



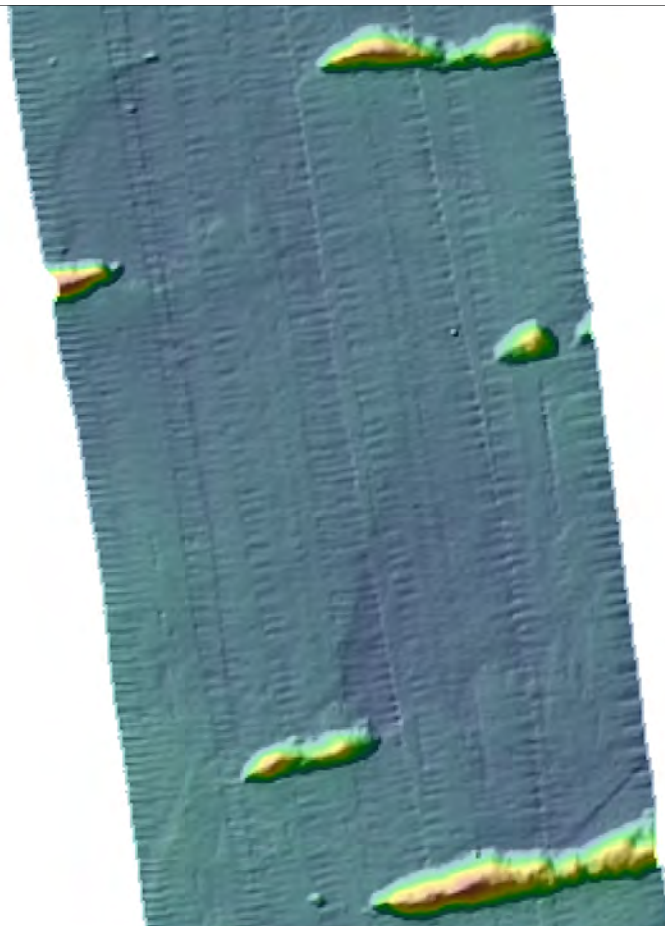
Stockholm
University

Bachelor Thesis

Degree Project in
Marine Geology 15 hp

Investigating the formation of De Geer moraines in Kalmarsund, offshore southern Sweden

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Stockholm 2023

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Acknowledgements

I want to thank Dr. Sarah L. Greenwood for the incredible support and reviews of this thesis which has been of great help. I also want to thank her for giving me the confidence to work with this new set of data collected in Kalmarsund and for all the knowledge she has given me throughout all the other courses in the field.

Abstract

Multibeam bathymetry data and subbottom profiler data collected in Kalmarsund, Sweden by the vessel RV Electra in 2019 and 2020 has been investigated after findings of possible De Geer moraines (DGMs). A digital elevation model (DEM) from the multibeam data was used to map landforms and buried ridge-crests in the subbottom data were recorded. After visualising connecting DGM ridges between buried and visible seabed ridges, the data showed an increase of sediment load and dispersed DGMs in areas of higher topography along with more preserved and narrow DGMs in areas of lower relief. By comparing the spacing of ridges with a pattern of retreat isochrons from Avery et al. (2021) based on a local varve chronology, results suggest that several mechanisms of DGM formation exist and not only annual but subannual formation probably occurred. However, a subset of regularly spaced and elongated DGMs might support De Geer's initial hypothesis of annual moraine formation. There is an absence of information on the glacial geomorphology in the offshore area of southeastern Sweden. Results of DGMs give further insight to the deglaciation of Fennoscandia which in the study area has been dated to ca. 15 ka BP. Information about the dynamics of the ice sheet in connection to recorded DGMs indicate a northward direction of ice retreat with ridges situated roughly east to west formed by an ice sheet with locally crevassed sections in the marginal zone. By understanding the dynamics of the former ice sheets we can better predict and prepare for the future of the melting ice sheets of today along with consequences that arise such as the rising sea level.

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1. Introduction

During the Bølling warm period around 14.7 ka BP, the Fennoscandian Ice Sheet (FIS) retreated northwards from southern Sweden. Glacial and glacialfluvial sediment was transported to the huge proglacial lake that had been dammed in the Baltic basin, in front of the retreating ice margin. The ice margin was subaqueous and calved here, but very little knowledge of either the pace or stability of ice retreat in the Baltic Sea and Gulf of Bothnia however exist. Glacial geological records acquired from these areas are furthermore very limited (Greenwood et al. 2017; Avery et al. 2020; Björck 1995; De Geer 1940; Andrén et al. 2011).

De Geer moraines (DGMs) are low-amplitude (m-scale) ridges, closely and semi-regularly spaced, thought to form at retreating ice margins (De Geer 1940; Ojala 2015; Lindén & Möller 2005; Bouvier et al. 2015). These moraines were formed during a few hundred years more recently in the north of Sweden (Norrbotten and Västerbotten) between 10 700 - 9900 cal years BP and earlier to the south central regions (north of the Middle Swedish End Moraine Zone) 11 500 - 11 000 cal years BP. DGMs have been identified even further south in Halland in proximity to coastal moraines in the region (Bouvier et al. 2015).

Formation of DGMs typically develops in areas where the ice retreat rate was high and where local relief and sedimentation rate is low (Bouvier et al. 2015). In the region around the Gulf of Bothnia and parts of southern and western Finland, especially fast ice flow characterised the retreating Fennoscandian ice sheet. Water at the time potentially reached a depth of 300 m (Ojala 2015; Boulton et al. 2001). It was in an environment like this that calving was prone to occur along the ice sheet's margin since the lobes of the ice sheet and their grounding line were exposed to climatic cyclic fluctuations. Based on these circumstances, De Geer moraines were formed (Ojala 2015; De Geer, 1940; Hoppe 1957, 1959; Golledge & Phillips 2008). De Geer moraines can be seen in large numbers around regions below the highest marine limit/shoreline and are assembled approximately transverse to ice flow direction of the former ice sheet (Lindén & Möller 2005). A great number of areas that were below the highest shoreline however are absent of DGMs (Bouvier et al. 2015).

De Geer moraines are landforms usually about 10-20 m in width and 0.5-3 m high although these numbers vary depending on the literature. In Finlayson et al. (2008) for example, measurements of 10-100 m wide ridges were stated. Hoppe (1959) states, for example, that the moraines can be 8 to 40 metres wide with a length of 7 km but this varies with some ridges being 2-3 km and others only 100 m in length. Furthermore, the relief of a DGM can fluctuate between 1-3 and 6-7m (Hoppe 1959). Lindén & Möller (2005) state that the measurement between sequential ridges in the direction of retreat is 50 to 200 m and sometimes up to 500 m with an average of ca. 100-150 m. These small-sized ridges consist of a variety of different sediments such as outwash, till, lacustrine and marine sediments

(Bouvier et al. 2015; Lindén & Möller 2005; De Geer 1940).

These landforms were first reported in 1889 by Gerard De Geer who thought they formed at the grounding line, and that they formed annually, by sediments being pushed and stacked by the largely retreating ice sheet during its winter readvances. Others have suggested alternative mechanisms of formations also connected to subaquatic ice margin processes such as squeezing into subglacial crevasses, annual and sub-annual pushing during winter readvance, deformation from calving events and deposited as subaquatic fans. DGMs are thus considered to be equifinal landforms formed by a number of related mechanisms (Ojala 2015; Lindén & Möller 2005; De Geer 1940; Bouvier et al. 2015).

A better understanding about the formation of DGMs might be valuable for ice sheet reconstruction since it is largely agreed among studies that when it comes to distinguishing an ice margin's curvature and the orientation of deglaciation, De Geer moraines play a significant role. They can also give insight to the transition of the ice-margin going from subaqueous to terrestrial according to their dynamic differences (Avery et al. 2021; Ojala 2015). Characteristics of DGMs demonstrate the behaviour and dynamics of the FIS deglaciation. By acquiring information about DGMs it is possible to better understand not only the dynamics of ice sheets such as the difference between glaciers terminating in water versus on land, DGMs can also help us understand the dynamics of glaciers better in terms of grounding-line processes. The annual formation hypothesis by De Geer for example, would imply that evenly spaced DGMs can provide evidence of the local retreat rate of the ice-margin (Flink et al. 2015; Bouvier et al. 2015).

