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Are long subglacial bedforms indicative of fast ice flow?

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It has been suggested that extremely long subglacial bedforms (e.g. attenuated drumlins and mega-scale glacial lineations) record former areas of fast-flowing ice and that bedform elongation ratio is a useful proxy for ice velocity. Despite the availability of much data pertaining to the measurement and analysis of subglacial bedforms, these assumptions have rarely been explicitly addressed in detail. In this paper, we demonstrate that long subglacial bedforms (length:width ratios ≥10:1) are indicative of fast ice flow. Using satellite imagery, we mapped over 8000 lineaments associated with a highly convergent flow pattern near Dubawnt Lake, District of Keewatin, Canada. This flow pattern is unusual in that it displays a large zone of convergence feeding into a main 'trunk' and then diverging towards the inferred ice margin. The 'bottleneck' pattern is taken to record an increase and subsequent decrease in ice velocity and we analysed transverse and longitudinal variations in bedform morphometry. The main trunk of the flow pattern (down-ice of the convergent zone) is characterized by mega-scale glacial lineations of great length (up to 13 km) and high elongation ratios (up to 43:1). The down-ice variations in elongation ratio reflect exactly what we would expect from a terrestrial ice stream whose velocity increases in the onset zone passes through a maximum in the main trunk and slows down as the ice diverges at the terminus. It is suggested that any unifying theory of drumlin formation must be able to account for the association between long subglacial bedforms and fast ice flow, although it is not assumed that fast ice flow always produces attenuated bedforms. A further implication of this work is that many more ice streams may be identified on the basis of attenuated subglacial bedforms, radically altering our views on the flow dynamics of former ice sheets.

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Elucidating the influence of ice sheets on the ocean-atmosphere system and predicting their future stability demands an understanding of former ice sheets and their interactions with climate change (MacAyeal 1992; Hughes 1992; Clark *et al*. 2001). A range of geomorphological evidence is available to reconstruct the spatial extent and thickness of palaeo-ice sheets (e.g. terminal moraines and trimlines), but the distribution of subglacial bedforms is arguably the most informative evidence, providing information regarding their flow patterns and position of ice divides (Boulton & Clark 1990a, b; Kleman & Hättestrand 1999; Clark *et al*. 2000). It has also been recognized that specific subglacial bedforms can be attributed to certain conditions at the ice-bed interface and mapping them at the ice-sheet scale has uncovered the dynamic nature of palaeo-ice-sheet behaviour and associated changes in their basal thermal regime (e.g. Boulton & Clark 1990a; Kleman & Hättestrand 1999).

The geometry of subglacial bedforms may reveal something about the processes acting at the ice-bed interface. Despite no general consensus on the origin of drumlins, for example, many workers would agree that the diversity in their morphometry reflects the large variability of controlling factors (e.g. sediment availability, ice velocity, etc.). However, clear-cut relationships have often remained elusive. In a comprehensive review of the drumlin literature, Menzies (1979) commented that 'many relationships that have been suggested in the past remain untested and therefore exist only as hypothetical statements'. Here, we examine the assumption that attenuated drumlins and mega-scale glacial lineations are indicative of fast ice flow. It has been argued that these bedforms record former areas of fast flowing ice (Clark 1993) and that bedform elongation ratio is a useful proxy for ice velocity (e.g. Hart 1999). Despite the availability of data pertaining to the measurement and analysis of subglacial bedforms, these hypotheses have rarely been rigorously tested.

Long subglacial bedforms and fast ice flow: a brief history

Much of the early work on drumlin morphometry established the view that they were an equilibrium form produced by the action of overriding ice. It was logical, therefore, that faster ice velocities and/or unidirectional ice flow would produce more streamlined features and several authors noted this apparent relationship (e.g. Alden 1905; Wright 1912; Hollingworth 1931; Charlesworth 1957; Chorley 1959).

Quantitative work by Heidenreich (1964) on the

Peterborough drumlin field (Ontario, Canada) found that drumlin length and width tend to increase in a predictable manner until a critical width is reached. Thereafter, only an increase in length is observed. He speculated that the increase in elongation ratio after a critical width is likely to be governed by sediment availability and/or ice velocity. In contrast, Trenhaile's (1971) analysis of six drumlin fields in southern Ontario found no evidence that the width:length ratio is dependent upon width attaining an equilibrium value after which only length continues to increase.

Other workers have argued that the constancy of flow direction is likely to be a more significant factor than ice velocity in controlling the elongation of a bedform (Doornkamp & King 1971; Mills 1987). Mills (1987) presented evidence which showed that high elongation ratios occur where the standard deviation of drumlin orientation is least (i.e. parallel bedforms), arguing that longer drumlins tend to occur along the central axis of glacier lobes, where the ice-flow direction is more constant (cf. Charlesworth 1957). It should be remembered, however, that the central zone of a lobe is likely to be flowing faster than those areas nearer the lateral margins.

Variations in drumlin elongation ratios have also been explained in terms of variations in ice velocity and thickness. Jauhiainen (1975) analysed several drumlin fields in north Central Europe and concluded that the large variability in elongation ratios both within and between individual drumlin fields can be explained by variations in ice pressures. This work was criticized by Menzies (1979) because it failed to recognize the importance of the differing properties of the underlying sediment. For example, in the Woodstock drumlin field, Ontario, Canada, Piotrowski (1987) found that smaller, more elongate drumlins are comprised mainly of finer grained material, whereas the larger more 'oval' drumlins are comprised of generally coarser grained till. Rose (1987) viewed these 'lithological' factors as independent controls which introduce variability to what would otherwise be a relatively uniform subglacial bedform continuum where longer bedforms are produced by thicker, faster ice flow.

