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Rapid subglacial streamlined bedform formation at a calving bay margin

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ABSTRACT: Using the LiDAR derived Swedish national height model we have identified previously undescribed shallow streamlined glacial bedforms, small-scale drumlins, on the Närke plain in south-central Sweden. These drumlins could only be detected with high resolution LiDAR, due to both their subtle size and forest cover. In this area the ice margin receded in a subaqueous environment with a proglacial water depth in the order of 100 m during the last deglaciation. As indicated by the configuration of marginally formed De Geer moraine ridges draping the drumlinoids, the receding ice margin formed deeply indented calving bays. These were located around subaqueous outlets of the subglacial melt-water drainage, with their apex position marked geomorphologically by beaded esker ridges. The mapped small-scale drumlins are aligned perpendicular to the reconstructed ice sheet margin and suggest formation along flow lines adjusted to the configuration of these calving embayments as they propagated up-flow with ice margin retreat. Based on these geometric relationships we argue that the emplacement of the drumlins was near-marginal, ~7.7-1 km from the margin, on a short timescale (~5-35 years).

Running title: Flow reorganisation at calving bay margin quickly constructs drumlins.

KEYWORDS: streamlined terrain, drumlin, calving bay, De Geer moraine, ice recessional history

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Introduction

Streamlined subglacial bedforms, such as drumlins, are common geomorphic features on the relict ice beds of formerly glaciated regions. As such, they have drawn intense research attention as their formation is considered key for understanding ice sheet dynamics. Many theories, widely inspired by various morphometric and sedimentological observations, have been put forward regarding the formation of drumlins, but the debate is far from closed (see discussions in, e.g., Clark, 2010; Stokes et al., 2011; Eyles et al., 2016; Möller and Dowling, 2016). Two aspects of key relevance that have perhaps seen relatively less attention, especially in recent years, are *where* drumlins form with respect to the ice margin and the *time frame* in which they form.

From a process point of view the location of formation for a drumlin must meet some combination of sediment erosion, transport and/or deposition. These three elements are in turn dependent on a number of things, including basal ice flow velocity and the induced basal shear stress on the subglacial sediment. The latter is highly dependent on the effective stress (normal stress reduced by pore water pressure) induced by the glacier at its bed. All of these parameters will vary along any given flow line and the resulting criteria for drumlin formation may be met sporadically or continuously throughout time. There are thus likely to be zones where basic conditions for bedform formation are met better than in other places due to presence of obstacles and/or a significant sediment supply (Stokes et al., 2013).

Drumlins are often described as forming within the main body of ice sheets (Raukas and Tavast, 1994), generally in areas of fast flow (ice streams) and at significant distances from the margin (Wellner et al., 2001). However, other studies suggest that they may also form relatively close to ice margins (Menzies, 1979). For example, Glückert (1973, 1987) describes drumlin fields in the central lake district of Finland that form outwards diverging flowsets along flow lines adjusted to the lobate configuration of the Younger Dryas ice-marginal zone, less than 100 km from that ice margin and over a single short ice streaming event. Other examples of near-marginal streamlining include the SE Baltic where Lamsters and Zelčs (2014) show that drumlins form flow sets that diverge towards strongly lobate ice-marginal positions, as marked by end moraine zones. More recently at Múlajökull, Iceland, Johnson et al. (2010) have suggested that drumlins might form at the very margin of a surging glacier.

There is relatively little in the literature that considers the chronological aspect of drumlin formation as there is both a dearth of syn-formational observations and a lack of dateable material within the features themselves. However, the time period in which a feature forms is a critical component in efforts to reconstruct past ice sheets from the relict landscape. Of the evidence thus far gathered there is a wide disparity in suggestions of how fast or over which time frames subglacial bedforms are formed; Hättestrand et al. (2004) have suggested that large drumlins in northern and central Sweden are the result of sediment accretion from multiple glaciations and therefore have a very long formation time. In contrast to this, Smith et al. (2007) and King et al. (2009) found that the formation of contemporary subglacial features under an Antarctic ice stream are formed and evolve on the time scale of a few years. Rapid formation times are also suggested from the work of Johnson et al. (2010).

In this paper we investigate the time of formation of a number of small drumlins mapped within the streamlined terrain on the Närke plain, an area situated in south-central Sweden (Fig. 1), using high-resolution LiDAR-derived topographic data. The spatial association of these smaller features with nearby esker and De Geer moraine complexes is here investigated. In particular, the geometry of these landforms, their relationships with both one another and to the Swedish varve chronology, all provide an indication of where the small-scale drumlins formed in relations to the retreating margin of the Fennoscandian Ice Sheet and the amount of time it took them to form.

Regional and local geologic setting of the study area

The Närke plain in the Kumla–Örebro area, south-central Sweden (Fig. 1), on which the drumlins investigated here are located, is a low-elevation area at ~30-80 m above present-day sea level (m a.s.l.). Below the covering Quaternary deposits are down-faulted and tilted blocks of crystalline basement, overlain in varying occurrence by Palaeozoic sandstone, clay slate, alum shale and limestone, in that stratigraphic order (Ericsson, 1979).

During the deglaciation of the Kumla–Örebro area (Fig. 1), the subsequent northwards ice recession was primarily subaqueous with the retreating ice margin standing in water depths often in excess of 100 m (sea level at deglaciation, c. 150-160 m a.s.l. (Fig. 1), minus present-day elevation). The area was deglaciated in conjunction with a marine ingression from the west into the Baltic Basin (Brunnberg, 1995) a few hundred years after the final drainage of the Baltic Ice Lake at Mount Billingen (11.62 cal ka BP according to Stroeven et al. (2015). Thus, at deglaciation the water basin in front of the receding ice margin changed from freshwater conditions to marine with the onset of the Yoldia Sea (Brunnberg, 1995; J. Björck et al., 2001). This saline environment is indicated by the occurrence of the marine mollusc *Portlandia (Yoldia) arctica* in the lowermost clay of the area (Bergdahl, 1961). Also due to the marine environment at deglaciation, suspended clay was prone to flocculation (Krank, 1973; Skei and Syvitski, 2013) resulting in poorly developed (symmict) varves or close to massive clay, thus making a complete annual varve reconstruction, based on clastic rather than symmict varves, not possible for this area. Indeed, Nilsson (1968) reports a maximum of only 48 annual varves from the area within the basal section of the up to 5-10 m thick fine-grained subaqueous deposits, which was not enough to construct a detailed varve chronology.

Varved clay chronology is based on the between-site lateral correlation of peaks in vertically measured and graphically plotted summer/winter bed thicknesses for specific sites; the 'classical' method as described in De Geer (1940) is to count the difference in basal 'missing' varves between two sites which then is a measure of difference in deglaciation age in years between the two sites. From these differences in deglacial age, varve isochrones are interpolated; in the case of the varve chronology from the Stockholm-Uppsala area (Fig. 2) this was done in 20 year steps. The basal varves formed close to the receding ice margin and the constructed varve isochrones thus mirror not only deglaciation time but also the configuration of the ice margin in temporal steps during continuous ice margin recession.

In addition to the Stockholm-Uppsala chronology northeast of our study site a detailed and precise varved clay chronology has been reconstructed just south of our investigated area, between Västergötland (Strömberg, 1994) and Närke/Östergötland (Brunnberg, 1995; J. Björck et al., 2001). This chronology can be extended to provide an overall indication of the deglaciation time just south of the Kumla–Örebro region. The -1200 varve isochrone of Brunnberg (1995) trends directly south of Kumla (Fig. 1) and the deglaciation of the Kumla–Örebro area should thus have occurred between the -1200 and -1100 isochrones. As the 'zero year' (±0) in the Swedish time scale is set to 10 090 cal yr BP (Stroeven et al., 2015), this is equivalent to c. 11.3 – 11.2 cal ka BP (Stroeven et al., 2015) as an approximate deglaciation age for the Kumla–Örebro area.

Eskers in the area have a general S-N trend on the Närke plain (Fromm, 1972; Ericsson, 1979). This concurs with the general glacial striae pattern, varying between N10˚W and N10 ˚E, and the primary drumlin flow sets, indicating the regional ice flow direction (Möller and Dowling, 2016). The eskers occur with 4 to 9 km wide gaps between them, as calculated from

7 eskers identified from the Quaternary deposits maps of the area (Fromm, 1972; Ericsson, 1979) over a 40 km long profile from west to east. Central through the Kumla–Örebro area runs the Hallsberg–Kumla esker; although this is the 'official' name (Bergdahl, 1961), it will in the following be called the 'Kumla esker' for short. Parts of these eskers formed infra-marginally as subglacial tunnel fillings, but most of the glaciofluvial sediment was deposited as tunnel mouth subaqueous fans of varying widths lined up after each other as the ice margin retreated (De Geer, 1897). Such types of eskers, along with more modern facies models for their formation, have been described as beaded eskers by Bannerjee and McDonald (1975) or as subaqueous short bead fan eskers by Warren and Ashley (1994).

A frequently occurring feature at deglaciation in this part of Sweden was the formation of large, often highly indented calving bays that during their existence were closely associated with the larger eskers of south-central Sweden. The first description of these paleo-bays was as early as Frödin (1916), who named them 'glaciofluvial estuaries' due to their connection to eskers. The more general concept of calving bays at subaqueously retreating ice margins was introduced by Hoppe (1948, 1957) for the Fennoscandian Ice Sheet. Calving bays formed close to the larger eskers due to intensified – possibly intermittent – calving (see later discussion), induced at, and lateral to, the mouth of subglacial drainage channels which also were depocenters for the formation of De Geer eskers. The calving bays propagated backwards, following the general retreat of the ice margin. The outlines of such calving bays are often indicated from striae on bedrock outcrops close to the larger eskers and the orientation of near-by De Geer moraines (Strömberg, 1981). The older regional-flow striae from north to south are often then seen to be cut by younger striae coming from ~NE, east of the eskers, and from ~NW, west of the eskers (e.g., as described in fig. 3 in Magnusson (1984)). Examples of calving bays associated with eskers from the Stockholm-Uppsala region, not far from the studied Kumla–Örebro area, are shown in Fig. 2 (reproduced from Strömberg, 1989). Here, calving bays of varying depths into the receding ice margin are also indicated from the configuration of reconstructed ice recession lines, in turn based on data from varve measurements (varve isochrones) (e.g. Strömberg, 1981, 1989).

The strongest indicator for the existence of calving bays around eskers is, however, the configuration of subaqueously formed ice-marginal moraines, generally known as De Geer moraines (e.g. Lindén and Möller, 2005). These moraines occur in a bimodal distribution in Sweden, one population is located in the coastal area of north-eastern Sweden and the other as a broad belt across the deglacial subaqueous part of south-central Sweden (Fredén, 2009; map on p. 134; Bouvier et al., 2015). A significant pattern for this southern De Geer moraine belt is that that the ridges at a distance from the eskers are arranged approximately perpendicular to the esker trends, regional striae direction and drumlins, while closer to the esker ridges they usually turn in orientation, coming in at an increasingly oblique angle to an esker on both sides. This relationship is seen from the Quaternary deposits map of the Kumla–Örebro area (Fromm, 1972) (Fig. 3A) and is highlighted by the extraction of De Geer moraines and striae (Fig. 3B). This pattern has also been described from studies of aerial photographs over the area in the past (Bergdahl, 1959, 1961, 1965). Taken together, the geometric relationship between De Geer moraines and the Kumla esker indicates that the studied area was also occupied by a highly indented calving bay during ice retreat.

Materials and methods

The topographical data used in this paper is the LiDAR derived digital elevation model (DEM) supplied by the Swedish national mapping agency (Lantmäteriet; http//:www.lantmateriet.se). This arrives to the end user with an average vertical accuracy of ~0.1 m and a pixel resolution of 2 m. The data is pre-processed to remove both vegetation cover and urban areas down to ‘true’ ground level. The technical details for this height model can be found in Dowling et al. (2013). Data handling was carried out in ArcGIS© 10.0 and Matlab© R2014[a].

Mapping of the landforms was manually carried out on hill-shade models illuminated from a variety of angles. The small scale drumlins are only visible with x5 height exaggeration applied and the careful manipulation of the angle of illumination. Typically the best angle of illumination with which to see these features is either from 120° or 250°. Switching between these angles and 90° reveals the small, shallow, drumlins. The mapping itself was carried out as part of the work outlined in Dowling et al. (2015), and the drumlins are part of that larger dataset. Height was extracted using the method of Spagnolo et al. (2012), whilst length and width were extracted using minimum bounding geometry (Napieralski and Nalepa, 2010).