Apart from any DGMs that formed at the grounding line, other sediments were transported out from the ice margin and formed a large collection of varves composed of clastic, fine-grained sediments. These were formed on the bed of the Baltic Ice Lake, away from the reworking of sediments near shores and below the wave base. Some areas are now visible because of the post-glaciation isostatic land uplift that has raised them up above today's sea level. These laminations were analysed by Gerard De Geer in industrial claypits. The term 'varve' is derived from De Geer (1912), who defined these laminations as cyclical clay (sw. hvarfving). He first proposed the idea that these laminations had been deposited annually in 1878 formed from meltwater sediment influx and settling that varied between seasons, with the consequence that factors such as the climate, ablation and meltwater regimes can also be linked and interpreted from these proglacial varves (Avery et al 2021; De Geer 1912; Wohlfarth et al. 1993, 1998; Andren & Sohlenius 1995; Ridge et al. 2012).

Just as DGMs, varves can also facilitate the mapping of the location of the retreating margin by composing a local chronology of an area of the corresponding group of varves. The varve earliest in order located above the glacial substrate marks a year suggested to reflect when the

ground first lost its ice cover. Fluctuating varve thickness in the sequence above indicates interannual variability of sedimentation, and these up-record varve thickness patterns can be matched with varves from different sites. A collection of varve records retrieved from different locations in an area, each with so-called ‘bottom varves’, would, as a collective, chart the pattern and timing of ice sheet retreat. For instance, in the middle of what is now the island of Öland and Sweden’s mainland, the rate of offshore retreat reached three to five times higher the rate of terrestrial retreat (Avery et al. 2021). By analysing the correlation between the reconstruction of a retreating ice-sheet based on varves and the distribution of DGMs, we can further evaluate hypotheses about the formation of this landform (De Geer 1912; Antevs 1915; Avery et al. 2021; Wohlfarth et al. 1993, 1998; Ridge et al. 2012).

The purpose of this project is to test the hypothesis that De Geer moraines formed at the grounding line of a retreating ice sheet in an annual pattern. The dataset used for this project has been gathered in the Kalmar Strait, (Kalmarsund), offshore southern Sweden. Both multibeam bathymetric data and sub-bottom profiler data image landforms that appear to be potential De Geer moraines. This data was gathered onboard RV Electra in 2019 and 2020. After mapping and characterising landforms in southern Kalmarsund based on their distribution and morphology, i) the landform properties will be compared to other reported De Geer moraines from the literature, to evaluate the interpretation of De Geer moraine landforms in Kalmarsund; and ii) from a locally-established varve chronology, I will compare the landforms’ distribution with the pattern of the independently-derived retreat isochrons (Avery et al. 2021) to evaluate De Geer’s hypothesis of annual formation.

1.1 Study area

Kalmarsund is a narrow and shallow strait about 10-20 km wide with a maximum depth of 40 m between the Swedish mainland and Öland. It is covered with sandstone, between the crystalline mainland and the limestone and shale of Öland. Ice is thought to have retreated across here around 15 ka BP (Fig. 1) (Hughes et al. 2016; Avery et al. 2021), in northward direction – but is not well constrained (Avery et al. 2021; Greenwood et al. 2017). Avery et al. (2021) built a 725 year varve chronology here, based on varved sequences in Kalmarsund as well as on land. This chronology is not tied to an absolute timescale, but gives the local pattern and relative timing of ice margin retreat.

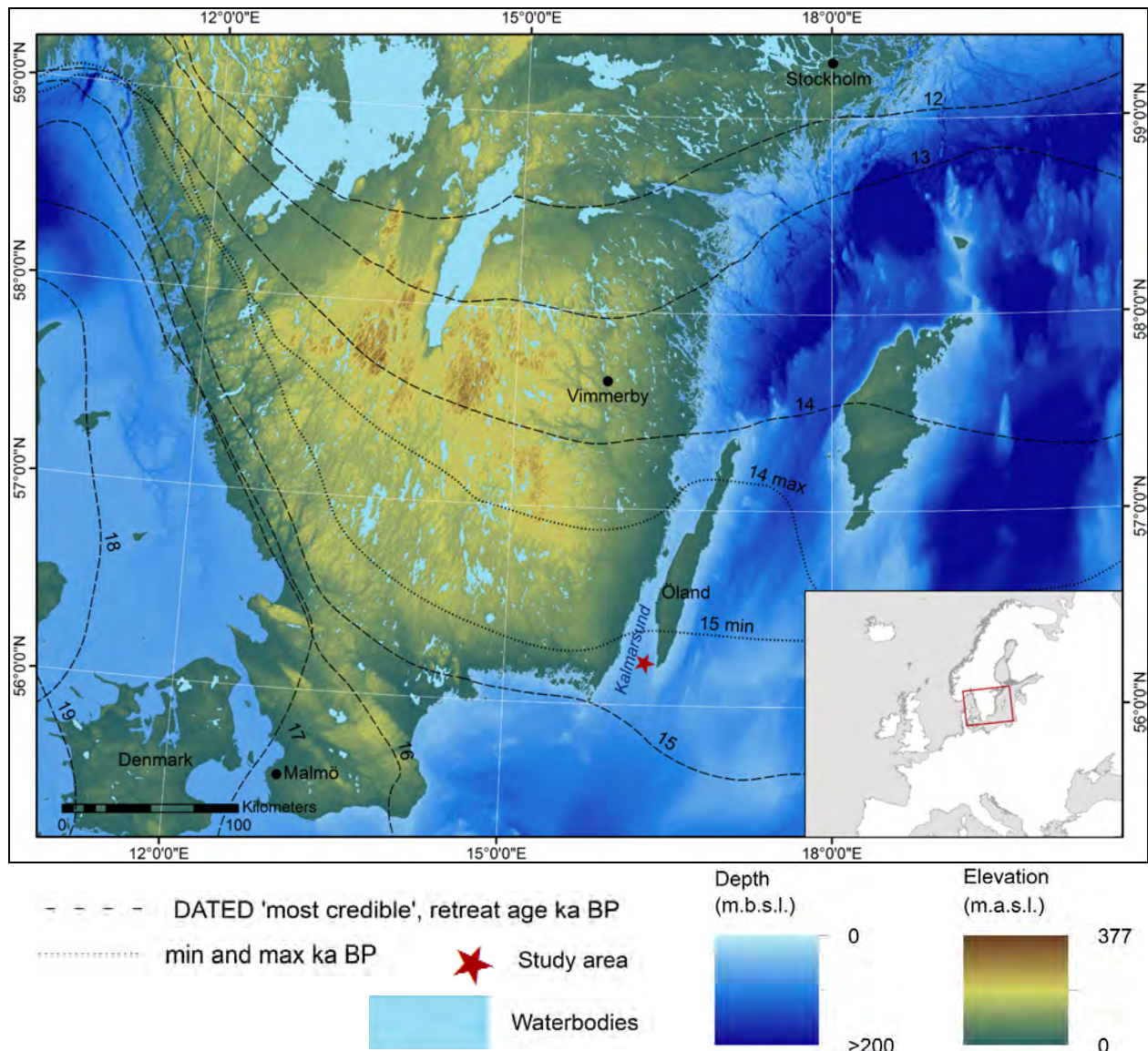


Fig. 1. Study area and geographic setting. Inferred DATED retreat lines from Hughes et al. (2016) have been included as well as minimum and maximum estimations of these in proximity to the study area.

2. Method

2.1 Multibeam landforms

The multibeam data was gathered onboard RV Electra during cruises EL19-IGV02 and EL20-IGV04 and the digital elevation model (DEM) raster has a gridded resolution of 2 m. This DEM raster was imported to ArcGIS with a projected coordinate system: WGS 1984 UTM Zone 34N, and two hillshade rasters were then created using illumination angles of 45° and 315° and a vertical exaggeration of 3. By being able to switch between the 45° and 315° hillshades that covered the same area, better visual interpretation of the form of the landform

ridges was possible. If, for example, no ridge or only parts of a ridge for one specific landform are visible from 45°, switching to the 315° raster could give a better visual representation. Using multiple visualisations for geomorphology mapping has previously been suggested to be beneficial for visual interpretation (Smith & Clark 2005; Chandler et al. 2018).

Using a minimum/maximum colour gradient scheme for the original DEM also aids for visualising topography and thus facilitates mapping the landforms since it would allow me to clearly detect where one landform started and ended (Fig. 3A). Switching between a depth-coloured and grey-scale DEM gave me a more holistic visual understanding of what I was looking at. Each one of these “visual aids” made mapping the area as objective as possible. Furthermore this mapping was guided by literature examples of DGMs.

