[RADIOCARBON, VOL. 37, NO. 1, 1995, P. 63–70]

THE YOUNGER DRYAS COLD EVENT—WAS IT SYNCHRONOUS OVER THE NORTH ATLANTIC REGION?

TOMASZ GOŚLAR,[1] MAURICE ARNOLD[2] and MIECZYSŁAW F. PAZDUR[1,3]

ABSTRACT. Determined independently from annually laminated ice cores and lake sediments, and German pines, the calendar ages of Younger Dryas (YD) boundaries significantly disagree with one another. ^{14}C dates, plotted *vs.* calendar ages for samples from different sediments, also reveal distinct offsets. The adjustment of varve chronologies to synchronize the boundaries of the YD nearly cancels the discrepancies between ^{14}C data, and supports the synchronism of the YD cold period over the North Atlantic region. However, the exact timing of the event cannot be estimated in this way.

INTRODUCTION

The Younger Dryas (YD), an abrupt, temporary cooling *ca.* 12 ka ago, was the last in a long series of brief climatic oscillations during the past 70 ka. These events were associated with an apparent shift of surface-air temperature in the North Atlantic region of 4–7°C within several decades, as recorded in Greenland ice cores (Johnsen *et al.* 1992; Taylor *et al.* 1993b; Grootes *et al.* 1993). Although the YD has been documented mainly in Greenland ice (Johnsen *et al.* 1992; Alley *et al.* 1993; Dansgaard *et al.* 1993; Dansgaard, White and Johnsen 1993; Mayewski *et al.* 1993; Taylor *et al.* 1993a,b; Grootes *et al.* 1993), in lacustrine sediments in Europe (Watts 1980; Pons *et al.* 1987; Lotter *et al.* 1992; Zolitschka, Haverkamp and Negendank 1992; Goslar *et al.* 1993), and in deep-sea cores from the North Atlantic Ocean (Bard *et al.* 1987; Lehman and Keigwin 1992), evidence of this event has also been found in northeastern America and eastern Canada (Peteet *et al.* 1990; Mott *et al.* 1986; Levesque *et al.* 1993). In Colombia (van Geel and van der Hammen 1973), as well as in deep-sea cores from the Northwest Pacific and the Sulu Sea (Kudrass *et al.* 1991), observations of similar oscillations suggest that the YD was at least a hemispheric event. YD-like events have also been recognized in Africa and Antarctica (Roberts *et al.* 1993; Jouzel *et al.* 1992). Nevertheless, only a few records document the YD cold event with an annual resolution and provide an independent time scale of calendar years. Until now, such records have been concentrated in the North Atlantic region – Greenland Summit (GRIP and GISP2) ice cores, European annually laminated sediments (Swedish varves, Lake Gościąż, Lake Holzmaar and Soppensee) and German pine wood. These records are crucial for better understanding the response of climate in different parts of Europe to major climate shifts in the North Atlantic region. We discuss here the question of synchronism of YD reconstructed in these archives.

DEFINITIONS OF YD BOUNDARIES AND THEIR CALENDAR AGES IN DIFFERENT ARCHIVES

Table 1 lists estimates of the calendar age of the YD/Holocene boundary. The definitions of this boundary differ among archives. The boundary is defined most sharply in the change of accumulation rate of Greenland snow (completed in 20–30 yr). The changes of oxygen isotope ratios in Greenland ice and Lake Gościąż carbonates (50–70 yr) were as rapid as changes of fluxes of calcium and magnesium. The boundary, by convention, is placed in the middle of the period of rise (decline) of appropriate data. The transitions in vegetation cover (Gościąż, Soppensee, Holzmaar) responding to climate warming took a longer time, but major changes were completed in 100–200 yr. Here, the YD/PB (Preboreal) boundary is defined as a boundary between pollen assemblage

[1]Radiocarbon Laboratory, Institute of Physics, Silesian Technical University, Krzywoustego 2, PL-44-100 Gliwice, Poland
[2]Centre des Faibles Radioactivités, CNRS-CEA, F-91198 Gif sur Yvette, France
[3]Deceased 11 May 1995

