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Cold reversal on Kodiak Island, Alaska, correlated with the European Younger Dryas by using variations of atmospheric ^{14}C content

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ABSTRACT

High-resolution AMS (accelerator-mass-spectrometer) radiocarbon dating was performed on late-glacial macrofossils in lake sediments from Kodiak Island, Alaska, and on shells in marine sediments from southwest Sweden. In both records, a dramatic drop in radiocarbon ages equivalent to a rise in the atmospheric ^{14}C by ~70‰ coincides with the beginning of the cold period at 11 000 yr B.P. (^{14}C age). Thus our results show that a close correlation between climatic records around the globe is possible by using a global signature of changes in atmospheric ^{14}C content.

INTRODUCTION

Radiocarbon chronologies of the last deglaciation reveal that climatic events of this period were accompanied by dramatic changes in atmospheric content of the cosmogenic radioisotope of carbon. An abrupt increase in atmospheric ^{14}C content marked the onset of the Younger Dryas, which lasted from 11 000 to 10 000 yr B.P. (^{14}C conventional age). This was followed by a decrease in the atmospheric ^{14}C content indicated by similar radiocarbon ages obtained for stratigraphically different levels, i.e., the "radiocarbon age plateau". German oak and pine chronologies (Kromer and Becker, 1993) produced detailed reconstruction of the late Younger Dryas and Preboreal plateaus at 10 000 and 9 500 yr B.P. Although short-term fluctuations in atmospheric ^{14}C content can also be caused by solar variability (Beer et al., 1988), the origin of the changes observed in atmospheric radiocarbon of the Younger Dryas period has been mainly attributed to changes in late glacial ocean thermohaline ventilation and gas exchange between the atmosphere and the deep ocean (Goslar et al., 1995; Stocker and Wright, 1996; Hughen et al., 1998).

In order to understand mechanisms of climatic changes, we must be able to reconstruct the timing of climatic events. Attempts at correlation between various archives such as ice cores, deep-sea sediments, and terrestrial records show a need for precise chronologies of climatic records (Bond et al., 1993). Although the nature of the late glacial radiocarbon time scale might appear as problematic and the ^{14}C method as not applicable to the precise dating of the late glacial sites, variations in atmospheric ^{14}C can actually be used as a tool for a close correlation between records. In this paper we present an example of synchronization based on reconstructing atmospheric ^{14}C variations in Alaskan and European records of the cooling at 11 000 yr B.P.

CHRONOLOGY OF THE YOUNGER DRYAS ON KODIAK ISLAND, ALASKA

In their studies of lake sediments from Kodiak Island, Peteet and Mann (1994) showed that this part of Alaska had a pattern of deglaciation similar to that of the North Atlantic region. After the Alaskan Peninsula was deglaciated at ca. 14 000 yr B.P., the climate remained cold and moist. Vegetation of this period consisted of herbs; heath was dominant. After 13 000 yr B.P. however, the climate was warmer and moister, as demonstrated by the presence of ferns and a higher organic content of lake sediments. Then around 11 000 yr B.P., warming was interrupted by a cold and dry period. Low organic carbon content coincides with a return of heath *(Empetrum nigrum)* and disappearance of ferns. This "fern gap", as it has been termed by Peteet and Mann (1994), lasted until 10 000 yr B.P. The original radiocarbon data obtained on terrestrial macrofossils from sediments of Phalarope Pond and Teich Section (Peteet and Mann, 1994) placed the timing of the fern gap event on Kodiak very close to the Younger Dryas cold reversal of the North Atlantic region.

Additional ^{14}C ages (Table 1) obtained on terrestrial macrofossils (seeds of *Empetrum nigrum*) on a core from Phalarope Pond, a small kettle, show that the onset of the cold and dry period on Kodiak Island coincides with a change in atmospheric ^{14}C content. The sample selected above the level corresponding to the cooling (i.e., at the beginning of the fern gap) is ^{14}C dated at 11 080 $\pm$ 90 yr B.P. (Fig. 1) whereas the next sample selected 3 cm above is only 10 470 $\pm$ 65 yr B.P. These ages suggest that the drop in radiocarbon ages of 600 ^{14}C yr occurred in less than 200 cal. yr. Throughout the whole Kodiak cold event (640 to 583 cm depth) radiocarbon ages are between 10 400 and 10 600 yr B.P., which is consistent with other findings of a long radiocarbon plateau inside the Younger Dryas period (Björck et al, 1996; Hughen et al., 1998). Because *Empetrum* disappears as the climate warms up and no seeds were found (Peteet and Mann, 1994). the youngest part of the fern gap was only dated by two data points, and the whole 10 000 yr B.P. plateau in radiocarbon ages at the beginning of the Holocene could not be reconstructed here. However, from these data it appears that the warming at the end of the fern gap happened in the middle of the 10 000 ^{14}C plateau, which is synchronous with the Younger Dryas–Holocene transition in Europe (Goslar et al., 1995; Björck et al., 1996).

