DRUMLIN FORMATION TIME: EVIDENCE FROM NORTHERN AND CENTRAL SWEDEN

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ABSTRACT. Large-scale drumlins occur abundantly throughout central and northern Sweden. Whereas many drumlins in the north are an integral part of a relict glacial landscape >100,000 years old, those to the south are generally interpreted as of last deglaciation age. Typically, the latter ones have not been overprinted by younger glacial landforms. Despite this apparent difference in formation history, drumlins in both regions have similar directional and morphological characteristics. A systematic analysis of >3000 drumlins in (i) areas within relict landscapes, (ii) areas with an ambiguous deglaciation age assignment, and (iii) areas within deglacial landscapes, indicates that these latter deglaciation drumlins differ clearly in both shape and size from drumlins in the other two types of landscapes. In addition, numerical modelling indicates that basal melting conditions, a prerequisite for drumlin formation, prevailed only for a very limited time over much of northern Sweden during the last deglaciation, but lasted for longer periods of time during earlier stages of the Weichselian. A reconnaissance radionuclide bedrock exposure date from the crag of a large drumlin in the relict landscape indicates that glacial erosion, and presumably drumlin formation, at this location predated Marine Isotope Stage 7. We conclude, therefore, that the large-scale drumlins of central and northern Sweden did not form during the last deglaciation, or during any other specific ice flow event. Instead, we suggest that they were formed by successive phases of erosion and deposition by ice sheets of similar magnitude and configuration.

Key words: drumlins, ice sheet, Sweden

Introduction

Reconstructions of former ice sheets utilize a wide range of glacial geology data. The spatial evolution of the ice sheets is typically reconstructed from analysis of the glacial geomorphological record, and the timing of different glacial events is constrained by geochronology and stratigraphical records (Boulton and Clark 1990; Kleman and Borgström 1994). Of the glacial landforms that are used to infer ice flow patterns, flow-parallel glacial lineations are by far the most commonly used (e.g. Boulton *et al.* 1985, 2001; Kleman 1990; Clark 1993). Flow-parallel glacial lineations include drumlins, flutes, and glacial striae. They are particularly well suited for this type of analysis because they all show fairly accurately the direction of warm-based ice flow. Unfortunately, these landforms are often treated together, despite large variations in size or shape. If we regard glacial geomorphological maps, for example, a drumlin symbol (e.g. Fig. 1) can either represent individual forms, from a 10 m long flute up to a 70 km long mega-drumlin (cf. Clark 1993), or be used as a general map symbol to indicate the general direction of multiple features. Further, sometimes drumlins are used together with information on the direction of glacial striations, which typically are 10–100 cm long. These mapped features may differ in length by seven to eight orders of magnitude. Moreover, if we compare the bulk of material required to excavate or accumulate these landforms, there is a volume variation of 16 orders of magnitude, from *c.* 10^{-7} m^3 (glacial striae; 10 cm long, 1 mm wide, and 1 mm deep) to *c.* 10^9 m^3 (mega-lineation; 70 km long, 500 m wide, and 50 m high). Hence, the time it takes to form large drumlins, for example, is likely vastly different from the formation of striae and small drumlins alike. If all these landforms were to be treated indiscriminately within an ice sheet reconstruction, biased or erroneous results may arise.

If drumlins are crosscut by younger glacial landforms, the inference is that they have formed during

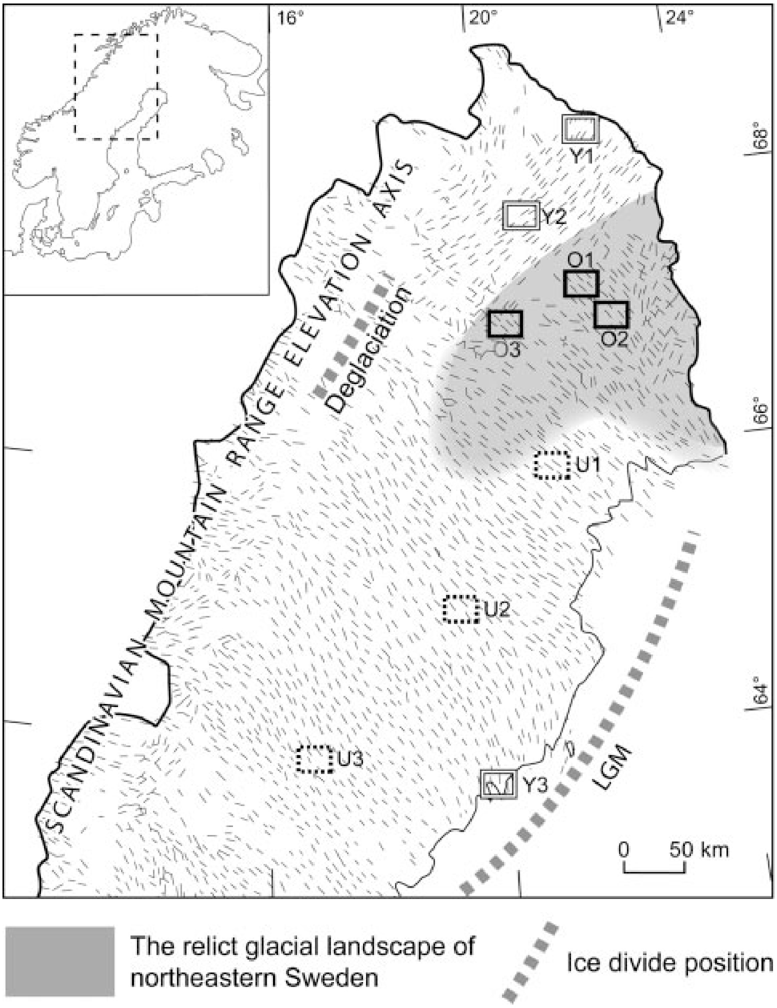

Fig. 1. Location map. General pattern of drumlin distribution and direction in central and northern Sweden, after Hättestrand (1998). The outline of the relict area of northeastern Sweden is a compilation from data in Kleman *et al.* (1997, 1999), Hättestrand (1998), and Kleman and Hättestrand (1999). Ice divide positions are derived from Kleman *et al.* (1997).

an earlier ice flow event. If, on the other hand, they lack the signs of younger crosscutting, they are considered to have formed during the last deglaciation (Clark 1993; Kleman and Borgström 1996; Hättestrand *et al.* 1999). This strategy in reconstructing the conditions during past ice flow events appears straightforward and sound. However, the implicit assumption is that the ice flow direction during the last deglaciation differed in direction from previous glacial events.