TABLE 1. Comparison of Calendar-Age Estimates of the Younger Dryas/Holocene Transition

Archive	Definition of boundary	Age (yr BP)	Reference
GRIP ice core	Abrupt increase of ^{18}O	11,550 ± 90	Johnsen *et al.* (1992)
GISP2 ice core	Abrupt increase of ^{18}O	11,640 ± 250	Alley *et al.* (1993);
	Abrupt increase of snow accumulation rate, drop of fluxes, *e.g.* of calcium, magnesium		Taylor *et al.* (1993a,b); Mayewski *et al.* (1993)
Lake Gościąż	Abrupt increase of ^{18}O, changes in terrestrial and lacustrine vegetation	11,440 ± 120	Goslar *et al.* (ms.)
Lake Soppensee	Changes in terrestrial vegetation	10,986 ± 69	Hajdas *et al.* (1993)
Lake Holzmaar	Changes in terrestrial vegetation	10,630 ± 180*	Zolitschka, Haverkamp & Negendank (1992);
		11,510 ± 180†	Hajdas (1993)
Swedish varves	Onset of rapid retreat of ice margin	10,940	Strömberg (1994)
	Second drainage of Baltic ice lake	10,980	
German pines	Increase of ^{13}C and D in wood	(10,970)‡	Becker, Kromer and Trimborn (1991);
		11,045§	Kromer and Becker (1993)

*Varve chronology of Lake Holzmaar
†Varve chronology of Lake Holzmaar corrected with the match of AMS ^{14}C dates to the ^{14}C calibration data
‡Boundary set originally in the pine chronology
§Boundary set originally in the pine chronology, shifted with a tentative tree-ring match to the oak master chronology

zones, and is placed approximately in the middle of the period of rapid change in vegetation. The slowest transition was that observed in isotopic composition of carbon and hydrogen in German pines (*ca.* 500 yr), and here the YD/PB boundary was set at the beginning of the period of change. The duration of major change in the Swedish study is difficult to determine. We must stress that the durations of major climate change, when reconstructed by proxy data of the same type, are similar, but the calendar ages of major change are different, and the differences are well beyond the durations of individual transitions. For that reason, the delay between climate warming recorded in Lake Gościąż, Lake Holzmaar and Greenland Summit, and those recorded in the Swiss lake, Swedish varves and German pines must be regarded as real unless an error is found in the calendar age estimates of appropriate archives. The same problem can be observed in the climate cooling recorded at the transition between the Allerød (AL) and the YD (Table 2).

TABLE 2. Comparison of Calendar-Age Estimates of the Allerød/Younger Dryas Transition

Archive	Age (yr BP)	Reference
GRIP ice core	12,700 ± 100	Johnsen *et al.* (1992)
GISP2 ice core	12,820 ± 260	Alley *et al.* (1993)*
Lake Gościąż	12,580 ± 130	Goslar *et al.* (ms.)
Lake Soppensee	12,125 ± 86	Hajdas *et al.* (1993)
Lake Holzmaar	11,080 ± 210†	Zolitschka *et al.* (1992);
	11,960 ± 210‡	Hajdas (1993)
Swedish varves	11,800	Wohlfarth *et al.* (1993)

*Age reported by Alley *et al.* (1993) was based on the changes in accumulation rate; the quoted age is that of the midpoint of major drop of ^{18}O (Grootes, personal communication)
†Varve chronology of Lake Holzmaar
‡Varve chronology of Lake Holzmaar corrected according to the match of AMS ^{14}C dates to the ^{14}C calibration data

Comparison of Calendar Chronologies

It is always possible that the uncertainties of chronologies, constructed by counting thousands of annual increments, are underestimated. To verify the non-synchronism of AL/YD and YD/PB boundaries apparent in different archives, independent, undoubtedly synchronic markers are necessary. Here, either the layers of volcanic tephra or the global synchronous changes of ^{14}C age can be used.

