The Characteristics of Ribbed Moraine and Assessment of Theories for Their Genesis.

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Chapter 9: Global Characteristics of Ribbed Moraine

9.1. Study site overview

Chapter 4 discussed in detail the rational for choosing the areas that were studied during this thesis (see Section 4.3.2). The main objective of site selection was to obtain a sample of ribbed moraines that would be representative of the global population. As was previously discussed, the sample included ribbed moraines that were formed beneath three separate ice sheets, and were chosen from a wide variety of ice dynamical and topographical settings. Using various sources of imagery a combined area of 81,000 km^2 was mapped from which approximately 36,000 individual ribbed moraine ridges were recorded. This makes this the largest sample of ribbed moraine ridges ever mapped and it is felt that the sampling strategy employed has helped ensure the findings are representative of global ribbed moraine population. The previous four chapters investigated the characteristics of ribbed moraines in some detail and discussed the qualitative and quantitative observations made at each locality. This chapter summarises these findings and compares them with the published accounts of ribbed moraine characteristics.

9.2. Regional-scale picture of ribbed moraine fields

The large scale distributional pattern of ribbed moraines showed that in three of the sites, Lac Naococane, River Kaniapiskau and the Lake Rogen region, the ribbed moraines were formed synchronously during a single ice phase. In Ireland, the ribbed moraine formation history was more complex and ribbed moraine orientation patterns indicate 3 separate phases of ribbed moraine development in this locality. Clark and Meehan (2001) suggested this was due to a shifting ice divide during the last glaciation. The ribbed moraine distribution maps (Maps 5.1, 6.1, 7.1 & 8.1) showed that ribbed moraine fields are formed at a wide range of scales and can vary anywhere between a few km^2 to extremely large expanses of continuous ribbed moraine measuring several thousand square kilometres in extent. For example, in Québec, the largest unbroken ribbed moraine field observed during this study measured approximately 2300 km^2 and in Ireland the mega-scale ribbed moraine belonging to flow set rm-1, was estimated to be approximately 3000 km^2. These observations have extended the known field size range significantly. Previous estimates of field size in Quebec stated they ranged from only 2 to 30 km^2 (Bouchard, 1989) and in Sweden, the largest field in the Glacial Geomorphology Map of Central and Northern Sweden (Hättestrand, 1997a) measures approximately 1000 km^2. We thus find the ribbed moraine fields (i.e. continuous tracts of ribbed moraine) are far more extensive than hitherto reported.

It was found that in general the distribution pattern of ribbed moraine fields could be classified into the following categories:

1. Extensive continuous fields of large size
2. Elongate ribbons and narrow tracks
3. Densely packed or dispersed clusters of ribbed moraine
4. Isolated fields
5. Cross-cutting ribbed moraine

9.3. Morphology

Most papers dealing with ribbed moraine normally describe the size and shape of the ridges (e.g. Lundqvist, 1969; Bouchard, 1989; Aylsworth and Shilts, 1989; Hättestrand, 1997b). Hättestrand and Kleman (1999) synthesised the published accounts of ribbed moraine morphology into a concise summary and gave a detailed description of what ribbed moraine ridges are supposed to look like (see Section 3.4). According to these authors the ridges:

1. are generally curved or concave downstream, or are anastomosing,
2. often have horns that point downice,
3. in cross section are asymmetric with commonly a steeper distal side,
4. have accordant summits,
5. commonly have multiple sub-crests, or flat crests giving ridges a tabular appearance,
6. have regular spacing between ridges which are typically of 300-1200 m, ridges are 150-300 m wide and 10-30 m high,
7. tend to be of similar size throughout a field,
8. fit together like a jigsaw puzzle.

According to point 1 above, ribbed moraine ridges should be generally curved or concave downstream, or be anastomosing. (Aylsworth and Shilts, 1989; Lundqvist, 1989; Bouchard, 1989; Menzies and Shilts, 1996; Hättestrand. 1997b, Benn and Evans, 1998). Detailed investigations of ridge morphology conducted during this study, concluded that although it was possible to identify ridges that fitted this classic description, their morphology was more complex than this. This was true of the ribbed moraines at all of study sites and the various plan view morphologies identified during this study have been summarised schematically in Figure 9.1. As is shown, ridge shape is quite diverse and this study identified ridges that are arcuate and concave up ice (opposite to what is usually stated), straight ridges that are not curved at all, barchan shaped ridges, broad rectangular ridges and many poorly developed ridges that lack a distinct morphology. Hättestrand and Kleman (1999) also assert that ribbed moraine ridges commonly have horns that point down ice and claim that they are generally anastomosing (point 2). Both of these features were observed at the various sites, however, they were not overly common features, which suggest they may not be an important ribbed moraine trait and may simply reflect local variations.

Under point 3 it is stressed that ribbed moraine ridges are generally asymmetric in cross-section and that their distal slope is normally much steeper than the proximal slope (Minell, 1980, Shilts *et al.*, 1987; Bouchard, 1989; Aylsworth and Shilts, 1989; Hättestrand and Kleman, 1999). To investigate these assertions, transects totalling approximately 500 km in length were taken across ribbed moraine fields in the Lac Naococane region and in Ireland (Sections 5.4.2 & 7.4.2). The results supported the observations that ribbed moraine ridges tend to be asymmetric in cross-section (91 % of the sample at Lac Naococane & 100 % in Ireland). However, the assertion that ribbed moraine ridges are normally much steeper on the distal side was found not to be true. Observations made during this study found that in the Lac Naococane area only 51 % of the ridges in the sample had a steeper distal slope whilst 40 % had a steeper proximal slope, and in Ireland 52 % of the ridges sampled were found to have a steeper distal slope and 48 % a steeper proximal slope. These data therefore rejects the commonly cited characteristic of a steeper distal slope, and indicates an approximately equal split between steeper distal and proximal slopes.

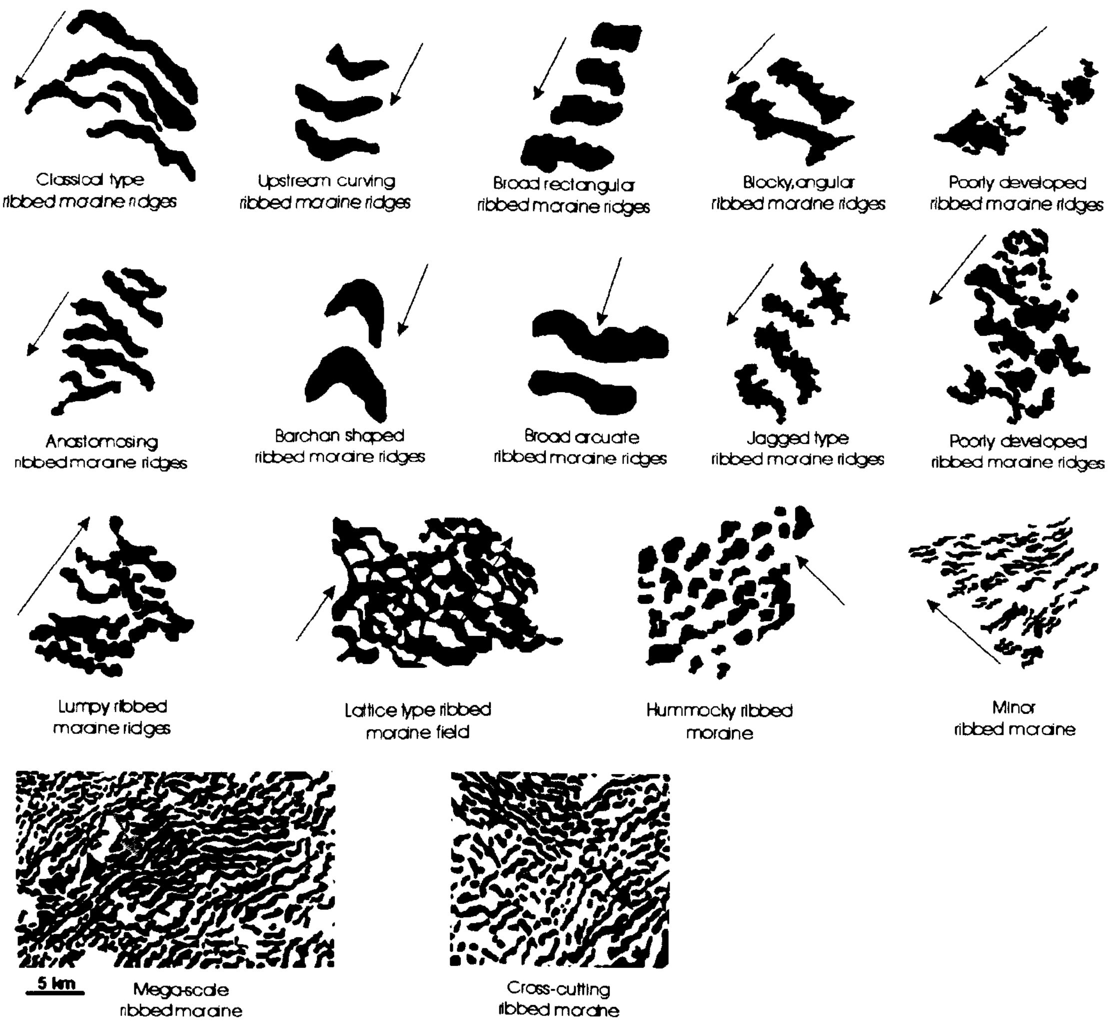

Figure 9.1. Classification of ribbed moraine ridges based on morphological distinctions. Each ridge type is discussed in more detail in the previous chapters. Poorly developed ridges lack a distinct morphology and therefore two examples are included to illustrate their diversity of form. Arrows show the direction of ice flow.

A commonly held assumption about ribbed moraines is that over large areas of terrain the ridge crest heights are remarkably accordant (point 4) (Bouchard, 1989; Menzies and Shilts, 1996; Hättestrand and Kleman, 1999). It was noted earlier that this opinion is supported by very little data, Bouchard (1989) being the only author to have produced any empirical evidence in support of this claim. Access to high-resolution elevation data meant this assertion could be critically evaluated. Using DEMs, transects totalling 565 km were taken across ribbed moraine fields in the Lac Naococane area and in Ireland. Regression analysis applied on these data to derive the R Squared value showed that in the majority of cases the ribbed moraine ridges were not accordant (Table 9.1). Based on these results it appears that Bouchard's findings were site specific and that the accordant summit characteristic is not applicable to ribbed moraines in general.

Table 9.1. R Squared values derived by regression analysis using transect data taken from DEMs of the Lac Naococane region and the northeast midlands of Ireland. Note that only 3 of the fields sampled have high R Squared values (greater than 0.7). This means that in 90 % of the fields sampled, the ridge summits are not accordant

0.56	0.07	0.36	0.08	0.19
0.24	0.11	0.04	0.66	0.19
0.01	0.57	0.28	0.15	0.53
0.92	0.29	0.28	0.36	0.48
0.52	0.57	0.00	0.08	0.53
0.04	**0.77**	**0.80**	0.13	0.12

According to point 5, another common morphological characteristic is that ribbed moraine ridges occasionally have multiple sub-crests, or flat crests giving the ridges a tabular appearance. Visual assessment of transect data taken across ribbed moraines in the Lac Naococane region and in Ireland showed that in many cases, the ridges did have a stepped cross-sectional profile, indicating the ridges do commonly have multiple sub-crests. However, the assertion that the ridges are generally flat and have a tabular appearance was not supported by investigations conducted during this study (see Sections 5.4.2 & 7.4.2). Both longitudinal profiles and 3-D surface plots taken across ridges in Ireland and in the Lac Naococane region revealed they normally have undulating crests, and rarely appear as flat-topped.

Point 6 lists the "typical dimensions" of ribbed moraine ridges summarised from the literature by Hättestrand and Kleman (1999). Detailed morphometric analysis conducted during this study found a much greater range in all of the measured parameters (Table 9.2). New histograms were plotted using the combined data from each of the study sites to illustrate the new "global" distribution for each measured parameter. Figure 9.2 shows the combined ridge length distribution measured in the four study sites. This partly supports the observations made by Hättestrand and Kleman (1999) as the data set shows strong clustering in the sample (80 % of the sample) between the lengths of 300-1200 m, which is the length commonly reported in the literature. However, many ridges measured are both shorter and longer than their estimates and the measured range is now much wider than previous estimates (Table 9.2).

Table 9.2. Morphometric measures of ribbed moraine ridges made during this study and comparison with "typical dimensions" from the literature. Values were obtained by combining data from the four study sites. Ridge length was estimated using a combined sample of 31,247 individual ridges, ridge width estimated from a sample of 1000 ridges, height from 800 ridges and wavelength was derived from transect data totalling approximately 15,000 km in length.

Parameter	Mean (m)	Range (m)	"Typical dimensions" reported in literature (m)
Length	688	32-16214	300-1200
Width	278	17-1116	150-300
Height	17	1-64	10-30
Wavelength	505	12-5800	30-1925 - see Table 3.3

The distribution of ribbed moraine ridge widths can be seen in Figure 9.3. According to Hättestrand and Kleman (1999), ridges are typically 150-300 wide. However, as the graph demonstrates, the distribution is much wider than these estimations and approximately 90 % of the ridges are actually between 25-500 m, with the other 10 % being wider still. Figure 9.4 shows the distribution of ridge height estimated from a sample of 1000 ridges from the Lac Naococane and the Irish ribbed moraine fields. This clearly demonstrates the assertion that ridges vary in height between 10-30 m is inaccurate. Like the other parameters, measurements in this study show ribbed moraine ridges vary more in height that was previously thought (Table 9.2). For example, 35 % of the ridges in this sample are less than 10 m high and 15 % are higher than 30 m.

Hättestrand and Kleman (1999), do not give an estimate of ribbed moraine wavelength, however, they do state that ridges are regularly spaced within ribbed moraine fields (point 6). Observations at the four study sites support this assertion. However, ribbed moraine wavelength was shown to vary between the localities (see Sections 5.6, 6.6, 7.6 & 8.6). When the wavelength data from each of the study sites was combined and a histogram plotted to show the distribution, the graph clearly demonstrated there was a much wider wavelength range than has been previously reported (Fig. 9.5). Measurements conducted in this study showed that 90 % of the sample had a wavelength between 100-1000 m, but with a significant positive tail.

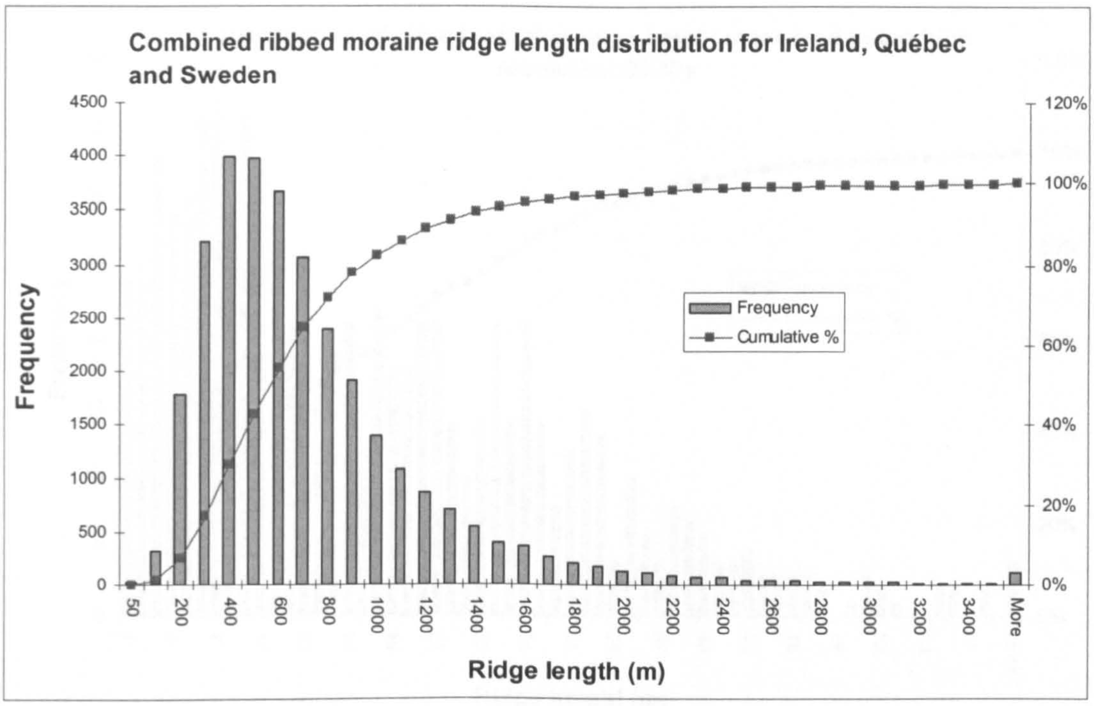

Figure 9.2. Distribution of ribbed moraine ridge lengths taken from a sample of 31247 measured at Lac Naococane, River Kaniapiskau, Ireland and lake Rogen regions.

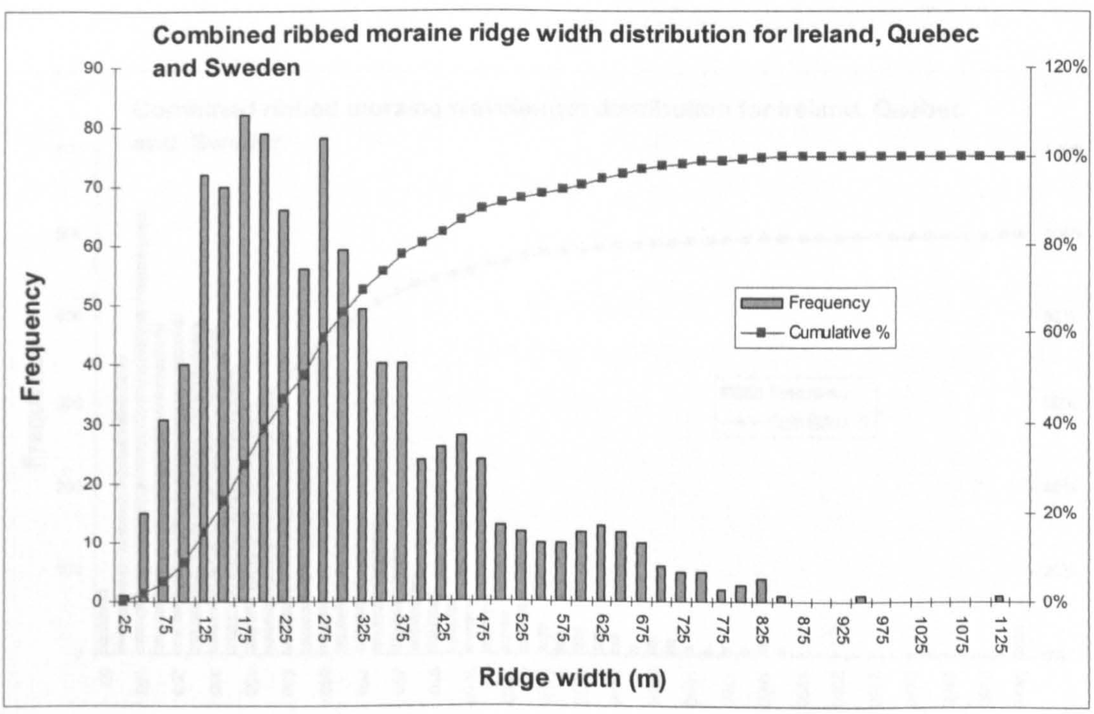

Figure 9.3. Distribution of ribbed moraine ridge widths taken from a sample of 1000 ridges in the Lac Naococane, River Kaniapiskau, lake Rogen and Irish study areas.

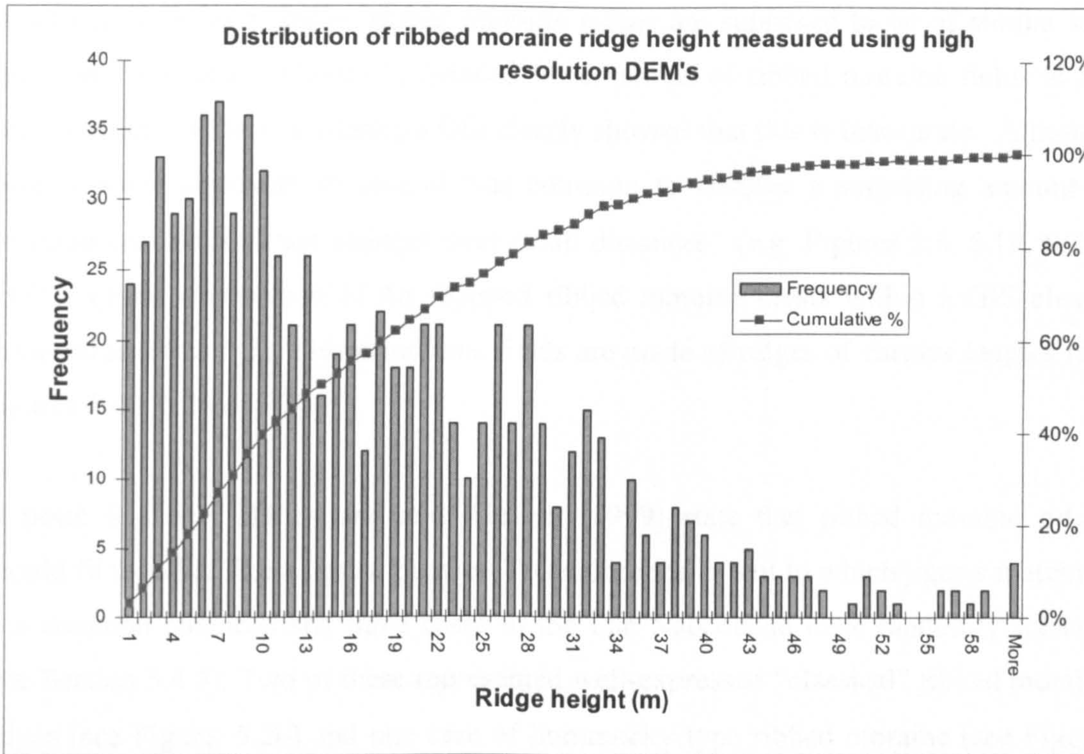

Figure 9.4. Distribution of ribbed moraine ridge height taken from a sample of 1000 ridges from DEM's of the Lac Naococane and Irish study sites.

