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ScienceDirect
Global and Planetary Change 57 (2007) 355–370
GLOBAL AND PLANETARY CHANGE
www.elsevier.com/locate/gloplacha

Reconstructing the Younger Dryas ice dammed lake in the Baltic Basin: Bathymetry, area and volume

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Received 18 August 2006; received in revised form 12 January 2007; accepted 19 January 2007
Available online 6 February 2007

Abstract

A digital 3D-reconstruction of the Baltic Ice Lake's (BIL) configuration during the termination of the Younger Dryas cold phase (ca. 11 700 cal. yr BP) was compiled using a combined bathymetric–topographic Digital Terrain Model (DTM), Scandinavian ice sheet limits, Baltic Sea Holocene bottom sediment thickness information, and a paleoshoreline database maintained at the Lund University. The bathymetric–topographic DTM, assembled from publicly available data sets, has a resolution of 500 × 500 m on Lambert Azimuthal Equal Area projection allowing area and volume calculations of the BIL to be made with an unprecedented accuracy. When the damming Scandinavian ice sheet margin eventually retreated north of Mount Billingen, the high point in terrain of Southern central Sweden bordering to lower terrain further to the north, the BIL was catastrophically drained resulting in a 25 m drop of the lake level. With our digital reconstruction, we estimate that approximately 7800 km^3 of water drained during this event and that the ice dammed lake area was reduced by ca. 18%. Building on previous results suggesting drainage over 1 to 2 years, our lake volume calculations imply that the freshwater flux to the contemporaneous sea in the west was between about 0.12 and 0.25 Sv. The BIL reconstruction provides new detailed information on the paleogeography in the area of southern Scandinavia, both before and after the drainage event, with implications for interpretations of geological records concerning the post-glacial environmental development.

Keywords: ice dammed lakes; paleotopography; paleobathymetry; Younger Dryas; Baltic Sea; isostasy

1. Introduction

Ice dammed lakes comprise key components of the glacial environment and have been shown to influence the regional climate due to a summer cooling effect and modification of precipitation (Hostetler et al., 2000; Krinner et al., 2005). Furthermore, geological records witness large influxes of cold freshwater to the oceans attributed to catastrophic drainages of ice dammed lakes

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doi:10.1016/j.gloplacha.2007.01.006

(e.g. Baker and Bunker, 1985; Clarke et al., 2004). Such outbursts of cold water into the North Atlantic during the last deglaciation have been proposed to dramatically changing climate by impacting the North Atlantic deep water formation and causing significant cooling events (e.g. Björck et al., 1996; Barber et al., 1999; Teller et al., 2002). The potential importance of ice dammed lakes for the environmental evolution from glacial to inter-glacial conditions has resulted in an increasing interest from the modelling community to include these lakes in their models. However, the first step towards incorporating pro-glacial lakes into climate and ocean circulation modelling or hydraulic experiments is to reconstruct their spatial extents and accurately determine lake properties such as bathymetry, volume and hypsometry.

Together with some of the most well-known ice dammed lakes such as Glacial Lake Missoula (e.g. Baker and Bunker, 1985) and Lake Agassiz (e.g. Teller, 1987), the Baltic Ice Lake (BIL) is probably among the most studied. The knowledge of an ice dammed lake in the Baltic Basin during the last deglaciation is now more than 100 years old; it was first mentioned in the literature by the Swedish geologist Henrik Munthe (1902). Key to our present understanding of the BIL is the initial geological mapping of the region in south central Sweden where the lake finally drained at the end of the late-glacial period (Lunqvist, 1921; Lundqvist, 1931), at the termination of the Younger Dryas cold phase. This final drainage occurred when the damming Scandinavian ice sheet retreated to lower terrain north of Mount Billingen, the mountain that acted as the constraint for the lake extension. From studies of clay varves and shoreline displacements, this final drainage has been proposed as a more or less catastrophic outburst resulting in a lake lowering of ca. 25 m (Björck and Digerfeldt, 1984, 1989; Andrén et al., 2002), although a less dramatic drainage scenario taking place over several decades has also been advocated (Strömberg, 1992). However, recently the existence of the BIL was questioned by Påsse and Andersson (2005) who, based on a mathematical shoreline displacement model, argue that the lake surface was at sea level during the end of the Younger Dryas implying that an outburst never took place as there was no lake damming.

Studies of the BIL have resulted in numerous publications (see review by Björck, 1995a), and the accumulated field observations related to the lake's final stage during the last deglaciation has grown into a

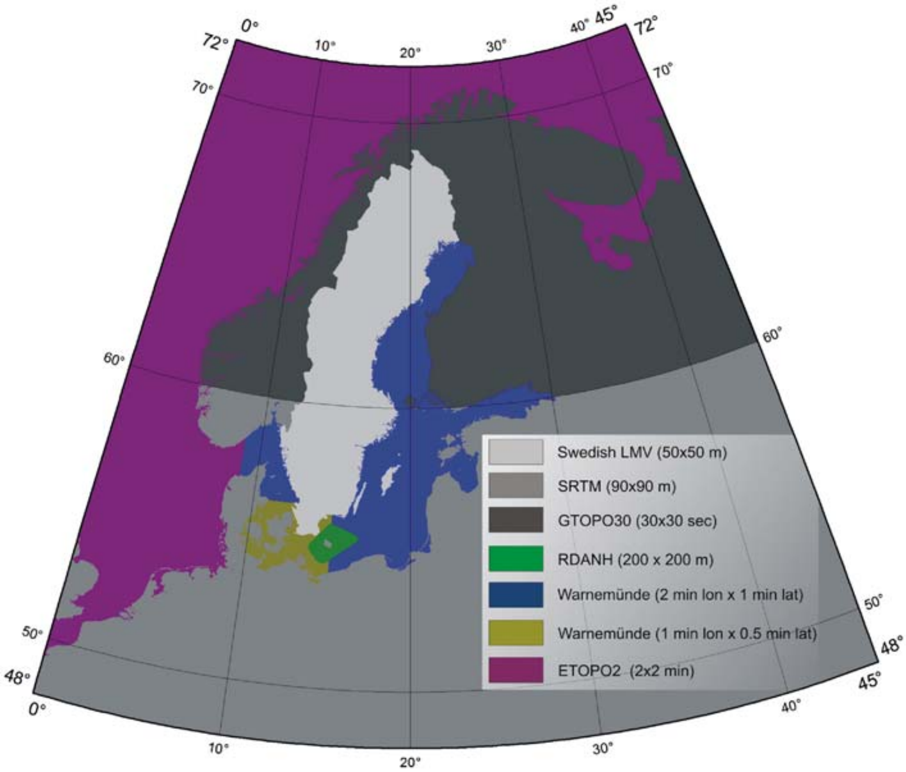

Fig. 1. Data sources used to compile the combined bathymetric–topographic Digital Terrain Model (DTM).

valuable database maintained at Quaternary Sciences at Lund University (Svensson, unpublished). Using the paleoshoreline information from this database, we have compiled a digital 3D-reconstruction of the final stage of the ice dammed lake in the Baltic Basin dated to the very end of the Younger Dryas cold phase (ca. 11 700 cal. yr. BP, Björck et al., 1996; Andrén et al., 2002). In addition to paleoshoreline data, our lake reconstruction builds on a combined bathymetric–topographic Digital Terrain Model (DTM) specifically constructed for this study, Scandinavian ice sheet limits (Lundqvist and Wohlfarth, 2001), and Baltic Sea Holocene bottom sediment thickness information assembled within this study. The BIL model was constructed through a series of experiments where mathematical algorithms were applied to fit the paleolake's surface through the shoreline database.