DEGLACIATION CHRONOLOGY OF FENNOSCANDIA

The deglaciation of Fennoscandia occurred in steps with several pauses and readvances of the Fennoscandian ice sheet during its retreat. The Younger Dryas glacial pauses are evident as end moraines deposited along the coast of Norway, in southern Sweden and Finland, and in northwest Russia (Andersen et al., 1995, and references therein). A record of oxygen isotopes on shallow benthic foraminifera from a core at Solberga, a site close to the former ice sheet, shows an interval during which the deglacial trend toward a decrease in $\delta^{18}O$ was interrupted. Bodén et al. (1997) interpreted the interval to indicate reduced melting of the Fennoscandian ice sheet during the cool Younger Dryas and ^{14}C dated the onset of the event to 11 150 yr B.P. Sediment accumulation rates in southwest Sweden were high during the deglaciation, and the Solberga-2 core allowed for a new and more detailed dating of the Younger Dryas and a reconstruction of the atmospheric ^{14}C variability.

Benthic foraminifera and bivalve shells were used for radiocarbon dating. Bivalve shells were leached to remove surface contamination. All ages were corrected by 440 yr to compensate for the reservoir effect (Mangerud and Gullikson, 1975) (Table 2). The age of 11 150 yr B.P. for the onset of the Younger Dryas in the Solberga core was obtained at 2655 cm depth (Bodén et al., 1997). Our new results also show that ages in the interval between 2665 and 2690 cm depth cluster around 11 000 yr B.P. (Fig. 2). The following drop from 11 000 yr B.P. to younger radiocarbon ages takes place shortly after the onset of the Younger Dryas as interpreted from the oxygen isotope record (Bodén et al., 1997). Similar to the Kodiak Island record, the ^{14}C ages yielded by the Solberga core level off to form a plateau of 10 200 to 10 600 yr B.P. throughout the Younger Dryas. The cluster of ages around 10 200 yr B.P., which occurs in the early stage of the Younger Dryas coincides with the Baltic ice lake lowering (BILL-1, 2505 cm depth) (Fig. 2).

DISCUSSION AND CONCLUSIONS

Results from both sites show a striking coincidence between the cooling at 11 000 yr B.P. and a change in radiocarbon age of 11 000 to 10 500 yr B.P. (Figs. 1 and 2), which implies that within the dating error, the cooling in Alaska was synchronous with the Younger Dryas in Europe. At 11 000 yr B.P., there is also evidence from different sites around the world of an abrupt change in ^{14}C age from 11 000 to 10 600 yr B.P. suggesting that this marker is worldwide (Ammann and Lotter, 1989; Cwynar and Watts, 1989; Hajdas, 1993; Goslar et al., 1995; Björck et al., 1996; Maenza-Gmelch, 1997; Hughen et al., 1998).

Although the changes in atmospheric ^{14}C ($\Delta^{14}C$) are also observed throughout the Holocene, their amplitudes are lower than 40‰ and result in changes in radiocarbon age of ~300 yr. Part of these fluctuations could possibly be explained by changes in production rate of cosmogenic isotopes due to heliomagnetic modulation (Finkel and Nishiizumi, 1997). However, our reconstruction of the late glacial $\Delta^{14}C$ based on the Kodiak record show that at 11 000 yr B.P. the radiocarbon content in the atmosphere increased by as much as ~70‰ during ~200 cal. yr (Figure 3). Similarly, results of varve counting and radiocarbon dating from the Cariaco Basin record indicate that the increase in $\Delta^{14}C$ of ~50 to 80‰ at the onset of the Younger

