AMS RADIOCARBON MEASUREMENTS FROM THE SWEDISH VARVED CLAYS

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ABSTRACT. The Swedish varve chronology, or Swedish Time Scale, is an annual chronology based upon the successive correlation of more than 1000 varve-thickness diagrams. The Late Glacial-Early Holocene varved clays were deposited as glaciolacustrine sediments in the Baltic Sea during the recession of the Scandinavian ice sheet. Formation of varved clays continued throughout the Holocene and is still going on in the estuary of River Ångermanälven in northern Sweden. Accelerator mass spectrometry (AMS) radiocarbon measurements, which have been performed on terrestrial plant macrofossils extracted from the varved clays, show—in comparison with other annual chronologies—that several hundreds of varve years are missing in the varve chronology. These findings are supported by, among others, pollen stratigraphic investigations on time-equivalent varve year intervals. If an effort were undertaken to evaluate the erroneous parts, the Swedish Time Scale would have the potential of becoming a continuous annual chronology.

INTRODUCTION

Since De Geer's (1912) famous publication, where he introduced the Swedish Time Scale (STS) to an international audience and presented the first annual (varve) chronology based upon glaciolacustrine and estuarian sediments, the interest in the Swedish varved clays has varied considerably. Initially, De Geer's (1912) chronology was greatly acknowledged (see e.g. Zeuner 1950). But later, when radiocarbon dating became more and more common, several errors became obvious (Olsson 1970), which gradually led to a decreasing international interest in the STS. In Sweden, however, large efforts were undertaken to revise the varve chronology and to firmly connect it to present time (Strömberg 1983, 1985a, 1985b, 1994; Cato 1987; see e.g. also the summaries in Björck et al. 1992 and Wohlfarth et al. 1995, 1993).

In general, the STS is composed of two different types of clastic, varved sediments (see Figure 1). The older "gotiglacial" and "finiglacial" varves are glacio-lacustrine varved clays with distinct couplets of thin fine sand/silt and thicker clay layers (Wohlfarth et al. 1993, 1995). They were deposited in the Baltic basin during the retreat of the inland ice and reflect the melting of the ice during summer as well as the gradual settling of clay particles during winter, when the Baltic was ice covered. The younger postglacial varves are delta sediments, which were and still are deposited in the estuary of River Ångermanälven in northern Sweden (Cato 1987, 1998; Wohlfarth et al. 1997). They are composed of thick and fairly coarse silt or sand and thin clay, to fine silt couplets and mirror river discharge variations in spring/summer and calmer conditions during winter.

