a factor ranging from $Ex = 0.88$ to $Ex = 1.10$, and the mean-square difference for the best fit (S^2_{min}) was calculated for each value of Ex. If the varve counting is correct, the minimum of S^2_{min} is expected for $Ex = 1.00$. The plot of $S^2_{min}(Ex)$ (Fig. 6.6b) clearly shows that any proportional expansion of varve chronology does not improve the match distinctly. It is also clear that the Gif dates alone cannot prove the reliability of varve counting in the floating chronology with satisfactory accuracy, probably because the time span between the youngest and oldest samples is too short (ca. 1700 yr). With the Swiss dates included (time span ca. 4800 yr), the function S^2_{min} has a distinct broad minimum for the expansion between 0.93 and 1.02, and the absolute minimum for $Ex = 1.002$ (i.e. for the expansion of varve time scale by only 0.2%). With all the scepticism according to the significance of narrow minimum at $Ex = 1.002$, one can state at least that the ^{14}C dates in the section 4800 years long do not contradict the reliability of varve counting.

6.3. RECORD OF LAMINAE THICKNESS OF THE LAKE GOŚCIĄŻ SEDIMENTS, AND ITS CORRELATION WITH ABSOLUTELY DATED TREE-RING WIDTH SEQUENCES

Tomasz Goslar

The record of laminae thickness

Although the varved sediment of Lake Gościąż has the potential of annual resolution of investigations, the majority of results are based on sampling intervals of ca. 50 years. One exception is the parameter of varve thickness which has annual resolution. The thickness of varve has been used by many authors as a parameter of palaeolimnological and paleoclimatic importance. One example is the annually laminated sediment of Lake Van, Turkey (Kempe & Degens 1979). The sequence of varve thickness, consisting mostly of allochthonous material, is interpreted as the record of annual water inflow from the catchment. In other circumstances, the thickness of authigenic varves may be related to precipitation. This was the case of Malo Jezero at the lagoon of the Adriatic (Seibold 1958), where the thickness of the calcareous laminations was inversely correlated with precipitation. Presumably in drier years, greater sunshine allowed greater photosynthesis and the precipitation of more calcite. Another case are the varves deposited during the prairie stage (ca. 3.8–8.0 kyr BP) of Elk Lake, Minnesota (Anderson 1992), which have a dominant eolian component. The variations of varve thickness in this stage have been explained by the changes of zonal winds, suspending and carrying the loess, and, by comparison with the variations of atmospheric radiocarbon concentration, used to dem-

Fig. 6.6. The results of wiggle matching of radiocarbon dates of Lake Gościąż macrofossils with the radiocarbon calibration curve obtained on German oaks. a – mean square differences between radiocarbon dates of LG samples and calibration curve as a function of the age of floating varve chronology (FVC): 1 – for all the samples dated in Gif, 2 – for all the samples dated in Gif, except the critical one (see the text), 3 – for all the samples dated in Gif and in Zürich, except the critical one. b – minimum mean square differences between radiocarbon dates of LG samples and calibration curve versus the expansion of calendar chronology of LG sediments with respect to constructed varve chronology. 2, 3 – description same as above.

is older but still agrees within the limit of error with that estimated by varve counting, i. e. $2900\,^{+500}_{-200}$ cal BP.

The value of S-square at the broad minimum ($S^2_{min} = 1.7–1.9$) is higher than the expected value. This may be due both to the effects of redeposition and to some overestimation of laboratory precision. For example, multiplying of ^{14}C errors by a factor of 1.3 would reduce the value of S^2_{min} to ca. 1. Another cause might be the uncertainty of varve counting. The error of varve counting (ca. 50 years in the Holocene section of FVC), however, is cumulative, and significant errors of varve counting in short fragments, i. e. between adjacent samples, seem unlikely. To check the effect of systematic error in varve counting, the following test has been made: the time spans between samples were changed proportionally to that determined by varve chronology (the calendar time scale of sediment was thus expanded or compressed), by

onstrate the link between climate and solar activity (Anderson 1992, 1993). Saarnisto et al. (1977) correlated the occurrence of thin varves in the sediments of Lovojärvi, Finland, with the periods of unfavourable climate and poor agricultural performance. It is clear that the changes of varve thickness in different lakes (and, sometimes, in different periods) may be interpreted in different ways, and the reliable interpretation requires the correspondence between variations of varve thickness and sediment composition to be known.

