent of isotopic fractionation during the process of crystal growth (Turner 1982). Contrary to oxygen-18, the temperature dependence of carbon-13 equilibrium fractionation factor is very small. Bicarbonate is usually the main form of dissolved inorganic carbon (DIC) in the lake waters. In Lake Gościąż, the carbon-13 isotope composition of DIC is controlled by two main processes: (i) photosynthetic activity of phytoplankton, which preferentially removes $^{12}CO_2$ from the epilimnion, and (ii) decomposition of organic matter, both in the water column and in the sediments which is associated with liberation of CO_2 strongly depleted in carbon-13 in case of aerobic respiration, or strongly enriched in case of methanogenesis (Whiticar et al. 1986). The exchange of CO_2 between the atmosphere and the lake results in the enrichment of carbon-13 in DIC while precipitation of calcite, which is enriched in carbon-13 with respect to the solution, acts in the opposite direction. Other sources of DIC in a given lake are surface and groundwater inflows.

This paper presents a Holocene record of oxygen-18 and carbon-13 isotope ratios in carbonate fraction of the sediments deposited in Lake Gościąż. It is part of an interdisciplinary project aimed at reconstructing climatic and environmental changes during the Late-Glacial and Holocene in Central Europe by exploring laminated sediments of Lake Gościąż as an environmental archive (Chapter 1).

Analysed material

Over the past eight years, a number of cores were retrieved both from deep and shallow parts of Lake Gościąż (Więckowski et al., Chapter 5.1). As far as the Holocene period is concerned, their lamination is of a varying quality. The cores retrieved from the central deep part of the lake reveal relatively good lamination throughout the nearly entire sediment column.

From all cores retrieved to date, core G2/87 originating from the central deep of the lake (a twin core to G1/87) was most extensively analysed for isotopic composition of the carbonate fraction. High-resolution, continuous sampling was performed for the basal part of the core (Kuc et al., Chapter 7.6.). The Holocene part of the core was sampled at 50-year intervals, combining approximately 10 varves into one sample. The varve chronology was elaborated by Goslar (Chapters 6 and 8.1).

For more technical details of sample preparation and measurement see Chapter 4.

Isotopic record of the Holocene sediments

The $\delta^{18}O$ and $\delta^{13}C$ profiles obtained for the Holocene part of the G2/87 core are shown in Fig. 8.35. They extend from ca. 11,300 cal BP (onset of Preboreal) to ca. 1200 cal BP. The Late-Glacial portion of the core is discussed in detail elsewhere (Kuc et al., Chapter 7.6).

During early Holocene, between approximately 11,300 and 8500 cal BP, the isotope profiles shown in Fig. 8.35 are characterized by a slight increase of $\delta^{13}C$ from about –8.0 to –6.5‰, with the $\delta^{18}O$ fluctuating between –7.5 and –8.5‰. For the remaining portion of the record, the $\delta^{13}C$ continues to grow, gradually approaching the level of about +1.5‰ between 2000 and 1200 cal BP. Short and medium-term fluctuations of varying amplitude are superimposed on this general trend.

The $\delta^{18}O$ reveals a decreasing trend, from about –8‰ around 8500 cal BP to –10.5‰ in 1200 cal BP. However, the record is relatively noisy, with numerous short-term fluctuations, and periods when the trend levels off or

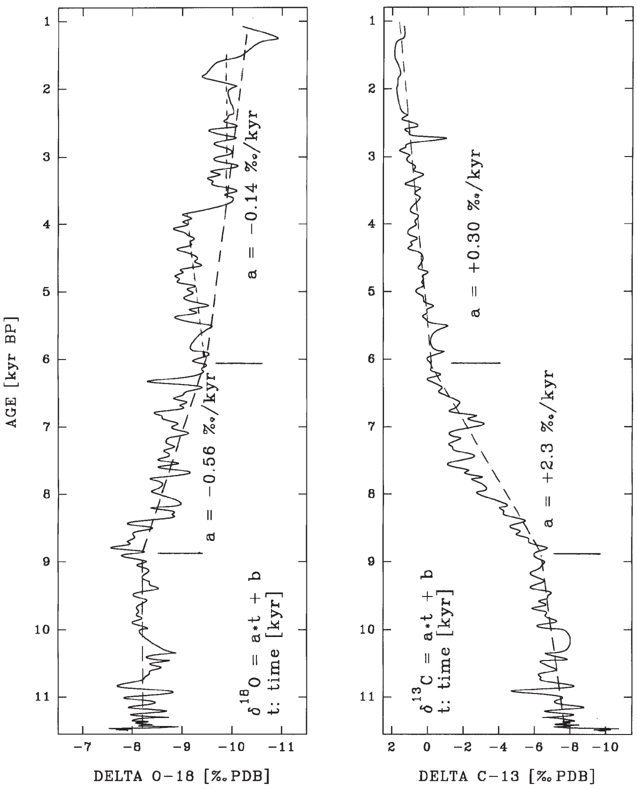

Fig. 8.35. Isotopic composition of authigenic carbonates in the Holocene section of the sediments from Lake Gościąż (core G2/87). Shown are only smoothed profiles (spline fitting). Scale in calendar years after Goslar (Chapter 6 and 8.1).

even changes the sign (for instance, between ca. 6500 and 3700 cal BP).