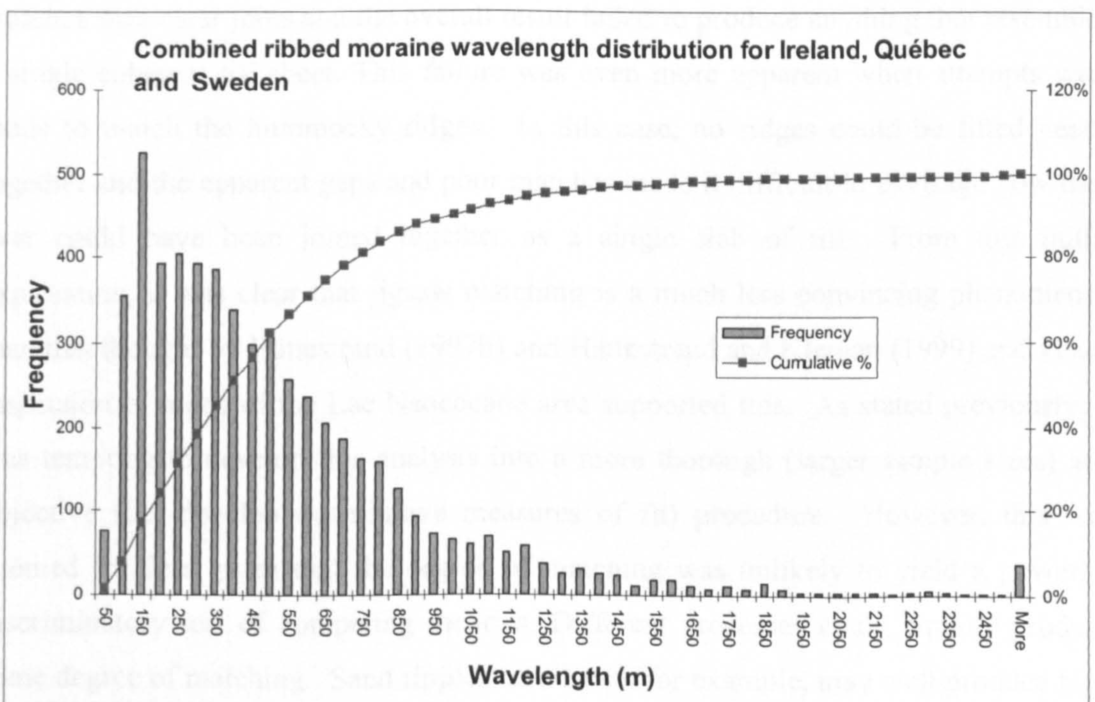

Figure 9.5. Combined wavelength data from Lac Naococane, River Kaniapiskau, Ireland and lake Rogen regions. Wavelength measurements obtained from transects totalling 15000 km in length.

According to point 8 above, ribbed moraine ridges are supposed to be of similar size throughout the field. However, detailed observations of ribbed moraine fields at the four locations and analysis using a GIS clearly showed that this is inaccurate. Although there is some similarity in size, it was common to observe a surprising amount of variation and often abrupt changes over small distances. (e.g. Figures 5.8, 5.19, 6.7 & 6.15). Visual exploration of the mapped ribbed moraine crests within a GIS clearly demonstrated that most ribbed moraine fields are made of ridges of various lengths (see Figures 5.40, 6.26 & 8.21).

In point 8 above, Hättestrand and Kleman (1999) state that ribbed moraine ridges should fit together like a jigsaw puzzle. To explore the extent to which jigsaw matching is a common characteristic three cases in the Lac Naococane were randomly selected (see Section 5.4.3). Two of these represented well-expressed "classical" ribbed moraine ridges (see Figure. 5.26) and one case of hummocky type ribbed moraine (see Figure. 5.27). In all cases, the end result was less convincing than that presented by Hättestrand and Kleman (1999). When matching the classical type ridges it was possible to match some ridges reasonably well. However, in general, there were more gaps and miss-matches than clear joins and the overall result failed to produce anything that resembled a single coherent till sheet. This failure was even more apparent when attempts were made to match the hummocky ridges. In this case, no ridges could be fitted neatly together and the apparent gaps and poor matches made it difficult to envisage how they ever could have been joined together as a single slab of till. From this initial exploration, it was clear that jigsaw matching is a much less convincing phenomenon than that thought by Hättestrand (1997b) and Hättestrand and Kleman (1999) and visual inspection of much of the Lac Naococane area supported this. As stated previously, it was tempting to develop this analysis into a more thorough (larger sample sizes) and objective (i.e. develop quantitative measures of fit) procedure. However, this was deemed fruitless given that the degree of matching was unlikely to yield a powerful discriminatory test of competing theories. Different processes could equally produce some degree of matching. Sand ripples on a beach for example, may well produce high matching but this does not indicate that they were "pulled apart".

9.4. Post-formation modifications

The range of different morphologies and characteristics of ribbed moraine reported earlier (Section 9.3), are complicated by the fact that some of the characteristics (e.g. horns) might not be relevant to the genesis of ribbed moraine, but might simply reflect post-formation modification by subsequent overriding ice flow, or post-glacial processes such as slumping of ridge material caused by solifluction. Given that there are uncertainties in how ribbed moraine are formed (see Section 3.2.3.9), it is difficult to partition what exactly are primary and secondary (i.e. post-formation) features of ribbed moraine. Ideally we would wish to image the bed beneath existing ice masses (by geophysics) during and immediately after ribbed moraine production as this would provide the primary characteristics (i.e. ridge shape, amplitude, wavelength etc) of ribbed moraine, and then to image the bed again after some elapse of time to ascertain any secondary characteristics. In the absence of this approach (not yet viable), caution is required in determining what the primary characteristics really are. The correct theory of ribbed moraine genesis, for example might not need to include the generation of horns, anastomosing structures, curved ridges etc if these are merely modifications that came later.

9.5. Relationship to topography

It is often reported that ribbed moraines are a feature of basins, swales and topographic lows (Lundqvist, 1969,1989; Sugden and John. 1976; Shaw, 1979; Markgren and Lassila, 1980; Mollard and James, 1984; Bouchard, 1989; Sollid and Sørbel, 1994, Menzies and Shilts 1996). Whilst a long-standing association of ribbed moraine and depressions has been widely reported, our evidence and that of other researchers (Aylsworth and Shilts, 1989; Hättestrand and Kleman, 1999; Clark and Meehan, 2001) demonstrates that it is not a universal or defining feature of ribbed moraine. We note that there is an interpretative bias that might unwittingly support the association, in that on aerial photographs or satellite images, ribbed moraine are most easily recognised when the ribs are surrounded by water (i.e. in lakes in depressions, e.g. see Figure 8.9). It is notable for example that nearly all published illustrations of ribbed moraine are in these kind of settings, quite simply they look best like this and as such are most easily recognised. However, detailed mapping conducted during this thesis (Chapters 5-8) and evidence presented by Aylsworth and Shilts (1989) and Hättestrand and Kleman (1999), find them to be distributed largely independent of topography. For example, in Québec, ribbed moraines were observed on slopes running in and out of major basins, on hilltops and on relatively open terrain (see Figures 5.29 & 5.30). Transects taken across ribbed moraine fields in Ireland demonstrated that the distribution of ribbed moraines was in no way influenced by topography at all as they are found on a wide range of topographies including valleys, hill slopes (both proximal and distal) and also hilltops (see Figures 7.15 & 7.16). The best method for avoiding the interpretative bias is for mapping to be performed using stereo aerial photographs or from DEM's, where the expression of ribs is evident from their actual morphology, rather than by a strong contrast with the background (i.e. water).

It is undoubtedly true however that in some locations the association does hold (e.g. it is common in the Lake Rogen area, see Figures 8.14 & 8.15), but we regard this as a localised phenomena, that likely relates to the fact that in regions where till cover is thin and variable, it is only likely to be thick enough in basins and hollows for the sediment to be shaped into ribbed moraine.

Coupled with the apparent association of ribbed moraine and their occurrence in concave terrain is the idea that they preferentially form in these locations due to localised compressive stresses (Shaw, 1979, Minell, 1980; Sollid & Sørbel, 1994; Bouchard, 1980,1989). This hypothesis was tested using a GIS in the Lac Naococane, River Kaniapiskau and Lake Rogen sites. The GIS was used to map the area in each locality that would have experienced compressive and extending glacial stresses and assess the relative proportion of ribbed moraine in each category. This clearly demonstrated that no preferential relationship existed between ribbed moraine occurrence and compressive glacial stresses arising from topography (see Sections 5.5.2, 6.5.2 & 8.5.2). Further analysis using a GIS also demonstrated there was no systematic relationship between topographic setting and ribbed moraine wavelength.

The fact that ribbed moraines appear not to be influenced by topography strongly indicates the primary control mechanism for ribbed moraine formation lies in conditions within the ice sheet itself.

9.6. Relation to other landforms

The relationship between ribbed moraines and other glacial landforms was also investigated in the four study areas. As described previously, it was common to find glacial landforms, such as drumlins and mega-scale glacial lineations, in close spatial association with ribbed moraine. All observations made during this study have been summarised schematically in Figure 9.6. As the diagram shows, ribbed moraines and drumlins appear to be strongly linked, which suggests they may share a common origin. This hypothesis has been advocated by other authors who see these bedforms as being highly related and form part of a bedform continuum (Aario, 1977; Boulton, 1987; Menzies, 1987; Rose, 1987; Boulton and Clark, 1990a,b; Clark, 1993, Hindmarsh, 1998a, b, 1999). The fact that drumlinization of the ribbed moraines at all the locations was a common characteristic, and that transitions between the two were observed at all the localities supports this hypothesis. Probably the clearest indication of this continuum was observed in Ireland. Here, it is obvious a continuum exists between ribbed moraines and drumlins, where mega-scale ribbed moraine passes downstream into drumlinized ribbed moraine and then into to classic shaped drumlins (see Figure 7.22). Whilst the observations strongly support the downstream ribbed moraine to drumlin transition, it is clear that numerous other and surprising relationships exist. In particular, are the abrupt lateral transitions (ribbed moraine to drumlins), the ladder type arrangement and the relative age sequences that shows the drumlins have been subsequently broken into "ribbed moraine". By expanding the observed relationships with other landforms, it is hoped that some of these may prove critical diagnostic tests for formative theories.

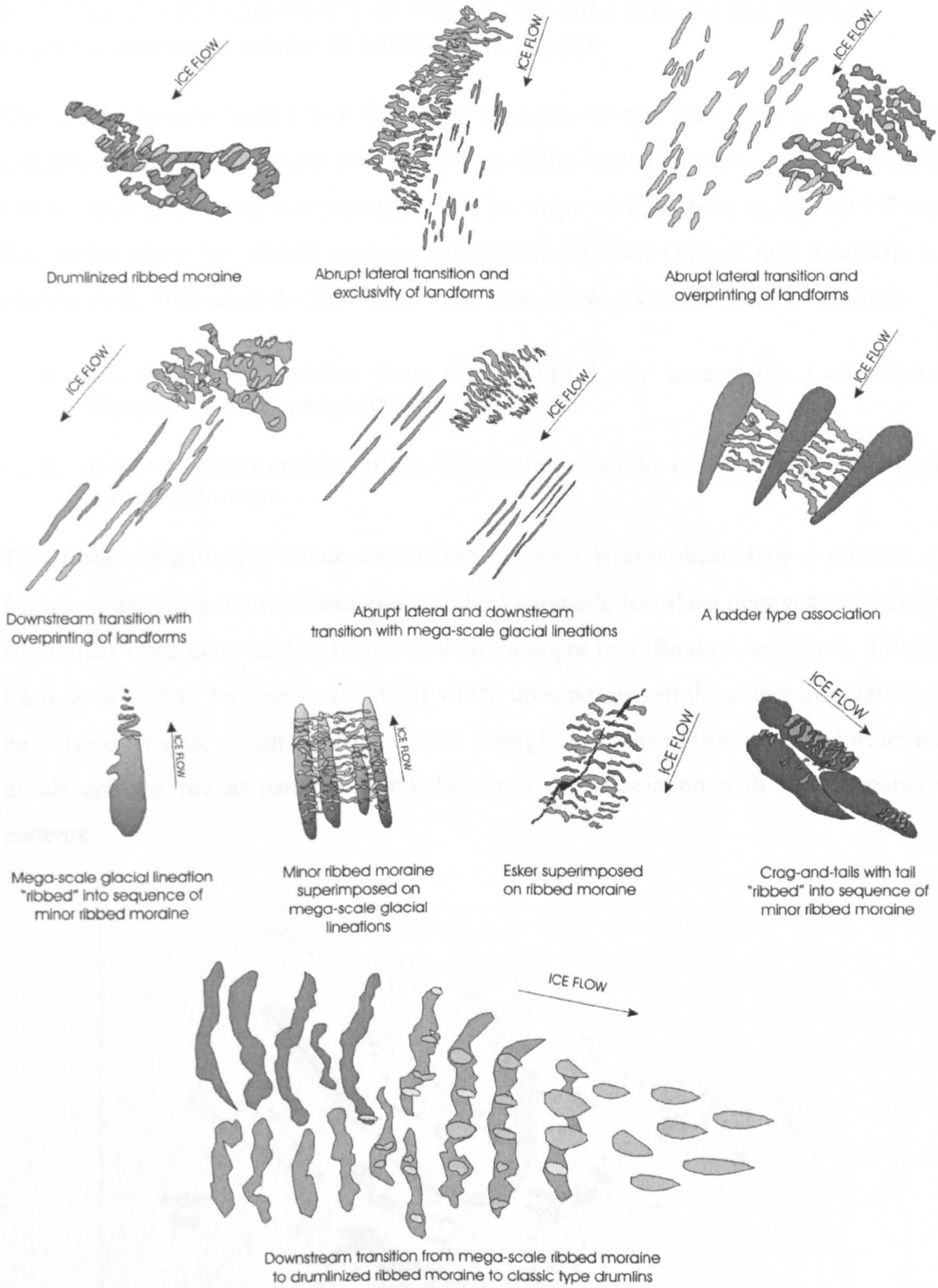

Figure 9.6. Schematic diagram illustrating the spatial relationships observed between ribbed moraine and other glacial landforms.

9.7. Geographic clustering of ribbed moraine around ice divide regions and core areas of former ice sheets

One of the longest held views of ribbed moraines is that they tend to occur in a peripheral ring around former ice divides (e.g. Shilts and Aylsworth, 1989; Bouchard, 1989). This association has been supported by maps such as those in Figures 9.7 and 9.8, which show the ribbed moraine distribution in both Québec and Keewatin in relation to the former ice divide. This observation allows two inferences to be made;

1. that the ribbed moraine were either formed say around the Last Glacial Maximum (LGM), peripheral to the ice divide,
2. or that they were created during deglaciation when the ice sheet had shrunk back to these core areas.

This ribbed moraine/ice divide association however is complicated by a number of factors. Firstly, glacial reconstructions of the Laurentide Ice Sheet demonstrate that the ice divides were more mobile than previously thought (e.g. Boulton and Clark, 199a,b; Clark *et al.*, 2000; Jansson *et al.*, 2002) which does not permit the above association to be reliable. That is, we simply do not know enough about the positions of the former ice divide and the retreat patterns to reliably draw an association with ribbed moraine patterns.

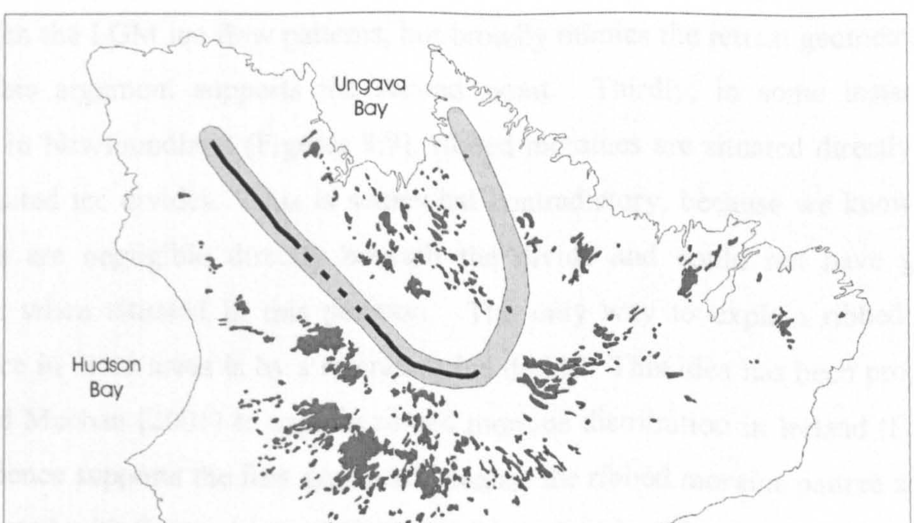

Figure 9.7. Ribbed moraine distribution in Quebec in relation to the former Nouveau-Québec Ice Divide. The ribbed moraines were mapped from the Glacial Map of Canada 1: 500 000 (Prest *et al.*, 1968) and the position of the ice divide is that estimated by Bouchard (1989). The Nouveau-Québec Ice Divide Is the grey horseshoe shaped line, the black lines within this are well-defined segments of the ice divide. Note how the ribbed moraine fields tend to surround the ice divide.

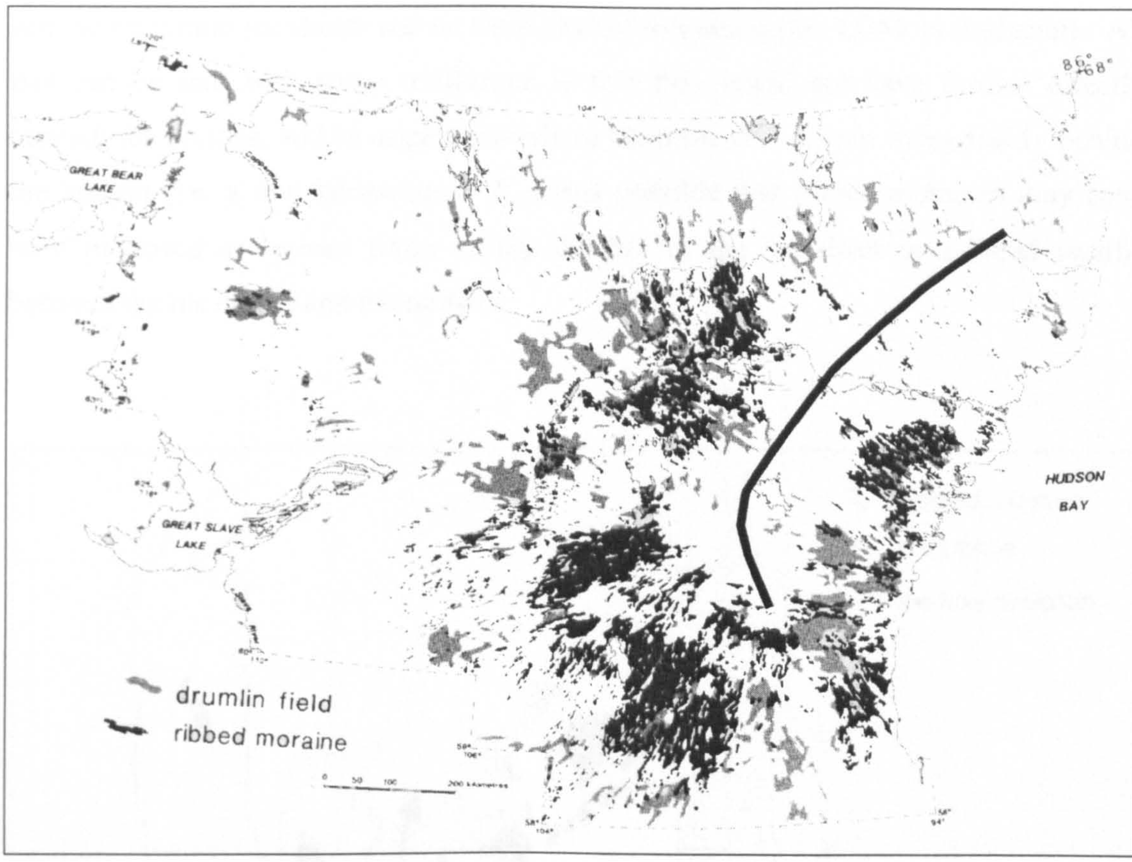

Figure 9.8. Distribution of ribbed moraine in Keewatin in relation to the Keewatin Ice Divide. The position of the ice divide is marked by the thick black line. Note that the largest ribbed moraine fields encompass the area surrounding the ice divide. (After Aylsworth and Shilts, 1989).

Secondly, in Fennoscandia, Kleman *et al.* (1997) have been able to demonstrate that the ribbed moraine pattern is mostly restricted to the core areas of the ice sheet and does not match with the LGM ice flow patterns, but broadly mimics the retreat geometry (Figure 3.19). This argument supports the second point. Thirdly, in some instances, for example in Newfoundland (Figures 9.9), ribbed moraines are situated directly beneath reconstructed ice divides. This is somewhat contradictory, because we know that ice velocities are negligible directly beneath the divide and could not have generated bedforms when situated in this position. The only way to explain ribbed moraine occurrence in these areas is by a migrating ice divide. This idea has been proposed by Clark and Meehan (2001) to explain ribbed moraine distribution in Ireland (Fig. 9.10). This evidence supports the first argument because the ribbed moraine pattern appears to be associated with the position of the ice divide rather than the retreat geometry of the ice sheet.