When it came to actually drawing the polylines for each landform the viewing scale in ArcMap ranged between ca. 1:10.000 and 1:30.000. It was important to not follow the ridge of the landform into too much detail since that would misinterpret the true size of the landform when later measuring it, since the line drawn would in some cases have a serpentine shape and a very winding pattern. Thus the lines were drawn mostly to mark the detected landform and to follow its more general shape rather than following every depression or topographic outline (Fig. 3B). Each detected landform was recorded by drawing a shapefile line on each of the ridges, throughout the whole available dataset. It is important to note that one line represents one ridge fragment and not necessarily an entire landform. The continuity of ridges and ridge fragments was established in a later phase of the study.

2.2 Subbottom data

Once completed mapping what could be found from the entire multibeam bathymetry data, the next step was to investigate if these landforms continued underneath the seabed since earlier ridges, buried by laminated sediments, had been identified in the subbottom data and after comparing shapes from the multibeam and based on earlier figure example shapes for DGMs, I ought to find a connection of ridges here. By adding the collected navigation lines for RV Electra to the ArcGIS project (Fig. 3C), I could identify what subbottom files belonged to what navigation lines (Fig. 3C, D)

There was a great amount of individual subbottom files and given the time that I had for the project, it was not possible to investigate the whole study area the same way I covered the multibeam landforms. Therefore the decision was made to focus on a particular strip of the study area which covered the longest south to north distance available. This was decided since it has been concluded that the retreat direction of the ice margin was from south to north from Avery et al. (2021) and therefore collecting data in this direction was of higher priority compared to for example recording information from east to west. The background for this choice was also a strategic decision to be able to take on the second goal of the study;

evaluating De Geer's hypothesis if the alleged DGMs formed annually (e.g. De Geer 1940).

Every subbottom file within the chosen N-S strip was investigated. In each subbottom profile I marked every ridge detected, which in shape and size appeared similar to the geometry of those landforms mapped from the multibeam data. The aim was to record till ridge crests in the lower unit that had been buried by laminated sediments (Fig. 3D). These ridges ought to show no internal acoustic reflection but consist of a curved or wavy surface. These are the ridges that potentially could be connections to the mapped multibeam landforms earlier identified. Markers were also placed on top of ridges that broke the surface in order to work as shape and size references (Fig. 3D). Extracting markers to ArcGIS as shapefiles with the same coordinate system allowed for the markers to be placed at their accurate locations on the map (Fig. 3E).

2.3 Connecting landform ridges

After recording landforms observed in both multibeam and subbottom data a new investigation began which included identifying any possible connections between the ridges identified in the multibeam bathymetry data and those identified by nearby subbottom markers (Fig. 3F). Connected ridge lines were only drawn if the next in-line navigation line had a visible marker available to draw to. Thus, if no markers were present between adjacent navigation lines that was assumed to mean that the ridge had ended.

Connecting lines were drawn in three zones bounded by retreat isochrons reconstructed by Avery et al. (2021) (Fig. 4). All data lines and markers that I considered appropriate were connected regardless of whether a seabed ridge was exposed or whether all data points were buried. The interpretation of the connected lines was based on earlier identified examples of DGMs from literature and on the previously recorded visible seabed ridges from the multibeam data.

2.4 Morphometric statistics

In order to be able to compare data statistics for DGMs from other literature, I gathered statistics of my own investigated landforms of the same type as of those found in earlier literature. This section describes the quantitative morphometric properties of both the multibeam bathymetric data and the subbottom acoustic data along with additional information derived from after drawing extension lines. Measures of relief of ridges were taken by using an interpolation line through a desired zone (later named Avery Zone 2) (Fig. 2, 4), in ArcGIS, and then extracting this data into a profile graph in Excel. Length, width and spacing of ridges was measured using the Measure tool in ArcGIS.

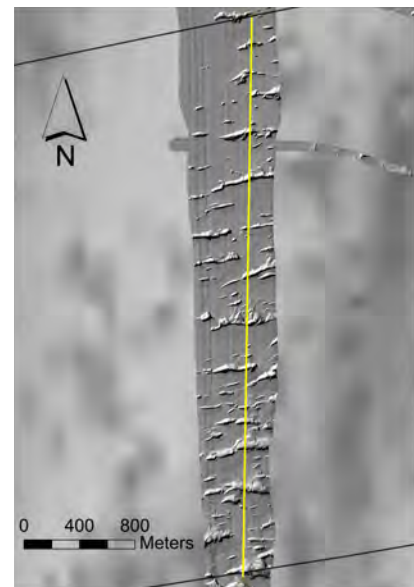


Fig. 2. Yellow line represents the interpolation line in Avery Zone 2. Black lines are 20 yr retreat isochron from Avery et al. (2021).

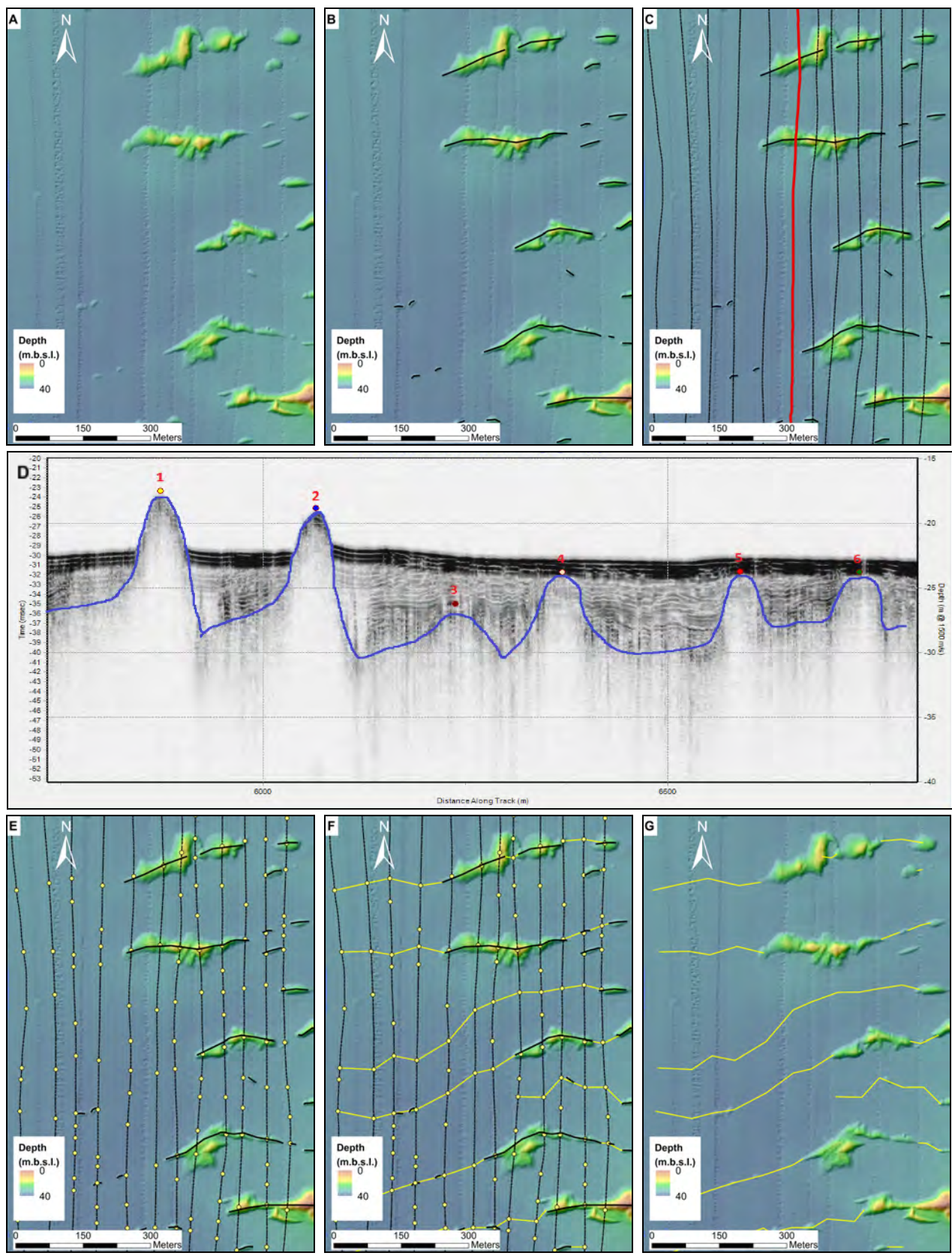


Fig. 3. Step by step method progression from A, B) multibeam mapping, C) navigation lines for RV Electra, D) subbottom profile markers and outlines of buried and visible ridge crests; this profile is marked by the red navigation line in C). Two ridge crests are visible above the seabed and four ridges can be seen buried. E) markers denoting ridge crests visible in subbottom data were plotted spatially F, G) interpreted connecting lines are shown.