More recent work has invoked the activity of palaeo-ice streams to explain attenuated subglacial bedforms and the observed variations in elongation ratios within specific drumlin fields. Dyke & Morris (1988) reported a zonation of drumlin sizes within a convergent erratic dispersal plume associated with ice stream activity on Prince of Wales Island, Arctic Canada. Drumlins within the dispersal plume were larger near its axis, where presumably flow was fastest. Smaller drumlins were found in the upstream convergent zone and towards the margins of the inferred ice stream, reflecting the expected patterns in ice velocity.

Mitchell (1994) discovered similar relationships in the western Pennines of northern England. He found that shorter drumlins occurred in close approximation to inferred ice divides and the more elongated bedforms depicted zones of convergent (and presumably faster) ice flow. Mitchell (1994) argued that drumlin elongation records the former driving stresses of the ice sheet (i.e. higher stresses produce longer bedforms) but that the resistance of the bed to deformation is also important.

If subglacial till deformation is an important control on the fast flow of some ice streams (cf. Alley *et al.* 1986), then the deforming material might be attenuated in the downstream direction. However, if pervasive deformation is inhibited, some workers have suggested that the development of elongated bedforms may be hindered. This scenario was invoked by Boyce & Eyles (1991), who suggested that decreased duration of subglacial sediment deformation was responsible for a downstream decrease in drumlin elongation ratio in the Simcoe Lobe of the Laurentide Ice Sheet. A similar downstream decrease in drumlin elongation ratio characterizes the M'Clintock Channel palaeo-ice stream bed, Victoria Island, Arctic Canada (Clark & Stokes 2001). They argued that it is related to a reduction in the availability of sediment for subglacial deformation immediately prior to ice stream shut-down.

Several arguments were given by Clark (1993) to suggest why mega-scale glacial lineations (up to 70 km in length) are most likely to record the location of former ice streams. Assuming point initiation of features and their downstream attenuation, long bedforms may arise from high velocities over short timescales or slower velocities over longer timescales. As more evidence is being uncovered which suggests that former ice sheets changed their volume and area rapidly, the latter option becomes less likely (cf. Andrews *et al.* 1983; Boulton & Clark 1990a, b; MacAyeal 1993). This led Stokes & Clark (1999) to postulate highly attenuated bedforms (elongation ratios >10:1) as a specific geomorphological criterion for identifying palaeo-ice streams. Hart (1999) performed a more quantitative analysis to substantiate this proposition by matching variations in elongation ratios across the Lake Cayuga area of the New York State drumlin field with the lateral velocity patterns across two contemporary ice streams. This lateral variation in elongation ratios, whereby longer bedforms occur towards the central axis of flow within a lobe/ice stream, is well documented (e.g. Dyke & Morris 1988; Mitchell 1994) and provides strong evidence that bedform attenuation is related to ice velocity.

To summarize, three main factors have been advocated to account for attenuated bedforms both within and between drumlin fields:

1. Long duration of ice flow combined with constancy of direction.
2. High ice velocities.
3. Longitudinal/transverse/random variations in sediment characteristics beneath the ice sheet.

Methodology

Our study focuses on a distinctive flow pattern trending in a northwesterly direction, north of Dubawnt Lake, District of Keewatin, Canada (Fig. 1). This flow-set has been mapped previously (e.g. Bird 1953; Lee 1959; Shilts *et al*. 1979; Aylsworth & Shilts 1989a, b) and is also represented on the Glacial Geological Map of Canada (Prest *et al*. 1968). Aylsworth & Shilts (1989b) speculated that the flow pattern could have been produced by an ice stream, and Boulton & Clark (1990b) attributed it to a late glacial event (*c*. 10 000 yrs BP) related to a southeast shift in the Keewatin Ice Divide. Kleman & Borgström (1996) identified the flow pattern as a type landscape for a 'surge fan' in their glaciological inversion model for reconstructing former ice sheets.

Of most importance to this investigation is the unusual shape of the flow pattern (Fig. 1). It can be seen that it exhibits a highly convergent zone up-ice that feeds into a narrow 'trunk' and then diverges again towards the inferred ice-sheet margin (Fig. 1). We take this 'bottleneck' pattern to reflect ice velocities that increase down-ice, reach a maximum in the narrow trunk and then decrease again towards the lobate terminus. Furthermore, the flow-set is in no way topographically controlled, adding to the evidence that the flow convergence is attributable to an increase in ice velocity and was not simply steered by underlying topography (Stokes 2000). The shape of this flow

Fig. 1. Location map of the Dubawnt Lake flow-set. Mapping from Landsat MSS imagery was concentrated on the southern half of the flow-set because of cross-cutting bedforms in the north producing a complication. The flow-set is gridded at 20 km intervals in the centre of the flow-set but these broaden up-ice and down-ice such that each grid square contains a sample representative of the palaeo-flow line immediately up-ice or down-ice. Note the position of the three flow corridors 'A', 'B' and 'C'. In total, over 11 000 lineaments were mapped. Ice-flow direction from southeast to northwest.

pattern provides an ideal template for testing the assumption that long bedforms are indicative of fast ice flow. If this assumption is valid, then we would expect to find more elongated bedforms in the narrow trunk of the flow-set and smaller bedforms up-ice and down-ice.