In summary, these complications, coupled with our recent realisation of more dynamic ice sheets makes it much harder to comment on the inferred position of ribbed moraine generation within ice sheets and on their time of formation (i.e. LGM vs deglacial). All that can be said with some confidence is that they could not have formed directly beneath ice divides, and as argued elsewhere (Section 10.1.4.) not immediately behind the margin (i.e. a few kilometres). It seems possible that ribbed moraines may have been produced at various times during the life of the ice sheet in a broad swathe between the ice divide and the margin.

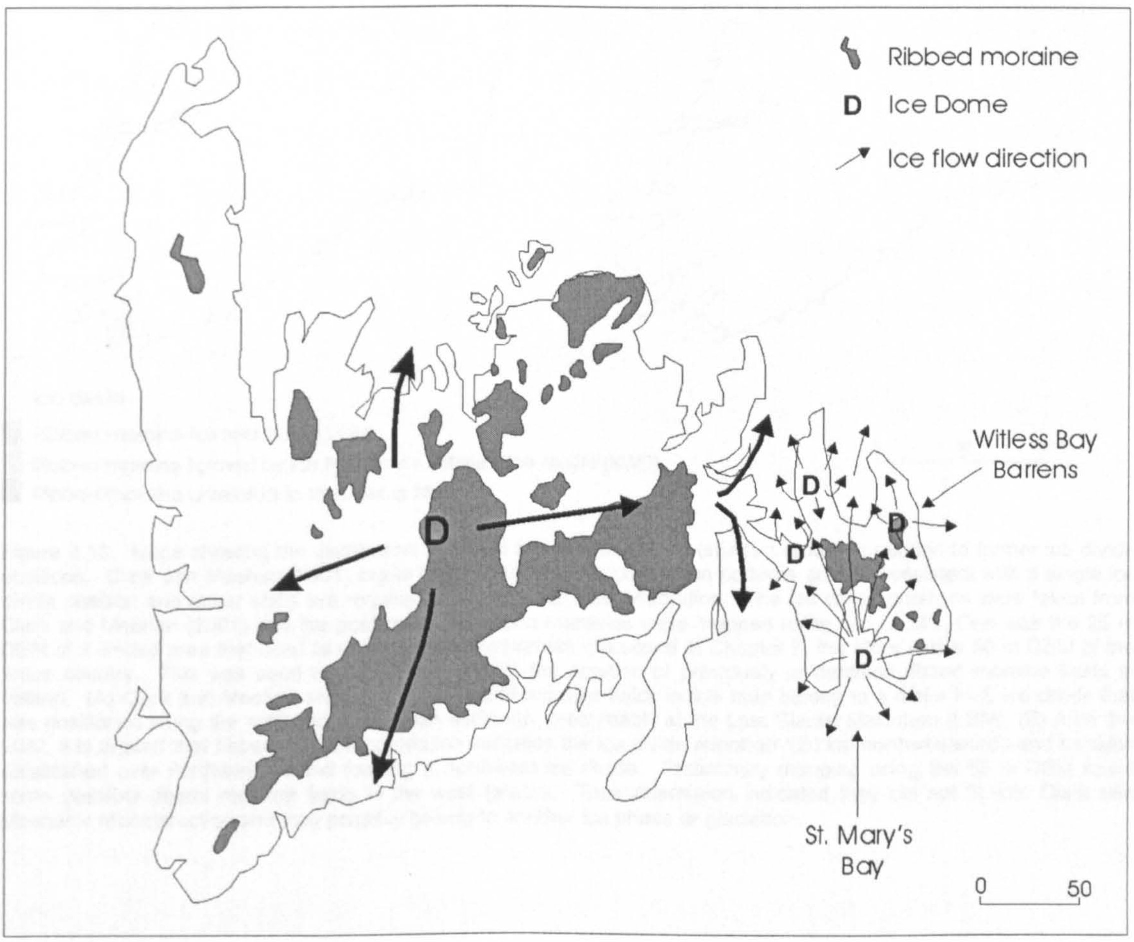

Figure 9.9. Ribbed moraine distribution in Newfoundland mapped from the Glacial Map of Canada 1: 500 000 (Prest *et al.*, 1968). The position of the ice divide on mainland Newfoundland is taken from Grant, 1989. The story on the Avalon Peninsula is somewhat more complex. Field evidence presented by Catto (1998) suggest that at the LGM, ice entirely covered the Avalon Peninsula and that 4 separate ice centres operated in this area. Note how many ribbed moraines are situated directly beneath the main ice divide on Newfoundland and beneath one of the sub domes on the Avalon Peninsula.

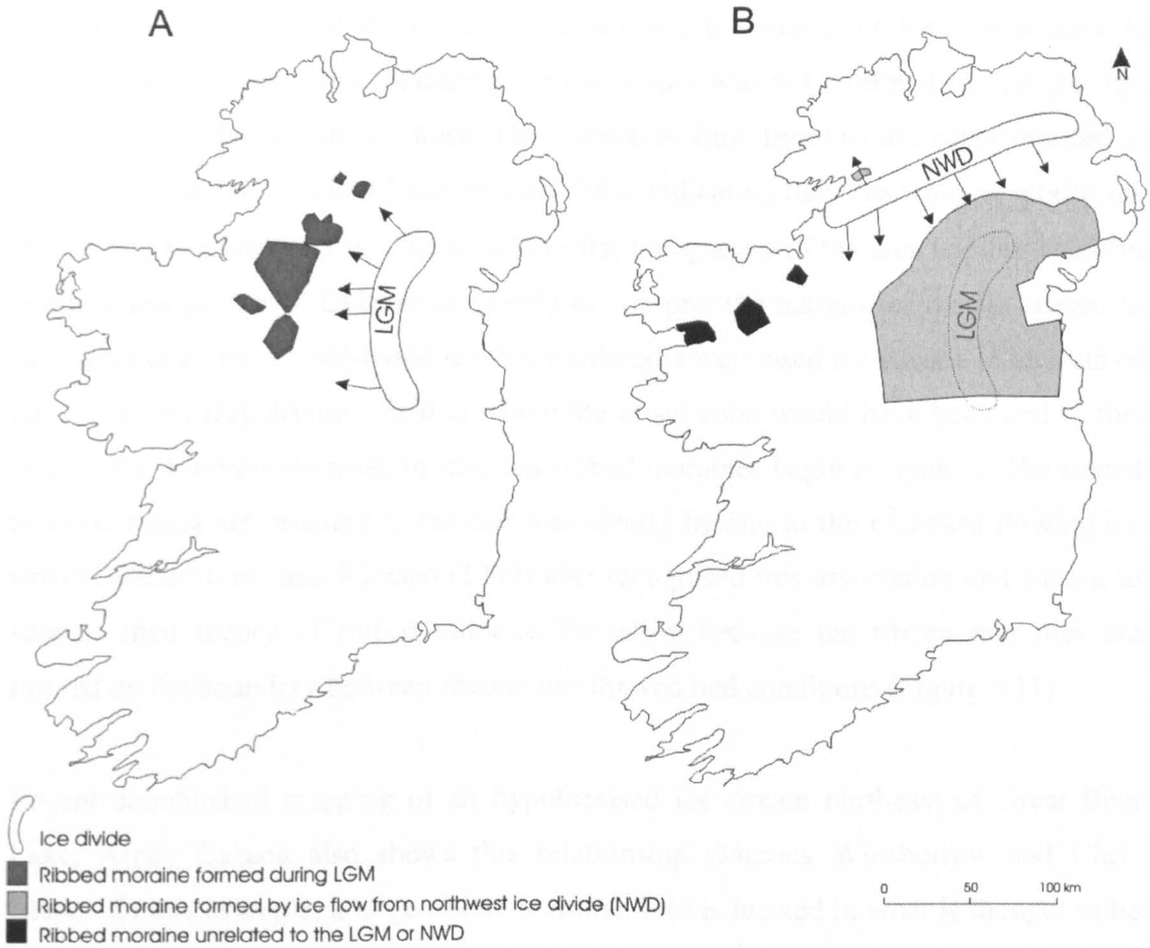

Figure 9.10. Maps showing the distribution of ribbed moraine in Ireland (shaded areas) in relation to former ice divide positions. Clark and Meehan (2001) argue that ribbed moraine orientation patterns are not consistent with a single ice divide position and major shifts are required to account for their orientation. The ice divide positions were taken from Clark and Meehan (2001) and the position of the ribbed moraines were mapped using two DEM's. One was the 25 m DEM of a limited area that used to map the ribbed moraines discussed in Chapter 7, the other was a 50 m DEM of the entire country. This was used to identify and record the position of previously unidentified ribbed moraine fields in Ireland. (A) Clark and Meehan argued that the ribbed moraine fields in this map belong to a major N–S ice divide that was positioned along the northeast of the Irish Midlands, presumably at the Last Glacial Maximum (LGM). (B) After the LGM, it is argued that ribbed moraine orientation indicates the ice divide migrated 120 km northwestwards and became established over northwest Ireland forming a northwest ice divide. Preliminary mapping using the 50 m DEM found some possible ribbed moraine fields in the west (black). Their orientation indicated they did not fit with Clark and Meehan's reconstruction and may possibly belong to another ice phase or glaciation.

9.8. Ribbed moraine and ice streams

As well as there being a longstanding association between ribbed moraines clustering around ice divides, new research has demonstrated there is a spatial relationship between ribbed moraines and ice streams. Several researchers have recognised this and ribbed moraines have been identified in both the onset zones and within the main truck of palaeo-ice streams. Dyke *et al.* (1992), were the first to recognise this on Prince of Wales Island in Arctic Canada (Fig. 9.11). In the south-eastern part of the island, a striking drumlin field that converges eastwards into Transition Bay indicates the presence of a late-glacial ice stream. The whole area around the ice stream track is characterised by low relief indicating the ice stream was not confined by topography. At the head of the ice stream track, the Transition Bay drumlins are superimposed at right angles on the Crooked Lake drumlin field, indicating they are younger landforms that belong to a later phase. The relatively flat topography of the area and the bedform relationships prompted Dyke *et al.* (1992) to interpret the margins of the ice stream to be related to zones of cold-based ice that bordered a wet-based ice stream. The head of the Transition Bay drumlin field is where the onset zone would have been and in this region, the drumlins decrease in size and ribbed moraines begin to appear. The ribbed moraine ridges are oriented to the east and clearly belong to the eastward flowing ice stream. Hättestrand and Kleman (1999) also recognised this association and used it to support their theory of ribbed moraine formation because the ribbed moraines are formed on the boundary between frozen-and-thawed bed conditions (Figure 9.11).

Recent unpublished mapping of an hypothesised ice stream northeast of Great Bear Lake, Arctic Canada also shows this relationship (Monica Winsborrow and Chris Clark). In this example, a large ribbed moraine field is located in what is thought to be the onset zone of this ice stream (Fig. 9.12). In the Dubawnt lake palaeo-ice stream, Northwest Canada, Stokes and Clark (2003c) have observed and mapped ribbed moraines that are superimposed on the ice stream bedforms in the main trunk of the ice stream (Fig. 9.13). Some examples of this phenomenon were also observed in an ice stream track in the River Kaniapiskau region (see Section 6.7.1). Where this has happened, the ribbed moraines clearly postdate the formation of the ice stream bedforms and indicate they were formed either during or after the shut down of the ice stream. This is an important observation because it indicates that slower ice velocities may be implicated in the formation of ribbed moraines.

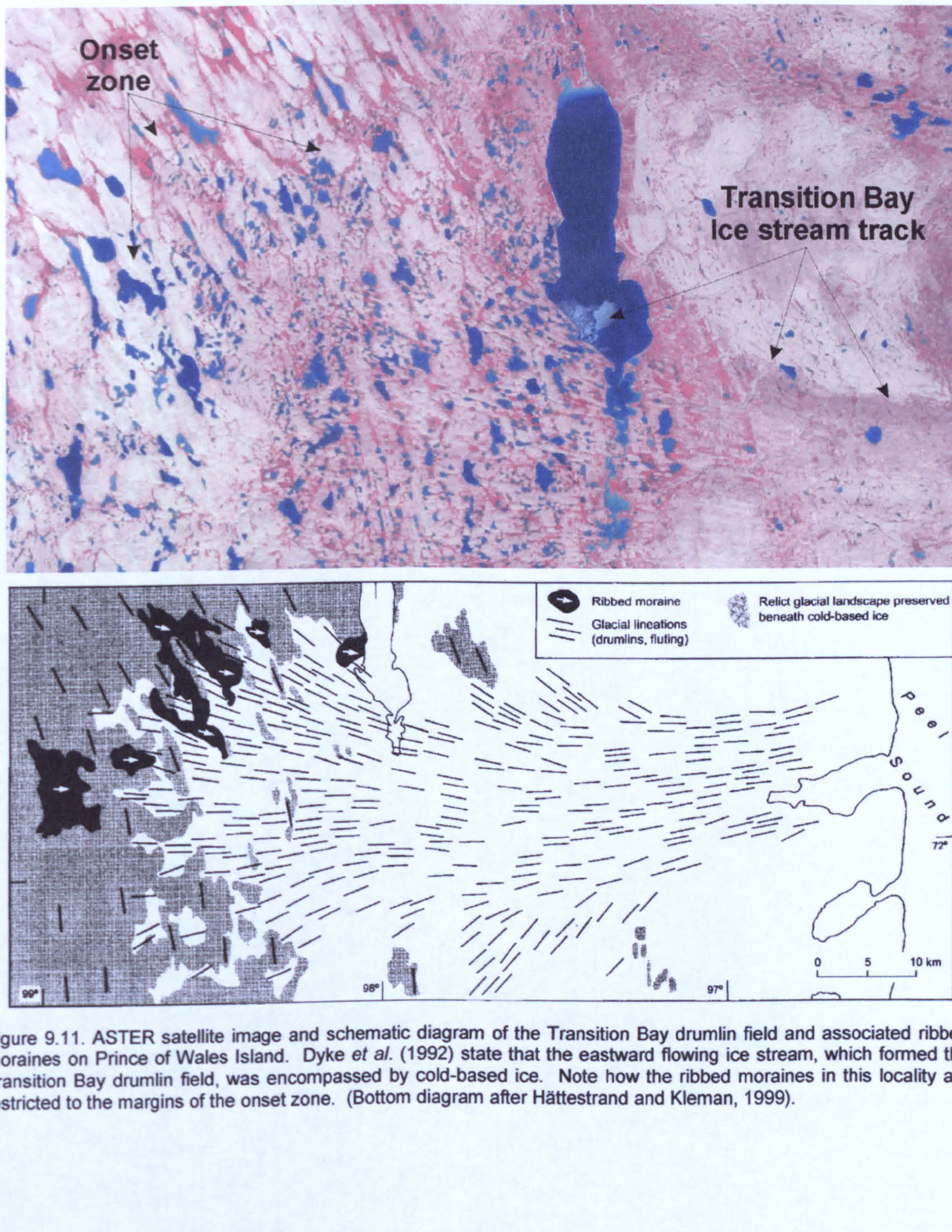

Figure 9.11. ASTER satellite image and schematic diagram of the Transition Bay drumlin field and associated ribbed moraines on Prince of Wales Island. Dyke *et al.* (1992) state that the eastward flowing ice stream, which formed the Transition Bay drumlin field, was encompassed by cold-based ice. Note how the ribbed moraines in this locality are restricted to the margins of the onset zone. (Bottom diagram after Hättestrand and Kleman, 1999).

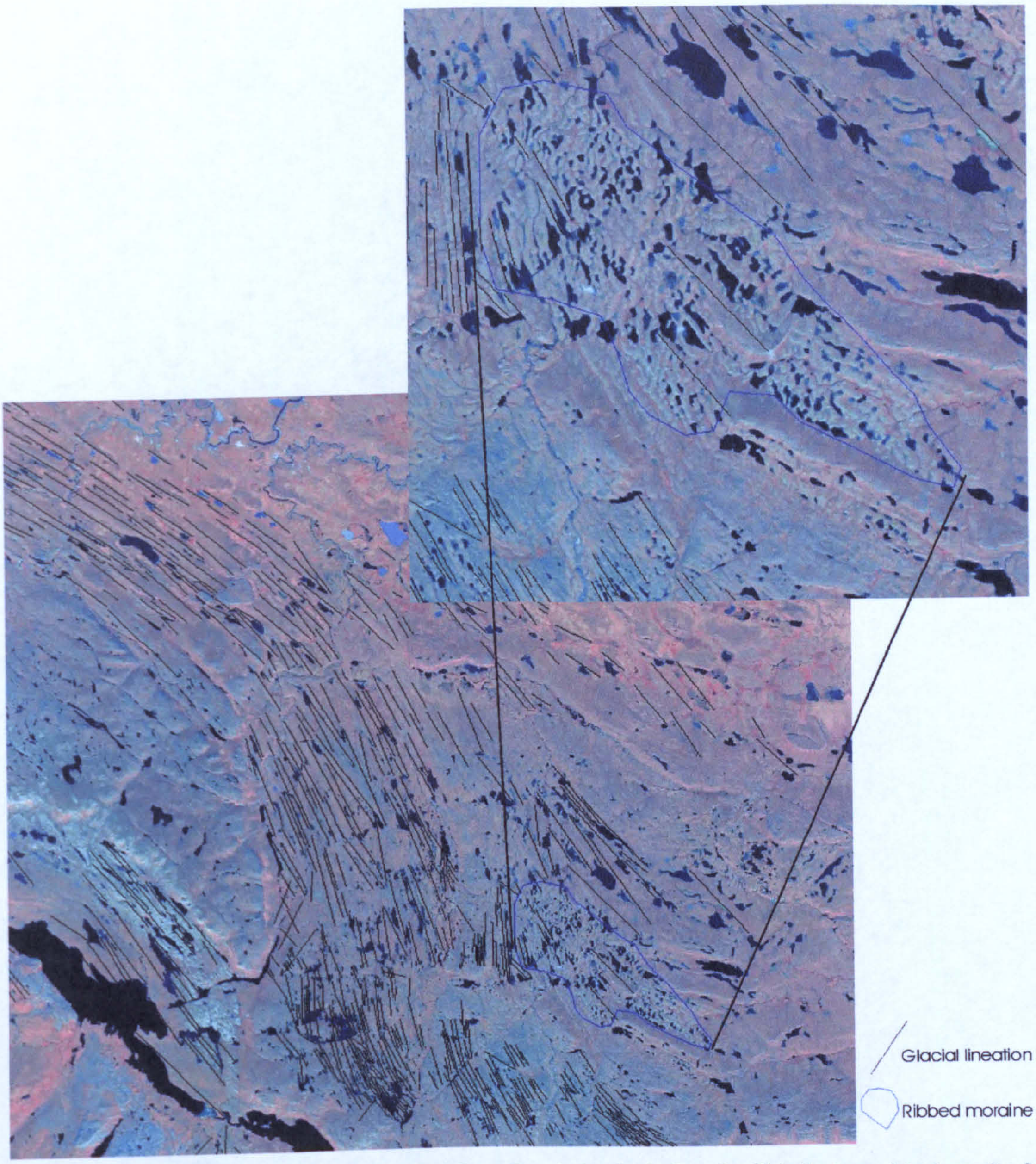

Figure 9.12. Hypothesised ice stream northeast of Great Bear Lake, Arctic Canada. Note the large ribbed moraine field in the onset zone of the ice stream track. (From unpublished mapping by Monica Winsborrow and Chris Clark, Department of Geography, University of Sheffield).

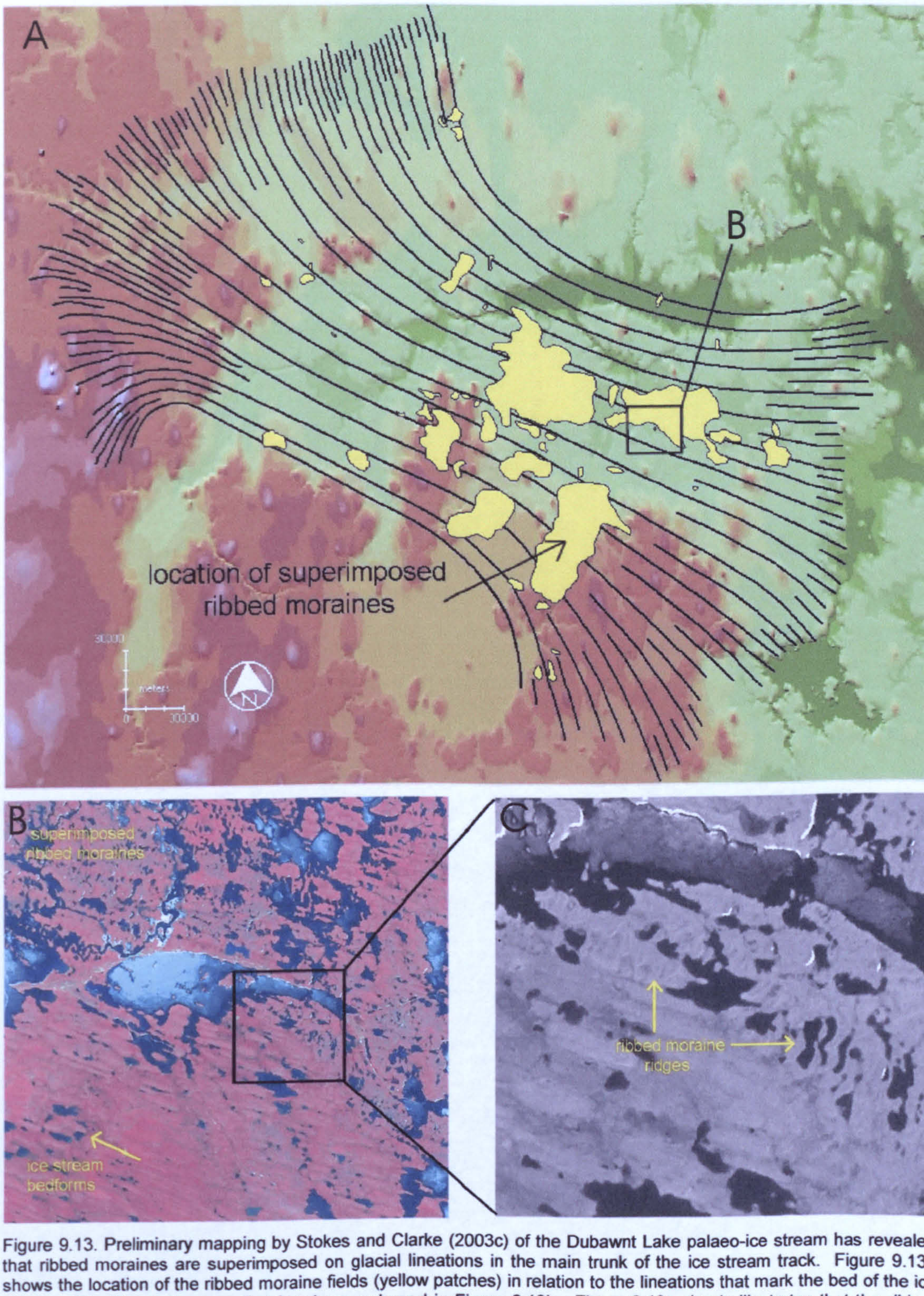

Figure 9.13. Preliminary mapping by Stokes and Clarke (2003c) of the Dubawnt Lake palaeo-ice stream has revealed that ribbed moraines are superimposed on glacial lineations in the main trunk of the ice stream track. Figure 9.13a shows the location of the ribbed moraine fields (yellow patches) in relation to the lineations that mark the bed of the ice stream. The Box is the area that has been enlarged in Figure 9.13b. Figure 9.13c clearly illustrates that the ribbed moraine in this ice stream track are superimposed on the lineations.