Results

Landform descriptions

The studied Kumla–Örebro area (~13 by 8 km), depicted in Figs. 3 and 4, contains streamlined bedforms (drumlins) in two size ranges (Fig. 4). The larger features are typically

430-2200 m long, 110-400 m wide, and 8-15 m high (Table 1) and, when compared to the metrics of global datasets (Clark et al., 2009; Spagnolo et al., 2012), could be considered 'classic' drumlins. These drumlins are part of the general streamlined flow set of the wider region of the Närke plain and are aligned approximately north to south (Möller and Dowling, 2016). The second size range of streamlined bedforms is an order of magnitude smaller and is distributed at an angle to these larger features. Perpendicularly overlaid on these small-scale drumlins are suites of De Geer moraines (Fig. 4). The distribution of, and relations between, these geomorphic forms are further detailed in our LiDAR-derived DEMs over three chosen smaller type areas, the Härminge and Brickebacken sub-areas, to the east of the Kumla esker (Figs. 5 and 7), and the Stora Ulvgryta sub-area, to the west of said esker (Fig. 8).

The features in the Härminge sub-area (Fig. 5) clearly indicate the calving-bay orientation relationship between small-scale drumlins, De Geer moraines and the esker. The area (~7 km^2) hosts small-scale drumlins (n = 48) that are 41-245 m long and 10-71 m wide, with a P_{10}-P_{90} height of 0.4-1.8 m (Table 1). Drumlin axes are orientated ~35/215°. Draped over the drumlins is a dense set of De Geer moraines (Fig. 6), all trending ~305/125°. These are thus perpendicular to the Härminge small-scale drumlins, but skewed relative to the larger drumlins (e.g. right-hand side on Fig. 5). The De Geer moraines in the Härminge area (Fig. 5) measure 25-832 m in length, 10-21 m in width and 2-3 m in height. The Härminge small-scale drumlins and the De Geer moraines associated with them are thus at an angle of ~38° to the north-south esker trend. It should be noted that for both the De Geer moraines and especially for the small-scale drumlins in this sub-area there is the potential for a shrouding effect (Finlayson, 2014; Spagnolo et al., 2014) when surrounded by on-lapping glacial/postglacial aquatic sediments (silt and clay; Fig. 3). In some areas with deep successions of aquatic sediments and/or organic deposits this shrouding effect can be several meters (e.g., Möller and Dowling (2016) for the nearby Hackvad drumlin field); this can come close to completely 'drowning' smaller geomorphic features.

The Brickebacken sub-area (Fig. 7) is due north of the Härminge sub-area (Fig. 4), covering about 24 km^2. Small-scale drumlins in this set (n = 155) are 68-176 m long, 17-57 m wide and 1.5-2.3 m high (P_{10}-P_{90} values). Drumlin axes are orientated ~35/215°, i.e. the same direction as at Härminge, but these features are here more densely packed. Bedrock outcrops associated with the drumlins are often detectable from the Quaternary mapping and from visual inspection of the hill shade model, suggesting that mapped drumlins are of the rock-cored type. As at Härminge, the drumlins are superimposed by De Geer moraines that trend

~305/125°, although some of the moraines start to shift towards a ~290/105° alignment towards the eastern margin of the demarcated area. The De Geer moraines are 12-264 m long, ~20-21 m wide and ~1-2 m high. The shrouding effect is likely minimal here, as the features are located on a slightly elevated till plain with no subaquatic sediments preserved between moraine ridges. However, just outside of our mapped subarea there are features drowned in subaquatic fine-grained sediment which are now only visible as crop marks in aerial photos and as faint shadows in the hillshade models.

The Stora Ulvgryta sub-area (Fig. 8) is situated west of the Brickebacken area, covering about 30 km^2. Importantly, it is located on the western side of the Kumla esker (Fig. 4). The small-scale drumlins in this set (n = 54) have the same general pattern of morphometrics as the sub-areas on the eastern side of the esker. The drumlins are 65-241 m long, 22-70 m wide and 1-3 m high (P_{10}-P_{90} values) and have axes orientated ~350/170°. Rock outcrops associated with the mapped drumlins are often detectable from the Quaternary mapping and the hill shade model. The drumlins are sparsely distributed and overlain by a small number of De Geer moraines that are 55-183 m long, ~14-21 m wide and ~0.5-1 m high, trending ~70/250°.

Taken together, the orientation of the small drumlins and their associated De Geer moraines on opposite sides of the Kumla esker provide strong evidence of the geometric development of the calving bay and ice margin retreat in the Kumla-Örebro region, as well as indicating the local, late-stage ice flow direction.

Discussion

Advantages of using LiDAR terrain data

Without high resolution LiDAR it would be impossible to detect the small-scale drumlin features described here. Their small size, in particular their shallow height, makes their detection in the field or from traditional aerial photograph mapping very difficult. This is especially the case when located under forest cover, making the capability of LiDAR to 'look through' vegetation as important as a high spatial resolution for their detection. The work done here shows the ability of high resolution LiDAR datasets to create detailed reconstructions of palaeo-landform assemblages, combining both previously identified landforms and newly identified relationships between these landforms with newly discovered features. Furthermore, the mapping of De Geer moraines with LiDAR-based DEM's results in much denser and detailed patterns as compared to previous ground- and aerial photograph-based mapping (see also Bouvier et al., 2015). This enhancement is very evident when comparing their mapped distributions in Fig. 3B versus Figs. 4, 5, 7 and 8. This further strengthens any assessment of probable calving bay configuration.

Palaeo-calving bay formation

The pattern and direction of near-to-esker De Geer moraines provide evidence that the receding ice margin formed pronounced indentions – a calving bay – around the Kumla esker that formed transgressively backwards at the subaqueous outlet of the subglacial drainage at deglaciation of the area. As the bay retreated northwards it also opened out, i.e. the angle between the ice-front and the esker/drainage outlet increased as the margin moved north (see Fig. 9 and mapping in Fig. 4).

The retreat of water-terminating ice margins is due to a balance of and feedbacks between calving, topography and atmospheric warming (e.g. Venteris, 1999; Cook et al., 2005; Benn et al., 2007a). Localized areas with higher ice loss over longer or shorter time periods, caused by preferential calving at an active sub-surface drainage outlet (Benn et al., 2007b), might thus result in concave calving bays. According to Benn and Evans (2010) this is most likely the result of longitudinal extension occurring in conjunction with simple shear at the ice margin. The effect of this is to generate distinctive crevasse patterns along which the enhanced calving occurs, forming the concave planform of calving bays near eskers. An important factor in a given calving rate is water depth (Benn et al., 2007a); postulated palaeo calving bays across the subaqueously deglaciated south-central part of Sweden (Fig. 1) were evidently tied to the positions of the larger eskers of this area. This might indicate the importance of this factor: the eskers are usually situated in the lowermost positions of this once submerged landscape.

However, water depth differences along the receding ice margin were not that large. Possibly more important in controlling calving rate was the *per se* existence of the subglacial drainage conduits, marked in their deglacial positions by the resulting eskers. Melting of the ice above these conduits and in their immediate surroundings would thin the ice, reduce basal effective stresses and thus basal drag, introduce positive feedback into dynamic thinning and propagation of deep surficial crevasses up-glacier, thus resulting in localized increases in calving rate (e.g. Benn et al., 2007; Benn and Evans, 2010). A continuous fast differential ice loss close to the eskers as compared to the areas between the eskers would, however, theoretically mean that the calving bays would get progressively deeper with time.

When scrutinizing the maps of calving bay configurations as suggested from constructed varve isochrones, e.g. Strömberg (1989), see Fig. 2B, or further north in the county of Dalarna (Fromm, 1991) with very deep calving bays, it is evident that there was a tendency for calving bays to grow progressively deeper with time, but only over portions of their recessional paths. This suggests that the calving rate in the calving bays was larger than the regional ice recession rate only over shorter periods of time, i.e. intermittent periods of fast calving. This was followed by a reduction in the rate of ice loss back to the typical regional ice recession rate with the generated calving bay configuration moving back into a more typical marginal alignment.

Location of drumlin formation and ice flow adjustment

Based on their perpendicular relationship with the ice-marginal De Geer moraine ridges we argue that the orientation of the small-scale drumlins in the Kumla–Örebro area, as depicted in Fig. 4, reflects the direction of ice flow near the Kumla esker at a late stage of deglaciation. The smaller-scale drumlins formed within a near-marginal area where the regional north to south-directed ice flow had shifted as a response to the formation of an indented calving bay (Fig. 9). The orientation of De Geer moraine ridges changes slightly throughout the study area as the ice margin geometry was modified during retreat. However, these differences are too small to be able to associate individual drumlins to specific De Geer ridges. Thus it is not possible to establish whether an individual drumlin formed while the margin was only a few hundred metres away in distal direction or some kilometres, as its orientation remains roughly perpendicular to that of most De Geer ridges. Yet, since the orientation of the latter shifts abruptly on either side of the Kumla-esker it is almost certain that the maximum distance between the forming drumlins and the ice margin is represented by the distance to the esker. This has to be measured along the once existing ice flowlines as evidenced by the small-scale drumlins, and can be practically obtained by simply projecting down-flow the drumlin long axis until this intercepts the esker. In the other direction a hypothetical flow line would gradually fall into the primary N-S directed flow lines that are not influenced by the calving bay configuration. The measured distances of this varies from 1 km in the south of the study area (near the ‘x’ of the transect marked in Fig. 4), to 7.7 km, further north.

The concept of retreating margins controlling drumlin orientations has previously been discussed by Mooers (1989). In a time-transgressive model of drumlin formation located under the Rainy and Superior lobes of the Laurentide ice sheet, it was shown that the trend of drumlin axes was primarily set by a retreating ice margin. However, Mooers' model only located this within a distance of 20-30 km of said ice margin, rather than the more proximal distance of approximately 1-7.7 km that we report here.

Formation time

Based on our proposed model of *where* the small-scale drumlins formed in relation to the ice margin it is possible to calculate the time frame over which individual/adjacent near-marginal drumlins were formed. This is a function of the time period over which the calving bay-adjusted ice flow was operating over the ice-bed interface of the area in question. Therefore it is possible to infer the maximum formation time from a known local ice recession rate. Ideally we would be able to use the De Geer moraine ridges to do this, and this was the original idea by De Geer (1989), i.e. that the ridges had geochronological significance in that they were formed annually. This has also lately been suggested from a study of Swedish De Geer moraines by Bouvier et al. (2015). However, such annuality has been rejected by, e.g., Hoppe (1959) and Strömberg (1965), as well as by Lindén and Möller (2005), who all argued that multiple moraines could form within the same year. We thus argue that we cannot use the mean distance between De Geer moraines in the Kumla–Örebro area as a reliable chronometer.

However, it is possible to use the Swedish varve chronology to gain an appreciation of local deglaciation time and the time frame over which the small-scale drumlins were formed. The close to parallel and regularly spaced isochrones between -1200 and -900 over and north of Stockholm (Fig. 1) suggest that these isochrones can, with a relatively high confidence, be transferred laterally west-southwest-wards. This allows us to infer that the whole Kumla-Örebro area was deglaciated between varve isochrones -1200 and -1100, i.e. in less than 100 years. This is then an absolute maximum time period for all the mapped small-scale drumlins to form as their formation must have taken place during the passage of the Kumla-esker calving bay, with their orientation showing an adjustment to this ice marginal configuration. The 20 varve-year isochrones of Strömberg (1989) between years -1200/-1100 give an annual mean steady state recession rate of ~220 m/yr. Although the recession rate value could have varied locally along the gradually receding calving bay margin due to differences in calving rates/events, and therefore not be a steady-state retreat, we argue that it can be used as a good average for the northwards propagation of the calving bay margin.

With this assumption in place the transect X-Y in Fig. 4 with a length of 7.7 km in the Härminge and Brickebacken sub-areas, was deglaciated within ~30-35 years from the first mapped De Geer moraine to the last. This was then a period that also time-transgressively sustained the NE to SW-directed ice flow towards the eastern flank of the calving bay at which point the smaller-scale drumlins were formed. A formation time of only a few decades is further reinforced by the situation verified in the Stora Ulvgryta sub-area, on the opposite side of the Kumla esker (Fig. 8). A SE-directed, 5.3 km long, transect across De Geer moraines draping the Stora Ulvgryta drumlins gives, under the same assumptions as above, a deglaciation time of the whole transect of ~24 years. The slight chronological difference between the two sides of the esker also demonstrates that De Geer moraines are not a reliable chronometer for ice retreat rate. There are sections along the X-Y transect (Fig. 4) over which there are very small spaces between the ridges (12 moraines over 1000 m; i.e. a mean spacing of 83 m) which means that the number of ridges formed could have been as high as 2-3 ridges per year or even more over shorter steps of ice margin retreat.