A well-developed relict glacial landscape consisting of large drumlins, eskers, and hummocky moraine, of an inferred Early Weichselian age, exists in northern and central Sweden (Lagerbäck 1988; Lagerbäck and Robertsson 1988; Kleman *et al.* 1997; Hättestrand 1998). These landforms are in places crosscut by younger small-scale flutes and lateral meltwater channels, formed during the last deglaciation (Fig. 2). The relict landscape is sharply truncated to the north by a well-defined deglacial landform system dominated by drumlins and eskers, the 'Kiruna fan', extending through Finland towards the Barents Sea coast (Kleman *et al.* 1997; Hättestrand *et al.* 1999). To the south, the boundary of the relict glacial landscape is not well expressed. This is because the ice flow direction during the last deglaciation closely matched the ice flow direction indicated by the relict landscape in this region, i.e. ice flow from the northwest. Hättestrand (1998) noted that the drumlins of the relict landscape appear to have a morphology and direction very similar to the drumlins in the last deglaciation land-

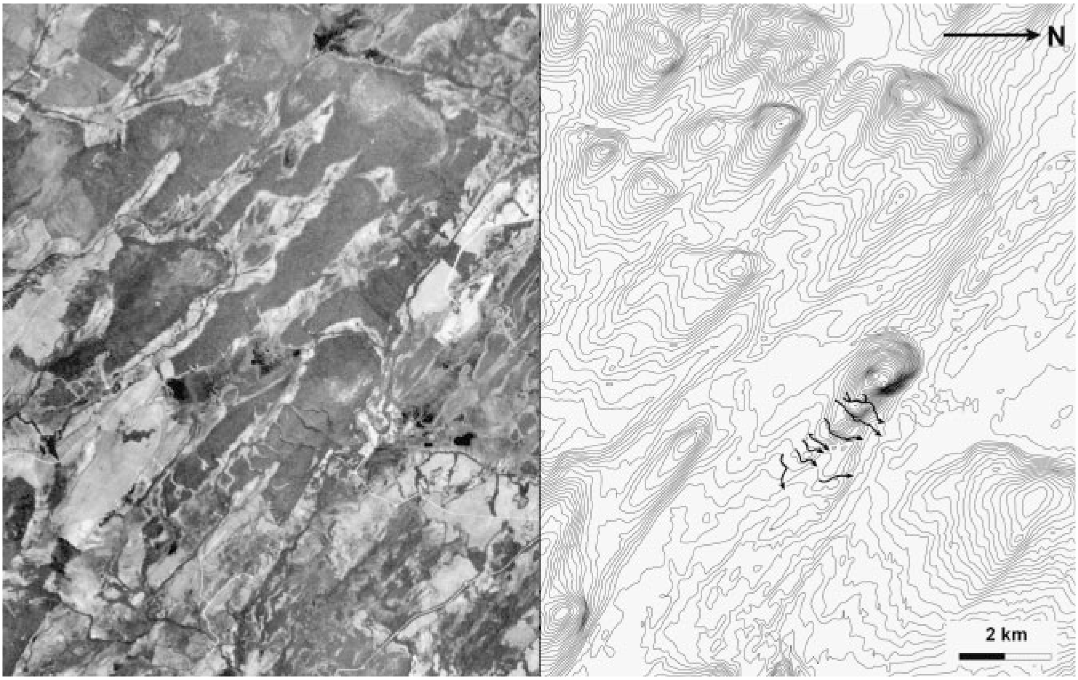

Fig. 2. Aerial photograph and contour map (interval 5 m) of drumlins in area O1. Most drumlins in this area have a crag-and-tail morphology. Note the lateral meltwater channels indicated by arrows, crossing the tail of one of the drumlins in the centre. These channels indicate a deglaciation ice surface slope, and, hence, ice flow direction, at right angle to the drumlins. The drumlins themselves are interpreted to be older than the early Weichselian. The location of the area covered by the aerial photograph and map is show in Fig. 4.

scape to the south. He therefore suggested that the drumlins of both landscapes may have experienced a similar formation history, and, therefore, that they were formed by consecutive ice sheets with roughly the same ice flow direction.

In order to test whether the drumlins in northern and central Sweden belong to two different populations, or if they all have a similar formation history, we mapped and measured more than 3000 drumlins distributed over nine areas in northern and central Sweden (Fig. 1). Three of the areas are located in the relict glacial landscape (O1–O3), three are located in landscapes of last deglaciation age (such as the Kiruna fan; Y1–Y3); and three are located in areas with an ambiguous deglacial age assignment in the inner part of central and northern Sweden to the south of the relict landscape (U1–U3).

We follow the premise that careful mapping and analysis of the drumlins will reveal systematic similarities or differences in morphology between the three regions, thus improving our ability to correlate areas where the age of the drumlins is unknown to either the old relict landscape or to the young deglaciation landscape.