The laminae thickness in the lower section (below 7.34 m) of Lake Gościąż sediment was measured with the equipment designed for dendrochronological studies (Goslar 1987). The material used was the photo-negatives of lamination in cores G1/87 and G2/87. The thickness of light layers (calcite, diatom+calcite) and dark layers (organic, Fe or Fe+Mn rich) layers were measured separately, with a precision of 0.01 mm. The investigation of the youngest sediments shows that the light layers were deposited in spring and summer, while the formation of dark layers took place in autumn and winter. Since the laminae are rarely ideally flat, and their thickness is different in different places, they were measured in both cores two times, along two lines crossing the layers, and the results were averaged. When tracing the lines the regions of disturbed laminae thickness were being avoided. In the upper part of the profile (above 7.34 m), only the mean sedimentation rates in ca. 50 yr-long periods were determined.

The smoothed record of laminae thickness is shown in Fig. 6.7. The dark layers (0.5–1.0 mm) are always thicker than the light ones (0.3–0.8 mm), and their thickness reveals greater variability but the thicknesses of light and dark layers are strongly correlated. Such a correlation points to some common signal controlling the growth of sediment in both seasons. This could be the organic productivity of lacustrine biota, since photosynthesis is one of the processes causing the formation of calcite (Kelts & Hsü 1978, Wachniew & Różański, Chapter 3.6). The influence of that common signal is reduced in the sequence of the ratio of thickness of the light layer to the whole varve (ThR), shown in Fig. 6.7. The individual laminae have not been measured above the depth of 7.34 m.

The thickness and the ThRs reveal long-, medium- and short-term variations. The strongest long-term changes occur at the boundaries of stratigraphic units of the Late-Glacial and Holocene. In Fig. 6.7, the boundaries of Allerød/Younger Dryas and Younger Dryas/Preboreal denote the abrupt climatic transitions well reconstructed in the study of the sediment (see Goslar et al. 1993, Ralska-Jasiewiczowa et al. 1992). The units within Holocene are the chronozones proposed by Mangerud et al. (1974), and the calendar ages of boundaries were obtained by calibration of their conventional radiocarbon ages. The chronozones reflect to some degree the periods

of different climate and vegetation cover. The ages of climato- and biostratigraphical boundaries may be geographically dependent, and some authors attempted to adjust the timing of chronostratigraphical units, according to reconstructions of local or subregional scale (e.g. Starkel 1977, 1991). The use of the same terminology and different ages in chronostratigraphy, however, may lead to confusion, and for that reason the ages proposed by Mangerud et al. (1974) are applied here.

The thinnest varves occur in the bottommost section. This, however, is mostly an artificial effect of compression by the weight of the ca. 60 cm layer of sand, which is much heavier with respect to the surrounding water than the calcareous gyttja. The thickest varves were deposited during the dry, cool (subarctic) period of Younger Dryas. In the last few hundred years of YD the thickness of var-
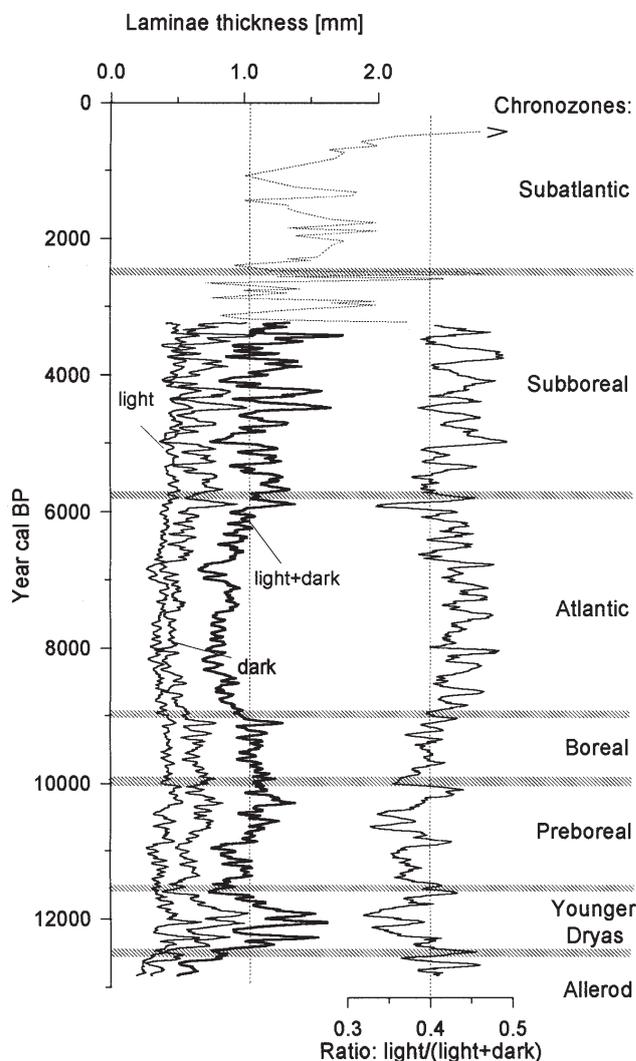