Our calculated period for the formation of the small-scale drumlins is a maximum time period, referring as discussed above to the total deglacial age span with a sustained ice flow direction from NE and NW on either side of the Kumla esker. Should the minimum distance to the esker of 1 km, verified for some of the drumlins, be taken into consideration, the formation time of these features is reduced to only 5 years. This is compatible with recent observations such as the repeat seismic and radar investigations under the Antarctic Rutford Ice Stream, which revealed a 10 m high and 100 m wide streamlined bedform forming/evolving within a period of only 7 years (Smith et al., 2007; King et al., 2009). In agreement with these results there is also a recent study on the formation time of drumlins at Fláajökull on Iceland (Jónsson et al., in press), similar in size to the ones analysed here, with a suggested ~29 year formation time-frame. This is particularly interesting as a modern example in a non-surge setting with a well-controlled formation time. The calculated drumlin formation time of our study also fits within the broad time frame for drumlin formation calculated by Rose (1989) of 8-292 years, falling within the lower end of that range. The calculations by Rose (1989) build on sediment transfer rates applied to volume of tills in their investigated drumlins; though an interesting approach this is hard to apply to the drumlins described here. This is because the transfer rate of till for our region is largely unknown and the volume of till in the drumlins is hard to evaluate as these features are likely rock cored, as drumlins predominantly are in southern Sweden (Dowling et al., 2015).

In summary, the small-scale drumlins identified here formed ~1-7.7 km behind a retreating calving bay ice margin and over formation periods of 5 to 35 years. The larger drumlins of the area, which are an order of magnitude larger than the small-sized features and which are parallel to the regional north to south-directed ice flow, should have formed over a much longer period. Our reconstructions are further supported by the following lines of evidence:

(i) Smaller drumlins over-print the larger drumlins. The survival of the larger drumlins, despite the near ice-marginal change in flow direction and subsequent sediment reorganisation into the smaller drumlins shown here suggests that the duration of the flow event that created the small-scale drumlins was not long enough, or lacked the erosive/deformative capacity, to alter the orientation of the large drumlins.

(ii) The small-scale drumlins are only present in connection to closely spaced De Geer moraines. This indicates that the small-scale drumlins only formed in places where the ice margin had a quasi-stable ice retreat rate without large calving events that could have generated large frontal retreats greater than several hundreds of metres.

Conclusions

We have found that small-scale drumlins in the Kumla–Örebro area are aligned – and thus formed – parallel to flow lines that were adjusted to the configuration of calving embayments in the receding ice margin at the last deglaciation. These embayments were located close to the position of where larger eskers formed and were the product of enhanced calving at the subaqueous outlets of the subglacial melt-water drainage. Furthermore, the area/calving margin under which our mapped small-size drumlins formed was likely deglaciated over a period of ~25-35 years, suggesting a maximum timeframe for their formation. To summarise, the key findings of this paper are:

- Enhanced calving processes around the subaqueous outlets of well-developed subglacial drainage networks caused marginal ice flow direction to converge towards the outlet/resulting esker. The result of this was the formation of calving bays and an altered near-marginal ice flow direction. This is demonstrated by the geometric relationship of drumlins, De Geer moraines and the Kumla esker in the studied area.

- Mapped small-scale drumlins can form behind calving bays in response to the change in flow direction. This has been verified in the Kumla-Örebro region where the drumlins must have formed within c. 1-8 km of the active glacial margin.
- Our studies suggest that drumlins of the size described can form under major ice-sheets over very short time periods, 5-35 years.

Acknowledgements

The work presented here is part of a larger project (with P. Möller as PI) on formation of streamlined terrain over south Sweden which, together with the papers by Dowling et al. (2013), Dowling et al. (2015), Möller and Dowling (2015), Möller and Dowling (2016) and Dowling et al. (2016) lead to, and are summarized in, the PhD thesis by Dowling (2016). The LiDAR data used in this work is the property of Lantmäteriet (http//:www.lantmateriet.se) and is done so under agreement number: i2014 / 00579. Comments by JQS rewievers Julia Wellner, Clas Hättestrand and an anonymous revier greatly improved the focus of the paper.

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Captions and Tables

	n	*Mean Height*	*Height P_{10}*	*Height P_{90}*	*Mean Length*	*Length P_{10}*	*Length P_{90}*	*Mean Width*	*Width P_{10}*	*Width P_{90}*	*Mean Orientation*
Area 1	48	0.9	0.4	1.8	113.5	64.8	188.8	31	15.3	57.6	35-215
Area 2	155	1.5	0.8	2.3	112.7	68.4	175.3	33	17.7	56.4	30-210
Area 3	54	1.8	1	3	117.4	65	240.8	40.4	22.2	70.8	210-30

Table 1. Summary statistics for flow set morphometrics. All values are in meters and rounded to 1 decimal point. Mean orientation is given to the nearest whole degree, the values representing the orientation of the a-axis, with the upstream polarity given first.

Fig. 1. (A) Overview of NW Europe. Red dashed line = proposed Fennoscandian Ice Sheet margin to the west/south at LGM (Svendsen et al., 2004); blue dashed line = the Younger Dryas Ice Marginal Zone (Mangerud et al., 2011). (B) Map of southern Sweden (for location, white box in (A)), showing areas above and below the highest shoreline (marine limit in the west), and altitude of the highest shoreline at deglaciation. The highest shoreline east of Billingen is the shore altitude for the Baltic Ice Lake prior to its 2nd drainage at retreat from Billingen after the Younger Dryas advance, while highest shoreline isobases north thereof were formed in the following Baltic Basin stages Yoldia Sea and Ancylus Lake (Björck, 1995), following the northwards receding ice margin. Inferred ice-marginal positions during the Younger Dryas are according to Lundqvist (2009). Deglacial varve isochrones are transferred from Brunnberg (1995) (south of Stockholm), Strömberg (1994) (Lake Vänern-Askersund) and Strömberg (1989) (north of Stockholm). Base map compiled from the Swedish National Atlas (Fredén, 2009). Red box marks the investigated area between Örebro and Kumla (Fig. 3) and orange boxes mark the positions of Figs. 2A and 2B. Typical ice flow for the local area was north-south.

Fig. 2. Examples of reconstructed calving bays arround some of the larger eskers north of Lake Mälaren, south-central Sweden (Fig. 1B), based on varved clay measurements (redrawn from Plates 2 and 3 in Strömberg (1989)). Eskers are shown in green, striae outcrop locations are marked with a red with the direction indicated by the red line and the black lines indicate varve isochrones. The latter are based on lateral correlation of basal varves and are drawn with 20 years interval. Indicated varve years for deglaciation is in the relation to the so called ‘zero year’ in the Swedish varved clay chronology (Cato 1985, 1987). Measured youngest striae are marked from oposite sides of the esker/calving bays, indicating near-marginal ice flow re-adjustment (from the general ice flow direction north to south), being approximately perpendicular to the calving bay configuration at ice-margin gradual retreat. (A) The moderately indented calving bay gradualy forming arround the Uppsala esker at ice recession between varve years -1100 and -920 (180 years) over a distance of ~40 km (mean recession ~222 m/year). Note a slight increase with time in claving bay depth towards the north. Calving bay depths and widths are hard to define, but depths are only in the order of 2-4 km,

marked as shallow indentions in the close to west to east-treding receding ice margin. Centre of the map is N59˚43'; E17˚36' (position marked with orange box in Fig. 1B). (B) The strongly but variably indented calving bays gradually forming around the Enköping and Gävle eskers at ice recession between varve years -800 and -700 (100 years) over a distance of ~47 km (mean recession ~470 m/year). Calving bay depths north of isochrone -800 vary between 6-15 km and widths between 6-17 km at bay mouths, with both calving bay depth decreases and increases at gradual ice margin recession. Centre of the map is N60˚25'; E16˚53' (position marked with orange box in Fig. 1B).

Fig. 3. Overview of Quaternary sediments and landforms in the Kumla–Örebro area. (A) Extract of the Quaternary geology map Örebro SW (Fromm, 1972). For full legend, see online version at http://resource.sgu.se/produkter/ae/ae5-karta.pdf. (B) Extract of De Geer moraines (blue lines), eskers (green) and youngest striae (red bullet arrows) from (A). The north to south trending Kumla esker has nearby De Geer moraines trending towards WSW to SW west of the esker, while De Geer moraines east of the esker trend towards SE, indicating local ice margin rearrangement from the general W–E trend around the esker and thus suggesting the formation of a calving bay at the northwards retreat of the subaqueous ice margin (Bergdahl 1959, 1965; Fromm 1972). Place names Härminge, Brickebacken and Stora Ulvgryta, and their black frames, indicate the positions of LiDAR-derived DEM scenes shown in Figs. 5, 7 and 8, revealing much denser patterns of De Geer moraines than shown here as based on ground survey mapping.

Fig. 4. Overview LiDAR-based mapping of drumlins and De Geer moraines in the Kumla-Örebro area (the same geographic extent as in Fig. 3). Drumlins are divided into large-scale drumlins (black outlines) showing the same N-S trend as for the rest of the streamlined flow sets of the Närke plain (Möller and Dowling, accepted), while the small-scale drumlins (red) when occurring deviate from this regional direction, trending NW-SE and NE-SW on the respective sides of the Kumla esker. De Geer moraines are perpendicular to the small-scale drumlins and thus trend NE-SW and NW-SE on opposite sides of the said esker. Coverage of the three zoomed in Lidar DEM's in Figs. 5, 7 and 8 are marked by black frames.

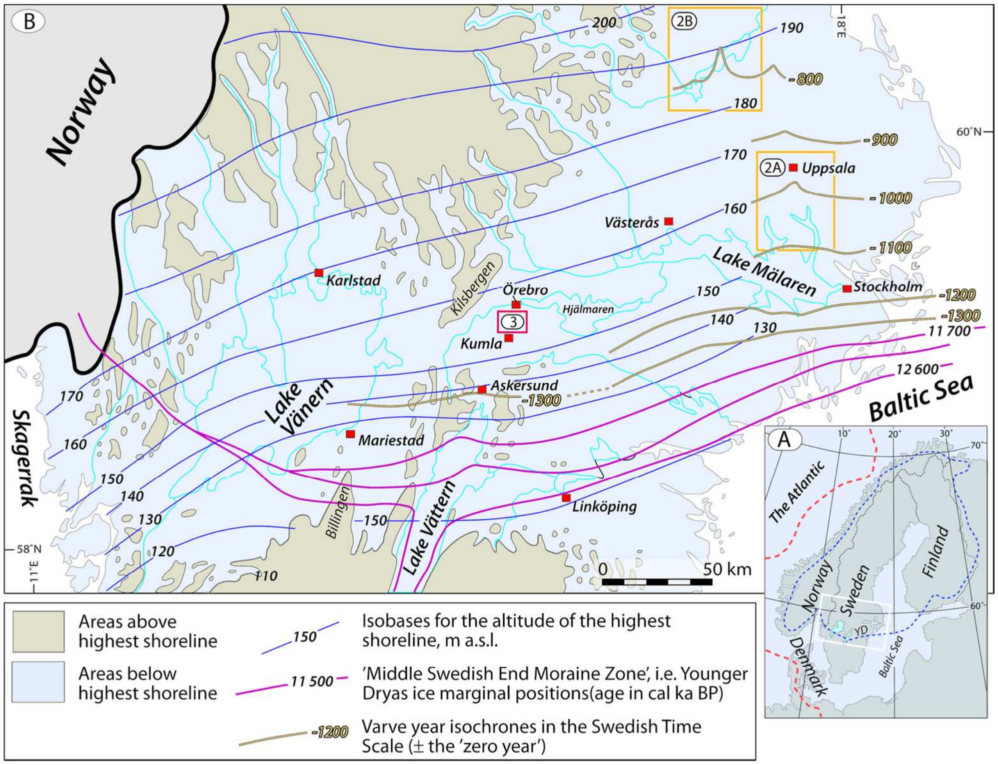
Fig. 5. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Härminge subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration.

Fig. 6. A drone image (view towards NE) of De Geer moraines in the Härminge subarea (Figs. 4 and 5). Five De Geer moraine ridges are here protruding through surrounding clay, which are the agricultural fields in the fore- and mid-ground. The moraine closest to the viewer is approximately 50 m long. The ridges trend NW-SE and tentative ice margins at their formation are indicated by white hatched lines.

