



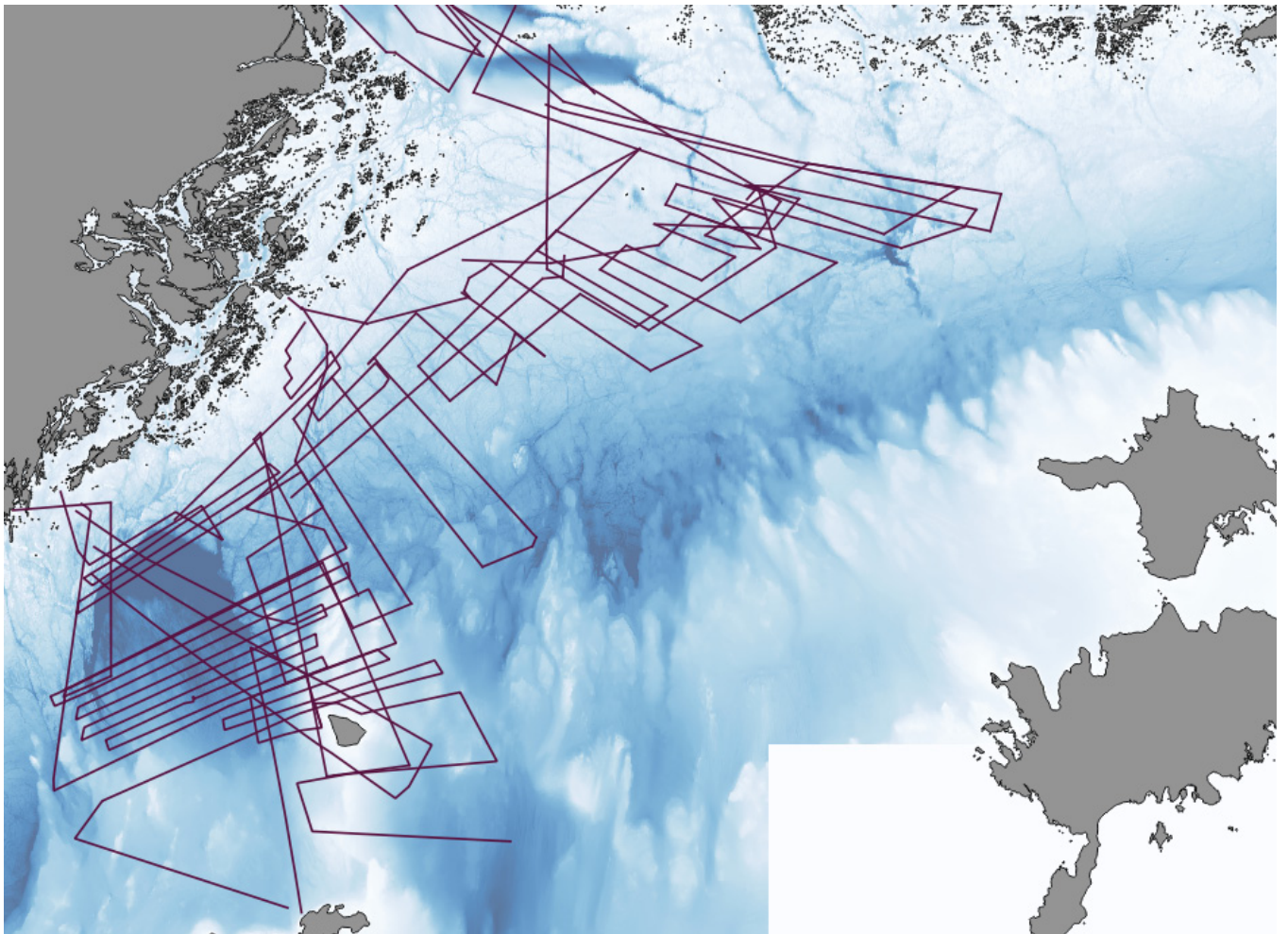
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Mapping Younger Dryas ice marginal positions in Baltic Sea using legacy seismic data

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ERRATA

This is version 2 of known errata.

Page, section	Line starts with
22, 4	"BEM 1 is assumed to be located on the western side of Bogskär..."
Correction	"BEM 3 is assumed to be located on the western side of Bogskär..."

Mapping Younger Dryas ice marginal positions in Baltic Sea using legacy seismic data

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Front page: Figure shows the track lines between the years 1970 and 1985 converted to Cartesian coordinates, overlaying a geo referenced map with bathymetry from EMODnet in the Baltic Sea.

Abstract

The Baltic Sea is an attractive area of research, and studies have been done on the geological history in order to improve results in Weichselian after the peak of Last Glacial Maximum. After the Fennoscandian ice sheet (FIS) retreat, a temporary advance during Younger Dryas (YD) occurred 12800-11700 years ago. The ice-margin has been mapped with various techniques and by looking at landforms such as end moraines. The exception of mapping is across the Baltic Sea counts as one of the largest gaps in data in order to achieve complete FIS-mapped structure around YD. Much uncertainty exists regarding the accurate positions of submarine ridges belonging to YD.

During 1970 to 1985, surveying in the Baltic Sea was performed, and the data was later used by Söderberg (1988) to map the continuation of Salpausselkä (Ss) I-III.

In this work, geophysical- and positional methods have been used in order to analyze and test the quality of previous results. Further, ice marginal positions are mapped with the help of legacy seismic data from the years described above. A proposed general term Baltic End Moraine (BEM) is used corresponding to the Ss phases. The results show computer program Decca-SEA-01, convert Decca positions to Cartesian coordinates with proven accuracy. Surveying between 1970 and 1985 presents detailed intersections of track lines connected to seismic data. BEM ridges are presented with linked positions in the Baltic Sea.

1. Introduction

The Baltic Sea is the largest brackish water body in the World (415 km²). It has terrestrial borders to nine countries with Sweden and Finland sharing the longest coastal regions. Its average depth is 54 m, and the deepest point is located SE of Nynäshamn.

The Fennoscandian ice sheet (FIS) ice margin in the Baltic Basin retreated in a largely northerly direction during the last phase of Weichselian after the peak of Last Glacial Maximum (LGM). In early Holocene, the centre of FIS located in northern Scandinavia with a rapid deglaciation recovery from the East (16000 to 10000 years BP). The Baltic basin filled up with glacial melt water, forming the Baltic Ice-Lake (16000-11700 years BP), and the ice sheet margin retreated in a glacio-lacustrine environment (Hughes et al., 2016).

The Younger Dryas (YD) is a remarkable milestone between 12800-11700 years ago (Muscheler et al., 2008). The stadial has left geomorphological and sedimentary traces throughout Scandinavia. The Younger Dryas was a period of climate cooling which temporarily halted ice front retreat with some even advancing during the late Weichselian. Not all glacier fronts of the FIS were advancing, but documented advances occurred in western Norway (Mangerud et al., 2019), southern Sweden and ice marginal positions of the eastern part there (Nilsson, 1968) and the Salpausselkä in Finland (Donner, 1978). The formation of new end moraines was asynchronous (Hughes et al., 2016), making it difficult to extrapolate reconstructed ice margin timelines where no end moraines have been mapped. The reconstructed positions of the terrestrial Younger Dryas moraines form an almost closed shape. The YD moraines stretch along the west coast of Norway, curving across the Dalsland and Nynäshamn areas in Sweden, through the southern archipelago of Finland and finally extends into the White Sea off Russia (Andersen et al., 1995; Lundqvist and Wohlfarth, 2001; Mangerud et al., 2004; Donner, 2010; Pasanen et al., 2010; Olsen et al., 2013). However, the position of the YD margin in the Baltic basin is much more unclear and difficult to map because of the water cover.

Several reconstructions of the FIS deglaciation have been done (Lundqvist and Saarnisto, 1995; Kleman et al., 1997; Boulton et al., 2001; Stroeve et al., 2016), but all of these extrapolate the position of the YD margin across the Baltic basin. A data-based mapping of the YD deposits across the Baltic would therefore fill an important data gap in our knowledge of the deglaciation of the FIS. Reconstructions of ice margin positions are also important for numerical ice sheet models, where reconstructions are used either as constraints or validation of results (Gyllencreutz et al., 2007; Hughes et al., 2016).

Based on the mapped YD-margin in Finland and Sweden, its marine continuation most likely crosses the northern part of the Baltic Proper. This part of the Baltic Sea stretches from Öresund to the sea of Åland and the peninsula of Hanko (Hangö) in Finland. The area of investigation presented is mainly in the northern Baltic Proper and the southern parts of Gulf of Bothnia with help of legacy data. The seismic profiling method was described in 1963 (Hersey, 1963).

This contribution applies seismic legacy data acquired from between 1970 and 1985 and collected with vessels surveying in the Baltic Proper (figure 1a). The data from this time is navigationally linked to Decca coordinates being the standard navigation for its time which was a deprecated radio navigation system in use, up until GPS was developed. The motivation for using this older data, is that no newer seismic or hydroacoustic data has been published from this area using more modern technologies. Another reason is that sub marine glacial morphologic traces may be buried and obscured by subsequent sedimentation, in which case bottom-penetrating acoustic methods are needed for mapping the ice retreat.

Previous attempts to map the data and redraw the moraine ridges positions around the YD event have been incomplete. The cartographic coordinates corresponding to YD-ridges in the Baltic Proper, have consequently been made based on simplified or limited interpretations. This has consequently led to heterogenous and scattered visualizations.

The scientific aim for this report was to

- convert and calculate Decca coordinates for early seismic data into cartographic coordinates
- plot accurate track charts of the seismic lines based on the new coordinates to enable mapping of morphologic features
- interpret the general sea floor morphology and acoustic stratigraphy, and interpret the profiles with respect to late glacial morphology and sedimentation
- map the ice margins around the YD-position based on interpretation of till and end moraine in legacy data

An early geological survey, Jouko (1971), is including Salpausselkä (Ss) phases in the Finnish archipelago, noteworthy Ss III is visible 50 km outside the coastal region. A map from the late 1970s showed early work with the ice lobes of the FIS (Punkari, 1979, fig 2). The figure excluded any cartographic coordinates and had limited information of mapping method but show the end moraines some tens of km outside Swedish and Finnish archipelagos. The only known research on continuation of Ss (I-III) with sea floor analyses based on airgun and acoustic soundings is covered by Söderberg (1988). It resulted in an interpretation map with YD ice margins extrapolated from the Finnish side. A sub marine ridge interpreted as Ss I was detected somewhere between Finland and Sweden, was mapped as a continuous feature along the basin floor for at least 85 km after EEZ. The only example of the data used show a section of a seismic profile without vertical distance from side to side in the image is approximately 4 km (Söderberg, 1988, figure 1b). However, Söderberg's (1988) findings were not sufficiently described and too little metadata was given to assess its validity.

1.1 Previous work

It has been proposed that the YD ice margin ridges continue into the submarine domain of the Baltic sea, although a complete continuation is not yet documented (Lundqvist and Wohlfarth, 2001; Mangerud et al., 2004; Donner, 2010; Pasanen et al., 2010). The chronology of the YD ice margins in Finland and Sweden is based on ¹⁴C and ¹⁰Be-dates, showing that Ss I was formed ~12.300 cal. BP, and Ss II at ~12.000 cal. BP, whereas Ss III most likely was formed after 11.600 cal. BP. On the Swedish side, the Skövde moraine was formed ~12.600 cal. BP (Hughes et al., 2016).

Little is known on the halted YD position after ice retreat in the Baltic Sea (Noormets and Flodén, 2002b). Many works describing the YD ice margin connection, draw a line or a bending curve over the Baltic Proper based on extrapolation from land on either side since no prominent ridge in the bathymetry has been observed due to lack of data (Kleman et al., 1997; Boulton et al., 2001; Saarnisto and Lunkka, 2004; Uścińowicz, 2014; Stroeven et al., 2016). Geomorphology-based mapping of the ice margin exist on land on both sides of the Baltic Sea (Donner, 1978; Punkari, 1979; Persson, 1983; Rainio, 1991; Björck, 2008). Limited studies on the marine continuation of the YD ice margin have been done within the Finnish EEZ. One study shows the locations of Ss I and II within the Finnish archipelago (Häkkinen, 1982). To our best of knowledge, no other studies in the Finnish EEZ waters exist. This was confirmed by Geological Survey of Finland, GTK (pers. comm. Jyrki Rantaro, 2019-06-03).

The Baltic Sea continuation of Ss (I-III) has previously been interpreted by Söderberg (1988), where proposed ice margins of Ss I, II and III were marked on a map. These were later adopted as valid lines of the Younger Dryas in the Baltic Proper by Noormets and Flodén (2002b).