9.9. Summary and conclusions

This chapter summarised the findings of investigations carried out on ribbed moraine characteristics made during this study and compared these with observations reported in the literature. This allowed the assertions made about ribbed moraines in the literature the to critically evaluated. As was shown, mapping conducted during this study has significantly increased the known scale range of ribbed moraine *fields* and it is now known that they are much larger than was previously reported. For example, the assertion made by Bouchard (1998) that ribbed moraine fields in Québec range from 2-30 km^2 is clearly wrong as ribbed moraine fields as large as 2300 km^2 were observed in this part of Canada.

The observations made on ribbed moraine ridge morphology also highlighted many inadequacies in the literature and found them to be more complex than has been previously reported (Figure 9.1). Although it was possible to support some longstanding opinions, such as the ridges being asymmetric in cross section, many of the reported characteristics were found to be either untrue or inaccurate. For example, it has now been established that ribbed moraine ridges do not have accordant summits, are not commonly steeper on their distal side, are not tabular but are more likely to have undulating crest profiles, are not always anastomosing, are not of similar size throughout a single field and do not necessarily fit neatly together like a jigsaw puzzle. The detailed morphometric measures made during this thesis have also significantly extended the known size range of ribbed moraine ridges and there now exists the first morphometric database of ribbed moraine characteristics that can be used to test ribbed moraine theories.

The topographic analysis clearly demonstrated that ribbed moraines are not a feature of topographic depressions and hollows but in fact are formed independently of topography. This fact was clearly demonstrated in each of the four study sites, as ribbed moraines were located in various topographic settings including hilltops. Analysis conducted using a GIS clearly demonstrated that no preferential relationship existed between ribbed moraine occurrence and compressive glacial stresses arising from topography, and it was also established that ribbed moraine wavelength was not effected by topography.

The relationship between ribbed moraines and other glacial landforms was studied at each of the sites. These are summarised schematically in Figure 9.6 and clearly demonstrates there are strong spatial associations between ribbed moraines and glacial lineations. The simplest association is in the form of drumlinized ridges, and previous studies have recognised this (e.g. Lundqvist, 1969, Hättestrand, 1997b, Hättestrand and Kleman, 1999, Aylsworth and Shilts, 1989). However, there are also more complex relationships such as lateral transitions between ribbed moraines and drumlins, and glacial lineations being "ribbed" into ribbed moraine ridges. These are important observations because it lends support to the idea that drumlins and ribbed moraine are genetically linked and may form part of a bedform continuum.

This chapter also investigated the long-held assumption that ribbed moraines tend to cluster in a peripheral ring around former ice divides. As was discussed, more recent glacial reconstructions have challenged this idea, as new evidence indicates that ice divides were quite mobile and prone to major shifts during glacial cycles. This makes it complicated when trying to associate ribbed moraine with ice divides since we do not know the timing of bedform generation. For example, it is not clear whether the ribbed moraines were formed at the LGM, during deglaciation or somewhere in between the two. Furthermore, evidence presented by Kleman *et al.* (1997) indicates the ribbed moraine distribution in Fennoscandia is not related to the LGM at all but rather broadly conforms to the geometry of retreat. These are important observations because they help break the association between ribbed moraines and ice divides.

Recent research has also shown a new association between ribbed moraines and ice streams. They have been recognised in the onset zones of two ice streams (Dyke *et al.*, 1992; Winsborrow and Clark, unpublished) and superimposed on top of bedforms in the main trunk of the Dubawnt Lake ice stream (Stokes and Clarke, 2003) and in a hypothesised ice stream in the River Kaniapiskau region (Section 6.7.1). The superimposition of ribbed moraines on top of the lineations indicates they most likely formed during or after the shut down of the ice stream. At this time, ice velocities would be expected to have been slower compared to when the ice stream was fully functioning. Slow ice velocities would also be expected in the onset zone of the ice stream, which may suggest ribbed moraines are formed under slow ice velocities.

Chapter 3 discussed the published accounts of ribbed moraine characteristics and introduced the reader to the main theories of ribbed moraine genesis. All of these theories are based on observations of ribbed moraine characteristics and each author has used these to support their hypothesis. This study however has shown many of these observations to be either inaccurate or untrue which means the competing ribbed moraine theories need to be reassessed in light of this new evidence. The following chapter will examine each formational theory and make an assessment regarding whether or not they can be considered valid in light of the new findings made during this study.

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Chapter 10: Assessment of Theories of Ribbed Moraine Genesis

10.1. Introduction

From the literature review presented earlier, it is apparent that a range of ideas, hypotheses and theories for the genesis of ribbed moraine have been postulated. In this chapter, a qualitative assessment of these will be made, drawing on the known properties of ribbed moraine (Chapters 5-8) and the physical plausibility of the processes. A more formal testing or falsification is not appropriate, or indeed possible, due to the lack of maturity of the various theories. Most are descriptive hypotheses that have not been fully developed into physically-based process models and hence lack detailed prescriptions that could be formally tested. From the authors descriptions we will utilise predictions they cite or attempt to develop our own and compare these with what has now been discovered about ribbed moraine properties.

10.2. Shear and stack model of ribbed moraine genesis

As Chapter 3 outlined, there are several advocates of this model of formation, the basic principle is that slabs of basal sediment or near basal debris-rich ice are sheared up and stacked against each other due to localised compressive stresses. There are various arguments as to the exact mechanism and conditions that caused the compressive flow and the glaciodynamic environment in which the ribbed moraine were suggested to have formed. These can be separated into five main areas that are outlined below. Each of these models will be discussed individually in detail.

- **Topographic obstacle** (Minell, 1980; Sollid & Sørbel, 1984; Bouchard, 1980,1989)
- **Freeze on and entrainment** (Sollid & Sørbel, 1994)
- **High basal debris concentrations changing ice viscosity** (Dredge *et al.*, 1986; Shilts & Aylsworth, 1989; Aylsworth and Shilts, 1989)
- **Frozen outer margin** (Shaw, 1979; Punkari, 1984; Bouchard & Salonen, 1989)
- **Stick-slip at cold-based/warm-based ice transition** (Dyke *et al.*, 1992)

10.2.1. Topographic obstacles

Several authors have argued that topographic obstacles located at the downstream end of rock basins produce conditions at the bed that promote shearing and stacking of basal rich ice. The first author to suggest this model of formation was Minell (1980) who conceived the idea whilst proposing a model of basal sediment transport for the inner part of northern Sweden. His observation that ribbed moraines are characteristic features of low-lying concave basins underpins the hypothesis. Minell argued that ribbed moraines were produced during deglaciation when the ice sheet was warm-based. His theory discusses the various ways in which topography would have influenced ice flow and discusses how this in turn would have affected sediment transport beneath the ice sheet. He stated that ice flowing across a basin would have been obstructed on the distal side of depressions by a topographic barrier, producing compressive stress fields in these regions. This is thought to have retarded ice flow and decreased basal temperatures, which in turn would have promoted onfreezing of basal material. This entrained material is thought to have been subsequently sheared up and stacked under compressive ice flow. The stacked slabs of debris would then be deposited as a series of ridges once the ice sheet melted (Fig. 10.1).

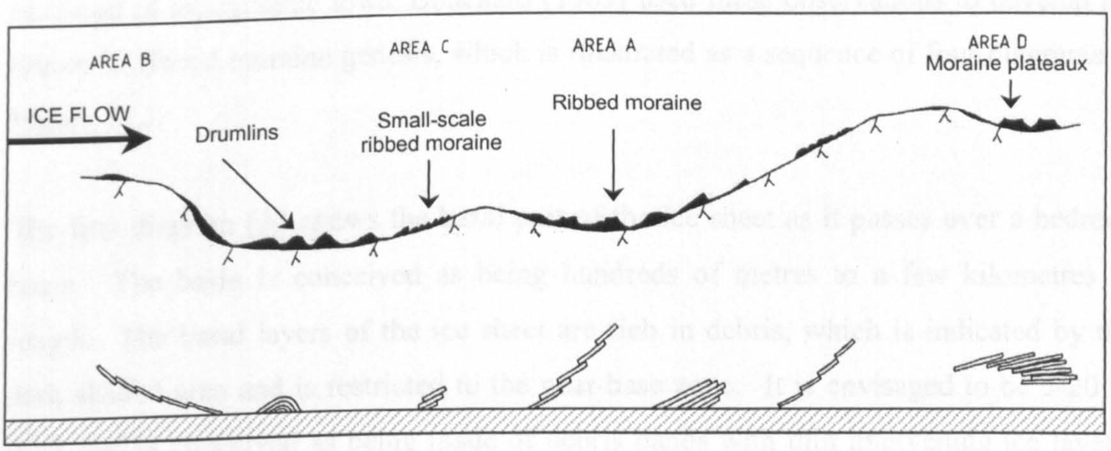

Figure 10.1. A hypothetical model of the main processes occurring at the time of deglaciation. Areas A-D correspond to field sites used in the study. The lower diagram shows the shear planes or the differential transport for dispersed debris within the ice. The upper diagram shows the moraine morphology after meltout. Area A is characterised by large transverse ridges within lower concave basins. In slightly convex areas, proximal to hills, outspread clusters of small transverse ridges appear. Area B is situated on a raised plain limited distally by a hill and consists of drumlins. Area C is situated on the proximal inclination of a large hill. The moraine morphology consists of very distinct small transverse ridges. Area D is situated in an elevated area without any marked relief. The morphology is dominated by large, concave upwards moraine plateaux divided by deep ravines. (After Minell, 1980).

The hypothesis proposed by Sollid & Sørbel (1984) is similar to that of Minell (1980) and is based on an observation they made that ribbed moraines are a feature of topographic basins in southern Norway. These authors implied ribbed moraine formed in these areas due to compressive stresses when the ice flowed against a topographic obstruction on the downstream end of rock basins. They do not explain the mechanisms involved but simply stated compressive stresses would have sheared and stacked basal layers of debris rich ice.

The shear and stack model due to topographic obstructions was outlined most extensively by Bouchard (1989). In this paper, Bouchard discussed the distributional pattern of subglacial bedforms in northern Québec stating ribbed moraines were restricted to a zone 150-350 km from the former ice divide. He also described the morphology of the ridges and stated what he thought were common features of this landform. For example, that the ridges were asymmetric with steeper distal sides; had accordant summits and appeared to fit together like a jigsaw puzzle; often had flutings and boulders on their surface. He also reported the relationships between ribbed moraines and drumlins and noted transitions between both bedform types. An important characteristic for him was the observation that ribbed moraines most commonly occurred in topographic lows. Bouchard (1989) used these observations to develop his theory of ribbed moraine genesis, which is illustrated as a sequence of four diagrams in Figure.10.2.

The first diagram (A) shows the basal part of the ice sheet as it passes over a bedrock basin. The basin is conceived as being hundreds of metres to a few kilometres in length. The basal layers of the ice sheet are rich in debris, which is indicated by the dark shaded area and is restricted to the near-base zone. It is envisaged to be 5-20 m thick and is conceived as being made of debris bands with thin intervening ice layers. The upper limit of the drift-laden ice is thought to be sharp and probably occurs within an interval 1 m or less. In this model, an obstacle to flow is created by the down-glacier end of the rock basin, which causes compression in these zones and creates shear planes in the basal part of the glacier. These in turn lead to shearing and stacking of slices of debris-laden ice (B). The process of shearing and stacking of slices will continue at the base of the ice sheet as long as ice flow is obstructed. Once the rock basin is filled with stacked slices of debris-laden ice or the obstacle is reduced by erosion, the glacier overcomes the resistance to flow by the development of a sub-horizontal plane of décollement (C). Ice now flows along this plain shearing the tops of the ridges and makes flutings on the surface of the ridges. Since resistance to flow has been greatly reduced, ice velocity will increase and this leads to renewed quarrying on the up glacier side of the basin (C). These boulders are picked up, entrained by the ice sheet and transported to positions over the stacked debris slices. On meltout, these would be draped on top of the ridges, accounting for the occurrence of boulder cover observed on the ribbed moraine ridges in Bouchard's study areas.

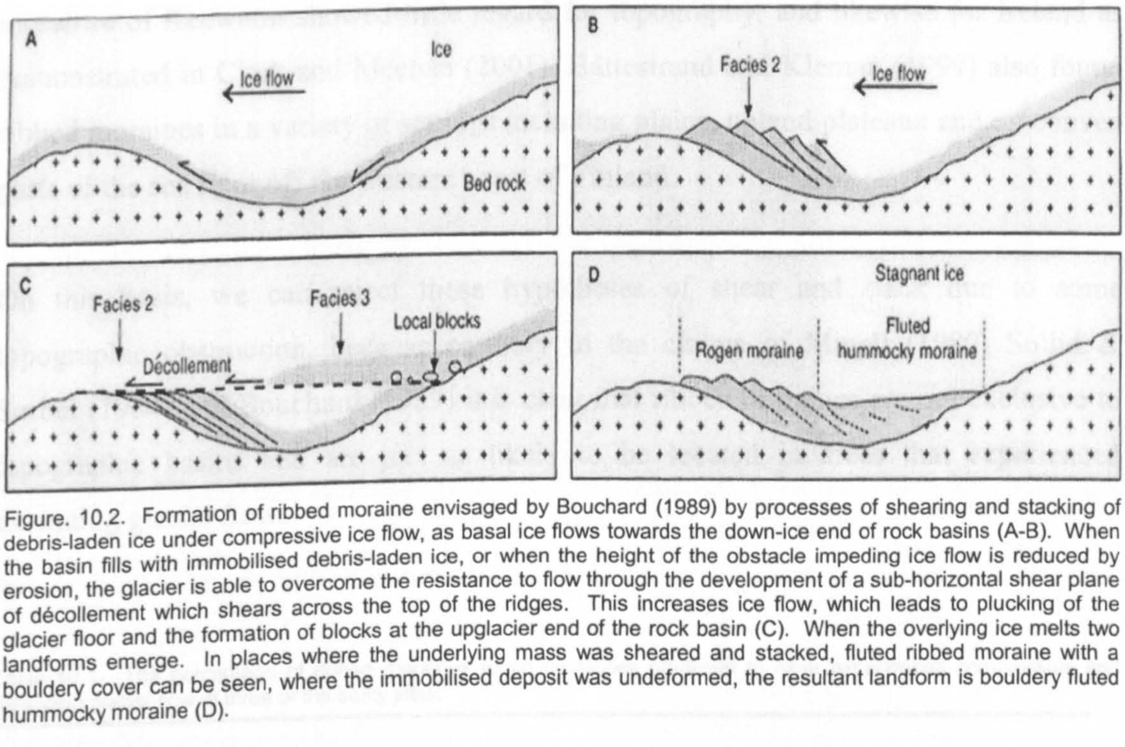

Figure. 10.2. Formation of ribbed moraine envisaged by Bouchard (1989) by processes of shearing and stacking of debris-laden ice under compressive ice flow, as basal ice flows towards the down-ice end of rock basins (A-B). When the basin fills with immobilised debris-laden ice, or when the height of the obstacle impeding ice flow is reduced by erosion, the glacier is able to overcome the resistance to flow through the development of a sub-horizontal shear plane of décollement which shears across the top of the ridges. This increases ice flow, which leads to plucking of the glacier floor and the formation of blocks at the upglacier end of the rock basin (C). When the overlying ice melts two landforms emerge. In places where the underlying mass was sheared and stacked, fluted ribbed moraine with a bouldery cover can be seen, where the immobilised deposit was undeformed, the resultant landform is bouldery fluted hummocky moraine (D).

The above ideas are similar in that they all appeal to the same mechanism of formation in a similar topographic setting. According to these authors, ribbed moraines would only have formed in areas that experienced compressive glacial stresses due to the ice sheet flowing against a topographic barrier on the downstream end of rock basins. If this is correct, then one would expect to find ribbed moraines exclusively in topographic depressions and on the upstream facing slopes of basins as these are the places proposed to be most conducive for shearing and stacking. However, detailed observations made during this study do not support this. As Chapters 5, 6, 7 and 8, clearly demonstrated, whilst there are some associations with topographic lows, the majority of ribbed moraines do not occur in areas explained by compressive ice flow due to topography. At all of the study sites, ribbed moraines were observed in a wide variety of topographic settings including slopes running in and out of topographic basins, on hilltops and in areas of open undulating terrain. Analysis conducted using a GIS also found no relationship between ribbed moraine occurrence and compressive ice flow caused by topography. At the Lac Naococane, River Kaniapiskau and Lake Rogen sites, the GIS clearly demonstrated that a large percentage of ribbed moraines were located in regions where topography would have caused extending glacial flow (Table 10.1). In addition, the detailed mapping of Shilts and Aylsworth (1989) established that the ribbed moraines of Keewatin showed little regard for topography, and likewise for Ireland as demonstrated in Clark and Meehan (2001). Hättestrand and Kleman (1999) also found ribbed moraines in a variety of settings including plains, upland plateaux and on convex parts of the sea floor off the western coast of Finland.

On this basis, we can reject these hypotheses of shear and stack due to some topographic obstruction, because contrary to the claims of Minell (1980) Sollid & Sørbel (1984) and Bouchard (1989) it is clear that ribbed moraines are not exclusive to topographic basins and are just as likely to be located in areas that experienced extending glacial flow.

Table 10.1. The percentage of ribbed moraines found on slopes predicted to have experienced compressive and extending glacial flow at three of the study sites.

Location	% of ribbed moraine in areas of compressive flow	% of ribbed moraine in areas of extending flow
Lac Naococane	43	51
Central region of River Kaniapiskau	58	28
Eastern region of River Kaniapiskau	31	51
Western region of River Kaniapiskau	31	52
Lake Rogen	47	43

10.2.2. Freeze on and entrainment

This model of formation was presented by Sollid & Sørbel (1994). In this paper, the authors discussed the distributional pattern of morainic landforms in southern Norway and related this pattern to the thermal regime of the ice sheet during the last part of the Weichselian glaciation. They described ribbed moraine ridge dimensions stating they are normally 100-200 m long and 10-20 m high and discussed their regional and local distribution. They strongly assert that ribbed moraines form exclusively in hollows and this observation underpins their formational hypothesis.

According to their model, ribbed moraines occur at lower elevations in the zone where the glacier gradually changed from warm-based to cold-based. They argued that when ice underwent this change, it firstly began freezing on drier patches of the convex parts of the subglacial bed. At the same time water accumulated in terrain depressions at some lower level where the ice was still temperate. They envisaged that freezing of water filled hollows probably took a long time, as long as thousands of years depending on the amount of trapped water. This is due to the low conductivity of ice, which inhibits dispersion of latent heat released during the freezing of the water. Due to their location, they assume that ribbed moraines are formed in isolated patches of trapped water bodies or water-soaked debris in areas where the ice sheet was elsewhere frozen to the ground. They avoid explaining the actual mechanism that formed the ridges in these depressions and simply stated "the Rogen moraines are assumed to be made by ice movement in this kind of environment" (Sollid & Sørbel, 1994, p34). The type of ice movement they envisaged is also not explained but presumably, because of the shape of the basin, a compressive stress field would have been initiated as the ice flowed against the slope on the downice side of the basin. If this presumption is correct, they may have envisaged a mechanism of shear and stack similar to that proposed by Minell (1980) Sollid & Sørbel (1984) and Bouchard (1980, 1989) (Fig. 10.3).

According to this hypothesis ribbed moraines should only be formed in hollows as this is the only place water could have accumulated. However, since we know from our observations in Chapters 5 to 8 that ribbed moraine form independently of topography it is rejected as a general theory because it cannot account for ribbed moraines in other topographic settings.