Subsequently, we compare the morphometric analysis with numerically modelled Fennoscandian ice sheet dynamics for the last glacial cycle (Näslund *et al.* 2003). One output parameter of the model is the basal sliding distance, i.e. the accumulated length of wet-based ice flow over a particular area. This yields a measure of the amount of ice that was available to form drumlins of a particular size and direction (in this case ice flow from the NW sector is of interest), for a particular time period.

Finally, we present cosmogenic nuclide data from one of the larger drumlins in the relict landscape of northeastern Sweden, to gain insight into the absolute age of the drumlins in this area.

Area description

Y1–Y3

Drumlins occur in distinct deglaciation landform assemblages within the Kiruna fan (Y1 and Y2) and on the coast of northern Sweden (Y3). At these locations, they are situated in the proximal part of well-defined landform systems that extend from the Younger Dryas moraines in northern Norway and eastern Finland, respectively, to the eastern flank of the northern Swedish mountains (Kleman *et al.* 1997). Prior to deglaciation, area Y3 was situated underneath the proximal part of an ice stream in the Bothnian Bay, which terminated in the westward continuation of the Salpausselkä end moraine belt of Younger Dryas age (Kleman *et al.* 1997). Because of the direct geographical links between these drumlin swarms and the Younger Dryas end moraines, we feel confident that the three 'young' drumlin landscapes are of last deglaciation age.

O1–O3

The drumlins in the relict areas O1–O3 are partly overlain by, and therefore predate, a relict deglaciation assemblage consisting of eskers and hummocky moraine (Veiki moraine) of inferred marine oxygen isotope stage (OIS) 5d/5c transition age (Lagerbäck 1988; Lagerbäck and Robertsson 1988). Lagerbäck and Robertsson (1988) suggested that the drumlins were formed during the same event (OIS 5d) as the eskers and hummocky moraine, because they were all indicating ice flow from the NW and because sections in the upper 4–6 m of the drumlins display the same type of grey till (with the clast fabric predominantly oriented NW–SE) that is present also within the hummocky moraine. Lagerbäck and Robertsson (1988) correlate this till with till bed III in Finland (Hirvas and Nenonen 1987). Later, Kleman *et al.* (1997) adopted this explanation in their reconstruction of the Fennoscandian ice sheet through the last glacial cycle. However, we want to stress that these drumlins are up to 200 m high. Consequently, sections in the upper few metres of the drumlin need not be representative for the bulk of the drumlin. This suggested to Hättestrand (1998) that these drumlins have experienced an even longer history of formation, comprising multiple depositional, deformational and erosional events.

U1–U3

The drumlins in the interior parts of central and northern Sweden, south of the relict landscape, have traditionally been attributed to the last deglaciation. They have therefore been used as an important piece of evidence in reconstructing the ice flow direction during the last deglaciation (e.g. Kleman *et al.* 1997; Kleman and Strömberg in press). However, this conventional wisdom has been questioned by Hättestrand (1998), who argued that the time available to construct such large drumlins by ice flow from the northwest was too short during the deglaciation. In this study, we test the hypothesis that these drumlins are of deglaciation age (presently uncertain age; U1–U3), by comparing their morphology to the morphology of relict (O) and deglaciation (Y) drumlins.

Drumlin composition and formation processes

There is a noticeable gap in our knowledge on the stratigraphy of drumlins in northern and central Sweden. This is primarily because most sections only are a few metres deep (at most 15–20 m), although many drumlins or drumlin tails probably consist of at least 100 m of sediment. Hence, stratigraphic information only exists, albeit infrequently, for the uppermost sediments in these drumlins. The drumlins in central and northern Sweden are primarily of the crag-and-tail type, with a bedrock hill constituting the crag (e.g. Högbom 1905; Lundqvist 1987; Hättestrand 1998). Even more symmetrical 'classical' drumlins may expose bedrock outcrops (e.g. Johansson 1972). We expect, therefore, that bedrock commonly constitutes an important component of the total drumlin volume. Drumlins in northern Sweden that lack bedrock outcrops are mostly confined to areas with young drumlins (Y1–Y3). The few studies on drumlin composition indicate that classical drumlins are commonly composed of the same basal till that exists in surrounding terrain, whereas crag-and-tails usually display tills interbedded with glacially tectonized extensive waterlain sediment lenses (Johansson 1972; Lundqvist 1987; Eklund 1991).

Because of this lack of stratigraphic control, there is limited evidence of drumlin formation processes in northern and central Sweden. However, there is a general tendency to favour erosional or deformational processes over depositional processes (Högbom 1905; Hättestrand *et al.* 1999), although all three processes were likely involved (Johansson 1972). We refer to Benn and Evans (1998), for a more extensive discussion on drumlin formation theories.

Methods

Geomorphological mapping

The drumlins in each of the nine areas were mapped by stereoscope interpretation of black-and-white aerial photographs at the scale of 1:150000. Each area covers 26×18 km (468 km^2), equal to the coverage of one stereopair of the aerial photographs. The potential geometric resolution of these images is 4.8 m, which ensured that image quality was not the limiting factor in mapping the drumlins. In contrast, only drumlins larger than approximately 50 m long and a few metres high can be observed due to limits imposed by the forest canopy. The outline of each drumlin was mapped on transparent overlays on the aerial photographs. For cartographic and practical reasons, all drumlins smaller than 400×150 m were mapped as a single line. The overlays were scanned and digitally transferred to a base map with 10 m elevation contours for determination of length, width and height of individual drumlins. The smallest drumlins (single line) were assigned standardized values (a length of 300 m, a width of 75 m, and a height of 5 m) that we consider to be close to true averages. We also approximated the volume of the drumlins, the *index volume*, by simply taking the average cross-section area of the drumlins multiplied by their length. Because most drumlins are tapered, we approximated the average width (W_a) to equal 70% of the maximum width and the average height (H_a) to equal 50% of the maximum height. The average cross-section area was calculated as $A_a = 0.6H_aW_a$. The index volume yields an approximate size measure, rather than true sediment volumes (because most drumlins include rock cores), but it still enables a comparison of the average drumlin size between different areas. The longitudinal orientation of the drumlins was generally consistent within each area and is presented as an average value only.

