A new middle Holocene varve diagram from the river Ångermanälven, northern Sweden: indications for a possible error in the Holocene varve chronology

BARBARA WOHLFARTH, SVANTE BJÖRCK, INGEMAR CATO AND GÖRAN POSSNERT

BOREAS

Wohlfarth, B., Björck, S., Cato, I. & Possnert, G. 1997 (December): A new middle Holocene varve diagram from the river Ångermanälven, northern Sweden: indications for a possible error in the Holocene varve chronology. *Boreas*, Vol. 26, pp. 347–353. Oslo. ISSN 0300-9483.

A new varve diagram from the river Ångermanälven could be correlated to the postglacial varve chronology to between 4903 and 4415 varve years BP. An AMS ^{14}C measurement on terrestrial macrofossils obtained between 4715 and 4706 varve years BP gave a calibrated age of between 5730 and 5040 calendar years BP. The discrepancy between varve and calender-year age indicates that an error or part of an error in the Swedish varve chronology may be situated between 2000 and 5000 varve years BP.

Barbara Wohlfarth, Department of Quaternary Geology, University of Lund, Tornavägen 13, S-22363 Lund, Sweden; Svante Björck, Geological Institute, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark; Ingemar Cato, Geological Survey of Sweden, Box 670, S-751 28 Uppsala, Sweden; Göran Possnert, Tandem Laboratory, Box 533, S-75121 Uppsala, Sweden; *received 30th January 1997, accepted 21st August 1997.*

The importance of annually laminated sediments as proxy data for past climate reconstructions has led to a renewed focus on the Swedish Time Scale or Swedish varve chronology with the initiation of several new research projects. Both the youngest Holocene and the Late Weichselian varves are currently investigated regarding their suitability as past climate indicators.

Following the last decade's major revisions (Strömberg 1985; Kristiansson 1986; Cato 1987; Strömberg 1989; Cato 1992; Björck *et al.* 1992; Brunnberg 1995; Lidén & Cato unpublished), the Swedish varve chronology had been regarded as a continuous annual record, as far back as *c.* 13 300 BP (Wohlfarth *et al.* 1995). However, when AMS ^{14}C dates from the Late Weichselian varves and their corresponding varve years BP were compared with other AMS ^{14}C-dated calendar-year records, such as the laminated lake sediment sequence from Gosciaz (Goslar *et al.* 1995a, b) or the U/Th coral record (Bard *et al.* 1993, 1996), an offset between the Swedish varve chronology and these data sets was clearly visible (Wohlfarth 1996).

Recently, the calibration of the densely spaced AMS ^{14}C measurements derived on terrestrial plant macrofossils from three Swedish lakes made it possible to assign a calendar-year age to the Younger Dryas–Preboreal climatic change and to the so-called Preboreal Oscillation (Björck *et al.* 1996). Based on a preliminary revised dendro-calibration curve, the new calendar-year age for the Younger Dryas–Preboreal transition was placed at 11 450–11 390 BP and the Preboreal Oscillation could be dated to 11 200–11 050 calender years BP (Björck *et al.* 1996). In addition to this revision, it was recently possible to overlap the 9000–8800 ^{14}C-year plateau with radiocarbon dates from both oak and pine tree-rings (B. Kromer, pers. comm.). With this new calibration the German pine chronology becomes 154 years older than in the preliminary revision by Björck *et al.* (1996). Accordingly, the onset of the Younger Dryas–Preboreal transition is now situated at 11 600 calendar years BP and the beginning of the Preboreal Oscillation at 11 350 calendar years BP.

Following pollen stratigraphic investigations in lakes and peat bogs on the Swedish east coast, the Preboreal Oscillation coincides with the ingression of saline marine water into the Baltic Sea, the so-called Yoldia ingression (Svensson 1989; Björck *et al.* 1996). This marine ingression is also clearly marked in the varved clays by a change from distinct grey varves to symmict clays and by the occurrence of marine bivalves (*Portlandia arctica*) and forminifera (e.g. *Elphidium excavatum*) (Strömberg 1989; Brunnberg & Possnert 1992; Brunnberg 1995, Wastegård *et al.* 1995). According to the varve chronology, the marine ingression commenced at *c.* 10 430 varve years BP (Strömberg 1989; Brunnberg 1995) and lasted for *c.* 70–120 varve years (Wastegård *et al.* 1995). The Younger Dryas–Preboreal climatic transition in the varved clays has not yet been assessed by direct pollen stratigraphic evidence, but may indirectly be interpreted from the rapid increase in ice recession (Strömberg 1994). Accelerated ice recession started *c.* 10 940 varve years BP, but is most pronounced from *c.* 10 740 varve years BP onwards (Strömberg 1994; Brunnberg 1995).

