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High-resolution stable isotope records from southwest Sweden: The drainage of the Baltic Ice Lake and Younger Dryas ice margin oscillations

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Abstract. Benthic foraminifera in two shallow marine sediment cores from southwest Sweden were analyzed for oxygen isotopes. Several deglaciation events, previously recognized in terrestrial and lake sediments throughout the Baltic region, are identified and radiocarbon dated. An initial Baltic Ice Lake (BIL) drainage at the Mount Billingen threshold is inferred from a distinct 2.4‰ $\delta^{18}O$ oscillation in one of the investigated cores. The estimated radiocarbon age for this event is approximately 10,900 ^{14}C years. The final drainage, which ended BIL history, occurred in two steps during the younger part of the radiocarbon plateau at 10,000 ^{14}C years. Biostratigraphy suggests that the final drainage took place in the climatically warm early Preboreal. At approximately 11,150 ^{14}C years, the deglacial trend toward lighter isotopic composition was interrupted and slightly reversed and is interpreted to represent the onset of the cold Younger Dryas period. For a few hundred years prior to the Younger Dryas, melting of the Fennoscandian ice sheet appears to have been rapid. Besides the dramatic drainage events and reduced melting during the Younger Dryas, the records display several other salinity variations. These variations may reflect ice margin oscillations during the Younger Dryas, previously identified throughout Scandinavia as ice marginal deposits. The isotopic records suggest approximately 10 climatically induced ice margin recession/readvances of the southeastern Fennoscandian ice sheet during the Younger Dryas.

Introduction

Meltwater trapped by retreating ice sheets and topography during deglaciation creates ice-dammed lakes. When the ice front draws back and passes a topographic threshold, these ice-dammed lakes are drained or catastrophically lowered. In Scandinavia, the Baltic Ice Lake (BIL) was created during the Bølling and Allerød interstadials. During the Younger Dryas, the BIL was probably at its maximum size (Figure 1), with an estimated 10,000 km^3 of glacial meltwater [*Olausson*, 1982]. A westward drainage of the BIL at the northern tip of Mount Billingen (Figure 1) was first hypothesized over 85 years ago [*Munthe*, 1910], and the geomorphological features in this area have been the subject of debate ever since. More conclusive evidence supporting the Mount Billingen drainage hypothesis was lacking until barren bedrock and coarse gravel deposits, indicative of a large flood event with a westward route, were discovered in an area 5-10 km west of Mount Billingen [*Strömberg*, 1992]. A radiocarbon date for the final drainage of the BIL indicates an age of approximately 10,300 ^{14}C years [*Wohlfarth et al.*, 1993]. This date is regarded as a maximum age and is based on terrestrial macrofossil remains found in redeposited sediments in the former BIL area which are thought to represent the final drainage.

Olausson [1982] presented the first stable isotope evidence for short-lived freshwater injections in the shallow marine environment of the Swedish west coast during the last deglaciation. His $\delta^{18}O$ results from benthic foraminifera revealed two distinct meltwater spikes in one of four cores investigated. Owing to contamination, conventional radiocarbon dating on shell fragments found in the cores was problematic [*Olsson,* 1982] and could not be used to establish an age model [*Cato et al.*, 1982]. Nevertheless, on the basis of biostratigraphic age control [*Knudsen*, 1982; *Miller*, 1982; *Robertsson*, 1982], these meltwater events were assigned to the Allerød and Preboreal chronozones [*Working Group*, 1982]. Two distinct $\delta^{18}O$ oscillations in benthic foraminifera were later also observed in a core from the Skagerrak, south of Norway [*Erlenkeuser*, 1985]. These events were tied by tephrastratigraphy to the Younger Dryas chronozone [*Stabell and Thiede*, 1985] but were regarded as too old to represent the final drainage of the BIL [*Erlenkeuser*, 1985].

It is evident that the final drainage of the BIL passed through the Mount Billingen threshold [*Strömberg*, 1992] and likely that it left its imprint in the marine sediment record west of the drainage outlet. The meltwater events observed [*Olausson*, 1982; *Erlenkeuser*, 1985], however, can obviously not be correlated, and none seem to agree with the age proposed for the final BIL drainage [*Wohlfarth et al.*, 1993]. This age discrepancy may be due to different dating techniques. Moreover, the drainage may have been a dramatic event with a duration of only one or a few years [*Johansson*, 1926, 1937;

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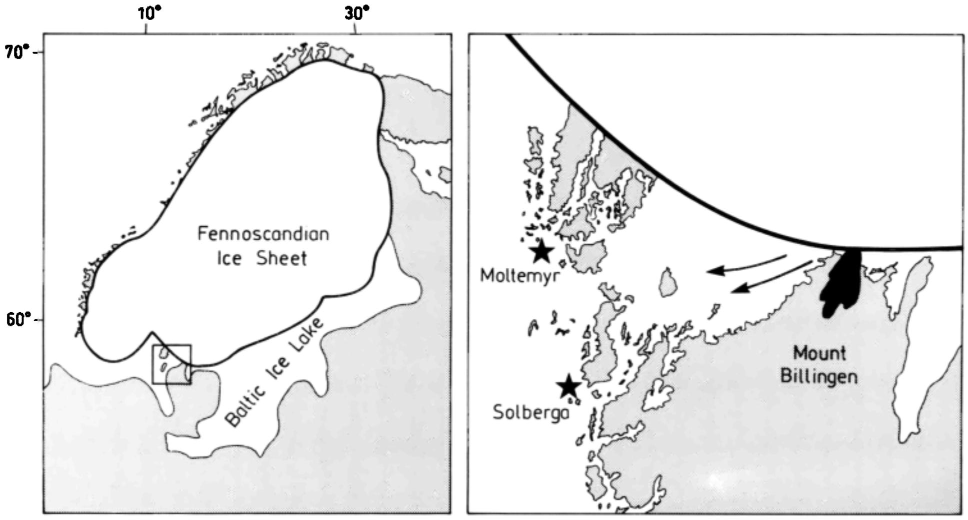

Figure 1. Maps showing the areal extent of the Fennoscandian ice sheet and Baltic Ice Lake during the Younger Dryas deglaciation standstill. The detailed map shows the paleogeography during Younger Dryas and the position of the ice margin in southwest Sweden and its relation to the Mount Billingen threshold. Black area indicates Mount Billingen. Stars indicate the positions of the Moltemyr and Solberga-2 cores. Arrows indicate the drainage route for the Baltic Ice Lake. (Adapted from *Björck and Svensson* [1994]).

Björck, 1995]. An event of such short duration could easily be overlooked in a sediment core. Thus the final drainage may not have been recorded in previously investigated cores.

This study is an attempt to unravel some of the ambiguities concerning the late history of the BIL as revealed in the shallow marine environment. To accomplish this goal, we reinvestigated the core containing the evidence of short-lived meltwater events (Moltemyr) and one additional site (Solberga) where these events originally were not observed, using high-resolution sampling and accelerator mass spectrometry (AMS) ^{14}C dating.