Fig. 6.7. The records of thickness of light and dark laminae and whole varve of the Lake Gościąż sediments, plotted on the time scale. The records have been smoothed by the method described in the text. For the younger part of sediment, only the mean annual sedimentation in 50-yr intervals is plotted. The sedimentation rate in the youngest sediment was beyond the scale of diagram. At the right side of diagram the record of ratio of thickness of light layer to whole varve is shown.

ves declines gradually. According to palynological and stable-isotope data, this period, called "the descending part of Younger Dryas" (Ralska-Jasiewiczowa et al. 1992, Goslar et al. 1993), is characterized by a warmer and milder climate. In the Preboreal and Boreal chronozones the varves are thick, with the maximum at the Preboreal/Boreal transition. The sharp drop of thickness occurs almost exactly at the boundary between Boreal and Atlantic, and the varves in Atlantic chronozone are the thinnest, with very little variability. The boundary between Atlantic and Subboreal chronozones is slightly delayed with respect to abrupt increase of varve thickness; the varves deposited in Subboreal are thick, and their thickness reveals regular variations with large amplitude. In spite of large variations, the overall trend of increase is visible, and the sedimentation rate is maximum at Subboreal/Subatlantic boundary. The increasing trend does not occur in the first half of Subatlantic, and the deposition rate rises strongly only after ca. 1000 cal BP, up to more than 10 mm/yr in 20-th century. The change of thickness in the upper part of the sediment is an effect of compaction. The record of varve thickness in the youngest part of the sediment is discussed elsewhere (see Goslar, Chapter 9.2.2).

The long-term changes of varve thickness are somewhat related to the glacial-interglacial cycle of climatic changes, as being thickest in the dry, cold Younger Dryas and thinnest at the climatic optimum. However, the changes of varve thickness at chronozone boundaries are surprisingly sharp, and this is difficult to explain unless climatic change is involved. Unfortunately, the explanation of those changes has not been found. The ratio of light and dark laminae thickness, l/(l+d), does not change distinctly at the boundaries, and on average it is lower in the cold and higher in the warm parts of a climatic cycle (Fig. 6.7).

To understand the causes of medium-term (100 yr) variations of laminae thickness, the changes of sediment composition must be analysed. The records covering the whole profile densely enough are those of loss-on-ignition (LOI), carbonate, and Fe_2O_3 provided by Wicik (1993 and Chapter 4.3). The comparison of those records with the analyses of organic carbon and of calcium and iron content (Łącka et al., Chapters 7.3 and 8.2) shows stoichiometric agreement between content of carbonate and calcium as well as between ferrous oxide and iron. LOI, representing the content of organic matter, is approximately twice the content of organic carbon. The chemical analyses (Łącka et al., Chapters 7.3 and 8.2) show that the only other element that forms significant amount of authigenic sediment is manganese. The residuum: $RES = 1-CaCO_3-LOI-Fe_2O_3$ may therefore represent the content of allochthonous mineral matter and biogenic silica plus manganese compounds (presumably hydroxides). The content of manganese is ca. 12% in the

Late-Glacial, 5–7% in the older part of Holocene before ca. 8.5 kyr BP, and below 1% after 8.5 kyr BP.