Two of the ridges of YD-formations were mapped as extending out hundreds of kilometres east from Nyköping and a similar submarine pattern was reconstructed on the Finnish side from Hanko, Rosala and Jurmo Island, with Ss I-III marked with continuity from the Finnish archipelago. The unmapped gaps in the YD ridges between Finland and Sweden were optimistically set to less than 200 km across sea (Punkari, 1979) and later revised with less points (Rainio, 1991).

The YD deposits in the Middle Swedish Ice Marginal Zone (MSIMZ), was mapped by Persson (1983) by studying sediments and attributing them to glacial material. The corresponding ridge of Ss I and II (Finland) were suggested to connect with the MSIMZ a few tens km around Nynäshamn archipelago with the two oldest YD stadials in (Berglund and Mörner, 1984). End moraines corresponding to Ss III has not been found in Sweden (Söderberg, 1988).

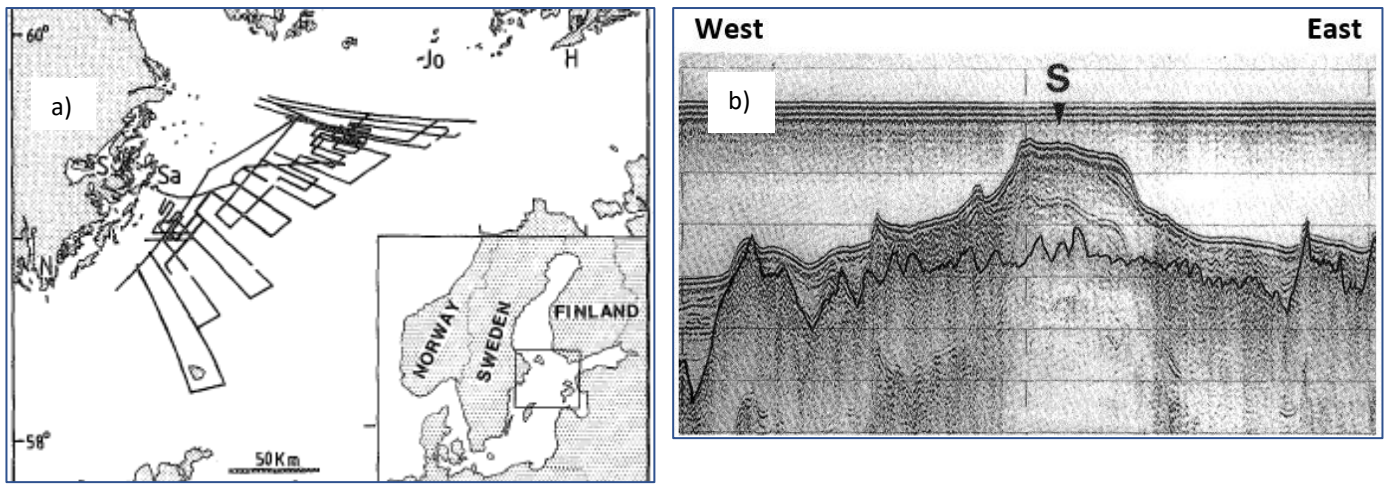


Fig 1. Track lines in central and northern parts of the Baltic Proper. N: Nyköping, S: Stockholm, Sa: Sandhamn, H: Hanko peninsula, Jo: Jurmo Island (a). The YD ridge denoted Salpausselkä I (S) in the northern Baltic Proper (b). Both figures modified after Söderberg (1988).

1.2 Geology background

The Baltic Sea, together with the Bothnian Sea and the Bothnian Bay reveal an interplay of geological forces of tectonics and ice age stadials that could be traced back to Proterozoic age. The crystalline bedrock of the Fennoscandian shield belongs to Precambrian (1770-1950 Ma) and found in the northern parts of the Baltic Sea. The rock types are a mixture of igneous and metamorphic rocks, formed during the Svecofennian orogeny (Winterhalter, 1972; Lundqvist, et al., 2011).

There is a distinct border in the bathymetry between the crystalline and sedimentary sea floor rocks. This border forms a curved irregular line from the South West (SW) coast of Finland, SW-wards to North of Gotland continuing southwards along the South East (SE) coast of Sweden (figure 2a). The sedimentary cover in sea floor rocks from oldest to younger from Cambrian, Ordovician, Silurian and last Devonian on the east side of the Baltic Sea was in detailed mapped and described by Flodén (1980).

Jotnian sandstone has been a useful marker for the provenance of erratics displaced during the glaciation. They have been irregularly preserved due to earlier tectonic events. The Jotnian sandstone have a low metamorphic grade and the burial metamorphism is low (Nyström and Levi, 1980; Nyström, 1982). The thickness of Cambrian sandstone is increasing in southerly direction from around 80 meters closed to Gotska Sandön down to some hundred meters moving southwards in the Baltic Sea (Winterhalter et al., 1981). The Ordovician sediment has been more resistant to erosion, which has an impact on the relief of the border to Cambrian strata. The relief structure is explained by the differences of resistance due erosion, because the Ordovician is overlying the Cambrian and this way protecting Cambrian rocks form erosion. In the relief this is seen as saw-tooth pattern on top of Cambrian peneplane (Winterhalter et al., 1981). The younger sediments are eastwards in the Baltic Basin, succeeding with Silurian- and finally Devonian sandstone. These sedimentary rock types are outside the survey area and further described by Noormets and Flodén (2002a; 2002b).

While the sedimentary strata are dipping to the SE, the elevation of the sea floor is generally deeper in the North West (NW) parts towards shallower areas in the SE. A generalized bathymetry over the seafloor from the Åland Sea and Hanko peninsula over the central Baltic to the passage between Gotland and Latvia is visualized to give an overview of the main features (figure 2b).

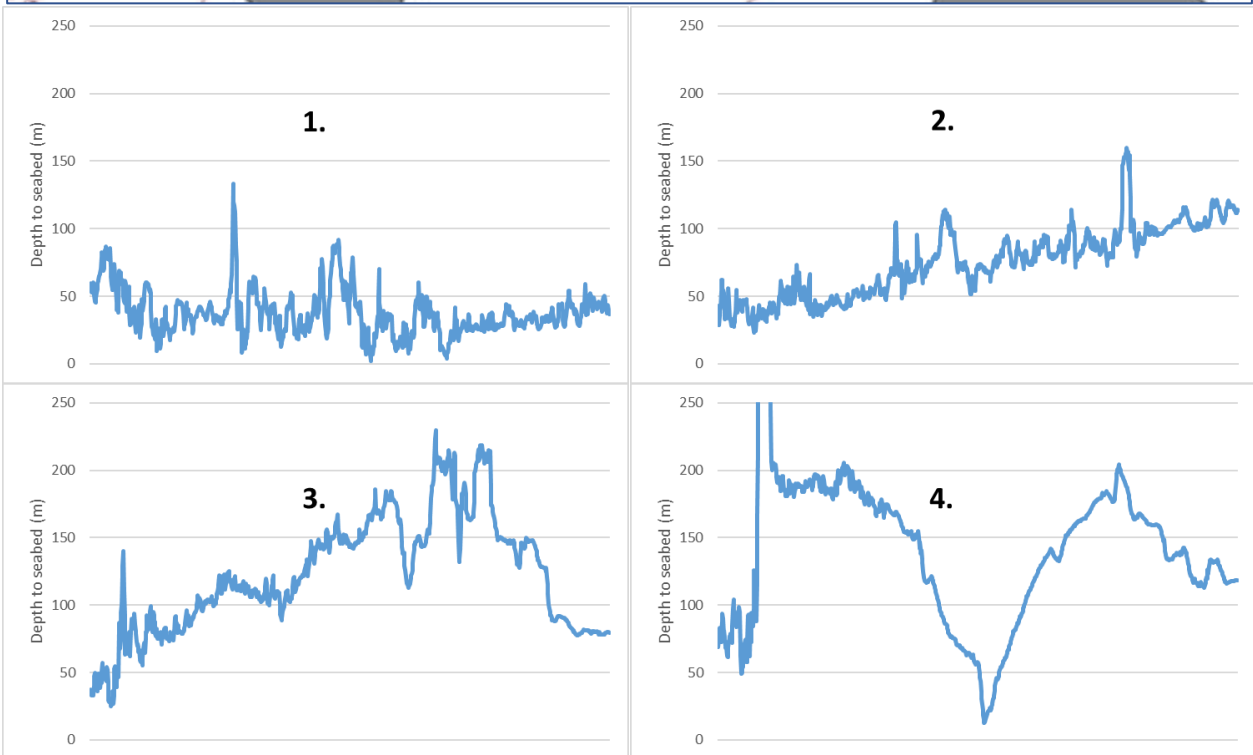
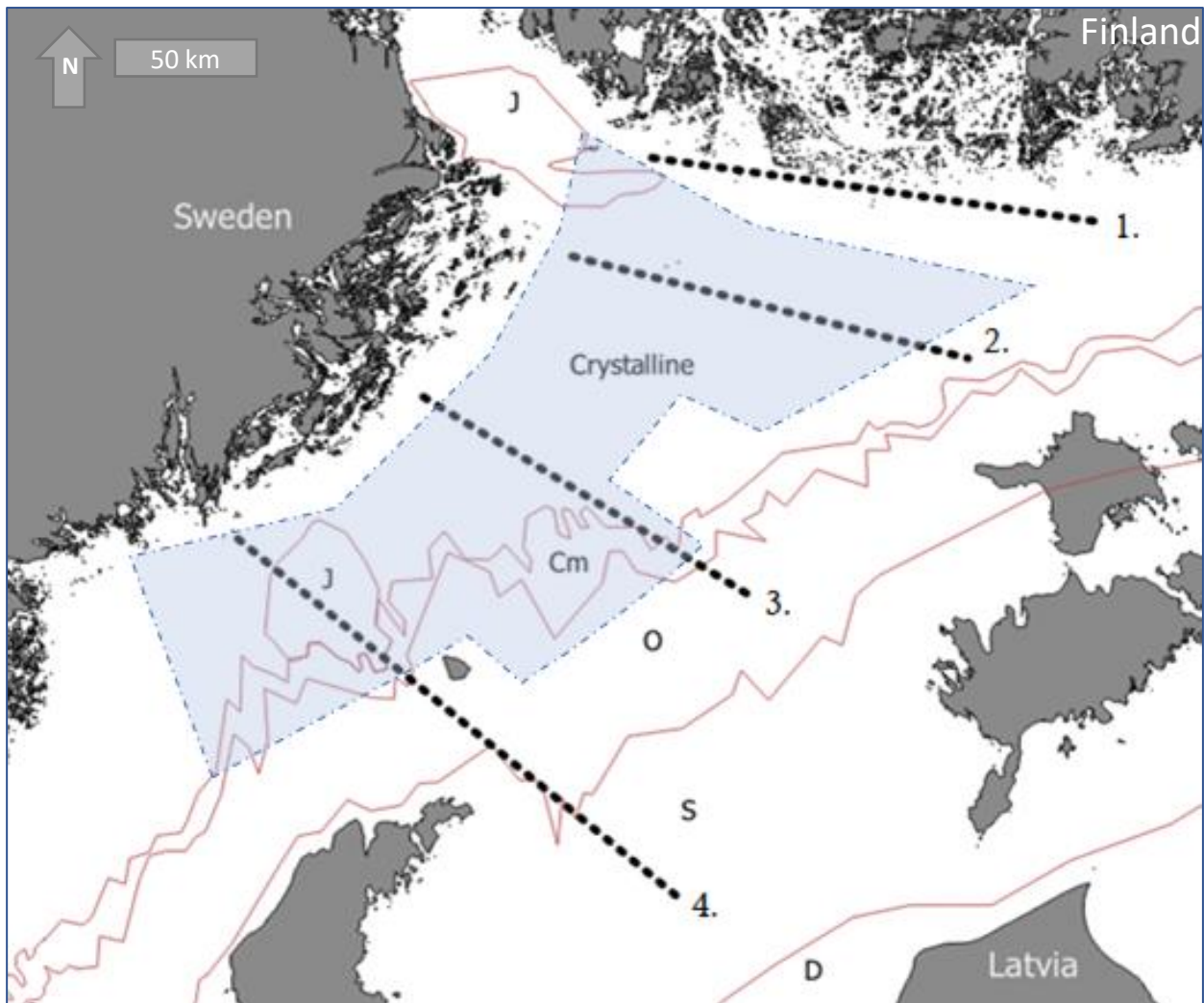


Fig 2. Geological background in the Baltic Sea in scale 1: 2000000 after Flodén (1980) with depth profiles generated from EMODnet bathymetry (<http://portal.emodnet-bathymetry.eu/> [access: date 2019-05-15]) and an approximate research area in blue overlay (top figure). Sedimentary rocks denoted as J: Jotnian, Cm: Cambrium, O: Ordovicium, S: Silurian, D: Devonian. Four depth profiles in East-West on x-axis with depth to seafloor on y-axis (meter). The fourth profile with a shallow depth south of Gotska Sandön has truncated data over Landsort Deep.