The STS is based on a visual correlation of more than 1000 successively overlapping varve-thickness diagrams, which have been established based upon varve thickness measurements in open sections (e.g., De Geer 1912, 1940; Lidén 1913; Cato 1998) or on sediment cores (e.g. Cato 1987; Ringberg 1991; Strömberg 1989, 1994; Brunnberg 1995; Wohlfarth et al. 1998a). The dense net of investigated varved clay sites in many of the local chronologies (Figure 1) facilitates the correlation between single varve diagrams and provides several replicate time series. Therefore, if varves are missing or disturbed due to local processes at one site, the problematic time interval can easily be covered by varve measurements at a neighboring locality (see e.g. Figure 2). The same holds true for erroneous measurements due to an over- or underestimation of varves, although this is a rarely encountered problem because the boundaries between summer and winter layers are very distinct. In
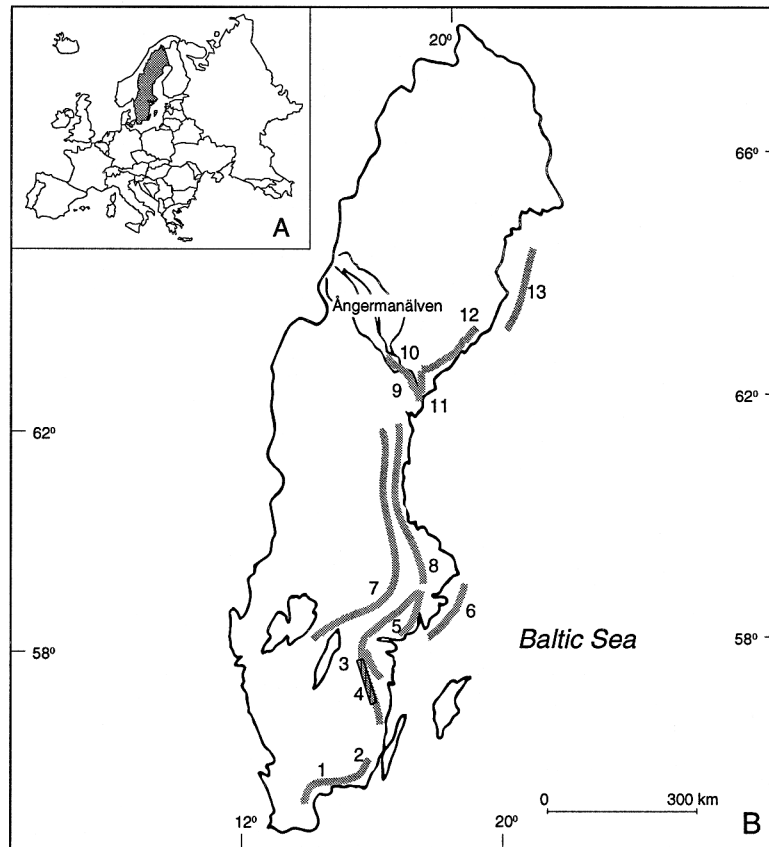
Figure 1 Europe and Sweden (A) and geographical location of the different local varve chronologies which are part of the Swedish Time Scale (B). Modified after Andrén et al. (1999) and Cato (1998). The different local chronologies were established by: 1) Ringberg (1991), 2) Ringberg and Rudmark (1985), 3) Kristiansson (1986), 4) Wohlfarth et al. (1998a), 5) Brunnberg (1995), 6) Andrén et al. (1999), 7) Strömberg (1989; 1994), 8) De Geer (1940), 9) Cato (1998), 10) Hörnsten and Olsson (1964), 11) Cato (1987), 12) Bergström (1968), and 13) Andrén (forthcoming). The gotiglacial varved clays are covered by the local chronologies 1–6 and by the older part of chronologies 7 and 8. The finiglacial varved clays are contained in the younger part of chronologies 7 and 8 and in chronologies 10, 12, and 13. The postglacial part of the STS is represented in the youngest part of chronologies 7 and 8 and in chronologies 9 and 11. Links between the gotiglacial and finiglacial parts of the STS were made according to varve-diagram correlations in chronologies 7 and 8 and between the finiglacial and postglacial parts of the STS according to correlations presented in chronologies 7–9. The link to the present is made through chronology 11 (Cato 1987). The AMS ^{14}C measurements shown in Table 1 were obtained on varve sequences from chronologies 4, 7, and 9.

general, the structure of the STS has more resemblance with a tree-ring chronology than with a varve chronology established upon sediment cores in a single lake basin. For the gotiglacial and finiglacial varves the correlations follow the receding ice margin, i.e. the varved clays/varve-thickness diagrams become younger from south to north (e.g. Strömberg 1983; Holmquist and Wohlfarth 1997). In the case of the postglacial varves, the correlation is from northwest to southeast, i.e. following the isolation of the delta surfaces (Cato 1987, 1998).
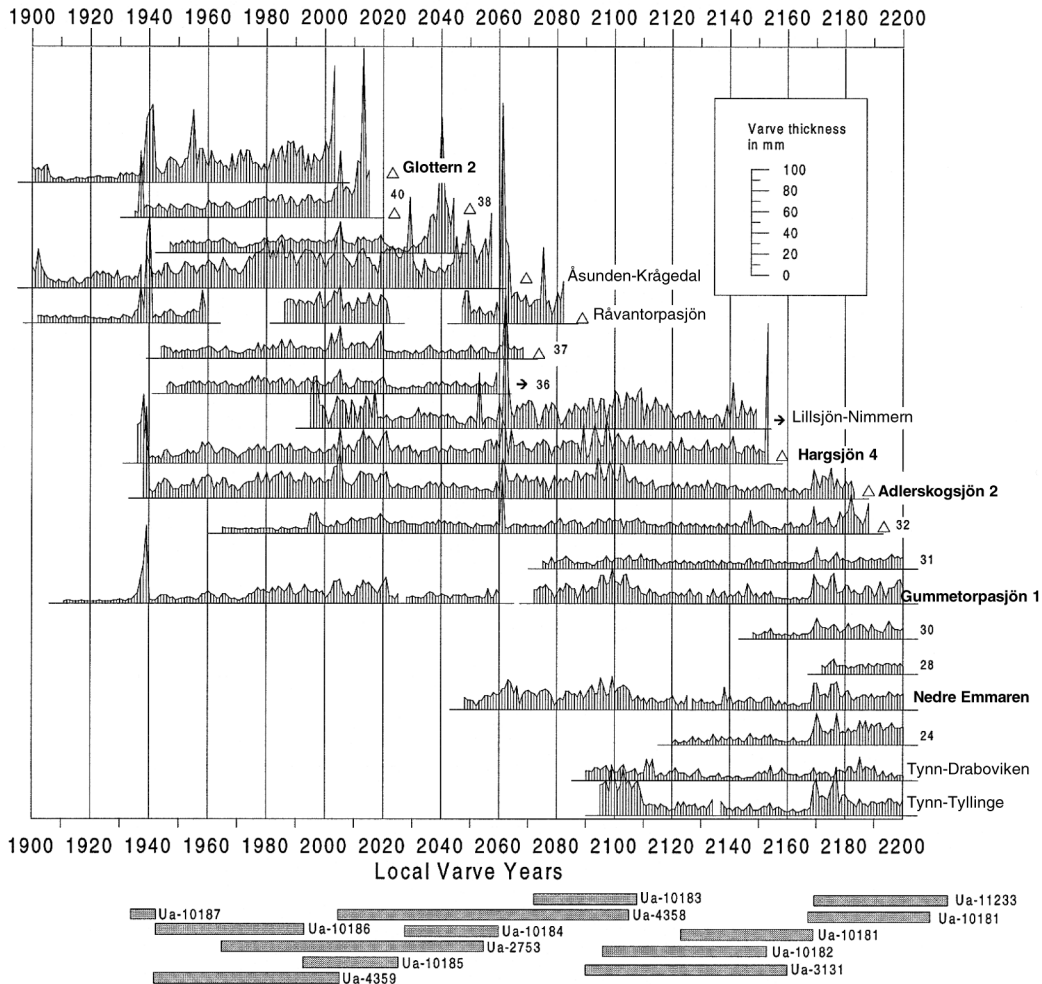
Figure 2 Example of a varve-diagram correlation from chronology 4 (Wohlfarth et al. 1998a). The varve-year intervals covered by the AMS ^{14}C measurements from southeastern Sweden (see Table 1) are marked. The localities from which the ^{14}C-dated varve sequences were obtained are shown in bold letters.