Of critical importance to this comparison of drumlin properties is that the different areas are similar in their physiography and geology: all nine areas are situated in undulating hilly terrain or on plains with residual hills, with a typical relief of 100–300 m (Lidmar-Bergström 1996). Till dominates the surficial deposits in all areas (covering *c.* 70–90% of the land surface; e.g. Hirvas *et al.* 1988). Although the thickness of the till sheet is not known very well, it is believed to be at least 6 m thick, on average (Hirvas *et al.* 1988), and exhibit a maximum thickness of almost 60 m (Fredén 1994). Hence, sediment availability should not be a restricting factor for drumlin formation.

Numerical ice sheet model

Computer ice sheet models can simulate, for example, ice sheet configurations, ice flow directions, and basal ice temperatures of an ice sheet during a glacial cycle. Several such modelling experiments have been performed on the Fennoscandian ice sheet, with varying objectives (*e.g.* Fastook and Holmlund 1994; Siegert and Dowdeswell 1995). In recent years, it has become increasingly meaningful to compare results from ice sheet models with geological information, since computers are faster and ice sheet models more refined. The Fennoscandian ice sheet has been the subject of a few of these studies, with varying degrees of detail (Siegert *et al.* 2001; Arnold and Sharp 2002; Näslund *et al.* 2003).

The numerical model used here to simulate the Weichselian glaciation over Fennoscandia is a time-dependent thermo-mechanical ice sheet model developed by Fastook (for details see Fastook and Chapman 1989; Fastook 1994; Fastook and Prentice 1994; Johnson and Fastook 2002). The main input to the ice sheet model is a digital elevation model describing landscape topography and a parameterized mass balance at each grid node. The grid size in the present study was *c.* 70×100 km. The ice flow parameters were set according to Paterson and Budd (1982) and Payne *et al.* (2000). Calculated ice temperatures, together with ice density variations with depth, control ice hardness and ice flow velocities. The climate forcing of the ice sheet model was achieved by varying the mean annual air temperature at sea level according to the temperature curve from the GRIP ice core (Dansgaard *et al.* 1993). Model input data, setup, and calibration follow Näslund *et al.* (2003).

We present modelled basal ice flow directions over a specified period of time and for a specific region as rose diagrams (Näslund *et al.* 2003). The entity presented in the diagrams is basal sliding distance (including deformation of subglacial sediments), under thawed bed conditions. It is calculated by multiplying the basal ice flow velocity with time that the velocity persisted in a certain direction, integrated over 5° intervals. Subsequently these values were summed up for the two time slots of interest, the complete glacial cycle and the last 5000 years of glaciation. Rose diagrams for these time periods were constructed for the areas with drumlins of unknown age (U1–U3).

Cosmogenic nuclides

A bedrock sample was collected for cosmogenic nuclide analysis from about 70 m below the summit of the Teletöisentunturi drumlin at 575 m a.s.l., in area O1 (Fig. 3). The sample was collected from a horizontal outcrop of coarse granite on the down-

Fig. 3. (a) Photograph of two drumlins at the northwestern corner of area O1. These drumlins, about 2–3 km long and 100 m high and displaying a clear crag-and-tail morphology, are representative for drumlins in most areas in northern and central Sweden. Note that these drumlins are located in the relict glacial landscape of northeastern Sweden (Fig. 1), and are therefore at least 100,000 years old. (b) Photo of the strongly weathered summit surface of the Teletöisentunturi drumlin in the northwestern corner of area O1, indicating long exposure to subaerial weathering after drumlin formation. The hammer marks the cosmogenic nuclide sample location (Table 3).

stream crest of the crag, just above the till-tail. The analytical procedure adopted to extract beryllium from the sample follows standard procedures by Kohl and Nishiizumi (1992), and has been detailed by Stroeven *et al*. (2002b). Approximately 18 grams of pure quartz were separated for determination of $^{10}Be/^{9}Be$ by accelerator mass spectrometry (AMS) at the Purdue Rare Isotope Measurement (PRIME) Laboratory. Procedural blanks were used to correct the measured ratio. We used a sea level, high latitude (>60°) ^{10}Be production rate of 5.1 ± 0.3 atoms g^{-1} a^{-1} scaled to altitude and latitude to calculate cosmogenic ages (Stone 2000). A correction was applied for the sample thickness using an attenuation coefficient of 160 ± 10 g cm^{-2} and a density of 2.8 g cm^{-3} for rock.

Results

Morphometry

Between 150 and 589 drumlins were mapped for each of the nine areas, totalling 3280 individuals (Figs 4, 5; Tables 1, 2). The maximum number of drumlins in any one area is likely considerably higher than the 589 recorded in Y3 because almost 50% of its area is covered by the Bothnian Bay.

Table 1. Morphometric characteristics of the drumlins.