The sea floor signature from the Quaternary sediments outside the southern coast of Finland varies. In trenches and areas protected from currents, softer sediments are deposited. The sea floor over crystalline and resistant rock types exposed for transport with less overlying sediments have a harder bottom. There is a corridor between Åland, and the east coast of Sweden has an influx of softer sediments (silt, clay and mud) with steeper sides because of the erosional carving on each side of the depression. The border between crystalline bedrock and younger sediments consists of soft bottom such as silt, clay and mud. The Quaternary deposits over Devonian rocks tend to show a mixture of soft and hard deposits again. A more detailed view is presented with help of surveying and coring in the Central Baltic by Flodén (1980), and additional information is given by Winterhalter et al. (1981).

Today, salinity is around 5-7 ‰ in the area of investigation but depending on in- and outflows in the Late Glacial Baltic Sea stages, it has been fluctuating from fresh water to weak saline to fresh water and now recently saline again. The Baltic Sea experience little exchange of water with the Danish Straits. The basin is generally shallow, but a huge variation of ongoing wind and wave erosional processes cause differences in relief with trenches, deeps, ridges and depression basins. The thickness of the Quaternary deposits (Pleistocene and Holocene) is around 280 m east of Gotland. Besides varying rock types, erosion and tilting bathymetry, tectonics are also responsible for the present morphology (Winterhalter et al., 1981).

1.3 Younger Dryas

An end- or terminal moraine is caused during a state of equilibrium between advance and retreat of a glacier. During this equilibrium the glacier continues to transport unsorted sediment, building up a ridge. When the glacier retreats and pauses at a new point, it leaves a new ridge. The continuations of the YD ridges detected vary in size and shape due to geographic position, and range in length from hundreds of meters to kilometres mostly localized in terrestrial regions. In contrary, a ridge in the subaquatic domain is not always well preserved. A ridge exposed on seabed where currents or high energy waves causes erosion to occur in the Baltic Sea (Schmager et al., 2008). A ridge is not necessarily shaped by erosional material such as till. The back- and forth movement of the FIS ice front, provided erosion both during advance of the ice, as well in traces from melt water from tunnels in subglacial environments of the Baltic (Gudelis and Litvin, 1976).

The last advance of the Weichselian FIS occurred during the YD. It has been described based on glacial signatures such as: striations, eskers, drumlins and end moraines. Other features associated with YD are: an ice marginal zone on the Swedish Eastern coast, and Ss (I-III) in Finland. These together with Ra in Norway are identified to be from the same period as the YD (Andersen et al., 1995; Rainio et al., 1995; Lundqvist and Wohlfarth, 2001; Mangerud et al., 2004; Donner, 2010; Pasanen et al., 2010; Olsen et al., 2013).

1.3.1 The YD event and history of the Baltic Sea

The Baltic Ice Lake (BIL) formed after the last glacial maximum (LGM) and existed c. 14 – 11.6 cal. ka BP (Andrén et al., 2011;) with a peak area of 349000 km² (Jakobsson et al., 2007). During the Baltic Ice-lake stage, little biogenic material existed in the basin complicating the process of ¹⁴C dating commonly used in glacial feature dating (Winterhalter et al., 1981).

After the LGM It took around 4000 years for the ice to retreat from the southern Baltic to the YD position (Hughes et al., 2016). During the YD, the centre of the Baltic Ice Lake ice dome was situated in the Gulf of Bothnia (Boulton et al. 1985). Ice removal during YD glacial retreats caused isostatic uplift which was faster than the sea level rise due to ice melt, so that the Baltic Ice-lake remained an isolated fresh water body throughout the YD (Winterhalter et al., 1981).

With a growing area available for the Baltic Sea due to deglaciation, and in combination with land uplift and gravity, a corridor was suddenly created between a topographic higher elevation of the hills in Billingen and the ice margin when the ice melted at the end of the YD. This gave the water a possibility to run out into the Skagerrak. The final drainage of Billingen occurred rapidly, within 1-2 years, and involved a volume of 7000-8000 km³ of water and a lake level decrease of 25 meters (Jakobsson et. al, 2007). The final drainage took place at the end of Pleistocene and marked the end of the Baltic Ice-lake. The chapter of Yoldia Sea begun which lasted for around 1000 years with influx of brackish and fresh water in turns. Following by the shore-level depth (m b.s.l.) had its most relatively decrease

during Ancylus Lake for another 1000 years. Southern Baltic Sea experienced transgression implying deposits of post-glacial sedimentation (Björck et al., 2008).

1.3.2 The YD event in Southern Finland

It took Finland around 3000 years to be free of the Weichselian Ice Sheet. The duration of the YD event was around 1.5 kyr. During this time, parts of southern Finland were under water and therefore calving along the glacial margin was a common deglaciation process. During the YD two of the largest end-moraine deposits were formed and started after the ice advance, when Ss I was created. During its retreat to the other stadials, Ss II and III were created. Ss III is probably post-YD and is dated either younger than 11600 years BP (Hughes et al., 2016) or when using the Greenland core calibration around 11400 years BP (Stroeve et al., 2016).

Based on LiDAR and Digital Elevation Models (DEM) in the SE zone of the SIS in Finland, Lunkka et al. (2019) concluded that the Baltic Ice-lake was less than 70 m deep in front of ice margin for Ss I, and less than 50 meters for Ss II. The Salpausselkä ridges are widely accepted as formed during the YD stadial. This is established for Ss I and II, partly consisting of glaciofluvial deposits (Rainio et al., 1995; Donner, 2010). Although both Ss formations are sub-parallel curved lobes, the western and southern arcs of Ss I and II were asynchronous (Saarnisto, 1982) with an offset of a couple of hundred years between them.

The traces of Ss (I-III) are well described in Finland and over terrestrial areas, but offshore near the coast, the ridges vanish without a distinct shape left on the sea floor. The signature of the ridges for mapping are based on the morphology and thickness of unconsolidated sediments. Ss I is 0.5-1.0 km wide, 80 m high over the landscape in Finland and measure a continuous length of 200 km. Ss I and II is around 25 km apart on land. Both are end moraines and form continuous ridges. The second Salpausselkä also shows distinct ridges but in some parts during the YD stadial an impact of glaciofluvial material is smearing out the ridge into fields. This was because of low topographical environment so the melt water had an impact. The third Salpausselkä, consisting of moraine ridges and sandy deltas, has more scattered ridges of a couple of kilometres each, with no complete continuation (Leiviskä, 1920).

1.3.3 The YD event in Western Sweden

Moraine ridges were deposited along the ice front also in Sweden. During halts of the retreat, deposits were in the form of ploughed moraine ridges. Many of these have been dated with ^{14}C and varve chronology connected to the Swedish Time Scale (STS) to find absolute age. Dating using ^{14}C has been a powerful tool to improve dating of deglaciation events and signatures (Dyke et al., 2003; Gyllencreutz et al., 2007). Age mapping of end moraines with corrected varve chronology has been useful. An end moraine belt between Dalsland, Linköping and Nynäshamn marks the onset of the YD (Lundqvist, 1995) and Ss (I-II) corresponding age was found in YD ridge in Skövde (Lundqvist and Wohlfarth, 2001). MSIMZ, also called as the Middle-Swedish end moraine zone (MSEZ) is thought to leap out into the Baltic Sea south of Nynäshamn and corresponds to Ss I in Finland which is some tens of kilometres more to the South on the eastern shore (Persson, 1983).

A map of southern Sweden shows the YD moraines with an assumed continuation close to Nyköping, north of the Levene moraine formed 13400 cal. years BP (Lundqvist and Wohlfarth, 2001). The first moraine signature immediately after the YD event is the Norrpada moraine, which is assumed to coincide with Ss III. Its only visible location on the Swedish side is located 45 km NW from Sandhamn (Hagenfeldt pers. Comm.; Söderberg 1988).

1.4 Decca

The Decca system belongs to the hyperbolic group of navigational systems and originates from the USA. As a precursor to GPS for half a century, the Decca system was primary in use on aircrafts and on marine vessels among European countries (Fisher, 1993). A basic Decca system consists of several land-based radio beacons, usually built up of a master beacon and two- or three slave nodes termed Red, Green, and Purple. One master plus its slaves assemble into a Decca chain. If three slaves are used, they should ideally be placed forming an equilateral triangle with the master in the centre for even distribution of the signals. The Decca system calculated positions via phase shift between two approaching radio waves. Differences in the phase shift resulted in two- or three hyperbolas. The slave stations communicated with unique frequencies linked to their chain id from a dedicated Decca band between 70-130 kHz. These frequencies were multiples of a basic frequency, defined for the chain of use. Analogue instruments indicated where the electromagnetic waves intersected, and a position was marked (Fisher, 1993). A mesh consists of the two most suitable slaves forming a sheared rectangular grid. A zone is defined as the positional area contributed by electromagnetic waves of two slaves intersecting in four points. Finally, a Decca lane is defined as the curved line with a central bending around any station (hyperbolic) forming the chain (figure 3a).

In Sweden the first station was brought in 1947 by Swedish Maritime Administration to refine nautical maps. During the first setup of Decca in the Baltic, only one chain was installed with the purpose to cover as great terrestrial and marine area as possible. The chain was however only in use for marine purpose and not for airplanes. Some decades later, a subdivision of South- and North Baltic coverage was made with 0A resp. 4B chain. The Decca system was phased out in Sweden in the year of 2000 (Malmquist 2000).

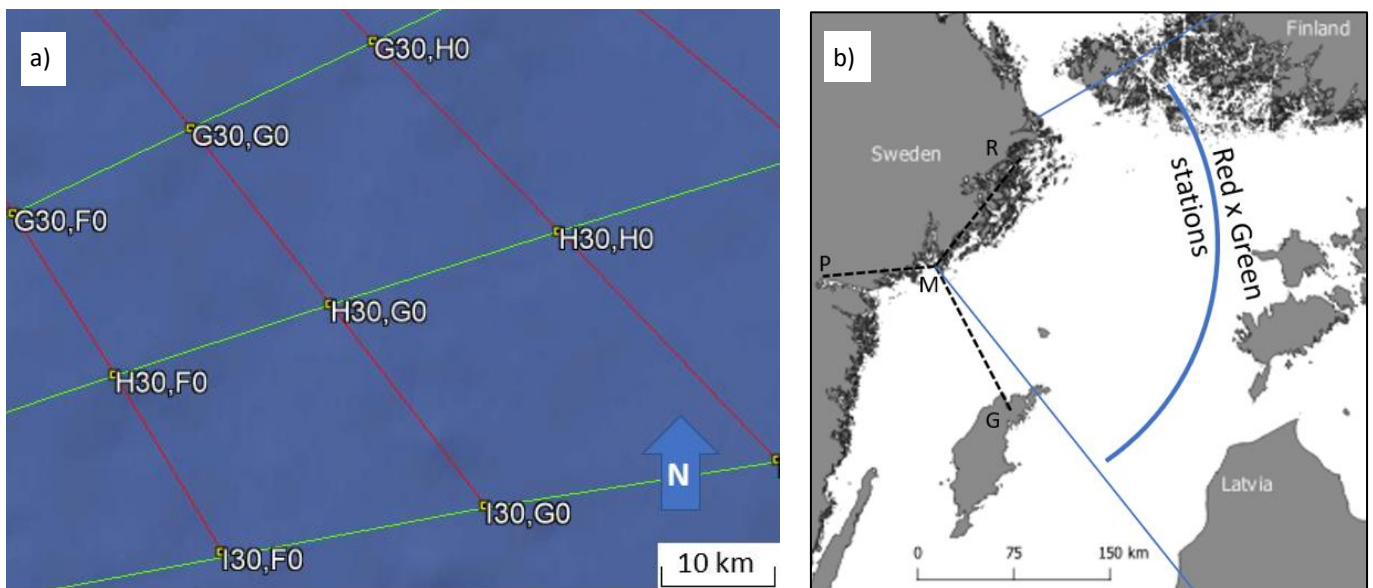


Fig 3. An authentic example of Decca chain 4B, showing a part of mesh, zones between red and green line and the onset of lane breaks (green start by 30, red by 0). Notice the geometrical differences for lane segments (a). A circle sector of 200 km away from Master (M) station to illustrate range in the Baltic Sea. R: red, G: green, P: purple on the edges of the dashed lines. The two lines are illustrating the preferable use of R and G for preferable Decca reads (b).