Dryas appeared in a short period of ~200 cal. yr (Hughen et al., 1998). While there is no evidence for dramatic changes in production rates of cosmogenic isotope of ^{10}Be in the Younger Dryas section of GISP2, Greenland ice core (Alley et al., 1995), models of atmosphere-ocean exchange can reproduce such a rise in atmospheric ^{14}C content by switching off North Atlantic Deep Water formation and cutting down transport of ^{14}C to the deep ocean (Edwards et al., 1993; Goslar et al., 1995; Björck et al., 1996; Hughen et al., 1998). Deep ventilation of the Southern Ocean (Mikolajewicz. 1996) and increased ventilation of the North Atlantic Intermediate Water (Hughen et al., 1998) have been proposed to reduce atmospheric ^{14}C content and produce a long radiocarbon age plateau inside the Younger Dryas. Climatic response to either of these scenarios can only be tested by studies of paleoclimatic records. That involves chronological reconstruction of cooling and warming events around the globe. For example, a warm Younger Dryas in Vostok ice core from Antarctica (Sowers and Bender, 1996) and a warm Southern Ocean (Charles et al., 1996) supports models which involve an increase in deep-sea ventilation in the Southern Ocean at the time of a reduced North Atlantic Deep Water formation (Broecker, 1998). On the other hand, new sites add to the evidence of a Younger Dryas-like cold spell in the Southern Hemisphere. Recently published radiocarbon and exposure ages of glacial advances in New Zealand show that they were synchronous with the Younger Dryas in Europe (Denton and Hendy, 1994; Ivy-Ochs et al., in press).

Problems such as the question of the most southern sites that experienced the cooling at 11 000 yr B.P. as well as occurrence of the Younger Dryas in South America can be resolved by using radiocarbon dating. Because of its global character, the increase in atmospheric ^{14}C at

11 000 yr B.P. can be used as a marker for the onset of the Younger Dryas event.

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FIGURE CAPTIONS

Figure 1. Radiocarbon chronology of Younger Dryas section in sediments of Phalarope Pond, Kodiak Island, Alaska. Seeds of *Empetrum nigrum* were used for AMS ^{14}C dating (filled circles). Radiocarbon ages are plotted with 2σ error bars. Open circles show ^{14}C ages published by Peteet and Mann (1993). Sediment depth was corrected for presence of "Purple volcanic ash"(666 to 778 cm), the top of which is marked by dashed line. Solid lines on depth scale show levels of Younger Dryas cooling (640 to 642 cm) and warming at beginning of Holocene (583-584 cm). Solid lines on age axis show radiocarbon ages for boundaries of Younger Dryas (11 000 to 10 000 yr B.P.). Hatched area shows interval (~200 cal. yr on the basis of sedimentation rate and total duration of Younger Dryas of ~1200 cal. yr (Goslar et al., 1995)) in which change in atmospheric radiocarbon content occurred.

Figure 2. Results of AMS ^{14}C dating of Swedish marine record of deglaciation plotted vs. depth in core. Benthic foraminifera and leached bivalve shells were used (Table 2) (filled circles). Ages published by Bodén et al. (1997) are shown as open circles. All ages are shown with 2σ error bars. We subtracted 440 yr to compensate for reservoir effect observed in this region (Mangerud and Gullikson, 1975). Some of corrected ages in first half of Younger Dryas appear to be too young, which might be due to changes in reservoir age after input of fresh water during the Baltic ice lake lowering (BILL-1 2505 cm; marked by dashed line). Cooling observed as a change in $\delta^{18}O$ (2700 to 2650 cm; Bodén et al., 1997) and the fauna change at the end of the Younger Dryas (1905 to 1875 cm) (Knudsen, 1982) are marked by solid lines. Radiocarbon ages of Younger Dryas boundaries (11 000 to 10 000 yr B.P.) are marked by horizontal solid lines. Hatched area depicts change in atmospheric ^{14}C content at beginning of Younger Dryas.

Figure 3. Variations in atmospheric ^{14}C content during Younger Dryas. Radiocarbon ages of terrestrial macrofossils from Kodiak record (Table 1) were used to calculate $\Delta^{14}C$, i.e., difference between ^{14}C activity of sample and the standard after corrections for fractionation and sample age (Stuiver and Polach, 1977). Boundaries of Younger Dryas cold period are shown by dashed lines: end of Younger Dryas was placed at 11 500 cal. yr B.P. with the duration of 1200 yr (Goslar et al., 1995). Sedimentation rate of 4.7 mm/yr (= 57.5 cm per 1200 cal. yr) was used.