The diagram in Fig. 6.8 illustrates the main components responsible for the variations of varve thickness. The mean varve thicknesses in the samples analysed by Wicik were divided into four parts, proportionally to the contents of organic matter (LOI), residual matter (RES), carbonate, and ferrous oxide. The proportional division of thickness according to mass content assumes the same densities of all varve components, which is not exactly the case, but the differences are not great, for all the components are suspended in water. The Late-Glacial varves are thick because of the high accumulation of residual matter. The variations of manganese content (a drop at the beginning of Holocene by ca. 5%) explain only a minor part of the thickness change. The maximum of varve thickness in Younger Dryas is then caused by the distinctly higher accumulation of detrital minerals and biogenic silica (diatoms), the first factor perhaps being the consequence of discontinuous vegetation cover and higher erosion at that time. The significance of allochthonous accumulation in the Late-Glacial is confirmed by the substantial aluminium content (Łącka et al., Chapter 7.3), which after the YD/PB transition drops below 0.1%.
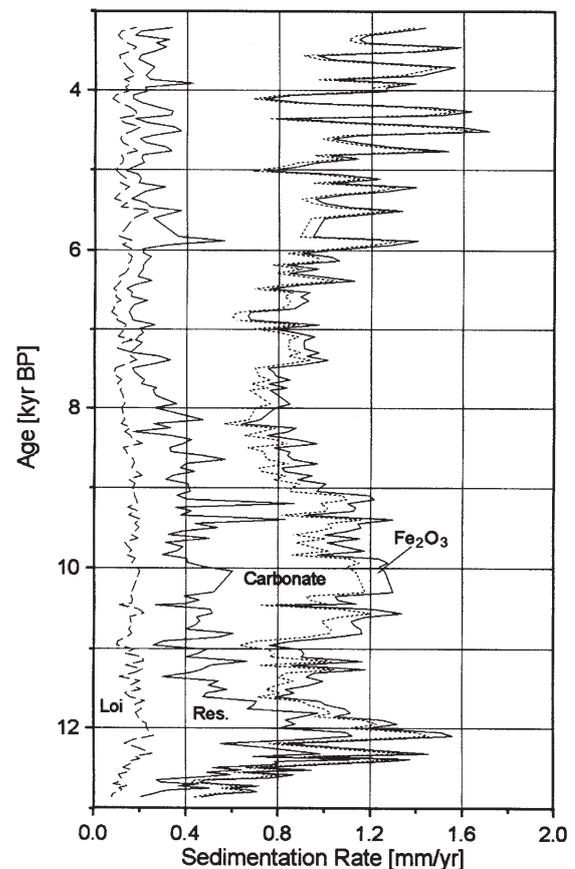

Fig. 6.8. The mean varve thickness corresponding to the samples with analysed content, in the range covered by floating varve chronology of the Lake Gościąż sediments. The thickness of each sample was divided proportionally to the weight percentage of main sediment components.
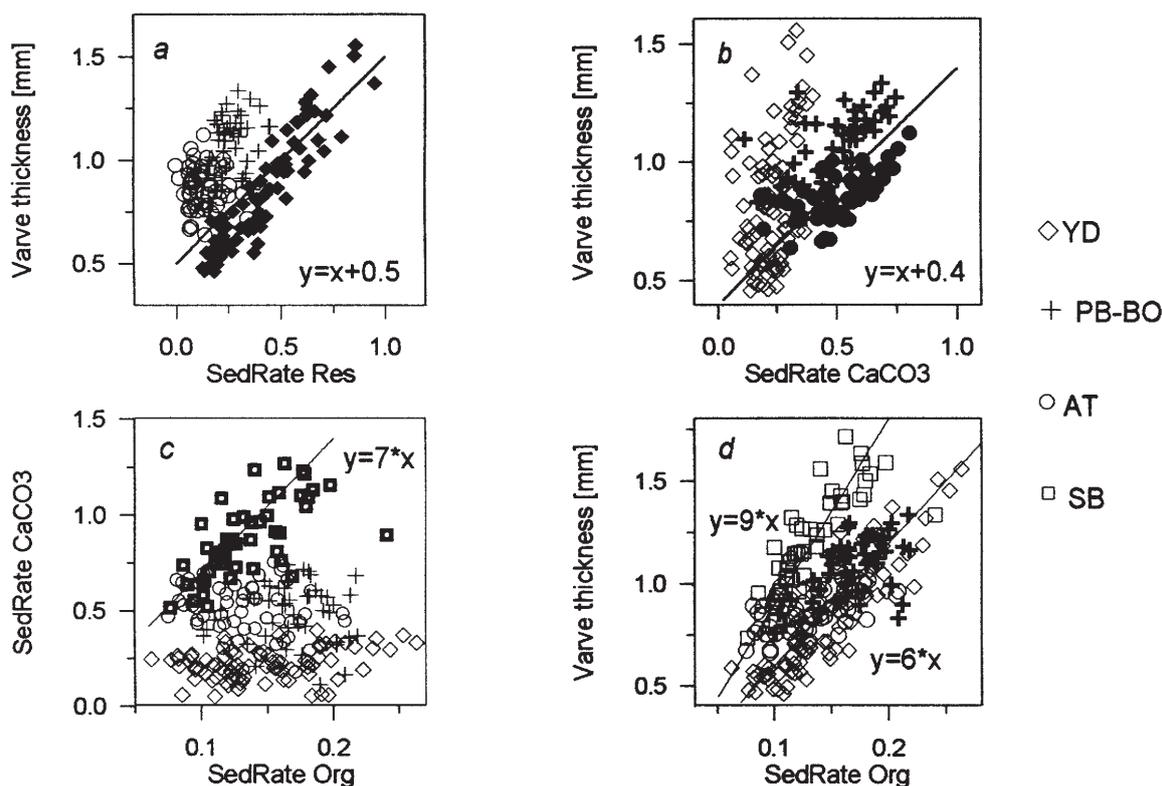
Fig. 6.9. Correlation between annual sedimentation rate and sedimentation rate of main components of the Lake Gościąż sediments in the part covered by floating varve chronology. The correlations in the Late-Glacial section (YD) and in several chronozones of Holocene (PB through SB) are distinguished. Each point represents a single sample with analysed content. a, b, d – correlation between thickness of whole varve and sedimentation rate of main components, c – correlation between sedimentation rate of carbonate and organic components of sediment. For better differentiation, some symbols in some graphs are bold-faced.