2. Methods

The data used in this investigation is selected from 13 track lines within an area (~11.000 km²) with a circumference of 700 km in the Baltic Proper. The track line data was collected during surveys from 1970 to 1985 from the area most likely to find sub marine features of interest for reconstructing the YD ice margin (Söderberg 1988).

Most of the data were Seismic Reflection Profiles (SRP), although overlaps with other acquisition methods occur in a few occasions. In the central Baltic when high resolution SRP was required higher frequency of up to 900 Hertz were used but lowered to 100-400 Hz when a higher level of penetration was preferred (Flodén, 1980).

For some surveys, the acoustic signal from SRP and SBP were acquired simultaneously to obtain matching profiles (table 2). The vessels for these surveys were R/V Strombus, R/V Aranda and R/V Admete and surveying was done at a speed between 7 and 10 knots depending on survey. The speed was kept constant, unless stated in the log files. Pneumatic Air Release (PAR) with chamber size of 1 cm³ was acquired using a signal between 100-900 Hz, and Sub bottom profiler (SBP) used a signal of 4 kHz as written on the Decca logs. Seismic and acoustic profiling data was plotted with a needle printer with sweep velocity (pen speed over the paper surface of the plotter) between 0.5 and 2 seconds. The sweep velocity is set by the user and determines the spacing of two-way-travel time (TWT) grid lines on the plots.

Plots (or paper copies thereof) were scanned and saved to tif-format for analyses, using a large-format scanner (SmartLF Ci 40) set to greyscale with 200 dpi resolution.

2.1 Geophysical methods

For data collected from 1970 to 1985 single channel seismic was used providing rapid images of the stratigraphy. The TWT was used to acquire thickness in the analyses of ridges between two different layers and measured in milliseconds (ms). The seismic velocity used for depth conversion in the central Baltic was 1460 m/s (Flodén, 1980) after formulas and tables from Wendt (1967). For the northern Baltic the velocity through water column was altered slightly to 1447 m/s and the sedimentary units used were from an averaged table by Sviridov and Emelyanov (2000).

The TWT equation used to acquire thickness in the seismic profiles and TWT is measured in milliseconds (ms), as:

$$D = v * (TWT * 1000 / 2), \quad (1)$$

where D is distance and v is velocity (m/s). A velocity in crystalline rock of 5900 m/s was generally accepted for sedimentary rocks covering a crystalline bedrock (Axberg, 1979; Flodén et al., 1980) except for exposed areas for the first couple of 10 meters where it was lowered to 3000-4000 m/s (Flodén, 1980).

The equation used to determine the wavelength for obtaining Decca coordinates is calculated as:

$$\lambda = v / f, \quad (2)$$

where velocity (v) divided by the frequency (f) gives the wavelength (λ). For the North Baltic, the Decca chain 4B was used with the different frequencies of master (84.825), green (127.238), red (113.100) and purple (70.688) measured in kHz.

A critical limiting factor in using electromagnetic waves for navigation is the curvature of the Earth. For this, the radius of the Earth (6371000 m) and height of the slaves and master nodes which may be 30 m plus the terrestrial elevation where the stations are situated must be considered.

The distance (D) until an object (such as a vessel with a Decca receiver) vanish below the earth's horizon is approximately measured as follow:

$$D = \sqrt{2 * R * h}, \quad (3)$$

where R is the radius of the object and h is the height of the observation point.

2.2 Positional methods

2.2.1 Surveying

To determine relevant Decca zones in the Baltic Proper, a list of metadata for seismic records and sub-bottom and echo soundings between 1964 and 2015 were used (written communication, Flodén, 2016). The list contained coordinates in Decca for the starting point of every survey, the ship's name, and not precise names for each survey. After conversion of Decca coordinates (Decca-SEA-01, 2019), the most relevant of these matched the survey tracks

used in earlier studies (figure 1a). Seismic records from echo sounder surveys exist on printed paper, with regular hand-written time marks. These were matched to handwritten log-book entries containing Decca coordinates (red, green and purple) at the same regular time stamps. Seismic profiles were chosen that were roughly perpendicular to the expected extension of the Ss ridges. In addition to Söderberg's collection of profiles, six profiles (7053, 7332, 8509, 8511, 8218, 7619) were added.

2.2.2 Maps

For the location of the Decca lanes, all available nautical Decca charts from Gegerfelt (1959; 1964a; 1964b; 1964c; 1964d; 1982a; 1982b; 1982c; 1983; 1985a; 1985b; 1985c; 1985d) were used. The Decca charts were photographed from above using a vertical mount, in full size and with close-up photos for details of available charts. Every Decca chart has a prefix 'D' in front of a number. Used in this work were charts covering the Central Baltic, the Northern Baltic, and a closure chart from Nynäshamn up to Åland Sea (D5, D7, D8 and D71), in the scales 1:200 000, 1:500 000 and 1:550 000. The maps were used to acquire precision in calculations and verification of Decca coordinate conversion.

2.2.3 Geographical information system (GIS)

The freeware tool QGIS on Windows (version 3.6.2 Noosa) was used with the coordinate system WGS 84, UTM zone 34 N. As a base map a raster of bathymetry was used (<http://portal.emodnet-bathymetry.eu/> [access: date 2019-05-15]). The plug-in tool Georeferencing was used to vectorise Ss (I-III) after Noormets and Flodén (2002b). Map with Ss (I-II) was georeferenced from map figure in Häkkinen (1982) and set WGS to 1972.

2.2.4 Decca

A new program was written in Java for calculation of Cartesian coordinates from Decca positions. For navigation, the north chain (4B) and south chain (0A) were used to cover the Baltic. Chain 4B has the best cover in the research area, and therefore consequently been chosen for the aim of this work. Since chain 4B consisted of three slave stations, ideally distributed to 120° each, a maximal intersection angle will be obtained. The chain could then be subdivided into different sectors depending on accuracy (figure 3b). In this work it has been preferable to use the red and green slaves that coincide with territorial space of North Baltics above that border.

For the calculations and converting from Decca into proper coordinates, log file with seismic data provided by Stockholm University was used. The propagation velocity (P_v) is to consider regarding ionospheric effects, or domination of coniferous forests in Sweden, muting signals (Malmquist, 2000), and used as constant:

$$P_v = 299.650 \cdot 10^6, \quad (4)$$

measured in ms^{-1} . which is an accepted choice. Acquired positions were converted to UTM and for the algorithm, best suited was to use same zone (34). The conversion from zone 33 to 34 was made with a negligible difference. The distance calculations between fixed points have been done using Vincenty's algorithm which is based on a WGS 84 ellipsoid rather than a spherical Earth and therefore gives better precision (Vincenty, 1975).

2.2.5 Decca accuracy

The best accuracy for position ranges +/- 50 meters for Decca (The Decca Navigator Company Ltd., 1976). The Decca range was at its most 740 km or 400 nautical miles during the day and 460 km (250 n.m.) at night. At the longest ranges, the error could be up to 1 nautical mile under good conditions, but over longer distances such as 400 nautical miles or 740 km, it could be reduced but normally it was around 200 meters. The uncertainty of position is increasing over radial distance from the Master station. A normal displacement would be around half a nautical mile when surveying is made in the outer ranges. This was true for more than 75% of the positions obtained (Personal experience by Flodén, T. 1970-1980; Course Compendium in Marine geological surveying methods, Marine Geology, Stockholm University).

One of the calibration points chosen was Bogskär, the southernmost point of Finland, which consist of three cliffs where the centre of the biggest Island was chosen. In Decca chain 4B, Bogskär is a point on a relevant distance away from the Master beacon in the North Baltic Proper over many zones, especially on the red hyperbola setup. Gotska Sandön was chosen as a calibration point because of its location close to the southernmost survey positions. Here

two points were chosen, due the uncertainty to define this position on a nautical map. In chain 4B, Gotska Sandön is a point far away on the green hyperbola setup (table 1). The motivation for choosing these points are to get concrete marks that can be measured because they have distinct features on the nautical maps used in the comparison described above. Then the points should be in areas where surveying has been made. To calibrate accuracy, longer distances have been chosen with increasing length of each lane.

Only the end nodes following a lane have been used by applying track lines, except where more detail was needed. A greater level of detail was needed in analysing sedimentary cross sections, narrowing possible ridges that may coincide with YD event, or because of the geophysical problem to survey cross Islands or skerries (i.e. > 0m.a.s.l). Gotska Sandön (58°21'51.00"N, 19°14'50.00"E) is an example of this third reason (7619 and 8511). With a better resolution of recalculated positions every 20 minutes applied, the surveying vessel is moving around of authentic distance to the Island. Else it would collide with it (figure 4).

2.2.6 Mapping of ice margins

Mapping the end moraines in Baltic Sea is done with respect to an error margin. The error is shifting in different directions, depending on how much of each slave beacon is used visible in the interference lines and the angle of building up the Decca mesh (grid). A close to 90° among the edges in a zone confirm an almost equal interplay of two slaves, and thus positions between them. The Master beacon is approximated to latitude 58°56'50"N. In conversation done with software (Söderberg, 1988; Decca-SEA-01, 2019) all points below or equal to this latitude are applying the SE error margin, while points above apply NE error margin.

Table 1. Calibration points for accuracy in calculations over long distance compared to visible locations on nautical charts (Decca-SEA-01, 2019). An extra description field is chosen to specify position on nautical charts.

Locality	Description	Latitude, Longitude	Decca coords (R:red, G:green, P:purple)	Feature	Accuracy (m)	Distance from Master (km)
Bogskär	Centre point of largest Island	59°30'16.45"N, 20°20'48.14"E	G: D47.5, R: B11.9	Skerry	120	150
Gotska Sandön	Most NW point of the Island 1	58°23'55.48"N, 19°10'30.99"E	G: H46, R: D2.7, P: A71.01	Island	350	90
Gotska Sandön	Most NW point of the Island 2	58°23'53.06"N, 19°10'28.70"E	H46.01, D02.454, A71.012	Island	300	90

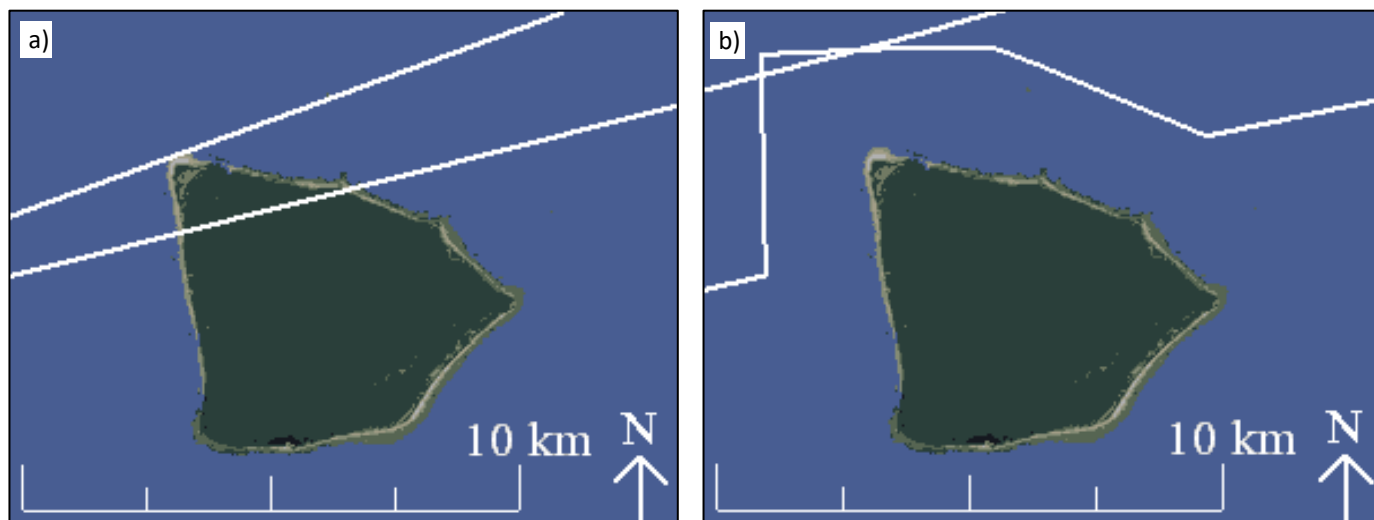


Fig 4. One explanation where level of detail is supporting a geophysical space problem. In first figure, it looks like the surveying is crossing Gotska Sandön (a). In second figure this is modified with authentic data (b), so the track line is moved northwards (7619) or move around the Island (8511).