The comparison between the above cited calendar years and the varve years assigned to the Younger Dryas–Preboreal transition and to the Preboreal Os-

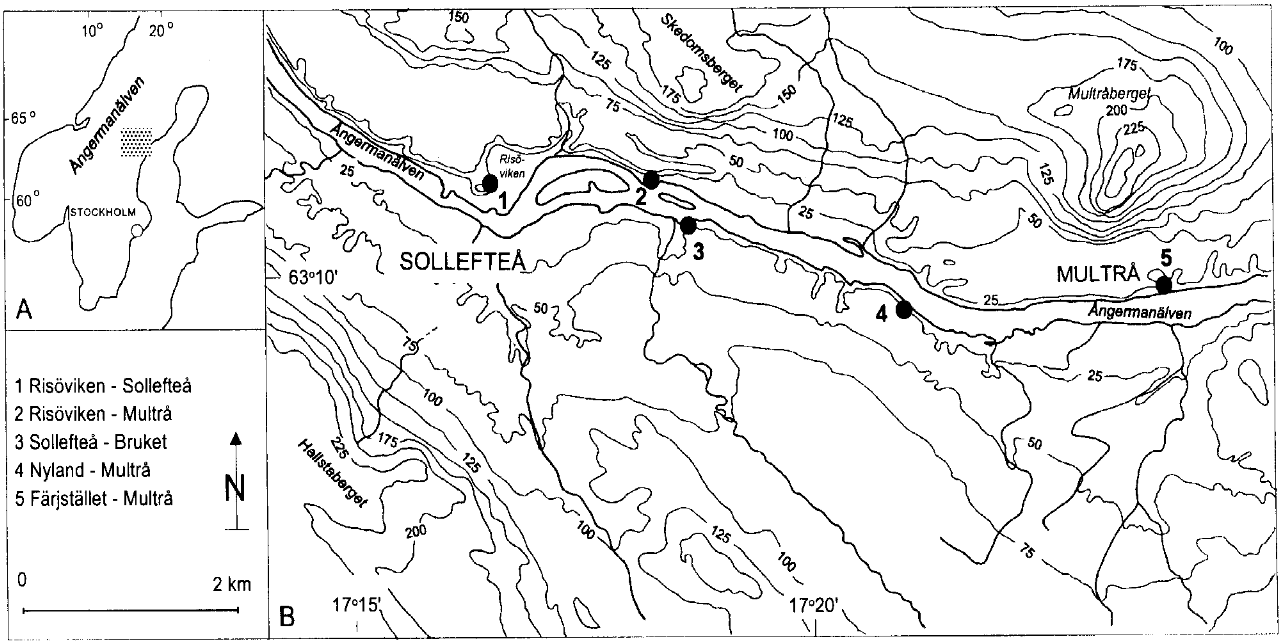

Fig. 1. A. Sweden and the location of the river Ångermanälven. B. Location of the measured varve diagram and Lidén's (1913, 1938) diagrams from the surroundings of Sollefteå.

cillation/Yoldia ingression shows a discrepancy of *c.* 800–900 years and indicates that this large error should be situated in the Holocene part of the Swedish Time Scale. The correlation of the youngest Holocene varve diagrams, which cover the last *c.* 2000 varve years (AD 37–1978) (Cato 1987, 1985) could be verified by cross-correlation analysis (Wohlfarth *et al.* unpublished). Therefore, we assume that the error must lie in the older part of the Holocene chronology (Strömberg 1989; Lidén & Cato unpublished), i.e. prior to 2000 varve years BP. The most convenient way of detecting errors in the varve chronology is to AMS ^{14}C date terrestrial macrofossils sieved out from the varved clays and to compare their calibrated ages (Stuiver & Reimer 1993) to the corresponding varve ages.

In a first attempt and, as a feasibility study, we tested whether it was possible to find enough terrestrial macrofossils in the Holocene varved clays of the Ångermanälven valley for AMS ^{14}C dating (Fig. 1). This approach is similar to the method applied to the Late Weichselian varves where varved-clay sections along a previously established varve chronology are measured and sampled and the obtained varve diagrams correlated to the existing chronology (Wohlfarth *et al.* 1993, 1994, 1995). Here, we present preliminary results based on a new Middle Holocene varve diagram from Ångermanälven and on its correlation to Lidén's diagrams (Lidén & Cato unpublished) and discuss the significance of the obtained AMS ^{14}C measurement.

The Holocene varve chronology

Lidén (1913, 1938) has originally established the younger part of the Holocene chronology. Based on clay-varve measurements in numerous bluffs along the river Ångermanälven, he presented a 7522 varve-year long chronology. In contrast to the glaciolacustrine Late Weichselian and early Holocene varves, these varves were deposited as annually laminated delta sediments. The down-river sloping delta was gradually built up during the isostatic uplift from areas now situated *c.* 230 m a.s.l. and down to the present coast of the Gulf of Bothnia (Cato 1987). Accordingly, each varve in the delta sediments begins at the delta surface, where its proximal part corresponds to the river mouth situation for the corresponding year. From the delta surface the varve plunges distally towards the lower reaches of the valley at the same time as it progressively becomes finer grained, thins out, and is overlain by gradually younger varves. In this way, the upper postglacial sediment series of the alluvial sediments was successively formed along the valley down to the position of the present river mouth.