In Figure 1, we compare the ^{14}C dates from all the archives discussed here (except Greenland ice, of course), with the calibration data based on Barbados and New Guinea corals. In the upper part of the

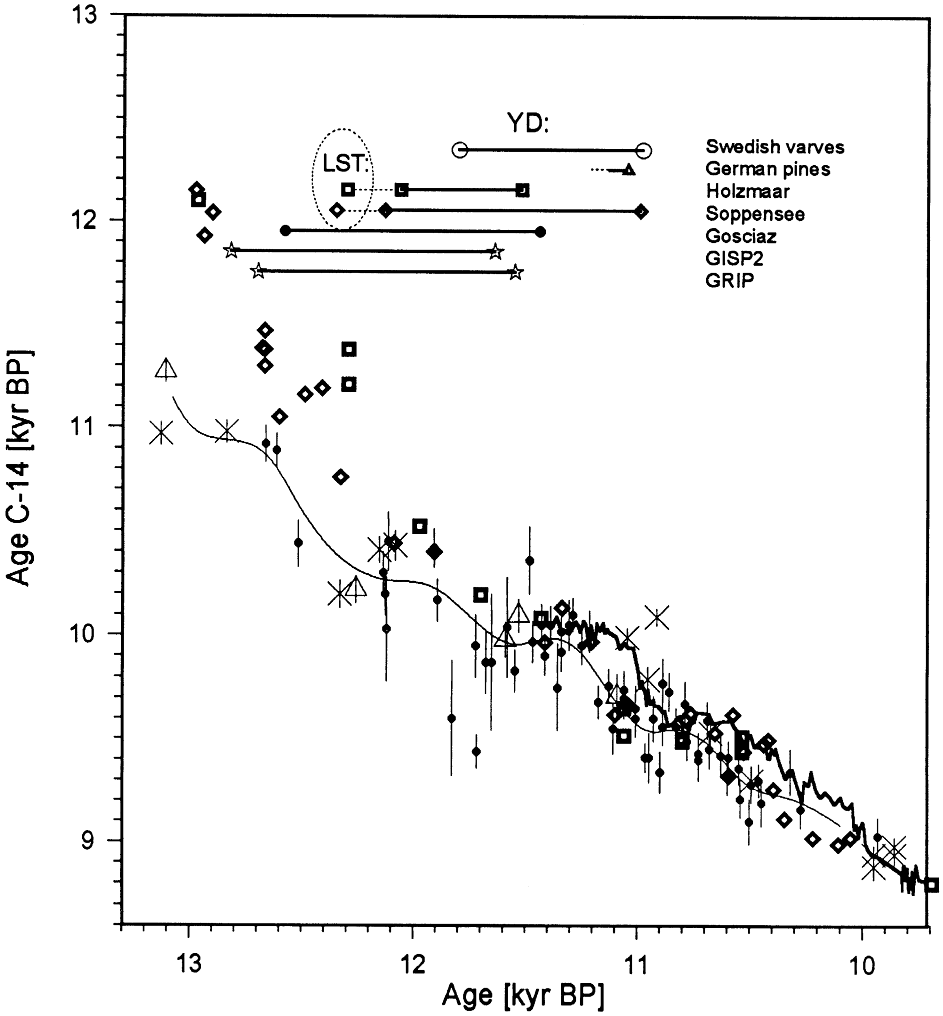

Fig. 1. Comparison of ^{14}C and calendar ages, derived from U/Th dates, dendrochronology and varve chronologies in the Late Glacial and Early Holocene, and of the age of boundaries of the YD cold period, reconstructed in different archives. In the upper part of the figure, the YD boundaries are shown by points connected with heavy lines (except the YD/PB boundary in German pines). The age of the Laacher See tephra is shown to the left of the Holzmaar and Soppensee bars. ▬ = German pines (Kromer and Becker 1993); ◘ = Lake Holzmaar macrofossils (Hajdas 1993); ◆ = Soppensee macrofossils (Hajdas *et al.* 1993); ● = Lake Gościąż macrofossils (Goslar *et al.* ms.); △ = Barbados corals (Bard *et al.* 1993); ⚹ = Huon Peninsula corals (Edwards *et al.* 1993). — = spline function fitted to Lake Gościąż data. ▲ shows the age of the YD/PB boundary reconstructed in German pines (Becker, Kromer and Trimborn 1991); ☆ = YD boundaries reconstructed in Greenland ice cores.