Satellite imagery (Landsat MSS; spatial resolution 80 m) was geocoded and processed to highlight geomorphology and over 11 000 lineaments were digitized on screen, mainly from the southern half of the flow-set (cf. Clark 1997 for review of methodology). Lines were digitized representing the long axis of the bedform and the following lineament parameters were measured: length and width (used to calculate elongation ratio: length/width), orientation, and parallel conformity (standard deviation of orientation for a sample of lineaments). In addition, the surface area of each bedform was calculated by approximating it with an ellipsoid so that the degree of packing (surface area of bedforms per unit area) could be calculated in addition to density (number of bedforms per unit area).

Bedform characteristics of the Dubawnt Lake flow-set

All of the lineaments that were identified as part of the Dubawnt Lake flow-set are shown in Fig. 1 with the inferred palaeo-flow lines, gridded into flow corridors at 20 km intervals. In the centre of the flow-set, lineaments were binned into 20 by 20 km grid squares parallel to ice flow. Immediately up-ice and down-ice the flow corridors were broadened to reflect the convergence and divergence of the former flow lines. The flow-set is reconstructed as having a maximum length of around 450 km. In the convergent 'onset zone' (*c.* 0–100 km down-ice) the flow-set approaches widths of 305 km and this narrows into the main 'trunk', which maintains a fairly constant width of around 140 km. Towards the inferred margin, the lobate terminus broadens to around 190 km. The surface area of the flow-set is estimated to be around 72 000 km^2.

The geology of the ice sheet bed is characteristic of the Canadian Shield, comprised of granitic gneiss interrupted in places by sedimentary and volcanic strata (Aylsworth & Shilts 1989a). The basement rocks (e.g. granites) can be broadly described as 'hard rock', largely resistant to glacial erosion. In contrast, the sedimentary outcrops were more friable, yielding abundant glacial debris which probably influenced the glacier dynamics (Aylsworth & Shilts 1989a).

Elevations across the ice-sheet bed (taken from 1:250000 topographic maps; contour interval 20 m) range from 170 to 250 m in the onset zone, lowering to 150 to 200 m in the main trunk of the flow-set before climbing to between 200 and 300 m towards the terminus. Any topographic control on the flow pattern or its margins is negligible given its large size (Stokes 2000).

The down-ice variation in mean bedform length for each of the three flow corridors A, B and C is shown in Fig. 2. A distinctive pattern reveals that bedforms are longest approximately half way down the flow-set between around 200 and 280 km down-ice. The lineations increase from an average length of 750 m (maximum 9636 m) in the onset zone to an average of 4000 m (maximum 12 248 m) in the main trunk (between 100 and 300 km down-ice), after which they steadily decrease in length towards the terminus.

Down-ice variations in average lineament width are shown in Fig. 3. It can be seen that the peaks in average width do not coincide with the peaks in average length. Average widths of 400 m (maximum 990 m) peak between 100 and 160 km down-ice and this indicates that the longest bedforms are not necessarily the widest bedforms. Rather, an increase in streamlining is observed around 200 km down-ice. This is confirmed

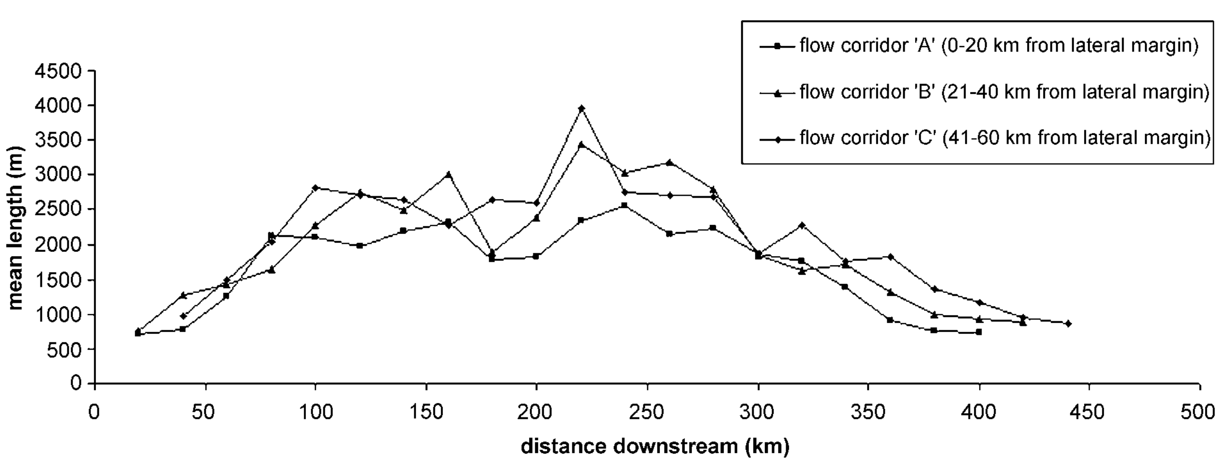

Fig. 2. Down-ice variations in mean bedform length along the Dubawnt Lake flow-set. See Fig. 1 for flow corridor location.