Given the time limitation, I decided to focus on taking morphometric measurements from a sub-set of the landform dataset. Dividing the mapped data according to the retreat intervals reconstructed by Avery et al. (2021; Fig. 4). I selected three zones for these analyses, with particular focus on Zone 2, hence the name Avery Zone 2.

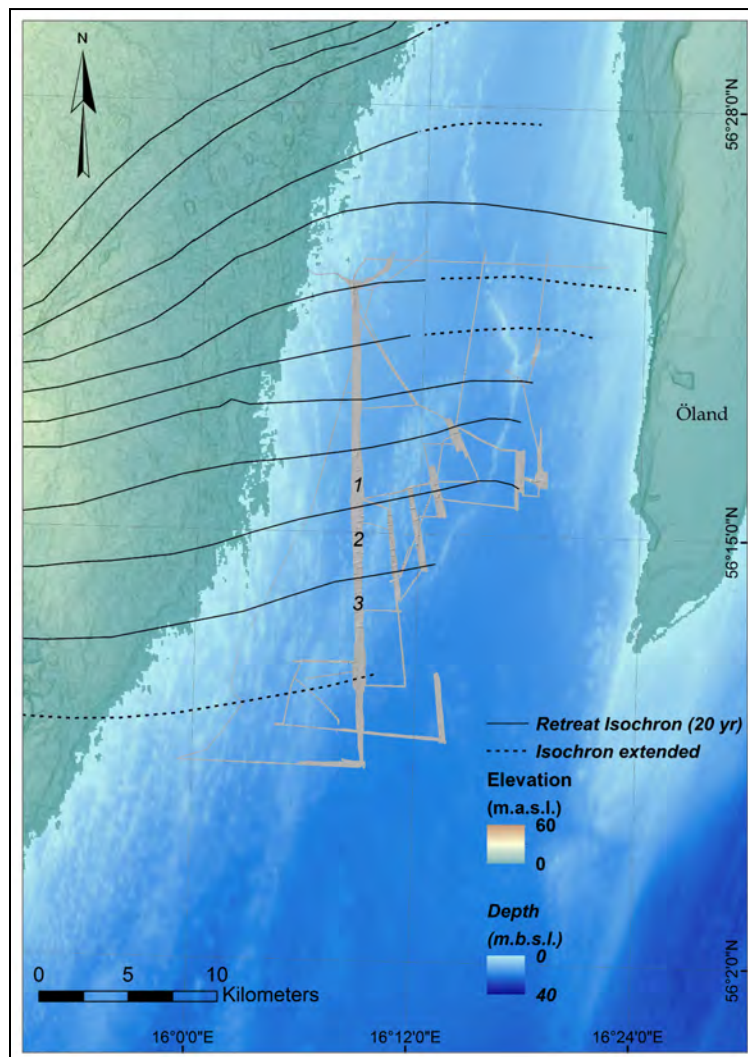


Fig. 4. Numbers indicating each zone where morphometric data has been recorded situated between each retreat ice margin position of the local retreat isochron. The dotted retreat line is an estimated continuation of the land-based retreat isochron (Avery et al. 2021).

3. Results

3.1 Distribution and shape

A total of 599 multibeam landforms and 1738 ridge crests from the subbottom data were identified, and connections interpreted (Fig. 5). The subbottom crests are collected from 100 individual subbottom profile envelopes out of which 23 profile envelopes comprise the 1738 buried ridge crests. A total distance of ca. 120 km of subbottom data was inspected.

The majority of identified landforms in the multibeam dataset have a linear and elongated shape oriented roughly west-east (Fig. 5). However, ridges east of the large N-S strip are oriented with a more northeastern angle compared to the majority of north facing ridges.

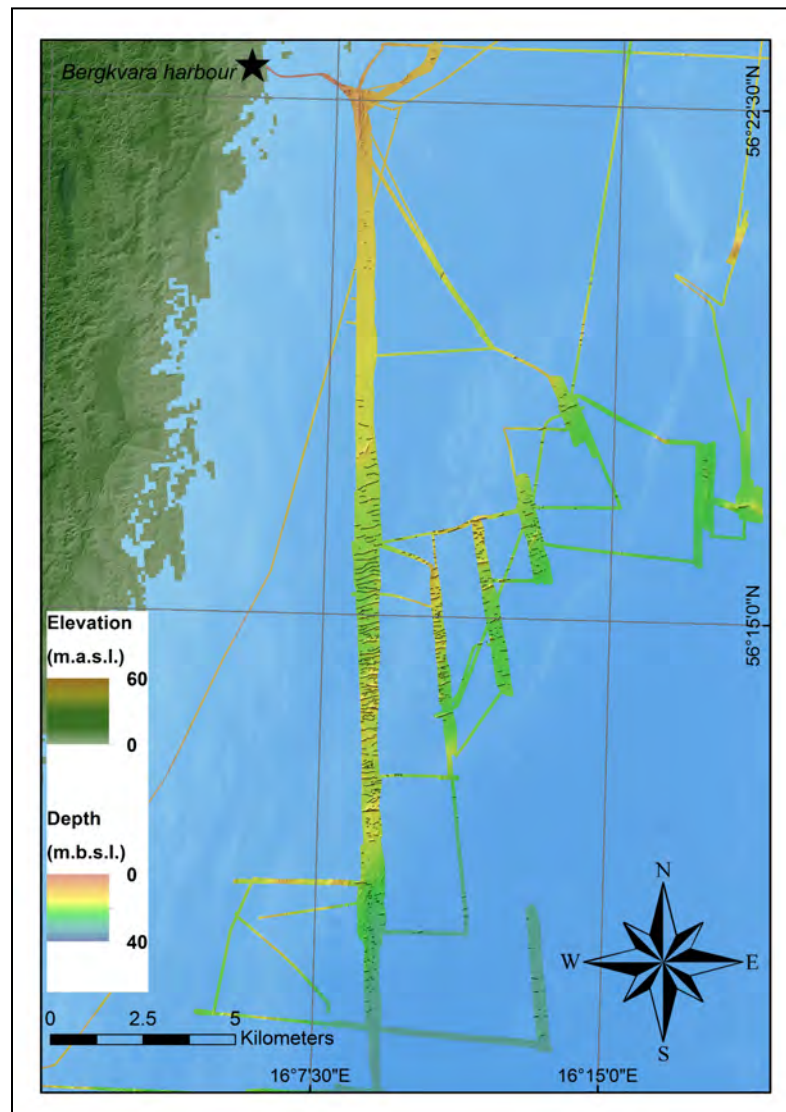


Fig. 5. Showing distribution and the swath of strips making up the study area with drawn lines of every recorded buried and seabed ridge connected to each other.

The landforms have a steeper distal side and a more gentle proximal side, seen mainly on the multibeam data (Fig. 6). There is some irregularity in the laterally linear shape of the ridges with some being more convex and others concave. There are also ridges with cusped shapes pointing either slightly north or south (Fig. 7).

Observations specific to Zone 2 show that landforms are larger further south which infers a higher sediment load (Fig. 6). The southern landforms are also situated in more shallow water compared to the area in the north. The ridges situated in the north consist of a more defined narrow ridge. Where topography increases further south, the ridges are not as narrowly defined and they are also surrounded by more fragments of interpreted connecting ridges. The distinct morphology of DGMs in Zone 2 transitions into a criss-cross pattern of crevasse squeeze ridges in southern zone 3 (Fig. 8).