During recent years, Cato (1987, 1985) revised the youngest part of Lidén's (1913, 1938) chronology, between AD 37 and 1978, and could thus prolong Lidén's chronology to 9266 varves (up to AD 1979) or 9237 varves BP (AD 1950). He showed that the varves were deposited annually and that varve formation is still in progress in the estuary of Ångermanälven.

A validation of the older part of Lidén's chronology has indirectly been made by comparing shore-displacement curves derived from the isolation of lake basins with Lidén's shore-displacement curve established upon former delta surfaces along the river Ångermanälven (Renberg & Segerström 1981; Lundqvist 1987; Cato 1992). For these comparisons, both Lidén's uncorrected (Renberg & Segerström 1981; Lundqvist 1987) and, according to Cato (1992) revised curves were used (Lundqvist 1987). On the whole these comparisons showed a fairly good agreement with Lidén's curve and indicated that the Holocene varve chronology can be regarded as acceptable. However, the lake-isolation studies had all been made at lakes located far outside the region of the Ångermanälven valley. Cato (1992), therefore, compared the extended and revised shore-displacement curve of Lidén (Lidén & Cato unpublished) with lake isolation studies from within the Ångermanälven valley (Segerström *et al.* 1984; Wallin 1993). The two curves overlap between 3000 and 8000 varve years BP and show a good agreement at their end points, but display an offset of *c.* 300 years between *c.* 4000 and 7000 varve years BP. Lundqvist (1987), who found a corresponding discrepancy around 6000 varve years BP, interpreted this as a slow-down of the general regression of the sea. This slow-down, which cannot be seen in Lidén's curve, was interpreted as an effect of the eustatic sea-level movement which, outside the central parts of the former glaciated area, appears as a transgression between 6000 and 8000 varve years BP (Cato 1992).

Field and laboratory methods

Lidén's (1913, 1938) main sections are located along river Ångermanälven, north and south of the town of Sollefteå (Fig. 1), where several of the 20–30 m high bluffs of blueish-grey and orange-coloured fine sand to silt and clay laminae are now a nature conservation area. During summer 1996, we measured a new varve section in a bluff, located between Lidén's (1913) sites Sollefteå-Risöviken and Multrå-Nyland.

The measured bluff is situated NE of the Sollefteå at the locality 'Sollefteå-Bruket' (N63°10′10″; E17°18′45″) between an altitude of 5 and 30 m a.s.l. (Fig. 1). The total thickness of the section was estimated at approximately 25 m. However, only the uppermost *c.* 11 m was accessible, while the lower part was covered by debris. To reach into the underlying varves, a 1-m-deep hole had to be excavated. Before measuring the varves, the outcrop was cleaned carefully. Varve thickness was measured with a ruler and the thickness of each summer and winter lamina was noted. The data set (available in an ASCII format from the authors) is displayed in Fig. 2.

A total of eight sediment samples (*c.* 3–5 kg each) was taken at irregular intervals throughout the whole section and covered between 1 and 20 varve years. Within one month after fieldwork, the samples were sieved wet through an 0.5 mm mesh and visible macrofossils were continuously picked out. Clearly determinable, terrestrial macrofossils were immediately dried overnight at 50°C and submitted in sterilized glass bottles to the AMS facility in Uppsala.

Description and results

The measured section has a total thickness of 9.14 m and comprises 489 varve years. Varve thickness increases gradually upwards, but is most pronounced from varve no. 446 upward (Fig. 2). The varves are generally composed of blueish-grey clayey winter and orange to reddish silty summer laminae. However, from varve no. 448 and upwards and coinciding with an increase in varve thickness, the winter laminae are made up of silt and summer layers of fine sand. The uppermost 3 m of the bluff, where the varve thickness was not measured, consists of thick coarse sandy and silty flood-plain sediments, which overlie the varved delta sediments. Characteristic features, such as organic content, uncertain varves, erosive varve boundaries and eroded summer and winter laminae were observed in a few cases and are noted in Table 1.

Out of eight samples, only samples 3 (varves 95–105) and 4 (varves 188–197) contained terrestrial macrofossils, i.e. seeds and catkin scales of *Betula* (Fig. 2). The organic material in sample 3 was not enough for an AMS ^{14}C measurement (dry sample weight 1.0 mg), but sample 4 with a dry weight of 1.7 mg gave an age of 4720 ± 135 ^{14}C BP (Ua-11230). When calibrated according to Stuiver & Pearson (1993), this ^{14}C date gives a calendar-year age of 5610–5290 BP (one standard deviation) or 5730–5040 BP (double standard deviation).