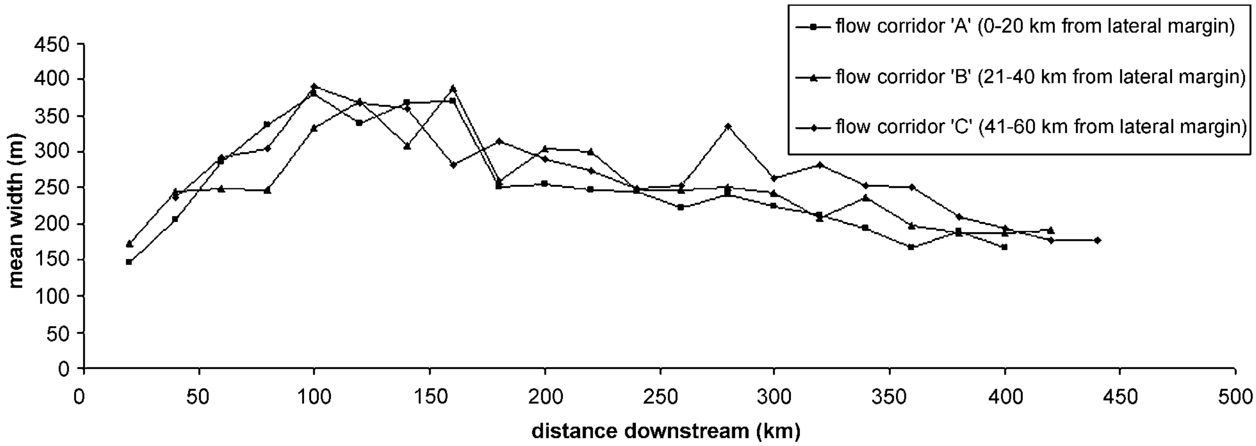

Fig. 3. Down-ice variations in mean bedform width along the Dubawnt Lake flow-set. See Fig. 1 for flow corridor location.

by plotting the down-ice variation in average elongation ratio for each of the three flow-corridors (Fig. 4).

Average elongation ratios (length/width) peak between 200 and 300 km down-ice (Fig. 4). Here, the bedforms comprise mega-scale glacial lineations (cf. Clark 1993) of great length (up to 13 km) and high elongation ratios (up to 48:1). Fig. 5 is a map of mean elongation ratios for the southern half of the flow-set which illustrates how the bedforms become more attenuated immediately down-ice of the flow convergence. Fig. 6 is a Landsat ETM+ image of a sample of these bedforms from the centre of the flow-set. They exhibit a remarkable degree of parallel conformity with their neighbours and over an area of 720 km^2 in the main trunk, the standard deviation of lineament orientation does not exceed 3.8°.

In addition, bedforms are generally longer, wider and more elongated towards the central axis of the flow-set (comparing results between flow corridors A, B and C on Figs. 2–4). Lineaments also tend to become more closely packed together and occupy greater surface areas towards the central axis of the flow-set (*c.* 240 km down-ice). Fig. 7 is a map of bedform packing (percentage lineament surface area per unit area) for the southern half of the flow-set. It can be seen that the pattern resembles that of bedform elongation ratio, indicating that lineaments not only get longer in the narrowest part of the flow-set, but also become more closely packed together and occupy greater surface areas.

Discussion

Are long bedforms (attenuated drumlins and mega-scale glacial lineations) indicative of fast ice flow?

The attenuated drumlins and mega-scale glacial linea-

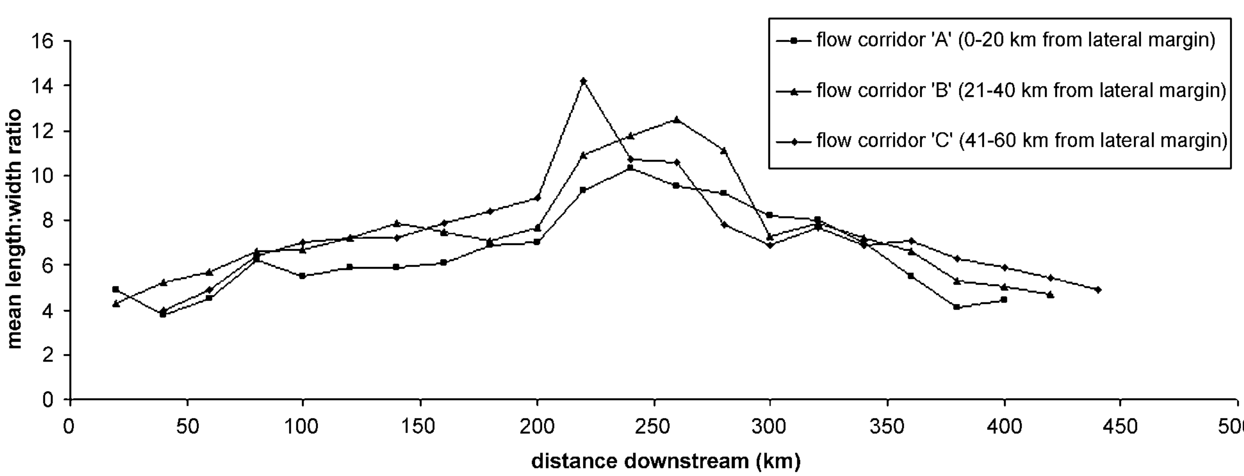

Fig. 4. Down-ice variations in mean bedform elongation ratio (length/width) along the Dubawnt Lake flow-set. See Fig. 1 for flow corridor location.

tions from the Dubawnt Lake flow-set bed could have been formed by (i), rapid ice velocities, (ii) slow ice velocities over a long time period, or (iii), arise from variations in sediment characteristics beneath the ice sheet.

Given the strongly convergent flow pattern, the abrupt southern margin of the flow-set (a characteristic of ice streams), and the fact that neither was controlled by topography (cf. Kleman & Borgström 1996; Stokes 2000), we reject the idea that the flow-set was produced by slow ice velocities over a long time period. In addition, we argue that the parallel conformity of the bedforms, which gives the appearance of a ridge/groove structure, can only have been generated by rapid ice flow (see Fig. 6). If the flow pattern were produced over longer time periods we would expect lineaments to display a variety of orientations, arising from fluctuations in flow directions, producing a time-transgressive or 'smudged' imprint (cf. Clark 1999). The superimposition of the Dubawnt Lake flow-set across older flow patterns also confirms that it was a relatively short-lived event prior to deglaciation (cf. Boulton & Clark 1990b; Kleman & Borström 1996).