Fig. 7. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Brickebacken subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

Fig. 8. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Stora Ulvhytta subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 250° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

Fig. 9. Idealised ice flow re-organisation and calving bay formation (left-hand scenes). The selected area is a random snapshot of the main Kumla esker body (pannels A, C and E), along with an idealised geomorphological evolution sketch map (pannels B, D and F). The area in front of the depicted calving embayments was occupied by the marine Yoldia Sea with water depths in the order of 80-130 m. (A) Flow lines further back from the ice margin at formation of the large-scale streamlined bed forms. (B) Large drumlinoids (black elipses) developed parallel to the regional ice flow direction further back from the receeding ice margin. (C-D) A calving bay is formed at ice margin recession (arbitrarily chosen time-transgressive position), in which apex the esker (green line) formed as lined-up subaqueous fans at the subglacial tunnel mouth. Ice flow (indicated by blue flow lines) was re-arranged from regional flow to be ajusted perpendicular to the new ice margin configuration of the approaching calving bay. De Geer moraines (blue lines) formed gradually at the receeding ice margin at an ~30-35˚ angle to the N-S directed esker. Small-scale drumlins (red) formed parallel to the near-marginal flow lines. (E-F) The final stages of the calving bay, the bay has opened out and ice flow is readjusting to a north-south direction. No small drumlins are seen to form with this flow orientation. The De Geer moraines formed at this stage are not perpendicular to the small drumlins formed early on.



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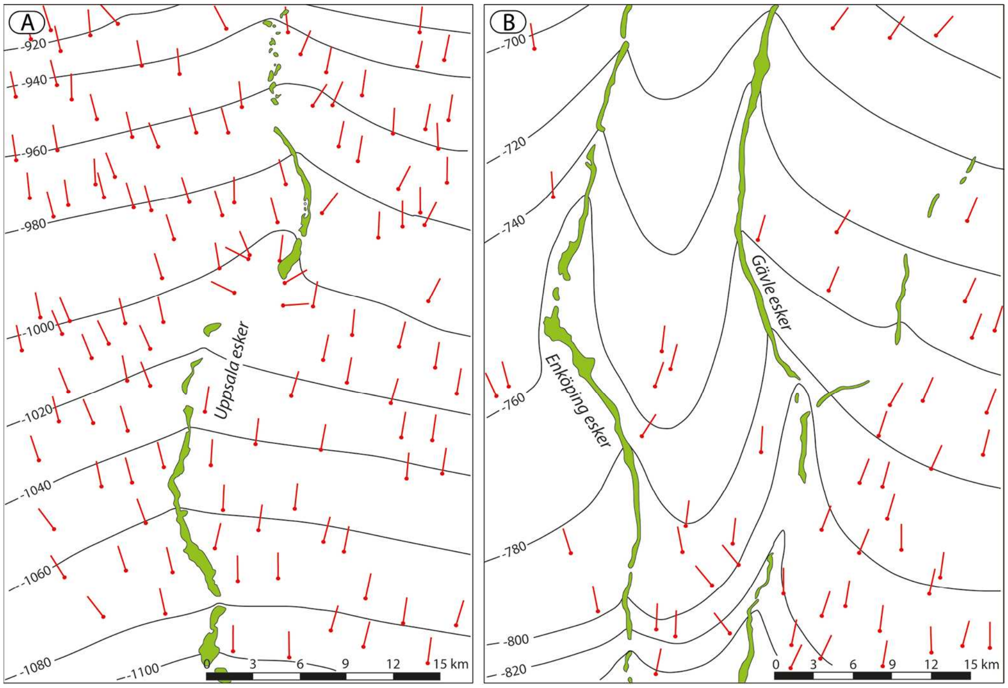

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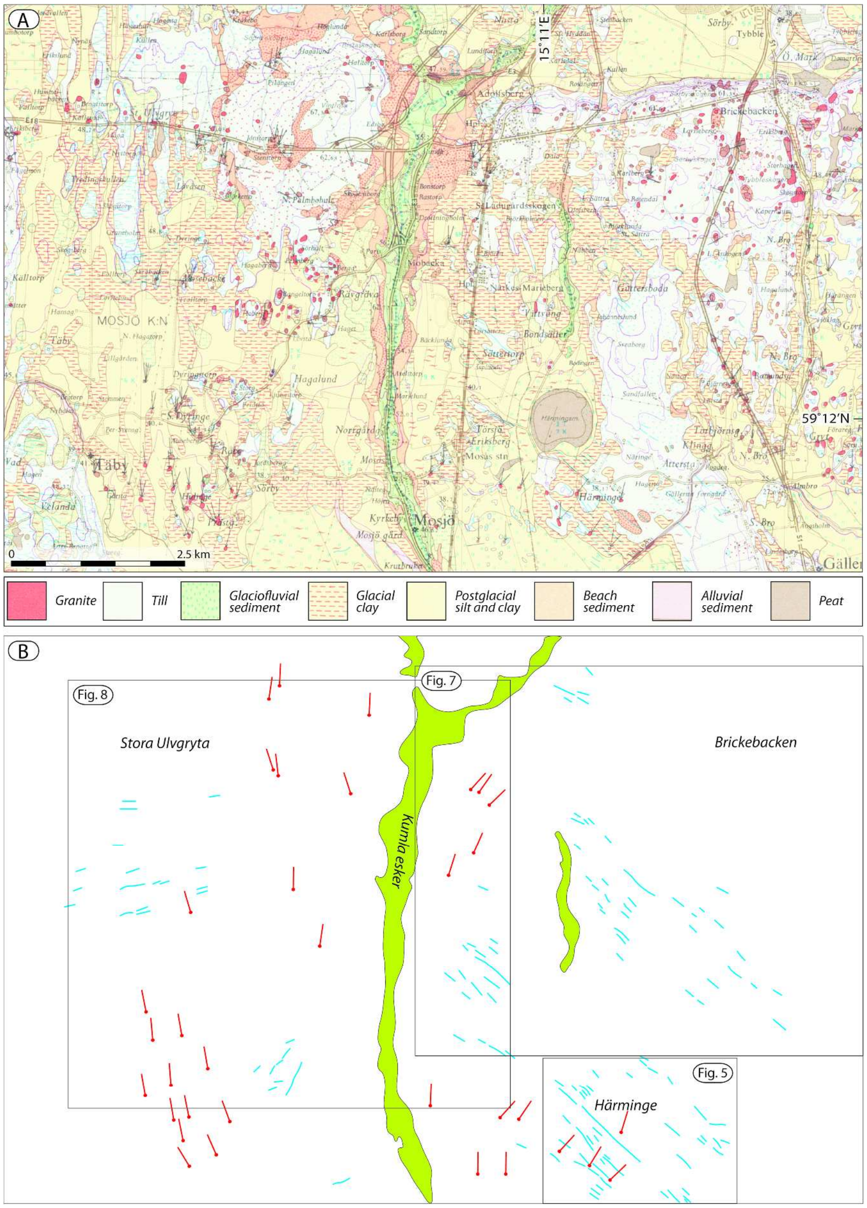

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243x339mm (300 x 300 DPI)

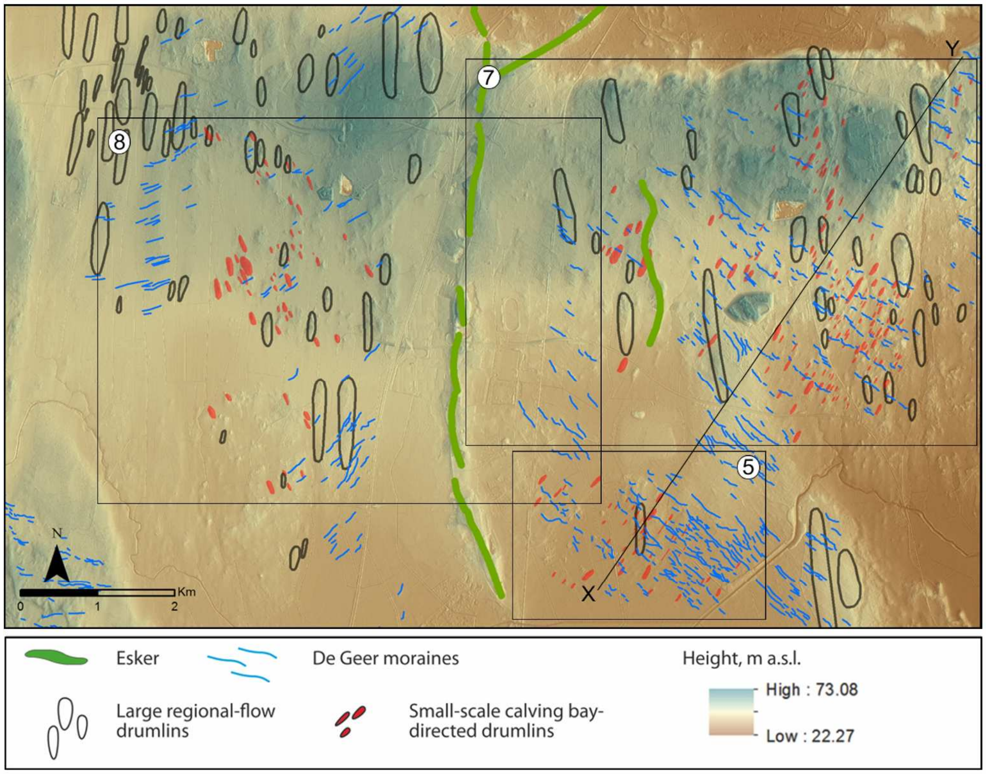

Fig. 4. Overview LiDAR-based mapping of drumlins and De Geer moraines in the Kumla-Örebro area (the same geographic extent as in Fig. 3). Drumlins are divided into large-scale drumlins (black outlines) showing the same N-S trend as for the rest of the streamlined flow sets of the Närke plain (Möller and Dowling, accepted), while the small-scale drumlins (red) when occurring deviate from this regional direction, trending NW-SE and NE-SW on the respective sides of the Kumla esker. De Geer moraines are perpendicular to the small-scale drumlins and thus trend NE-SW and NW-SE on opposite sides of the said esker. Coverage of the three zoomed in Lidar DEM's in Figs. 5, 7 and 8 are marked by black frames.

203x163mm (300 x 300 DPI)

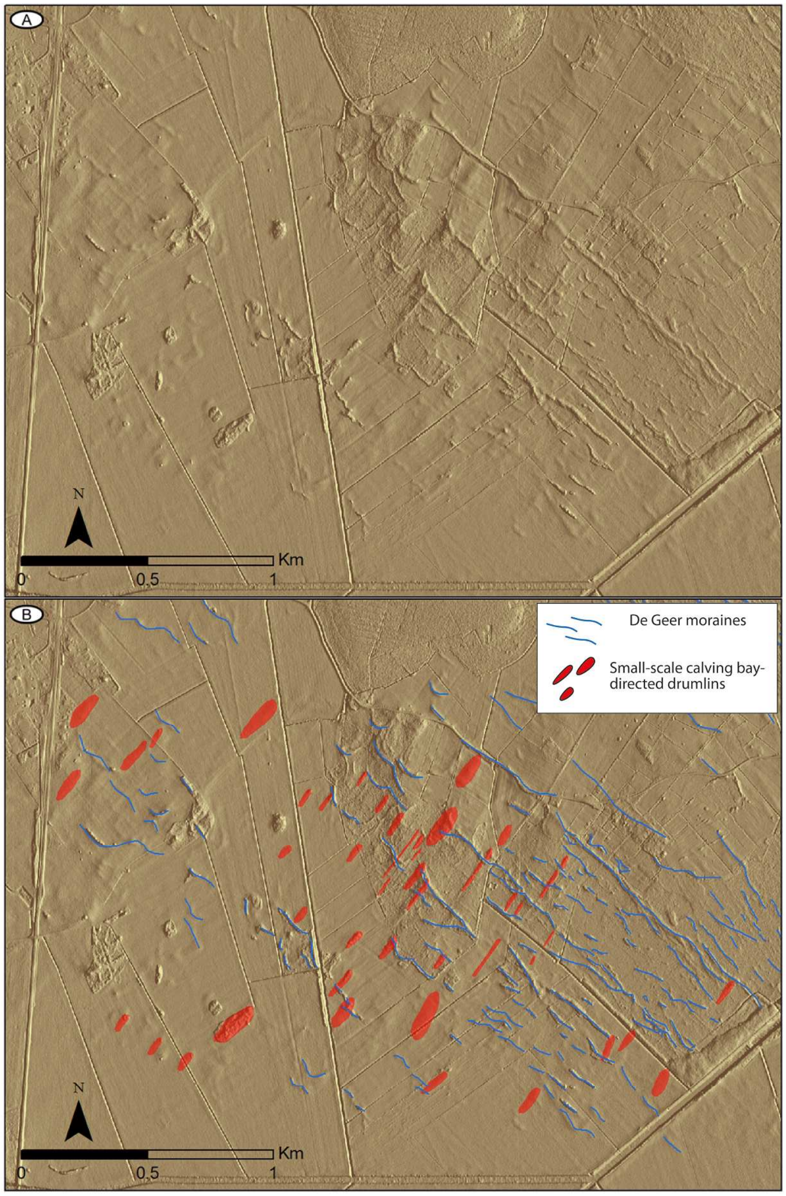

Fig. 5. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Härminge subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration.