According to the most recent revisions of the varve chronology (summarized in Wohlfarth et al. 1993 and Björck et al. 1992), it was assumed that the STS covers about the last 13,300 calendar years (Wohlfarth et al. 1995). However, based among others on AMS ^{14}C measurements on terrestrial macrofossils extracted from the varved clays, it became gradually clear that the chronology is still not complete and that several hundreds of years are missing, both in the older (Björck et al. 1996; Wohlfarth 1996; Wohlfarth et al. 1998a) and in the younger part (Wohlfarth et al. 1997; Andrén et al. 1999; Björck et al. forthcoming) of the time scale. Consequently, the STS cannot yet be regarded as a continuous annual chronology. Here we present these ^{14}C dates, their varve ages (according to the Swedish varve chronology) and their estimated calendar-year ages and show where likely errors in the time scale may be situated.

METHODS

The methodological approach for obtaining the AMS ^{14}C measurements has been in detail described in Wohlfarth et al. (1995; 1998a) and is only shortly summarized here:

1. Coring for varved clays in areas where varve chronologies have already been established. Thickness measurements of the individual summer and winter layers, establishment of computer-drawn varve-thickness diagrams for each coring site, visual and statistical correlations to close-by varve-thickness diagrams (Figure 2), which are part of the STS, assignment of local varve years.

2. Sampling of 25–100 varve-year segments from the obtained clay-varve cores, sieving the samples under running water (mesh width 0.5 mm), selecting suitable terrestrial plant macrofossil remains (e.g. leaves, fruits, seeds and flowers of *Betula nana*, *Dryas octopetala*, *Salix polaris*, and *Salix* sp.) for AMS ^{14}C measurements.

3. The first set of samples was stored in distilled water, to which several drops of 2% HCl were added to attain a pH of ~2. The samples were kept in a cold room for 1 month to 1 year prior to the AMS measurements. After realizing that bacteria and/or fungi easily attack wet-stored samples, the samples were submitted immediately to the ^{14}C laboratory following sieving and identification. Although this procedure largely reduced the errors, the dating results were still not completely satisfactory. Therefore, and based on results from a parallel study (Wohlfarth et al. 1998b), the selected plant macrofossils were immediately dried after sieving and determination on aluminium foil overnight at 50–60 °C.

4. Sample preparation at the ^{14}C laboratory included acid-alkali-acid (AAA) chemical pre-treatment (1% HCl and 0.5% NaOH at 80 °C for 4 h) followed by combustion with CuO, Fe-catalytic graphitization (Vogel et al. 1984) and AMS measurements with the Uppsala EN-tandem accelerator (Possnert 1990).