The alternative, therefore, is that the attenuated bedforms and mega-scale glacial lineations resulted from variations in sediment characteristics rather than from enhanced ice flow. It is difficult to reconcile this hypothesis with the evidence in favour of fast ice flow (i.e. abrupt lateral margin, convergent ice flow), but we acknowledge that sedimentary characteristics beneath

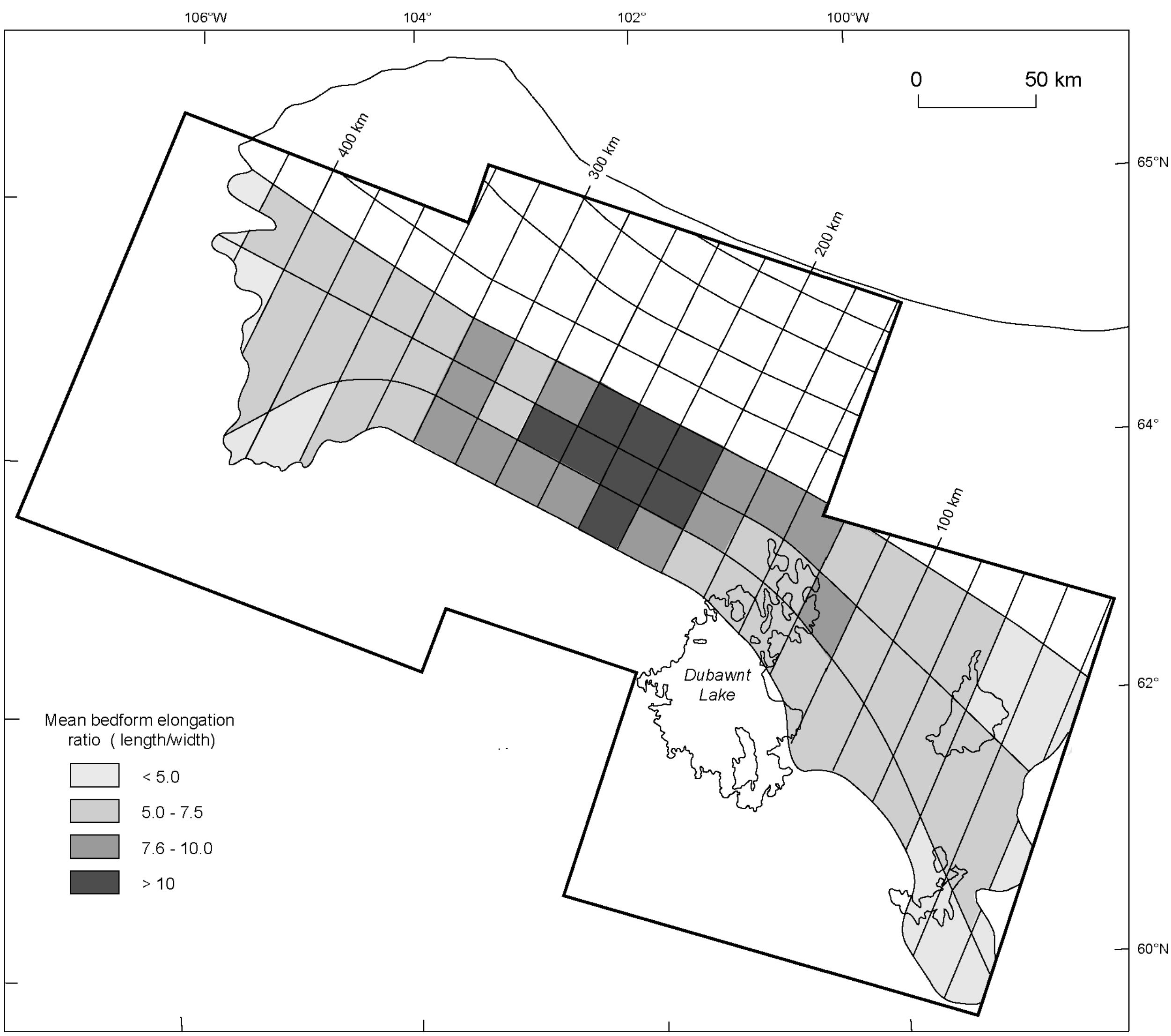

Fig. 5. Variations in bedform elongation ratios along the southern half of the Dubawnt Lake flow-set. Although there is a degree of 'patchiness', elongation ratios would appear to match the expected velocity pattern, whereby ice speeds up in the onset zone reach a maximum in the main trunk and decreas towards the divergent terminus.