790x1116mm (72 x 72 DPI)

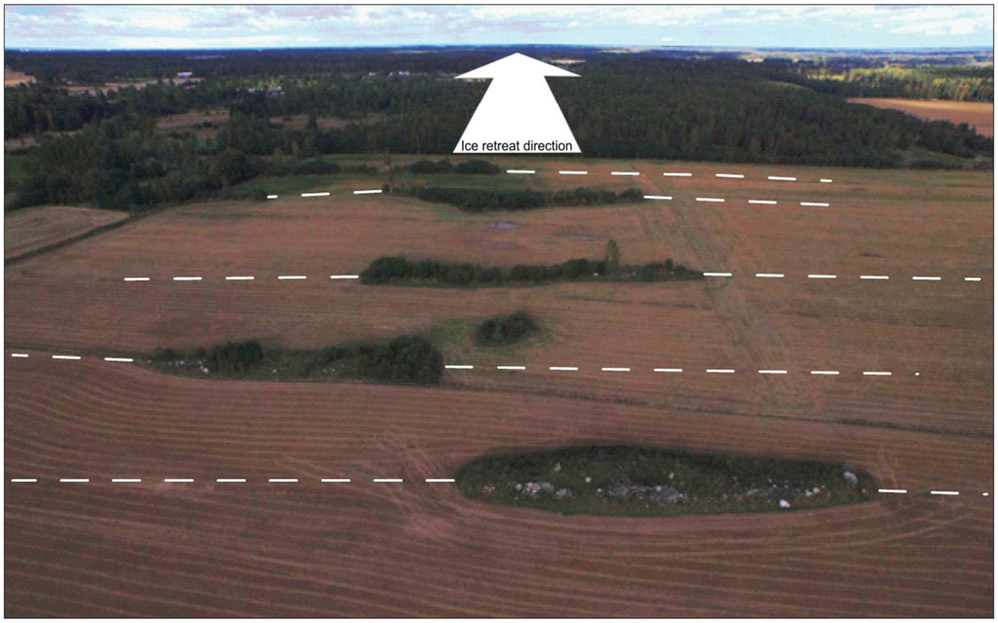

Fig. 6. A drone image (view towards NE) of De Geer moraines in the Härminge subarea (Figs. 4 and 5). Five De Geer moraine ridges are here protruding through surrounding clay, which are the agricultural fields in the fore- and mid-ground. The moraine closest to the viewer is approximately 50 m long. The ridges trend NW-SE and tentative ice margins at their formation are indicated by white hatched lines.

327x204mm (96 x 96 DPI)

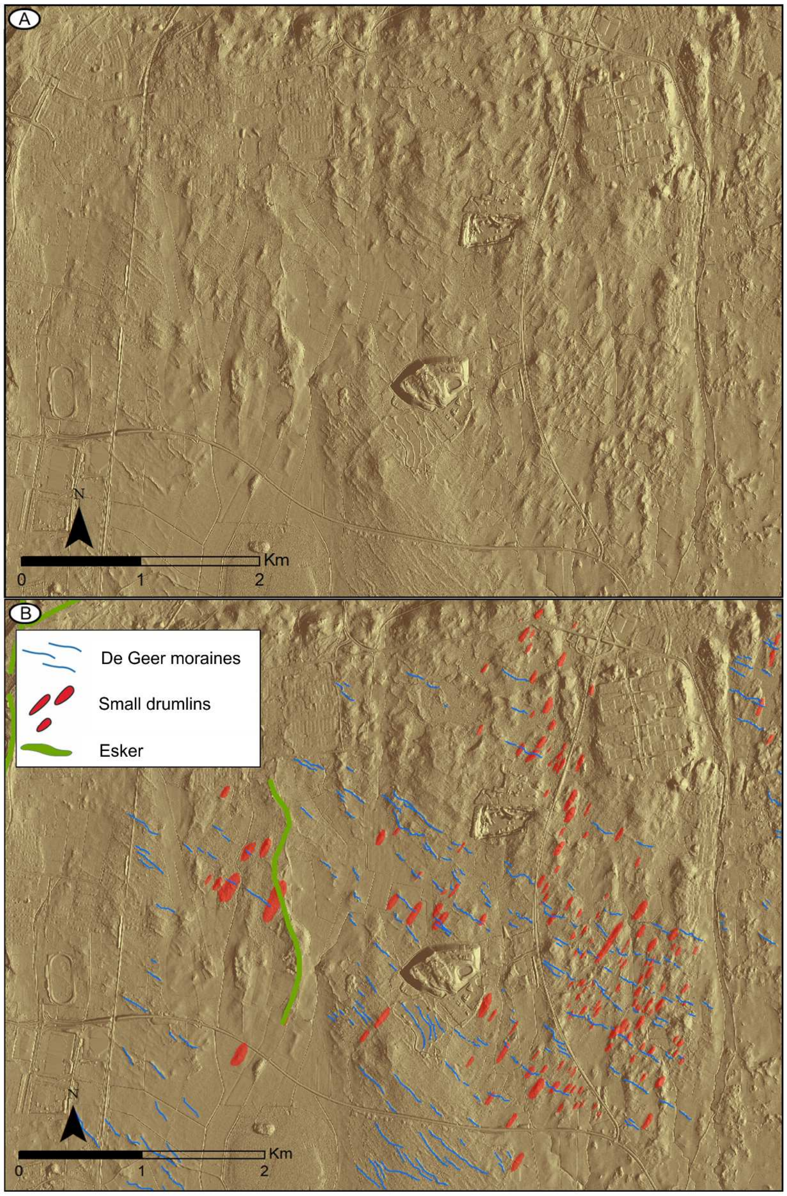

Fig. 7. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Brickebacken subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

210x297mm (300 x 300 DPI)

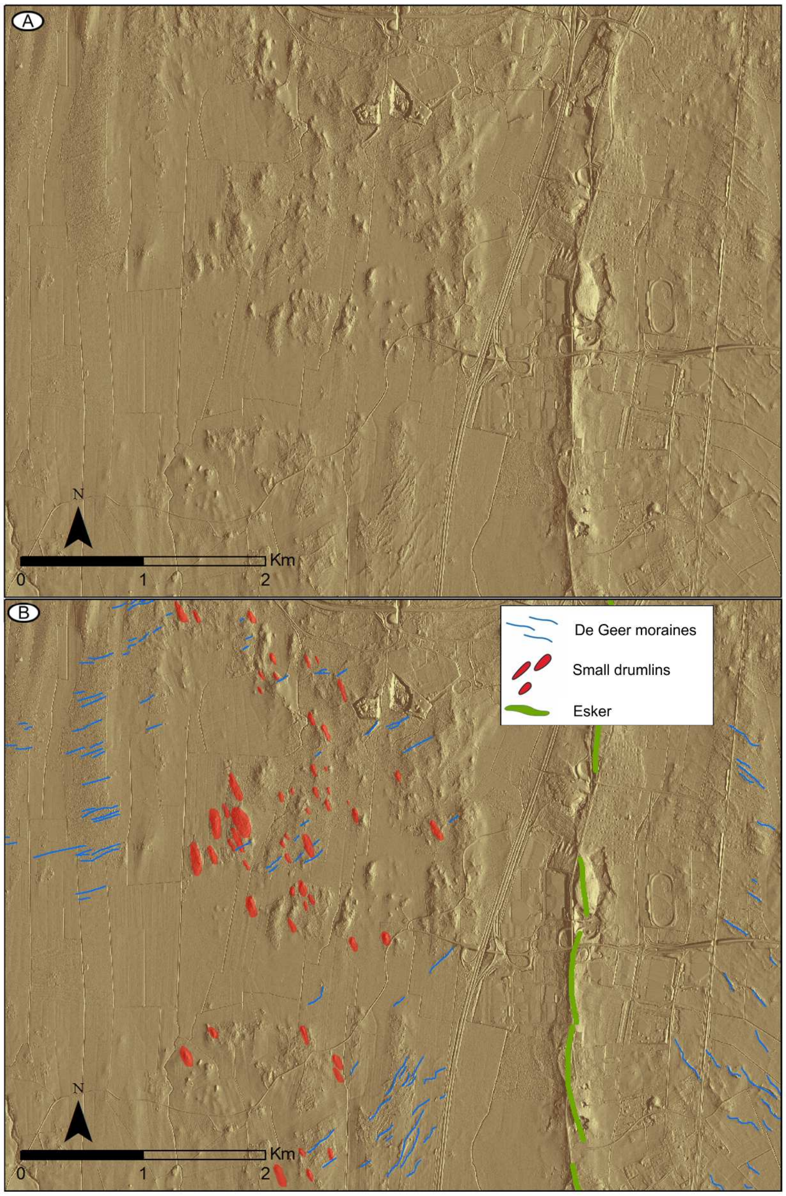

Fig. 8. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Stora Ulvhytta subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 250° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

210x297mm (300 x 300 DPI)

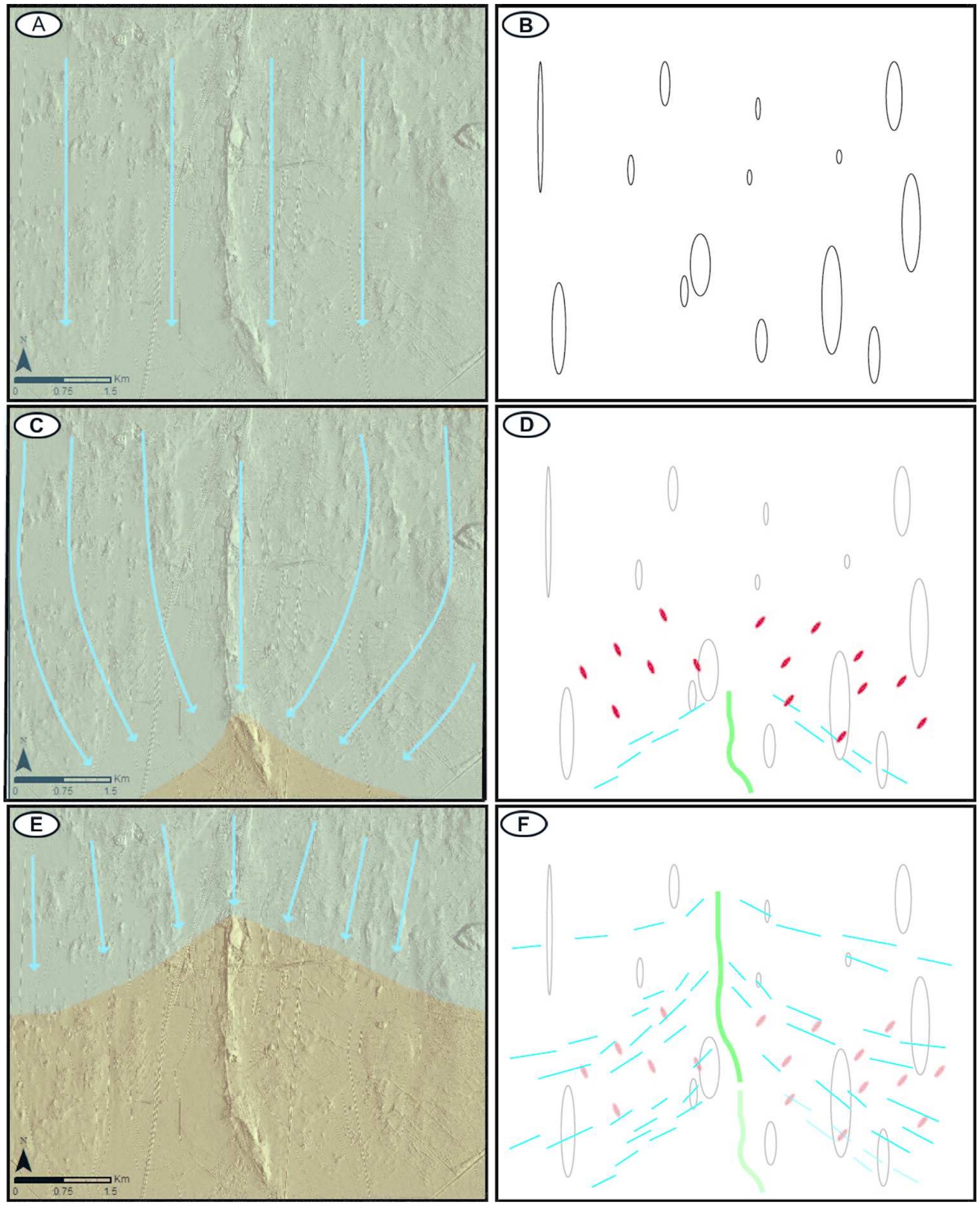

Fig. 9. Idealised ice flow re-organisation and calving bay formation (left-hand scenes). The selected area is a random snapshot of the main Kumla esker body (pannels A, C and E), along with an idealised geomorphological evolution sketch map (pannels B, D and F). The area in front of the depicted calving embayments was occupied by the marine Yoldia Sea with water depths in the order of 80-130 m. (A) Flow lines further back from the ice margin at formation of the large-scale streamlined bed forms. (B) Large drumlinoids (black elipses) developed parallel to the regional ice flow direction further back from the receeding ice margin. (C-D) A calving bay is formed at ice margin recession (arbitrarily chosen time-transgressive position), in which apex the esker (green line) formed as lined-up subaqueous fans at the subglacial tunnel mouth. Ice flow (indicated by blue flow lines) was re-arranged from regional flow to be ajusted perpendicular to the new ice margin configuration of the approaching calving bay. De Geer moraines (blue lines) formed gradually at the receeding ice margin at an ~30-35° angle to the N-S directed esker. Small-scale drumlins (red) formed parallel to the near-marginal flow lines. (E-F) The final stages of the calving bay, the bay has opened out and ice flow is readjusting to a north-south direction. No small drumlins

are seen to form with this flow orientation. The De Geer moraines formed at this stage are not perpendicular to the small drumlins formed early on.