Material and Methods

Among 14 sites surveyed on the Swedish west coast for a type locality for the Pleistocene/Holocene boundary, Moltemyr and Solberga were found suitable as stratotype and hypostratotype sections [*Working Group*, 1982]. Moltemyr is a small bog situated approximately 55 m above sea level in a hilly area, and the Solberga site is situated in a valley a few meters above sea level [*Fredén*, 1982]. After ice withdrawal, the subsequent isostatic uplift created an archipelago in southwest Sweden (Figure 1). At the beginning of the Holocene, the Moltemyr and Solberga sites were located in the outer rim of this archipelago at paleodepths of approximately 30 and 50 m, respectively [*Olausson*, 1982].

The Moltemyr core is 6.5 m long and was taken with a modified Russian peat sampler [*Cato*, 1982a]. The core was originally cut into 10-cm sections in the lower part, 5-cm sections in the middle part, and 2.5-cm intervals in the upper part. These samples are stored in plastic containers, and it is not possible to determine the top and bottom of each interval. The sampling resolution used is partly determined by the storage intervals. Sampling was also limited to those intervals containing a sufficient amount of sediment left after the extensive examination by the Pleistocene/Holocene boundary working group. At Solberga, two 27.3 m long cores were collected with a Foil piston corer [*Cato*, 1982a]; one was used up by the working group and the other was stored for future investigations. The Solberga-2 core was almost complete, and the sampling resolution used was constrained only by the 5-cm storage sections applied throughout the core. We measured oxygen isotopes in benthic foraminifera from 58 samples from the Moltemyr core and 278 samples from the Solberga-2 core. Compared with the previous study [*Olausson*, 1982], sample density is increased by nearly a factor of 3 at Moltemyr and 10 at Solberga.

Sediment consisted of clay, clayey silt, and silty clays [*Cato*, 1982b], and foraminifer abundances vary from almost barren to more than 700 specimens per gram of sediment [*Knudsen*, 1982]. Foraminifera were extracted by disaggregating the samples in hot water and wet-sieving through a 63-µm mesh. Specimens of the benthic foraminifer *Elphidium excavatum* were picked from the >125-µm size fraction, and oxygen isotopes were analyzed using a Finnegan MAT 251 mass spectrometer with an attached Carousel-48 automatic preparation system. Accelerator mass spectrometry radiocarbon dating were made at the National Ocean Sciences AMS Facility at Woods Hole Oceanographic Institution and the Tandem Laboratory at Uppsala University. All ^{14}C ages are based on benthic foraminifera and, when possible, monospecific samples were used. Sampling for radiocarbon dating was limited to those intervals containing sufficient foraminifera, and direct dating of the meltwater events observed in the $\delta^{18}O$ records was therefore not possible. In the Solberga-2 core, sample intervals of up to 30 cm had to be used in order to obtain a sufficient amount of material for dating. Chronostratigraphic terminology follows *Mangerud et al.* [1974].

Table 1. Accelerator Mass Spectrometer ^{14}C Dates

Core	Depth, cm	^{14}C Age, years	^{14}C Age*	Source material	Accession Number
Solberga-2	1125-1140	9,610 ± 45	9,170	*E. excavatum*	OS-4532
Solberga-2	1140-1155	8,885 ± 90	8,445	*E. excavatum*	Uu-10300
Solberga-2	1330-1355	4,550 ± 80	4,110	*E. excavatum*	Uu-10301
Solberga-2	1530-1555	7,730 ± 85	7,290	*E. excavatum*	OS-4527
Solberga-2	1815-1830	10,300 ± 110	9,860	*E. excavatum*	OS-4528
Solberga-2	1930-1935	10,800 ± 85	10,360	*N. labradoricum*	OS-4526
Solberga-2	2200-2230	10,700 ± 75	10,260	*E. excavatum*	OS-4529
Solberga-2	2650-2660	11,600 ± 95	11,160	*E. excavatum*	OS-4530
Solberga-2	2730-2735	12,400 ± 95	11,960	*N. labradoricum*	OS-4531
Moltemyr	272.5-275	10,650 ± 40	10,210	Mixed benthic	OS-2350
Moltemyr	277.5-280	10,500 ± 40	10,060	Mixed benthic	OS-2353
Moltemyr	425-430	10,900 ± 55	10,460	Mixed benthic	OS-2352
Moltemyr	560-570	12,450 ± 55	12,010	*N. labradoricum*	OS-2351
Moltemyr	590-600	12,750 ± 45	12,310	*N. labradoricum*	OS-2349

*Correction is made for an assumed ocean reservoir effect of 440 years.

Radiocarbon ages include the correction of an ocean reservoir effect of 440 years, which is based on radiocarbon ages obtained from recent marine shells from the coast of Norway and southwest Sweden [*Mangerud and Gulliksen*, 1975]. Marine and terrestrial radiocarbon dates for the Vedde ash bed indicate a higher ocean reservoir effect during the Younger Dryas and that the correction could be on the order of 700-800 years [*Bard et al.*, 1994]. It is thus possible that some of the estimated ^{14}C ages for the events identified and discussed in this paper are a few hundreds years too old. However, as the 400-year correction has commonly been used in the past, it will make it possible to compare our results with previous observations of the Younger Dryas in marine environments of the North Atlantic region.

Results

Chronology and Estimated Sedimentation Rates

Nine monospecific foraminifer samples were AMS ^{14}C dated in the Solberga-2 core (Table 1). Using a 440-year correction for reservoir age [*Mangerud and Gulliksen*, 1975], the sequence covers the time interval from 11,960 to 4,110 ^{14}C years. Above 1330 cm, there is a major age reversal which is attributed to reworked sediment in the upper part of the core. During isostatic uplift, hills surrounding Solberga reached sea level long before the Solberga coring site and were exposed to wave action with subsequent redeposition of surface sediment. Some of the abraded sediment was likely redeposited at Solberga. Samples at 1935 and 2230 cm have ages of 10,360 and 10,260 ^{14}C years, respectively, suggesting that these levels fall into the plateau period of constant ages at about 10,000 ^{14}C years on the radiocarbon calibration curve [*Bard et al.*, 1990; *Edwards et al.*, 1993; *Kromer and Becker*, 1993; *Goslar et al.*, 1995]. Rather than indicating sediment reworking, this age inversion more likely reflects a high sediment accumulation rate at Solberga during the late Younger Dryas.