Correlation to the Holocene varve chronology

Lidén's (1913, 1938) varve diagrams are all characterized by a drastic increase in varve thickness in the youngest part of each diagram. This change in thickness is also accompanied by a change in lithology from silty summer and clayey winter laminae to sandy summer and silty winter laminae, reflecting the gradual build-up to the delta surface and the change from distal to proximal formed delta varves. The varve diagrams, which were established in the vicinity of Sollefteå (Figs. 1, 3), clearly illustrate this development. The revised Holocene chronology (Lidén & Cato unpublished) places Lidén's Sollefteå diagrams between 5651 and 3996 varve years BP (Table 2).

The visual correlation of our new diagram from Sollefteå-Bruket to Lidén's diagrams Nyland-Multrå and Risöviken-Sollefteå shows that they correlate well

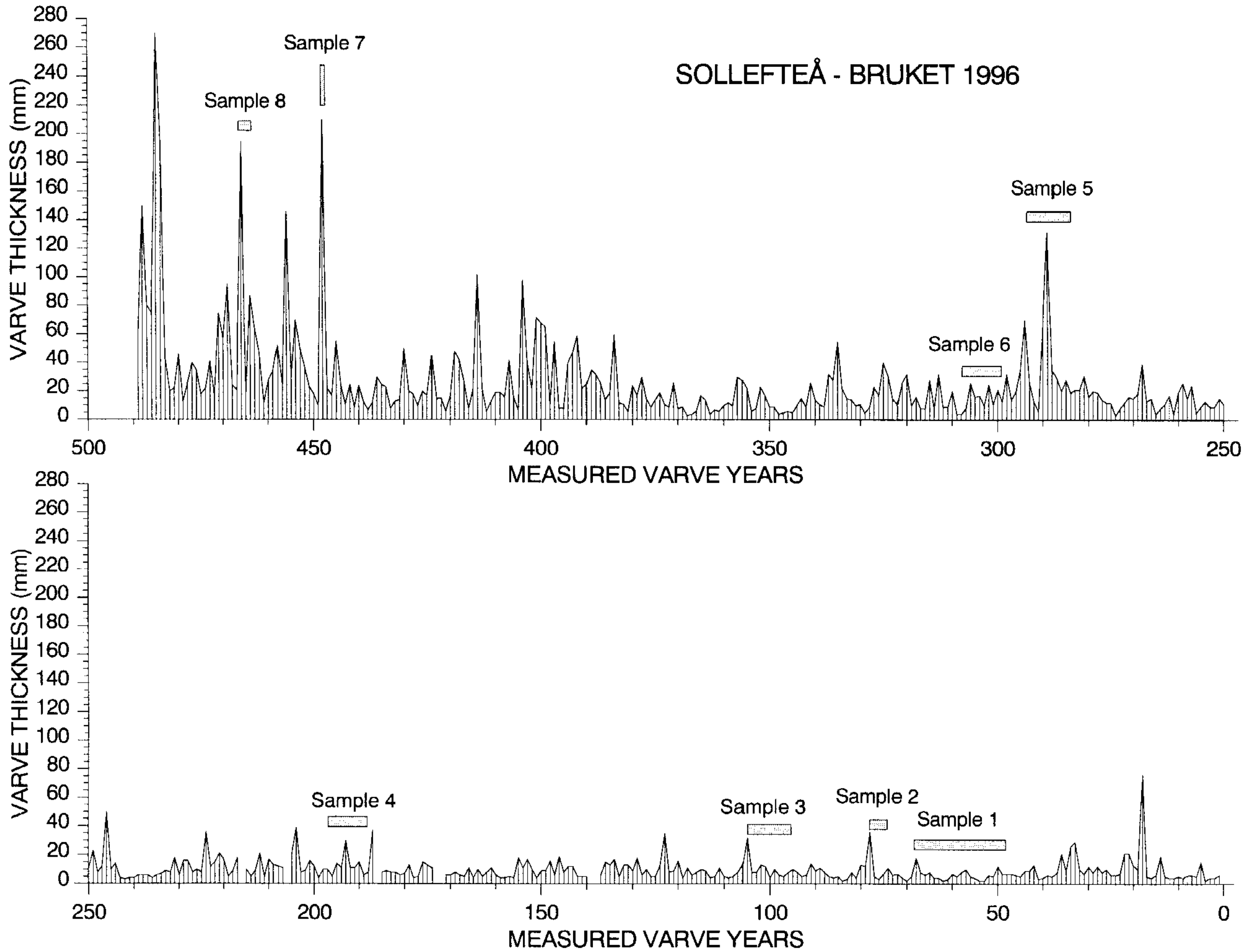

Fig. 2. Varve diagram from Sollefteå–Bruket, measured in 1996. The sequences sampled for sieving are indicated.

with each other in the time period between 4903 and 4415 varve years BP (Fig. 4). The varve age BP for our AMS ^{14}C date, obtained on sample 4, is situated between 4715 and 4706 varve years BP, while the calibrated date gives an age of 5610–5290 (one standard deviation) and 5730–5040 (double standard deviation) calendar years BP. Although these values show a wide age range, they indicate that the varve age of our sample is at least 300 years or as much as 1000 years younger than the time-span covered by the calibrated date.