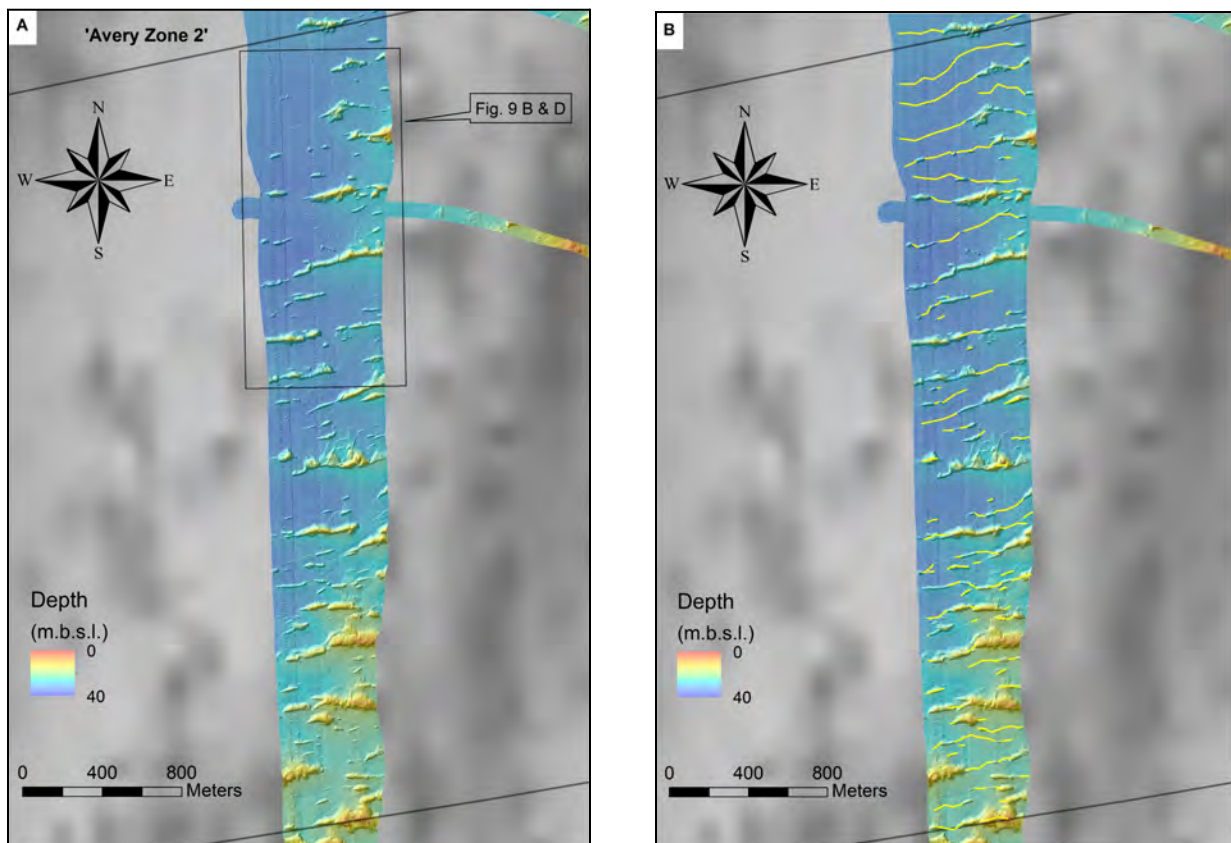


Fig. 6. An increase in the size of seabed ridges is observed further south in Zone 2. Black rectangle depicts the area of fig. 9 B & D. The slightly angled parallel lines in the top and bottom of the picture represent the 20 year Avery et al. (2021) retreat isochron lines. Yellow lines in B) represent connecting lines drawn between buried and visible seabed DGM ridges.

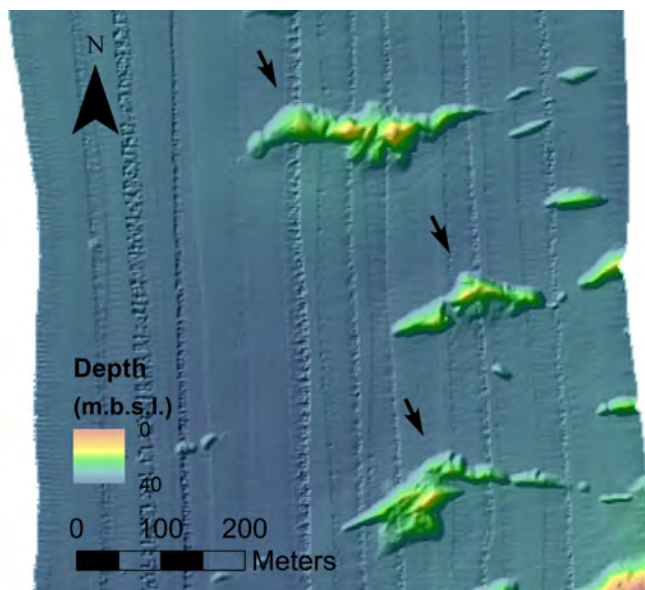


Fig. 7. Arrows pointing at cusped shaped DGMs.

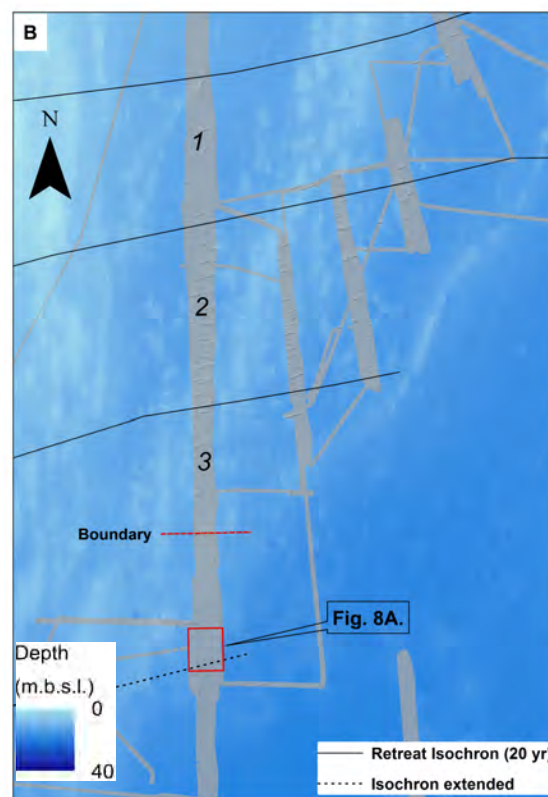
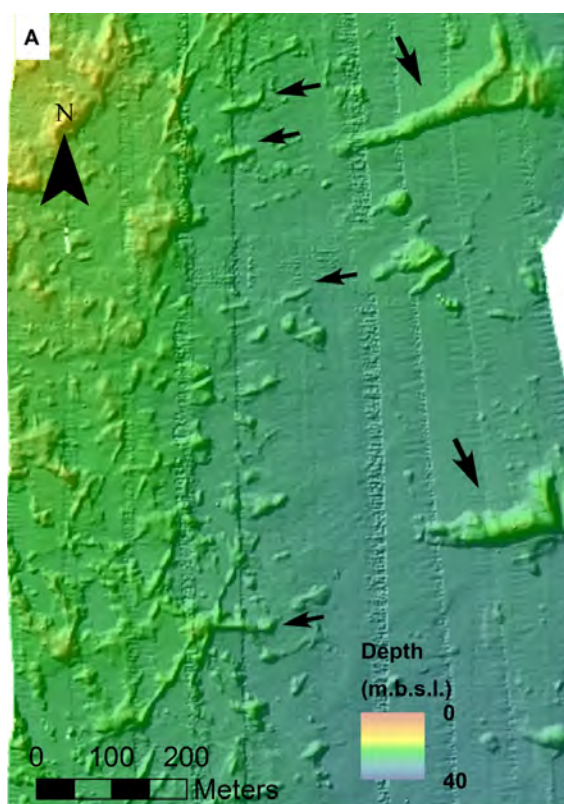


Fig. 8. A) Depict crevasse area south of Zone 3. Arrows are pointing towards DGMs in different sizes. B) Shows area of A) in the red box and a red dashed boundary-line of where measuring and connecting buried and seabed ridges was stopped due to ridges becoming unidentifiable. Retreat isochrons in B) are derived from Avery et al. (2021).