Five samples in the Moltemyr core were AMS dated (Table 1). Assumed linear sedimentation rates between the dates indicate that the Moltemyr sequence ranged in age from approximately 12,800 to 10,000 ^{14}C years. As in the Solberga-2 core, a small age reversal is recorded at the radiocarbon plateau at approximately 10,000 ^{14}C years. The average sedimentation rate at Solberga (Figure 2) during the Older Dryas and Allerød was approximately 1.5 mm/^{14}C year which increased to about 6 mm/^{14}C year in the Younger Dryas. Holocene average sedimentation rates decreased to about 1 mm/^{14}C year. At Moltemyr, the average sedimentation rate during the late Bølling was approximately 1 mm/^{14}C year. The almost 1500 ^{14}C years representing the Older Dryas, Allerød, and early Younger Dryas (between 560 and 430 cm) have an estimated sedimentation rate of less than 1 mm/^{14}C year while

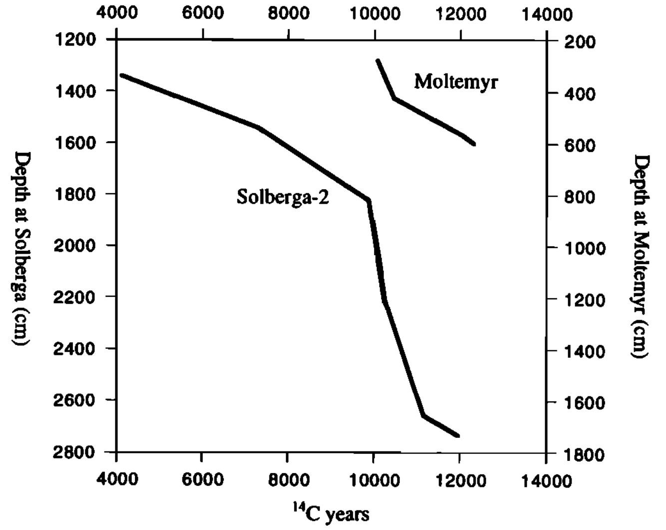

Figure 2. Age-depth relations in the Solberga-2 and Moltemyr cores. Graphs are based on the younger age alternative of 10,260 ^{14}C years at 2230 cm in the Solberga-2 core and 10,060 ^{14}C years at 280 cm in the Moltemyr core (see text and Table 1). Graphs are plotted at same depth scale, and ages are corrected for an assumed 440-year reservoir age.

during the late Younger Dryas the estimated average sedimentation rate is about 4-6 mm/^{14}C year.

Oxygen Isotopes

The $\delta^{18}O$ records from Solberga and Moltemyr display the expected deglacial trend toward lower values (Tables 2a and 2b and Figure 3). In Solberga, this change occurred in two steps. The first was a 1.5‰ decrease between approximately 2700 and 2650 cm. The overlying 7 m have a $\delta^{18}O$ record marked by a gradual trend toward higher values. As is evident in the smoothed record (Figure 4), the magnitude of change is about 0.5‰. A second decrease of 1.5‰ occurs between approximately 1950 and 1600 cm. A stepwise deglaciation trend toward generally lighter isotopic composition is also evident in the less complete Moltemyr core. In the smoothed record (Figure 4), the first step appears as a decrease from 3‰ to average values of around -1‰. The second distinct drop at 280 cm reflects the dramatic oscillation that occurred in the beginning of the final deglacial step.

A striking feature of the $\delta^{18}O$ records is the appearance of several oscillations with amplitudes above 1‰. These high-amplitude oscillations, superimposed on the deglacial trend toward lower $\delta^{18}O$, appear to have been created quite rapidly and are in many cases based upon single samples. The most conspicuous of the oscillations recorded at Solberga are, however, represented by two samples each. The first of these distinct $\delta^{18}O$ spikes occurs at 2505 cm and shows a maximum amplitude of 2.4‰. Two other distinct oscillations defined by more than one sample are also recorded at 1890 cm (2.5‰) and 1865 cm (3.7‰) in the Solberga-2 core.

The Moltemyr record is different from Solberga-2. This can be attributed, in part, to the lower sampling frequency used for the Moltemyr core. The difference in pattern and amplitude of the $\delta^{18}O$ oscillations can also be explained by different water depths. Because the Moltemyr site was situated about 20 m shallower than the Solberga site during the time of sediment deposition, it is likely that the bottom water composition at Moltemyr was more affected by regional meltwater discharge than the deeper Solberga. Although the records display differences in both pattern and amplitude, it is important to note that the two distinct high-amplitude oscillations found closely above the 19-m level at Solberga are also evident in the top of the Moltemyr record at 272.5 cm (9‰) and 267.5 cm (5‰).

Discussion

Allerød

The deglaciation of southern Sweden occurred in several steps, as is evident in end moraine lines created in southwest Sweden during short glacial standstills or readvances during the Bølling, Allerød and Younger Dryas [*Fredén*, 1988, and references therein]. The first $\delta^{18}O$ decrease that could reflect deglaciation in the Solberga-2 core (2700-2650 cm) occurred between approximately 11,300 and 11,150 ^{14}C years. This abrupt change in $\delta^{18}O$ was likely caused by increased meltwater discharge when the Fennoscandian ice sheet in southwestern Sweden retreated rapidly and corresponds to a period of increased sea surface temperatures (SST) in the southeast Norwegian Sea [*Koç Karpuz and Jansen*, 1992; *Lehman and Keigwin*, 1992]. Preceding the distinct drop, there is a 0.7‰ $\delta^{18}O$ increase that culminates at about 11,600 ^{14}C years. This increase may reflect reduced glacial melting during a glacial readvance that created one of the moraine ridges in southwestern Sweden during the Allerød [e.g., *Fredén*, 1988]. The age of this event closely corresponds to the Norwegian Sea cold SST phase observed between 11,800 and 11,500 ^{14}C years [*Koç Karpuz and Jansen*, 1992] and at 11,700 ^{14}C years [*Lehman and Keigwin*, 1992]. In the Moltemyr core, this interval is poorly dated.

Table 2a. The Record of $\delta^{18}O$ in *Elphidium excavatum* Versus Depth From Moltemyr

Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB
242.5-245	-1.65	317.5-320	-0.61	395-400	-0.29	510-520	0.76
245-247.5	-3.00	320-322.5	0.28	405-410	-3.98	520-530	1.08
262.5-265	-6.14	322.5-325	-0.68	410-415	0.71	530-540	2.84
265-267.5	-6.75	327.5-330	0.08	415-420	1.21	540-550	2.46
267.5-270	-1.42	330-332.5	-0.55	420-425	-1.04	560-570	2.89
270-272.5	-8.83	332.5-335	-3.58	425-430	-2.03	570-580	2.76
272.5-275	-4.60	337.5-340	-0.96	430-435	-1.12	580-590	2.87
275-277.5	-4.18	340-342.5	0.36	435-440	-1.51	590-600	3.17
277.5-280	-2.95	345-347.5	-1.24	445-450	0.00	600-610	2.93
280-282.5	-3.41	347.5-350	-1.90	450-460	0.22	610-620	2.89
282.5-285	-2.43	355-360	-2.02	460-470	-1.68	620-630	2.77
287.5-290	0.17	360-365	0.30	470-480	-1.54	630-640	2.74
302.5-305	-1.94	370-375	-0.95	480-490	-0.76	640-650	2.57
305-307.5	-2.62	375-380	-1.07	490-500	0.95		
307.5-310	-0.74	385-390	-1.86	500-510	2.12		