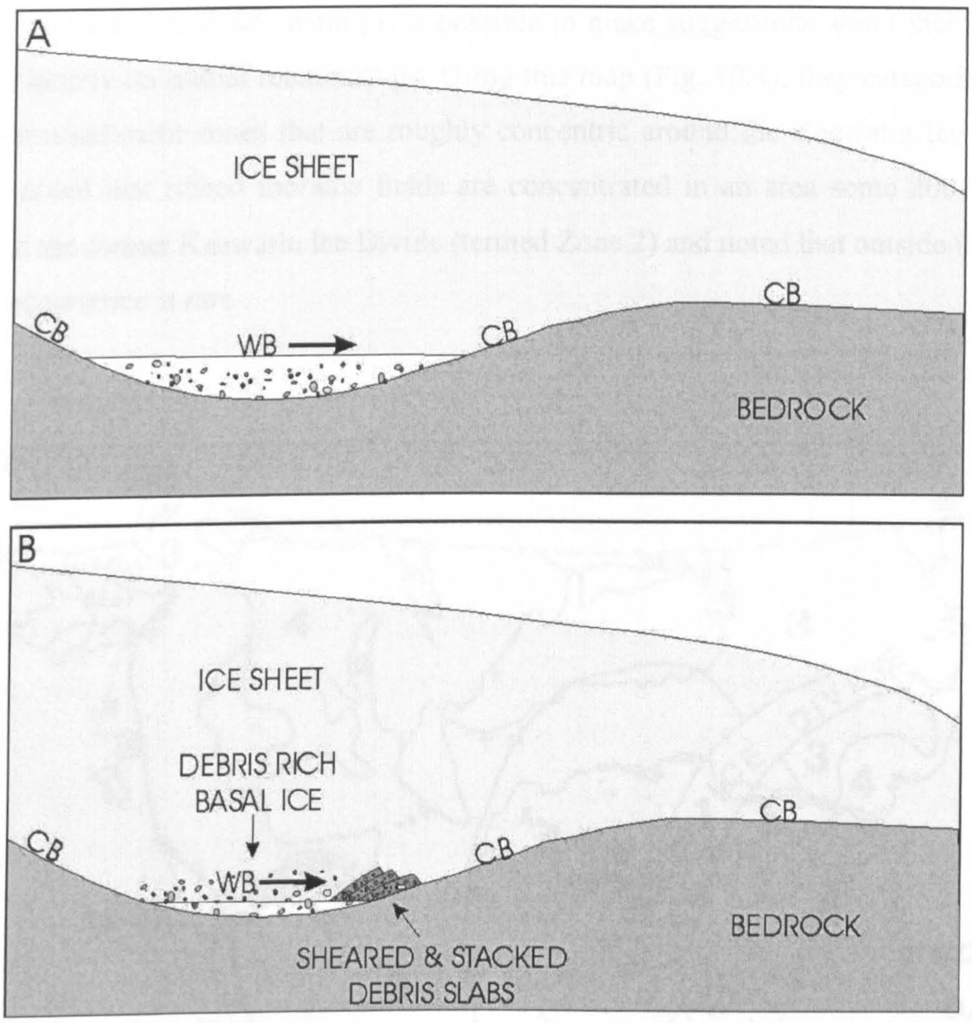

Figure 10.3. A conceptual diagram derived from the descriptions of Sollid & Sørbel (1994) illustrating the inferred model of ribbed moraine genesis proposed by these authors. Figure 10.3a shows that large parts of the ice sheet are cold based (CB) and are frozen to the bed. In terrain depressions, ice remains warm based (WB) due to the presence of water or water soaked sediment. Figure 10.3b demonstrates that after some time this water-soaked debris eventually becomes entrained in the basal ice by freeze-on. Because water in the depression is not completely frozen, the ice remains warm-based and can therefore move. It is inferred by these authors that the movement of ice in this region makes the Rogen moraine ridges. Although they do not specify a mechanism, it is thought that the layers of entrained debris sheared and stacked due to the compressive flow resulting from ice flowing against the downstream slope.

10.2.3. High basal debris concentrations changing ice viscosity

In this hypothesis, it is argued that high concentrations of basal debris within the ice changed ice viscosity, causing a decrease in the plastic behaviour of the ice. It is thought that this induced compression and basal shearing of layers of debris-rich ice. This idea was proposed by several authors (Dredge *et al.*, 1986; Shilts and Aylsworth, 1989 and Aylsworth and Shilts, 1989), however the paper by Aylsworth and Shilts (1989) gives the most detailed account of the hypothesis which is summarised below. In this study, the authors compiled a map of glacial bedforms in the Keewatin sector of the Laurentide Ice Sheet, stating it is possible to make suggestions about their genesis based largely on spatial relationships. Using this map (Fig. 10.4), they categorised four landform/sediment zones that are roughly concentric around the Keewatin Ice Divide. They noted that ribbed moraine fields are concentrated in an area some 200-250 km around the former Keewatin Ice Divide (termed Zone 2) and noted that outside this zone their occurrence is rare.

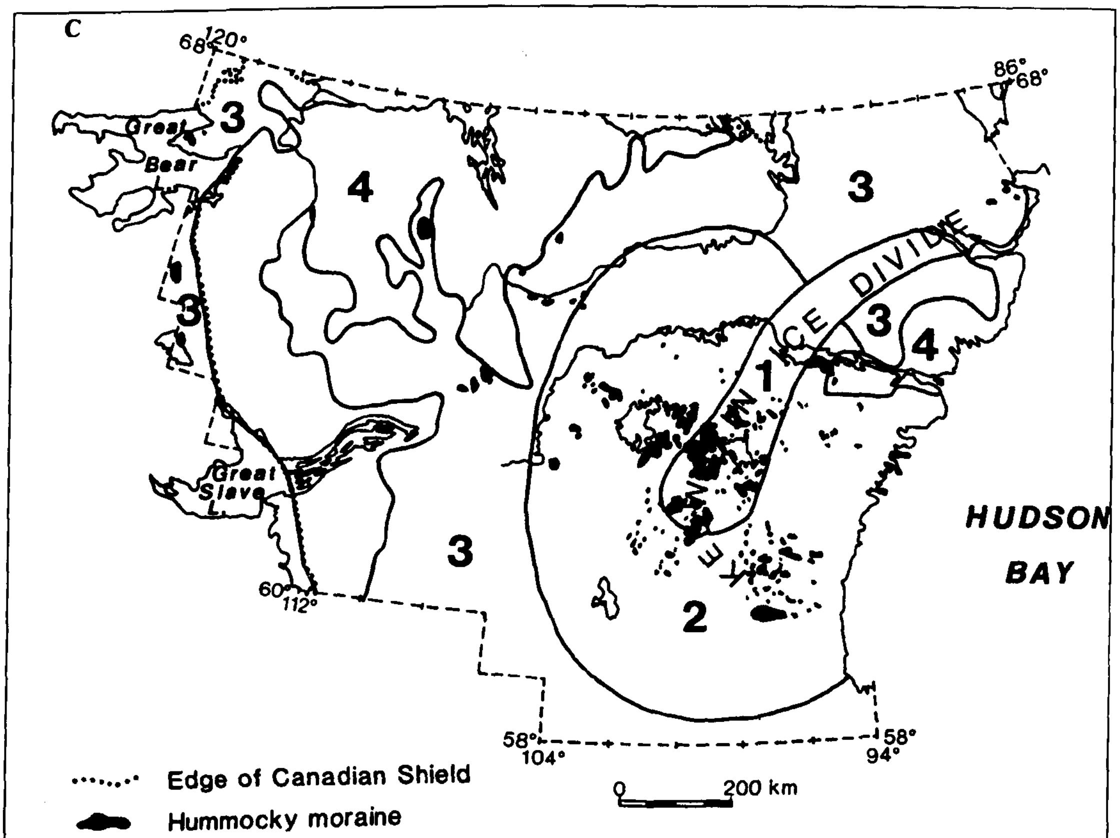

Figure 10.4. Landform/sediment zones around the Keewatin Ice Divide proposed by Aylsworth and Shilts (1989). Black regions represent hummocky moraine, the characteristic landform of the ice divide. Zone 1, including the divide is characterised by a lack of eskers or oriented landforms and includes significant areas of hummocky moraine. Zone 2, is delimited by the distribution of ribbed moraine, but also includes extensive drumlin swarms and esker systems. Zone 3, is characterised by fairly continuous, commonly drumlinized drift cover. Many eskers cross this zone, but they decrease in size and frequency outwards. Zone 4 comprises of large tracts of bedrock outcrop with minimal drift cover.

Within Zone 2, ribbed moraine fields were found to be ribbon shaped and elongated in the direction of ice movement and typically consisted of short sinuous ridges less than 1 km in length and 10 m in height. They noted that individual ridges are often asymmetric with steeper distal sides, which to them suggested they were like plates of sediment thrust one on the back of the other giving the ribbed moraine a "fish scale" appearance on aerial photographs. The authors noted that ribbed moraine is developed across the landscape independent of topography, although they do recognise this part of the Canadian Shield is somewhat flat. Drumlins were also noted to occur in intimate association with ribbed moraine in Zone 2. As well as there being drumlinized ribbed moraine, drumlins were observed to have been broken into incipient ribs and lateral transitions are common throughout this zone. The close lateral relationship between the two landforms prompted Aylsworth and Shilts (1989) to believe that similar glaciodynamic conditions existed during their formation. However, they note the universal presence of drumlins across Keewatin contrasted noticeably with the restricted occurrence of ribbed moraine around the ice divide. For Aylsworth and Shilts (1989), this restricted zonation indicated some condition changed or existed in this zone throughout or at some point in time during the existence of the Keewatin Ice Sheet that was conducive for generating ribbed moraines. They proposed these conditions occurred when during deglaciation, the ice sheet melted back to approximately the outer edge of Zone 2, where at this time the Keewatin Ice Sheet was abruptly reactivated by climatic deterioration. They stated that because the glacier profiles were low and the ice thin, reactivation would have "shattered" the glacier into stacked thrust plates of ice, englacial and subglacial sediment. This is proposed to have happened because debris rich ice is less plastic, more brittle, and can therefore more readily shear. They believed that if such shattering occurred in parts of the glacier where concentrations and physical properties of sediment and ice promoted internal thrusting, melting under subsequent stagnant conditions would have exposed sediment beds draped over one another just as they were stacked in the ice.

The mapping and observations of Aylsworth and Shilts (1989) are extremely useful, and their argument that basal debris concentrations affecting ice viscosity is of interest, but we argue against their tentative formative theory on three grounds;

1) The glaciological plausibility of an ice sheet that re-activates (re-advances) and somehow 'shatters' during this phase is highly questionable. The concept as described in Aylsworth and Shilts (1989) invokes widespread development of thrust planes (or 'shatters') during this reactivation of flow from presumably a more stagnant situation. Whilst contemporary examples of thrust plane development exist, (e.g. Croot, 1988; Krüger, 1993) they tend to occur only at the absolute margin and on a much smaller

scale (10's m) than km's typical of ribbed moraine. We therefore caution against invoking widespread and very extensive shattering of the whole ice sheet periphery until such time as ice-rheological modelling experiments could verify thrust development at this large scale (i.e. faulting at the km-scale of ribbed moraine and over wide areas). Furthermore, in order for their theory to work, the ice sheet is required to virtually cease flowing (become stagnant) and for the debris-laden thrust planes to melt out *in situ*. This does not seem a likely scenario given that landform systems (drumlins and eskers) indicate active retreat and a still large Keewatin Ice Sheet has no reason to stagnate *in situ* as it would have still been gravitationally driven.

2) Since the writing of their paper the concept of a stable Keewatin Ice Divide that the ice sheet shrank back to has been seriously questioned. Boulton and Clark (1990a) for example demonstrated that the landform systems either side of the divide were likely of different ages, and the appearance of a central zone defining an ice divide is misleading (i.e. 'bogus ice divide'). Additionally it has since been discovered (Stokes and Clark, 2003a,b) that the major Dubawnt Lake ice stream cut through this area. This indicates that the landform systems are considerably more complex than Aylsworth and Shilts (1989) suggested and severely lessens the validity of a simple ribbed moraine pattern surrounding an ice divide association.

3) Furthermore, Hättestrand and Kleman (1999) argued that the distribution of ribbed moraine (10% of the area covered by Laurentide and 20% of Fennoscandian ice sheet) does not appear to coincide with ice marginal positions at a specific time. For example, the ribbed moraine limit coincides with the 12 thousand B.P. (Ka) ice marginal position in Newfoundland, the 10 Ka ice margin in Fennoscandia, the 9 Ka ice margin in Keewatin, and the 8 Ka ice margin in Québec. Therefore, it is unlikely that the start of the formation of ribbed moraines at the last deglaciation was induced by climatic changes as suggested by Aylsworth and Shilts (1989). Rather, it appears likely that the distribution pattern is controlled by specific conditions or events in the subglacial environment.

10.2.4. Frozen outer margin

The idea of a frozen outer margin producing compressive stresses and forming ribbed moraines has been presented by several authors (Shaw, 1979; Punkari, 1984; Bouchard & Salonen, 1989). The models proposed by Punkari (1984) and Bouchard & Salonen (1989) is based on an inferred thermal distribution at the base of the ice sheet that includes a melting inner area that graded into a frozen outer margin through an intermediate freezing zone. These authors do not explain the mechanism that created the ridges, but Punkari (1984) suggested, "the genesis of Rogen-type moraines evidently involves the compression caused by the obstructed flow of an ice sheet" (Punkari, 1984, p 85). In such an environment, this would have been at the junction between warm-based sliding ice and cold-based ice at the margins. It is implied that ice flowing against the frozen margin created a compressive stress field, which would have lead to thrusting and shearing of unfrozen sediments or basal-rich ice at this junction. Figure 10.5 is a conceptual diagram illustrating the mechanism that it seems the authors have implied.

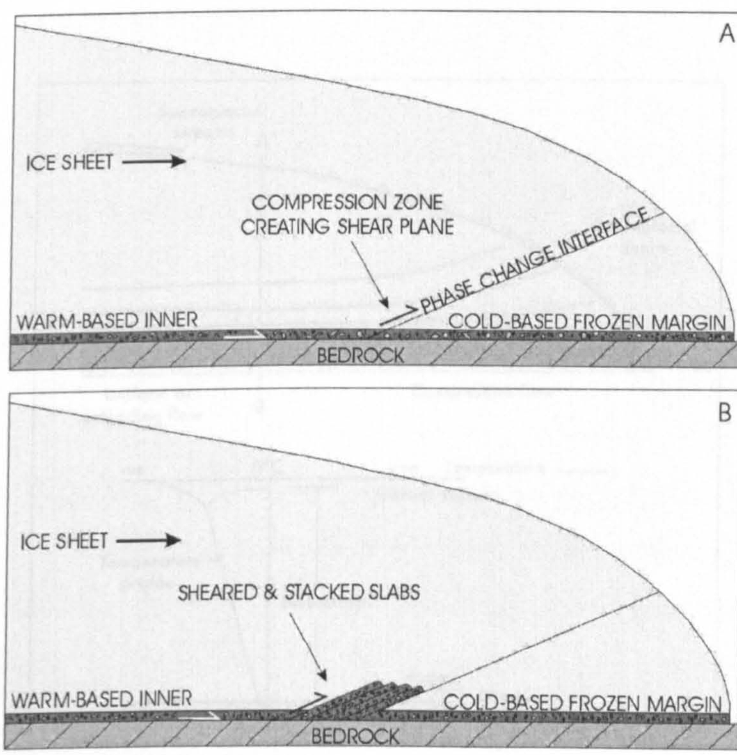

Figure 10.5. Conceptual diagram developed from descriptions given by Shaw (1979) Punkari (1984) and Bouchard and Salonen (1989) of the how a frozen outer margin might create a zone of compression that results in the theoretical genesis of ribbed moraine. The top diagram shows that the inner portion of the ice sheet is warm-based and is therefore sliding forward. The outer margin is cold-based and is frozen to the ground. The phase change interface marks the zone of transition between warm-based and cold-based ice. It is along this interface that a shear plane is created as the mobile warm-based ice is forced to shear upwards along this plane. Figure 10.5b shows the hypothetical formation of ridges due to unfrozen sediments at the base of the ice sheet shearing up along the phase change plane and stacking up against it. Each newly stacked layer shifts the shear plane back, creating a new shear plane surface where another slab can be sheared up along it.

The hypothesis presented by Shaw (1979) is also based on the idea that ribbed moraines are formed by compressive stresses which lead to thrusting and folding of debris-rich basal ice or basal material. Although the hypothesis emphasises a frozen margin explanation for ribbed moraine genesis other factors that cause compressive stresses were also recognised. He stated that topographic depressions and areas where deep narrow valleys opened into flatter terrain would also have caused compressive ice flow.

His ideas are based largely on observations he made on ridge morphology and on investigations of the internal structure of ribbed moraine ridges in Jämtland, Sweden. Observations included individual ridges often having curved horns pointing down ice, ridges often having flutings on their surface and the distal sides being commonly stepped in a series of small escarpments. Internally he found that ridge material commonly showed signs of being stacked by folding and thrusting and he argued this was evidence that compressive stresses were involved in ridge formation (Fig. 10.6).

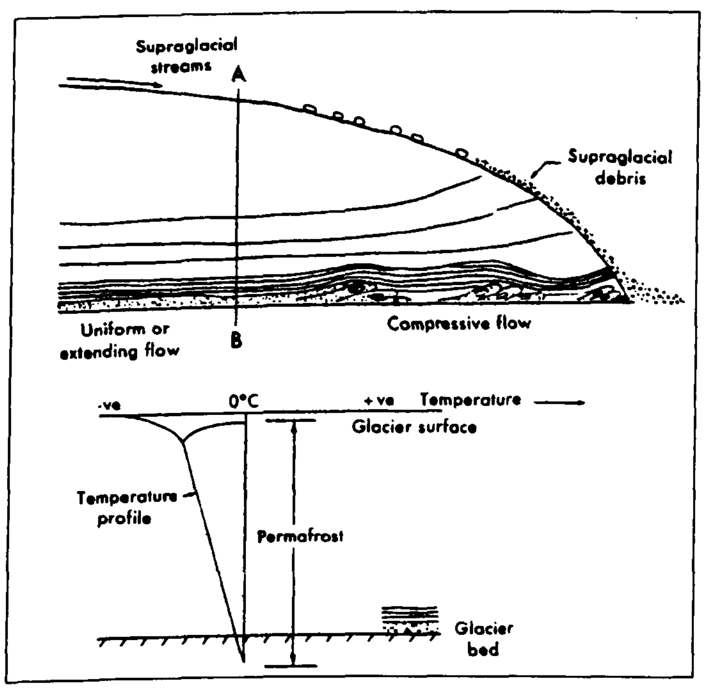

Figure 10.6. Temperature profile, internal structure and flow characteristics of a cold-based ice sheet. The vertical line on the temperature diagram represents the pressure melting temperature. Note how compressive flow in the margin produces a series of englacial folds that are stacked on top of each other. Note also that in regions of uniform or extending flow the basal-rich ice or sediment is thin and attenuated (After Shaw, 1979).

He also found these tectonic structures were often crosscut by horizontal, stratified attenuated layers known locally as Sveg tills, which Shaw argued formed under extensional or uniform flow (Fig. 10.7). Shaw explained the survival of these delicate structures through a slow meltout process under permafrost conditions whereby the glacier thinned at the margins, stagnated and melted out largely from beneath. He stated the net result of a relatively slow, basal melt-out is one where the attributes of the debris in transport are retained.

Figure 10.7. Example of a laminated Sveg till exposed in a ribbed moraine ridge near Sveg, Sweden. (Photo J. Lundqvist, in Benn and Evans, 1998)

Based on these observations, Shaw envisaged a general sequence of events leading to the formation of a ribbed moraine ridge (Fig. 10.8). In the initial phase, a series of overlapping plates are created by small-scale overfolds in the basal, debris-rich ice in a region of compression. Folds formed further upglacier migrate towards the margin and catch up with other, distal folds producing a sequence of stacked folds. Eventually the glacier buckles into a steep fold at this concentration of debris and thrusting may occur in association with this buckling. In some cases where the initial folded plates are of limited lateral extent it is proposed that smaller folds will be carried around this zone forming down-ice pointing horns (Stage 1). This high concentration of debris causes relative stagnation and overriding by clean, plastic ice. Ice passing through such a restricted area will be forced to accelerate causing extending flow in the upper ice. This is thought to have produced the surface flutings that Shaw stated were a common characteristic. A new debris layer is also made by this ice shearing over the stagnant mass, producing a band of englacial debris on the lee side of the folds. It is proposed similar debris bands are produced in the same manner by englacial ridges upglacier. These bands are then carried across the ridge under construction downstream. Meltout by the process outlined above preserves the englacial ridge complex and the horizontal sorted layers.

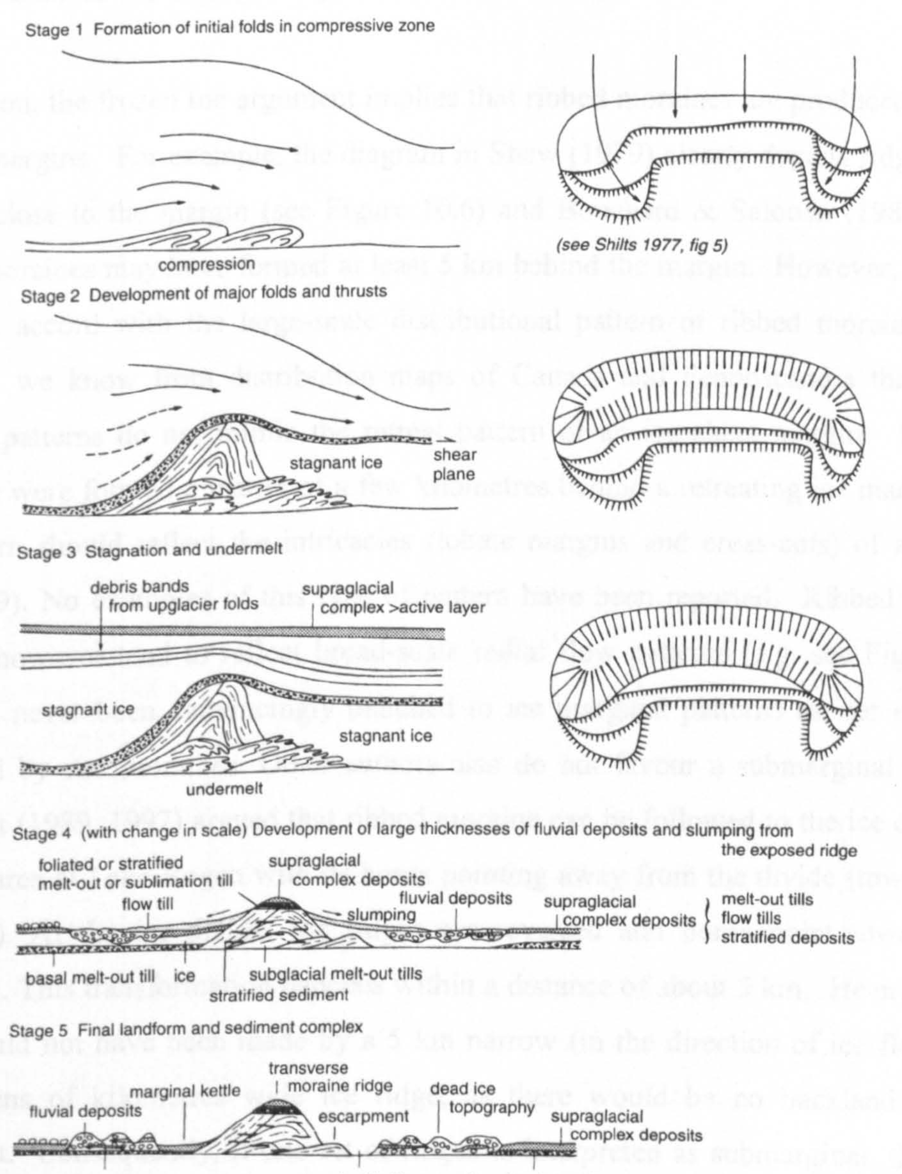

Figure 10.8. Genesis of ribbed moraine ridge and associated deposits. (After Shaw, 1979).