Our reconstruction clearly shows that there was an ice dammed lake in the Baltic Basin during the end of the Younger Dryas and, thus, no support is provided for the hypothesis of a lake surface concomitant with the sea level at this time as proposed by Påsse and Andersson (2005). Furthermore, our reconstruction allows us to estimate bathymetry and calculate lake volume and hypsometry both before and after the drainage that resulted in a ca. 25 m drop in lake level. The substantially higher resolution of our BIL reconstruction compared to previous compiled maps makes it possible to view the paleogeography of the region from a new perspective and assess the environmental impact from the final drainage scenario.

2. Materials and methods

2.1. A bathymetric–topographic model for the Baltic region

The input data used for the compilation of our combined bathymetric–topographic DTM were derived from existing DTMs with large variations in resolution (Fig. 1; Table 1). Our combined model has a grid cell size resolution of 500 × 500 m on a Lambert Azimuthal Equal Area projection ($\lambda_0 = 20°$E, $\varphi_0 = 60°$N). This resolution is high enough to capture the main characteristics of the BIL for the purposes of our study. The horizontal datum is WGS84 and the vertical datum is Mean Sea Level. All input data had the vertical datum assigned to Mean Sea Level implying that no vertical datum conversions were required before data merging. The bathymetric data sets together with GTOPO30 and SRTM of the topographic data were treated to be referenced to the WGS84 geodetic horizontal datum following the accompanying data descriptions. The Swedish elevation data is registered in the National Grid (RT 90 2.5 g West), which has a known relation to the WGS84 datum and was, thus, properly transformed using a seven parameter model (translation (3), rotation (3) and scaling (1)).

All bathymetric data points from the individual DTMs were imported to a Microsoft Access™ database configured for Intergraph's GIS software Geomedia Professional™. Merging of the bathymetry was performed through spatial queries following the principle

Table 1
Bathymetric and topographic data used in the compilation of a combined bathymetric–topographic DTM with a resolution of 500 × 500 m on Lambert Equal Area projection

Dataset	DTM resolution	Original projection, horizontal and vertical datum	Reference
Topography of Sweden from the Swedish cadastral service (LMV)	50 × 50 m	Gauss, RT 90 2.5 g West, mean sea level	LMV: www.lantmateriet.com
Global topography from Shuttle Radar Topography Mission (SRTM)	3 × 3 s	Platte Carre (unprojected), WGS 84, mean sea level	U.S. Geological Survey's National Center for Earth Resources Observation and Science (EROS): http://srtm.csi.cgiar.org
Global topography from GTOPO30	30 × 30 s	Platte Carre, WGS 84, mean sea level	EROS: http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html
Bathymetry around Bornholm from the Royal Danish Administration of Navigation and Hydrography (RDANH)	200 × 200 m	UTM (Zone 33), WGS 84, mean sea level	RDANH, courtesy of John Woodward
Bathymetry of the Baltic Sea by the Baltic Sea Research Institute, Warnemünde (IOW)	1′ longitude × 0.5′ latitude	Platte Carre, WGS 84, mean sea level	Seifert et al., 2001: http://www.io-warnemuende.de
Cont. IOW	2′ longitude × 1′ latitude	Platte Carre, WGS 84, mean sea level	Seifert et al., 2001: http://www.io-warnemuende.de
Global bathymetry from ETOPO2	2 × 2′	Platte Carre, WGS 84, mean sea level	National Geophysical Data Center (NGDC): http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html

that higher resolution data override lower resolution. The topography was treated separately due to the large amount of data; in fact too large to efficiently use Access™ as a database. Instead the raster software Erdas Imagine™ was used to merge all the topographic data according to the same principle as was applied for the bathymetry, i.e., higher resolution data override lower resolution. In order to complete the combined DTM at a grid cell size resolution of 500 × 500 m both subsampling and interpolation had to be implemented on the source data. Bathymetry and topography were treated separately. Subsampling of the higher resolution topographic data sets (Swedish national elevation data and SRTM) was performed using a near neighbour algorithm. This algorithm was also used to interpolate additional values in the region where only the GTOPO30 topography existed, which is coarser than 500 × 500 m. The interpolation of the bathymetry used a minimum curvature surface spline in tension algorithm (tension set to 0.35) as implemented in the Generic Mapping Tools (GMT) software (Wessel and Smith, 1991) and the coastline was constrained using the World Vector Shoreline Plus (Soluri and Woodson, 1990). Finally, bathymetry and topography were merged and since the topography must be considered of generally higher quality, the topography was set to govern the coastline. The area of interest for this work of the final combined bathymetric–topographic DTM is shown as a shaded relief in Fig. 2.

2.2. BIL shoreline database

Over the years, Swedish paleoshoreline data have been accumulated in a database at the Department of Quaternary Sciences, Lund University (Svensson, unpublished). The shoreline database was derived from a plethora of studies and contains information on where (latitude/longitude) and when (years BP) the Baltic Sea/Lake level was in relation to today's sea level. For example, this information has been acquired through shore displacement studies or dating of raised beaches. Almost exclusively, the age control has been achieved by ^{14}C dating organic material. Table 2 lists the shoreline information retrieved from the Lund database to be used in this study for the reconstruction of the BIL ca. 11 700 cal. yr. BP. Calendar year calibration of the ^{14}C ages (in this work referred to as cal. yr. BP) in the Lund University database has been to a large extent facilitated by the southern Sweden time-synchronous Younger Dryas–Preboreal transition (YDP) pollen zone (Björck

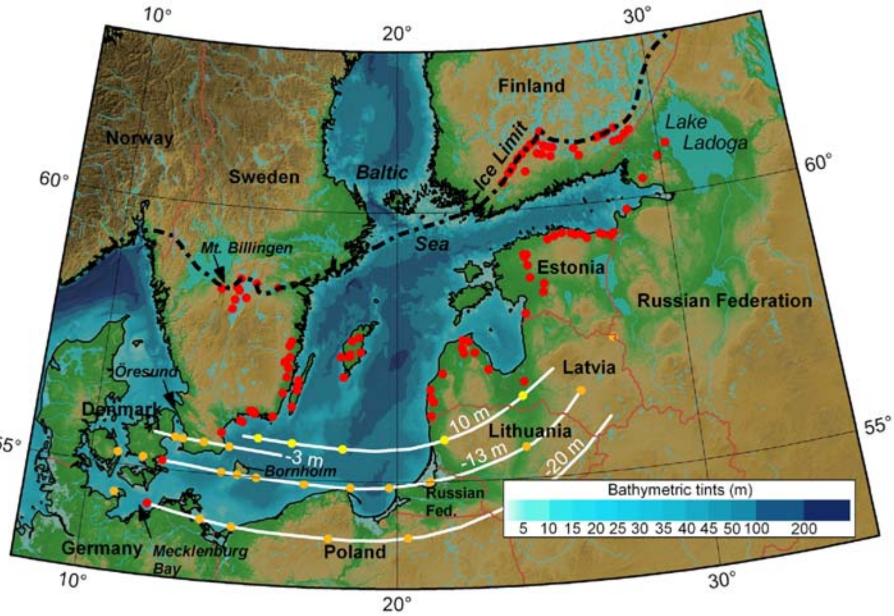

Fig. 2. Shaded relief map portraying the main area of interest of the topographic–bathymetric DTM compiled in this study from source data shown in Fig. 1. The map also shows the key base data used in the reconstruction of the Younger Dryas (ca. 11 700 cal yr BP) Baltic Ice Lake (BIL): Black dashed-dotted line represents the ice limit from Björck (1995a), which had to be adjusted slightly to fit exactly the shoreline observations; red dots are the locations of Younger Dryas shoreline observations listed in Table 2; yellow and orange dots are inferred lake surface constraining points and the white lines are connecting points with the same inferred elevation with respect to the present Baltic Sea level (see Materials and methods and Table 2). LD indicates the 459 m Landsort Deep.