Area	N	Length, *L* Average (m)	Length, *L* Max. (m)	Width, *W*, average (m)	Height, *H*, Average (m)	*L*/*W*, average	Index volume*, average (10^6 m^3)	Orientation, average (°)
O1	184	1471	5600	324	29	5.83	10.23	316
O2	428	829	6400	224	13	3.80	1.43	324
O3	150	1335	7500	341	28	4.73	20.18	316
U1	279	1138	4800	305	33	4.13	8.74	319
U2	445	791	6400	207	16	4.23	3.84	318
U3	381	729	3500	213	23	3.87	1.99	322
Y1	528	703	3500	152	9	5.98	0.59	37
Y2	296	492	1400	169	10	3.37	0.25	60
Y3	589**	737	2200	149	7	6.24	0.23	357
Total	3280	830	7500	208	16	4.80	3.34	NA

* Index volume = $0.6\,L \times 0.7W \times 0.5H$ (accounting for the tapering of the drumlins)

** The Bothnian Bay covers almost 50% of area Y3. The true number of drumlins is probably significantly larger than 589.

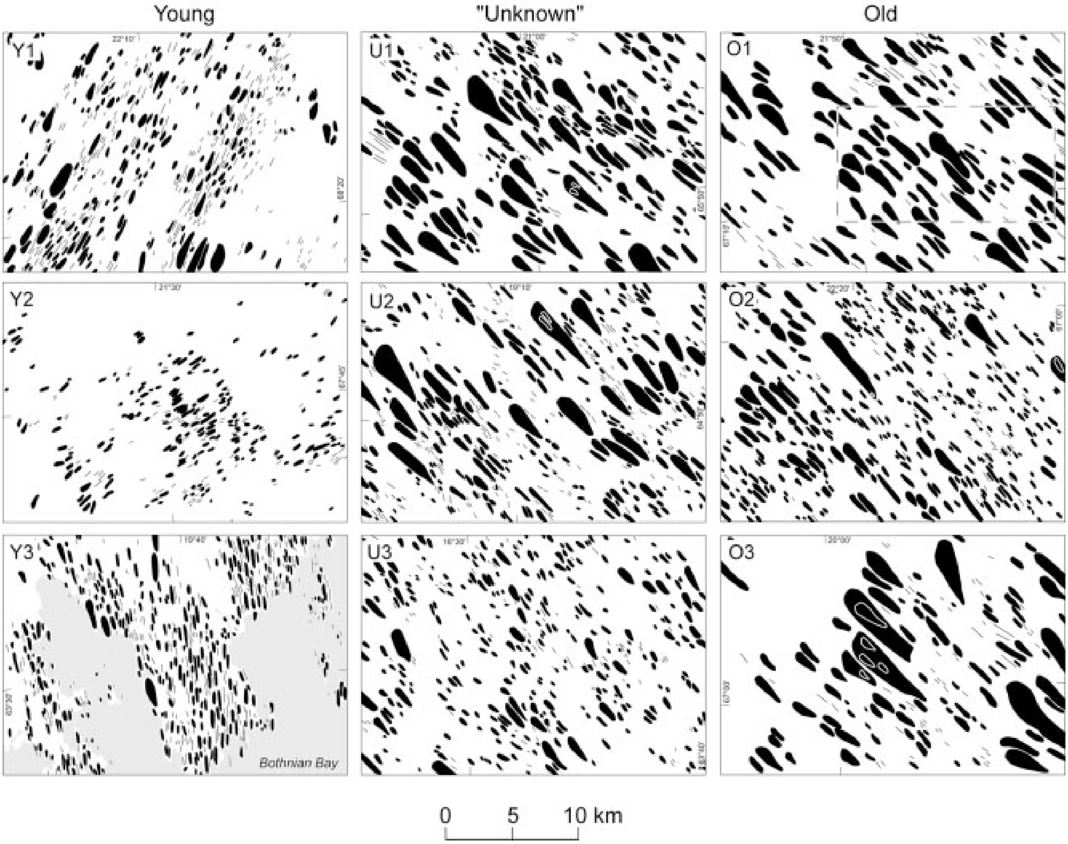

Fig. 4. Nine maps of the drumlins equally distributed over the three age categories represented: young, unknown and old. The hatched frame in area O1 marks the location of the aerial photograph in Fig. 2.

The length of individual drumlins varies between 300 m and 7500 m, with an average of 830 m. In this context, it should be noted again that all drumlins smaller than 400 m were given a standard value of 300 m. About two-thirds of the drumlins are between 400 m and 700 m long, and the number of longer drumlins decreases exponentially with length to about 3500 m. There are 29 drumlins larger than 3500 m.

There are significant variations in drumlin morphometry between the areas with old, young, and unknown-aged drumlins (Tables 1, 2). The areas with old drumlins have the largest drumlins, with an average length of 1.2 km and a maximum length 7.5 km. In general, the drumlins in areas of unknown age are morphometrically more similar to the drumlins in areas of old age than to the drumlins in areas of young age. This is particularly true for

Table 2. Summary of the morphometric characteristics of the drumlins in areas of old, unknown and young age.

Drumlin age	*N*	Length, *L*, average (m)	Width, *W*, average (m)	Height, *H*, average (m)	*L*/*W*, average	Index volume, average (10^6 m^3)
Old	762	1212	296	23	4.79	2.23
Unknown	1105	886	242	24	4.08	1.36
Young	1413	644	157	9	5.20	0.20