https://doi.org/10.1017/S003382220001479X

figure, we compare the calendar ages of boundaries of the YD. We also show the ages of Laacher See tephra (van den Bogaard and Schmincke 1985) found in Holzmaar and Soppensee. The age of the floating varve chronology of Lake Gościąż was based on the match of ^{14}C dates to the calibration data from German oaks (Goslar *et al.*, ms.). The ages of the YD boundaries from these archives differ, but the discrepancies among ^{14}C data are also large. However, the differences among ^{14}C dates obtained using accelerator mass spectrometry (AMS) from adjacent samples in a single archive are not too large; thus, these dates seem reliable. Although the Lake Gościąż data generally fit the coral data, the ^{14}C dates from Holzmaar and Soppensee are older. Apparently, not all of the calendar chronologies of Lakes Gościąż, Holzmaar and Soppensee and corals are synchronous. The differences in age estimates of the AL/YD and YD/PB transitions may be due partly to errors in the calendar chronologies (Goslar *et al.*, ms.). An even higher offset is shown by recent Swedish data (Wohlfarth, Björck and Possnert 1995).

Thus, we tried to "correct" the calendar chronologies to obtain the ages of YD boundaries similar to those recorded in Greenland, and to synchronize exactly the level of Laacher See tephra. This required an addition of *ca*. 450 varves in the chronology of Soppensee below 10.4 ka BP, and *ca*. 600 varves to the sequence from Holzmaar below 11.8 ka BP. The age of the floating varve chronology of Lake Gościąż was also adjusted to fit the YD boundaries in Greenland. The adjusted age (100 yr older) is still in the range allowed by wiggle-matching to German oaks. The German pine chronology was shifted to synchronize with the Gościąż chronology. Goslar *et al.* (ms.) discuss in detail the synchronization of the Gościąż and German pine chronologies. The separate fits of Lake Gościąż dates to the ^{14}C calibration curve in the portion reconstructed on German oaks and pines suggest a revision of the tentative match of oak and pine chronologies.

In Figure 2, we compare the ^{14}C dates of "corrected" chronologies. We observe that the data from different archives are more consistent than in Figure 1. The plot in Figure 2 clearly demonstrates that the differences in the ages of YD boundaries in laminated sediments are produced mostly by the inadequate calendar chronologies. Some doubts may be connected with the two samples from the YD/PB boundary in Soppensee, distinctly younger than the plateau of 10 ka BP. However, the AMS data from non-laminated sediment of adjacent lake, Rotsee (Ammann and Lotter 1988), with a pollen diagram very similar to that for Soppensee, show the YD/PB boundary in the center of a distinct plateau at 10 ka BP, traced by as many as 11 dates (Fig. 3). Therefore, the two critical samples from Soppensee can be regarded as contaminated. As shown by Wohlfarth *et al.* (1993), the contamination of small macrofossils by modern carbon may sometimes alter a ^{14}C age by many hundred years. Obviously contaminated is one sample from Lake Gościąż sediment (indicated in Fig. 2 by a question mark).

The only non-synchronous YD/PB boundary is that in German pines which, without any doubt, is delayed by *ca*. 200 yr with respect to that in Lake Gościąż. Goslar *et al.* (ms.) discuss this delay elsewhere. Here, we note that the beginning of slow increases of $\delta^{13}C$ and δD in German pines, attributed to the YD/PB boundary (Becker, Kromer and Trimborn 1991) occurred *ca*. 200 yr after the main $\delta^{18}O$ increase in Lake Gościąż, during a period of distinct development of elm trees, *i.e.*, after the YD cold period in Poland. As both regions are only 1000 km apart, at the common direction of westerly winds, the main air circulation heating Central Europe from the North Atlantic, it is difficult to imagine that warming on such a scale occurred in the east earlier than in the west. Thus, we conclude that the increased $\delta^{13}C$ and δD in German pines are, for unknown reasons, delayed with respect to the warming at the termination of the YD. This conclusion does not depend on which chronology (German pines or Gościąż varves) needs to be revised.