Preliminary results available for the youngest portion of the sediments suggest that $\delta^{13}C$ has remained roughly constant at the level of around +1.5‰ till the beginning of intense agricultural exploitation of the lake catchment (ca. AD 1820) and then decreased gradually to about –3.5‰ around AD 1960 (Goslar et al. 1994). At the same time, $\delta^{18}O$ also decreased from about –8.7 to –10.5‰. The results available from sediment traps suggest that calcite being formed at present in the lake is enriched in both $\delta^{18}O$ and the $\delta^{13}C$, when compared with the values recorded around AD 1960 (Wachniew & Różański, Chapter 3.6). The evolution of oxygen-18 and carbon-13 isotope composition of authigenic calcite deposited in the lake during the industrial period is discussed in detail elsewhere.

Fluctuations and trends of $\delta^{13}C$ and $\delta^{18}O$

Carbon-13

The general increasing trend of $\delta^{13}C$ during the Holocene can be understood in light of the specific morphology of Lake Gościąż. This is a lake with a relatively small surface to depth ratio, especially during the early phase of its history. Under such circumstances, gradual filling up of the lake with sediments will result in a corresponding increase of the epilimnion to hypolimnion ratio (E/H), mainly due to the shrinking volume of the hypolimnion. At present, the E/H ratio of the lake is about 2.5.

Taking into account the fact that until now about 18 meters of sediments have accumulated in the deepest part of the lake, the E/H ratio at the onset of the Holocene could be as low as 0.5. During summer stratification, the $\delta^{13}C$ of DIC is enriched in the epilimnion due to photosynthetic activity of phytoplankton, and depleted in the hypolimnion due to decomposition of organic matter (e.g. McKenzie 1985, Wachniew 1995). The average $\delta^{13}C$ value in the epilimnion just after the spring turnover of the lake will therefore be largely determined by the actual mixing proportions of epilimnion and hypolimnion, assuming that all other processes influencing the carbon balance in the lake occur with the same intensity.

The $\delta^{13}C$ profile can be divided into two major parts: (i) from the onset of Preboreal to ca. 8500 cal BP and, (ii) from ca. 8500 cal BP till the endpoint of the profile (ca. 1200 cal BP). The mineralogical evidence (high Mn and Fe content, small size of carbonate crystals) suggests that conditions of sedimentation during early Holocene were analogous to those prevailing during the Younger Dryas (Łącka et al., Chapter 8.2). During that time, the E/H ratio could have changed only slightly, which is reflected by a relatively small increase of $\delta^{13}C$. Between ca. 8500 and 6500 cal BP, $\delta^{13}C$ increases relatively fast and then gradually approaches a constant value towards the end of the profile, with short- and medium-term fluctuations superimposed on the general trend. Whereas the long-term trend of $\delta^{13}C$ observed during the Holocene seems to be controlled mainly by the evolution of the E/H ratio, the short- and medium-term fluctuations were most probably caused by changes in the mean residence time of water in the lake and/or variations of its biological productivity.

Oxygen-18

The $\delta^{18}O$ profile representing the Holocene part of the sediments in the lake, is not well understood. The Late-Glacial and early Holocene part of the analysed core reveals a “typical” behaviour of $\delta^{18}O$, with more negative $\delta^{18}O$ values during Younger Dryas and relatively constant values during the early Holocene (Kuc et al., Chapter 7.6). Contrary to other studied lakes in Poland, where relatively constant $\delta^{18}O$ values were observed throughout the entire Holocene (Różański 1987, Kuc et al. 1993), in agreement with only minor fluctuations of temperature during that period, the $\delta^{18}O$ profile in the Lake Gościąż reveals a different behaviour. No definite explanation can be proposed at this stage to account for the observed gradual decrease of $\delta^{18}O$ starting around 8500 cal BP and continuing with some interruptions till the end of the available record (ca. 1200 cal BP). During the Holocene, the long-term mean oxygen-18 isotope composition of precipitation, and consequently of newly formed groundwater, did not vary more than by 1‰ in central Europe (Różański 1985). Therefore, substantial changes of the isotopic composition of groundwater feeding the lake during this time period are unlikely.