3. Results

Before any interpretation of the profiles is possible, their exact location must be established. The types of results from this study are therefore twofold: positioning accuracy and mapping of YD ice margins.

Track lines identified in Söderberg's article from 1988 have been identified using the Decca converting program (Decca-SEA-01, 2019). Each survey has continued for hours and sometimes over many days without paus in the surveying (figure 5a). The total amount of track numbers in this study are 13 (figure 5b).

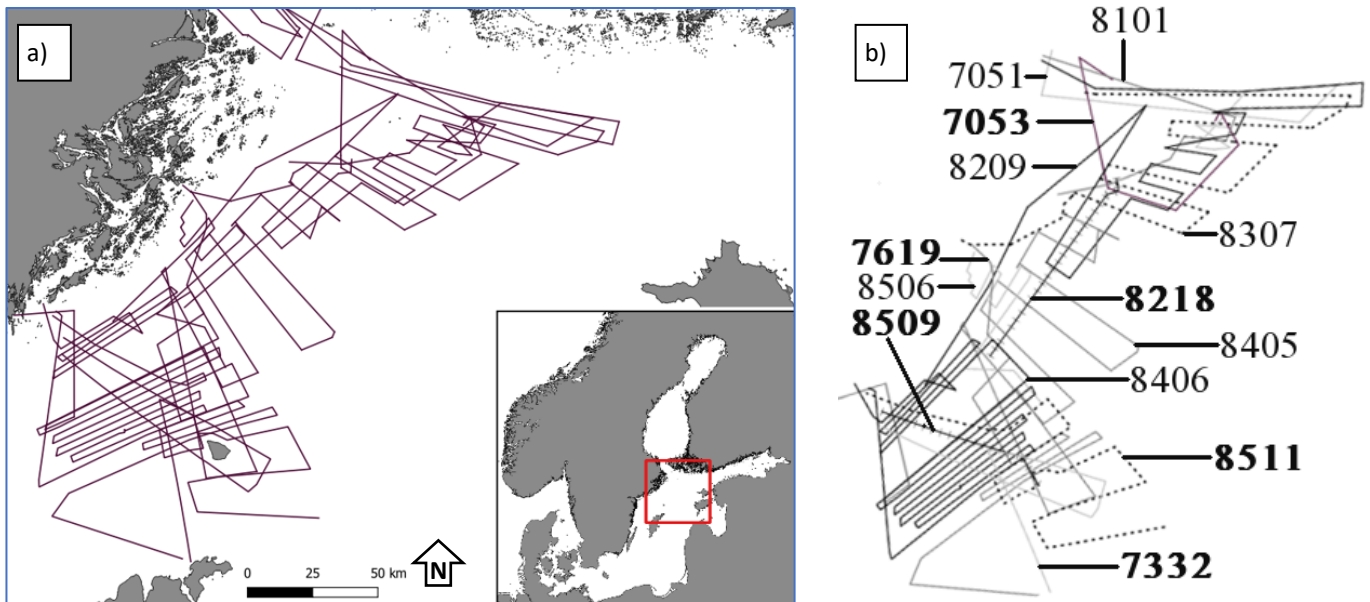


Fig 5. Track lines from 1970 to 1985 **(a)**. Track line identifications (slightly rotated and truncated) of the 13 tracks used, compared to their existence in survey mapping from Söderberg's figure in 1988 (figure 1a): Added survey lines from previous non-evaluated in bold **(b)**.

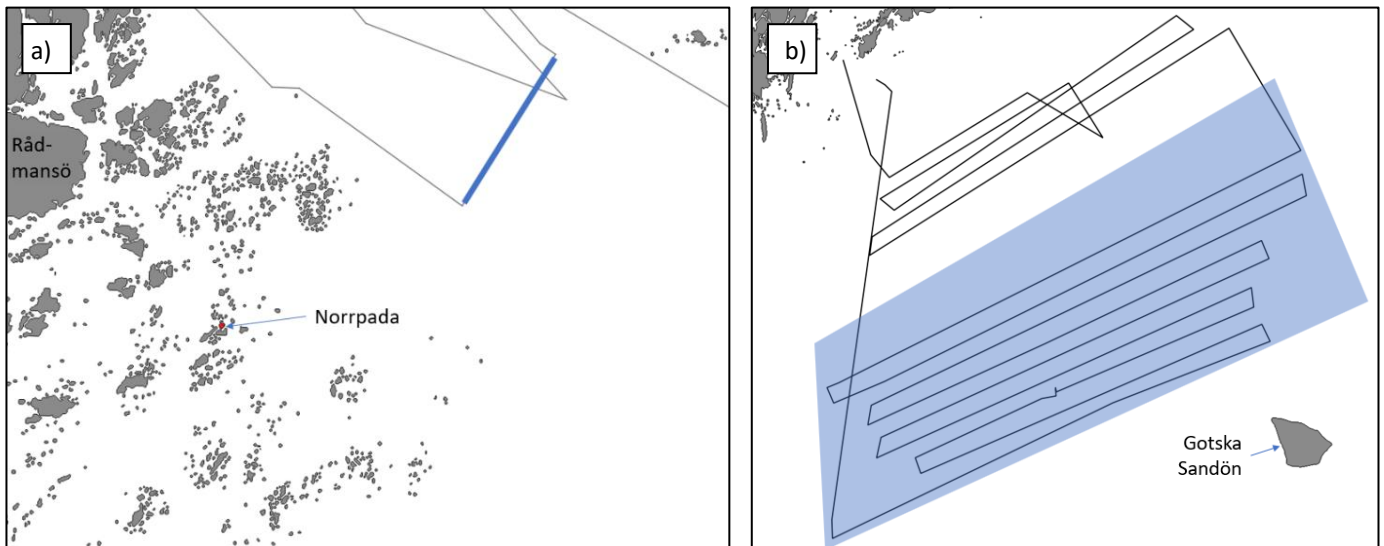


Fig 6. Additional tracks covered in detail. Track line 8101 thicker blue line **(a)**. Track 8406 with transparent blue polygon **(b)**.

Table 2. An overview of 13 unique track lines and 8406 added twice. Duration (dur.) is the active survey time (SRP and SBP) in the research area. Tracks in the second column are additional and not used in earlier work by Söderberg (1988) except of minor part of track 8406 where a shorter distance was covered hence duration written twice.

track	year	dur. (h)	track	year	dur. (h)
8307	1983	40	7053	1970	13 ^a
8209	1982	31 ^a	7332	1973	6 ^a
8101	1981	15 ^{a, b}	8509	1985	5
7051	1970	18	8511	1985	10 ^a
8506	1985	12	8218	1982	7
8405	1984	17	7619	1976	13 ^a
8406	1984	14 ^b	8406	1984	23

a Surveying outside research area excluded.

b Additional search from same track line (figure 6).

This study is focusing on finding the Baltic Proper YD end moraines correlative to the Ss (I-II) in Finland and the MSIMZ in Sweden. The Baltic proper end moraines formed around YD time are here referred in ascending age to Baltic End Moraine 1 to 3 (BEM 1-3) that would be correlative of Salpausselkä (I-III), where BEM 3 is younger than the YD (Hughes et al., 2016; Stroeven et al., 2016).

3.1 Intersects over BEM

BEM 1-3 are ridges interpreted as elongated submarine landforms in southward direction towards Sweden. At a latitude of 59° the continuation is described as a breakup for BEM 1-2 into a delta south of Bogskär. BEM 2 could be traced by glaciofluvial deposits of thickness of 50 meters. The surveying for the BEM 1 is mapped to half the length than BEM 2 and ends already in the northern parts of the Baltic Sea, while BEM 2 continues into the North-Central Baltic Proper (Söderberg, 1988).

The previous continuation of Salpausselkä drawn in the North Baltic Proper from Söderberg (1988) have a good fit to the results of Punkari (1979) for Salpausselkä III. The same goes for the first 100 km outside the Finnish coast for Salpausselkä I and II. This implies that the surveys used in previous work, to draw continuations of Salpausselkä I-III, are based on a few points intersecting with known tracks.

The count of intersects is a quantified amount of times that the surveying was passing over BEM 1-3 (figure 7) and an absolute amount of maximum occasions of legacy data could ideally be presented. In most of the cases, it is obvious how many times the surveying was crossing the features in the Baltic Proper. Track line 8209, 8101, 8307 and 8405 appear to systematically survey regions to find BEM (1-2) with changing Decca lanes (e.g. course of the surveying vessel). In the Central part of the Baltic, only the corresponding ridge to BEM 1 is shown with a profile figure by Söderberg (1988).

For BEM (1-2) it's stated that the ridge feature can be seen everywhere which would imply 11-13 occasions for BEM 1 and 26 to over 30 occasions for BEM 2. For BEM 3, the closest point is close enough for the interpretation of where Söderberg (1988) draw the continuation ridge. The only track lines close enough to the last marker used in the mapping coinciding with the interpretation of BEM 3 are three survey lines with their respectively seismic data (8209, 7051 and 7053) where 8209 is the closest profile matching the bathymetry, hence the smallest error margin.

3.2 Mapping accuracy

Possible error types are divided into three groups: Decca navigation (DeNaV), pixel by georeferencing on redrawn maps (GeoRef), and calculation error from conversion tools (ConCalc) were used (Söderberg 1988; Decca-SEA-01, 2019).

The positions acquired using Decca-coordinate conversion software (Decca-SEA-01, 2019) have been ground-truthed using landmarks, which give an accuracy of ±350 m for distance range of 90 km SE and ± 120 m for distance range of

150 km NE from Master (ConCalc). Decca itself (DeNav), has an error margin that is increased to maximal 1 n.m. (1852 m) for areas outside 460 km from the Master. All points for the Baltic End Moraines (BEM) analysed are ~230 km or less from Master, applying a generalized error of ± 400 m which is applied for all mapped features by Söderberg (1988). Same error margin is applied for BEM (2-3) above 90 km SE respectively above 150 km NE from the Master for BEM 2-3. For BEM 1, another 60 m is added due the difference of interference angle. A rounding up to 200 meter is last made for all BEM (1-3) with less- or equal to 90 km (ConCalc). The pixel error (GeoRef) are applied on Ss (I-III) in the Baltic Sea after the work of Söderberg (1988) together with Ss (I-III) 30-50 km outside EEZ of Finland. They showed a calculated error of maximal ± 200 , considered dimension of a pixel is 400x400 m.

A dominance of green in SE direction from Master beacon to Gotska Sandön, an adjustment from older conversion tool (Flodén, 1980) is set to 1000 m for distances >90 km (ConCalc).

Comparing the positions of earlier studies with ground-truthed position made with the new software, the old positions have an offset in NE direction of at least 1000 m for points >100 km distance from the Master node of Decca chain 4B. More realistic, a correction of 3000 meters shown for a point in extended direction from Master to Bogskär (NE), another 20 km away from Bogskär (figure 8). An assumption of the closest track line is made, else the updated position of BEM 3 would have a larger correction compared to previous results by Söderberg (1988). Error margins are summarized in table 3.

Table 3. A summary of error margins. Distances shown in parenthesis in mapping area are measured from Master station of chain 4B. BEM (1-3) are consequently done with Decca-SEA-01. Rounding BEM (1-3) to 200 m, is shown with '>'. All types of error margins are valid within 230 km. Units in meter (m).

Mapping area	Type of error	Sum error (\pm m)	
		SE	NE
Ss 1-3 30-50 km outside Finland EEZ	GeoRef	500	500
Ss 1-3 after Söderberg (1988) (>90 km)	GeoRef, ConCalc	1200	1200
Ss 1-3 after Söderberg (1988) (\leq 90 km)	DeNaV, GeoRef	600	600
BEM 2-3 (\leq 90 km)	ConCalc	350	120 > 200
BEM 1 (\leq 90 km)	ConCalc	350	180 > 200
BEM 1-3 (>90 km)	DeNaV	400	400

Four track lines (8209, 8307, 8101 and 7051) are fulfilling the criteria of being the end nodes in Ss III. Two points are used to calculate distance to possible positions on the bathymetry map. Point A is used as the absolute end node of the ridge (Ss III), and point B is used as the intersect between the depression and the ridge with a water depth of ~130 m (figure 8a). Comparing earlier studies with position plots with the software used in this study, there exist an error margin from the past that is not added to results presented here in all features within 100 km from the Master station of Decca chain 4B. At 100 km distance from the Master node, the adjustment made here is around 1000 m. Compared to previous tool results show less distance to the accurate positions.