The accumulation of carbonate, on the other hand, remains approximately constant through the Late-Glacial and early Preboreal. In Preboreal and Boreal, the variations of varve thickness are produced mostly by carbonate, although some changes are caused by the fluctuation of residual matter. The decrease of varve thickness at the beginning of Atlantic chronozone is caused by decreasing accumulation of carbonates which, ca. 1 kyr later, tend to rebuild gradually and replace residual matter. From the middle of Atlantic chronozone on, the major source of varve-thickness variations is fluctuations of carbonate content. Until the end of Atlantic they seem to be independent of changes in organic matter, but during Subboreal clear correlations between accumulation of organic matter and carbonates (r = 0.66) and between organic and residual matter (r = 0.48, the oldest 5 samples from SB excluded) are established. This would mean that the carbonate precipitation was controlled by lake productivity and would reflect the most stable hydrologic regime of the lake at that time. The exceptionally strong maximum of residual matter at the AT/SB boundary has been interpreted by Ralska-Jasiewiczowa & van Geel (1992) as reflecting strong erosion after opening of the forest canopy at the time of the elm decline. The variations of varve thickness in Subboreal reveal clear 200-yr periodicity (Walanus, Chapter 6.5).

As shown in Figs 6.9a and 6.9b the main component controlling varve thickness changed from residual matter in Late-Glacial to carbonate in Holocene. The best correlation between accumulation of organic matter and carbonate exists in Subboreal (Fig. 6.9c). The distinct correlation between accumulation of organic matter and deposition rate (Fig. 6.9d) appears in Late-Glacial and Subboreal sections of sediment.

The proportional dependence between the accumulation of organic and carbonate sediment in Subboreal does not imply the constant ratio of light to light+dark laminae thickness (ThR) because the carbonate is deposited also in the dark layer (see Goslar, Chapter 9.2.2). The light layers, on the other hand, are almost free of organic matter, and the calcite crystals there are much larger than in the dark layers. The study of seasonal succession in the youngest part of laminated sediment (Goslar, Chapters 9.2.2 and 9.2.3) suggests that the large calcite grains in the light layer are deposited in spring, when the oversaturation of hydrocarbon ions rises rapidly because of plankton blooms and rise of temperature. Therefore the thickness of the light layer would depend rather on the rapidity of plankton bloom and temperature rise during the late spring/early summer than on the total organic productivity. At this stage of calcite precipitation, the degree of oversaturation may decline, restraining the further
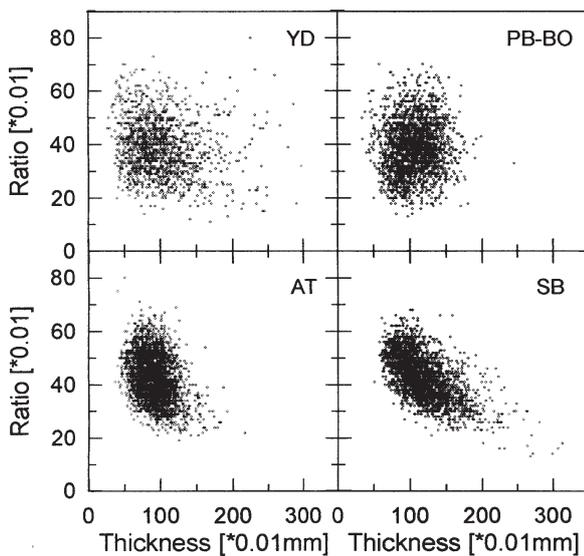
Fig. 6.10. Correlation between ratio of light laminae and whole varve thickness, and the varve thickness itself, in several sections of the Lake Gościąż sediment, in the part covered by floating varve chronology. Each point represents single year.

formation of large crystals and stopping the deposition of the light layer. Due to that, the ratio of carbonate deposited in light and light+dark layer also depends on total organic productivity and hence is inversely correlated with the varve thickness. As shown in Fig. 6.10, the highest correlation between that ratio and varve thickness (r = -0.61; 2500 points) occurs in the Subboreal section where the lamination is most regular, while the correlations in YD and PB-BO sections are rather weak.