The idea of a frozen margin explanation for ribbed moraine is not favoured for several reasons. Whilst many existing stable polar glaciers exhibit a frozen toe, this polythermal configuration may be unlikely to exist for margins that are rapidly retreating because it takes some time for permafrost conditions to become established. Hättestrand and Kleman (1999) argued that a frozen margin outside a thawed inner is only likely to result if permafrost conditions prevailed during deglaciation. They rejected the idea outright on the basis that almost all ribbed moraines in Sweden are found inside the Younger Dryas ice margin and stated it was unlikely that the ice sheet had a frozen margin during the rapid deglaciation during Pre-Boreal/Boreal times. Furthermore, Lundqvist (1962, 1981) argued there were no indications at all of deglacial permafrost conditions inside the Younger Dryas moraines in Sweden.

In addition, the frozen toe argument implies that ribbed moraines are produced close to the ice margins. For example, the diagram in Shaw (1979) clearly depicts ridges being formed close to the margin (see Figure 10.6) and Bouchard & Salonen (1989) stated ribbed moraines may have formed at least 5 km behind the margin. However, this idea does not accord with the large-scale distributional pattern of ribbed moraines. For example, we know from distribution maps of Canada and Fennoscandia that ribbed moraine patterns do not mimic the retreat pattern of an ice sheet margin. If ribbed moraines were formed a matter of a few kilometres behind a retreating ice margin then the pattern should reflect the intricacies (lobate margins and cross-cuts) of a margin (Fig. 10.9). No examples of this type of pattern have been reported. Ribbed moraine patterns however tend to reflect broad-scale radial flow patterns (e.g. see Figure 5.3) and have never been convincingly matched to ice marginal patterns as, for example, expressed by end moraines. Other authors also do not favour a submarginal genesis. Lundqvist (1989, 1997) argued that ribbed moraine can be followed to the ice divide in the type area at Lake Rogen with its horns pointing away from the divide (towards the southeast). At the ice divide, the ridges are reversed and horns point towards the northwest. This transformation happens within a distance of about 5 km. He argues the forms could not have been made by a 5 km narrow (in the direction of ice flow) and several tens of kilometres wide ice ridge, as there would be no backland for ice movement. Consequently, if one set of ridges is interpreted as submarginal, the other must have been formed very far behind the margin on the opposite side of the ice sheet. Lundqvist (1989) thought it more reasonable to interpret both sets of ribbed moraine to have been formed a considerable distance behind the margin and on this basis rejected all theories that assume a marginal origin.

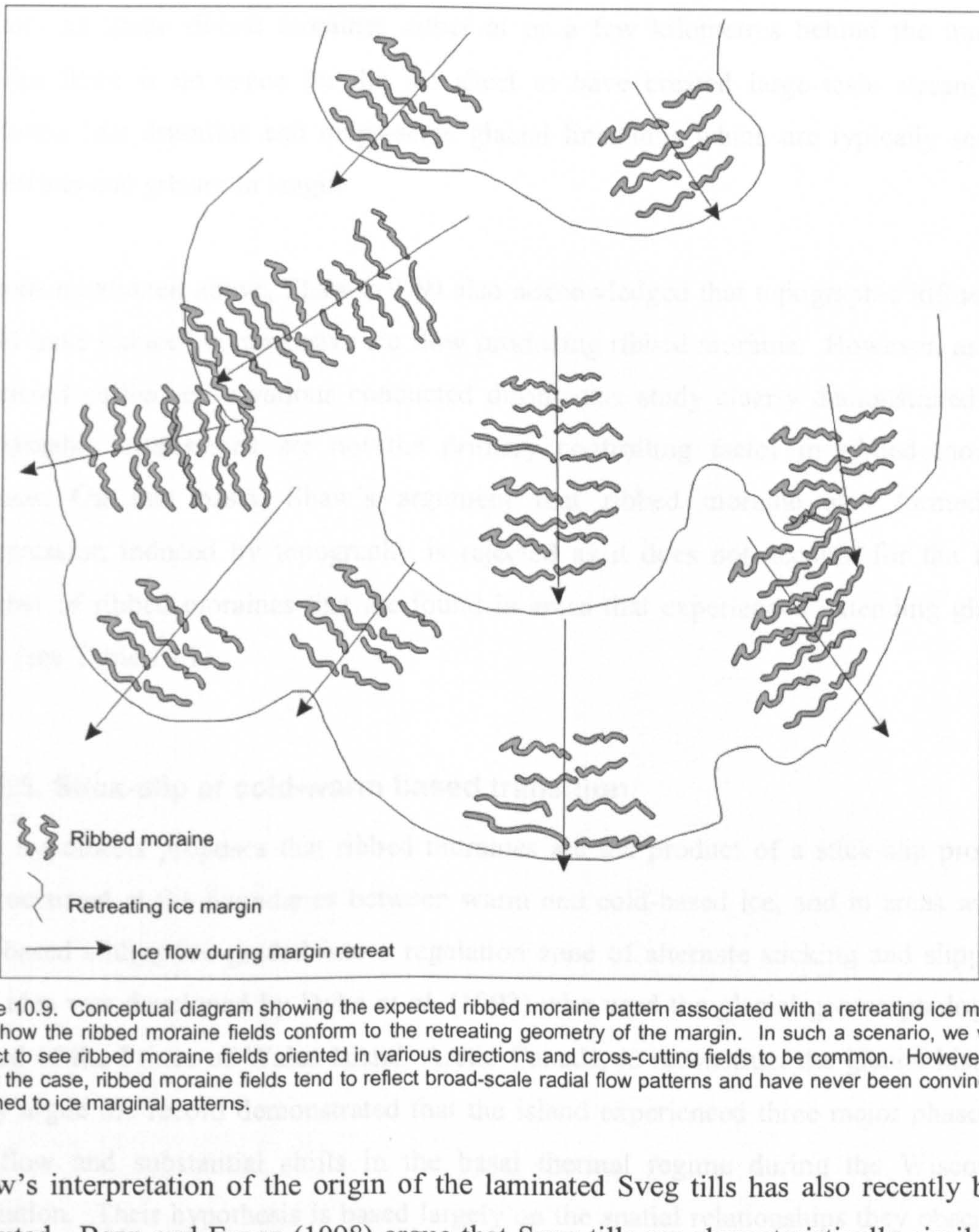

Figure 10.9. Conceptual diagram showing the expected ribbed moraine pattern associated with a retreating ice margin. Note how the ribbed moraine fields conform to the retreating geometry of the margin. In such a scenario, we would expect to see ribbed moraine fields oriented in various directions and cross-cutting fields to be common. However, this is not the case, ribbed moraine fields tend to reflect broad-scale radial flow patterns and have never been convincingly matched to ice marginal patterns.

Shaw's interpretation of the origin of the laminated Sveg tills has also recently been disputed. Benn and Evans (1998) argue that Sveg tills are characteristically similar to glacitectonites that are formed by shear and attenuation of pre-existing sediments (Hart and Roberts, 1994; Benn and Evans, 1996). Sveg tills may therefore record strain within the bed rather than within debris rich ice. Furthermore, observations conducted during this study do not support the assertion that the ridges formed due to meltout under stagnant ice conditions. The fact that ribbed moraine ridges are commonly drumlinized and that downstream transitions into drumlins and mega-scale glacial lineations were frequently observed, strongly indicates the ice sheet continued to actively flow for some time after the ridges had formed. The fact that transitions are common also rejects the arguments for a sub-marginal hypothesis. Considering these authors all place ribbed moraines either at or a few kilometres behind the margin, implies there is no space for the ice sheet to have created large-scale streamlined bedforms like drumlins and mega-scale glacial lineations which are typically several kilometres and greater in length.

As was mentioned above, Shaw (1979) also acknowledged that topographic influences could have induced compressive ice flow producing ribbed moraine. However, as was discussed earlier, observations conducted during this study clearly demonstrated that topographic expressions are not the primary controlling factor in ribbed moraine genesis. On this basis, Shaw's argument that ribbed moraine also formed by compression induced by topography is rejected as it does not account for the large number of ribbed moraines that are found in areas that experienced extending glacial flow (see Table 10.1).

10.2.5. Stick-slip at cold-warm based transition

This hypothesis proposes that ribbed moraines are the product of a stick-slip process that occurred at the boundaries between warm and cold-based ice, and in areas where wet-based sliding ice graded into a regelation zone of alternate sticking and slipping. The idea was developed by Dyke *et al.* (1992) who used the glacial geomorphological record of the Prince of Wales Island, Arctic Canada, to reconstruct the glacial history. They argue the record demonstrated that the island experienced three major phases of ice flow and substantial shifts in the basal thermal regime during the Wisconsin glaciation. Their hypothesis is based largely on the spatial relationships they observed between drumlins and ribbed moraines on the island and on the close proximity of some ribbed moraine fields to areas that switched between warm and cold-based ice. To understand the hypothesis it is necessary to examine these relationships in more detail. As ribbed moraines are proposed to have formed only during their ice flow phases 2 and 3 these are the only stages that will be discussed.

According to Dyke *et al.* (1992) the Crooked Lake drumlin field was formed during phase 2 when ice flowed northwestward across the island in a markedly curved fashion (Fig. 10.10a). The authors noted how the Crooked Lake drumlins graded northwards into a large ribbed moraine field that wraps around head of Ommanney Bay (Fig. 10.10a).

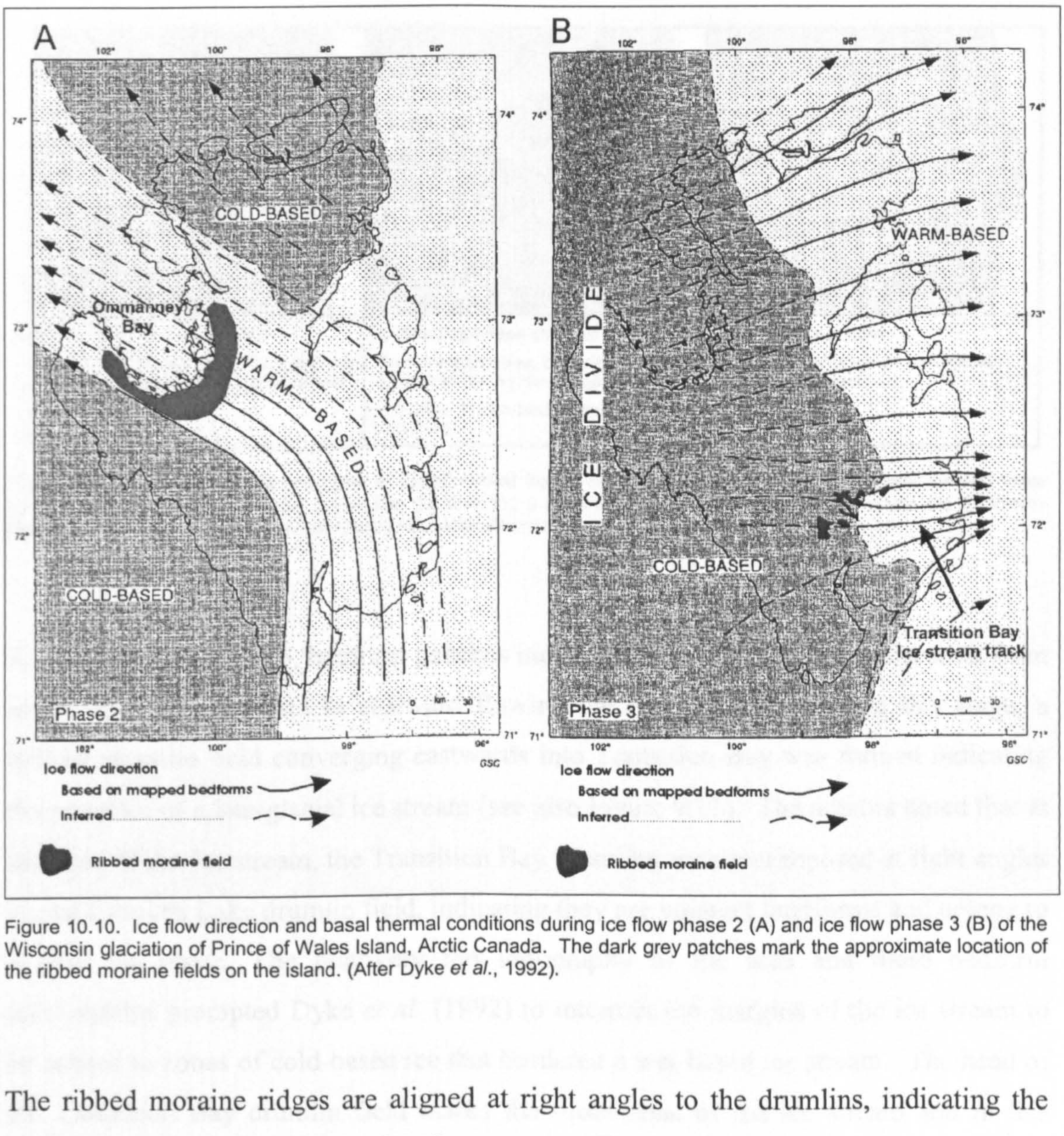

Figure 10.10. Ice flow direction and basal thermal conditions during ice flow phase 2 (A) and ice flow phase 3 (B) of the Wisconsin glaciation of Prince of Wales Island, Arctic Canada. The dark grey patches mark the approximate location of the ribbed moraine fields on the island. (After Dyke *et al.*, 1992).

The ribbed moraine ridges are aligned at right angles to the drumlins, indicating the landforms belong to the same ice flow event. They found the contact between both landform assemblages was gradational and difficult to discern and the few occurrences of streamlined till within the ribbed moraine field represented direct extensions of flowlines from the drumlin field. Dyke *et al.* (1992) proposed this gradation from streamlined longitudinal forms to non-streamlined, transverse forms reflected a change in flow dynamics. They postulate the change was possibly one where a wet sliding bed graded into a regelation zone of alternate sticking and sliding. Although not specifically stated, they seem to envisage a patchiness in the basal thermal regime, i.e. an archipelago thermal-type boundary (Fig. 10.11b) rather than a clear boundary between warm and cold-based ice (Fig. 10.11a).

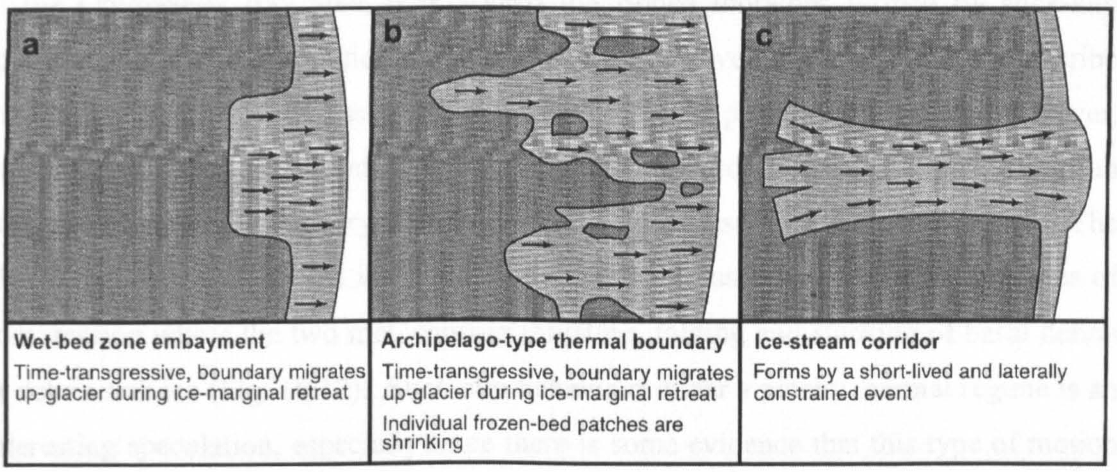

Figure 10.11. Illustrating different types of hypothesised frozen bed conditions. (a) Showing a clear defined linear boundary between cold and warm-based ice. (b) Showing a patchwork arrangement of cold and warm ice. (c) Warm-based streaming ice bounded by cold-based ice. (After Kleman *et al.*, 1999)

Between phases 2 and 3, bedform patterns indicate the ice flow switched direction from north and northwestward to eastward flowing ice (Fig. 10.10b). During this stage, a striking drumlin field converging eastwards into Transition Bay was formed indicating the presence of a late-glacial ice stream (see also Figure 9.11). The authors noted that at the head of the ice stream, the Transition Bay drumlins are superimposed at right angles on the Crooked Lake drumlin field, indicating they are younger landforms and belong to a later ice phase. The relatively flat topography of the area and these bedform relationships prompted Dyke *et al.* (1992) to interpret the margins of the ice stream to be related to zones of cold-based ice that bordered a wet-based ice stream. The head of the Transition Bay drumlin field marks the onset zone of the ice stream and in this region, drumlins decrease in size and ribbed moraine begins to appear. The ribbed moraine ridges are oriented to the east and therefore clearly belong to the eastward flowing ice stream. The authors noted how the ribbed moraine in this area is located in the contact zone between warm and cold-based ice, which prompted them to believe it formed under transitional, stick and slip, basal ice conditions. Dyke *et al.* (1992) suggested that alternate basal sticking and sliding could have resulted from oscillations of the boundary between warm and cold-based ice or from a patchwork arrangement of small cold and warm-based areas (i.e. archipelago boundary) such that the flowlines crossed from one to the other. It is argued that either would have caused accelerations and decelerations of flow and attendant infolding and stacking of basal debris.

In the Ommanney Bay area, it is argued the ribbed moraines formed by stick-slip conditions in zone of regelation. The authors did not develop the idea fully or describe the mechanisms, which makes it difficult to envisage the processes involved. However, they seem to infer the action of the ice slipping forward from the sticky spots in an archipelago thermal boundary sheared up and folded basal materials into ridges. The idea infers that warm-based ice flowing towards cold-based ice creates small zones of compression where the two met, causing thrusting, folding and stacking of basal debris or debris rich ice (Fig. 10.12). Stick-slip behaviour under a patchy thermal regime is an interesting speculation, especially since there is some evidence that this type of motion is possible (e.g. Annadakrishnan and Bentley, 1993; Ekström *et al.*, 2003). However, the idea has yet to be fully developed and thus is difficult to test.

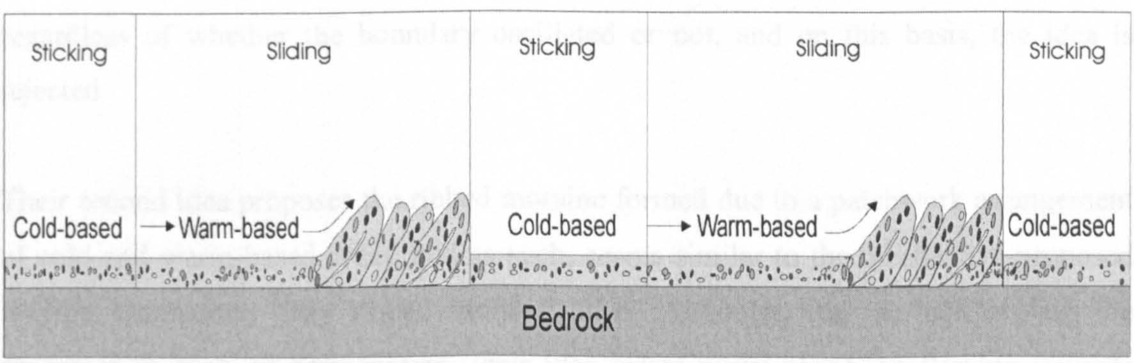

Figure 10.12. Conceptual diagram based on inferences made by Dyke *et al.* (1992) showing their inferred mechanism of folding and stacking of basal debris due to a patchwork arrangement of cold and warm-based ice. In cold-based patches the ice sheet is frozen to the bed and unable to move. In areas where the ice sheet is warm-based, ice is able to slide at the bed uninhibited until it meets another cold-based patch further downstream. At the junction between warm-based sliding and cold-based ice a compressive stress field would be initiated leading to infolding and stacking of basal debris.