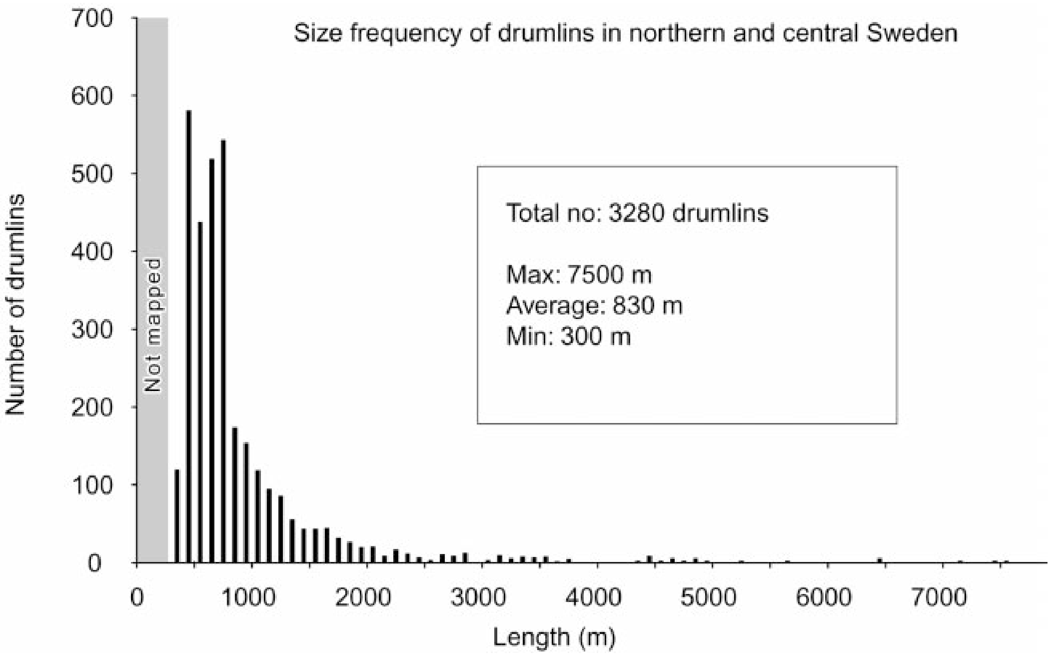

Fig. 5. Frequency diagram of drumlin length for all mapped drumlins.

the width and the height of the drumlins. The drumlins in areas of old and unknown age have an average width of around 240–300 m with a maximum at 900–1900 m, while the young drumlins have average widths of around 160 m and maximum widths ranging from 400 to 900 m. The average height of the drumlins in areas of old and unknown age is around 25 m, but only around 10 m for the drumlins in areas of young age. Maximum heights are 100–220 m for the old and unknown aged drumlin areas, and 30–80 m for the young drumlin areas. It should also be noted that areas within each category are not homogeneous. For example, the morphometry of drumlins in area U3 appears more similar to the morphometry of drumlins in areas of young age than to the morphometry of drumlins in areas U1 and U2.

The average L/W ratio varies between 3.37 and 6.24 for all areas, with individual maximum values of 10 to 11. There are no clear differences in L/W ratios between areas, except for a slight predominance for more elongated drumlins in areas Y1–Y3. Irrespective of the indiscriminate L/W ratios, drumlins in areas of old and unknown age are almost invariably of the tapered crag-and-tail type, whereas drumlins in the areas of young age are mostly more symmetrically cigar- or spoon-shaped (Fig. 4).

There is a remarkable consistency in drumlin orientation for all areas with drumlins of old and unknown age. The drumlin orientation in these six areas varies by only 8° (between 316° and 324°) over a 200 km distance. In contrast, the orientation between the two young drumlin areas in the Kiruna fan alone (Y1 and Y2) is more variable (difference of 23°), despite closer proximity. This is probably a result of strongly changing ice flow configuration at the time of drumlin formation.

Model results

The numerical ice sheet model was used to calculate basal sliding distances over the areas with drumlins of unknown age (Fig. 6). It yielded that the total basal sliding distance from the northwestern sector during the Weichselian glaciation was 650, 1400 and 1600 km for U3, U2, and U1, respectively. Only less than 1 km, 35 km, and 35 km of basal sliding distance can be accounted for during the last 5000 years of deglaciation for these same areas. It should also be noted that according to the model, the direction of ice flow was highly consistent over these areas for periods when basal sliding was active. Other ice flow directions certainly established over these areas, such as ice flow from the east em-

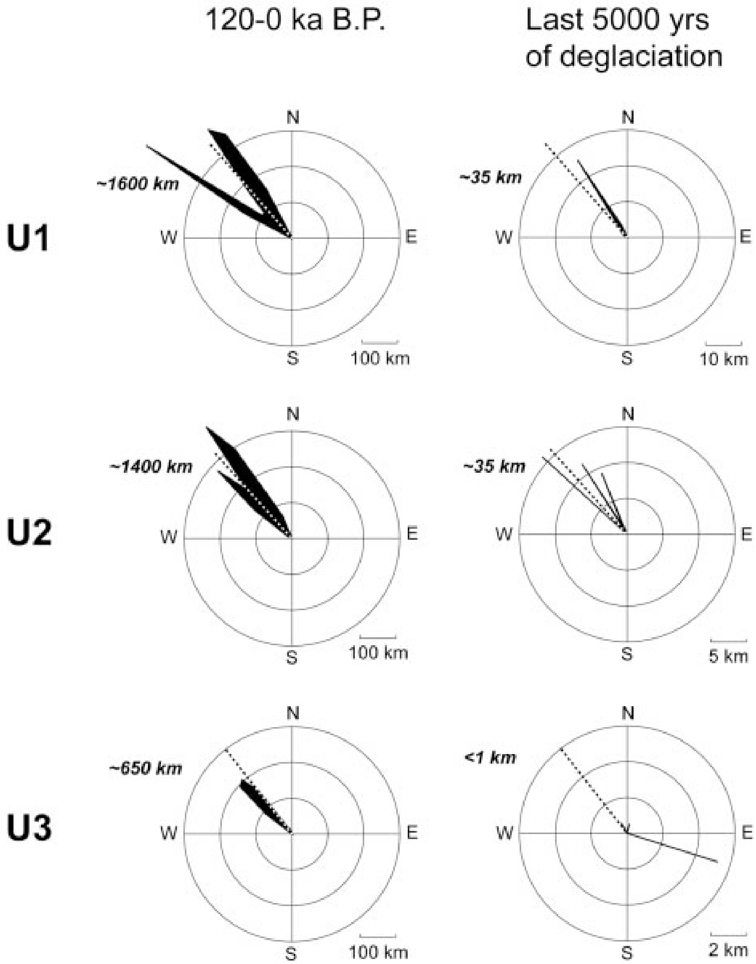

Fig. 6. Rose diagrams of modelled basal sliding distances for areas U1, U2, and U3, during the Weichselian and for the last deglaciation (last 5000 years of ice coverage for each area). Note that the radial scales of the rose diagrams vary. The numbers in bold italics are the total basal sliding distances from the NW sector. The broken line indicates average drumlin orientation (Table 1).

anating from an ice divide over the Bothnian Bay during the Last Glacial Maximum (Fig. 1). However, basal sliding was mostly inactive because the ice sheet was predominantly frozen to its substrate throughout most of the last glacial cycle (Kleman *et al.* 1999).