Table 2
Shoreline constraining points used in this study for reconstructing the surface of the BIL 11 600 calendar years BP. Records 1–101 represent actual field sites retrieved from the shoreline database maintained at Quaternary Sciences, Lund University. The last records (102–128) have been extrapolated and inferred during this work (see Materials and methods)

Record	Site	Author	Latitude	Longitude	Meter above present sea level	Estimated vertical error
1	Slättmossen Blekinge	Berglund (1966)	56.1507	15.8372	25	2.5
2	Norrsjön	Björck (1979)	56.2316	15.0729	25	2
3	Paddegölen	Björck (1979)	56.1799	15.2197	28	2.5
4	Finland	Donner (1978)	61.3439	28.3832	104	1
5	Finland	Donner (1978)	61.2791	28.9619	91	1
6	Finland	Donner (1978)	61.2729	28.0711	108	1
7	Finland	Donner (1978)	61.2076	28.7617	93	1
8	Finland	Donner (1978)	61.2461	27.9662	107	1
9	Finland	Donner (1978)	61.2330	27.8102	110	1
10	Finland	Donner (1978)	61.4184	25.5175	160	1
11	Finland	Donner (1978)	61.2005	27.6659	110	1
12	Finland	Donner (1978)	61.1201	28.5372	95	1
13	Finland	Donner (1978)	61.0952	28.3203	96	1
14	Finland	Donner (1978)	61.2493	25.3522	160	1
15	Finland	Donner (1978)	61.1927	25.1288	162	1
16	Finland	Donner (1978)	61.1485	25.6209	145	1
17	Finland	Donner (1978)	61.0505	26.7670	124	1
18	Finland	Donner (1978)	61.1173	25.7981	151	1
19	Finland	Donner (1978)	61.1050	25.9625	141	1
20	Finland	Donner (1978)	61.1142	24.9560	160	1
21	Finland	Donner (1978)	60.9091	26.9412	110	1
22	Finland	Donner (1978)	61.0140	25.3553	146	1
23	Finland	Donner (1978)	60.9920	25.5348	145	1
24	Finland	Donner (1978)	60.9412	25.8539	133	1
25	Finland	Donner (1978)	61.0189	24.7608	161	1
26	Finland	Donner (1978)	60.9399	24.5899	159	1
27	Finland	Donner (1978)	60.7997	24.3849	153	1
28	Finland	Donner (1978)	60.6964	24.8546	140	1
29	Finland	Donner (1978)	60.7334	24.2933	152	1
30	Finland	Donner (1978)	60.6847	24.2067	151	1
31	Finland	Donner (1978)	60.5105	23.9600	145	1
32	Brandstorp	Nilsson (1937)	58.0921	14.1973	115	1
33	Brevik	Nilsson (1937)	58.4356	14.3871	144	1
34	Flädesmon	Nilsson (1937)	58.5935	14.9827	155	1
35	Hjo, south of	Nilsson (1937)	58.2635	14.2577	127	1
36	Karlsborg NW	Nilsson (1937)	58.6604	14.4125	156	1
37	Karlsborg WsW	Nilsson (1937)	58.4974	14.2989	149	1
38	Omberg	Nilsson (1937)	58.3125	14.6480	139	1
39	Billingen	Strömberg (1977)	58.4450	13.7529	150	1
40	Allekviaburgen	Svensson (1989)	57.6172	18.4235	69	0.6
41	Arlebrunn	Svensson (1989)	58.5377	15.7636	152	1
42	Baltic republics	Svensson (1989)	59.4089	27.8973	32	1
43	Baltic republics	Svensson (1989)	59.4270	27.4053	39	1
44	Baltic republics	Svensson (1989)	59.3985	27.5199	37	1
45	Baltic republics	Svensson (1989)	59.4808	26.3553	57	1
46	Baltic republics	Svensson (1989)	59.3539	27.8064	33	1
47	Baltic republics	Svensson (1989)	59.4985	26.0227	60	1
48	Baltic republics	Svensson (1989)	59.4388	26.7510	47	1
49	Baltic republics	Svensson (1989)	59.4415	26.5029	53	1
50	Baltic republics	Svensson (1989)	59.3609	26.9208	45	1
51	Baltic republics	Svensson (1989)	59.4569	25.7435	63	1
52	Baltic republics	Svensson (1989)	59.4045	25.4797	64	1
53	Baltic republics	Svensson (1989)	59.1454	24.6849	62	1
54	Baltic republics	Svensson (1989)	59.1537	24.5640	64	1

(continued on next page)

Table 2 (*continued*)

Record	Site	Author	Latitude	Longitude	Meter above present sea level	Estimated vertical error
55	Baltic republics	Svensson (1989)	59.1058	24.6043	62	1
56	Baltic republics	Svensson (1989)	58.9467	24.6858	56	1
57	Baltic republics	Svensson (1989)	58.7166	24.7482	48	1
58	Baltic republics	Svensson (1989)	58.5913	25.2349	37	1
59	Baltic republics	Svensson (1989)	58.4318	25.1919	32	1
60	Baltic republics	Svensson (1989)	58.0559	24.5131	32	1
61	Baltic republics	Svensson (1989)	57.6234	22.2582	38	1
62	Baltic republics	Svensson (1989)	57.5943	22.4710	34	1
63	Baltic republics	Svensson (1989)	57.4716	22.2313	34	1
64	Baltic republics	Svensson (1989)	57.3856	22.6664	30	1
65	Baltic republics	Svensson (1989)	57.3782	22.2982	32	1
66	Baltic republics	Svensson (1989)	57.0626	23.1191	21	1
67	Baltic republics	Svensson (1989)	57.0101	21.5407	28	1
68	Baltic republics	Svensson (1989)	56.8071	24.3017	13	1
69	Baltic republics	Svensson (1989)	56.7138	21.1191	22	1
70	Baltic republics	Svensson (1989)	56.5508	21.1451	20	1
71	Baltic republics	Svensson (1989)	56.4847	21.2171	18	1
72	Baltic republics	Svensson (1989)	56.2274	21.1322	15	1
73	Borg	Svensson (1989)	56.6653	16.6030	36	0.6
74	Borgholm A	Svensson (1989)	56.8517	16.6336	45	2
75	Borgholm B	Svensson (1989)	56.8513	16.6336	45	2
76	Fanketorp	Svensson (1989)	56.9031	16.2326	47	0.6
77	Getterum A	Svensson (1989)	57.5676	16.3409	78	0.6
78	Getterum B	Svensson (1989)	57.5675	16.3409	77	0.6
79	Hajdgårde	Svensson (1989)	57.3698	18.3776	58	0.8
80	Hanö 1	Svensson (1989)	56.0140	14.8455	17	1.5
81	Hejnum Hällar	Svensson (1989)	57.6832	18.6572	70	0.6
82	Högsrum	Svensson (1989)	56.7687	16.6261	40	0.6
83	Leningrad area	Svensson (1989)	60.9410	30.2815	59	1
84	Leningrad area	Svensson (1989)	60.7158	29.9172	53	1
85	Leningrad area	Svensson (1989)	60.3407	29.2369	46	1
86	Leningrad area	Svensson (1989)	59.8058	28.4938	40	1
87	Lilla Karlsö	Svensson (1989)	57.3152	18.0608	57	1
88	Listershuvud	Svensson (1989)	56.0313	14.7745	17	1
89	Lojst haid	Svensson (1989)	57.3207	18.3468	56	0.8
90	Maglehem	Svensson (1989)	55.7883	14.1838	10	1
91	Pilekulla	Svensson (1989)	56.3534	16.4533	28	0.6
92	Ramshult A	Svensson (1989)	57.0740	16.2761	53	0.5
93	Ramshult B	Svensson (1989)	57.0739	16.2777	53	0.5
94	Ramshult C	Svensson (1989)	57.0780	16.2821	54	0.6
95	Syserum	Svensson (1989)	57.4854	16.2727	73	0.6
96	Södremo	Svensson (1989)	56.5985	16.1233	36	1.5
97	Torsburgen	Svensson (1989)	57.4066	18.7273	57	1
98	Västerbackar	Svensson (1989)	56.9368	18.1661	42	0.6
99	Århult	Svensson (1989)	57.2734	16.3103	62	0.6
100	Faxe Bugt	Jensen (1995)	55.1667	12.3333	−13	Unknown
101	Mecklenburg Bugt	Jensen et al. (1997)	54.3333	12.0000	−20	Unknown
102	Extrapolated from Maglehem, this work	This work	55.7734	21.5523	10	Unknown
103	Extrapolated from Maglehem, this work	This work	56.5421	24.2319	10	Unknown
104	Extrapolated from Maglehem, this work	This work	55.7318	15.3984	10	Unknown
105	Extrapolated from Maglehem, this work	This work	55.6724	16.5214	10	Unknown
106	Extrapolated from Maglehem, this work	This work	55.5972	18.1970	10	Unknown
107	Extrapolated, this work	This work	55.6224	12.6764	−3	Unknown
108	Extrapolated, this work	This work	55.6084	12.9303	−3	Unknown
109	Extrapolated, this work	This work	55.5825	13.6301	−3	Unknown
110	Extrapolated, this work	This work	55.5338	14.4718	−3	Unknown
111	Extrapolated, this work	This work	55.0483	14.2805	−13	Unknown
112	Extrapolated, this work	This work	54.9929	15.4140	−13	Unknown