The short-term (annual) variations of varve thicknesses and ThRs in the well dated uppermost part of laminated sediment section are correlative with that of tree-ring widths of oaks from different localities in Poland (Goslar, Chapter 9.2.2). Similarly, significant correlation between ThRs in the 2600 yr long sequence from Subboreal part of the sediment and tree-ring widths from Germany has been found (see next chapter). However, no direct correlation between short-term variations of varve thickness in the uppermost section and climatic parameters was found.

Correlation between laminae thickness and absolutely dated tree-ring width sequences

The excellent quality of lamination in the Subboreal part of Lake Gościąż sediments enabled the construction of a sequence 2636 varves long, with the uncertainties of single years occurring at only three levels. The minimal error of the long sequence (i.e. +2,-1 years) enables its realistic comparison with the thickness of accurately dated treerings elaborated by dendrochronologists. The reliability of such an approach is demonstrated by comparison of records of Gościąż varve thickness and thickness ratios for the period AD 1839–1926 with the oak chronologies from several localities in Poland (Ważny 1990). It has been shown that both types of sequence are correlative, and the correlation coefficient revealed reasonable dependence on geographical location of oaks (Goslar, Chapter 9.2.2). The ratios were positively correlated, while the thicknesses themselves negatively correlated with the tree-ring widths.

Since the oldest absolutely dated tree-ring sequences from Poland reach only to the first millennium BC, the oak chronologies from western Europe were used. The similarity of varve and tree-ring thickness could not be expected to be too high, so any significant correlation should only be found by comparison of very long sequences, made for several oak chronologies. The oak chronologies used (Fig. 6.11a) were: EUROPA 3218–2001BC "343M04A", EUROPA 3599–2501BC "343M04B", EUROPA 2129–1140BC "343M05A" (Schmidt pers. comm.) and the long Bog Chronology elaborated by Leuschner (Ważny, pers. comm.). The combined regional chronologies "Europa" contain the master chronologies from southern Germany, constructed by Becker (see e.g. Becker 1981, 1982, Becker & Schmidt 1993), from central Germany (elaborated by Schmidt, see Schmidt 1973, 1987), and Northern Ireland (elaborated by Pilcher and Baillie, see Pilcher et al. 1977, 1984). The correlation between tree-ring thickness and ratios of laminae thickness was expressed in terms of "t"-value used in dendrochronological dating (Baillie & Pilcher 1973). First, the thickness series d_i was transformed into sequence of indices x_i, where the fluctuations longer than 5 yr were filtered out:

$$x_i = ln(\frac{5 \cdot d_i}{d_{i-2} + ... + d_{i+2}})$$

and the t-value was calculated according to the formula:

$$t = \frac{r \cdot \sqrt{(N-2)}}{1 - r^2}$$

where r is the correlation coefficient and N is the length of the sequence.