Cosmogenic nuclide age

The apparent ^{10}Be exposure age of the Teletöisentunturi drumlin is 41.8 ± 5.4 ka (Table 3). Models of deglaciation over northern Scandinavia, although deviating in detail, typically predict ice-free conditions during the early Holocene, i.e. around 10 ka (e.g. Lundqvist 1986; Dansgaard *et al.* 1993; Kleman *et al.* 1997; Boulton *et al.* 2001; Kleman and Strömberg in press). We have recently confirmed this deglaciation estimate from detailed site investigations using cosmogenic nuclide abundances in significantly eroded upland and lowland bedrock surfaces and in upland erratics (Fabel *et al.* 2002; Stroeven *et al.* 2002a,b). Clearly, the cosmogenic nuclide concentration in the sample taken from Teletöisentunturi includes an inheritance signal from one or more previous exposure events.

To further constrain the exposure history of the sample requires knowledge of the glaciation history of the region in order to delineate periods of ice sheet coverage (and, hence, sample shielding) from ice-free conditions. We calculate the minimum total history required to produce the exposure and shielding duration for the drumlin, using the DSDP 607 marine benthic foraminifer oxygen isotope record as a proxy for the approximate duration of

Table 3. Cosmogenic nuclide data.

Sample	Location	Elevation (m a.s.l.)	^{10}Be concentration (10^5 atoms g^{-1})*	Apparent exposure age (ka)	Minimum DSDP 607 total history (ka)
98–01	Teletöisentunturi	575	1.83 ± 0.07	41.8 ± 5.4	202

* Sample was collected at latitude >67°N and measured nuclide concentration has been normalized to sea level using Stone (2000). Uncertainty in exposure age represents one standard error in AMS counting statistics, and uncertainties in radioactive decay and absolute production rate.

periods of ice sheet cover versus ice-free conditions (cf. Kleman and Stroeven 1997; Stroeven *et al.* 2002b). In this model the ice sheet covered the Teletöisentunturi drumlin site during marine oxygen isotope stage 5 (OIS 5) stadials and throughout OIS 4, 3 and 2 (Lagerbäck and Robertsson 1988; Kleman *et al.* 1997), yielding only short-lived periods (*c.* 10 ka each) of exposure during interglacial and interstadial events, including 10,000 years in the Holocene. The model accounts for cosmogenic nuclide accumulation during ice-free periods and radionuclide decay during shielding (ice cover), and can therefore address complex exposure histories (cf. Fabel *et al.* 2002; Stroeven *et al.* 2002b). Assuming that no erosion occurred during glacial and interglacial periods the model yields a minimum total history of 202 ka for Teletöisentunturi (Table 3).

Discussion

Morphology/morphometry

The drumlins of unknown age are more similar in morphometry to the drumlins of old age than drumlins of young age. Particularly U1 and U2 appear to be similar to O1 and O2 (Fig. 4). The relations here are ambiguous, but they offer an indication that the drumlins of unknown age share a similar formation history to the drumlins of old age. The drumlins of young age are different in that they are low (average of <10 m) and have low index volumes (average below 0.6×10^6 m^3). Hence, it appears that although late glacial ice flow was able to generate drumlins with a fairly extensive areal coverage (individual drumlins are up to 3.5 km long and 900 m wide; see, for example, Y1, Fig. 4), it did not form drumlins of significant thickness.

It is important to note that individual till beds, and other sediment sequences between till beds, in northern Sweden, are typically only a few metres thick (e.g. Nordkalott Project 1986). This applies to tills and sediment sequences from the Late Weichselian and earlier stages. Records of sediment thickness are generally not from drumlin tails (where lee-side positions may have promoted enhanced sediment infill), but from locations with complex stratigraphies and thin individual beds. Notwithstanding this information mismatch, because drumlin sediments are in the order of 100 m thick, it appears therefore likely that they required several ice flow events to accumulate. This is not direct evidence that the landforms themselves formed over many ice flow events (unless they are pure accumulation drumlins), but it does indicate that the very large drumlins have a complex formation history.

The frequency diagram of drumlin length (Fig. 5) indicates that the drumlins of northern Sweden form one coherent landform category. This result contrasts with a previous suggestion by Clark (1993) that lengths of flow-parallel lineations exhibit distinct frequency groups, such that small-scale flutes, drumlins, and mega-scale glacial lineations should be treated as separate landform types. For the length range under consideration here (300–7500 m), our results reveal a single skewed frequency distribution, peaking around 400–700 m.

Ice sheet model time versus drumlin size

The size of a flow-parallel lineation depends on a number of parameters, such as length of time, basal ice-flow velocity, and basal sediment availability (cf. Clark 1993). If the landform is created by particle-by-particle addition or removal of material, the primary limiting factor controlling its size is that the basal sliding distance must at least match the length of the drumlin. This means that a 1 km long drumlin cannot be formed in shorter time than it takes basal ice to flow 1 km over that particular site, regardless of formation process. For a basal flow velocity of for example 10 m a^{-1}, this would imply an absolute minimum formation time of 100 years. However, in order to allow for enough time to build up thick drumlins (by deposition, deformation, or erosion processes), it is probably realistic to assume that the basal sliding distance required equals several times its length.