Table 1. Characteristics of the varves measured in the bluff at Sollefteå–Bruket 1996.

Varve No.	Remarks
75, 77	Organic material in summer lamina
156–159	Perhaps 1 or 4 varve years
309–311, 321	Upper boundary eroded
335–339	Varves uncertain and difficult to measure
357	Upper boundary (summer lamina) eroded
385–391	Symmict varves
402	Upper boundary (summer lamina) eroded
404–411	Varves uncertain and difficult to measure
406–411	Uncertain, summer lamina may be eroded
412	Upper boundary (summer lamina) eroded
446–454	Varves uncertain and difficult to measure
448	Diffusely laminated sand layer with reworked clay balls (possibly winter lamina)
454	Only silt lamina present
472	Upper boundary (summer lamina) eroded

Discussion

When only one radiocarbon date has been obtained on a sediment sequence, it is not possible to cross-check the reliability of such a date. Although the measurement may give the correct age, possible sources of error exist; the date may be unreliable because of contamination by older, redeposited material, or it may become too young because of the small sample size. In our case, the radiocarbon sample could be too old, owing to redeposition as a consequence of

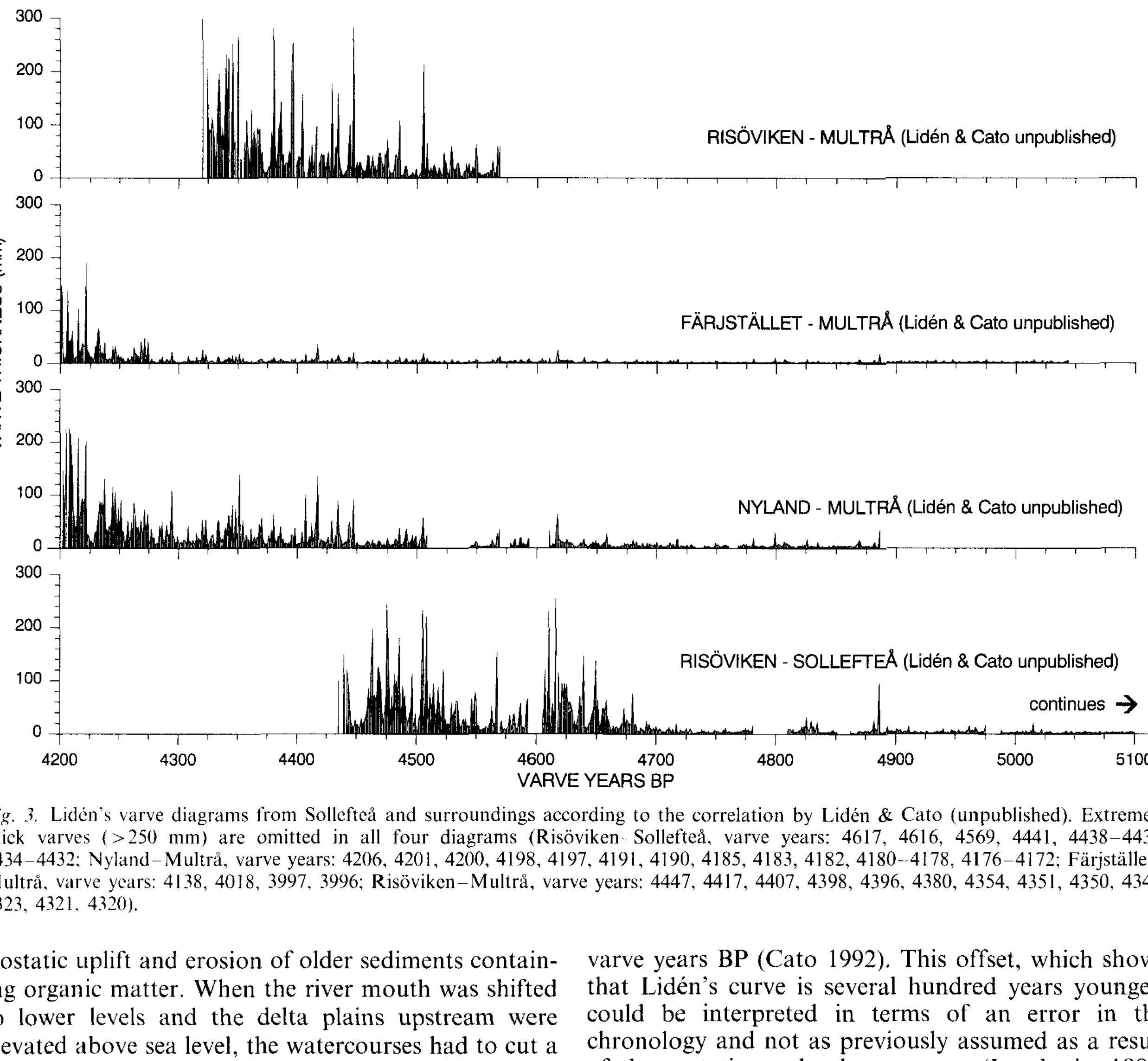

Fig. 3. Lidén's varve diagrams from Sollefteå and surroundings according to the correlation by Lidén & Cato (unpublished). Extremely thick varves (>250 mm) are omitted in all four diagrams (Risöviken–Sollefteå, varve years: 4617, 4616, 4569, 4441, 4438–4436, 4434–4432; Nyland–Multrå, varve years: 4206, 4201, 4200, 4198, 4197, 4191, 4190, 4185, 4183, 4182, 4180–4178, 4176–4172; Färjstället–Multrå, varve years: 4138, 4018, 3997, 3996; Risöviken–Multrå, varve years: 4447, 4417, 4407, 4398, 4396, 4380, 4354, 4351, 4350, 4348, 4323, 4321, 4320).