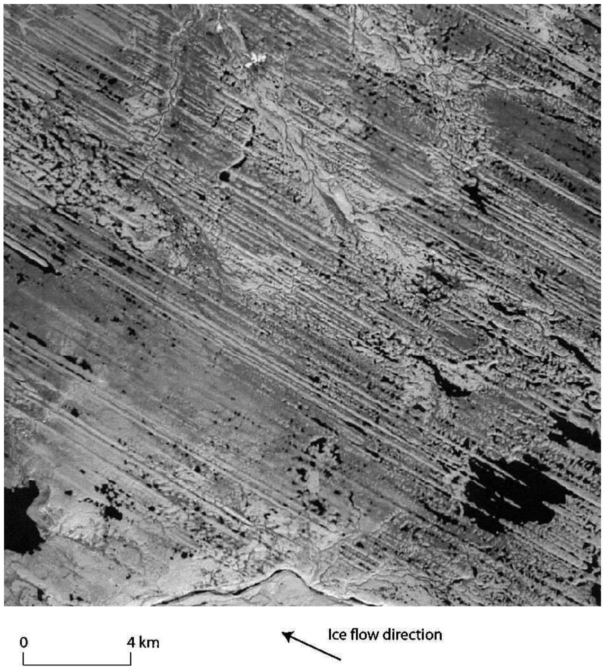

Fig. 6. Landsat ETM+ satellite image (band 5) of attenuated drumlins and mega-scale glacial lineations from the centre of the Dubawnt Lake flow-set. The exceptional parallel conformity of the bedforms and high elongation ratio gives the appearance of a ridge groove structure. Image centred on *c.* 101′50 W, 64′05 N (northwest of Dubawnt Lake), approximate width is 22 km. For image location, see Fig. 1.

the flow-set were important. Aylsworth & Shilts (1989a) commented that the most spectacular streamlined drumlins in the study area occur immediately down-ice of sedimentary basins. The Thelon Sedimentary Basin was particularly susceptible to glacial erosion and produced relatively large volumes of friable sediment eroded from poorly consolidated sandstone outcrops (Aylsworth & Shilts 1989a). This basin underlies a large part of the flow-set trunk, but significantly also spans a large area outside the inferred margin to the south. If sedimentary characteristics were the only control on bedform dimension, then it is difficult to explain why long bedforms were not generated on the part of the sedimentary basin which lies outside the southern margin. No elongated bedforms are found here, despite the availability of sediment. We favour an interpretation that the erodible sediments encouraged fast ice flow through the area, but that ice velocity was the primary control on their exceptional down-ice attenuation.

In summary, long bedforms are indicative of fast ice flow within the main trunk of the Dubawnt Lake flow pattern. Extrapolating this reasoning to other areas with relatively uniform geology and topography, we suggest that when highly attenuated bedforms display a high degree of parallel conformity and highly convergent, coherent flow patterns, fast ice flow can be invoked.

Does fast ice flow always produce long bedforms?

We do not propose that fast ice flow will always produce attenuated drumlins and mega-scale glacial lineations. For example, Evans (1996) suggested that topographic ice streams (i.e. those ice streams whose location is controlled by a bedrock trough) are erosional agents, sliding and plucking their beds. Marshall *et al.* (1996) also argued that these ice streams may leave little or no landform assemblages. Clearly, the degree of bedform development and attenuation depends on the flow mechanism and the degree of coupling between the ice and the substrate beneath. Fast ice flow can be achieved by rapid basal sliding or by the thermally enhanced deformation of the basal ice layers (Iken *et al.* 1993), neither of which may necessarily produce streamlined subglacial bedforms. When long bedforms are present, however, we suggest fast ice flow is the most likely explanation.

Is elongation ratio a useful proxy for ice velocity?

It has been argued that ice velocity and duration of flow are the primary controls on the elongation of a streamlined bedform (Clark 1993, 1994). Assuming these landforms are initiated at a point, the final length of a bedform is taken to be a function of the ice velocity and flow duration (cf. Clark 1993). If we assume complete coupling of the ice sheet to the underlying substrate, an ice sheet flowing at 15 m yr^{-1} for 10 years would be capable of moulding a bedform of 150 m in length. It becomes clear then, that highly attenuated bedforms, such as mega-scale glacial lineations, may be produced by either rapid ice flow over a short time, or slower ice flow over a longer duration. The weight of evidence in favour of rapidly changing ice-sheet configurations would appear to suggest that stable flow patterns were not common in former ice sheets (cf. Andrews *et al.* 1983; Boulton & Clark 1990a, b; MacAyeal 1993). Therefore, we infer that long bedforms are more readily explained by episodes of fast ice flow, especially where we have reliable indicators of ice stream activity, such as might be the case with the Dubawnt Lake flow pattern.

It could be argued that bedforms do not always arise from point initiation. Another alternative is linear initiation, whereby the length of the lineation is unrestricted by the velocity-duration product. If stress patterns within the basal ice are aligned in longitudinal zones, little forward ice motion may be required to produce lineations. Under these hypothetical conditions, landforms of great length may be formed under relatively slow flowing ice. A till squeeze theory was developed by Stalker (1960), who suggested that saturated till may be squeezed or 'pressed up' into subglacial cavitites at the base of the ice sheet which are aligned parallel to the ice-flow direction. However, as Menzies (1979) noted, while the theory appears sound the scale of the process remains unknown. We reject this hypothesis because it is difficult to conceptualize a plausible process of ice dynamics that can produce this effect over whole drumlin fields.

A more serious concern which undermines our assumption of the velocity-duration product is that of basal uncoupling. Put simply, if the base of the ice sheet is not strongly coupled to the underlying sediment (i.e. slides across the surface, perhaps aided by a thin water film), then the length of the subglacial bedform is not necessarily proportional to ice velocity. It is quite conceivable that an increase in velocity may be associated with a decrease in basal coupling and, therefore, no increase in bedform length. In this case, elongation ratio is a manifestation of the coupling at the ice-bed interface and till rheology, and is not related to velocity. This makes it difficult to make quantitative estimates of ice velocity from bedform dimensions. However, when long bedforms are produced, we can assume that basal uncoupling will not vary drastically within a flow-set and some qualitative relationships may be found. This is the case for the Dubawnt Lake flow-set, where down-ice variations in elongation ratios (Fig. 5) support the hypothesis that bedform attenuation is indicative of ice velocity.