Lack of information which of the four tracks (8209, 8307, 8101 and 7051) have been used, but the closest intersect with a matching depth profile is 3000 m away from 8209 (figure 8). In figure 8a, blue arrow 1 is marking the absolute end position defined by Söderberg (1988). Blue arrows 2-5 are marking the deepest spot in figure 8a (dark blue) and the cross-cutting track line over it. Blue arrow 6 is marking an potential area, also fulfilling the requirement of \geq 160 m depth, however, the seismic figure of the four track lines (7051, 8101, 8307 and 8209) have another cross cutting angel over the depression in arrow 6, making this not truth worthy with an error displacement in the North or Northwest direction. In figure 8b, the not filled circle between the transect x-x marks the distance of 500 meter, satisfying the condition of ~ 160 m marked with red arrows (1 and 2), 1700 meter to water depth of 180 meter (red arrow 3).

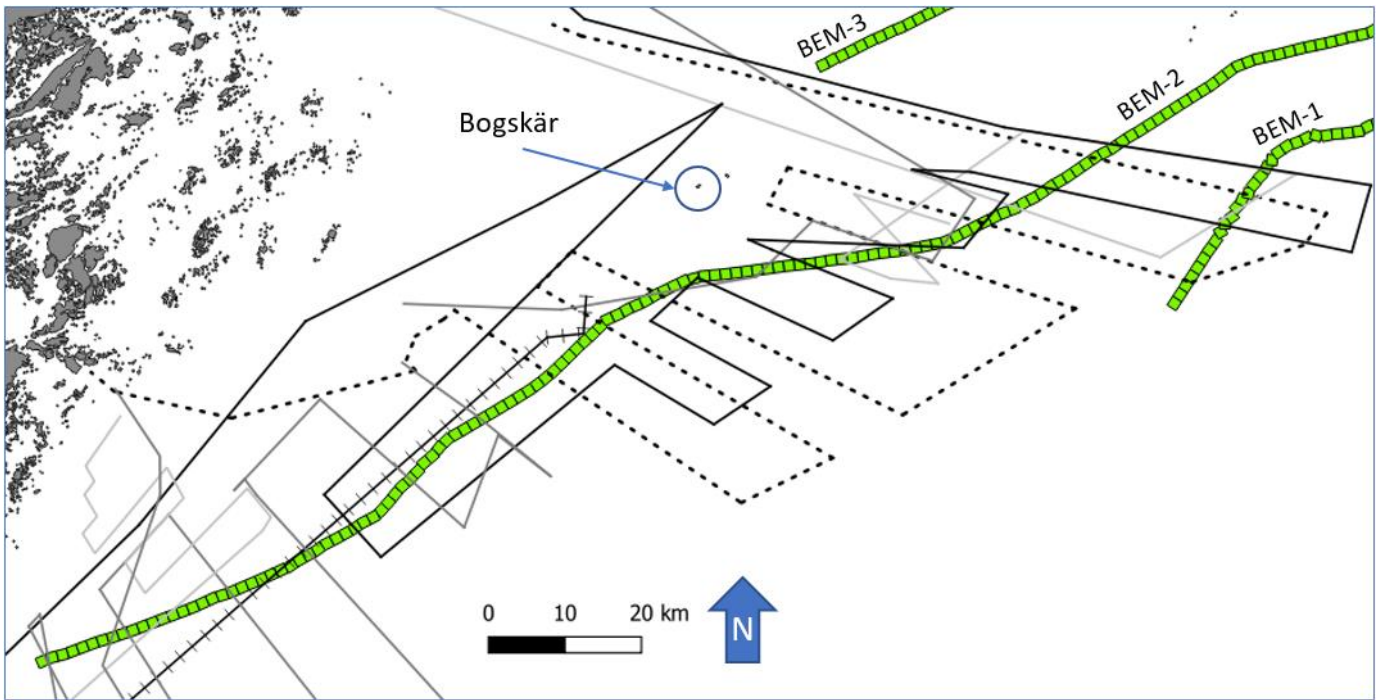


Fig 7. A visualized overview where the track lines are cross cutting BEM 1-3.

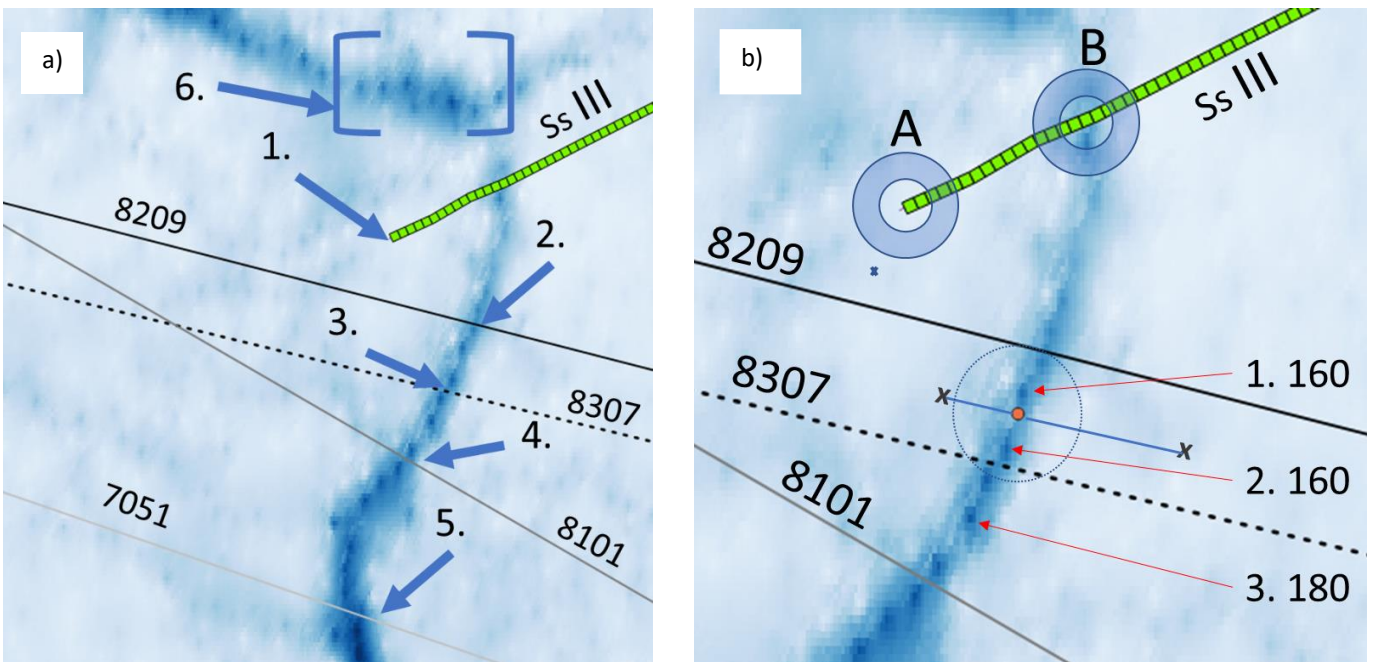


Fig 8. The end node of Ss III and its closest intersections with track lines marked (blue arrows) over a submarine canyon (blue shaded). Resolution on lane switch (i.e. vessel course change) as seen in figure 7. **(a)** A zoomed view with best possible resolution. The maximal water column depth in meters is written behind each number, showing the depth at position of red arrows. Resolution set to 20 minutes from Decca logs with weighted interpolation of 70% over distance between to obtain the solid orange dot **(b)**.

3.3 Sedimentary results

The acoustic stratigraphy is divided into five different units depending on their characteristic signatures (table 4). Unit I is usually a thin layer and the uppermost sedimentary unit. On the sea floor, they follow with high to medium amplitude and high continuous parallel reflectors, where bathymetry is not dipping over plateaus of less than 0.5 km. Unit 1 is interpreted as post glacial clay). Unit II follows the bottom topography very well seen in reflectors, sometimes divergent and is above Unit III and sometimes under post glacial (unit I) sediments. Unit II does not necessarily follow beneath unit I and more seen in smaller basins between higher surrounding ridges. In narrowing passages such as small depressions, the effect of a bow tie is sometimes seen. Unit II is interpreted as glacial marine clay. Unit III is resting upon bedrock in a quite noisy (incoherent) pattern and is interpreted as till. The till creates

layers that may not follow the bottom topography. In some places it vanishes or represent just a thin layer. Its scattered signature is different from the layers above but the contact to the acoustic basement (unit IV) is not always distinct. The last distinguished unit is the acoustic basement (bedrock, IV).

Table 4. Acoustic facies of the interpreted profiles. The table describes the typical acoustic signature, but deviations occur along the profiles.

Unit	Seismic signature	Geometry characteristics	Interpretation
I	Medium to high amplitude with a distinct sharp black colour. High continuity and convergent in slopes and parallel in horizontal sea floor	Following the bottom topography. Thickness from a very thin layer less than one meter to tens of meters. Covered by unit I.	Post glacial clay.
II	Low amplitude to invisible. Incoherent intervals when visible.	Homogenous layer thickness 10 to 50 meters. The unit is seen in depressions and in troughs. Covered by unit I.	Clay with sometimes weak various stratified layers but mainly homogenous with low dense bulk composition.
II b	Gradient from medium to low amplitude with parallel reflectors and incoherent intervals.	Uniform draping geometry with equidistance between layers on horizontal deposits and divergent reflectors in steeper sea floor topography. Seen in depressions and faults. Covered by unit I.	Post glacial clay or glacial clay. Not seen everywhere.
III	A gradual scatter from black to grey. Low continuity and coherent intervals.	A gradual scatter from black to grey (thickness 1-70 meters). The scatter, not necessarily following the bathymetry of unit IV. Covered by unit I, II and IIb. Ridges up to tens of meters.	Till.
IV	Low amplitude, low continuity	A saw tooth pattern, with a darker greyish texture gradual into a lighter greyish colour. Covered by all units.	Bedrock. Seen in the deepest areas of the Baltic basin. Also exposed on the sea floor.

3.3.1 Cross sections sedimentary

Crossing seismic profiles are useful for mapping features in more dimensions and have been done to give as good positions as possible and recognize the surroundings of sea floor.

Surveying in the Baltic Sea, two profile crossings have been studied in more detail, in west direction of the ice margin ridge of Salpausselkä II (Söderberg, 1988). The 7051 survey is intersecting with itself, and the second intersect is between track line 8209 and 8405 is approximately 70 km further SE (figure 9; figure 10; figure 11).

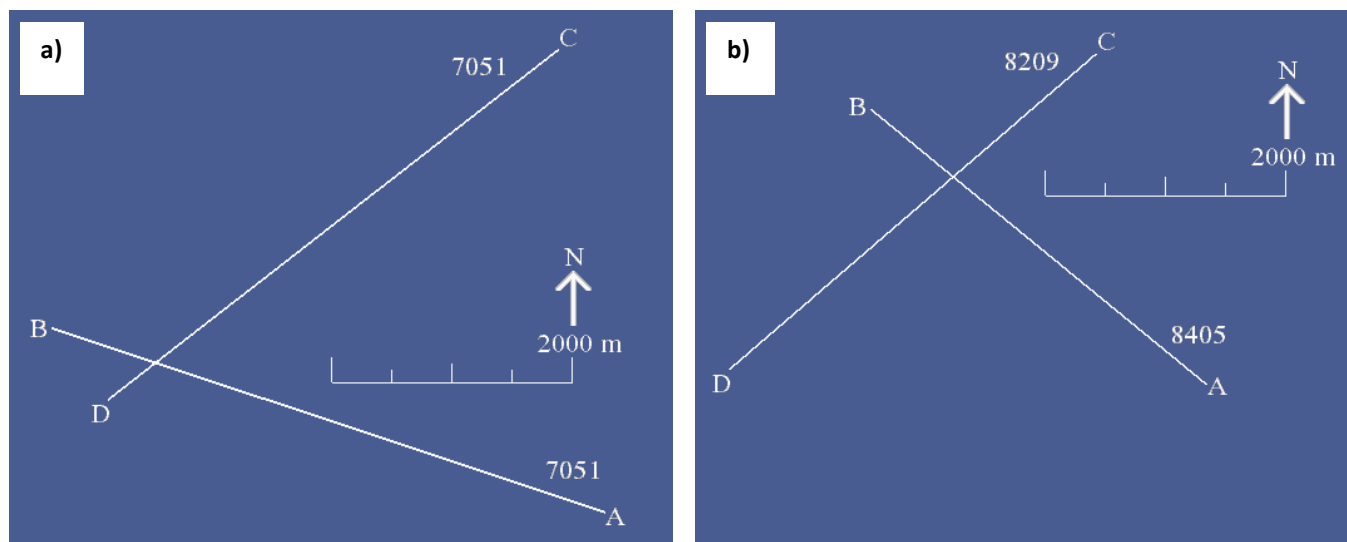


Fig 9. The cross cuts of the sedimentary profiles in the North Baltic Proper. The intersection position is approximately 59°27'24"N, 20°45'47"E (a), and 59°11'43"N, 19°36'49"E (b).