Table 2 (*continued*)

Record	Site	Author	Latitude	Longitude	Meter above present sea level	Estimated vertical error
113	Extrapolated, this work	This work	54.9203	16.9727	−13	Unknown
114	Extrapolated, this work	This work	54.8807	18.4725	−13	Unknown
115	Extrapolated, this work	This work	54.8868	19.7296	−13	Unknown
116	Extrapolated, this work	This work	54.9985	21.0589	−13	Unknown
117	Extrapolated, this work	This work	55.5912	24.2458	−13	Unknown
118	Extrapolated, this work	This work	56.5533	26.2047	−13	Unknown
119	Extrapolated, this work	This work	57.4910	27.4819	−13	Unknown
120	Extrapolated, this work	This work	54.1407	13.7146	−20	Unknown
121	Extrapolated, this work	This work	54.0465	14.7304	−20	Unknown
122	Extrapolated, this work	This work	53.9219	17.8083	−20	Unknown
123	Extrapolated, this work	This work	53.9498	20.3377	−20	Unknown
124	Extrapolated, this work	This work	54.5047	23.5818	−20	Unknown
125	Extrapolated, this work	This work	54.4776	10.9046	−20	Unknown
126	Extrapolated, this work	This work	55.1920	11.6998	−13	Unknown
127	Extrapolated, this work	This work	55.2233	10.8710	−13	Unknown
128	Extrapolated, this work	This work	55.0245	14.7966	−13	Unknown

et al., 1996). It should be noted that the new time scale of the NGRIP ice core assign a revised age of 11 653 cal. yr. BP to the YDP (Rasmussen et al., 2006).

2.3. Reconstruction of the Younger Dryas BIL lake surface

As a result of the differential uplift (isostatic rebound) of Scandinavia after the last deglaciation, the Younger Dryas ice dammed lake surface is not a simple plane at a given level. Therefore, the paleolake's surface must be reconstructed using the shoreline database at hand (Table 2) and some interpolation between this information. The procedure for reconstructing the BIL can be summarized in the following steps:

1. Interpolate the lake surface from the shoreline database using a mathematical algorithm.
2. Intersect the interpolated lake surface with the combined bathymetric–topographic DTM and visualize the result in 3D together with the original shoreline data and the Younger Dryas ice limit.
3. Iterate 1 and 2 using different mathematical algorithms for the interpolation of the lake surface. The iteration results are shown in Fig. 3A–C.

In step 2, all the objects, i.e. the computed lake surface, DTM, ice limit, shoreline database, were merged for analysis in the dynamic 3D-visualization environment of the Fledermaus™ software. During the iteration process it was found that some manually interpolated "steering" points for the lake surface in the south had to be entered in order to constrain the lake surface far from the source data. These points are shown in Table 2 and Fig. 2. Once the lake surface is computed, the BIL and surrounding area can be reconstructed by subtracting the lake surface's *z*-values from the topographic–bathymetric DTM. In other words, an isostatic readjustment to ca. 11 700 cal. yr. BP is performed using the calculated BIL surface.

2.4. Baltic Sea bottom sediments compilation

The accumulation of Holocene sediments in the Baltic Basin was compiled through assembling information from available sediment distribution maps (Sjöberg, 1996) and information retrieved from the Swedish Geological Survey's mapping archives. A digital grid model containing thickness information was constructed at the resolution of 500 × 500 m on a Lambert Azimuthal Equal Area projection to be compatible with our bathymetric–topographic model for the Baltic region. This sediment thickness model was used to compensate the final BIL reconstruction for accumulated Holocene sediments. However, we cannot determine to which extent the non-organic part of the Holocene sediments is composed of reworked glacial deposits.

2.5. Area and volume calculations

These properties are estimated by simply calculating pixels of our digital reconstruction of the BIL on a Lambert Azimuthal Equal Area projection and summarizing the results. Each pixel has an area of 250 000 m^2 (500 × 500 m) and this value may be regarded as good approximation over the entire BIL due to the equal area projection, albeit with greater distortion with increasing distance from the central meridian (λ_0 = 20°E) and standard parallel (φ_0 = 60°N). In the area calculation, pixels with the value of 0 (the BIL's shoreline) were