isostatic uplift and erosion of older sediments containing organic matter. When the river mouth was shifted to lower levels and the delta plains upstream were elevated above sea level, the watercourses had to cut a new way through the loose sediments down to the underlying substratum. Consequently, already deposited sediments including organic material were transported and redeposited on the continuously expanding delta downstream.

The comparison between Liden's shore-displacement curve and the timing of the isolation of lake basins in the Ångermanälven area points to a divergence of *c.* 300 years between *c.* 4000 and *c.* 7000 varve years BP (Cato 1992). This offset, which shows that Lidén's curve is several hundred years younger, could be interpreted in terms of an error in the chronology and not as previously assumed as a result of the eustatic sea-level movement (Lundquist 1987; Cato 1992). If our radiocarbon date reflects the true age of the sediments and not older, reworked material, this discrepancy between calibrated ages and corresponding varve years will be in the order of 300 to 1000 years. Such an error is comparable to the conclusions drawn by Björck *et al.* (1996), who discuss a 800–900-year difference between the calendar-year and varve-year age for both the Preboreal Oscillation/Yoldia ingression and the beginning of the Holocene.

Table 2. The time period covered by Lidén's (1913) diagrams from Sollefteå and Multrå, according to Lidén & Cato (unpublished).

Site name	Varve years BC	Varve years BP
Risöviken - Sollefteå	3701–2482	5651–4432
Risöviken - Multrå	2619–2370	4569–4320
Nyland–Multrå s:n	2936–2222	4886–4172
Färjstället - Multrå s:n	3094–2046	5044–3996

Although we certainly need a larger series of radiocarbon measurements to confirm the discrepancy of 300 to 1000 years between the calibrated age and the varve age of our radiocarbon date, our results add to the fact that an error is present in the Holocene varve chronology. This error may be entirely or partly found between 5000 and 2000 varve years BP. Since the Swedish varve chronology is among those high-resolution geological records, which allow the recon-