TABLE 1. AMS ^{14}C AGES OBTAINED FOR THE YOUNGER DRYAS SEDIMENTS IN PHALAROPE POND, KODIAK ISLAND, ALASKA

Sample no.	Depth (cm)	^{14}C age (yr B.P.)	$\delta^{13}C$ (‰)	Material		C (mg)
				Empetrum seeds	Twigs	
ETH-14794	588-589	10 350± 85	-25.2±1.2	9	1	1.6
ETH-14795	592-594	10 430± 80	-25.9±1.2	20		3.1
ETH-14796	596-598	10 380± 95	-22.9±1.2	9	1	1.2
ETH-14797	600-602	10 220± 60	-23.9±1.0	20		3.3
ETH-14798	602-604	10 460± 95	-21.4±1.2	7	1	1.2
ETH-14799	610-612	10 500± 95	-20.4±1.2	15		1.4
ETH-14800	616-618	10 690± 85	-24.1±1.2	20		2.0
ETH-14801	620-622	10 570±100	-20.7±1.2	10	1	1.4
ETH-14802	624-626	10 350± 95	-26.2±1.2	16		1.5
ETH-14803	628-630	10 250±100	-18.7±1.2	15		1.0
ETH-14804	632-634	10 470± 65	-26.8±1.1	20		2.9
ETH-14805	636-638	11 080± 90	-23.8±1.2	17		1.7
ETH-14806	640-642	10 860± 70	-22.6±1.1	20		2.9
ETH-14807	668-670	10 990± 70	-25±1.1	17		2.4
	(780-782)					
ETH-14808	672-674	11 340±180	-15±2.1	14		1.9
	(784-786)					
ETH-14809	676-678	11 410±85	-25.6±1.2	17		2.3
	(788-790)					

Note: Original depths for the samples on the bottom of the dated section are given in parentheses. Errors are ±1σ.

TABLE 2. RESULTS OF AMS ^{14}C DATING OF BIVALVE SHELLS AND MIXED BENTHIC FORAMINIFERS FROM SOLBERGA, SWEDEN.

Sample no.	Depth (cm)	^{14}C corr age (yr B.P.)	$\delta^{13}C$ (‰)	Material	C (mg)
ETH-16275	1685-90	9 125±150	6.5±1.3	Bivalve, 36%	1.2
ETH-16278	1725-30	9 470±70	0.0±1.2	Bivalve, 20%	2.6
ETH-15308	1730-35	9 600±110	3.0±1.2	Bivalve, 24%	1.1
ETH-15309	1770-75	9 750±100	-1.0±1.2	Bivalve, 40%	1.8
ETH-15309	1770-75	9 290±110	1.0±1.2	Bivalve outside*	1.1
ETH-15626	1785-90	9 370±100	1.9±1.5	Bivalve, 28%	1.5
ETH-15627	1845-50	9 265±110	0.8±0.9	Bivalve, 37%	0.6
ETH-15311	1985-90	10 190±130	1.7±1.1	foraminifera	0.5
ETH-15312	2045-50	10 190±100	-4.0±1.2	foraminifera	1.0
ETH-15313	2120-30	10 460±100	-3.0±1.2	foraminifera	0.9
ETH-15314	2255-60	10 030± 90	-3.0±1.2	Bivalve, 20%	4.9
ETH-15315	2305-10	9 990± 80	0.5±1.1	Bivalve, 26%	2.3
ETH-15316	2365-70	10 470±130	1.0±1.2	Bivalve, 15%	2.4
ETH-15316	2365-70	10 280±130	2.0±1.1	Bivalve outside*	0.4
ETH-15317	2425-30	9 940±100	1.0±1.5	Bivalve, 21%	2.0
ETH-15318	2480-85	9 870± 95	1.6±1.2	Bivalve, 35%	1.7
ETH-15319	2510-15	10 170± 95	1.1±1.2	Bivalve, 57%	3.0
ETH-15319	2510-15	9 920± 85	1.1±1.2	Bivalve outside*	2.2
ETH-15320	2540-45	10 000± 95	0.0±1.2	Bivalve, 30%	2.2
ETH-15322	2630-40	10 800±120	2.3±1.1	foraminifera	0.8
ETH-15323	2640-50	10 610±150	1.0±1.2	foraminifera	1.0
ETH-15324	2660-65	10 100±130	1.6±1.2	foraminifera	1.0
ETH-15325	2665-70	11 360± 95	-1.0±1.2	foraminifera	1.4
ETH-15326	2670-75	11 170±100	0.5±1.2	foraminifera	1.6
ETH-15327	2675-80	10 810±100	-1.0±1.1	foraminifera	1.2
ETH-15328	2680-90	11 030±150	1.6±0.9	foraminifera	0.6

Note: Bivalve shells were leached; percent given shows the amount of the shell (by weight) removed before the inner part was dated.