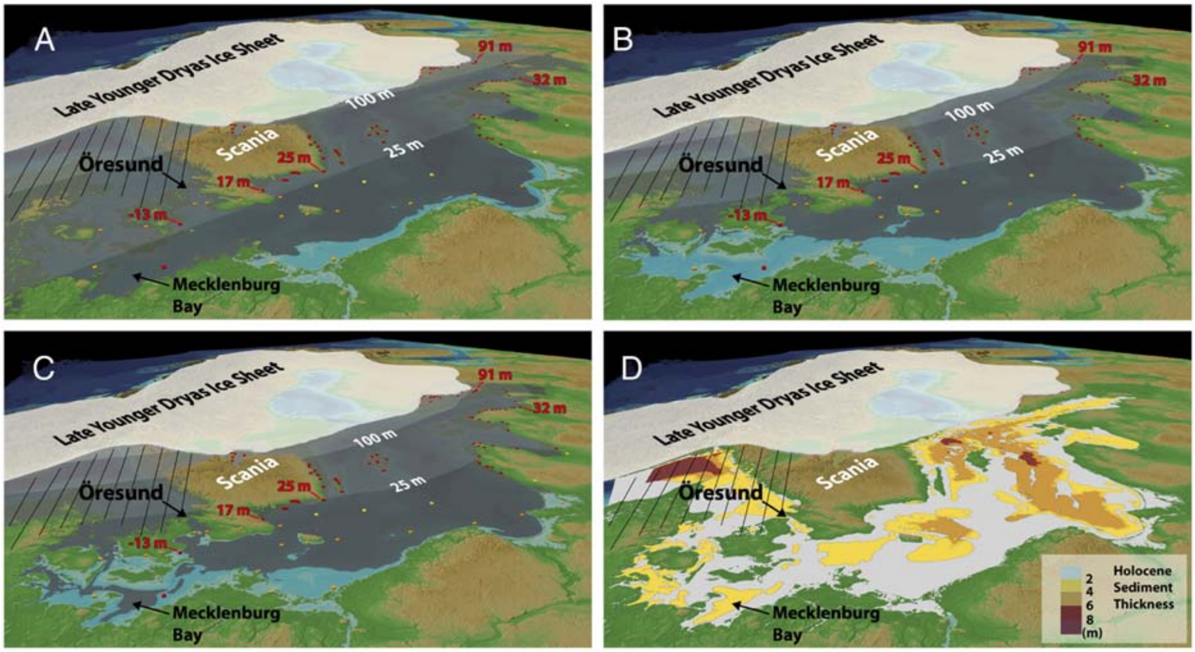

Fig. 3. The 3D-visualizations in A–C show the results from applying different mathematical algorithms on the available shoreline database to interpolate the lake surface of the final stage of the Baltic Ice Lake (BIL). The paleoshoreline resulting from this reconstruction procedure appears where the interpolated lake surface intersects with the topography. In order to evaluate the BIL reconstructions, the locations of shoreline observations are shown as red dots and the extrapolated points in this study as yellow and orange dots (see text and Table 2). The yellow dots have inferred elevations above the present Baltic Sea level whereas the orange have elevations below. This visualization exercise helps identifying the algorithm generating a lake surface intersecting the present topography closest to the shoreline observations on land (the red dots on land). The calculated lake surface elevation referenced to present Baltic Sea level is color coded using a gray color table with increments of 75 m. In addition, elevations of selected shoreline observations from Table 2 have been added in order to emphasize the tilting of the BIL surface with respect to the present day topography. The hatched area in figures A–D falls outside the up-dammed BIL; here the plane's interaction with the topography is not relevant for this study. A) The BIL surface reconstructed by fitting a plane through the available shoreline database. B) The BIL surface reconstructed using a quadratic function. This clearly gives a better result than a tilted linear plane. In particular, the area near Öresund is improved. The shoreline data point in the Mecklenburg Bay is at 20 m below sea level, which is even below the present sea floor. For this reason, the BIL surface should cut through the sea floor, as is evident in this visualization. C) The BIL surface reconstructed using a Minimum Curvature algorithm without tension. The results generally resemble that of a quadratic trend surface, but with a further improved result particularly in Öresund since the algorithm manages to locally divert from the overall region trend, which is well described with a quadratic polynomial. D) Generalized Holocene sediment thickness model compiled in this study (see text). This model was used in the Younger Dryas BIL reconstruction to compensate for accumulated sediments in the Baltic Basin during the Holocene.

included to derive the area. The uncertainties of the area and volume calculations are largely dominated by the errors associated with our BIL reconstruction, which primarily is dependant on the used bathymetric–topographic DTM, the interpolated BIL waterplane and the location of the Younger Dryas ice sheet margin. All these components have associated errors with large spatial variations that depend on the source data. For example, the lack of shoreline observations in the Lund University database in the southern part of our study area (Fig. 2) implies gross extrapolations in this region. For this reason it is not straightforward to assign an uncertainty to the derived BIL area and volume without a comprehensive error modelling, which has not been included in this study.

3. Results

3.1. Lake surface reconstruction through a plane

A plane was fitted through the shoreline database by a least square linear regression (note that a plane fitted through our projected database in reality represents a slightly curved surface due to the curvature of the Earth's surface). The result is described by:

$$z(x,y) = -1.07 \times 10^{-4}x + 2.84 \times 10^{-4}y + 122.51 \tag{A}$$

where z is the interpolated lake surface height in relation to the present day sea level at the location (x, y) given in

Lambert Azimuthal Equal Area coordinates ($\lambda_0=20°$E, $\varphi_0=60°$N). The fit between the calculated plane and the original database, including the inserted points in the south, reach a squared correlation coefficient (R^2) of ≈ 0.83. It is clearly seen in Fig. 3A that the reconstructed BIL surface using a plane is not satisfactory in the southwest, the area of and around Denmark. This is simply related to the fact that the isostatic rebound history is here more complex and cannot be described by a simple plane.

3.2. Lake surface reconstruction through a quadratic trend surface

A quadratic polynomial trend surface was fitted to the shoreline database using the same approach as for the plane, i.e. by applying a least square regression through the shoreline data points. The result after the regression to the quadratic trend surface is described by:

$$z(x,y) = -2.45\times10^{-4}x + 5.22\times10^{-4}y - 7.47\times10^{-11}x^2 + 3.79\times10^{-10}y^2 - 4.45\times10^{-10}xy + 167.05. \quad \text{(B)}$$

This approach gives a much better match between the shoreline database and the calculated BIL surface compared to the linear plane (Fig. 3B versus A). The R^2 coefficient increases from ≈ 0.83 to ≈ 0.99. Furthermore, Fig. 3B reveals that the Danish area is vastly improved. This shows that the isostatic rebound has followed more closely a quadratic function than a simple linear one. However, the function fails to fit the two supporting points in Öresund, which where added based on the knowledge that the Öresund Strait, with its threshold at approximately −7 m, functioned as an outlet for the BIL during the later part of Younger Dryas, when its water level was finally dammed up 25 m above the contemporaneous sea level (Björck, 1995a). Even if it is only a matter of a few meters, the mismatch is clearly seen in the 3D-visualization of Fig. 3B. However, there are problems with mapping and establishing a paleoshoreline in the threshold region. The reason for this is the difficulty in estimating the water depth of the outlet since it is related to the amount of out-flowing water and bottom topography (paleobathymetry); the latter may have been significant altered by erosion in a later stage and water depth may have been several meters at the sill. The southernmost shoreline data point (Mecklenburg Bay, Jensen et al., 1997) is located at −20 m. This data point explains why the BIL surface disappears into the present sea floor in this area. It emphasizes the importance of subtracting the Holocene sediment thickness in order to finally reconstruct the BIL during the latest part of Younger Dryas.

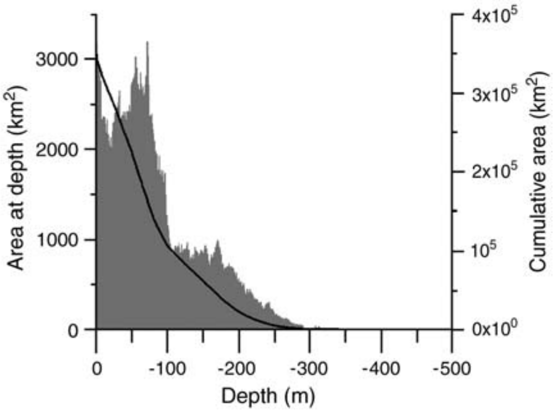

Fig. 4. Calculated hypsometry (area versus depth) for the Late Younger Dryas BIL. Each bin in the histogram plot is representing a depth increment of 1 m.

Table 3
Calculated volume and area of the BIL. Results are shown both with and without compensating for accumulated Holocene sediments as well as before and after the drainage north of Mount Billingen resulting in a 25 m drop of the lake level

BIL	Area (km^2)	Volume (km^3)
Compensated for accumulated Holocene sediments	349 400	29 300
Uncompensated for Holocene sediments	349 100	28 900
After drainage resulting in a 25 m lower lake level (compensated for accumulated sediments)	287 800	21 500

3.3. Lake surface reconstruction through a minimum curvature surface algorithm

A minimum curvature algorithm may be pictured as a linearly elastic plate, which is fitted through each of the data points; in our case the database of the final BIL Younger Dryas shoreline. The algorithm generates the smoothest possible surface while honouring the data points within a set maximum residual value. In the BIL reconstruction experiment, the maximum residual value was set to 0.2 m (see GMT settings for minimum curvature surface algorithm: Wessel and Smith, 1991). A common problem while applying a minimum curvature is that the computed surface in its attempts to be as smooth as possible bends up or down between data points in a clearly unrealistic fashion. This phenomenon is often referred to as an “over shoot” or “under shoot”. To avoid this artefact, the surface can be constrained by applying a tension factor between 0 and 1, where 0 is no tension and 1 is maximum tension. A maximum tension will result in a surface where sharper breaks appear at the location of the data points. We found that the distribution and relationship between the BIL Younger Dryas shoreline data observations do not require a tension parameter.