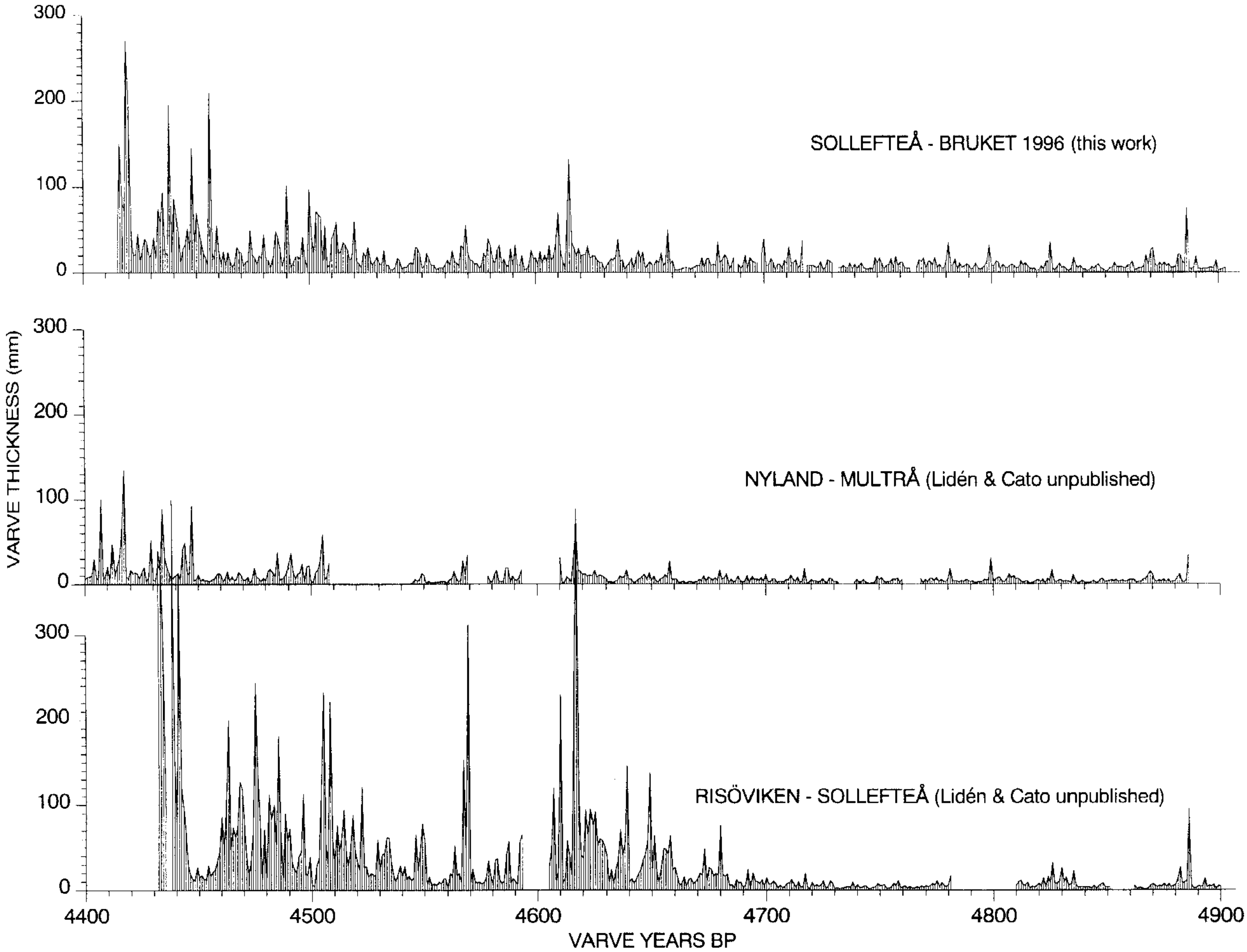

Fig. 4. Correlation of the varve diagram Sollefteå–Bruket to Lidén's diagrams (Lidén & Cato unpublished) from Risöviken–Sollefteå and Nyland–Multrå.

struction of decadal to centennial climate fluctuations, a thorough revision of this time scale would certainly seem appropriate.

Conclusions

1. A new middle Holocene varve section from the river Ångermanälven was sampled and measured. The obtained varve diagram, which could be correlated to Lidén's revised varve chronology (Lidén & Cato unpublished), spans the varve years 4903–4415 BP. Out of eight sediment samples, one sample with a varve age of 4715–4706 BP could be radiocarbon dated.
2. The AMS ^{14}C date performed on seeds and catskin scales of *Betula* gave an age of 4720 ± 135 ^{14}C BP or, a calibrated age 5610–5290 BP (one standard deviation) or 5730–5040 BP (double standard deviation).
3. The discrepancy of 300 to 1000 years between varve ages and calibrated years is a strong indication that an error may be present in the Holocene varve chronology between 5000 and 2000 varve years BP.
4. Although the Swedish varve chronology has been revised several times in recent decades, efforts for a new revision of this geological record should be undertaken.

Acknowledgements. We extend our thanks to the Geological Survey of Sweden for generous financial support, Jessica Ademark for sieving the samples, Ian Snowball for correcting the language and Bo Strömberg and Eiliv Larsen for their constructive comments on the manuscript.

References

Bard, E., Arnold, M., Fairbanks, R. G. & Hamelin, B. 1993: ^{230}Th-^{234}U and ^{14}C ages obtained by mass spectrometry on corals. *In* Stuiver, M., Long, A. & Kra, R. (eds.): Extended ^{14}C Data Based and Revised CALIB 3.0 ^{14}C Age Calibration Program 1993. *Radiocarbon 35*, 191–199.

Bard, E., Hamelin, B., Arnold, M., Montaggioni, L., Cabioch, G., Faure, G. & Rougerie, F. 1996: Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature 382*, 241–244.

Björck, S., Cato, I., Brunnberg, L. & Strömberg, B. 1992: The clay-varve based Swedish Time Scale and its relation to the Late Weichselian radiocarbon chronology. *In* Bard, E. & Broecker, W. S. (eds.): *The Last Deglaciation: Absolute and Radiocarbon Chronologies*, 25–44. Springer, Berlin.

Björck, S., Kromer, B., Johnsen, S., Bennike, O., Hammarlund, D., Lemdahl, G., Possnert, G., Rasmussen, T. L., Wohlfarth, B., Hammer, C. U. & Spurk, M. 1996: Synchronised terrestrial-atmospheric deglacial records around the North Atlantic. *Science 274*, 1155–1160.

Brunnberg, L. 1995: Clay-varve chronology and deglaciation during the Younger Dryas and Preboreal in the easternmost part of the Middle Swedish Ice Marginal Zone. *QUATERNARIA Ser. A*, 3–94.