All together, 74 samples were measured, but only the 32 samples presented in Table 1 are considered reliable. All other samples provided measurements that were several thousand years younger than expected. Replicate AMS ^{14}C samples covering the same varve year intervals (Wohlfarth et al. 1998a) and experiments with plant macrofossil samples (Wohlfarth et al. 1998b) showed that bacteria and/or fungi had affected the samples, which gave erroneously young ages (see above). The too young ^{14}C age of the samples could furthermore be confirmed by pollen stratigraphic investigations over the ^{14}C dated varve year intervals.

RESULTS

Following the arguments outlined in Björck et al. (1996), Wohlfarth (1996), Wohlfarth et al. (1997; 1998a), Andrén et al. (1999), and Björck (1999, 2000), major correlation problems still exist in the Swedish varve chronology. Although several of the individual local and regional chronologies are fairly well established (Figure 1), problematic areas with weak varve-diagram correlations remain. It is, therefore, at present not possible to assign calendar-year ages based upon a continuous varve chronology to the AMS ^{14}C dates presented below. Alternative approaches, such as wiggle-matching and calibration of the ^{14}C dates with the OxCal Program (Ramsey 1999), comparisons with the ^{14}C/varve curve presented by Kitagawa and van der Plicht (1998), correlations of pollen stratigraphic zones to the GRIP Event stratigraphy (Björck et al. 1998; Walker et al. 1999) or the synchronization of the AMS ^{14}C dates with Lake Gościąż presented in Goslar et al. (1999), allow circumventing some of the problems (Table 1). In the following, the ages that were obtained through wiggle-matching/calibration (Ramsey 1999) and through a visual correlation with the curve presented by Kitagawa and van der Plicht (1998) are expressed as cal BP and those obtained from the synchronization with Lake

Table 1 AMS ^{14}C measurements on terrestrial plant macrofossils from the Swedish varve chronology and the local varve years covered by each sample; the years were obtained through a correlation of the varve diagrams to the local varve chronologies in each area. See below for details.[a]

Lab nr (Ua-)	[14]C AMS age (BP) ±1 σ	Local varve years	Cal BP ±2 σ[b]	Estimated cal BP[c]	Estimated cal GZ BP[d]	GRIP Events	Adjusted varve BP[e]
Southernmost Sweden							
4247	12,595 ± 360	+108 − +170	14,950 ± 600	ca. 15,150		GI-1e	
2469	12,740 ± 150	+142 − +226	14,850 ± 600	ca. 14,700		GI-1e	
4245	12,330 ± 370	+167 − +181	14,850 ± 600	ca. 14,820		GI-1e	
4248	12,310 ± 145	+171 − +214	14,850 ± 600	ca. 14,620		GI-1e	
4246	12,590 ± 130	+182 − +216	14,850 ± 600	ca. 14,580		GI-1e	
3132	12,090 ± 185	+266 − +299	13,950 ± 500	ca. 13,750		GI-1d	
Southeastern Sweden							
2725	11,820 ± 150	Correlation not possible	13,850 ± 500				
2750	11,520 ± 225		13,550 ± 600				
4945	11,539 ± 130		13,500 ± 500				
11233	10,740 ± 240	2273–2169	—[f]		12,871	GI-1a	
10181	11,450 ± 240	2231–2167	—		12,849	GI-1a	
11234	10,885 ± 250	2169–2123	13,058 ± 40		12,769	GI-1a	
10182	11,470 ± 130	2153–2093	—		12,788	GI-1a	
3131	10,890 ± 120	2160–2090	13,038 ± 38		12,775	GI-1a	
10183	11,030 ± 120	2108–2072	13,003 ± 38		12,740	GI-1a	
4358	10,980 ± 100	2105–2005	12,968 ± 38		12,705	GI-1a	
10184	10,970 ± 90	2060–2028	12,958 ± 38		12,694	GI-1a	
2753	10,480 ± 150	2055–1965	—		12,660	GI-1a	
10185	11,230 ± 100	2025–1993	—		12,659	GI-1a	
4359	10,610 ± 110	2004–1942	—		12,623	GS-1	
10186	11,040 ± 110	1993–1943	—		12,618	GS-1	
10187	10,420 ± 220	1942–1934	—		12,588	GS-1	
4496	10,585 ± 465	1906–1806	12,768 ± 38		12,506	GS-1	
Eastern Middle Sweden							
4217	10,330 ± 175	11,485–11,457	12,210 ± 200			GS-1	12,346
4216	10,620 ± 155	11,456–11,418	—			GS-1	12,312
2742	9945 ± 115	11,381–11,331	—			GS-1	12,231
4215	10,140 ± 155	11,228–11,128	11,915 ± 195			GS-1	12,053
4214	10,170 ± 195	11,126–11,104	11,850 ± 200			GS-1	11,990
2741	9640 ± 190	11,081–10,973	11,745 ± 205			GS-1	11,902
4212	10,160 ± 115	11,020–11,000	—			GS-1	11,885
11829[g]	9970 ± 120	10,618–10,546	11,320 ± 200			Holocene	11,457
Northeastern Sweden							
11230	4720 ± 135	4710 ± 5	5350 ± 350			Holocene	

[a]Calibrated BP are based on:

[b]Wiggle-matching with the OxCal Program (Ramsey 1999), except for samples 2725, 2750, and 4945, which were only calibrated.