The reconstructed BIL surface using minimum curvature to a large extent resembles the quadratic trend surface in front of the Younger Dryas ice margin in the central Baltic between the Swedish east coast and coasts of the Baltic countries (Fig. 3C). However, in the

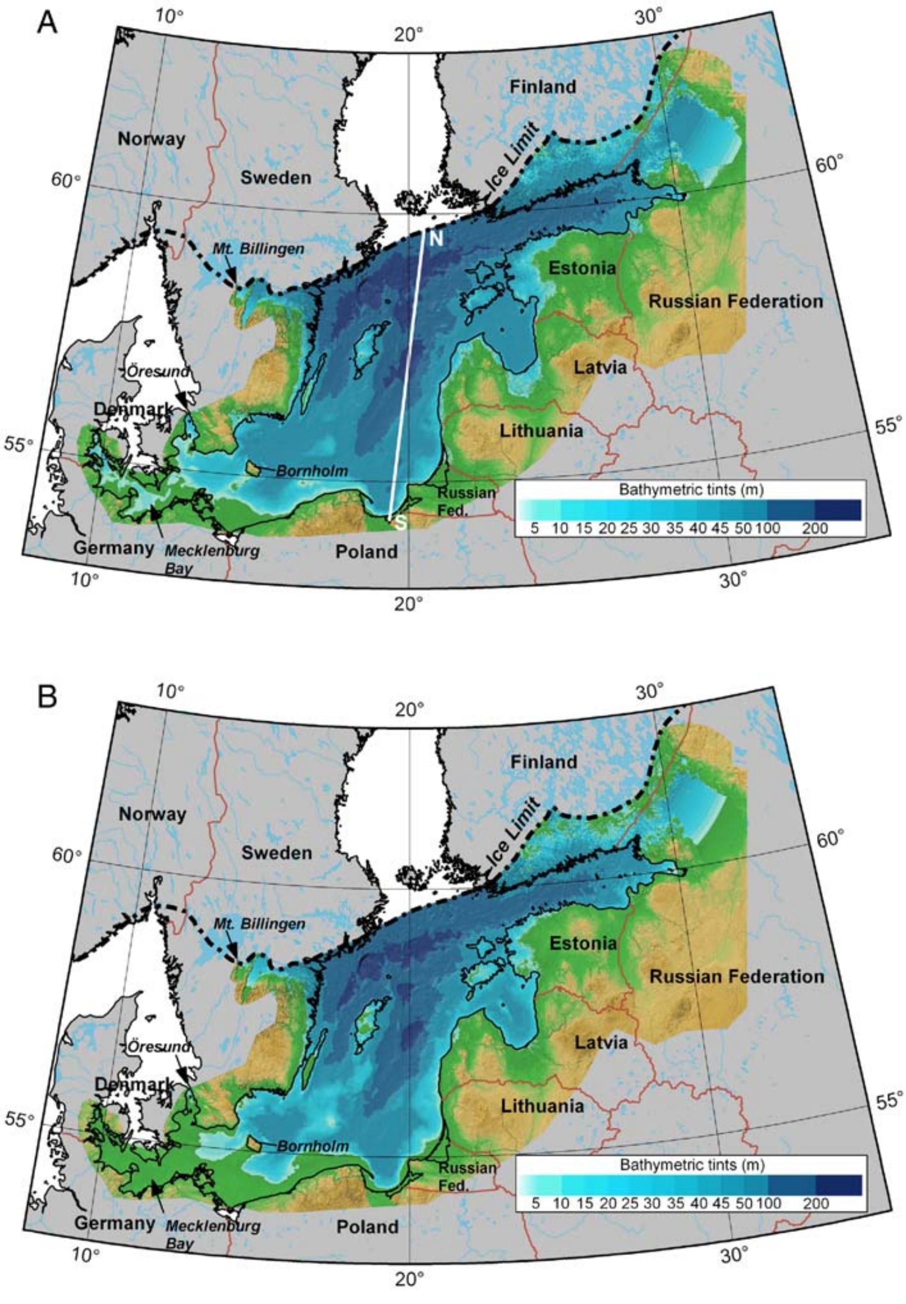

Fig. 5. A) Bathymetry of the Younger Dryas BIL based on the lake reconstruction derived using a minimum curvature algorithm and the shoreline database in Table 2. The bathymetry has been compensated for accumulated Holocene sediments. The reconstructed bathymetry of the BIL in the area of Lake Ladoga should not be considered due to that no bathymetric data from this lake was included in our compilation of the combined bathymetric–topographic DTM. B) The Younger Dryas BIL after the drainage north of Mount Billingen that resulted in an approximately 25 m drop in lake level. C) Comparison between our lake reconstruction shown in A and the BIL shoreline compiled by Björck (1995a).

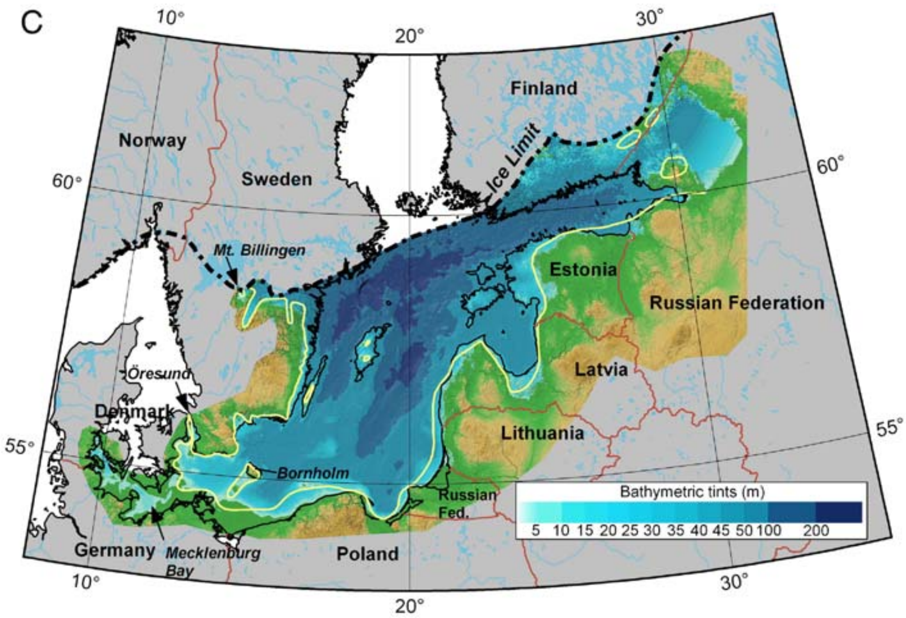

Fig. 5 (*continued*).

southernmost area of the shoreline database, particularly in Mecklenburg Bay and Öresund, the minimum curvature better honours the data points compared to the quadratic trend surface (Fig. 3B versus C). This is completely expected since the algorithm locally has no problem diverting from a larger trend and these areas obviously have experienced a Holocene isostatic rebound history that differs from the larger regional trend in the area of the Younger Dryas BIL shoreline database.

3.4. Volume and area calculations

The Younger Dryas BIL digital reconstruction based on the minimum curvature algorithm (Fig. 3C) was selected for volume and area calculations since it best fits the geological observations, i.e. the shoreline database and information on the lake's threshold area in Öresund. The calculated BIL total area and volume are shown in Table 3 both with and without compensating for Holocene sediment accumulations. The reconstruction taking into account the accumulated Holocene sediments resulted in an approximately 1% larger lake volume than if these sediments were ignored. This figure may even be smaller considering the fact that the Holocene sediments to some extent consist of redeposited glacial sediments. Fig. 4 shows the hypsometric function for the BIL reconstruction compensated for the accumulated Holocene sediments. A map of the Younger Dryas BIL and its paleobathymetry is shown in Fig. 5A.