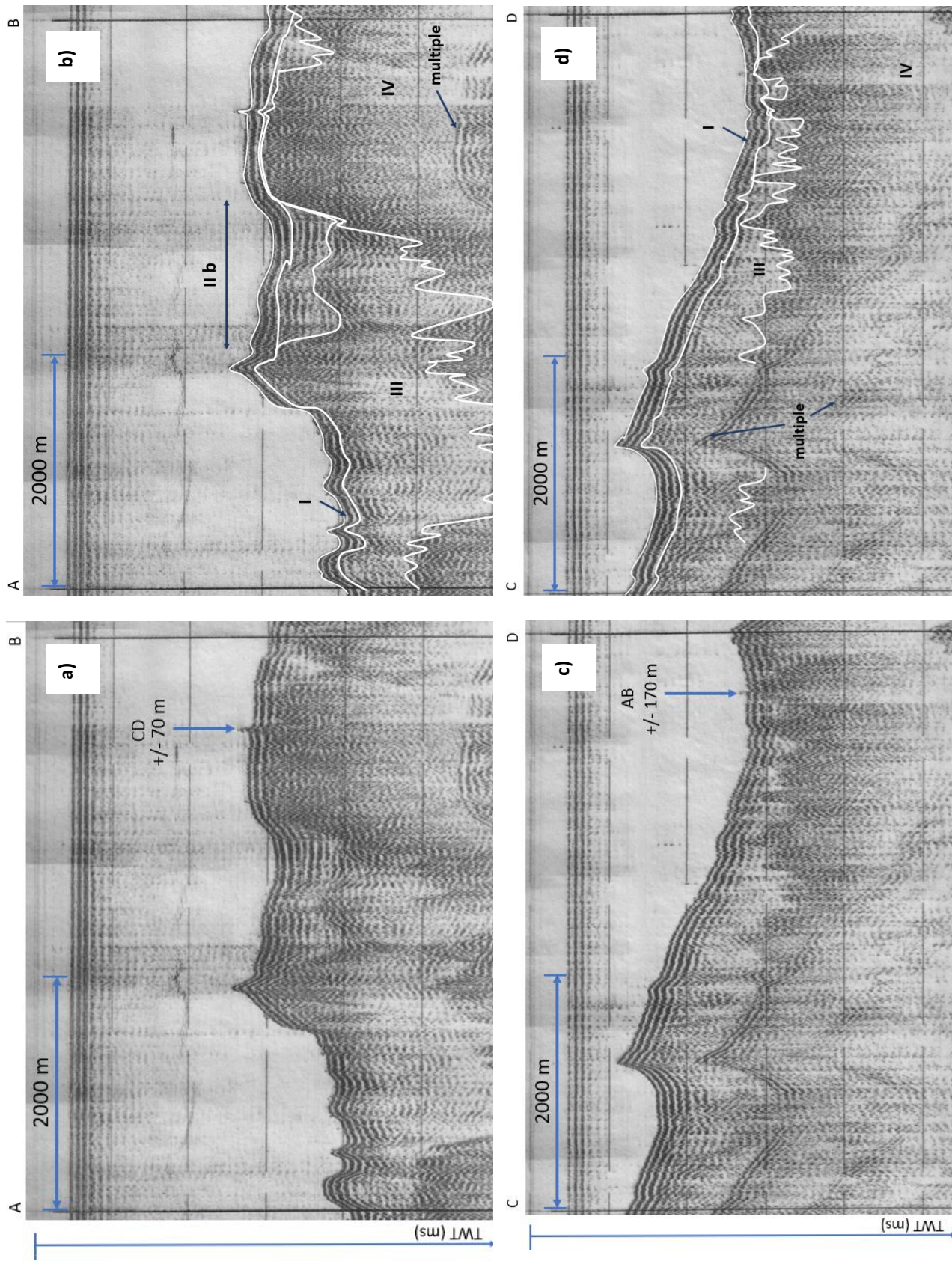


Fig 10. Seismic profile of 7051 (a) with its geological interpretation (b) crosscutting AB seismic profile in same track line (c) and its interpretation (d). Error margin presented with the cross cutting transect. Depth is measured in TWT (ms).

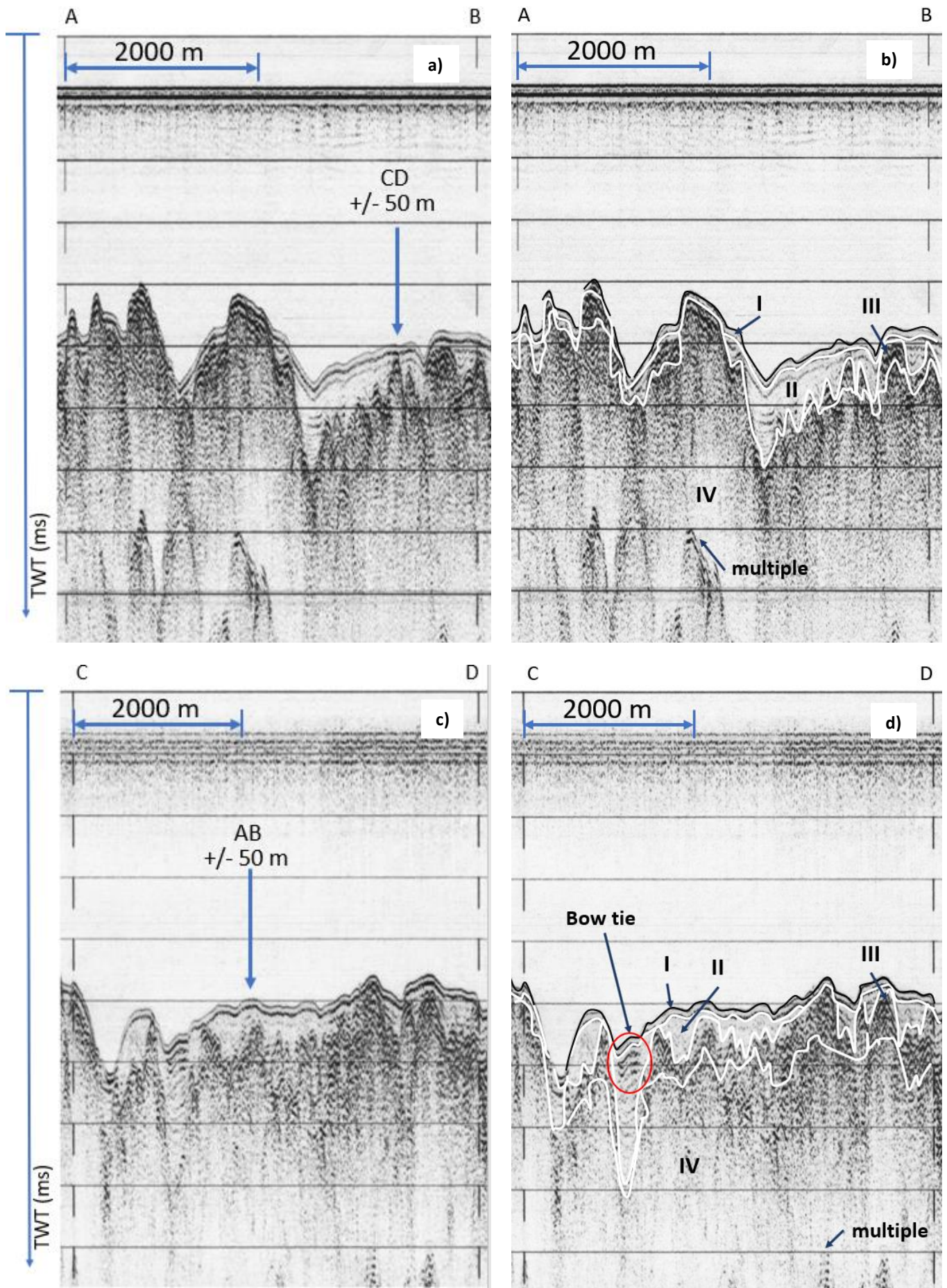


Fig 11. Seismic profile transects of 8405 (a) and its geological interpretation (b). The seismic profile of a crosscutting transects CD of 8209 (c) with its interpretation respectively (d). Error margin presented with the cross cutting transect. Depth is measured in TWT (ms).

3.4 BEM 1-3

The end moraine observed earlier (Söderberg, 1988), within the research area of BEM 1, identified as a continuation somewhere between Finland and Sweden, was a distinct ridge. A thin moraine deposit is seen on the flatter top plateau of the ridge, dipping slightly to the East. A gradual flattening of descending moraine deposit starts at around 40 m b.s.l. both sides of the ridge. The western side of the ridge has a concave geometry of the slope of till deposits, while the eastern part has a sharper break from the crest (figure 1b).

End moraine ridges from the BEM achieved during surveying 1970-1985 presented below (Figure 12). The distance between vertical lines differ. Depth is measured in TWT. West and East directions (E and W) are marked on top of the figures.

In figure 12a, track line 8209 shows an interesting ridge plateau for BEM 2, that does not follow the bottom topography. The horizontal ridge plateau is approximately 500 m long. In figure 12b, another seismic image from BEM 2 from track line 8307, contains a ridge with a concave deposit on the eastern side, while the western part of the ridge has a 20-30 meter highly steep angle down to the bedrock. Sedimentary deposits are filling the depressions. A possible multiple may add extra post glacial material (unit I) on top of the ridge showing many parallel distinct black reflectors making the sedimentary thickness look thicker than it should. In figure 12c, another seismic image from track 8307 is shown but from BEM 1. The deposit (blue pointing arrow) points at an end moraine ridge. The sedimentary unit is thick, possible 20-30 m of deposit. The homogenous deposit in the thick bed shows weak reflectors and could possibly be unit II or unit IV. The final seismic image (figure 12d) is showing a mapped ridge from BEM 3 from 8209 with the same marked position on bathymetry map from figure 8. The deep canyon is around 180 m (measured through water column down to unit I), and the distance between the dashed vertical lines (EW) are 4900 m. On the eastern side of the highest ridge in the image, there is a staircase pattern of sedimentary deposit with post glacial clay (unit I) on top. The reflectors in the area below this unit, is interpreted as till with no connectivity in the reflectors.

A final mapping presented below, introduces a few positions of assumed BEM (1-3) in the Baltic Sea, together with Ss (I-III (georeferenced) and MSIMZ (rough sketch). Earlier work shows continuation of Salpausselkä I and II mapped in sub marine area South West from Hanko (Häkkinen, 1982) and Punkari (1979) for Ss III. For MSIMZ and YD in Sweden, the work from Lundqvist and Wohlfarth (2001) is considered (figure 13).