418x515mm (300 x 300 DPI)

Rapid subglacial streamlined bedform formation at a calving bay margin

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ABSTRACT: Using the LiDAR derived Swedish national height model we have identified previously undescribed shallow streamlined glacial bedforms, small-scale drumlins, on the Närke plain in south-central Sweden. These drumlins could only be detected with high resolution LiDAR, due to both their subtle size and forest cover. In this area the ice margin receded in a subaqueous environment with a proglacial water depth in the order of 100 m during the last deglaciation. As indicated by the configuration of marginally formed De Geer moraine ridges draping the drumlinoids, the receding ice margin formed deeply indented calving bays. These were located around subaqueous outlets of the subglacial melt-water drainage, with their apex position marked geomorphologically by beaded esker ridges. The mapped small-scale drumlins are aligned perpendicular to the reconstructed ice sheet margin and suggest formation along flow lines adjusted to the configuration of these calving embayments as they propagated up-flow with ice margin retreat. Based on these geometric relationships we argue that the emplacement of the drumlins was near-marginal, ~7.7-1 km from the margin, on a short timescale (~5-35 years).

Running title: Flow reorganisation at calving bay margin quickly constructs drumlins.

KEYWORDS: streamlined terrain, drumlin, calving bay, De Geer moraine, ice recessional history

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Introduction

Streamlined subglacial bedforms, such as drumlins, are common geomorphic features on the relict ice beds of formerly glaciated regions. As such, they ~~and~~ have drawn intense research attention as their formation is considered key for understanding ice sheet dynamics. Many theories, widely inspired by various morphometric and sedimentological observations, have been put forward regarding the formation of drumlins, but the debate is far from closed (see discussions in, e.g., Clark, 2010; Stokes et al., 2011; Eyles et al., 2016; Möller and Dowling, 2016). Two aspects of key relevance that have perhaps seen relatively less attention, especially in recent years, are *where* drumlins form with respect to the ice margin and the *time frame* in which they form.

From a process point of view the location of formation for a drumlin must meet some combination of sediment erosion, transport and/or deposition. These three elements are in turn dependent on a number of things, including basal ice flow velocity and the induced basal shear stress on the subglacial sediment. The latter is highly dependent on the effective stress (normal stress reduced by pore water pressure) induced by the glacier at its bed. All of these parameters will vary along any given flow line and the resulting criteria for drumlin formation may be met sporadically or continuously throughout time. There are thus likely to be zones where basic conditions for bedform formation are met better than in other places due to presence of obstacles and/or a significant sediment supply (Stokes et al., 2013).

Drumlins are often described as forming within the main body of ice sheets (Raukas and Tavast, 1994), generally in areas of fast flow (ice streams) and at significant distances from the margin (Wellner et al., 2001). However, other studies suggest that they may also form relatively close to ice margins (Menzies, 1979). For example, Glückert (1973, 1987) describes drumlin fields in the central lake district of Finland that form outwards diverging flowsets along flow lines adjusted to the lobate configuration of the Younger Dryas ice-marginal zone, less than 100 km from that ice margin and over a single short ice streaming event. Other examples of near-marginal streamlining include the SE Baltic where Lamsters and Zelčs (2014) show that drumlins form~~formed~~ flow sets that diverge towards strongly lobate ice-marginal positions, as marked by end moraine zones. More recently at Múlajökull, Iceland, Johnson et al. (2010) have suggested that drumlins might form at the very margin of a surging glacier.

There is relatively little in the literature that considers the chronological aspect of drumlin formation as there is both a dearth of syn-formational observations and a lack of dateable material within the features themselves. However, the time period in which a feature forms is a critical component in efforts to reconstruct past ice sheets from the relict landscape. Of the evidence thus far gathered there is a wide disparity in suggestions of how fast or over which time frames subglacial bedforms are formed; Hättestrand et al. (2004) have suggested that large drumlins in northern and central Sweden are the result of sediment accretion from multiple glaciations and therefore have a very long formation time. In contrast to this, Smith et al. (2007) and King et al. (2009) found that the formation of contemporary subglacial features under an Antarctic ice stream are formed and evolve on the time scale of a few years. Rapid formation times are also suggested from the work of Johnson et al. (2010).

In this paper we investigate the time of formation of a number of small drumlins mapped within the streamlined terrain on the Närke plain, an area situated in south-central Sweden (Fig. 1), using high-resolution LiDAR-derived topographic data. The spatial association of these smaller features with nearby esker and De Geer moraine complexes is here investigated. In particular, the geometry of these landforms, their relationships with both one another and to the Swedish varve chronology, all provide an indication of where the small-scale drumlins formed in relations to the retreating margin of the Fennoscandian Ice Sheet and the amount of time it took them to form.

Regional and local geologic setting of the study area

The Närke plain in the Kumla–Örebro area, south-central Sweden (Fig. 1), on which the drumlins investigated here are located, is a low-elevation area at ~30-80 m above present-day sea level (m a.s.l.). Below the covering Quaternary deposits are down-faulted and tilted blocks of crystalline basement, overlain in varying occurrence by Palaeozoic sandstone, clay slate, alum shale and limestone, in that stratigraphic order (Ericsson, 1979).

During the deglaciation of the Kumla–Örebro area (Fig. 1), the subsequent northwards ice recession was primarily subaqueous with the retreating ice margin standing in water depths often in excess of 100 m (sea level at deglaciation, c. 150-160 m a.s.l. (Fig. 1), minus present-day elevation). The area was deglaciated in conjunction with a marine ingression from the west into the Baltic Basin (Brunnberg, 1995) a few hundred years after the final drainage of the Baltic Ice Lake at Mount Billingen (11.62 cal ka BP according to Stroeven et al. (2015).

in press)). Thus, at deglaciation the water basin in front of the receding ice margin changed from freshwater conditions to marine with the onset of the Yoldia Sea (Brunnberg, 1995; J. Björck et al., 2001). This saline environment is indicated by the occurrence of the marine mollusc *Portlandia (Yoldia) arctica* in the lowermost clay of the area (Bergdahl, 1961). Also due to the marine environment at deglaciation, suspended clay was prone to flocculation (Krank, 1973; Skei and Syvitski, 2013) resulting in poorly developed (symmict) varves or close to massive clay, thus making a complete annual varve reconstruction, based on clastic rather than symmict varves, not possible for this area. Indeed, Nilsson (1968) reports a maximum of only 48 annual varves from the area within the basal section of the up to 5-10 m thick fine-grained subaqueous deposits, which was not enough to construct a detailed varve chronology.

Varved clay chronology is based on the between-site lateral correlation of peaks in vertically measured and graphically plotted summer/winter bed thicknesses for specific sites; the 'classical' method as described in De Geer (1940) is to count the difference in basal 'missing' varves between two sites which then is a measure of difference in deglaciation age in years between the two sites. From these differences in deglacial age, varve isochrones are interpolated; in the case of the varve chronology from the Stockholm-Uppsala area (Fig. 2) this was done in 20 year steps. The basal varves formed close to the receding ice margin and the constructed varve isochrones thus mirror not only deglaciation time but also the configuration of the ice margin in temporal steps during continuous ice margin recession.

In addition to the Stockholm-Uppsala chronology northeast of our study site a detailed and precise varved clay chronology has been reconstructed just south of our investigated area, between Västergötland (Strömberg, 1994) and Närke/Östergötland (Brunnberg, 1995; J. Björck et al., 2001). This chronology can be extended to provide an overall indication of the deglaciation time just south of the Kumla–Örebro region. The -1200 varve isochrone of Brunnberg (1995) trends directly south of Kumla (Fig. 1) and the deglaciation of the Kumla–Örebro area should thus have occurred between the -1200 and -1100 isochrones. As the 'zero year' (±0) in the Swedish time scale is set to 10 090 cal yr BP (Stroeven et al., 2015), this is equivalent to c. 11.3 – 11.2 cal ka BP (Stroeven et al., 2015in press) as an approximate deglaciation age for the Kumla–Örebro area.

Eskers in the area have a general S-N trend on the Närke plain (Fromm, 1972; Ericsson, 1979). This concurs with the general glacial striae pattern, varying between N10°W and N10

˚E, and the primary drumlin flow sets, indicating the regional ice flow direction (Möller and Dowling, 2016). The eskers occur with 4 to 9 km wide gaps between them, as calculated from 7 eskers identified from the Quaternary deposits maps of the area (Fromm, 1972; Ericsson, 1979) over a 40 km long profile from west to east. Central through the Kumla–Örebro area runs the Hallsberg–Kumla esker; although this is the 'official' name (Bergdahl, 1961), it will in the following be called the 'Kumla esker' for short. Parts of these eskers formed infra-marginally as subglacial tunnel fillings, but most of the glaciofluvial sediment was deposited as tunnel mouth subaqueous fans of varying widths lined up after each other as the ice margin retreated (De Geer, 1897). Such types of eskers, along with more modern facies models for their formation, have been described as beaded eskers by Bannerjee and McDonald (1975) or as subaqueous short bead fan eskers by Warren and Ashley (1994).

A frequently occurring feature at deglaciation in this part of Sweden was the formation of large, often highly indented calving bays that during their existence were closely associated with the larger eskers of south-central Sweden. The first description of these paleo-bays was as early as Frödin (1916), who named them 'glaciofluvial estuaries' due to their connection to eskers. The more general concept of calving bays at subaqueously retreating ice margins was introduced by Hoppe (1948, 1957) for the Fennoscandian Ice Sheet. Calving bays formed close to the larger eskers due to intensified – possibly intermittent – calving (see later discussion), induced at, and lateral to, the mouth of subglacial drainage channels which also were depocenters for the formation of De Geer eskers. The calving bays propagated backwards, following the general retreat of the ice margin. The outlines of such calving bays are often indicated from striae on bedrock outcrops close to the larger eskers and the orientation of near-by De Geer moraines (Strömberg, 1981). The older regional-flow striae from north to south are often then seen to be cut by younger striae coming from ~NE, east of the eskers, and from ~NW, west of the eskers (e.g., as described in fig. 3 in Magnusson (1984)). Examples of calving bays associated with eskers from the Stockholm-Uppsala region, not far from the studied Kumla–Örebro area, are shown in Fig. 2 (reproduced from Strömberg, 1989). Here, calving bays of varying depths into the receding ice margin are also indicated from the configuration of reconstructed ice recession lines, in turn based on data from varve measurements (varve isochrones) (e.g. Strömberg, 1981, 1989).

The strongest indicator for the existence of calving bays around eskers is, however, the configuration of subaqueously formed ice-marginal moraines, generally known as De Geer moraines (e.g. Lindén and Möller, 2005). These moraines occur in a bimodal distribution in

Sweden, one population is located in the coastal area of north-eastern Sweden and the other as~~Such moraines occur in~~ a broad belt across the deglacial subaqueous part of south-central Sweden (Fredén, 2009; map on p. 134; Bouvier et al., 2015). A significant pattern for this southern De Geer moraine belt is that that the ridges at~~). At~~ a distance from the eskers ~~these ridges~~ are arranged approximately perpendicular to the esker trends, regional striae direction and drumlins, while closer~~. Closer~~ to the esker ridges they~~, De Geer moraine ridges~~ usually turn in orientation, coming in at an increasingly oblique angle to an esker on both sides. This relationship is seen from the Quaternary deposits map of the Kumla–Örebro area (Fromm, 1972) (Fig. 3A) and is highlighted by the extraction of De Geer moraines and striae (Fig. 3B). This pattern has also been described from studies of aerial photographs over the area in the past (Bergdahl, 1959, 1961, 1965). Taken together, the geometric relationship between De Geer moraines and the Kumla esker indicates that the studied area was also occupied by a highly indented calving bay during ice retreat.