https://doi.org/10.1017/S003382220001479X

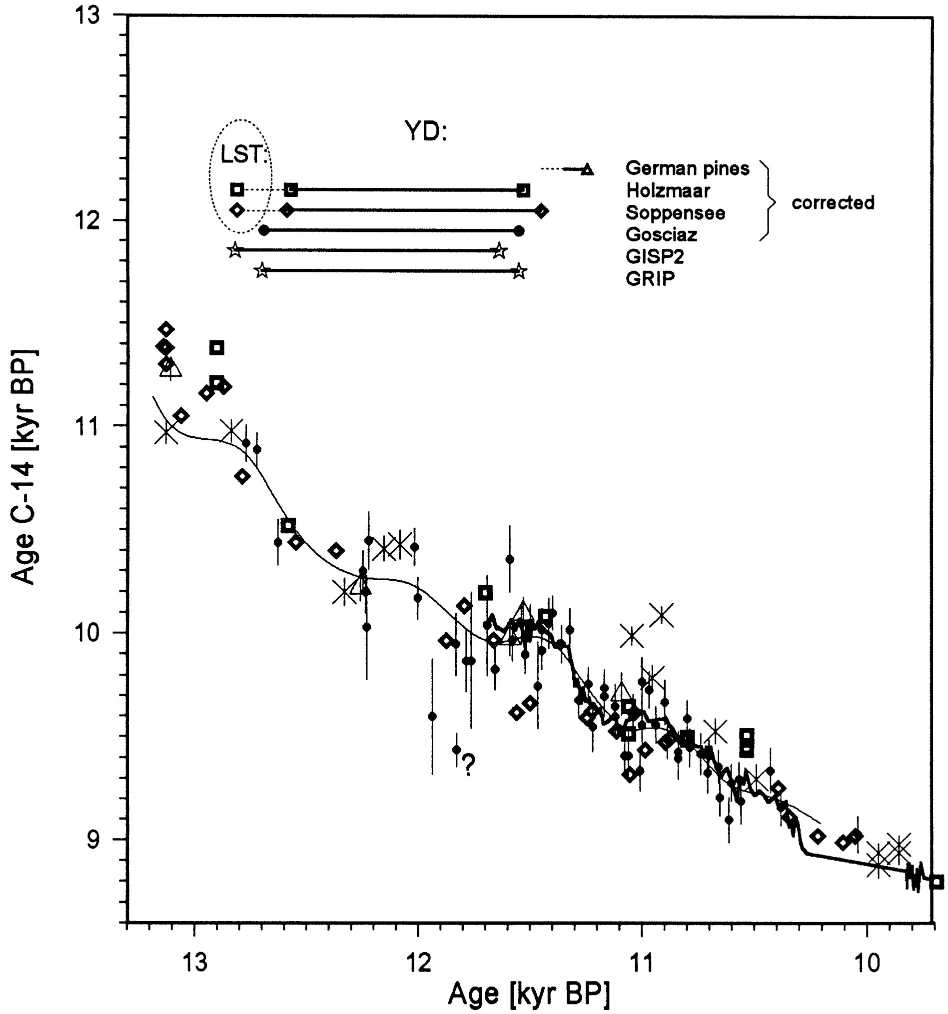

Fig. 2. Revised comparison of ^{14}C dates and boundaries of the YD cold period, reconstructed in archives considered in Fig. 1. The dates are modified after correction of varve chronologies of Lake Holzmaar and Soppensee to synchronize the boundaries of the YD in the North Atlantic region, the adjustment of the Lake Gościąż chronology, and the shift of the German pine chronology to synchronize with that of Lake Gościąż. Symbols are the same as in Fig. 1.