PDB, Pee Dee belemnite

Table 2b. The Record of $\delta^{18}O$ in *Elphidium excavatum* Versus Depth From Solberga-2

Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB	Depth, cm	$\delta^{18}O$, ‰ PDB
1325-1330	0.80	1675-1680	1.58	2025-2030	2.15	2395-2400	1.65
1330-1335	0.59	1680-1685	1.16	2030-2035	2.35	2400-2405	1.91
1335-1340	0.61	1685-1690	1.20	2035-2040	2.23	2405-2410	1.69
1340-1345	0.65	1690-1695	1.16	2040-2045	2.00	2410-2415	1.66
1345-1350	0.26	1695-1700	1.40	2045-2050	2.43	2415-2420	2.13
1350-1355	0.33	1700-1705	1.20	2050-2055	2.51	2420-2425	1.92
1355-1360	0.46	1705-1710	1.44	2055-2060	2.53	2425-2430	1.72
1360-1365	0.49	1710-1715	1.45	2060-2065	2.50	2430-2435	1.63
1365-1370	0.43	1715-1720	1.34	2065-2070	2.24	2435-2440	1.40
1370-1375	0.80	1720-1725	1.69	2070-2075	1.89	2440-2445	1.86
1375-1380	0.82	1725-1730	1.60	2075-2080	1.66	2445-2450	1.99
1380-1385	1.12	1730-1735	1.47	2080-2085	2.42	2450-2455	1.91
1385-1390	1.14	1735-1740	1.54	2085-2090	1.94	2455-2460	2.10
1390-1395	1.12	1740-1745	1.36	2090-2095	1.89	2460-2465	1.62
1395-1400	0.68	1745-1750	1.59	2095-2100	1.05	2465-2470	1.81
1400-1405	0.55	1750-1755	1.71	2105-2110	2.45	2470-2475	1.51
1405-1410	0.49	1755-1760	0.46	2110-2115	2.33	2475-2480	2.12
1410-1415	0.67	1760-1765	1.93	2115-2120	2.32	2480-2485	1.96
1415-1420	0.93	1765-1770	1.68	2120-2125	2.29	2485-2490	1.71
1420-1425	0.53	1770-1775	1.90	2125-2130	2.26	2490-2495	1.92
1425-1430	0.45	1775-1780	1.91	2130-2135	2.00	2495-2500	1.86
1430-1435	0.40	1780-1785	1.93	2135-2140	2.27	2500-2505	-0.54
1435-1440	0.20	1785-1790	1.98	2140-2145	2.16	2505-2510	0.55
1440-1445	0.43	1790-1795	1.98	2145-2150	1.92	2510-2515	1.88
1445-1450	0.73	1795-1800	1.80	2155-2160	2.03	2515-2520	1.07
1450-1455	0.54	1800-1805	1.91	2160-2165	1.76	2520-2525	2.04
1455-1460	0.73	1805-1810	1.63	2165-2170	1.62	2525-2530	2.14
1460-1465	0.97	1810-1815	0.57	2170-2175	1.59	2530-2535	1.66
1465-1470	0.65	1815-1820	2.09	2175-2180	1.54	2535-2540	2.12
1470-1475	0.37	1820-1825	1.78	2180-2185	1.70	2540-2545	1.40
1475-1480	1.40	1825-1830	2.04	2185-2190	1.43	2545-2550	1.63
1480-1485	0.28	1830-1835	1.85	2190-2195	1.65	2550-2555	1.94
1485-1490	-0.11	1835-1840	1.87	2195-2200	1.86	2555-2560	1.99
1490-1495	0.67	1840-1845	2.00	2200-2205	2.23	2560-2565	1.91
1495-1500	0.58	1845-1850	2.07	2205-2210	2.72	2565-2570	1.85
1500-1505	0.53	1850-1855	2.03	2210-2215	2.74	2570-2575	1.79
1505-1510	0.69	1855-1860	0.48	2215-2220	2.71	2575-2580	2.15
1510-1515	0.57	1860-1865	-1.61	2220-2225	2.54	2580-2585	1.64
1515-1520	0.79	1865-1870	1.34	2225-2230	2.48	2585-2590	2.04
1520-1525	1.26	1870-1875	2.23	2230-2235	1.73	2590-2595	1.62
1525-1530	0.76	1875-1880	2.29	2235-2240	1.96	2595-2600	1.93
1530-1535	0.49	1880-1885	2.12	2245-2250	0.93	2600-2605	1.89
1535-1540	1.02	1885-1890	-0.39	2250-2255	1.62	2605-2610	2.08
1540-1545	0.94	1890-1895	0.64	2255-2260	1.82	2610-2615	1.86
1545-1550	0.77	1895-1900	2.09	2260-2265	2.14	2615-2620	1.98
1550-1555	0.78	1900-1905	1.61	2265-2270	2.24	2620-2625	1.91
1555-1560	0.80	1905-1910	2.13	2270-2275	1.44	2625-2630	2.38
1560-1565	1.14	1910-1915	2.14	2275-2280	1.31	2630-2635	2.32
1565-1570	0.84	1915-1920	2.43	2280-2285	2.30	2625-2640	1.81
1570-1575	1.04	1920-1925	2.08	2285-2290	0.66	2640-2645	2.24
1575-1580	0.97	1925-1930	2.18	2290-2295	2.08	2645-2650	1.81
1580-1585	0.85	1930-1935	2.02	2295-2300	1.98	2650-2655	2.70
1585-1590	0.78	1935-1940	1.43	2305-2310	1.94	2655-2660	2.40
1590-1595	0.53	1940-1945	2.19	2310-2315	1.90	2660-2665	2.68
1595-1600	0.73	1945-1950	2.48	2315-2320	1.81	2665-2670	3.06
1600-1605	0.66	1950-1955	1.93	2320-2325	0.22	2670-2675	3.10
1605-1610	0.95	1955-1960	1.93	2325-2330	1.68	2675-2680	3.26
1610-1615	1.19	1960-1965	2.42	2330-2335	1.22	2680-2685	3.39
1615-1620	1.10	1965-1970	2.45	2335-2340	1.67	2685-2690	3.36
1620-1625	1.19	1970-1975	2.49	2340-2345	1.82	2690-2695	3.46
1625-1630	1.21	1975-1980	2.44	2345-2350	1.59	2695-2700	3.20
1630-1635	0.95	1980-1985	2.57	2350-2355	1.47	2700-2705	3.24
1635-1640	1.56	1985-1990	2.52	2355-2360	1.74	2705-2710	3.26
1640-1645	1.49	1990-1995	2.34	2360-2365	1.85	2710-2715	2.75
1645-1650	1.15	1995-2000	2.27	2365-2370	1.77	2715-2720	2.90
1650-1655	1.17	2000-2005	2.25	2370-2375	2.07	2720-2725	3.05
1655-1660	1.43	2005-2010	1.91	2375-2380	2.46	2725-2730	2.84
1660-1665	1.79	2010-2015	2.34	2380-2385	1.65	2730-2735	2.97
1665-1670	1.46	2015-2020	2.27	2385-2390	1.45		
1670-1675	1.48	2020-2025	2.13	2390-2395	1.26		