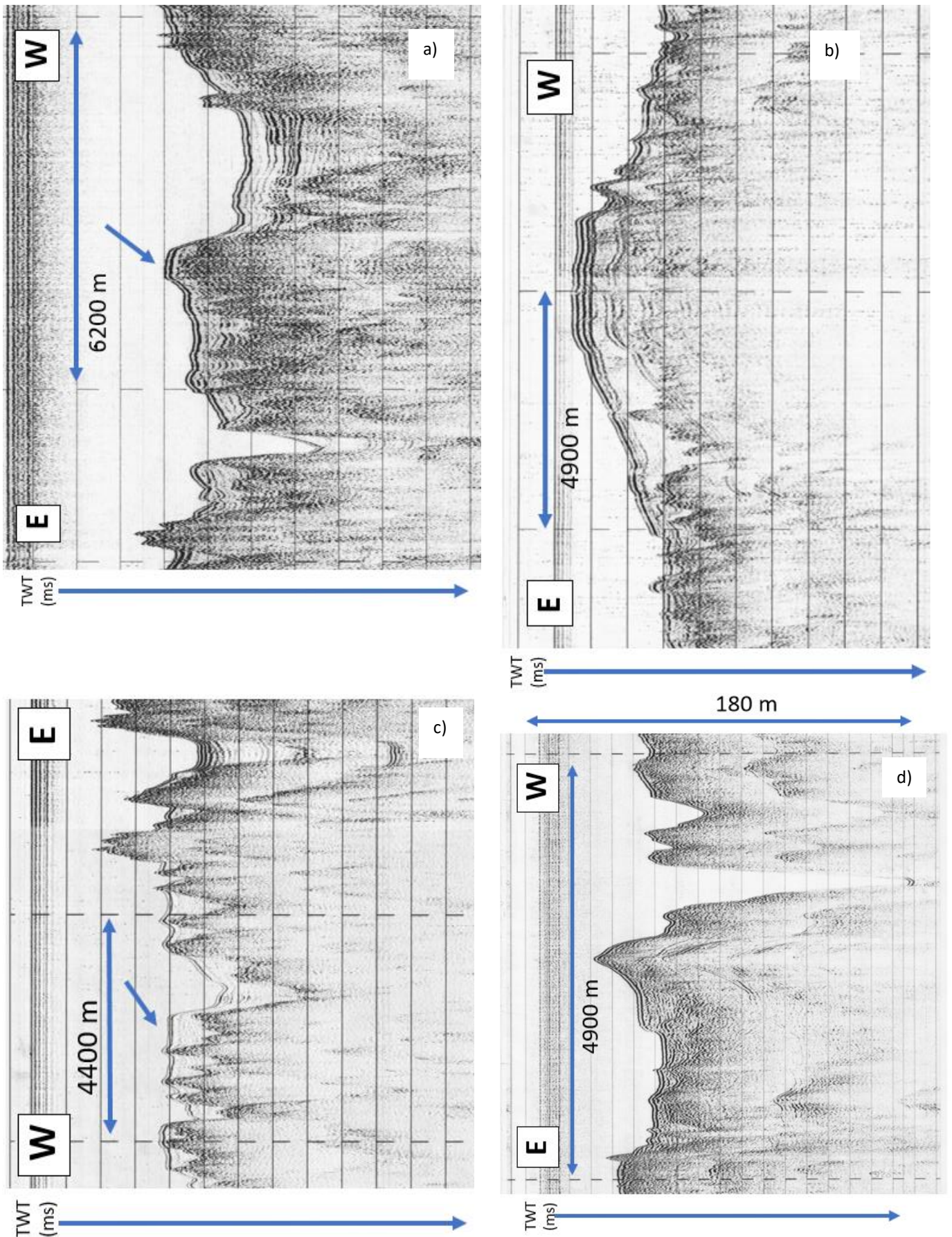


Fig 12. Various ridges from the Baltic belonging to BEM 1-3. BEM 2 (a-b), BEM 1 (c) and BEM 3 (d).

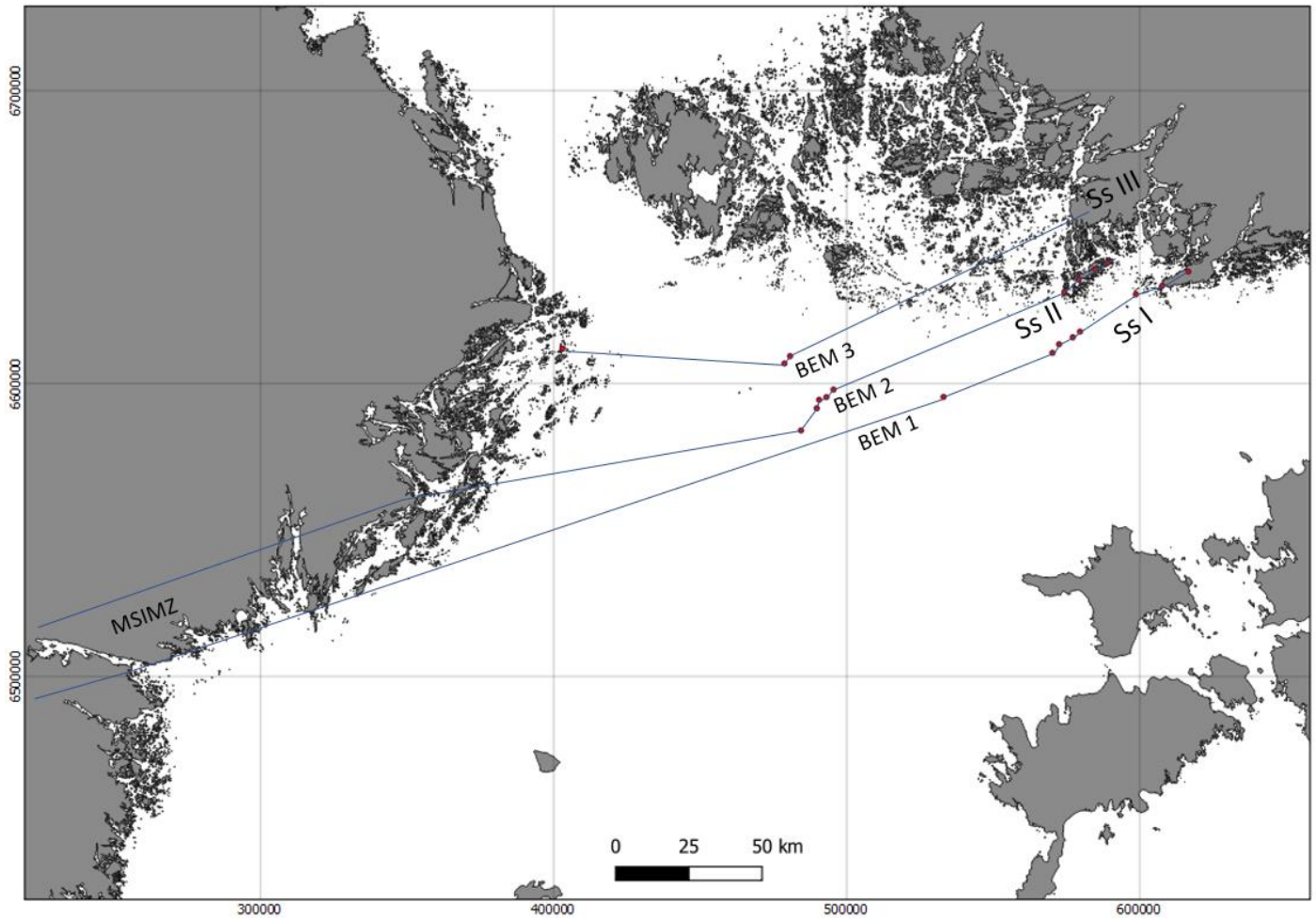


Fig 13. The BEM (1-3) mapping final image connecting end moraines in the Baltic Sea.

4. Discussion

This work presents refined positions of end moraines in the Baltic Sea using Decca SEA-01 software. Further possible locations of the ice margins linked to Ss (I-III) in Finland and a few positions on the Swedish east coast are also presented.

In Sweden as well as in Finland, apart from sub marine mapping, positions of MSIMZ and Ss (I-III) are well known respectively (Donner, 1978; Punkari, 1979; Persson 1983; Rainio 1991; Björck 2008). Some positions in the Finnish archipelago within EEZ exist for Ss I-II, which were adopted in this research from Häkkinen (1982). Inside the Swedish EEZ of the western coast, positions are mapped according to Berglund and Mörner (1984) and Lundqvist and Wohlfarth (2001). To my best of knowledge, no other data is available regarding the mappings of YD end moraine ridges in the Baltic Sea outside EEZ of Sweden and Finland, except the results from Söderberg (1988). Moreover, the data between the southernmost transect (KL) from Häkkinen (1982) and the northern most intersect (track line 8209 and BEM 1) of Söderberg (1982) is missing (~35 km).

For all BEM (1-3) and Ss (I-III), an applied error margin is used (table 3). However, the error margin when mapping Söderberg's ridges (1988) were much smaller than the absolute error at a distance of ~250 km from the Master beacon. The absolute displacement error was measured to ~2.5 km from his Ss I position westwards to the transect KL after Häkkinen (1982).

It is difficult to control data conversions from the tool described by Flodén (1980) and to pinpoint the accuracy when no source code from the program exists to stepwise go through the algorithm. Instead accuracy is tested on the visualized outcomes based from his work. The scale used in figure 9 presented by Flodén (1980) presents a track line

(7332A), measured that 1 mm in figure, correspond to over 2 km in reality. This implies that the thickness of a 7332A is calculated to less than or equal to 0.2 km. By measuring the shortest distance between 7232A and the coast of Gotska Sandön would then be 3860 m which is an absolute displacement error of 1000 m. In later research performed by Söderberg (1988), an update in the Software is not assumed.

BEM 1 is assumed to be located on the western side of Bogskär based on the continuation of the ridge. The final position of BEM 1 coincides with the results of Söderberg (1988) with only 20 km away from Bogskär. The continuation of the ridge needs to be further analysed on its way to the suggested position of Norrpada.

The interpretation of the sea floor morphology and acoustic stratigraphy has been done with seismic profiles. The only seismic data from Söderberg (1988) was a profile from Ss I. However, its location in the Baltic Sea was not shown in his results. The only approximate description of its position was in the sea between Finland and Sweden. Similar profiles found along his mapped Ss I ridge were used in this work and presented as BEM 1.

By looking at a single seismic image, many topological features in the bathymetry may match the pattern of an end moraine. An image from SRP does not show if the assumed till from YD is sorted or if the submarine landform belongs to a drumlin or esker for example. By coring and collecting samples from the sea floor, further analyses can be performed in order to date and examine the nature of the deposition of the till. A melt-out till for some clasts would show preferred orientation to support models parallel to the glacier flow (Krüger, 1984).

By using an airgun as the sound source, it is possible to penetrate deeper than with a sub-bottom profiler (SBP). SBP provides a lower vertical resolution but increased penetration, and details may be obscured by multiples caused by echoing several times between reflective strata and the water surface.

The calculated depth through the water column was achieved by using a seismic velocity of 1447 m/s generalized in the Baltic Sea (Sviridov and Emelyanov, 2000). The difference compared with the velocity of 1460 m/s (Flodén, 1980) was only a couple of meters for deeper parts such as depressions.

It was expected to find Holocene sediments, on top of post glacial clay, which in the basins of the Baltic often consist of muddy or clayey sediments rich in organic material. The sedimentary unit is interpreted as Holocene and tends to show many parallel reflectors especially the oldest profiles. The unit is mostly visible but may have been transported to lower depositional areas by events such as tectonic, subaquatic slide or underwater currents.

In this research, no continuation of YD (BEM 1-2) or the end moraine after YD (BEM 3) across the Baltic Sea have been found. End moraines and their traces in Baltic Sea, might have been buried so there is a challenge to find a continuation of a prominent ridge.

Newer profiles recorded today may contain more details and better resolution. It is worth mentioning that traces and signatures seen in legacy data from 1970-1985, might not be visible some decades later due to increased activity in the Baltic Sea.

For future research, survey mapping in combination with coring and samples would give a better understanding of the positions of the ice margin with detailed geomorphological studies of the bathymetry and samples of the ridges in order to estimate geological age. Combining such research areas, will lead to more precision where BEM (1-3) are located.

5. Conclusions

The study is summarized in following conclusions:

- The new computer program was successful in converting Decca positions into cartographic coordinates.
- Higher accuracy achieved with the new program compared to earlier studies.
- Successful mapped track lines of legacy data have been created and ground-truthed visualized data.
- By using legacy data, intersections of surveying over YD moraine ridges have been achieved.
- Identified ridges originate from BEM 1, BEM 2 and BEM 3 in the North Baltic Proper are presented.

Acknowledgements

I didn't know I could fill the head with so many things of this interesting topic, but there are some people that filled my brain with fresh inspiration, with no taste of brackish water.

Many thanks to supervisor Richard Gyllencreutz, University of Stockholm, for all your help during the journey. You've been right many times, when I've been wrong. Great support and actually been there when I asked for help. This journey started when you got me interest in Decca a year before this outcome with months of prework, so one extra thanks for your encouragement.

It feels natural to send appreciations to Tom Flodén, a marine Geologist I never met. I've tried to dive into the rings of waves you created and follow the tracks across the Baltic Sea. I've been careful and under respectful treatments explored your legacy data.

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Arjen Stroeven and Robin Blomdin confirmed suspects and added interpretation about a seismic image in North Baltic Proper.

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Finally, a warm embrace to my family and support on irregular time schedule. Adding my monologues over breakfast table just to ventilate findings is probably tiring. I cannot express this in words, so I say it with some polygons and a message in Decca with another European chain:

E4400,G1604;E3800,G2318;E3400,H0209;E3800,H0401;E4200,H0714; (CCW) and
F3412,G0815;D4222,G2205;E4588,G0225;F3415,G2221;D4755,H0420;
D4015,H1915;E3877,H1619;F3408,G2209;E3218,G0309;D4314,I0777; (random).

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