This reasoning was explored qualitatively by Hättestrand (1998). During the last deglaciation there was a steady shift in ice flow directions because the ice divide migrated from the Bothnian Bay to its final position in the eastern part of the mountain range (e.g. Ljungner 1949; Kleman *et al.* 1997). Hence, ice flow directions shifted continuously over northern Sweden and it is likely that there was not enough time of ice flow with a consistent direction to build large numbers of kilometre-sized parallel drumlins. Furthermore, because the frozen bed core of the ice sheet was continuously shrinking during the deglaciation (Kleman and Hättestrand 1999), one would potentially expect longer periods of northwesterly warm-based ice flow over the coastal areas of northern Sweden compared to the inland areas, where the last ice remnant was positioned. By analogy, coastal areas should have experienced longer periods of favourable formative conditions, and, hence, display larger drumlins. However, this cannot be observed (Hättestrand 1998). In areas of similar relief, coastal and inland areas tend to display drumlins of similar size.

Our interpretation of the modelled basal sliding distances (Fig. 6) is that it is impossible to form up to 3.5 km long drumlins in U3 during the last deglaciation with <1 km of basal sliding. The model predicts about 35 km of basal sliding for areas U1 and U2 during the deglaciation, which, in qualitative terms, could suffice for the formation of drumlins that are at most 6.5 km long. However, considering that U1 and U2 experienced 1600 and 1400 km of warm-based ice flow from the NW during the last glacial cycle, respectively, formation of their drumlins may have occurred at any time during this period, and it would be misleading to attribute them solely to the deglaciation.

In conclusion, the morphological/morphometric characteristics and the modelled basal sliding distances suggest to us that: (i) the drumlins of old and unknown age have a similar formation history; and (ii) most of the large drumlins have a formation history of a complexity and length beyond the deglaciation phase. We therefore suggest that consecutive ice sheets, with similar ice flow directions, formed the large drumlins of old and unknown age cumulatively. During each glacial phase the shapes of these drumlins were modified by erosional, depositional and deformational processes.

It is noteworthy in this context that the elevation axis of the northern Scandinavian mountain range has a NNE–SSW (235–240°) orientation. An ice sheet centred over the mountain range and terminating onto the north-Swedish lowland would therefore have an ice flow direction roughly perpendicular to the orientation of the mountain range, i.e. 325–330°. This is close to the average orientation of drumlins in areas of old and unknown age (316–324°), and may indicate that these drumlins were formed by such west-centred mountain ice sheets. These types of ice sheets have been the dominant glaciation style during the Quaternary, and have persisted for a total accumulated time of 50–80% of the Quaternary (Porter 1989; Kleman and Stroeven 1997; Fredin 2002). Hence, ice flow from the NW sector has dominated over much of northern Sweden since the late Tertiary. We consider this supporting evidence to suggest that the large drumlins in northern Sweden were formed cumulatively.

Modelled cosmogenic age of the relict drumlins

Our qualitative reasoning on the possible age of the drumlins is also corroborated by reconnaissance cosmogenic isotope data. The apparent exposure age of the Teletöisentunturi drumlin of 41.8 ± 5.4 ka (Table 3), however, has limited explanatory value on its own. It does indicate a substantial period of subglacial preservation because apart from the 10 ka of Holocene exposure (e.g. Stroeven *et al.* 2002b), approximately 32 ka of Pleistocene exposure remains to be accounted for (inheritance signal). Our most conservative, hence minimum, inferred total history is that the drumlin formed by significant glacial erosion of the crag (>2 m of bedrock eroded to remove the inherited ^{10}Be concentration) and deposition of glacial debris in the tail before OIS 7A. Subsequently, the crag of the drumlin has remained unmodified from an erosional point of view, but particle addition to the till tail may have occurred. The presence of a soil cover (partial shielding) and the presence of surface erosion, for example, would further increase our interpretation of the total history. The minimum total history of 202 ka of the Teletöisentunturi drumlin would render previous estimates of an Early Weichselian age of at least this particular northwest drumlin (Lagerbäck and Robertsson 1988; Kleman *et al.* 1997) insufficient. Rather, as the last event of erosion took place during OIS 7 stadials (or earlier), it supports the notion described above that the large northwest-oriented drumlins in northern and central Sweden are old features and cannot be linked to any specific glacial event.

Conclusions

The large crag-and-tail type drumlins that occur over much of central and northern Sweden are similar in their morphometrical properties, despite often being referred to as belonging to different glacial events, separated by up to 100,000 years. Also, we have shown, both in qualitative and quantitative terms that there is limited formation time available during the last deglaciation, whereas there is plenty of time available earlier during the last glacial cycle (and during earlier glaciations). Hence, we conclude that none of these large crag-and-tail drumlins can be linked specifically to the last deglaciation or, indeed, to the last glacial cycle. Rather, we interpret them to have formed over many consecutive glaciations with similar ice flow directions. Therefore, they reflect the dominant ice flow directions during the Quaternary, towards the southeast, consistent with an ice divide over the Scandinavian Mountain Range. Because it is apparent that large scale drumlins probably form over several glaciations, this would carry with it the prerequisite that intervening ice flow directions, with an oblique angle to the major drumlins, occurred only during periods of (i) cold-based conditions, (ii) warm-based conditions in near-ice divide positions (low horizontal basal velocities), or (iii) short periods of warm-based conditions (short enough to prevent major destruction of the pre-existing landforms).

This conclusion implies that greater caution must be taken when assigning an age to drumlin fields, for example when used in ice sheet reconstructions. This is especially true for laterally extensive drumlin systems with a consistent direction, suggesting sheet-flow conditions. In addition, we conclude that not only large-scale glacial landforms in bedrock (fjords, U-shaped valleys, and lake basins), form over several glaciations and reflect average glacial ice flow conditions, but also landforms in unconsolidated Quaternary deposits.

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