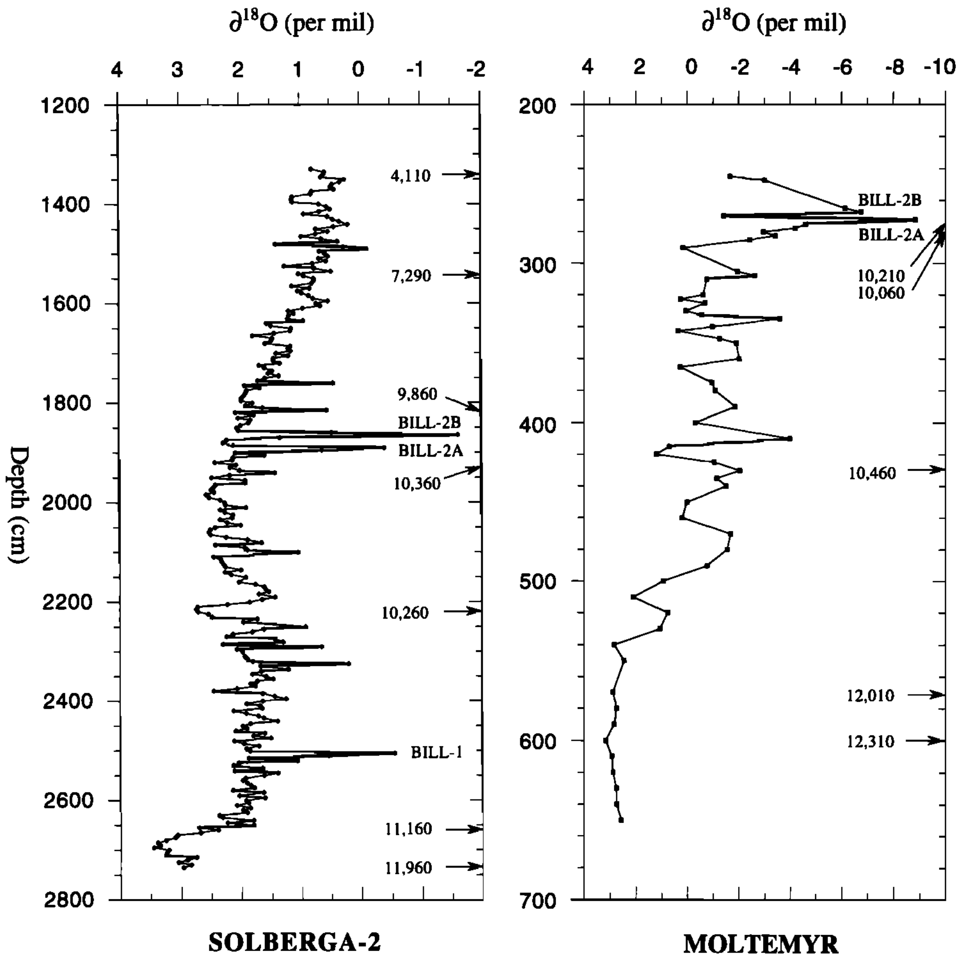

Figure 3. The benthic *Elphidium excavatum* $\delta^{18}O$ records in the Moltemyr and Solberga-2 cores. Radiocarbon ages are corrected for an assumed 440-year reservoir age.

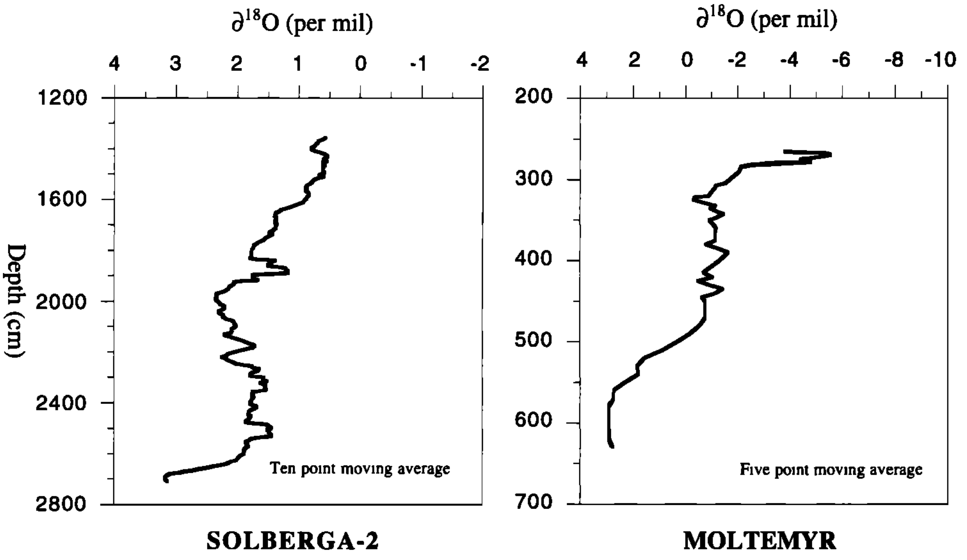

Figure 4. Same records as in Figure 3 but smoothed.

The Younger Dryas and the Drainage of the Baltic Ice Lake

Both deep-sea and eustatic sea level records show that the deglaciation occurred in two major steps, separated by reduced transport of glacial meltwater to the ocean during the Younger Dryas [e.g., *Fairbanks*, 1989; *Jansen and Veum*, 1990; *Polyak et al.*, 1995]. Paleoclimatic records also show that the Younger Dryas deglaciation standstill was accompanied by a return to nearly glacial atmospheric temperatures and SST in the North Atlantic region [e.g., *Dansgaard et al.*, 1982, 1993; *Grootes et al.*, 1993; *Ruddiman et al.*, 1977; *Koç Karpuz and Jansen*, 1992]. Recent ice core observations and marine records from low latitudes [*Thompson et al.*, 1995; *Guilderson et al.*, 1994; *Kennett and Ingram*, 1995; *Hughen et al.*, 1996], and geomorphological evidence from New Zealand [*Denton and Hendy*, 1994] indicate that the Younger Dryas cooling was global in extent.