Dyke *et al.* (1992) suggested two possible mechanisms of ribbed moraine formation in Transition Bay. They argued alternate basal sticking and sliding could have been the result of (1) an oscillating boundary between warm and cold-based ice or from (2) a patchwork arrangement of small cold and warm-based areas where ice flowed from one to the other. We shall first consider the idea of an oscillating boundary. In a situation where cold-based ice is located downstream from warm-based sliding ice it is easy to envisage how this might lead to thrusting and infolding of basal debris. At the junction where sliding ice meets cold-based ice, a compressive stress field could have promoted thrusting, infolding, and stacking of basal debris at the bed. However, if the situation is reversed whereby cold-based ice is located upstream from warm-based sliding ice, it is difficult to imagine how thrusting and stacking could have occurred. A downice transition from cold-based ice to warm-based sliding ice would result in extensional flow as the ice velocity increased due to basal sliding. If the boundary between the two did oscillate, the only effect this would have would be to either warm the frozen bed area (if it migrated upstream) enabling the ice to slide forward, or cool the warm-based ice (if it migrated downstream), freezing it to the ground. Either situation would not have induced compression at the bed. In the Transition Bay area, they reconstruct a single and clear cold-warm based boundary rather than an archipelago-type thermal boundary. They locate cold-based ice upstream from warm-based ice in the region where the ribbed moraine was formed (see Figure 9.11 and 10.11b). This means there would have been an extensional regime in place at the boundary between cold and warm-based ice. Such an extensional regime cannot promote thrusting of basal debris regardless of whether the boundary oscillated or not, and on this basis, the idea is rejected.

Their second idea proposes the ribbed moraine formed due to a patchwork arrangement of cold and warm-based areas, and as such, seems similar to the mechanism proposed for the Ommanney Bay ribbed moraine field. Although they do not explain the processes in such an arrangement, their idea infers warm-based ice flowing towards cold-based ice created a zone of compression where the two met, causing thrusting, folding and stacking of basal debris or debris rich ice (see Figure. 10.12). Such a system requires the cold-based patches to be located downstream from warm-based sliding ice. However, Figure 9.11 clearly shows this was not the case in Transition Bay. The presence of drumlins immediately downstream from all the ribbed moraine fields in the area suggests the ice was warm-based and sliding, indicating the suggested mechanism was unlikely.

10.3. Modification of pre-existing ridges

The idea that ribbed moraines are formed in two-steps whereby glacial processes modify pre-existing ridge structures has been presented by Boulton (1987) and Lundqvist (1989, 1997). Boulton (1987) proposed they developed from drumlins or flutes following a change of glacier flow direction (Fig. 10.13). The deformation of weak bed materials around transverse ridges produces preferential downglacier transport of the outer limbs of the features, producing the characteristic downglacier planform. Different rates of sediment transport within the ridge cause the original structure to fragment, creating numerous short crescentic ridges. If the deformation process continues, it is argued that sustained attenuation of ribbed moraine ridges will produce barchanoid drumlins, then ellipsoidal drumlins followed by flutings as the bed adjusts to new ice flow conditions.

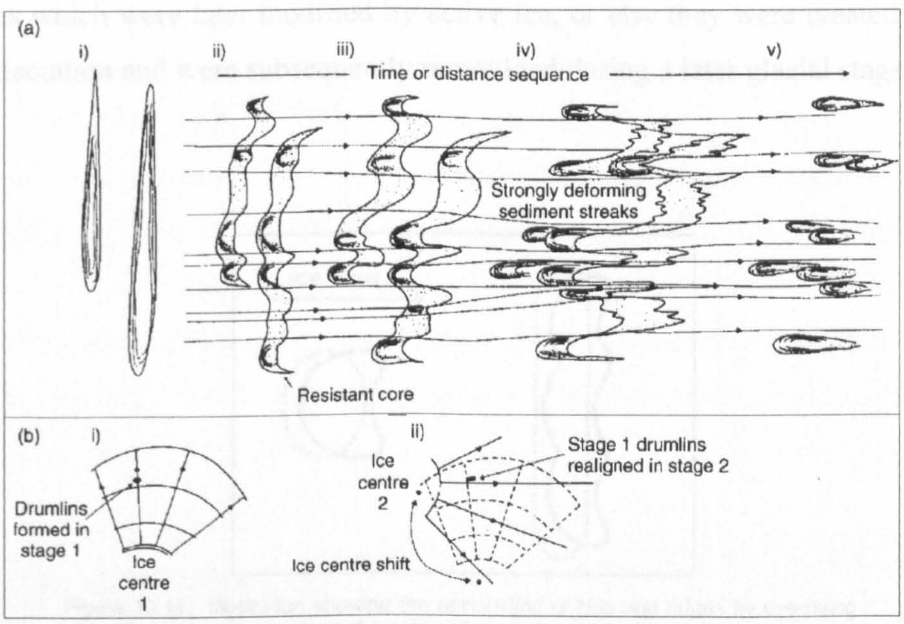

Figure 10.13. Schematic reconstruction of the progressive transformation of flutings to ribbed moraine and drumlins by subglacial deformation. (a) I) Original flutings produced by earlier ice flow direction; ii-iii) ribbed moraine stage; iv-v) drumlin stage. This can be either a time or distance sequence. (b) Explanation of the change in ice flow direction in (a) by a shift in the ice dispersal centre (After Boulton (1987).

Lundqvist (1969, 1997) conducted a review of the literature on ribbed moraine and noted that the internal structure of the ridges was quite varied. Internal examinations conducted by him and other researchers (e.g. Cowan, 1968; Shaw, 1979; Minell, 1979; Shilts *et al.*, 1987; Fisher and Shaw, 1992) demonstrated very different types of structures and sedimentology that ranged from compact basal till to meltwater sediments. In many cases, the ridges showed signs of glaciotectonic activity (e.g. Aylsworth and Shilts, 1989) whilst others were composed entirely of undisturbed sediments (Fisher and Shaw, 1992). Lundqvist stated that each formational theory could account for some, but not all of the observed characteristics and argued the only way to combine all of the observations into one model was to separate the processes of sedimentation and the development of the landform into two separate stages. During the first stage, it is argued that a variety of processes are involved in generating initial ridges, thereby explaining why ribbed moraines have various internal structures. During the second step, these ridges are subsequently remoulded by active ice, which shapes them into classically formed ribbed moraine ridges (Fig. 10.14). Based on this idea Lundqvist (1989) envisaged three alternative scenarios of formation. Either the ridges were originally formed subglacially and then modified by supraglacial-extraglacial processes, or the original ridges were created supraglacially, or by various processes which were later modified by active ice, or else they were created during an earlier glaciation and were subsequently remoulded during a later glacial stage.

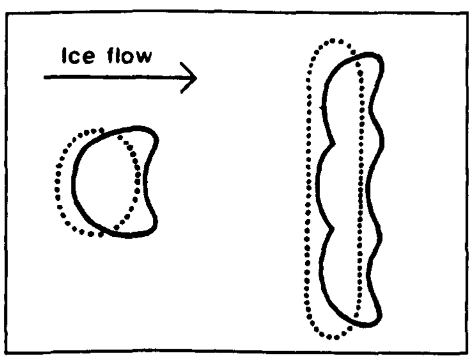

Figure 10.14. Illustration showing the remoulding of hills and ridges by overriding ice. Flow is strongest along the sides of the hills and in the places over ridges, which breaks them into shorter crescent-shaped ridges. Broken lines show the shape of the original landforms (After Lundqvist, 1989).

The main problem with both of these theories is explaining the occurrence of the original ridges. Boulton (1987) proposed they were originally drumlins or flutes, however the geographic distribution of ribbed moraine around the former centres of glaciation undermines his argument. As was shown in Chapter 9, there are far too many ribbed moraines around the centres of former ice sheets, which would have required multiple migration of ice divides around these centres to create the initial lineations. This situation seems highly unlikely. As it stands, Boulton's model may be able to explain the occasional ribbed moraine pattern, but cannot account for the large-scale regional distribution and as such is not a sufficient general theory of ribbed moraine formation. The two-step theory proposed by Lundqvist (1989, 1997) is of interest because it tries to account for both the varied internal structure and shape of the ridges. He argues the internal ridge structures are simply inherited features that reflect an original process of sedimentation that happened before the ridges were modified by overriding ice. However, an obvious failure is that the origin of the primary ridges is not specified and as such offers only a partial explanation of formation. Until the two-step hypothesis can account for the widespread creation of the initial ridges, we cannot accept it as a general theory of ribbed moraine formation. However, it does make the important point that the internal structure of the ribbed moraine ridges might be misleading in seeking a general theory of formation.

10.4. Megaflood hypothesis

The megaflood hypothesis for ribbed moraine formation was proposed by Fisher and Shaw (1992). In this model, a form analogy is drawn between ribbed moraine ridges and erosional ripples that are created on the underside of river ice by turbulent separated flows. They argue that cavities in the river ice look remarkably similar to ribbed moraine ridges (Fig. 10.15), which suggests they share a common origin.

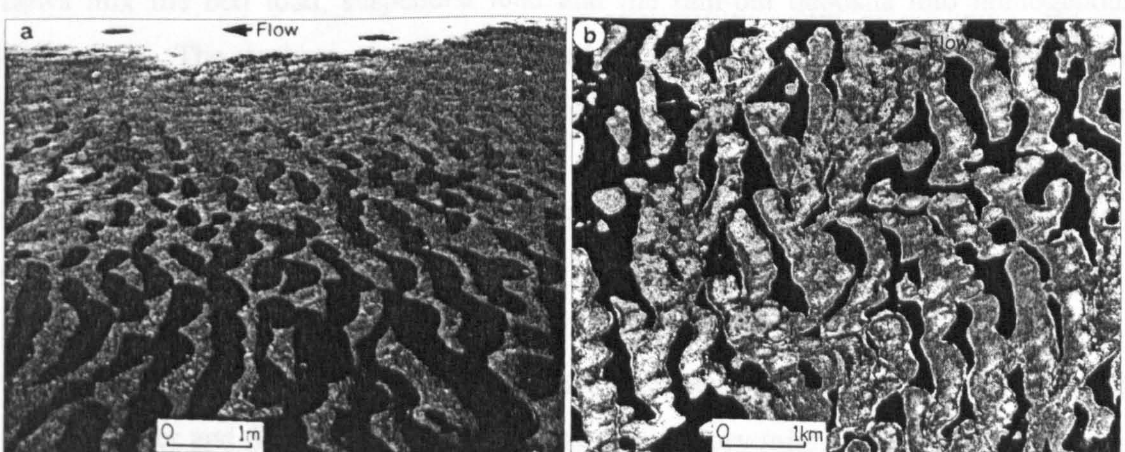

Figure 10.15. (a) Ripples cut into the underside of river ice break the surface in areas of exposed water (black areas). The water mirrors the shape of the cavities which these authors state look like ribbed moraine. (b) Aerial photograph of ribbed moraine in Boyd Lake area, Northwest Territories.

Their argument is that large subglacial sheet floods eroded the underside of the ice sheet creating transverse cavities on the glacier subsole. Once the floodwaters subsided, these cavities were then infilled by subglacial sediments. The authors studied the internal structure of ribbed moraine ridges on the Avalon Peninsula on Newfoundland and argued the interior composition of the ridges supported this hypothesis. All of the excavated sections showed the ridges were made predominantly of diamicton intercalated with sorted sediment, particularly poorly sorted and stratified gravel. Fisher and Shaw argued the silty matrix of the diamicton and its intercalation with sorted sediments suggested an origin by debris flows. Other sediments such as thin sand and silt stringers overlying the diamicton beds were interpreted as products of elutriation during debris flows and thin gravel beds, gravel lag deposits and the cross-bedded gravels reflect phases of subglacial meltwater erosion and deposition.

The stages leading to the development of ribbed moraine by the megaflood hypothesis are illustrated in Figure 10.16. During the initial stages of the flood, it is argued the ice sheet is separated from the bed by a thick sheet of turbulent, sediment-laden meltwater (Stage B). Flowing subglacial water ablates the underside of the ice, forming inverted, periodic erosional marks on the scale of ribbed moraine ridges. The erosional marks become local zones of flow expansion causing extreme deceleration of meltwater flow in these areas. This in turn promotes bed and suspension load deposition from heavily sediment-charged meltwater forming embryonic ridges beneath the cavities. At the same time, preferential ablation occurs above the cavity as the erosional marks grow and angular blocks of bedrock rainout from the ice above (Stage C). Continuous debris flows mix the bed load, suspended load and the rain-out deposits into homogenous diamicton. The authors argue that sorted beds were formed during intermittent cessation of the debris flows. During these phases, meltwater flowing at a much lower velocity than the debris flows reworked the diamicton into poorly sorted beds. Glaciotectonic structures are explained by thrusting and folding as the glacier resettles to its bed when the flood subsides.

There are several reasons why the megaflood hypothesis of formation is not favoured. Firstly, Fisher and Shaw (1992) acknowledge their theory might only explain some but not all ribbed moraine. However, given the ubiquity of ribbed moraine, we appeal to the notion of a single formational mechanism for all ribbed moraine.

In addition, by their thinking, floodwaters even under high hydrostatic pressures should interact with the topography of the bed (see stages B-D in Figure 10.16). We would therefore expect megaflood-produced ribbed moraine to develop patterns that reflect

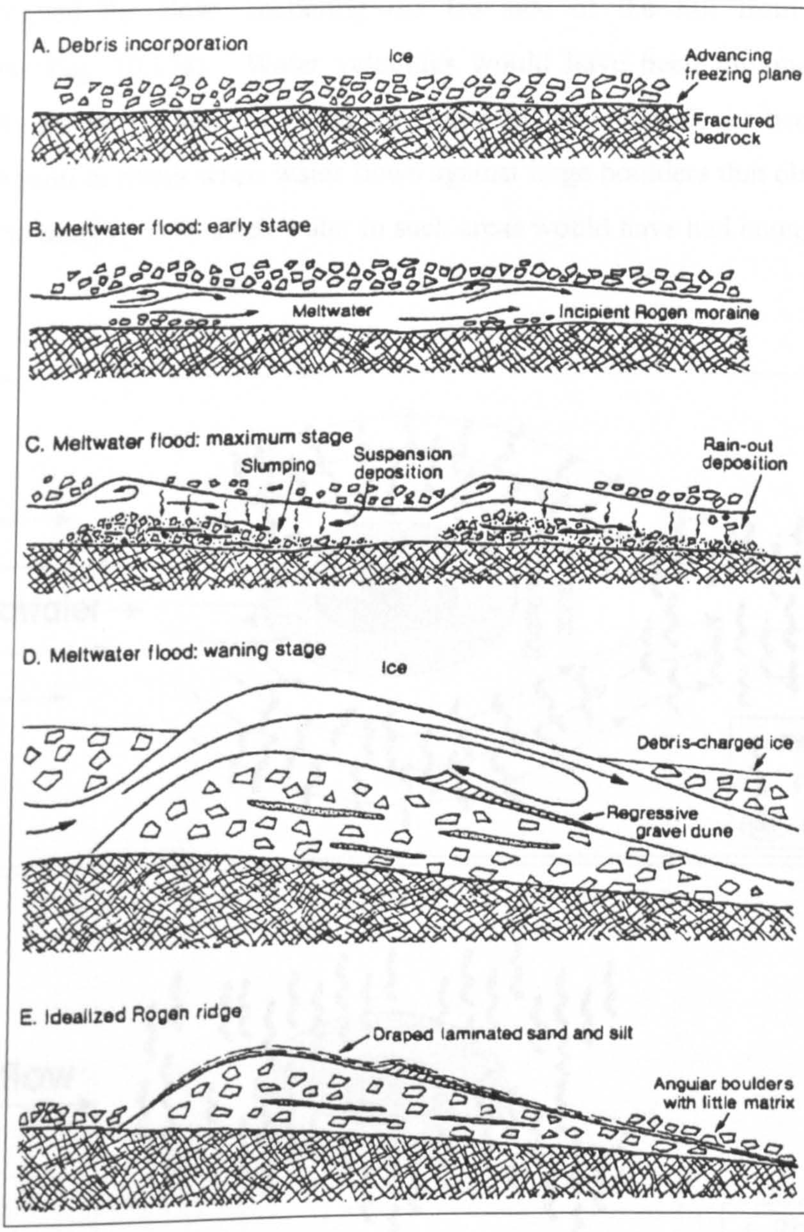

Figure 10.16. The stages involved in a depositional model for ribbed moraine by subglacial megafloods (After Fisher and Shaw, 1992).

this. Their model implies that large topographic obstacles would certainly have modified flow patterns. For example, if the floodwaters came up against a hill we would expect the water to be deflected around it and the ribbed moraine orientation pattern to reflect these flow patterns (Fig. 10.17a). However, this is not what we find in ribbed moraine regions. This study showed that ribbed moraines tend to ignore topography and go over the top of large hills with no deflection in ridge orientation (see Figures 5.29, 7.15 & 7.16). The overall pattern is not disrupted by large topographic obstacles, which is more consistent with the flow pattern of a thick ice sheet that is not gravity driven (Fig. 10.17b). In addition, large topographic obstacles would certainly have obstructed the flow, sheltering the lee side of the hill from the turbulent floodwaters (Fig. 10.17a). Water velocities would have been minimal in the zone immediately on the lee side. We can say this with some confidence because we see a similar situation in rivers when water flows against large boulders that obstruct flow. It is difficult to imagine how slack water in such areas would have had enough

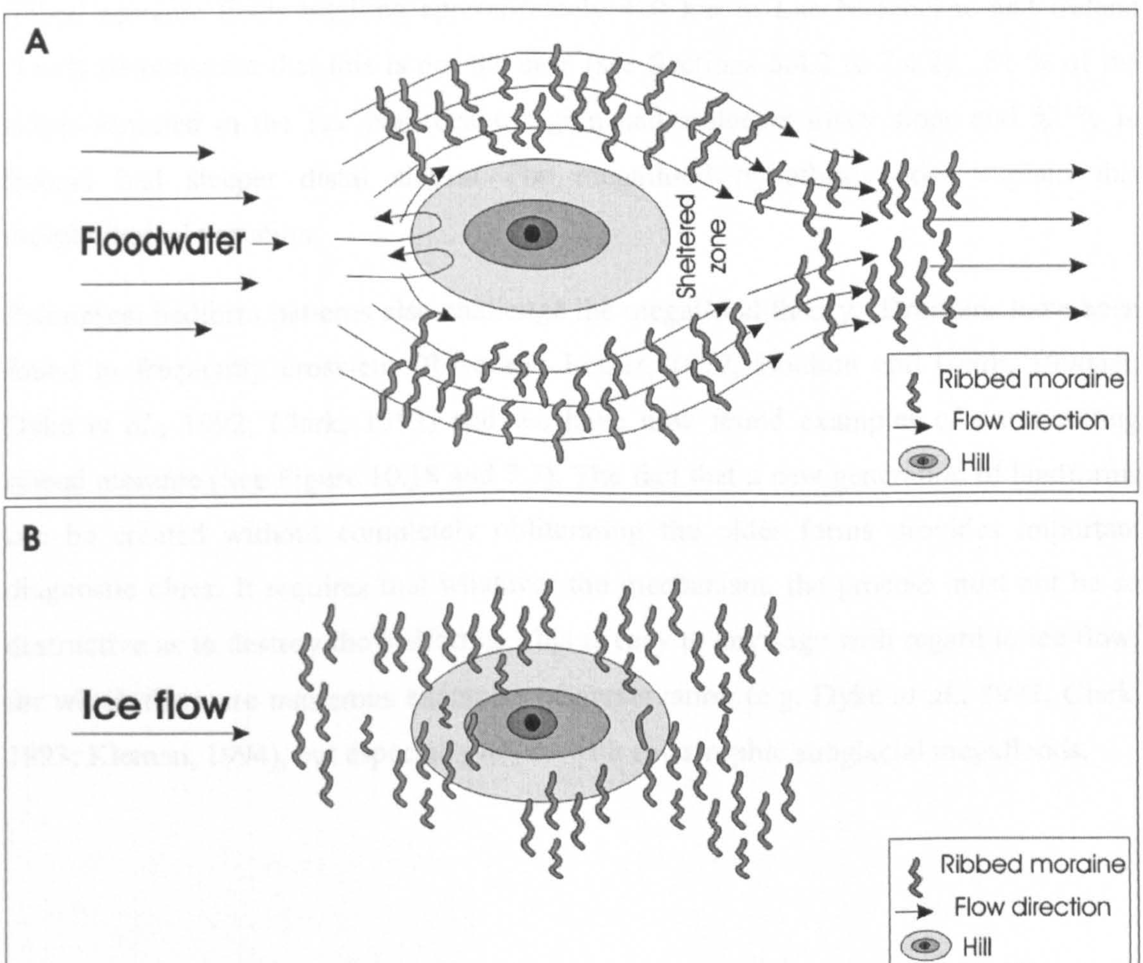

Figure 10.17. Conceptual illustration showing the proposed interactions between subglacial floodwaters and topography (A) and a thick ice sheet and topography (B). (A) In this situation, we expect the hill to modify the flow path of the floodwaters and for the bedform pattern to mirror this. In this example, floodwaters have been forced around the sides of the hill and ribbed moraine ridges are oriented with the direction of flow. However, we do not see such patterns in ribbed moraine areas. Observations made during this study clearly showed that ribbed moraine orientation was not influenced by topography. The orientation of ribbed moraine ridges as illustrated in (B) is the more usually case. Such a pattern is more consistent by formation by ice because a thick ice sheets that is not gravity driven are known to ignore topography and can easily flow over hills.

energy to carve large ripples the size of ribbed moraine ridges into the underside of the ice sheet. This implies that floodwaters could not have formed ribbed moraines on the lee side of hills. However, observations made during this study find no support for the above predictions. Many ribbed moraine fields are located both on and to the lee of many small hills throughout the four study sites (e.g. Figures 5.30 & 8.15).

Morphological data also conflicts with the megaflood hypothesis. Their theory does not predict ridge shapes consistent with descriptions in the literature (e.g. Bouchard, 1989, Hättestrand and Kleman, 1999) and observations made during this study. Their formational diagram clearly depicts ribbed moraine ridges being formed with steep sides that face upglacier (see Figure 10.16). However, cross-sections taken across ribbed moraine fields totalling approximately 400 km in Lac Naococane and Ireland clearly demonstrate that this is not the case (see Sections 5.4.2 & 7.4.2). 51 % of the ridges sampled in the Lac Naococane region had a steeper distal slope and 52 % in Ireland had steeper distal slopes. The megaflood hypothesis does explain this morphological variation.