Materials and methods

The topographical data used in this paper is the LiDAR derived digital elevation model (DEM) supplied by the Swedish national mapping agency (Lantmäteriet; http//:www.lantmateriet.se). This arrives to the end user with an average vertical accuracy of ~0.1 m and a pixel resolution of 2 m. The data is pre-processed to remove both vegetation cover and urban areas down to 'true' ground level. The technical details for this height model can be found in Dowling et al. (2013). Data handling was carried out in ArcGIS© 10.0 and Matlab© R2014a.

Mapping of the landforms was manually carried out on hill-shade models illuminated from a variety of angles. The small scale drumlins are only visible with x5 height exaggeration applied and the careful manipulation of the angle of illumination. Typically the best angle of illumination with which to see these features is either from 120° or 250°. Switching between these angles and 90° reveals the small, shallow, drumlins. The mapping itself was carried out as part of the work outlined in Dowling et al. (2015), and the drumlins are part of that larger dataset. Height was extracted using the method of Spagnolo et al. (2012), whilst length and width were extracted using minimum bounding geometry (Napieralski and Nalepa, 2010).

Results

Landform descriptions

The studied Kumla–Örebro area (~13 by 8 km), depicted in Figs. 3 and 4, contains streamlined bedforms (drumlins) in two size ranges (Fig. 4). The larger features are typically 430-2200 m long, 110-400 m wide, and 8-15 m high (Table 1) and, when compared to the metrics of global datasets (Clark et al., 2009; Spagnolo et al., 2012), could be considered 'classic' drumlins. These drumlins are part of the general streamlined flow set of the wider region of the Närke plain and are aligned approximately north to south (Möller and Dowling, 2016). The second size range of streamlined bedforms is an order of magnitude smaller and is distributed at an angle to these larger features. Perpendicularly overlaid on these small-scale drumlins are suites of De Geer moraines (Fig. 4). The distribution of, and relations between, these geomorphic forms are further detailed in our LiDAR-derived DEMs over three chosen smaller type areas, the Härminge and Brickebacken sub-areas, to the east of the Kumla esker (Figs. 5 and 7), and the Stora Ulvgryta sub-area, to the west of said esker (Fig. 8).

The features in the Härminge sub-area (Fig. 5) clearly indicate the calving-bay orientation relationship between small-scale drumlins, De Geer moraines and the esker. The area (~7 km^2) hosts small-scale drumlins (n = 48) that are~~vary between~~ 41-245 m long and 10-71 m wide, with a P_{10}-P_{90} height of 0.4-1.8 m (Table 1). Drumlin axes are orientated ~35/215°. Draped over the drumlins is a dense set of De Geer moraines (Fig. 6), all trending ~305/125°. These are thus perpendicular to the Härminge small-scale drumlins, but skewed relative to the larger drumlins (e.g. right-hand side on Fig. 5). The De Geer moraines in the Härminge area (Fig. 5) measure~~ between~~ 25-832 m in length, 10-21 m in width and 2-3 m in height. The Härminge small-scale drumlins and the De Geer moraines associated with them are thus at an angle of ~38° to the north-south esker trend. It should be noted that for both the De Geer moraines and especially for the small-scale drumlins in this sub-area there is the potential for a shrouding effect (Finlayson, 2014; Spagnolo et al., 2014) when surrounded by on-lapping glacial/postglacial aquatic sediments (silt and clay; Fig. 3). In some areas with deep successions of aquatic sediments and/or organic deposits this shrouding effect can be several meters (e.g., Möller and Dowling (2016) for the nearby Hackvad drumlin field); this can come close to completely 'drowning' smaller geomorphic features.

The Brickebacken sub-area (Fig. 7) is due north of the Härminge sub-area (Fig. 4), covering about 24 km^2. Small-scale drumlins in this set (n = 155) are 68-176 m long, 17-57 m wide and 1.5-2.3 m high (P_{10}-P_{90} values). Drumlin axes are orientated ~35/215°, i.e. the same direction as at Härminge, but these features are here more densely packed. Bedrock outcrops associated with the drumlins are often detectable from the Quaternary mapping and from visual inspection of the hill shade model, suggesting that mapped drumlins are of the rock-cored type. As at Härminge, the drumlins are superimposed by De Geer moraines that trend ~305/125°, although some of the moraines start to shift towards a ~290/105° alignment towards the eastern margin of the demarcated area. The De Geer moraines are 12-264 m long, ~20-21 m wide and ~1-2 m high. The shrouding effect is likely minimal here, as the features are located on a slightly elevated till plain with no subaquatic sediments preserved between moraine ridges. However, just outside of our mapped subarea there are features drowned in subaquatic fine-grained sediment which are now only visible as crop marks in aerial photos and as faint shadows in the hillshade models.

The Stora Ulvgryta -sub-area (Fig. 8) is situated west of the Brickebacken area, covering about 30 km^2. Importantly, it is located on the western side of the Kumla esker (Fig. 4). The small-scale drumlins in this set (*n* = 54) have the same general pattern of morphometrics as the sub-areas on the eastern side of the esker. The drumlins are 65-241 m long, 22-70 m wide and 1-3 m high (P_{10}-P_{90} values) and have axes orientated ~350/170°. Rock outcrops associated with the mapped drumlins are often detectable from the Quaternary mapping and the hill shade model. The drumlins are sparsely distributed and overlain by a small number of De Geer moraines that are 55-183 m long, ~14-21 m wide and ~0.5-1 m high, trending ~70/250°.

Taken together, the orientation of the small drumlins and their associated De Geer moraines on opposite sides of the Kumla esker provide strong evidence of the geometric development of the calving bay and ice margin retreat in the Kumla-Örebro region, as well as indicating the local, late-stage ice flow direction.

Discussion

Advantages of using LiDAR terrain data

Without high resolution LiDAR it would be impossible to detect the small-scale drumlin features described here. Their small size, in particular their shallow height, makes their detection in the field or from traditional aerial photograph mapping very difficult. This is especially the case when located under forest cover, making the capability of LiDAR to 'look through' vegetation as important as a high spatial resolution for their detection. The work done here shows the ability of high resolution LiDAR datasets to create detailed reconstructions of palaeo-landform assemblages, combining both previously identified landforms and newly identified relationships between these landforms with newly discovered features. Furthermore, the mapping of De Geer moraines with LiDAR-based DEM's results in much denser and detailed patterns as compared to previous ground- and aerial photograph-based mapping (see also Bouvier et al., 2015).~~.~~ This enhancement is very evident when comparing their mapped distributions in Fig. 3B versus Figs. 4, 5, 7 and 8. This further strengthens any assessment of probable calving bay configuration.

Palaeo-calving bay formation

The pattern and direction of near-to-esker De Geer moraines provide evidence that the receding ice margin formed pronounced indentions – a calving bay – around the Kumla esker that formed transgressively backwards at the subaqueous outlet of the subglacial drainage at deglaciation of the area. As the bay retreated northwards it also opened out, i.e. the angle between the ice-front and the esker/drainage outlet increased as the margin moved north (see Fig. 9 and mapping in Fig. 4).

The retreat of water-terminating ice margins is due to a balance of and feedbacks between calving, topography and atmospheric warming (e.g. Venteris, 1999; Cook et al., 2005; Benn et al., 2007a). Localized areas with higher ice loss over longer or shorter time periods, caused by preferential calving at an active sub-surface drainage outlet (Benn et al., 2007b), might thus result in concave calving bays. According to Benn and Evans (2010) this is most likely the result of longitudinal extension occurring in conjunction with simple shear at the ice margin. The effect of this is to generate distinctive crevasse patterns along which the enhanced calving occurs, forming the concave planform of calving bays near eskers. An important factor in a given calving rate is water depth (Benn et al., 2007a); postulated palaeo calving bays across the subaqueously deglaciated south-central part of Sweden (Fig. 1) were evidently tied to the positions of the larger eskers of this area. This might indicate the importance of this factor: the eskers are usually situated in the lowermost positions of this once submerged landscape.

However, water depth differences along the receding ice margin were not that large. Possibly more important in controlling calving rate was the *per se* existence of the subglacial drainage conduits, marked in their deglacial positions by the resulting eskers. Melting of the ice above these conduits and in their immediate surroundings would thin the ice, reduce basal effective stresses and thus basal drag, introduce positive feedback into dynamic thinning and propagation of deep surficial crevasses up-glacier, thus resulting in localized increases in calving rate (e.g. Benn et al., 2007; Benn and Evans, 2010). A continuous fast differential ice loss close to the eskers as compared to the areas between the eskers would, however, theoretically mean that the calving bays would get progressively deeper with time.

When scrutinizing the maps of calving bay configurations as suggested from constructed varve isochrones, e.g. Strömberg (1989), see Fig. 2B, or further north in the county of Dalarna (Fromm, 1991) with very deep calving bays, it is evident that there was a tendency for calving bays to grow progressively deeper with time, but only over portions of their recessional paths. This suggests that the calving rate in the calving bays was larger than the regional ice recession rate only over shorter periods of time, i.e. intermittent periods of fast calving. This was followed by a reduction in the rate of ice loss back to the typical regional ice recession rate with the generated calving bay configuration moving back into a more typical marginal alignment.

Location of drumlin formation and ice flow adjustment

Based on their perpendicular relationship with the ice-marginal De Geer moraine ridges we argue that the orientation of the small-scale drumlins in the Kumla–Örebro area, as depicted in Fig. 4, reflects the direction of ice flow near the Kumla esker at a late stage of deglaciation. The smaller-scale drumlins formed within a near-marginal area where the regional north to south-directed ice flow had shifted as a response to the formation of an indented calving bay (Fig. 9). The orientation of De Geer moraine ridges changes slightly throughout the study area as the ice margin geometry was modified during retreat. However, these differences are too small to be able to associate individual drumlins to specific De Geer ridges. Thus it is not possible to establish whether an individual drumlin formed while the margin was only a few hundred metres away in distal direction or some kilometres, as its orientation remains roughly perpendicular to that of most De Geer ridges. Yet, since the orientation of the latter shifts abruptly on either side of the Kumla-esker it is almost certain that the maximum distance between the forming drumlins and the ice margin is represented by the distance to the esker. This has to be measured along the once existing ice flowlines as evidenced by the small-scale drumlins, and can be practically obtained by simply projecting down-flow the drumlin long axis until this intercepts the esker. In the other direction a hypothetical flow line would gradually fall into the primary N-S directed flow lines that are not influenced by the calving bay configuration. The measured distances of this varies from 1 km in the south of the study area (near the ‘x’ of the transect marked in Fig. 4), to 7.7 km, further north.

The concept of retreating margins controlling~~setting~~ drumlin orientations has previously been discussed~~set out~~ by Mooers (1989). In a time-transgressive model of drumlin formation located under the Rainy and Superior lobes of the Laurentide ice sheet, it was shown that the trend of drumlin axes was primarily set by a retreating ice margin. However, Mooers’ model only located this within a distance of 20-30 km of said ice margin, rather than the more proximal distance of approximately 1-7.7 km that we report here.

Formation time

Based on our proposed model of *where* the small-scale drumlins formed in relation to the ice margin it is possible to calculate the time frame over which individual/adjacent near-marginal drumlins were formed. This is a function of the time period over which the calving bay-adjusted ice flow was operating over the ice-bed interface of the area in question. Therefore it is possible to infer the maximum formation time from a known local ice recession rate. Ideally we would be able to use the De Geer moraine ridges to do this, and this was the original idea by De Geer (1989), i.e. that the ridges had geochronological significance in that they were formed annually. This has also lately been suggested from a study of Swedish De Geer moraines by Bouvier et al. (2015). However, such annuality has been rejected by, e.g., Hoppe (1959) and Strömberg (1965), as well as by Lindén and Möller (2005), who all argued that multiple moraines could form within the same year. We thus argue that we cannot use the mean distance between De Geer moraines in the Kumla–Örebro area as a reliable chronometer.