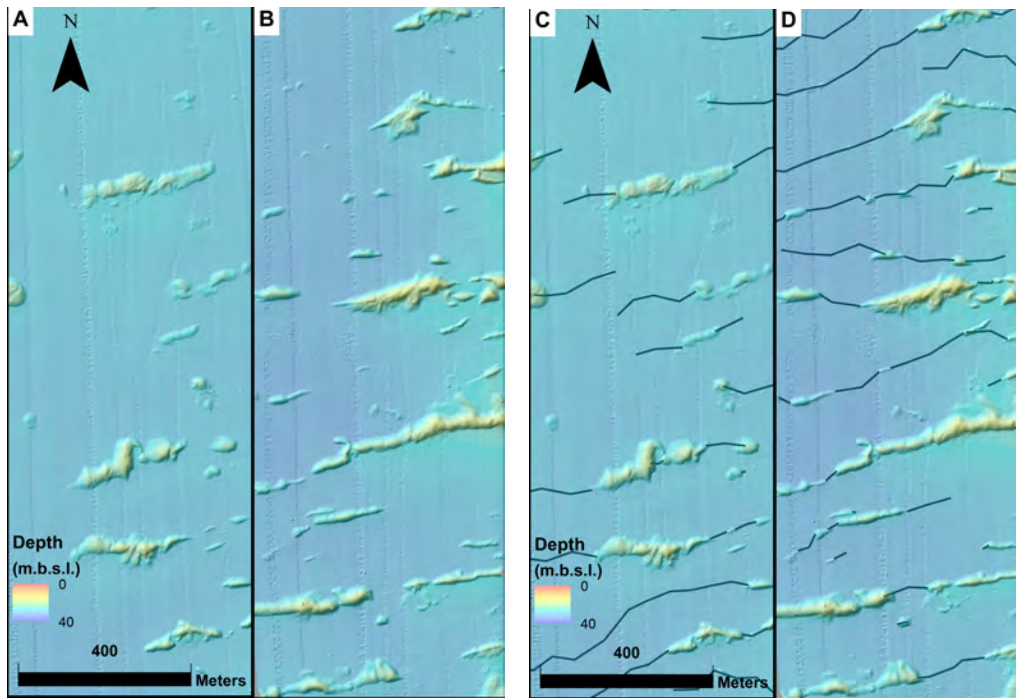


Fig. 9. Depicting distribution and shape of recorded DGMs in and slightly north of Zone 2. Area A), is situated just north of area B) which can be seen with the most southern DGM in A) seen at the most northern tip of (B). C & D) the same areas are shown with added connecting lines for buried ridges. The characteristics of the DGMs in the lower regions of B & D, displays more elongated and preserved ridges as well as a higher number of sequential ridges compared to A & C.

3.2 Morphometry of landforms

3.2.1 Length & width

I considered two data subsets for analysis of ridge length and width.

The First dataset comprises statistical analysis of length and width of 32 well-defined sequential seabed ridges selected in Avery Zone 2 (Fig. 6B). The mean length value for these ridges measures to 442 m with a standard deviation of 198 (Fig. 10A, Table 1). The shortest ridge identified among these ridges is 97 m and the longest 717 m. The median length of this dataset is 477 m, and the mode (rounding all values to the nearest 10) ca. 590. Thus, the mean, median and mode value for this dataset correlate quite well and indicate a rather symmetrical distribution of measurements.

The mean width is 56 m with a standard deviation of 28 (Fig. 10B). The median value of 53 sits close to the average. The maximum width here is 121 m and the minimum is 21 m, with a mode of 29 m.

The Second dataset consists of well-defined ridges as well as fragments of ridges that are interpreted to connect to them (Fig. 6B). This dataset covers the same area of Avery Zone 2 as for the first dataset. The number of measurements here is much greater compared to the previous, with 61 identified ridges (Fig. 10).

The mean length for the ridges and fragments measures 280 m with a standard deviation of 234 (Fig. 10C). The median length is 181 m which is almost 100 m shorter than the mean value. The shortest ridge identified in this dataset is 30 m along with the longest being 717 m and the mode at 53 metres.

The mean width is 40 m (Fig 10D) but the widest ridge was found to be 121 m and the most narrow 8 m with the latter most likely representing one of the smaller fragments identified in this map zone. The standard deviation for the width is 28 which indicates that the mean is not very accurate indicating that a lot of measurements are situated outside this value. The median value is 29 m and the mode is 16 m.

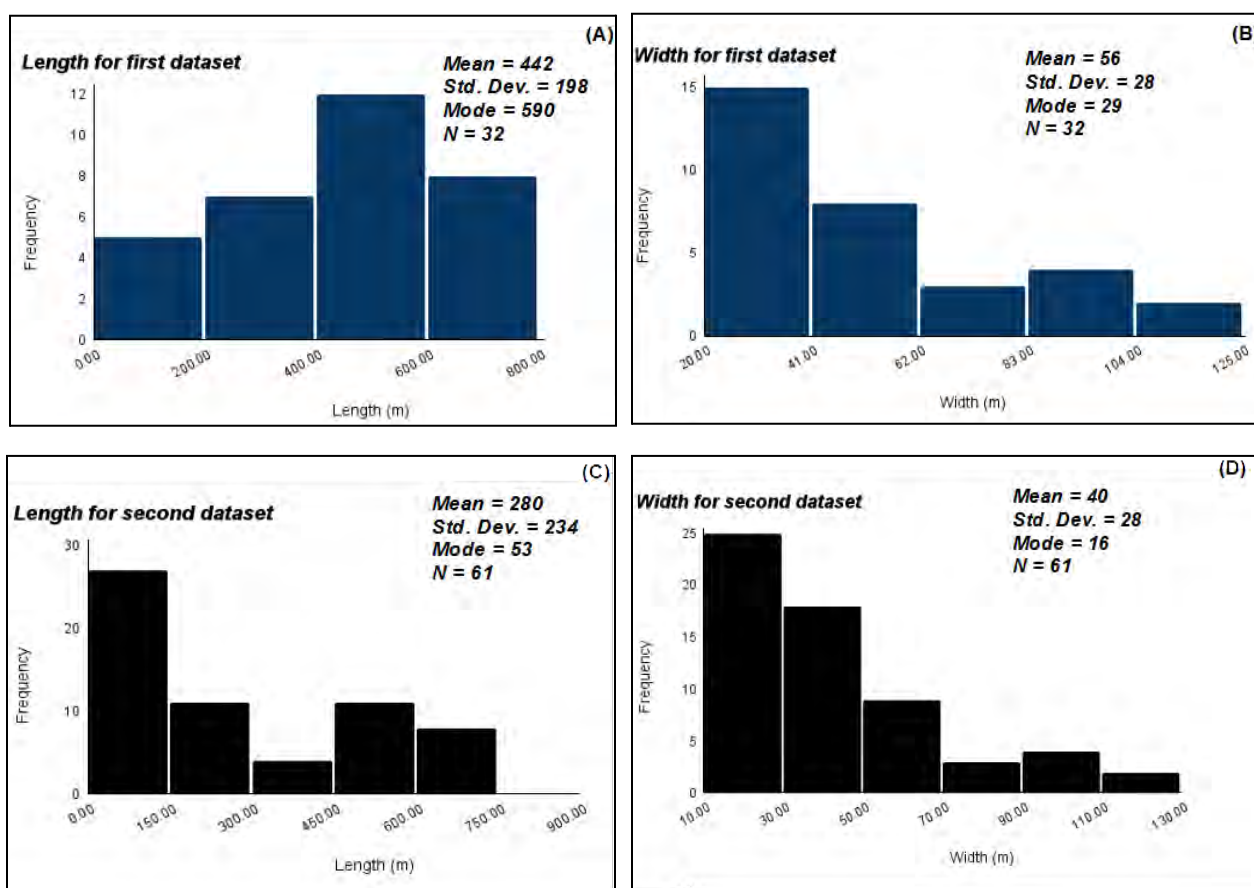


Fig. 10. Morphometric statistics of recorded length and width for the first dataset (A & B) and second dataset (C & D).

The full dataset of seabed landforms mapped from the multibeam bathymetry (Fig. 5), have a total count of 599 of which the smallest line measures to 2 m and the longest to 471 m. The mean value is 72 m with a standard deviation at 69. Since this dataset does not only represent a whole continuous ridge but also fragments of landforms, the much shorter mean length can be interpreted as representing an abundance of ridge fragments, which possibly could suggest a great number of buried ridges.

The lines for connecting landform ridges drawn in Zones 1-3 added up to a total of 188 polylines. These represent buried ridge landforms that either connect ridges with seabed expression or are fully sub-surface (buried) features, and have a minimum and maximum length of 6 and 516 m respectively. The mean length for this dataset is 90 m with a standard deviation of 80.

	Length (m)		Width (m)		Relief (m)		Spacing (m)	
	min-max	average	min-max	average	min-max	average	min-max	average
My data								
Zone 2, well-defined ridges	97-717	442	21-121	56				
Zone 2, all ridges + fragments	30-717	280	8-121	40				
Whole dataset					1-7.2	3.6	26-255	101
Only visible seabed ridges	2-471	72						
Bouvier et al. 2015			10-20		0.5-3			
Lindén & Möller 2005	100-3000			ca. 30	1-7		50 -200 or 500	ca. 100-150
Finlayson et al. 2008			10-100					
Hoppe 1959	100-7000		8-40		1-7			

Table 1: Recorded data results put into comparison with some morphometric values from earlier published literature.