"Real" age of Younger Dryas boundaries

Although demonstrating the synchronism of YD boundaries, the plot in Figure 2 cannot identify their real calendar ages, because one could argue that, along with the Soppensee and Holzmaar chronologies, the uranium/thorium (U/Th) chronology of corals and the varve chronology of Lake Gościąż are inadequate. The correction of Holzmaar and Soppensee chronologies would require some hundred varves missing from the sequences, whereas the error of Lake Gościąż would require the fragment of some hundred varves to be doubled. It must be stressed that, based on AMS ^{14}C dates, Hajdas (1993) demonstrated the lack of *ca.* 880 varves in the Lake Holzmaar sequence from the 4th millennium BP. This gap was not detected previously when analyzing the varve structures. On the other hand, it is difficult to imagine doubling the laminated sequences (by a slump?) with no

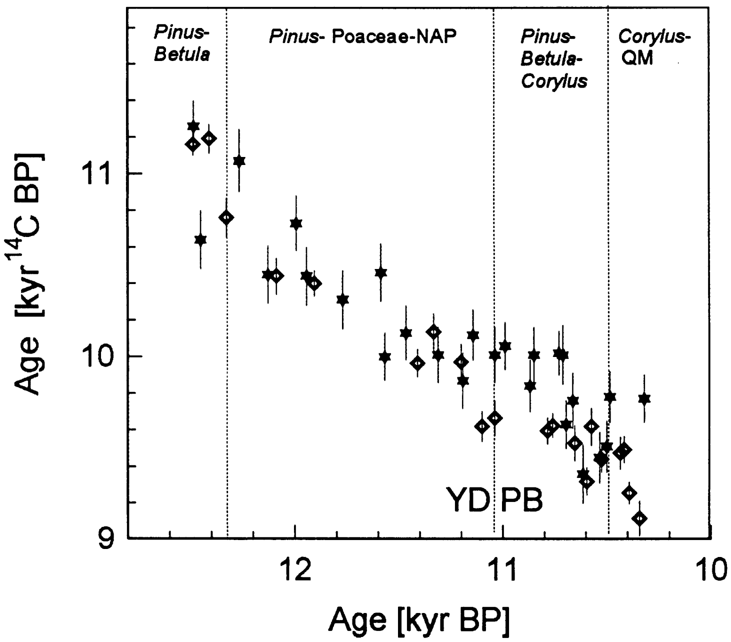

Fig. 3. Comparison of ^{14}C dates of macrofossils from Soppensee (◆) and non-laminated sediments of Rotsee (✱) (Ammann and Lotter 1988). The calendar ages of Soppensee samples are as published by Hajdas *et al.* (1993). The time scale for Rotsee was obtained by synchronization of boundaries between corresponding biozones in both lakes (Lotter *et al.* 1992) and linear interpolation between boundaries according to sample depth.

serious disturbance to the laminated structure, and thus seems impossible without visible evidence in varve quality. Further, the close varve-to-varve correlation of laminated sequences from two separate basins of Lake Gościąż (Goslar *et al.* 1993) seems to preclude the occurrence of a slump. The serious revision of Lake Gościąż chronology would also require the revision of the U/Th chronology of corals, which seems unjustifiable. Supporting the validity of Lake Gościąż and U/Th chronologies is the agreement of the ages of YD boundaries with those recorded in Greenland. That the above-mentioned arguments seem to indicate that varves are missing from the Soppensee and Holzmaar chronologies rather than the Lake Gościąż chronology is erroneous. If not, we must agree that climate changes at the onset and termination of the YD in Europe were delayed by a few hundred years with respect to the case in Greenland. Further study is necessary to resolve this problem.

Acknowledgments

The authors thank A. Walanus for critical remarks on the first version of this manuscript. This study was supported financially by the Commission of European Communities through the Associated Contract CIPDCT 925048.

References

Alley, R. B., Meese, D. A., Shuman, C. A., Gow, A. J., Taylor, K. C., Grootes, P. M., White, J. W. C., Ram, M., Waddington, E. D., Mayewski, P. A. and Zielinski, G. A. 1993 Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. *Nature* 362: 527–529.