The Scandinavian ice sheet margin eventually retreated north of Mount Billingen and the Younger Dryas BIL was drained through this area, resulting in a 25 m drop of the lake level (e.g., Lunqvist, 1921; Björck, 1995a). The amount of water released during this event and the BIL area reduction can easily be calculated using our digital model (Table 3). Approximately 7800 km^3 of water was drained and the BIL area was reduced by 61 600 km^2, ca. 18%, when it turned into the next Baltic stage, the Yoldia Sea, as an effect of the drainage down to sea level (Fig. 5B).

4. Discussion

The recent questioning by Påsse and Andersson (2005) of a ponded BIL towards the end of the Younger Dryas cold phase warrants an initial discussion in the light of our new reconstruction. They propose that the Baltic's surface was at the sea level during this time and, for that reason; the “Baltic Ice Sea” would be a more proper term than the “Baltic Ice Lake”. Indeed, if their proposition has any scientific significance, a great deal of field data will have to be reinterpreted and the Baltic geological history will have to be rewritten. For example, one obvious implication is that no sudden drainage affecting the Baltic's level on a regional scale could have occurred at the northern tip of Mount Billingen since there was no large scale damming of water in the Baltic Basin according to their model.

From our reconstruction of the BIL, it is evident that the lake surface was located at an elevation of approximately 150 m above present sea level along the eastern side of Mount Billingen at the very end of Younger Dryas. The contemporaneous sea level on the western side reached a level located at ca. 125 m in the present day topography (Strömberg, 1977; Björck and Digerfeldt, 1986, 1989), see Fig. 6A. This gives an altitude difference of 25 m between the BIL surface and sea level, and once the ice margin retreated northward of Mount Billingen the outburst took place (Fig. 6B). The field evidences, e.g. anomalies in shorelines on the eastern side of Mount Billingen and changes in clay varve deposition in the Baltic Basin, pointing to an outburst and drop of about 25 m of the Baltic's level (e.g. Lunqvist, 1921; Strömberg, 1977; Björck and Digerfeldt, 1984, 1986, 1989; Strömberg, 1992; Andrén et al., 2002) are instead attributed by Påsse and Andersson (2005) to a rapid regression caused by an extreme glacio-isostatic rebound. Furthermore, they propose that the deposits west of the northern tip of Mount Billingen interpreted to be caused by flowing water (Björck and Digerfeldt, 1984; Strömberg, 1992) were caused by the drainage of a much smaller ice dammed lake located between Mount Billingen and the mountains along the western side of Lake Vättern (Fig. 6A). This lake, Glacial Lake Tidan, was supposedly dammed to a level of 40 m above the contemporaneous sea level, which is 15 m higher than the level commonly proposed for the BIL. However, from our reconstruction it becomes evident that the passage to Lake Vättern to the east only was at 30 m above the sea level during the end of Younger Dryas, making it hard to understand how this damming to 40 m could have taken place at this time (Fig. 6A).

It should be emphasized that Påsse and Andersson (2005) try to mimic the glacio-isostatic rebound over time by constructing a mathematical model (a parameterized arctan function) derived from shore displacement curves, present isostatic uplift and their own field examinations of the lake's tilting over time due to isostatic rebound. For the time interval at the end of the Younger Dryas, four field sites with shore level curves are included to derive their model. In fact, due to dating uncertainties they raise criticism against our type of reconstruction methods where many supposedly time

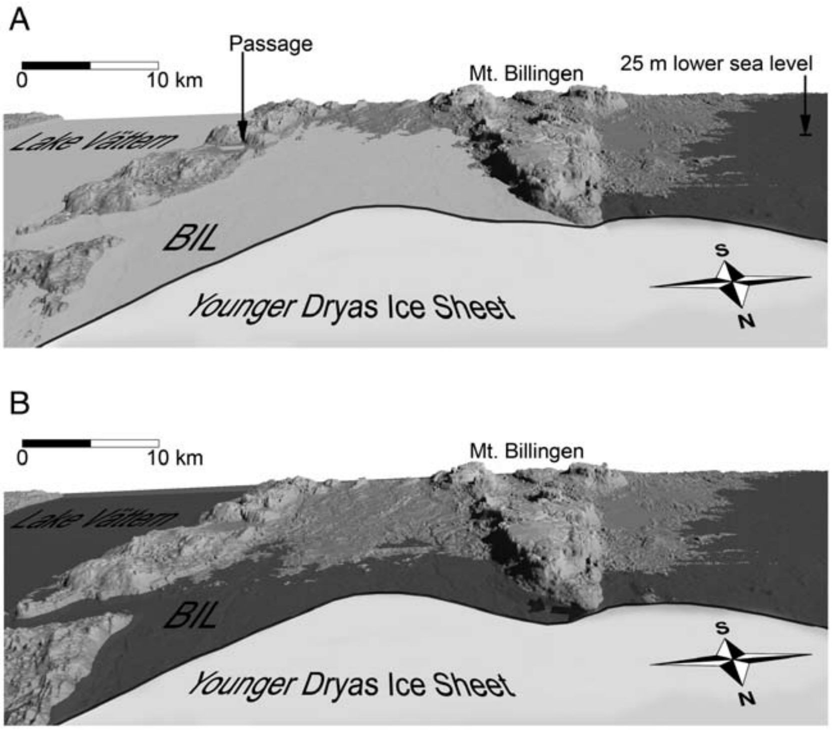

Fig. 6. A) The reconstruction of the area north of Mount Billingen based on a high-resolution (50 × 50 m) DTM available from the Swedish cadastral service (LMV). The minimum curvature BIL surface was used to compensate the 50 × 50 m DTM for the post-glacial isostatic rebound. The BIL level is shown with light gray shading and the contemporaneous 25 m lower sea is shown with a darker gray shading. The passage marked with an arrow would complicate the damming of the glacial lake Tidan to a level of 40 m above the sea level during the end of Younger Dryas as proposed by Påsse and Andersson (2005; see text for discussion). B) The Billingen area after the drainage causing a 25 m drop in the lake level.

synchronous shoreline observations are used for reconstructing a particular stage of a paleolake. However, our second experiment of fitting a quadratic trend surface through the shoreline database shows, on the contrary, how well all the widely distributed shoreline observations are spatially correlated ($R^2 \approx 0.99$; Fig. 3B). A spatial trend clearly exists in the shoreline database and if any dates would be significantly wrong one would expect outliers and local deviations from the fitted trend surface, in particular during times of extreme isostatic crustal movements, as being proposed for the end of the Younger Dryas. Moreover, it is well known that precise ^{14}C dating around the YDP is complicated due to a ^{14}C plateau causing large error bars for the calibrated ages (Reimer et al., 2004), but the onset of the so-called YDP pollen zone can be used as a time marker. This chronostratigraphic support has been widely used in the studies included in the Lund University shoreline database for the Younger Dryas, while Påsse and Andersson (2005) instead chose to derive another arctan function for ^{14}C calibration and also question the ^{14}C dating of the shorelines supporting the existence of BIL. Björck et al. (1996) have shown that the YDP pollen zone is synchronous within southern Sweden and also synchronous with the onset of the Preboreal warming in the Greenland Summit ice cores.