However, it is possible to use the Swedish varve chronology to gain an appreciation of local deglaciation time and the time frame over which the small-scale drumlins were formed. The close to parallel and regularly spaced isochrones between -1200 and -900 over and north of Stockholm (Fig. 1) suggest that these isochrones can, with a relatively high confidence, be transferred laterally west-southwest-wards. This allows us to infer that the whole Kumla-Örebro area was deglaciated between varve isochrones -1200 and -1100, i.e. in less than 100 years. This is then an absolute maximum time period for all the mapped small-scale drumlins to form as their formation must have taken place during the passage of the Kumla-esker calving bay, with their orientation showing an adjustment to this ice marginal configuration. The 20 varve-year isochrones of Strömberg (1989) between years -1200/-1100 give an annual mean steady state recession rate of ~220 m/yr. Although the recession rate value could have varied locally along the gradually receding calving bay margin due to differences in calving rates/events, and therefore not be a steady-state retreat, we argue that it can be used as a good average for the northwards propagation of the calving bay margin.

With this assumption in place the transect X-Y in Fig. 4 with a length of 7.7 km in the Härminge and Brickebacken sub-areas, was deglaciated within ~30-35 years from the first mapped De Geer moraine to the last. This was then a period that also time-transgressively sustained the NE to SW-directed ice flow towards the eastern flank of the calving bay at which point the smaller-scale drumlins were formed. A formation time of only a few decades is further reinforced by the situation verified in the Stora Ulvgryta sub-area, on the opposite side of the Kumla esker (Fig. 8). A~~Here a~~ SE-directed,~~ and~~ 5.3 km long, transect across~~ the time-transgressively formed~~ De Geer moraines draping the Stora Ulvgryta drumlins gives, under the same assumptions as above, a deglaciation time of the whole transect of ~24 years. The slight chronological difference between the two sides of the esker also demonstrates that De Geer moraines are not a reliable chronometer for ice retreat rate. There are sections along the X-Y transect (Fig. 4) over which there are very small spaces between the ridges (12 moraines over 1000 m; i.e. a mean spacing of 83 m) which means that the number of ridges formed could have been as high as 2-3 ridges per year or even more over shorter steps of ice margin retreat.

Our calculated period for the formation of the small-scale drumlins is a maximum time period, referring as discussed above to the total deglacial age span with a sustained ice flow direction from NE and NW on either side of the Kumla esker.~~, respectively.~~ Should the minimum distance to the~~ Kumla~~ esker of 1 km, verified for some of the drumlins, be taken into consideration, the formation time of these features is reduced to only 5 years. This is compatible with recent observations such as the repeat seismic and radar investigations under the Antarctic Rutford Ice Stream, which revealed a 10 m high and 100 m wide streamlined bedform forming/evolving within a period of only 7 years (Smith et al., 2007; King et al., 2009). In agreement with these results there is also a recent study on the formation time of drumlins at Fláajökull on Iceland (Jónsson et al., in press), similar in size to the ones analysed here, with a suggested ~29 year formation time-frame. This is particularly interesting as a modern example in a non-surge setting with a well-controlled formation time. The calculated drumlin formation time of our study also fits within the broad time frame for drumlin formation calculated by Rose (1989) of 8-292 years, falling within the lower end of that range. The calculations by Rose (1989) build on sediment transfer rates applied to volume of tills in their investigated drumlins; though an interesting approach this is hard to apply to the drumlins described here. This is because the transfer rate of till for our region is largely unknown and the volume of till in the drumlins is hard to evaluate as these features are likely rock cored, as drumlins predominantly are in southern Sweden (Dowling et al., 2015).

In summary, the small-scale drumlins identified here formed ~1-7.7 km behind a retreating calving bay ice margin and over formation periods of 5 to 35 years. The larger drumlins of the area, which are an order of magnitude larger than the small-sized features and which are parallel to the regional north to south-directed ice flow, should have formed over a much longer period. Our reconstructions are further supported by the following lines of evidence:

(i) Smaller drumlins over-print the larger drumlins. The survival of the larger drumlins, despite the near ice-marginal change in flow direction and subsequent sediment reorganisation into the smaller drumlins shown here suggests that the duration of the flow event that created the small-scale drumlins was not long enough, or lacked the erosive/deformative capacity, to alter the orientation of the large drumlins.

(ii) The small-scale drumlins are only present in connection to closely spaced De Geer moraines. This indicates that the small-scale drumlins only formed in places where the ice margin had a quasi-stable ice retreat rate without large calving events that could have generated large frontal retreats greater than several hundreds of metres.

Conclusions

We have found that small-scale drumlins in the Kumla–Örebro area are aligned – and thus formed – parallel to flow lines that were adjusted to the configuration of calving embayments in the receding ice margin at the last deglaciation. These embayments were located close to the position of where larger eskers formed and were the product of enhanced calving at the subaqueous outlets of the subglacial melt-water drainage. Furthermore, the area/calving margin under which our mapped small-size drumlins formed was likely deglaciated over a period of ~25-35 years, suggesting a maximum timeframe for their formation. To summarise, the key findings of this paper are:

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- Enhanced calving processes around the subaqueous outlets of well-developed subglacial drainage networks caused marginal ice flow direction to converge towards the outlet/resulting esker. The result of this was the formation of calving bays and an altered near-marginal ice flow direction. This is demonstrated by the geometric relationship of drumlins, De Geer moraines and the Kumla esker in the studied area.

- Mapped small-scale drumlins can form behind calving bays in response to the change in flow direction. This has been verified in the Kumla-Örebro region where the drumlins must have formed within c. 1-8 km of the active glacial margin.

- Our studies suggest that drumlins of the size described can form under major ice-sheets over very short time periods, 5-35 years.

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Captions and Tables

	n	*Mean Height*	*Height P_{10}*	*Height P_{90}*	*Mean Length*	*Length P_{10}*	*Length P_{90}*	*Mean Width*	*Width P_{10}*	*Width P_{90}*	*Mean Orientation*
Area 1	48	0.9	0.4	1.8	113.5	64.8	188.8	31	15.3	57.6	35-215
Area 2	155	1.5	0.8	2.3	112.7	68.4	175.3	33	17.7	56.4	30-210
Area 3	54	1.8	1	3	117.4	65	240.8	40.4	22.2	70.8	210-30

Table 1. Summary statistics for flow set morphometrics. All values are in meters and rounded to 1 decimal point. Mean orientation is given to the nearest whole degree, the values representing the orientation of the a-axis, with the upstream polarity given first.

Fig. 1. (A) Overview of NW Europe. Red dashed line = proposed Fennoscandian Ice Sheet margin to the west/south at LGM (Svendsen et al., 2004); blue dashed line = the Younger Dryas Ice Marginal Zone (Mangerud et al., 2011). (B) Map of southern Sweden (for location, white box in (A)), showing areas above and below the highest shoreline (marine limit in the west), and altitude of the highest shoreline at deglaciation. The highest shoreline east of Billingen is the shore altitude for the Baltic Ice Lake prior to its 2nd drainage at retreat from Billingen after the Younger Dryas advance, while highest shoreline isobases north thereof were formed in the following Baltic Basin stages Yoldia Sea and Ancylus Lake (Björck, 1995), following the northwards receding ice margin. Inferred ice-marginal positions during the Younger Dryas are according to Lundqvist (2009). Deglacial varve isochrones are transferred from Brunnberg (1995) (south of Stockholm), Strömberg (1994) (Lake Vänern-Askersund) and Strömberg (1989) (north of Stockholm). Base map compiled from the Swedish National Atlas (Fredén, 2009). Red box marks the investigated area between Örebro and Kumla (Fig. 3) and orange boxes mark the positions of Figs. 2A and 2B. Typical ice flow for the local area was north-south.

Fig. 2. Examples of reconstructed calving bays arround some of the larger eskers north of Lake Mälaren, south-central Sweden (Fig. 1B), based on varved clay measurements (redrawn from Plates 2 and 3 in Strömberg (1989)). Eskers are shown in green, striae outcrop locations are marked with a red with the direction indicated by the red line and the black lines indicate varveVarve isochrones. The latter are based on lateral correlation of basal varves and are drawn with 20 years interval. Indicated, and indicated varve years for deglaciation is in the relation to the so called 'zero year' in the Swedish varved clay chronology (Cato 1985, 1987). Measured youngest striae are marked from oposite sides of the esker/calving bays, indicating near-marginal ice flow re-adjustment (from the general ice flow direction north to south), being approximately perpendicular to the calving bay configuration at ice-margin gradual retreat. (A) The moderately indented calving bay gradualy forming arround the Uppsala esker at ice recession between varve years -1100 and -920 (180 years) over a distance of ~40 km (mean recession ~222 m/year). Note a slight increase with time in claving bay depth towards the north. Calving bay depths and widths are hard to define, but depths are only in the order of

2-4 km, marked as shallow indentions in the close to west to east-treding receding ice margin. Centre of the map is N59˚43’; E17˚36’ (position marked with orange box in Fig. 1B). (B) The strongly but variably indented calving bays gradually forming around the Enköping and Gävle eskers at ice recession between varve years -800 and -700 (100 years) over a distance of ~47 km (mean recession ~470 m/year). Calving bay depths north of isochrone -800 vary between 6-15 km and widths between 6-17 km at bay mouths, with both calving bay depth decreases and increases at gradual ice margin recession. Centre of the map is N60˚25’; E16˚53’ (position marked with orange box in Fig. 1B).

Fig. 3. Overview of Quaternary sediments and landforms in the Kumla–Örebro area. (A) Extract of the Quaternary geology map Örebro SW (Fromm, 1972). For full legend, see online version at http://resource.sgu.se/produkter/ae/ae5-karta.pdf. (B) Extract of De Geer moraines (blue lines), eskers (green) and youngest striae (red bullet arrows) from (A). The north to south trending Kumla esker has nearby De Geer moraines trending towards WSW to SW west of the esker, while De Geer moraines east of the esker trend towards SE, indicating local ice margin rearrangement from the general W–E trend around the esker and thus suggesting the formation of a calving bay at the northwards retreat of the subaqueous ice margin (Bergdahl 1959, 1965; Fromm 1972). Place names Härminge, Brickebacken and Stora Ulvgryta, and their black frames, indicate the positions of LiDAR-derived DEM scenes shown in Figs. 5, 7 and 8, revealing much denser patterns of De Geer moraines than shown here as based on ground survey mapping.

Fig. 4. Overview LiDAR-based mapping of drumlins and De Geer moraines in the Kumla-Örebro area (the same geographic extent as in Fig. 3). Drumlins are divided into large-scale drumlins (black outlines) showing the same N-S trend as for the rest of the streamlined flow sets of the Närke plain (Möller and Dowling, accepted), while the small-scale drumlins (red) when occurring deviate from this regional direction, trending NW-SE and NE-SW on the respective sides of the Kumla esker. De Geer moraines are perpendicular to the small-scale drumlins and thus trend NE-SW and NW-SE on opposite sides of the said esker. Coverage of the three zoomed in Lidar DEM’s in Figs. 5, 7 and 8 are marked by black frames.

Fig. 5. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Härminge subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration. ~~The colour ramp has been inverted.~~

Fig. 6. A drone image (view towards NE) of De Geer moraines in the Härminge subarea (Figs. 4 and 5). Five De Geer moraine ridges are here protruding through surrounding clay, which are the agricultural fields in the fore- and mid-ground. The moraine closest to the viewer is approximately 50 m long. The ridges trend NW-SE and tentative ice margins at their formation are indicated by white hatched lines.

Fig. 7. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Brickebacken subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 120° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

Fig. 8. LiDAR-based mapping of small-scale drumlins and De Geer moraines in the Stora Ulvhytta subarea (geographic coverage shown in Fig. 4). Hillshade illumination is from 250° with an azimuth of 25° and an x5 vertical exaggeration. The colour ramp has been inverted.

Fig. 9. Idealised ice flow re-organisation and calving bay formation (left-hand scenes). The selected area is a random snapshot of the main Kumla esker body (pannels A, C and E), along with an idealised geomorphological evolution sketch map (pannels B, D and F). The area in front of the depicted calving embayments was occupied by the marine Yoldia Sea with water depths in the order of 80-130 m. (A) Flow lines further back from the ice margin at formation of the large-scale streamlined bed forms. (B) Large drumlinoids (black elipses) developed parallel to the regional ice flow direction further back from the receeding ice margin. (C-D) A calving bay is formed at ice margin recession (arbitrarily chosen time-transgressive position), in which apex the esker (green line) formed as lined-up subaqueous fans at the subglacial tunnel mouth. Ice flow (indicated by blue flow lines) was re-arranged from regional flow to be ajusted perpendicular to the new ice margin configuration of the approaching calving bay. De Geer moraines (blue lines) formed gradually at the receeding ice margin at an ~30-35˚ angle to the N-S directed esker. Small-scale drumlins (red) formed parallel to the near-marginal flow lines. (E-F) The final stages of the calving bay, the bay has opened out and ice flow is readjusting to a north-south direction. No small drumlins are seen to form with this flow orientation. The De Geer moraines formed at this stage are not perpendicular to the small drumlins formed early on.