Ammann, B. and Lotter, A. F. 1989 Late-Glacial radiocarbon- and palynostratigraphy on the Swiss Plateau. *Boreas* 18: 109–126.

Bard, E., Arnold, M., Maurice, P., Duprat, J., Moyes, J. and Duplessy, J.-C. 1987 Retreat velocity of the North Atlantic polar front during the last deglaciation determined by ^{14}C accelerator mass spectrometry. *Nature* 328: 791–794.

Becker, B., Kromer, B. and Trimborn, P. 1991 A stable-isotope tree-ring timescale of the Late Glacial/Holocene boundary. *Nature* 353: 647–649.

Dansgaard, W., Johnsen, S. J., Clausen, H., Dahl-Jensen, D., Gundestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J. and Bond, G. 1993 Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature* 364: 218–220.

Dansgaard, W., White, J. W. C. and Johnsen, S. J. 1993 The abrupt termination of the Younger Dryas climate event. *Nature* 339: 532–533.

Edwards, R. L., Beck, J. W., Burr, G. S., Donahue, D. J., Chappell, J. M. A., Bloom, A. L., Druffel, E. R. M. and Taylor, F. W. 1993 A large drop in atmospheric $^{14}C/^{12}C$ and reduced melting in the Younger Dryas, documented with ^{230}Th ages of corals. *Science* 260: 962–968.

Goslar, T., Arnold, M., Bard, E., Kuc, T., Pazdur, M. F., Ralska-Jasiewiczowa, M. and Tisnerat, N. (ms.) Variations of atmospheric ^{14}C concentration at the Pleistocene/Holocene boundary. In preparation.

Goslar, T., Kuc, T., Ralska-Jasiewiczowa, M., Różański, K., Arnold, M., Bard, E., van Geel, B., Pazdur, M. F., Szeroczyńska, K., Wicik, B., Więckowski, K. and Walanus, A. 1993 High-resolution lacustrine record of the Late Glacial/Holocene transition in Central Europe. *Quaternary Science Reviews* 12: 287–294.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. and Jouzel, J. 1993 Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature* 366: 552–554.

Hajdas, I. (ms.) 1993 Extension of the radiocarbon calibration curve by AMS dating of laminated sediments of Lake Soppensee and Lake Holzmaar. Ph.D. dissertation, Swiss Federal Institute of Technology, Zürich: 147 p.

Hajdas, I., Ivy, S. D., Beer, J., Bonani, G., Imboden, D., Lotter, A.F., Sturm, M. and Suter, M. 1993 AMS radiocarbon dating and varve chronology of Lake Soppensee: 6000 to 12 000 years BP. *Climate Dynamics* 9: 107–116.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B. and Steffensen, J. P. 1992 Irregular glacial interstadials recorded in a new Greenland ice core. *Nature* 359: 311–313.

Jouzel, J., Petit, J. R., Barkov, N. I., Barnola, J. M., Chapellaz, J., Ciais, P., Kotkyakov, V. M., Lorius, C., Petrov, V. N., Raynaud, D. and Ritz C. 1992 The last deglaciation in Antarctica: Further evidence of a "Younger Dryas" type climatic event. *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation. Absolute and Radiocarbon Chronologies*. NATO ASI Series I. Berlin, Springer-Verlag: 229–266.

Kromer, B. and Becker, B. 1993 German oak and pine ^{14}C calibration, 7200–9439 BC. *In* Stuiver, M., Long, A. and Kra, R. S., eds., Calibration 1993. *Radiocarbon* 35(1): 125–135.

Kudrass, H. R., Erlenkeuser, H., Vollbrecht, R. and Weiss W. 1991 Global nature of the Younger Dryas cooling event inferred from oxygen isotope data from Sulu Sea cores. *Nature* 349: 406–408.

Lehman, S. J. and Keigwin, L. D. 1992 Sudden changes in North Atlantic circulation during the last deglaciation. *Nature* 356: 757–762.