[c]Visual matching to the ^{14}C/varve curve presented by Kitagawa and van der Plicht (1998).

[d]Synchronization with Lake Gościąż presented in Goslar et al. (1999) and Wohlfarth et al. (1998), correlation of pollen-stratigraphic zones to the GRIP Event stratigraphy (Björck et al. 1998; Walker et al. 1999).

[e]Adjusted varve BP are according to Andrén et al. (1999), who suggest that 875 years are missing in the STS.

[f]— indicates that wiggle-matching did not produce statistically significant results.

[g]Radiocarbon date published in Björck et al. (forthcoming). See text for further explanation.

Gościąż (Goslar et al. 1999) as cal GZ BP, in order to differentiate between the different approaches. "Local varve yr" refer to local varve years in each separate (local) varve chronology and "varve BP" to the chronology suggested for the STS (e.g., Strömberg 1994; Brunnberg 1995).

AMS ^{14}C–Varve Chronology in Southernmost Sweden

The varve chronology in southernmost Sweden was established by Ringberg (1991) and Ringberg and Rudmark (1985) and covers the local varve yr −325 to +314 (chronologies 1 and 2 in Figure 1). Later, additional clay-varve diagram correlations allowed prolonging the varve chronology to the year +368 (Ising 1998; Wohlfarth et al. 1994). The local varve chronology in southernmost Sweden has thus a total length of 694 varve yr. The tentative link between this and the local varve chronology in southeastern Sweden (chronology 3 in Figure 1), which had been suggested by Björck and Möller (1987), led Wohlfarth et al. (1995) to assume an age of around 12,650–13,300 varve BP for chronologies 1 and 2.

Based on pollen-stratigraphic investigations in varved clays by Björck (1981), Wohlfarth et al. (1994) placed the transition between the Bølling and Older Dryas pollen zones at the local varve year +220. The varved clays deposited between the years +108 to +220 would accordingly correlate with the Bølling pollen zone, while those between +220 and +299 would correspond to the Older Dryas pollen zone. Compared to the event stratigraphy suggested by Björck et al. (1998) and Walker et al. (1999) varve yr +108 to +220 would then relate to the youngest part of GI-1e (14,050–14,160 GRIP BP), while varve yr +220 to +299 would fall within GI-1d (14,050–13,970 GRIP BP) (see Table 1). Wiggle-matching (Ramsey 1999) and the visual correlation (to Kitagawa and van der Plicht's [1998] curve) of the AMS ^{14}C measurements presented in Table 1 (corresponding to the local varve yr +108 to +216), give considerably older ages, ranging at around 14,950–14,850 and 15,150–14,580 cal BP, respectively (Table 1). The cal yr age of the youngest AMS ^{14}C date, however, seems to be in good agreement with the GRIP age estimate for the Older Dryas/GI 1d (Table 1). The discrepancy between the two age estimates could be an artifact and explained by the fairly large standard error of some of the ^{14}C measurements, which makes their exact ^{14}C age highly uncertain. Furthermore, ^{14}C calibration during this time period is still weak due to the large ^{14}C plateau at around 12,600 BP. This, together with the standard error of our ^{14}C dates, makes cal yr age attributes very imprecise.

In accordance with other lake-sediment studies in this area (pollen stratigraphy, lake isolation, shore displacement curves) by e.g. Björck (1981) and Björck and Möller (1987) and based on the above outlined arguments, we assume that the AMS ^{14}C dated part of the varved clays was deposited between the end of the Bølling and during the early part of the Older Dryas pollen zone or, during the youngest part of GI-1e and during GI-1d according to Björck et al. (1998) and Walker et al. (1999). Although the cal BP attribution remains uncertain, except for the youngest sample, it is clear that the varves in southernmost Sweden are between 1200 and 2400 years older than earlier assumed by Wohlfarth et al. (1995) (Figure 3).