3.2.2 Relief

The measured average relief is 3.6 m out of the 21 distinct ridges of the seabed ridges measured from the interpolate line drawn through Zone 2 (Fig. 2). The standard deviation was calculated to 1.5 (Table 1). The highest and lowest ridge identified was measured to 7.3 and 1 m respectively with a mode of 2 m and a median of 3.5 m. Seabed ridges and buried ridges furthermore display similar characteristics in relief but also in width (Fig. 11A & B).

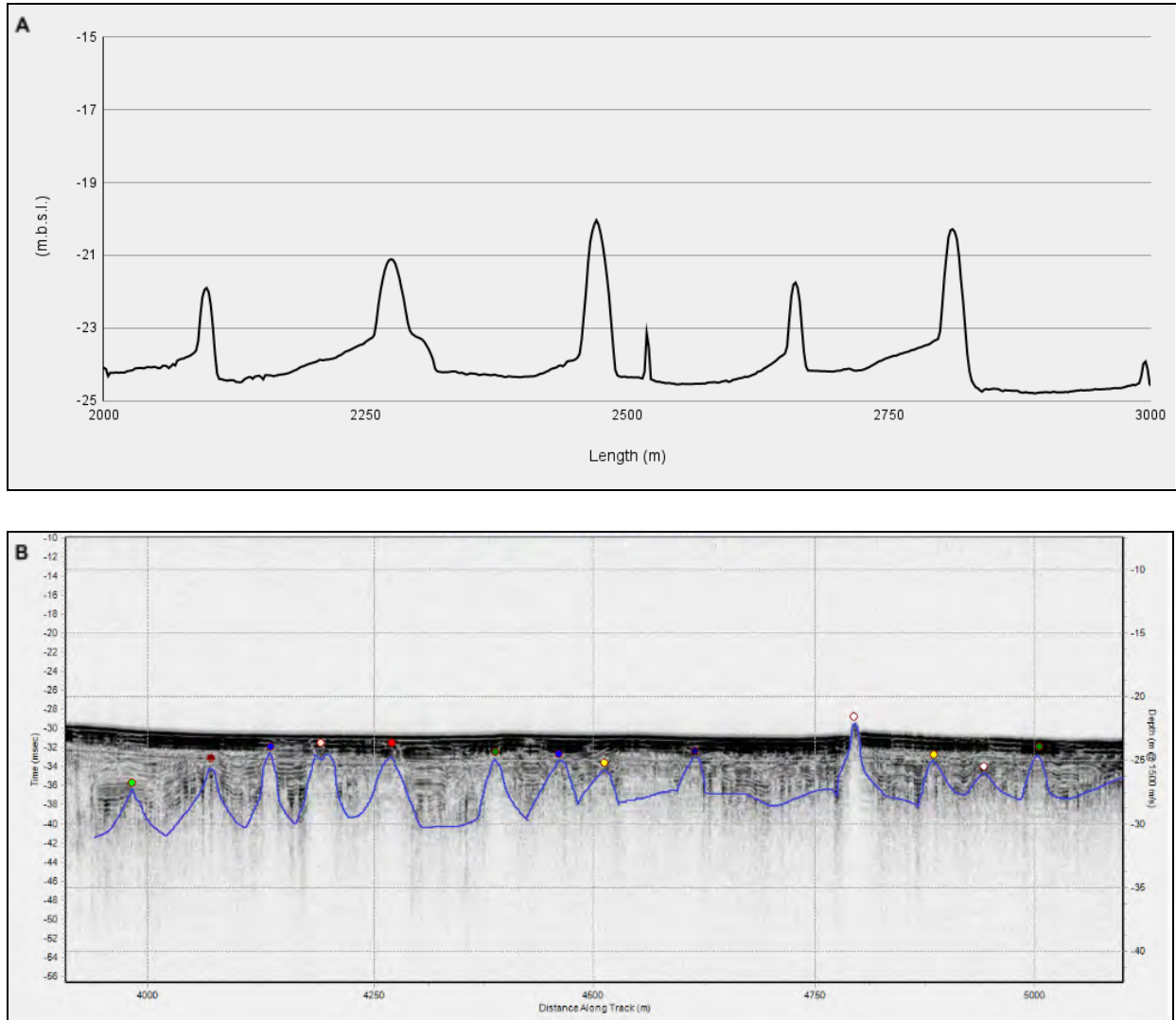


Fig. 11. A cross section of seabed ridges derived from the southern part of Zone 2 compared with a subbottom profile taken from an area west of the profile line. Thus, the two figures A & B depict two different areas of A) seabed ridges and B) buried ridges. A) is a zoomed-in figure of the profile graph derived from the red interpolation line in fig. 2. A) displays 7 out of the total 21 ridges for the whole profile graph that the interpolation line represents. The ridges in the subbottom data depicts wider ridges filled with more non-acoustic reflecting sediment (e.g. till). The seabed ridges in A) displays more narrow crests which could potentially be due to wave erosion and turbulent waters. Subbottom ridges and seabed ridges however generally display the same shape and size such as the relief in these two examples ranging around 5 m.

3.3 Spacing of ridges

These measurements are taken from Zones 1-3 (Fig. 4, Table 1), based on the distribution of ridges inferred from the combined seabed and buried data, as far south as seabed ridges were matching shapes with other mapped ridges and where they were clearly noticeable.

In Zone 1, 20 ridges occur sequentially south-to-north and therefore 19 measurements were

made of their ridge-to-ridge spacing resulting in an average value of 159 m and a standard deviation of 46. The median is 159 m with a maximum gap of 255 m and minimum 78 m.

In Zone 2, there are 48 identified sequential gaps in between inferred ridge positions. The average distance of the space between sequential ridges from north to south in this zone was calculated to 87 m with a standard deviation of 32. The median value here is 85 m with a maximum and minimum value of 159 and 30 m respectively.

In Zone 3, the average spacing is 89 m based on a number of 32 identified gaps making it the second largest number of sequential gaps even though ridges are only well-defined through about half the length of the zone. Here the average was calculated to 89 m and the standard deviation 45. The median value for the zone is 77 m and the maximum and minimum value of 178 and 26 m respectively.

The average distance of the space between all 99 sequential ridges from the whole north to south strip (Zones 1-3) was calculated to 101 m and a standard deviation of 48. The maximum and minimum ridge are 255 and 26 m respectively. The median for the whole strip was determined to be 95 m.

4. Discussion

4.1 Interpretation of ridges as De Geer moraines

Based on comparison with landforms previously identified as DGMs (e.g. Bouvier et al. 2015; Ojala 2015), the landforms mapped in Kalmarsund can accurately be identified as DGMs. An esker has also been identified in the studied area.

DGMs are described as having a steeper distal side and a proximal side which is more gently sloping (Lindén & Möller 2005; Hoppe 1959). After recording and inspecting ridges from the multibeam data using the different illumination angles, this strongly correlated to my studied area (Fig. 6A & 9A,B). Lindén & Möller (2005) also state that the cross-sectional shape varies and Hoppe (1959) furthermore mentioned that the majority of DGMs are oblique in shape seen from a cross-profile along with either symmetrical or asymmetrical ridges, which clearly can be seen in subbottom data profiles from Kalmarsund (Fig. 3D).

Different measurements of DGMs have been expressed by numerous studies (Table 1). The length can be 7 km although this number varies a lot with some ridges being 2-3 km and others only 100 m (Lindén & Möller 2005; Bouvier et al. 2015). The length measurements in this study are quite short compared to these length descriptions which could be explained by many ridges being partially and in some cases, even fully buried. Therefore the recorded DGMs in this study are still consistent with former reported descriptions of DGMs. Furthermore, the relief of a DGM can vary between 1-3 and 6-7 m (Hoppe 1959). Lindén & Möller (2005) state that the spacing between sequential ridges most commonly is 50 to 200 m and sometimes up to

500 m and has an average of ca. 100-150 m. All my recorded landforms consist of similar measurements and fit into these ranges (Table 1).

The most contradicting descriptions from earlier literature relate to the width measurements. Finlayson et al. (2008) describe some DGM ridges as wide as 10-100 m while Hoppe (1959) states that the moraines can be 8 to 40 metres wide and Lindén & Möller (2005) report an average width of only ca. 30 m. Lundqvist (2000) describes De Geer moraines as small ridges not more than 10-20 m wide. My width data range from 8 - >120 m, averaging 40-50 m, which is slightly larger than these previously mentioned width descriptions. However, the order of magnitude is comparable, the majority are 20-60 m (Fig. 10B), and the landforms are otherwise consistent in size, distribution and shape. Therefore they are still considered to be DGMs. A greater width could be accounted for with a higher sediment load and transport for these specific areas.