In Scandinavia, the Younger Dryas was characterized by deposition of extensive ice-marginal end moraines [*Andersen et al.*, 1995a]. These end moraines occur along the coast of Norway, in southern Sweden and Finland, and in northwest Russia [*Andersen et al.*, 1995b; *Lundqvist*, 1995; *Rainio et al.*, 1995] and mark the areal extent of the Fennoscandian ice sheet during the Younger Dryas deglaciation standstill (Figure 1). The Younger Dryas ice-marginal zone in Sweden, which consists of the Skövde and Billingen moraines, is developed both east and west of Mount Billingen [*Lundqvist*, 1995, and references therein]. These moraines are difficult to radiocarbon date, and estimated ages for their deposition are based on correlations to radiocarbon dated moraines in southern Norway, stratigraphy, clay varve chronology, or are inferred from radiocarbon dated marine shell deposits in southwestern Sweden. Such ages vary from approximately 11,300 to 10, 600 ^{14}C years for the Skövde moraine and 10,600 to 10,200 ^{14}C years for the more northerly Billingen moraine [*Berglund*, 1979; *Björck and Digerfeldt*, 1982, 1984; *Strömberg*, 1985; *Fredén*, 1988]. Nevertheless, the Skövde and Billingen moraines provide clear evidence that during the Younger Dryas the southernmost margin of the Fennoscandian ice sheet was situated south of the topographic threshold that served as the outlet for the final drainage of the BIL.

Shore displacement records for the Baltic area indicate that one major lowering of the BIL occurred long before its assumed final drainage in the late Younger Dryas. This first lowering of the BIL took place at a time close to the Allerød/Younger Dryas chron boundary [*Donner*, 1982, and references therein]. According to *Björck and Digerfeldt* [1984, 1989], the ice front was situated north of Mount Billingen in the late Allerød chron, with a subsequent readvance during the early Younger Dryas. Included in this model is a first BIL drainage, when the retreating ice front passed Mount Billingen and the lake level dropped dramatically by approximately 10-15 m [*Björck*, 1979]. When the ice front readvanced in the early Younger Dryas and the Skövde and Billingen moraines were deposited, the BIL was again dammed. The second and final drainage of the BIL lowered the lake by approximately 25 m and is generally believed to have occurred in the late Younger Dryas at 10,300 ^{14}C years ago [e.g., *Bergsten and Nordberg*, 1992; *Bergsten*, 1994; *Lundqvist*, 1995]. This is a maximum age for the drainage event and is obtained from radiocarbon dated bulk sediments [*Svensson*, 1989] and AMS dated leaves and insect remains found in redeposited sediments thought to represent the final drainage [*Wohlfarth et al.*, 1993].

Reduced melting of glacial ice sheets during the Younger Dryas and the drainage of the BIL are evident in the isotope records from Moltemyr and Solberga. In the Solberga-2 record, 11,150 ^{14}C years marks the beginning of the 7-m interval (2650-950 cm) of high-frequency oscillations superimposed on a trend of fairly constant or slightly increasing $\delta^{18}O$ (Figures 3 and 4). Considering the vast amount of geomorphological evidence for a standstill and subsequent readvance of the Fennoscandian ice sheet during the Younger Dryas [*Andersen et al.*, 1995a], it is likely that the observed $\delta^{18}O$ trend reflects the reduced release of glacial meltwater of local origin. Along the coast of Norway, early Younger Dryas readvances are radiocarbon dated to 11,000-11,300 ^{14}C years [*Andersen et al.*, 1995b; *Bergstrøm*, 1995]. The beginning of the slowdown or halt in glacial melting, as indicated in the Solberga-2 core, also closely corresponds to the onset of the climatic Younger Dryas which is AMS dated to 11,200 ^{14}C years in SST records from the Norwegian Sea [*Koç Karpuz and Jansen*, 1992; *Lehman and Keigwin*, 1992].

In terrestrial records from southern Sweden, a first BIL drainage predates the climatically cold Younger Dryas [*Björck*, 1979]. The freshwater spike recorded as a distinct $\delta^{18}O$ oscillation at 2505 cm in the Solberga-2 core, however, is apparently of early Younger Dryas age. As the minimum isotopic ratio of meltwater from the Fennoscandian ice sheet was -25‰ [*Olausson*, 1982], the 2.4‰ change in $\delta^{18}O$ indicates that bottom water salinity at Solberga decreased approximately 3‰. From the estimated sedimentation rate, the duration of the event appears to have been rapid and may have occurred on the order of approximately a decade or less. Using the radiocarbon date of 10,360 ^{14}C years at 1935 cm to create a linear age depth relation, the estimated age for this low-salinity event is 10,995 ^{14}C years. Using the younger age alternative of 10,260 ^{14}C years at 2230 cm gives an estimated age of 10,855 ^{14}C years for the event. The proposed age for a first (approximately 10-15 m) lowering of the BIL is 11,200 ^{14}C years [*Björck*, 1979]. This radiocarbon age is obtained on bulk sediment and may therefore be a few hundred years too old [*Wohlfarth et al.*, 1993, and references therein]. As there is no sign in the isotopic record for a rapid drainage event in the late Allerød chron, it may be that the conspicuous freshwater spike with an average age of 10,925 ^{14}C years represents the first drainage of the BIL, which is a documented event in shore displacement records in the Baltic region. The first Baltic Ice Lake Lowering (BILL-1) is not recorded at Moltemyr, probably due to the coarser sampling resolution used in the Moltemyr core. Since BILL-1 is recorded in only one core and its estimated age appears too young to represent the assumed late Allerød drainage, we regard its correlation to the circum-Baltic shore displacement records as tentative until its appearance and age are confirmed in other marine records of the Swedish west coast.

The second and final drainage of the BIL is clearly evident in both records and took place in two steps. In Solberga-2, the drainage is recorded as 2.5‰ and 3.7‰ oscillations occurring just above 1900 cm, and in the Moltemyr core as 9‰ and 5‰ oscillations at the top of the record. On the basis of the radiocarbon dates (Table 1), four different age estimates can be made for each event. For the older event (BILL-2A), estimated ages range between 9,930 and 10,205 ^{14}C years, and between 9,905 and 10,200 ^{14}C years for the younger event (BILL-2B) (Table 3). These dates indicate that the final drainage occurred during the radiocarbon plateau at approximately 10,000 ^{14}C years.