The dating of late-glacial events in the Baltic Sea basin is based on clay varve measurements and ages has been presented as traditional varve years related to the Swedish Time Scale (De Geer, 1940) or as clay varve years BP (Cato, 1987). By using the YDP as a fix point, Andrén et al. (2002) correlated the Swedish clay varve chronology from the central Baltic Sea with the GRIP ice core and, thus, converted the clay varve years into calendar years. The new revised age of 11 653 cal. yr BP for the YDP from the NGRIP chronology (Rasmussen et al., 2006) implies a slight revision of the previous calendar year conversion of clay varve years by Andrén et al. (2002). This revision is included in all ages presented below derived from clay varve studies.

The deglaciation model for the Billingen area by Strömberg (1994) places the ice sheet margin in contact with the northern tip of Mount Billingen at about 11 730 cal. yr BP. Approximately 100 years later, the ice sheet had retreated far enough to the north in order to open a connection between the BIL and the Kattegatt. Saarnisto and Saarinen (2001) propose from paleomagnetic and clay varve studies of sediment cores from Lake Onega, Russia, that the ice margin's retreat from the second Salpausselkä end moraine in western Finland coincides with the BIL drainage. They date this retreat and, thus, the BIL drainage to 11 590 ± 100 cal. yr BP. Furthermore, clay varve studies of sediment cores from central Baltic Sea date the final BIL drainage to 11 690 ± 10 cal. yr BP (Andrén et al., 2002) thus predating the YDP with 30 to 40 years. From this, it seems reasonable to assume that the final drainage of BIL predates the YDP with some tens of years (cf. Björck et al., 1996).

Our reconstruction of the BIL shoreline is fairly similar to the map compiled by Björck (1995a) for the same time interval, albeit, with some discrepancies in the northwest and in the south (Fig. 5C). A recent shoreline displacement study by Uscinowicz (2003) shows a more northerly located late Younger Dryas coast in some areas off Poland than our Fig. 5A. If this data includes the very last BIL shoreline, it suggests that future updates of the Lund database and our BIL reconstruction should include the source information from Uscinowicz (2003) for this area. However, the cost off Poland is very shallow implying that the computed volume in this present work will not be subject to significant changes due to small relative changes in this area.

With a computed area and volume of 349 400 km^2 and 29 300 km^3, respectively, the BIL is comparable in size to Lake Agassiz Upper Campbell level (9400 ^{14}C yr. BP; Teller and Leverington, 2004), which was calculated by Leverington et al. (2000) to have an area of 263 000 km^2 and a volume of 22 700 km^3. This makes the BIL one of

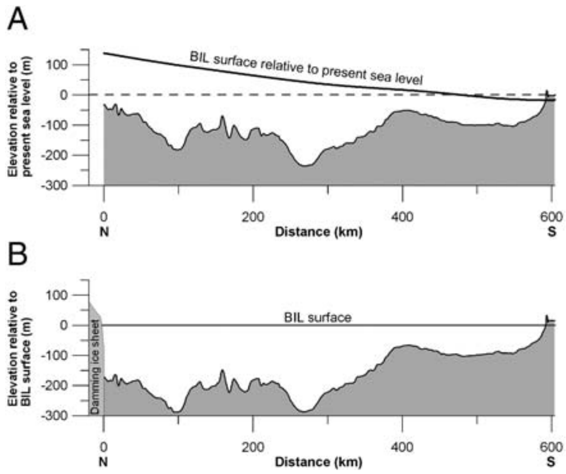

Fig. 7. A) Topography along the profile marked in Fig. 5A showing the floor of today's Baltic Sea together with the reconstructed minimum curvature BIL surface relative to the present sea level. B) The same profile location showing paleobathymetry across the reconstructed BIL derived by subtracting the minimum curvature surface from the present topography and compensating for the accumulation of Holocene sediments (see text). Note that the northern part of the profile is substantially deeper compared to present (A) due the isostatic depression of the Younger Dryas ice sheet.

the larger known ice dammed lakes, albeit considerably smaller than the last stage of Lake Agassiz when it merged with Lake Ojibway at 8400 cal. yr. BP (area: 841 000 km^2; volume 163 000 km^3, Teller et al., 2002) or the Early and Mid Weichselian pro-glacial lakes in Northern Russia (see Mangerud et al., 2001). The BIL maximum depth was most probably more than 100 m deeper than the Baltic Sea today and located in the Landsort Deep, which is marked to 459 m on current hydrographic charts (Fig. 2). The deepening of the Landsort Deep during the end of Younger Dryas was mainly due to isostatic depression, although the exact figure must be considered uncertain due to lack of nearby located shoreline constraining points and accurate information on the amount of accumulated Holocene sediments (Fig. 2). A north–south profile comparing the bathymetry between the present Baltic Sea and the paleobathymetry of the BIL clearly shows that isostatic depression was progressively larger towards the north during the end of the Younger Dryas (Fig. 7A,B).

No southern terrestrial connections existed that directly could link the European continent with southern Sweden. However, once the ice margin reached north of Mount Billingen, this picture changed dramatically due to the 25 m lowering of the BIL level (Fig. 5B). A large land bridge emerged, which most likely played a similar role for faunal migration (Björck, 1995b) as the Bering land bridge did between the Eurasian and American continent (Hopkins et al., 1982). It is also noteworthy that the island of Bornholm became a peninsula for a considerable period of time due to the sudden lowering and it is known that large areas outside today's shoreline were invaded by pine forests (Björck, 1995a).

Perhaps even more interesting than the total BIL volume and area is the amount of freshwater that was released during the drainage causing the 25 m drop in lake level. We calculate that this amounted to ca. 7800 km^3, a value not too far from the 7000 km^3 proposed by Strömberg (1992) from studies of topographic and bathymetric maps. Björck et al. (1996) estimated that the release of freshwater was somewhere between 4730 and 9461 km^3 which over 1 to 2 years would imply a flux of 0.15 to 0.3 Sv (10^6 m^2/s). With a 1–2 year long drainage, as advocated by Björck et al. (1996) and later supported by Andrén et al. (2002) from clay varve studies, we can conclude from our volume calculations that the flux of freshwater from the BIL to the Kattegatt was on the order of 0.12 to 0.25 Sv. In comparison with the large freshwater volumes that were released from the merged Lakes Agassiz–Obijway (modelled by Clarke et al., 2004: ~5 Sv over 0.5 years), the BIL outburst was rather modest. Nevertheless, the environmental impact may have been considerable. The influx of cold freshwater to the North Atlantic from the BIL drainage together with melt water from the contemporary melting Scandinavian ice sheet has been suggested to have disturbed the North Atlantic overturning circulation and, thus, affect parts of the global climate system, possibly resulting in the fairly unstable early Holocene climate with several small-scale climatic setbacks (e.g. Jessen, 2006).

5. Conclusions

A 3D-reconstruction of the water level in the Baltic Basin during the termination of the Younger Dryas cold phase compiled from shoreline information from more than 100 field sites shows that there was an ice dammed lake, "the Baltic Ice Lake", and thus no support is given for the recently proposed "Baltic Ice Sea" during this time. The new high-resolution reconstruction allows accurate area and volume calculations showing that the BIL is among the larger known ice dammed lakes, larger than the Lake Agassiz Upper Campbell level (9 400 ^{14}C yr. BP). Once the damming ice margin retreated north of Mount Billingen in south central Sweden, the BIL drained 25 m, shrunk 18% in area and released 7800 km^3 of freshwater to the Kattegatt, the part of the Nordic Sea occupying the area between the Swedish west coast and Denmark. Southern Sweden changed dramatically due to the drainage and a land bridge to Denmark developed as well as a connection between the island of Bornholm and northern Germany.

Acknowledgements

Richard Gyllencreutz, Jan Lundqvist, Jan Mangerud, Bo Strömberg, Peter Vogt, and an anonymous reviewer provided valuable comments on the manuscript. Jakobsson acknowledge the support provided by the Swedish Royal Academy through a grant financed by the Knut and Alice Wallenberg foundation.

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