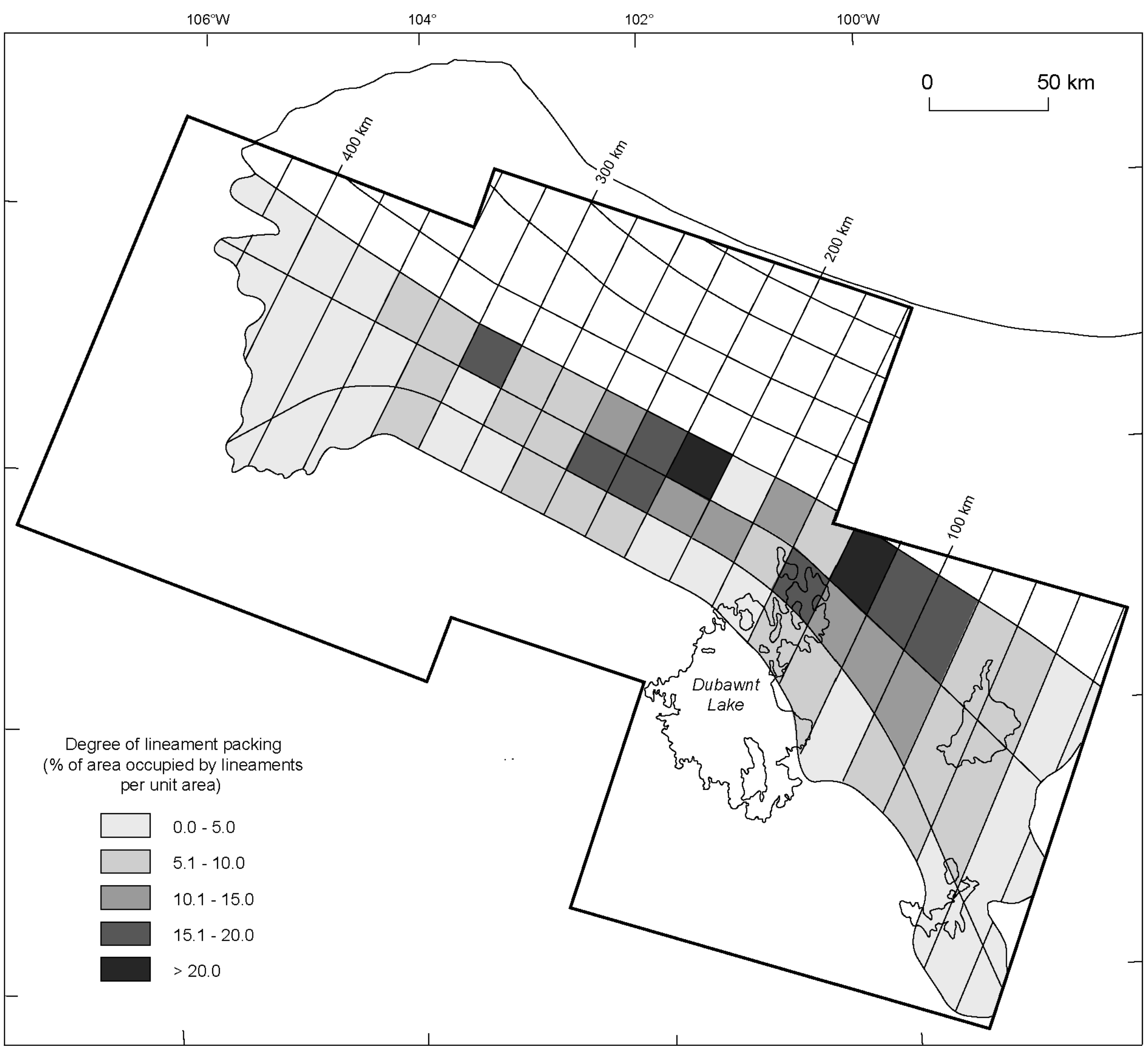

Fig. 7. Variations in lineament packing (percentage area covered by lineaments per unit area) along the southern half of the Dubawnt Lake flow-set. Bedforms tend to become more closely packed together and occupy greater surface areas towards the central axis of the flow-set. Like elongation ratio (Fig. 5), bedform packing also appears to reach a maximum in the main trunk of the flow-set.

Although we have no contemporary analogues from which to compare velocity, the variations in elongation ratio within the Dubawnt Lake flow-set reflect exactly what we would expect from a terrestrial ice stream, the velocity of which increases in the onset zone, passes through a maximum in the main channel and slows down as the ice diverges towards the terminus. Further evidence in favour of ice-stream activity is the abrupt southern margin to the bedform pattern which we interpret as a former shear margin (cf. Stokes 2000).

Fig. 5 also indicates that bedforms tend to be more elongated towards the central axis of the flow-set away from the southern lateral margin. This concurs with observations on contemporary ice streams, where side drag is imposed by the slower moving ice outside the margins (Whillans *et al*. 1993). Making inferences from internal variations of elongation ratio within an isochronous flow pattern appears to be valid, but comparing elongation ratios between separate flow-sets may not be so informative.

Another potential problem when estimating ice velocity from elongation ratios is that of sediment availability. If we assume the point initiation mechanism, then areas of abundant sediment are likely to become more attenuated simply because more sediment can be carried down-ice. This relationship becomes even more complex when considering the deforming bed model of drumlin formation, which allows individual drumlins to become 'uprooted' and migrate down-ice (Boulton 1987; Hindmarsh 1998). Clearly, further work is required on till rheology, basal uncoupling and the degree of cumulative strain at the ice/bed interface before elongation ratios can be extrapolated to provide a quantitative estimate of ice velocity. However, we propose that, at least qualitatively, they can be used as a relative indicator of strain rate, velocity and degree of bed coupling.