The distinct freshwater spike observed by *Erlenkeuser* [1985] in the Skagerrak south of Norway was dated by tephrachronology and is regarded as too old to represent the assumed BIL drainage at 10,300 ^{14}C years. The volcanic ash horizon found, the Vedde ash, was believed to indicate an age of 10,600 ^{14}C years at a level about 100 cm below the recorded freshwater spike. New radiocarbon dates on terrestrial vegetal material from three Norwegian sites, however, now suggest that the radiocarbon age for the Vedde ash is closer to approximately 10,300 ^{14}C years [*Bard et al.*, 1994; *Birks et al.*, 1996]. A younger age for the event was also indicated by radiocarbon dated bivalve fragments obtained from a 35-cm interval close to the ash horizon. The age of the fragments is 10,260 ± 280 ^{14}C years and is based on a 400-year correction for reservoir age [*Stabell*, 1985]. Thus, the recorded freshwater event appears to be younger than previously assumed. On the basis that the freshwater event is recorded as two closely spaced δ^{18}O oscillations, similar to the Solberga-2 and Moltemyr cores, it appears that BILL-2A and BILL-2B also left chemical imprints in the sediment record of the deeper Skagerrak. No volcanic ash horizons have been identified in the Solberga-2 and Moltemyr cores.

In a study of lacustrine records from the former BIL area [*Svensson*, 1989; see also *Wohlfarth et al.*, 1993], it is suggested that the final drainage took place at, or slightly before, the Younger Dryas/Preboreal boundary. On the basis of an observed warming, inferred from changes in benthic foraminifera, the end of the Younger Dryas is identified at 1890 cm in the Solberga core and at 345 cm in the Moltemyr core [*Knudsen*, 1982]. Using planktonic diatoms, *Miller* [1982] observed this change at 1935 cm in Solberga and at 345 cm in Moltemyr. This time lag between the benthic and planktonic record at the deeper Solberga may be reasonable because a climatic warming would first affect surface waters. In both cores, BILL-2A and BILL-2B is recorded at or above these levels (Table 3). Thus, on the basis of biostratigraphy, the final drainage appears to shortly postdate the Younger Dryas. The warming that marks the beginning of the Preboreal was very rapid and occurred in only a few decades [*Alley et al.*, 1993]. The temperature rise over Greenland was of the order of 8°-20°C [*Grootes et al.*, 1993; *Johnsen et al.*, 1995; *Kerr*, 1996] and in the southeast Norwegian Sea SST rose abruptly by 9°C [*Koç Karpuz and Jansen*, 1992]. This warming apparently caused the ice margin at Mount Billingen to retreat, and the BIL drained.

Table 3. Estimated Radiocarbon ages for Baltic Ice Lake Lowering (BILL) Events

Core	Depth, cm	Event	Age, ^{14}C years
Solberga-2	2505	BILL-1	10,855-10,995
Solberga-2	1890	BILL-2A	9,930-10,155
Moltemyr	270	BILL-2A	10,040-10,205
Solberga-2	1865	BILL-2B	9,905-10,040
Moltemyr	265	BILL-2B	10,025-10,200

Age range is minimum to maximum.

As seen in the δ^{18}O records from Solberga and Moltemyr and in the Skagerrak [*Erlenkeuser*, 1985], the final drainage took place in two dramatic steps, the first BILL-2A and the final BILL-2B. This may indicate that a readvance of the ice margin dammed the BIL after BILL-2A. As the drainage took place in a period when the climate was warm, and a readvance of the ice margin appears unlikely, a second threshold may have been involved. Such a threshold is located in an area approximately 30 km east of Mount Billingen [*Strömberg*, 1992]. This threshold, the narrow Örlen Valley, regulated the outflow after the lake level had been lowered by approximately 15 m. Another possibility is that icebergs may have dammed the narrow outlet either at the northern tip of Mount Billingen or at Örlen Valley, causing drainage to cease temporarily or slow down [*Strömberg*, 1992, and references therein]. However, a detailed explanation for the mechanism behind the two-step drainage is still to be determined.

The identification of BILL-1 is clear evidence of ice margin oscillations during the Younger Dryas and confirms the hypothesis of an ice margin position north of Mount Billingen before the readvance that created the Skövde and Billingen moraines [*Donner*, 1969; *Berglund*, 1979; *Björck and Digerfeldt*, 1984, 1989]. Our results indicate that the ice margin receded from the northern tip of Mount Billingen and the BIL was drained at about 10,900 ^{14}C years. Whether the Skövde moraine was deposited before or after BILL-1 cannot be determined since ages proposed for its deposition range between approximately 11,300 and 10,600 ^{14}C years [*Fredén*, 1988, and references therein]. Perhaps the Skövde moraine marks the onset of the Younger Dryas at 11,150 ^{14}C years, as suggested by our isotopic record from Solberga. A readvance of the ice front is evident by the Billingen end moraine which has ages varying between 10,600 and 10,200 ^{14}C years. This is also confirmed by the isotopic record, since the BIL must have been dammed again before BILL-2A took place. The Billingen end moraine appears as a swarm of small ice-marginal ridges within an approximately 10-km-wide zone just a few kilometers south of the drainage outlet (Figure 5). These features may indicate that the ice margin in this area oscillated with several recessions on the order of a few kilometers followed by smaller readvances which created the ice-marginal ridges. It is believed that the final drainage of the BIL started subglacially before the ice margin passed the threshold and the main drainage took place [*Strömberg*, 1977; *Björck and Digerfeldt*, 1984, 1989]. Considering the proximity of the oscillating ice margin to the Mount Billingen threshold, it is possible that some ice recessions reached a critical point, allowing the BIL to subglacially tap some of its water. Perhaps the BIL was lowered a few meters or less before a minor ice margin advance closed the subglacial outlet.

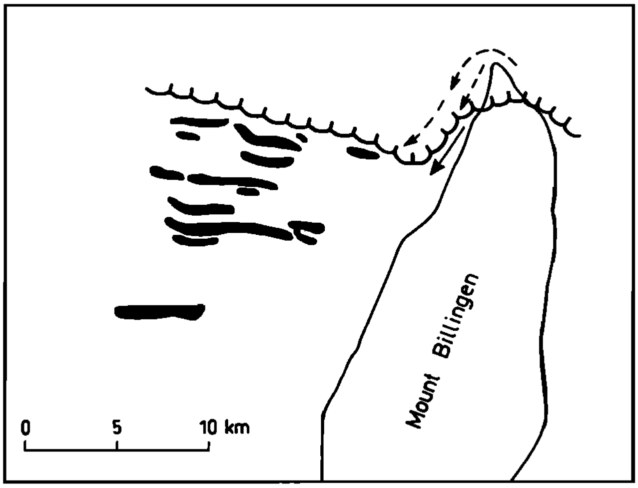

Figure 5. Detailed map of the ice margin position at the Mount Billingen threshold. Dark patches indicate the ice marginal-deposits of the Billingen end moraine. Arrows indicate a hypothesized subglacial drainage of the Baltic Ice Lake. (Adapted from *Björck and Digerfeldt* [1984]).