AMS ^{14}C–Varve Chronology in Southeastern Sweden

The varve chronology for southeastern Sweden had been established by Kristiansson (1986) (chronology 3 in Figure 1). It was partly revised by Brunnberg (1995), who tentatively connected it to his chronology (chronology 5 in Figure 1), which in turn is connected to the main part of the STS. Chronology 3 covers the local varve yr 2825–515, i.e. a total length of 2310 varve yr. Following Brunnberg's (1995) correlations, this part would correspond to 12,830–10,520 varve BP. However, detailed cross-correlation analyses of all varve diagrams in Kristiansson's (1986) chronology (Holmquist and Wohlfarth 1997) made it evident that many of the visual correlations are statistically
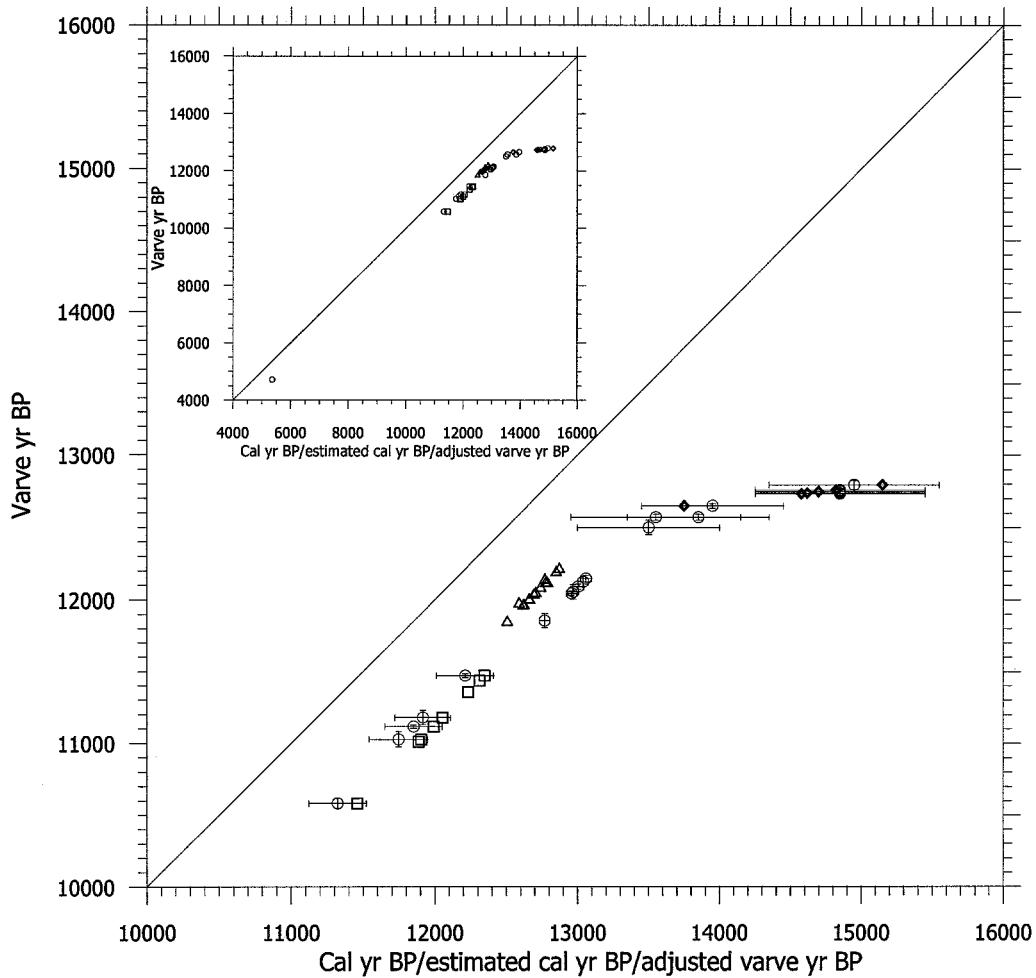
Figure 3 Comparison between varve BP (according to the STS, see Wohlfarth et al. 1995, Table 1) and different cal yr estimates for the AMS ^{14}C measurements (see text for discussion) shown in Table 1. Open circle = cal BP according to INTCAL98, open diamonds = cal BP according to Kitagawa and van der Plicht (1998), open triangles = calendar BP obtained through a comparison with Lake Gościąż (Goslar et al. 1999), open squares = adjusted varve BP according to Andrén et al. (1999).

not significant. New clay-varve measurements (chronology 4 in Figure 1), combined with AMS ^{14}C dates (Wohlfarth et al. 1998a) and pollen-stratigraphic investigations (Björck 2000), suggested that only the part between 2475–1700 varve yr should be regarded as a reliable chronology.