Brunnberg, L. & Possnert, G. 1992: Radiocarbon dating of the Goti–Finiglacial boundary of the Swedish Time Scale. *Boreas 21*, 89–96.

Cato, I. 1985: The definitive connection of the Swedish Geochronological Time Scale with the present and the new date of the zero-year in Döviken, northern Sweden. *Boreas 14*, 117–122. Oslo.

Cato, I. 1987: On the definitive connection of the Swedish Time Scale with the present. *Sveriges Geologiska Undersökning Ca 68*, 1–55.

Cato, I. 1992: Shore displacement data based on lake isolation confirm the postglacial part of the Swedish Geochronological Time Scale. *Sveriges Geologiska Undersökning Ca 81*, 75–80.

Goslar, T., Arnold, M., Bard, E., Kuc, T., Pazdur, M. F., Ralska-Jasiewiczowa, N., Rozanski, M., Tisnerat, K., Walanus, A., Wicik, B. & Wieckowski, K. 1995a: High concentration of atmospheric ^{14}C during the Younger Dryas cold episode. *Nature 377*, 414–417.

Goslar, T., Arnold, M. & Pazdur, M. F. 1995b: The Younger Dryas cold event – was it synchronous over the North Atlantic region? *Radiocarbon 37*, 63–70.

Kristiansson, J. 1986: The ice recession in the south-eastern part of Sweden. A varve-chronological time scale for the latest part of the Late Weichselian. *University of Stockholm, Department of Quaternary Research Report 7*, 1–132.

Lidén, R. 1913: Geokronologiska studier öfver det finiglaciala skedet i Ångermanland. *Sveriges Geologiska Undersökning Ca 9*, 4–31.

Lidén, R. 1938: Den senkvartära strandförskjutningens förlopp och kronologi i Ångermanland. *Geologiska Förening i Stockholm Förhandlingar 60*, 397–404.

Lundqvist, J. 1987: Beskrivning till jordartskarta över Västernorrlands län och förutvarande Fjällsjö k:n. *Sveriges Geologiska Undersökning Ca 55*, 1–270.

Renberg, I. & Segerström, U. 1981: The initial points on a shoreline displacement curve for southern Västerbotten, dated by varve-counts of lake sediments. *In* Königsson, L.-K & Paabo, K. (eds.): Florilegium Florinis Dedicatum. *Striae 14*, 174–176.

Segerström, U., Renberg, I. & Wallin, J.-E. 1984: Annual sediment accumulation and land history; investigations of varved lake sediments. *Verhandlungen des Internationalen Vereins für Limnologie 22*, 1396–1403.

Strömberg, B. 1985: Revision of the lateglacial Swedish varve chronology. *Boreas 14*, 101–105.

Strömberg, B. 1989: Late Weichselian deglaciation and clay varve chronology in east–central Sweden. *Sveriges Geologiska Undersökning Ca 73*, 1–70.

Strömberg, B. 1994: Younger Dryas deglaciation at Mt. Billingen, and clay varve dating of the Younger Dryas/Preboreal transition. *Boreas 23*, 177–193.

Stuiver, M. & Pearson, G. W. 1993: High-precision calibration of the radiocarbon time scale, AD 1950–500 BC and 2500–6000 BC. *Radiocarbon 35*, 1–23.

Stuiver, M. & Reimer, P. 1993: Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program 1993. *Radiocarbon 35*, 215–230.

Svensson, N.-O. 1989: Late Weichselian and early Holocene shore displacement in the central Baltic, based on stratigraphical and morphological records from eastern Småland and Gotland, Sweden. *LUNDQUA Thesis 25*, 1–195.

Wallin, J.-E. 1993: Den fasta jordbruksnäringens utveckling i Ångermanälvens nedre dalgång under järnåldern och medeltiden – en paleoekologisk undersökning. *Österbottens Högskolas skriftserie*. Umeå.

Wastegård, S., Andrén, T., Sohlenius, G. & Sandgren, P. 1995: Different phases of the Yoldia Sea in the north-western Baltic Proper. *Quaternary International 27*, 121–129.

Wohlfarth, B. 1996: The chronology of the Last Termination: a review of high-resolution terrestrial stratigraphies. *Quaternary Science Reviews 15*, 267–284.

Wohlfarth, B., Björck, S., Possnert, G., Lemdahl, G., Brunnberg, L., Ising, J., Olsson, S. & Svensson, N. O. 1993: AMS dating Swedish varved clays of the last glacial/interglacial transition and the potential/difficulties of calibrating Late Weichselian 'absolute' chronologies. *Boreas 22*, 113–128.

Wohlfarth, B., Björck, S., Lemdahl, G. & Ising, J. 1994: Ice recession and depositional environment in the Blekinge archipelago of the Baltic Ice Lake. *GFF 116*, 3–12.

Wohlfarth, B., Björck, S. & Possnert, G. 1995: The Swedish Time Scale – a potential calibration tool for the radiocarbon time scale during the Late Weichselian. *Radiocarbon 37*, 347–360.