The Younger Dryas ice margin oscillations may reflect ice sheet dynamics caused by differences in the rate of isostatic land rise at different areas along the ice margin or a reorganization of its mass during the standstill. If the end moraines were created due to mechanical ice sheet dynamics, there would likely be little or no glacial melting. On the other hand, if they were climatically induced, the recessions would be accompanied by melting. The meltwater released during these minor ice sheet recessions must have affected the salinity of waters proximal to the ice sheet. Apart from the major drainage event (BILL-1), the Younger Dryas isotopic record in Solberga-2 is characterized by the appearance of numerous 0.5-1‰ $\delta^{18}O$ oscillations and a few oscillations on the order of approximately 1.5‰. In the shallower Moltemyr record, these salinity variations are highly amplified. Minor ice margin oscillations during the Younger Dryas, as indicated in the Billingen area, are apparently also reflected in the isotopic records of Solberga and Moltemyr. The above speculated "leaking" events of the BIL at Mount Billingen may explain some of the 1-1.5‰ $\delta^{18}O$ oscillations observed in the interval between BILL-1 and BILL-2A in the Solberga-2 core (Figure 3). If our suggested correlation between ice margin oscillations and the observed variations in shallow bottom water salinity is correct, the results from Solberga indicate about 10 climatically induced recession/advance events of the southwestern part of the Fennoscandian ice sheet during the Younger Dryas. As it has been shown that ice margin fluctuations of the Fennoscandian ice sheet during the Younger Dryas differ in age and magnitude in different areas [e.g., *Andersen et al.*, 1995b; *Rainio et al.*, 1995; *Bergstrøm*, 1995], it is not possible to link the Solberga and Moltemyr records to variations in total Fennoscandian ice sheet volume.

Early Holocene

Following the drainage, when the Fennoscandian ice sheet was melting rapidly, deglaciation and the routing of vast amounts of meltwater to the sea were complex [e.g., *Björck*, 1995]. Shortly after the drainage, marine waters entered the Baltic basin, and a brackish water phase persisted for a few hundred years until isostatic rebound narrowed the main connection to the sea and the Ancylus Lake began to rise. Contemporaneous with land uplift in the north, isostasy had ceased in the southern Baltic or turned into land subsidence. Meltwater subsequently once again flooded large areas in the south, and a drainage outlet was developed through Denmark in the late Preboreal. Before the outlet was created in the south, the Ancylus Lake was drained through outlets on the Swedish west coast. Owing to land uplift, the inland basin east of Moltemyr and Solberga, the Vänern basin, was isolated from the sea and drained only through two narrow outlets [*Björck*, 1995]. These outlets reached the sea north of Moltemyr and south of Solberga. Thus the Solberga-2 record monitors the pattern of meltwater outflow from the Ancylus Lake until the southern Baltic outlet was opened approximately 1000 years after the final drainage of the BIL.

This part of the record (between approximately 1700 and 1900 cm; Figure 3) appears quite different from the Younger Dryas. With the exception of the BIL drainage and two 1-1.5‰ spikes at 1815 and 1760 cm, the record is fairly stable and shows a Preboreal decrease in $\delta^{18}O$ of approximately 0.5‰. This in contrast to the Younger Dryas part of the record, which shows several $\delta^{18}O$ oscillations and an increase of about 0.5‰. The remaining 1‰ decrease to mid Holocene values occurred in the succeeding 100 cm (Figure 3) and ends at approximately 8000 ^{14}C years, similar to the Skagerrak record [*Erlenkeuser*, 1985]. The more stable pattern of the Preboreal record may indicate that the vast amounts of meltwater from the melting Fennoscandian ice sheet generally were released to the sea at a fairly constant rate at the Solberga outlet. This pattern can be explained, in part, by the smoothing effect caused by the lower sediment accumulation rate (Figure 2) and sampling bias. A minor regulating, and smoothing, effect on the amount of meltwater released to the sea may also be linked to the increase in reservoir capacity provided by the submerging lowlands in the southern Baltic where the Ancylus Lake level rose by 10-25 m [*Björck*, 1995].

The two $\delta^{18}O$ oscillations recorded at 1815 and 1760 cm (estimated ages of about 9800 and 9300 ^{14}C years) may indicate periods of rapid melting of the Fennoscandian ice sheet or other dramatic Preboreal ice lake drainage events. Such events are known from eastern Finland, where ice-dammed lakes were drained shortly after the final drainage of the BIL [*Rainio et al.*, 1995]. Further, in the late Preboreal, the ice-dammed lake Nedre Glåmsjø in Norway was dramatically drained, and 100 km³ of water may have entered the Lake Vänern basin in 1 or 2 weeks [*Longva and Thoresen*, 1991]. As these spikes are single sample observations, they need to be confirmed in other cores.

Conclusions

We have tied a late glacial marine oxygen isotope record of the Swedish west coast to geomorphological features that can be seen throughout the Baltic area, for example, variations in the BIL shore level, drainage traces, and ice-marginal deposits. First and foremost, we have captured three major drainage events of the BIL (Table 3) and may have the evidence confirming the hypothesis of a first BIL drainage at the Mount Billingen threshold at a time close to the Allerød/Younger Dryas chron boundary [*Björck and Digerfeldt*, 1984, 1989]. An estimated radiocarbon age for this event is about 10,900 ^{14}C years. We have also identified the dramatic final drainage of the BIL. Our results show that this drainage was complex and occurred in two steps. The reason for this two-step drainage is not known but may have been caused by an ice margin readvance, or icebergs may have dammed one of the two narrow outlets regulating the drainage. On the basis of biostratigraphy [*Knudsen*, 1982; *Miller*, 1982], it is suggested that the final drainage took place at or shortly after a rapid warming in early Preboreal. The estimated radiocarbon age for the event falls into the radiocarbon plateau of 10,000 ^{14}C years [*Kromer and Becker*, 1993; *Goslar et al.*, 1995].

Numerous $\delta^{18}O$ oscillations and steps are interpreted to reflect glacial meltwater released during periods of melting of the southeastern portion of the Fennoscandian ice sheet. Rapid melting occurred a few hundred years prior to the Younger Dryas standstill, which appears to have begun at approximately 11,150 ^{14}C years, when salinity, although oscillating, shows no deglacial tendency toward lower values. During the Younger Dryas, approximately 10 salinity fluctuations, unrelated to the drainage of the BIL, are recognized. These variations are interpreted as climatically induced ice margin recession/readvance events. An oscillating behavior of the Fennoscandian ice sheet during the Younger Dryas is also indicated by ice-marginal deposits throughout Scandinavia.

During the Preboreal, when most of the remaining Fennoscandian ice sheet was rapidly melting, there is no distinct sign in the $\delta^{18}O$ record of increased meltwater outflow. With the exception of the two-step drainage of the BIL marking the beginning of Preboreal, the record appears more stable in contrast to the Younger Dryas. This more stable appearance may be connected to the inflow of seawater into the Baltic basin, a diminishing drainage capacity of the outlet due to isostatic uplift, or the development of a new drainage outlet in the southern Baltic.

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