An attempt to explain the observed changes of $\delta^{18}O$ of calcite during Holocene in terms of temperature changes would require that the effective temperature of the epilimnion during precipitation of calcite increased by as much as 8°C. Although a substantial spatial and temporal variability of temperature of water within epilimnion is observed nowadays during the period of calcite precipitation (Wachniew 1995), it is unlikely that modified deposition patterns of calcite in the lake (the period and depth of maximum calcite production) changed the effective temperature of calcite precipitation to such an extent. They possibly may account only for minor fluctuations of $\delta^{18}O$, superimposed on the general decreasing trend during the Holocene. Since the volume of the lake is being gradually reduced as a result of the sedimentation process (see discussion above), one may speculate that the mean residence time of water in the lake will also decrease. Consequently, the average enrichment of lake water in oxygen-18 due to evaporation would be gradually reduced, assuming that the inflow and evaporation rates remain constant. At present, the average enrichment of the epilimnion in oxygen-18 during the summer months, with respect to local precipitation and groundwater inflow, is about 2‰ (Wachniew 1995). Starting from early Holocene, a gradual reduction of the isotope enrichment by about 1.5‰ due to the diminishing residence time of water in the lake would be required to explain the observed general decreasing trend of $\delta^{18}O$. Although the fluctuations of the water balance of Lake Gościąż in Holocene cannot be reconstructed quantitatively, it is clear that they have a potential to modify substantially the average oxygen-18 content of the lake water and, consequently, the oxygen-18 content of the deposited calcite.

The $\delta^{18}O$ profile during early Holocene (ca. 11,500 to 8500 cal BP) reveals a relatively constant level, with two small maxima around 11,000 and 9000 cal BP, matching the high water-level stands of the Lake Gościąż system (Starkel et al., Chapter 8.5). As mentioned above, conditions of calcite formation during this period were very similar to those prevailing during the Younger Dryas. The beginning of relatively fast decrease of $\delta^{18}O$ (around 8500 cal BP) is marked by a dramatic reduction of Mn content in the sediments, by more than one order of magnitude (Łącka et al., Chapter 8.2). This is also the time when Ruda stream started to develop as a main drainage of the entire system of lakes, in response to a substantial increase of precipitation rate in the region (Starkel et al., Chapter 8.5.). Gradual decrease of $\delta^{18}O$ between ca. 8500 and 6300 cal BP could then be related to diminishing mean residence time of water in the lake and the resulting smaller evaporative enrichment of oxygen-18. Between ca. 6500 and 3700 cal BP the oxygen-18 trend is reversed: the $\delta^{18}O$ increases gradually by about 0.5‰. Mineralogical analyses indicate active growth of calcite crystals in the sediments deposited during this time period (Łącka et al., Chapter 8.2). Because the temperature of the re-crystallization process was at least 10°C lower than the typical temperature of calcite formation in the epilimnion, the newly formed calcite in the sediments will be substantially enriched in oxygen-18 (by about 2.5‰).

Gradually increasing content of secondary calcite in the bulk sediment might be responsible for the apparent increasing trend of $\delta^{18}O$ in the bulk carbonate. After a distinct drop around 4000 cal BP, the $\delta^{18}O$ record stabilizes again for about 2000 years, indicating a relatively stable water balance of the lake. Calcite crystals that are formed in the lake during this time period are similar in size and shape to those formed during early Holocene (Łącka et al., Chapter 8.2).

The above discussion clearly demonstrates that more detailed studies of the possible changes of water balance of Lake Gościąż during the Holocene would be required to better understand the parameters controlling $\delta^{18}O$ and $\delta^{13}C$ of authigenic carbonates deposited in the lake during this time period.

8.7. SPECTRAL ANALYSIS OF POLLEN INFLUXES FROM VARVED SEDIMENTS OF LAKE GOŚCIĄŻ, POLAND

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The sediments from Lake Gościąż are suitable for time series analysis, as they consist of annual laminae (Goslar, Chapter 6). The laminations provide almost absolute certainty about the duration of events registered in the cores. Lamination in the upper ca. 8 m of the cores is less clear than farther down, which makes the chronology a floating one. However, counting of laminae and radiocarbon datings show that the top contains ca. 3200 laminae, and that the total of ca. 12,800 annual laminae in the cores G1/87 and G2/87 were formed from late Allerød up to the present (Goslar, Chapters 7.2 and 8.1).

Autocorrelation analysis reveals a significant correlation of the winter-layer thickness to that of the year before, probably caused by the winter-material being so fine-grained and light that it takes up to a year to deposit. However, it provides no indications for periodic patterns, as the partial autocorrelation coefficients at lags 2 through 25 are not significant.

In the present study we have carried out a spectral analysis on pollen influxes in the Lake Gościąż sediment (data published earlier as percentages by Ralska-Jasiewiczowa & van Geel 1992). The samples had been taken at intervals regularly spaced in time, according to the annual lamination, which made these data more suitable for time-series analysis than palynological data usually are. Following the line of reasoning by Young (1997) we used global significance assessment procedures, for the analysis involved the calculation and testing of many power spectra including many powers themselves. We interpret the results in terms of cycles in climate or human influence.

Data

The time series analysed consist of pollen influxes for 19 selected taxa recovered in the G1/87 core. We selected the most abundant pollen taxa representing elements of the regional vegetation, and we excluded from the analysis the taxa most indicative for human influence. Observations in the time series represent the number of pol-

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