Evidence from the margins of contemporary ice sheets

If we were able to view attenuated drumlins and mega-scale glacial lineations at the foregrounds of contemporary ice streams we could firmly establish the link between their occurrence and fast ice flow. Unfortunately, contemporary ice streams terminate in marine environments, but recent technological advances over the last few decades have allowed us to view their submarine 'footprints'. These investigations provide strong evidence to link fast ice flow with attenuated drumlins and mega-scale glacial lineations.

Retreat of the West Antarctic Ice Sheet from the edge of the continental shelf during the Holocene was almost certainly facilitated by the Siple Coast ice streams whose former tracks have recently been delineated beneath the Ross Ice Shelf (Bindschadler *et al*. 1998). Here, geophysical investigations (Shipp & Anderson 1997; Shipp *et al*. 1999) identified lineations in excess of 20 km in length and attenuated drumlins (lengths 3–8 km, widths 0.5–0.75 km). Shipp *et al*. (1999) suggested that these features represent the first marine discovery of Clark's (1993) mega-scale glacial lineations. Canals *et al*. (2000) have also found submarine landforms analogous to mega-scale glacial lineations inferred to have been sculptured by a large ice stream which drained an expanded Antarctic Peninsula Ice Cap during the Last Glacial Maximum. These features are similar in scale and character to terrestrial mega-scale glacial lineations, but show uninterrupted continuity along their 100 km length. Canals *et al*. (2000) refer to this sinuous track of grooves and ridges as a 'bundle structure' and suggest that it may be the largest ice-flow-related landform ever identified. These findings considerably strengthen the hypothesis that attenuated drumlins and mega-scale glacial lineations are indicative of fast ice flow.

The discovery by Canals *et al*. (2000) raises a number of interesting questions with regard to the actual processes that facilitated fast ice flow and produce the observed mega-scale glacial lineation of ridges and grooves. It could be argued that it is unlikely that point initiation in the down-ice direction could account for their exceptional length and sinuosity (up to 100 km) and linear initiation is unlikely (see arguments above).

One possible explanation is that keels (or 'bumps') in the base of an ice sheet plough through unconsolidated sediments to produced the observed grooves (see Tulaczyk *et al*. 2001). Ploughing by ice keels may be a valid mechanism by which terrestrial mega-scale glacial lineations were produced. The remarkable length and parallel conformity of the bedforms from the Dubawnt Lake ice stream largely resembles a ridge/groove structure (Fig. 6). If this is the case, then attenuated bedforms produced by this mechanism are still the product of an ice velocity duration product, i.e. a rapidly moving ice keel will produce a longer groove than a slowly moving keel. It still holds true that extremely long bedforms would be indicative of fast ice flow. Clearly, methods are needed to confirm or falsify this, as yet, qualitative model of bedform production. One such method would be to develop predictions of the geomorphology that should arise from such a mechanism and compare it to the actual geomorphology found on exposed ice sheet beds.

Conclusions

It has been argued that attenuated drumlins and mega-scale glacial lineations are indicative of fast ice flow. Despite the availability of data pertaining to the measurement and analysis of subglacial bedforms, this long-held assumption has rarely been explicitly addressed in detail. To test this assumption, we used satellite imagery to map subglacial bedforms associated with an unusual 'bottleneck' flow pattern north-west of Dubawnt Lake, District of Keewatin, Canada.

In the main trunk of the flow-set (between 100 and 300 km down-ice) the bedforms comprise attenuated drumlins and mega-scale glacial lineations which are characterized by great lengths (up to 13 km), and elongation ratios are some of the highest ever documented on land (up to 48:1). The remarkable degree of parallel conformity with neighbouring bedforms provides further evidence that they were generated rapidly and gives the appearance of a ridge/groove structure.

The down-ice variations in elongation ratio reflect exactly what we would expect from a terrestrial ice stream, the velocity of which increases in the onset zone, passes through a maximum in the main channel and slows down as the ice diverges towards the terminus. Elongation ratios tend to increase towards the central axis of the flow-set and this concurs with observations on contemporary ice streams, where the slower moving ice beyond the lateral margins imposes side drag.

Transverse variations in elongation ratios across drumlin fields are well documented in the literature (e.g. Dyke & Morris 1988; Hart 1999) and provide strong evidence that bedform attenuation is related to ice velocity. In this paper, we provide evidence of longitudinal variations in elongation ratio, which also supports this hypothesis. The observed flow convergence (and presumably increased ice velocity) is matched by a concomitant increase in bedform elongation ratio and we see no other explanation for the variations in elongation ratio other than those related to ice velocity.

We conclude that highly attenuated subglacial bedforms (mega-scale glacial lineations; length:width ratios $\geq$10:1) are indicative of fast ice flow, although we do not assume that fast ice flow will always produce them. It is also suggested that under conditions of uniform geology and topography, bedform elongation ratio provides a qualitative proxy for ice velocity, strain rate and basal coupling. It is suggested that using bedform dimensions to make a quantitative estimate of ice velocity may not be entirely valid because of complications arising from variations in basal uncoupling.

Any unifying theory of drumlin formation must be able to account for the relationship between long bedforms and fast ice flow. A further implication of this work is that many more ice streams could be identified on the basis of highly attenuated bedforms, radically altering our views on the flow dynamics and stability of former ice sheets.

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