4.2 De Geer's hypothesis of annual formation

De Geer (1940) himself described these types of moraine as an "annual moraine" and it was not until later that Hoppe (1959) named this type of moraine after De Geer (Finlayson et al. 2008). De Geer described DGMs as a push moraine that each winter was formed by ice-front readvances at the ice sheet's grounding line. As a result, the ice-front recession during one summer equalled the distance between two subsequent ridges (Avery et al. 2021; Hoppe 1959; De Geer 1940; Ojala 2015; Lindén & Möller 2005). Evaluation of De Geer's hypothesis of annual formation was done by comparing results of the total count of identified DGMs with an independent published varve chronology from Avery et al. (2021).

Avery et al. (2021) reconstructed 20-year retreating ice margin positions based on their varve chronology. Thus, within each 20-year zone, 20 identified DGMs would be what to expect if De Geer's hypothesis of annual formation would be true, with one DGM representing each year. In Zone 1, there are 20 identified ridges. In Zone 2, the number depends on how one defines a ridge: there are 48 sequential gaps between inferred ridge positions (with 61 ridges and fragments), but there are 32 well-defined seabed ridges. In Zone 3, there are 32 sequential gaps between inferred ridges, over only ca. half the zone distance. However I define sequential ridges in Zones 2 and 3, to exceed the expected 20 and based on this, it is not plausible that De Geer's hypothesis of annual formation is true.

The hypotheses of equifinal landforms that have been formed by a number of different subaquatic ice margins have been described in earlier published literature. These landforms can potentially have been formed by a variety of different related mechanisms. These include hypotheses of for example sediment squeezing into subglacial crevasses and deformation from calving events (Bouvier et al. 2015; Lindén & Möller 2005; De Geer 1940). There might not be only one true answer to how the identified DGMs have been formed. Areas with regular

distributed spacing of ridges could independently match with De Geer's annual hypothesis but also a diversity of formation processes may be relevant for DGMs in areas with more irregular distribution. Connections could be drawn to Hoppe (1959) who acknowledged the alternative mechanisms for DGM genesis and suggested that more than one ridge had formed during ice retreat each year. Sedimentological studies distinctly appear to display sub-annual and multiple-year ridges (Bouvier et al. 2015; Lindén & Möller 2005; Hunter et al. 1996; Blake 2000)

The fact that fewer ridges are found north of Avery Zone 1 could be explained by the slowed rate of retreat towards the shore due to the rising bed concluded in Avery et al. (2021) and since formation of DGMs typically happens in areas where the ice retreat is high and where local relief and sedimentation rate is low. The moraines are furthermore thought to be preserved and developed better in areas with low sediment thickness (Bouvier et al. 2015). The DGMs in Zone 2 display better defined ridges in the northern part compared to the southern end of the zone (Fig. 6). The northern part might therefore have been governed by a lower sedimentation rate than the ridges with wider, less preserved ridges and a heavier sedimentation load further south. If that was to be true, it might be plausible that the sedimentation thickness would be lower in the northern part of the zone compared to the southern due to the sedimentation rate. This would therefore favour the development and preservation of DGMs in the northern part.

The DGMs in the southern end are also situated at a higher topography than those of the northern part (Fig.6). I present the hypothesis that the ice retreat was therefore lower here and thus not favouring the preservation of the DGMs, while the retreat was higher further north, favouring better defined DGM ridges that are present here at the lower topography. An increase of seabed topography can be observed to vary throughout the study area (Fig. 4 & 8B). Local topography has before been presented in Bouvier et al. (2015) as being a causing factor for different shapes of DGMs which might be why the shape of ridges are different in some areas of Kalmarsund by both linear, concave, cusped and convex ridges (Fig. 3, 5, 6, 7, 8).

The DGMs that have cusped forms have earlier been suggested to be produced by longitudinal crevasses in the glacier. A former crevasse is suggested to be indicated by every up-ice oriented apex (Bouvier et al. 2015). This can be linked to observations in this study by cusped shaped DGMs pointing in a slightly northern direction (Fig. 7). Other cusped or otherwise deformed formations have been observed throughout the study area which likely could correlate to the hypothesis of crevasse areas. The fact that the Avery Zone 3 consisted of more ridges and gaps even though counting here was stopped about halfway compared to the whole of Avery Zone 1 with included number of gaps and ridges (Fig. 4), furthermore suggests an increase of moraine ridges further south.

4.3 Wider significance

The risk of increased melting due to climate warming of the Greenland and Antarctic ice sheets has been acknowledged by the global research agenda and there is much focus on ice sheet deglaciation rates and processes. The reason is because an acceleration in ice sheet melt along with ice sheet mass loss through calving is expected to result in an increase of the global mean sea level. As a result this contributes to complications for coastal land use based around the spatial variations of the future mean sea level. It is therefore of uttermost importance to understand the processes and rates of today's ice sheets (Stroeve et al. 2016).

Water terminating glaciers plays a crucial role in the mass balance of an ice sheet. These glaciers are either situated in a marine environment or in an ice-marginal lake with ice margins that are somewhat floating. The reason as to why they play such an important role is because they promote episodic calving and these events have the potential to discharge large volumes of ice. It is even possible that these margins account for a greater mass loss compared to those of terrestrial margins (e.g. Gollledge & Phillips 2008; Rignot & Kanagaratnam 2006). This is supported by Avery et al. (2021) who found from their Skåne-Småland varve chronology that the retreat rate in the palaeo-offshore sector was 3-5 times faster than the margin above or in proximity to the palaeo-shoreline. Hoppe (1959) stated that regions with a greater water depth were home to a faster receding ice sheet in areas with a broken topography and that this dynamic of the former ice sheet can be observed even today in glaciated regions. It is therefore essential for us to understand the dynamics of these ice masses along with the climatic or internal forces that were behind them (e.g. Gollledge & Phillips 2008; Rignot & Kanagaratnam 2006; Reeh 1968; Paterson 1994; Peck et al. 2007).

Since De Geer moraines are features of the former ice front they therefore resemble the dynamics of ice retreat. Apart from comparing the glaciers' dynamics of terminating in different environments by studying characteristics of DGMs, they can also give us insight into grounding-line processes (Hoppe 1959; Flink et al. 2015; Bouvier et al. 2015).

There is a lack of evidence concerning the ice-margin positions in southern Sweden south of the Vimmerby Moraine (Fig. 1). This makes the retreat pattern for this southeastern part of Sweden unclear, most notably the margin retreat in the coastal areas. Regarding the offshore areas of this region there is essentially no existing evidence on the local glacial geomorphology and as a result, behaviour of margin retreat is unknown (Avery et al. 2021).

This study has contributed to recording the pattern of ice margin retreat in a before uncharted area, lacking in such data. DGMs identified in Kalmarsund indicate a general northward ice sheet retreat with some local variation of northeast angled ridges which might indicate variation in the FIS retreat direction in the area. This is especially prominent in the eastern sections of the visible seabed ridges and connections could be drawn to the local seabed

topography as the ice sheet seems to have wrapped and been governed by a new angle of ice retreat direction in proximity to the raised topography, perhaps due to the former paleoshoreline. Results indicate an excess of DGMs in relation to the expected distribution of an annual chronology, which might be suggested to be formed in basal crevasses as well as at the grounding line. I therefore propose the idea that the ice retreat in this area has been governed by a crevassed, broken up ice marginal zone that both display an annual and subannual formation process.

5. Conclusions

Multibeam and subbottom acoustic data has been analysed in an area that before was absent from glacial geomorphology studies and De Geer moraines were found. Connections from buried and visible DGM ridges have produced a new dataset that gives further insight about the dynamics and mechanisms of the former ice sheet.

The investigation of DGMs in Kalmarsund and their description is consistent with other information of DGMs from literature but largely consists of a higher sediment load than usual which is believed to be linked to a broken up marginal zone of the Fennoscandian ice sheet. Crevasses and cracks were likely prone to being filled by a high influx of squeezed sediments in some local areas resulting in a wider ridge. Apart from these wider DGMs, more elongated narrow present DGMs are believed to have formed annually by being pushed by the readvancing ice sheet during the winters but results also indicate sub-annual formation of DGMs interpreted as being formed due to summer calving events since a higher number of DGMs have been identified compared to the anticipated number corresponding to that of annual formation in the area.

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