The "t"-values were calculated for every position of overlap, in the range corresponding to the uncertainty of varve counting in the upper 7.43 m of sediment. This means that the age of the younger end of FVC could float between 2700 and 3400 cal BP (in other words: the age of the varve no. 5000 could float between 4700 and 5400 cal BP). It was assumed that in the true position of overlap the 't'-values should be high for the correlation with all dendroscales. Some complication arises from the three uncertainties in long varved sequences. Two of them allowed an addition of single year (correction: 0 or 1), and one allowed a subtraction of single year (correction: -1 or 0) from the chronology. For that reason, the correlations were checked for $2^3 = 8$ possible combinations of
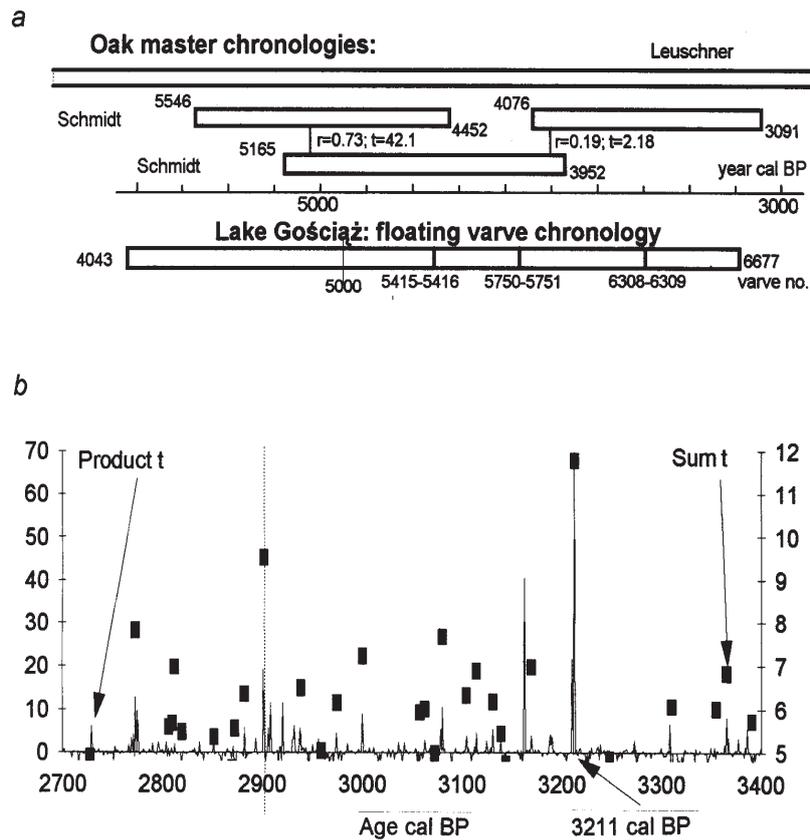
Fig. 6.11. Correlation of floating varve chronology (FVC) of Lake Gościąż with the absoluteily dated tree-ring width sequences. a – Diagram showing the time relationship between chronologies of German oaks (above the time axis) and the section of FVC (below). Correlation between dendroscales is expressed in terms of correlation coefficient and 't'-value. Near the bar representing the 2636-varves long sequence of FVC, varve numbers of the ends as well as the doubtful levels are displayed. The varve chronology is situated in the most probable position derived from the varve counting in the upper part of sediment ($2900 \, ^{+500}_{-200}$). b – Results of correlation of the section of FVC and four absolutely dated tree-ring width sequences, as a function of the age of the younger end of FVC. The correlation is expressed in terms of the sum (right scale) and product (left scale) of 't'-values (see the text).

corrections, and the highest correlation has been found for the combination (1,0,1). Since both the sum and product of 't'-values for the position 3211 cal BP are much higher than the next highest values (Fig. 6.11b), this correlation may be regarded as not incidental, and claims for the shift of the FVC towards the older age by 311 years.

The estimation of significance level of the correlation found is not a simple task. The 't'-value, if calculated for uncorrelated random sequences of normally distributed variables, has a Student's distribution with k = N–2 degrees of freedom. For example, probability of obtaining t = 5 for the sequences 1000 yr long is in such a case less than 0.000001. If the number of degrees of freedom is high, the Student's distribution can be approximated by the Gaussian one. In the case of comparison of one series with a few (say, k) sequences not correlated with one another, the probability of obtaining the sum of 't' values: Sumt = $t_1 + t_2 + ... + t_k$ has also normal distribution with the dispersion equal to the square root of k. Actually, the sequences of indices reveal autocorrelation, which causes the distribution of 't' to have similar shape but greater

dispersion than the Student's one (Goslar & Walanus 1987). Therefore high "t" values happen much more frequently than predicted by Student's distribution. Moreover, the tree-ring sequences correlate strongly with one another, and also for that reason the high values of Sumt happen much more frequently than in the ideal case. The last complication is that the value of Sumt considered is not a random one, but the highest from the large set of values. In the correlation of Lake Gościąż sequence with single oak chronology 700 positions of overlap and 8 combinations of corrections were checked. The effects of autocorrelation as well as intercorrelation of dendroscales may be taken into account if the given value of Sumt is related to its actual distribution. The crucial assumption is that the actual distribution of Sumt is normal, with the dispersion equal to standard deviation calculated from the set of values obtained (s = 2.78). This gives:

$$P_{rnd}\,(Sumt > 11.79) = P\,(x > \frac{11.79}{2.78} = 4.24) < 1.1 \cdot 10^{-5} = \alpha$$

where x has the normal distribution N(0,1). The probability that the maximum of M values of Sumt is greater

than 11.79 is approximately M (M = 5600) times higher (Barnett & Lewis 1978):

$$P(Sumt_{\max M} > 11.79) \approx 1 - (1 - \alpha)^M \approx \alpha \cdot M \approx 0.06$$

This would mean that the correlation observed for T_{FVC} = 3211 cal BP could be obtained by chance with the probability of 0.06, so presumably it is not incidental. It must be stressed that the estimation is highly approximate, mainly because the actual distribution of Sumt is not exactly known. It must be also stressed that calculated in the same way the probability for the second highest value of Sumt: M · P_{rnd}(Sumt > 9.53) = 1.4 agrees with the expectation that the second highest value happened by chance. The level of significance of the product of 't' values was not estimated.