The AMS ^{14}C measurements obtained between 2457 and 1700 local varve yr (Table 1, Figure 2) were compared to the AMS ^{14}C-dated laminated lake-sediment sequence from Lake Gościąż (Goslar et al. 1999). The best fit between the two sequences was obtained by paralleling the varve yr 2000 with 12,650 cal GZ BP or the Allerød/Younger Dryas boundary. Pollen stratigraphic investigations by Björck (2000) on the same clay-varve sequences later gave clear evidence for an Allerød/Younger Dryas pollen zone boundary at around the local varve year 2000. Based on the best fit with Lake Gościąż, calendar years (cal GZ BP) were calculated for each ^{14}C-dated varve segment (Goslar et al. 1999) (Table 1), as well as for the entire 775-yr long varve chronology (chronology 4) (Wohlfarth et

al. 1998a). Accordingly, this chronology covers the time period between 13,125–12,350 cal GZ BP. The resulting offset of 200–300 yr between the calculated cal yr estimates and those obtained by matching the sequence to Lake Gościąż (Table 1) is easily explained by different estimates for the length of the Younger Dryas. In Lake Gościąż, the length of Younger Dryas is given at around 1150 yr (Goslar et al. 1995), which is in accordance with the GRIP ice core (e.g. Björck et al. 1998). However, in the calibration program (Stuiver et al. 1998) as well as in the GISP isotope stratigraphy (Alley et al. 1997), the length of Younger Dryas is about 1300 yr. Based on the pollen-stratigraphic investigations, the AMS ¹⁴C dates and on their corresponding cal yr estimates, the reliable part of the local varve chronology would correspond to GI-1b, GI-1a and to parts of GS-1 in the event stratigraphy presented by Walker et al. (1999) and Björck et al. (1998). Independent of the divergence between the different cal yr estimates presented in Table 1, it is clear that an offset of >650–1000 yr exists between these and Brunnberg's (1995) and Wohlfarth et al.'s (1995) varve yr estimate for the same time period (i.e. 12,475–11,700 varve BP) (Figure 3).

AMS ¹⁴C–Varve Chronology in Eastern-Middle Sweden

Strömberg (1994) established the varve chronology for central Sweden and connected it to the main part of the STS (chronology 7 in Figure 1). The varved sequence, from which the AMS ¹⁴C dates were obtained, could be correlated to Strömberg's (1994) chronology (Table 1) and covers 11,471–11,010 varve BP in the STS. Based on pollen stratigraphic investigations of varved clays corresponding to 10,735–10,430 varve BP, Björck et al. (forthcoming) concluded, that these varves were deposited during the early Holocene. Andrén et al. (1999) could show that the distinct increase in varve thickness (in chronology 6) at 10,650 varve BP, coincides with the Younger Dryas/Holocene transition and that it compares nicely with the GRIP isotope stratigraphy. The tentative match to the GRIP ice core, led the authors to correlate 10,650 varve BP with 11,525 cal BP (according to GRIP). Björck et al. (forthcoming), on the other hand, based on pollen stratigraphy, correlated 10,740 varve BP (in chronology 7) with 11,525 GRIP cal BP. Despite the slight differences in defining the Younger Dryas/Holocene transition in the varved clays, both comparisons give evidence for an error amounting to 800–900 varve yr.

The adjusted varve yr presented in Table 1 were calculated following Andrén et al.'s (1999) estimate of 875 missing varves. The obtained years correspond well to the cal yr estimates obtained through wiggle-matching (Table 1, Figure 3). Compared to the GRIP Event stratigraphy (Björck et al. 1998; Walker et al. 1999), the time period covered by the AMS ¹⁴C dates shown in Table 1 would thus correspond to parts of GS-1 and to the earliest part of the Holocene.

AMS ¹⁴C–Varve Chronology in Northeastern Sweden

The postglacial varve chronology in northeastern Sweden is based on about a 2000-yr-long chronology from the estuary of River Ångermanälven, AD 1978–50 BC (Cato 1987) and a connection of this chronology to Lidén's (1913) old chronology (Cato 1998) (chronologies 11 and 9, respectively in Figure 1). The latter varve chronology had been established upon varve thickness measurements in bluffs along River Ångermanälven. Cato's (1998) recent revisions and correlations show that the whole postglacial chronology extends back to 9000 varve BP. A link between this chronology and the glaciolacustrine varved clays, which can be found along the east coast up to Ångermanälven, has been attempted by Strömberg (1989). Cato's (1987) 2000-yr long varve chronology has been validated by cross-correlation analyses (Holmqvist and Wohlfarth unpublished) and all varve-diagram correlations have been found to be statistically significant. One AMS ¹⁴C measurement performed on terrestrial plant macrofossils extracted from the postglacial varves at the varve year 4710 ± 5 gave

a calibrated age of 4720 ± 135 BP (5350 ± 400 cal BP, 2 σ) (Table 1, Figure 3). Wohlfarth et al. (1997) suggested that the offset between the varve age and the calibrated age of the sample may point to an error or parts of an error in the varve chronology between 2000 and 5000 varve BP. Unfortunately, due to the scarcity of plant material in the postglacial varves, this AMS ^{14}C date could so far not be supported by replicate ^{14}C measurements.