*For three samples both inside and outside fractions have been dated. The outside "date" is apparently as much as 400–500 yr younger than the inside date.

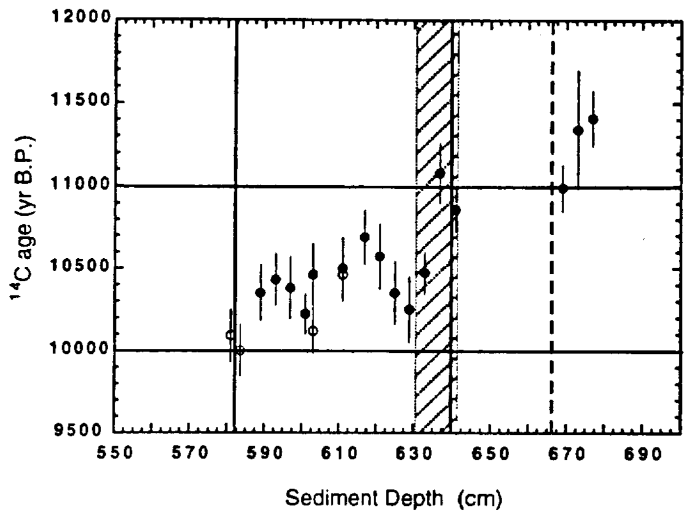
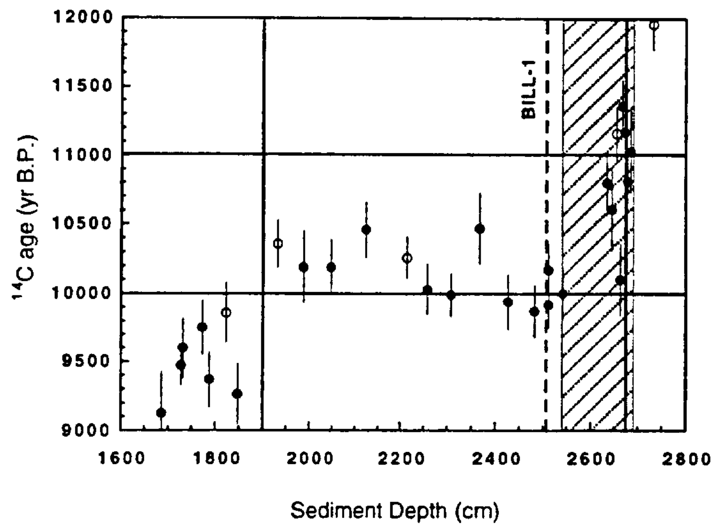
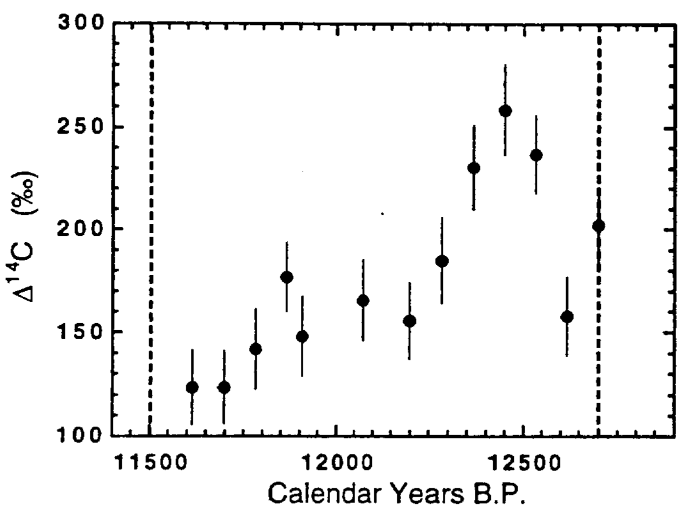

12000
11500
11000
10500
10000
9500
^{14}C age (yr B.P.)
550
570
590
610
630
650
670
690
Sediment Depth (cm)

Fig 1



12000
11500
11000
10500
10000
9500
9000
1600
1800
2000
2200
2400
2600
2800
BILL-1
^{14}C age (yr B.P.)
Sediment Depth (cm)

Fig 2



300
250
200
150
100
$\Delta^{14}C$ (‰)
11500
12000
12500
Calendar Years B.P.

Fig. 3