6.4. ABSOLUTE AGE OF FLOATING VARVE CHRONOLOGY OF LAKE GOŚCIĄŻ

Tomasz Goslar

According to varve counting in the upper part of the Lake Gościąż sediments (Fig. 6.12, see Goslar, Chapter 6.1), the age of the floating varve chronology (FVC) could be estimated with a relatively large error, i.e. 2900 $^{+500}_{-200}$ cal BP. More precise dating was possible by

radiocarbon dating and dendro-match. Both evidences point to a shift of FVC towards the older ages:

1. The wiggle match of AMS radiocarbon dates to calibration curve fixes the FVC at 3140±120 cal BP, (Goslar et al., Chapter 6.2), which means that the dating of FVC is older by 240±120 yr. It should be pointed out that the lowest minimum in the S-square curve in Fig. 6.6a (Chapter 6.2) occurs for T_{FVC} = 3216 cal BP.

2. The correlation between 2638 yr long series of laminae thicknesses and sequences of tree-ring widths of German oaks (Goslar, Chapter 6.3) suggests the dating of the younger end of FVC to 3211 cal BP, corresponding to the shift of FVC towards the older age by 311 yr.

The close agreement between results given by both methods allows us to believe that the dendro-match is real. Therefore the calendar age of younger end of floating varve chronology was determined to T_{FVC} = 3211 cal BP, and this age has been used in all reconstructions presented in this book, unless clearly stated otherwise. The [14]C – and dendro-match of FVC enabled reliable dating of two events reconstructed by palynological analysis, which, previously dated by varve counting only, appeared too young in comparison with independent estimates:

1. The maxima of *Secale cereale*, *Cannabis* cf. *sativa*, and other taxa in the first half of first millennium AD
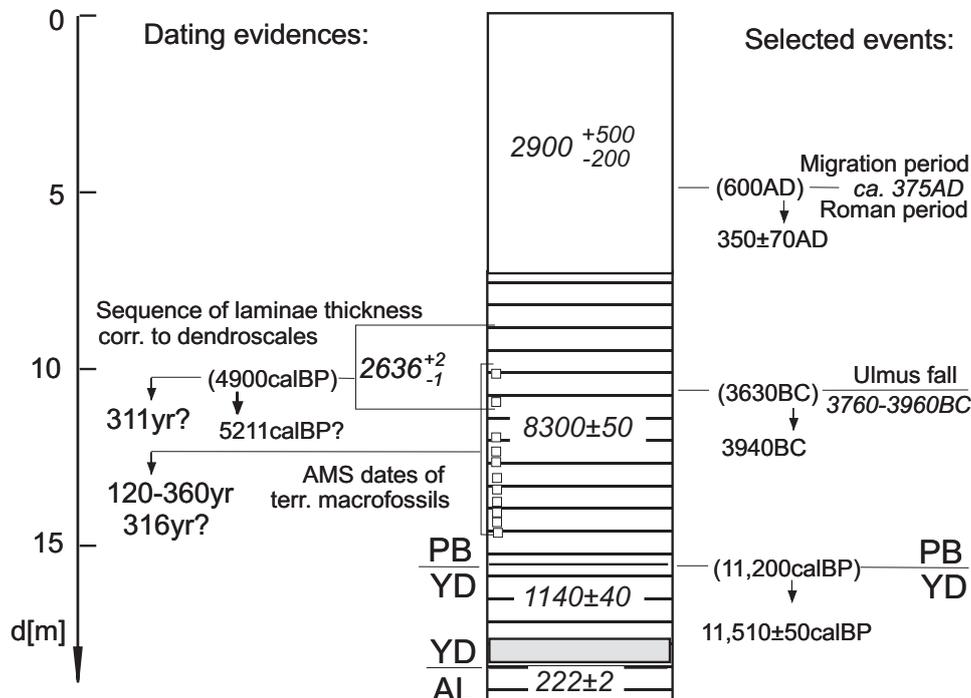

Fig. 6.12. Diagram illustrating the absolute dating of floating varve chronology (FVC) of the Lake Gościąż sediments in comparison to the age resulted from varve counting in the upper part of profile. The numbers of varves in the Allerød, Younger Dryas, and Holocene sections of FVC and in the upper part of profile are shown inside the column. Two kinds of evidence (left-hand side) point for the correction of the age of FVC by 311 yr or by 120–360 yr with respect to the age predicted by varve counting alone. At the right-hand side of figure, the ages of selected events derived from varve counting alone (shown in parentheses) and from the corrected absolute chronology, are compared with independent age estimates (shown in italics). Small open squares show the approximate positions of terrestrial macrofossils dated by radiocarbon.