Levesque, A. J., Mayle, F. E., Walker, I. R. and Cwynar, L. C. 1993 A previously unrecognized late-glacial cold event in eastern North-America. *Nature* 361: 623–626.

Lotter, A. F., Ammann, B., Beer, J., Hajdas I. and Sturm, M. 1992 A step towards an absolute time-scale for the Late-Glacial: Annually laminated sediments from Soppensee (Switzerland). *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation. Absolute and Radiocarbon Chronologies*. NATO ASI Series I. Berlin, Springer-Verlag: 45–68.

Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Morrison, M. C., Alley, R. B., Bloomfield, P. and Taylor, K. 1993 The atmosphere during the Younger Dryas. *Science* 261: 195–197.

Mott, J. R., Grant, D. R., Stea, R. and Occhietti, S. 1986 Late-glacial climatic oscillation in Atlantic Canada equivalent to the Allerød-Younger Dryas event. *Nature* 323: 247–250.

Peteet, D. M., Vogel, J. S., Nelson, D. E., Southon, J. R., Nickmann, R. J. and Heusser, C. E. 1990 Younger Dryas climatic reversal in northeastern USA? AMS ages for an old problem. *Quaternary Research* 33: 219–230.

Pons, A., de Beaulieu, J. L., Guiot, C. and Reille, M. 1987 The Younger Dryas in southwestern Europe: An abrupt climatic change as evidenced from pollen records. *In* Berger, W. H. and Labeyrie, L. D., eds., *Abrupt Climatic Change.* Dordrecht, Reidel Publishing Co.: 195–208.

Roberts, N., Taieb, M., Barker, P., Damnati, B, Icole, M. and Williamson, D. 1993 Timing of the Younger

Dryas event in East Africa from lake-level changes. *Nature* 366: 146–148.

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

Taylor, K. C., Hammer, C. U., Alley, R. B., Clausen, H. B., Dahl-Jensen, D., Gow, A. J., Gundestrup, N. S., Kipfstuhl, J., Moore, J. C. and Waddington, E. D. 1993a Electrical conductivity measurements from the GISP2 and GRIP Greenland ice cores. *Nature* 366: 549–552.

Taylor, K. C., Lamorey, G. W., Doyle, G. A., Alley, R. B., Grootes, P. M., Mayewski, P. A., White, J. W. C. and Barlow, L. K. 1993b The "flickering switch" of late Pleistocene climate change. *Nature* 361: 432–436.

van den Bogaard, P. and Schmincke, U. 1985 Laacher See tephra: A widespread isochronous late Quaternary tephra layer in central and northern Europe. *Geological Society of America Bulletin* 96: 1554–1571.

van Geel, B. and van der Hammen, T. 1973 Upper Quaternary vegetational and climatic sequence of the Fuquene area (eastern Cordillera, Colombia). *Palaeogeography, Palaeoclimatology, Palaeoecology* 14: 9–92.

Watts, W. A. 1980 Regional variation in the response of vegetation of Lateglacial climatic events in Europe. *In* Lowe, J. J., Gray, J. M. and Robinson, J. E., eds., *Studies in the Late Glacial of North-West Europe*. Oxford, Pergamon Press: 1–22.

Wohlfarth, B., Björck, S. and Possnert, G. 1995 The Swedish time scale: A potential calibration tool for the radiocarbon time scale during the Late Weichselian. *In* Harkness, D. D., Miller, B. F. and Scott, E. M., eds., Proceedings of the 15th International ^{14}C Conference. *Radiocarbon* 37(3): in press.

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

Zolitschka, B., Haverkamp, B. and Negendank, J. F. W. 1992 Younger Dryas oscillation – varve dated palynological, paleomagnetic and microstratigraphic records from Lake Holzmaar, Germany. *In* Bard, E. and Broecker, W. S., eds., *The Last Deglaciation. Absolute and Radiocarbon Chronologies*. NATO ASI Series I. Berlin, Springer-Verlag: 81–102.