Where are the 'Missing' Varve Years?

The above outlined arguments make it clear that the STS, despite the many efforts during the last decades, can still not be regarded as a continuous annual chronology. However, the obtained AMS ^{14}C dates combined with pollen stratigraphic investigations and new clay-varve measurements allow pointing to areas where these errors could be found and corrected.

The first package of "missing" varves (>800 yr) shows up at the beginning of the Holocene and/or in the middle part of the postglacial varves (Figure 3). Since Strömberg's (1989) and Brunnberg's (1995) chronologies (7 and 5 in Figure 1) are generally regarded as reliable, two possibilities remain for finding the weak points: within the postglacial chronology (chronology 9) or at the link between chronologies 9 and 7. A re-evaluation of some of the postglacial varve-diagram connections and new varve measurements in the area between chronology 7 and 9 would easily solve this problem.

Only 650 varves are missing at the Allerød/Younger Dryas boundary, if we adopt the match between the AMS ^{14}C dated varve sequence and Lake Gościąż (Goslar et al. 1999). However, if we follow the estimated cal BP obtained from wiggle-matching, the missing varves amount to about 1000 (Figure 3), which is more in agreement with the 875 missing years suggested by Andrén et al. (1999). But, since the younger part of chronology 3 is characterized by insignificant varve-diagram correlations (Holmqvist and Wohlfarth 1997), the link between chronology 3 and chronologies 7 and 5 is fairly weak, and Andrén et al.'s (1999) chronology does not reach as far back as the Allerød/Younger Dryas boundary, we do not know how many varve years are contained in the STS between the Allerød/Younger Dryas transition and the Younger Dryas/Holocene boundary. One important task would, therefore, be to reinvestigate the varve-diagram correlations in the younger part of chronology 3 in order to obtain a firm link between chronologies 3 and 5. Another possibility would be to prolong chronology 5 by new clay varve measurements and to link it to the well established chronology 4.

At the Bølling/Older Dryas boundary, which has been defined in varve chronology 1, the offset between estimated cal BP and the earlier assumption of 12,700–12,800 varve BP (Wohlfarth et al. 1995; Table 1) amounts to approximately 1200–2400 yr. This would mean that the number of "missing" varves has increased additionally as compared to the Allerød/Younger Dryas and Younger Dryas/Holocene transition. No valid link exists between chronology 2 and chronology 3, and the older part of chronology 3 is, furthermore, highly uncertain (Holmqvist and Wohlfarth 1997). The additional error may, therefore, very likely be found if new clay-varve measurements could be performed in the area between chronologies 2 and 3 and in the older part of chronology 3.

CONCLUSION

The Swedish varve chronology or STS is based upon the successive matching of more than 1000 varve-thickness measurements performed in open sections or on sediment cores. Deposition of the older glacio-lacustrine varved clays occurred in the Baltic basin during the recession of the Scandinavian inland ice. The younger postglacial varves are delta sediments, which are now exposed along the bluffs in River Ångermanälven and which are still deposited today in the estuary of River Ångermanälven in northeastern Sweden.

Although the Swedish varve chronology had been regarded as a continuous annual chronology, several independent lines of evidence have pointed to major errors. These errors may be found by re-evaluating older varve-diagram correlations and by establishing firm links between the different local varve chronologies through new clay-varve measurements. Until these errors are resolved, the STS remains a floating varve chronology, without a possibility to assign calendar years BP to its AMS ^{14}C dated and pollen stratigraphic investigated parts. Through wiggle-matching, calibration and/or synchronization of the AMS ^{14}C-dated intervals in combination with pollen stratigraphic investigations, tentative cal yr could be obtained, which allow estimating the number of "missing" varves within the varve chronology. The offset between the STS and the tentative cal BP presented in Table 1 can be assumed to be in the order of >800 yr at the Younger Dryas/Holocene boundary, of around either 650 yr or 900–940 yr at the Alleröd/Younger Dryas transition, of around 1300 yr at the Bölling/Older Dryas boundary and of >2000 yr in the oldest part of the chronology (Figure 3).

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