Palimpsest bedform patterns also challenge the megaflood theory. Drumlins have been found to frequently cross-cut (Rose and Letzer, 1977, Boulton and Clark, 1990a,b; Dyke *et al.*, 1992; Clark, 1993) and we have now found examples of cross-cutting ribbed moraine (See Figure 10.18 and 7.7). The fact that a new generation of landforms can be created without completely obliterating the older forms provides important diagnostic clues. It requires that whatever the mechanism, the process must not be so destructive as to destroy the bedforms. This is easy to envisage with regard to ice flow, for which there are numerous examples of preservation (e.g. Dyke *et al.*, 1992; Clark, 1993; Kleman, 1994), but especially not so with catastrophic subglacial megafloods.

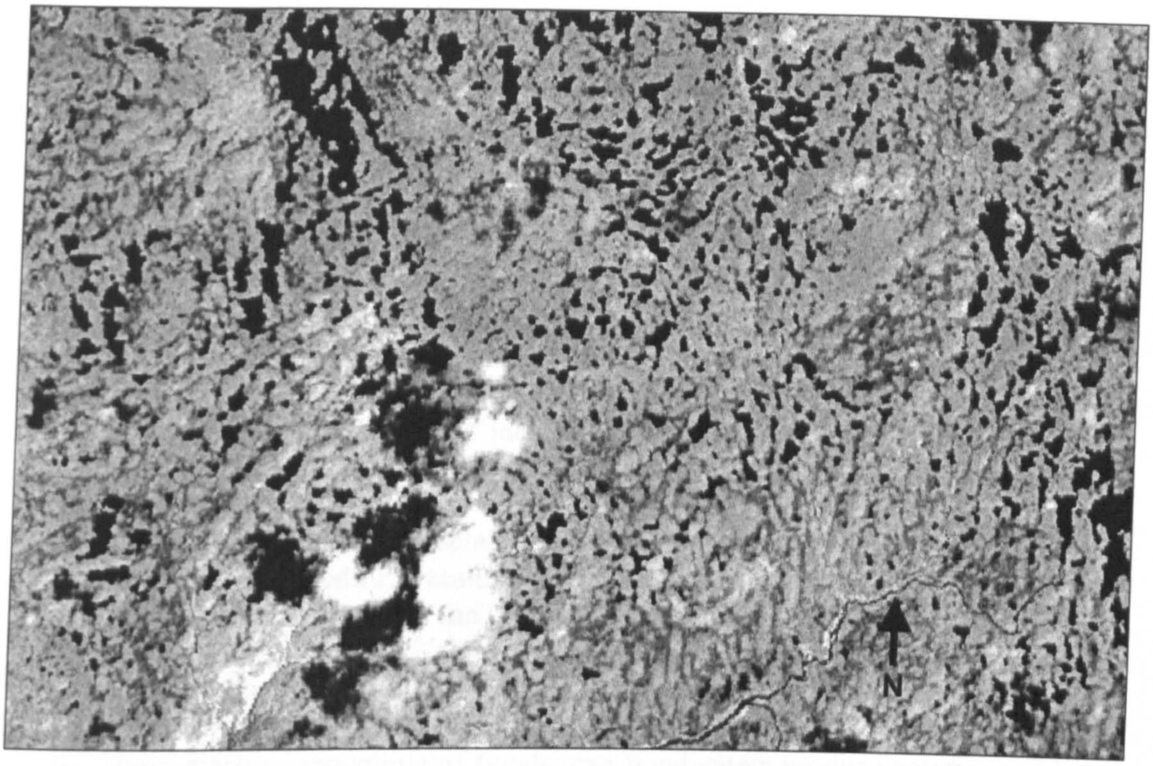

Figure 10.18. ASTER satellite image showing cross-cutting ribbed moraines in Newfoundland (58° 05 W & 48° 00 N). Note the orientation of the ridges on the left (oriented southeast) to ridges on the right (oriented southwest). Black arrow shows north.

Implicit in the megaflood hypothesis is the idea that bedform generation occurred in well-defined tracks beneath ice sheets and not by a huge flood that spread out in multiple directions from beneath the ice divide. This principle is indicated in many of the megaflood papers, including Fisher and Shaw (1992). However, what we find with ribbed moraine is the opposite of well-defined (i.e. with abrupt margins) linear pathways. At a regional scale, ribbed moraines tend to be clustered together into large tracts with no distinct linear boundaries (see Figures 9.7 to 9.10). Their failure to find well-defined linear tracks of ribbed moraine, seriously questions the notion of megafloods.

The greatest problem of extending the megaflood hypothesis to all ribbed moraine is they frequently are distributed around the centre of ice sheets (see Section 9.7), which is the last place that outburst floods would be expected. Ice domes would be above the equilibrium line altitude and so little or no melting would be expected in the central portions of the ice sheet. Hättestrand and Kleman (1999) also noted that the storage capacity of the ice sheet for subglacial meltwater reservoirs would have been minimal in Fennoscandia, as the ribbed moraines in this region exist right up to the position of the last ice divide. They also rejected en-or-supraglacial water reservoirs arguing that because the central parts of the ice sheet had basal temperatures below the pressure melting point, it must have been even colder higher at the surface of the ice mass.

There are three plausibility problems with the megaflood hypothesis;

1. Source of meltwater, i.e. can realistic ice sheet models that include climate, geothermal and frictional heating produce sufficient meltwater volumes in the required locations. Shoemaker (1991; 1992a,b) has proposed a possible meltwater source at the centre of the Laurentide Ice Sheet. However, Benn and Evans (1998) state that this idea is problematic and is not taken seriously by most researchers.

2. Can an outburst of subglacial water flow as a coherent sheet flood of > 10 m thickness (i.e. bedform scale). Modelling conducted by Shoemaker (1992b) indicates that outbursts can produce sheet floods. However, this has been severely disputed by Walder (1994) who demonstrated that a sheet flood configuration is unstable and that drainage would be through channels.

3. Hydrodynamic modelling of floods; can floodwaters produce cavities and hence ribbed moraine at the appropriate scales.

These have not been fully addressed, and until they have, the plausibility of the hypothesis remains suspect.

10.5. Thermal fracturing model

The idea that ribbed moraines are formed by thermal fracturing of frozen till at the bed has been proposed by Hättestrand (1997b) and Hättestrand and Kleman (1999). The theory was developed from an observation that ribbed moraine ridges appear to fit together like a jigsaw puzzle (Lundqvist, 1969; Bouchard, 1989; Hättestrand, 1997b). Whilst Bouchard and Lundqvist placed little emphasis on this observation, the whole idea inspired Hättestrand's theory of ribbed moraine formation. For him, the apparent close matching of the ridges is clear evidence they were once joined together forming a single coherent drift sheet. He claims the morphology of the ridges signifies that the till sheet was pulled apart under strong tensional stresses that led to "boudinage-like" fracturing of the till sheet into ribbed moraine (Figures. 10.19 & 5.25). Hättestrand (1997b) argues the tensional stresses were created at the boundary between cold-based (proximal) ice and warm-based (distal) sliding ice. The observation that ribbed moraine commonly occurs close to and distal of frozen bed areas is seen as evidence that these conditions existed during formation (see Section 3.2.3.10). It is argued that this frozen-warm boundary migrated inwards towards the centre of the ice sheet during the final stages of deglaciation (Fig. 10.20). This would have brought a narrow fracture-inducing zone of tensile stresses across pre-existing drift sheets, forming a time-transgressive pattern of ribbed moraine.

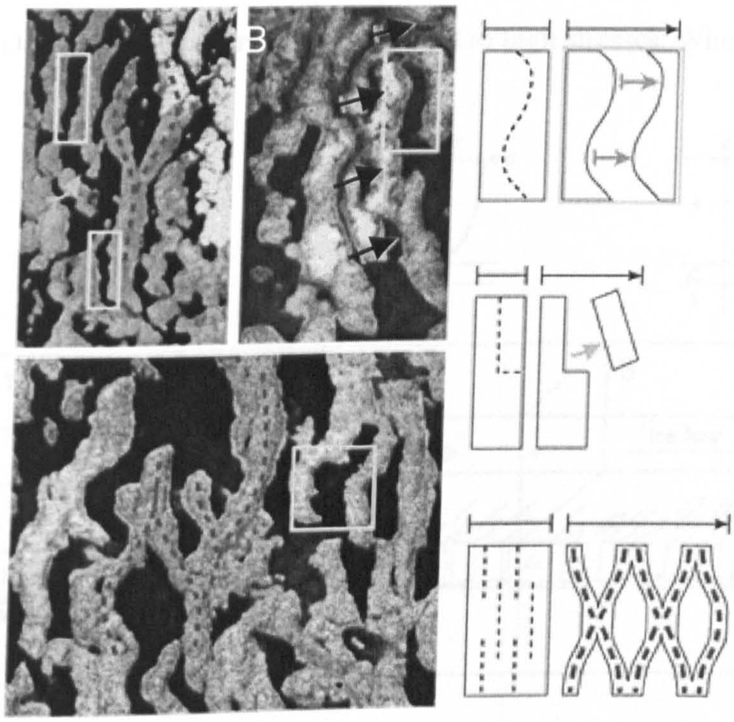

Figure 10.19. Vertical aerial photographs of ribbed moraines in central Québec-Labrador. The thermal fracturing theory argues the morphology indicates the ridges were pulled apart under extensional stresses. In the above examples it is argued that three types of morphology demonstrate the till sheet underwent extensional stresses and fracturing. These are grating splays (broken lines, A & C), slab detachment and rotation (curved arrow, A), and detailed ridge outline matching (boxes, A, B, C). An embryonic split between two till slabs is shown by the arrows in B. Ice flow direction in all photographs is from left to right (After Kleman and Hättestrand, 1999).

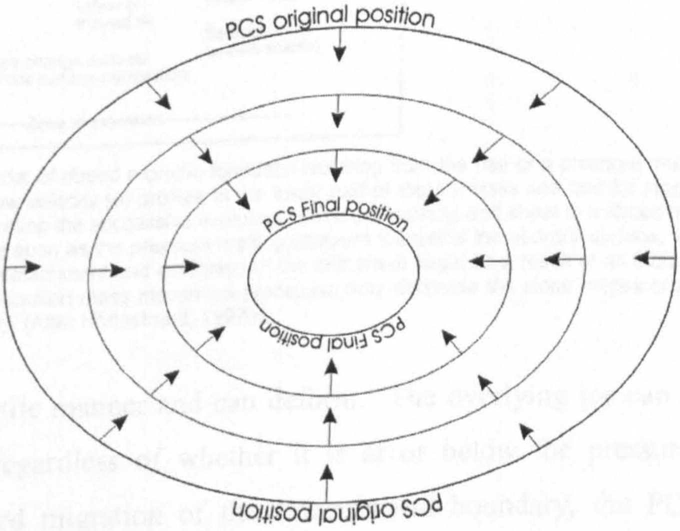

Figure 10.20. Conceptual diagram showing a simplified pattern of inward migration of the frozen-warm boundary towards the core area of a hypothetical ice sheet.

The formative conditions and sequence of events thought to produce ribbed moraine by this process are illustrated in Figure 10.21. The theory predicts the effects a phase change surface (PCS - a pressure melting isotherm) has on the till sheet as it rises through the bed. The subglacial environment they envisage is one where a drift sheet is sandwiched between bedrock and the overlying ice sheet. The bedrock cannot deform whether it is frozen or thawed. In a frozen state, the drift sheet will act as a competent material and exhibit brittle failure when subjected to high stresses. When thawed, it

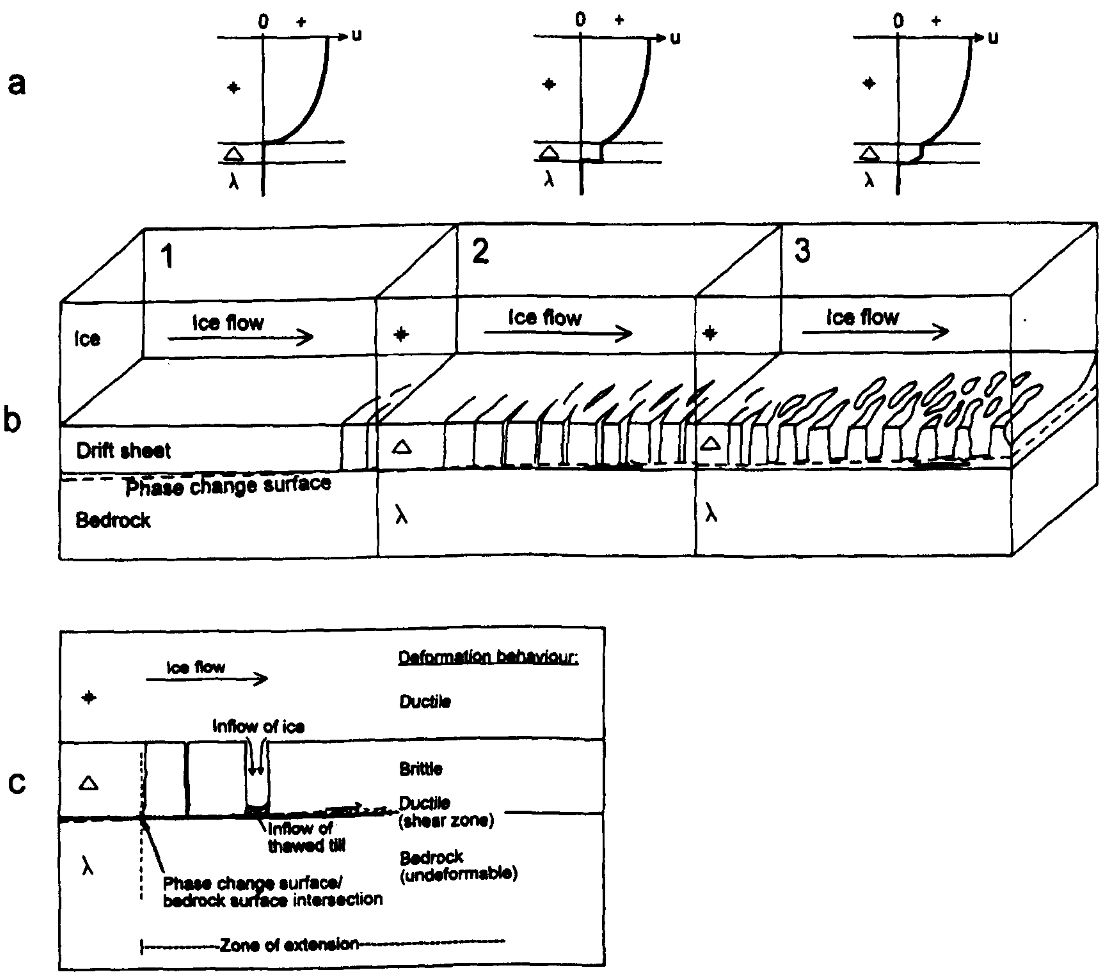

Figure 10.21. The model of ribbed moraine formation resulting from the rise of a pressure melting isotherm through a glacier bed. (a) Ice flow velocity (*u*) profiles in the lower part of the ice mass and bed for stages 1-3 in (b). (b) Time slice boxes (1-3), illustrating the successive evolution from a pre-existing drift sheet to a ribbed moraine. Detachment of frozen ribs will occur as soon as the pressure melting isotherm intersects the bedrock surface. (c) Close-up view of the fracturing zone where detachment and extension of the drift sheet begin as a result of an increase in ice flow velocity. During, and after, deglaciation mass movement processes may decrease the slope angles of the ridges and degrade their tabular morphology. (After Hättestrand, 1997b).

behaves in a ductile manner and can deform. The overlying ice can also deform in a ductile manner regardless of whether it is at or below the pressure melting point. During the inward migration of the frozen-warm boundary, the PCS intersects the glacier bed at a low angle, sloping upward in the ice-flow direction. At the point where the PCS intersects the till-bedrock interface the till begins to thaw. In a thawed state, the till will begin to deform and move forward, increasing basal ice velocity at this interface. This in turn produces a zone of longitudinal stress, which fractures the frozen drift sheet above. Because the PCS is inclined at a low angle, it takes a while for the thawed conditions to reach the drift/ice interface. During this time, extensional ice flow will continue to extend the fractures creating a series of transverse ribs in the till sheet, which will migrate downstream until thawed conditions reach the drift/ice interface (stages 2 & 3 in Figure 10.21). Once the PCS reaches the drift/ice interface, the ice sheet will begin to slide along the surface of the ridges and a drumlinization process may occur. If the ridges remain partially frozen, the result will be a minor fluting of the surface. Later when the ice is fully warm-based, the ridges can be gradually reshaped into drumlinoid forms.

Based on Hättestrand's description of the process it is possible to list several predications that can be tested. The theory implies there should be a spatial pattern of variation in ribbed moraine wavelength that is controlled by both first and second order factors. Each of these will be discussed in turn.

The first order control is based on the rate of migration of the PCS and Figure 10.22 demonstrates the detail of this argument. Near the place where the PCS halted its migration, there should be a gradual downstream increase in wavelength that becomes more regular thereafter. Hättestrand (1997b) envisaged that the PCS moved inwards towards the centre of the ice sheet where at some point it halted its migration (see Figure 10.20). This implies there should be a regional distribution of ribbed moraine wavelength, which begins with a transition in wavelength described above close to where the PCS stopped, to one where the wavelength becomes more regular further downstream. Based on this logic, we argue that the best place to observe the proposed transition is in the areas immediately downstream from where the PCS finished its migration. We acknowledge that it is difficult to locate with certainty the exact location where the PCS stopped. However, it seems reasonable to assume that this must have been somewhere just up-ice from the position of the last ribbed moraine fields, i.e. those fields closest to the ice divide. Figures 5.1 and 6.1 show the ribbed moraine fields in Québec that were studied during this thesis, and Figures 5.2 and 6.2 show the location of these ribbed moraines in relation to the Nouveau-Québec Ice Divide. As one can see, both of the sites have ribbed moraine fields in locations where we would expect to see the proposed transition. However, detailed examination of the imagery in both of these areas failed to find any examples. The same was true in Ireland and in the Lake Rogen area. Because we failed to find an example does not mean the transition does not exist in nature. For example, Hättestrand (1997b) describes a ribbed moraine field in a

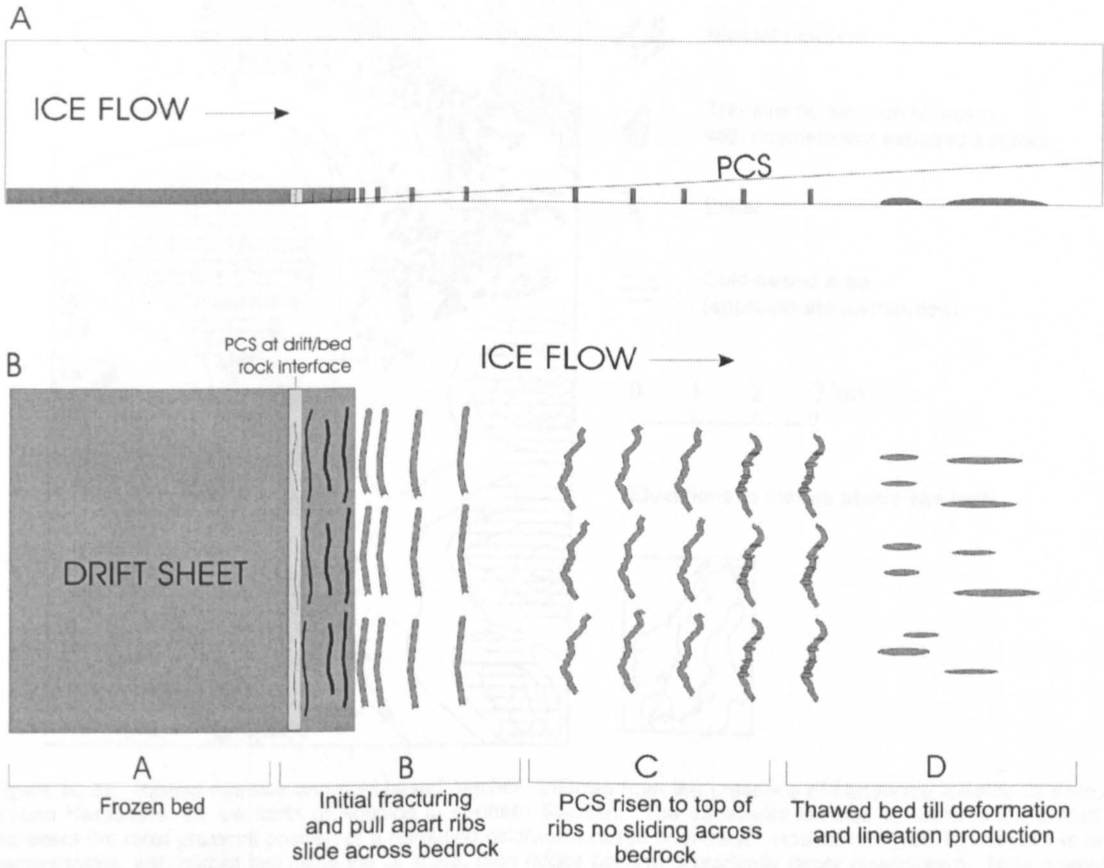

Figure 10.22. Cross-sectional (A) and plan view (B) Illustration of downstream transition in ribbed moraine wavelength produced by thermal fracturing process. Up-ice from where the PCS meets the bedrock/till interface there should be a continuous till sheet (A). Where the PCS meets the bedrock/drift interface minor incipient cracks will appear in the till sheet as the fracturing process is initiated. Immediately downstream, the till sheet will have larger cracks as extending ice flow continues to pull the sheet apart (B). Once the ribs become detached, they will initially be very closely spaced. Since the PCS has not yet reached the ice/drift interface, the ribs will be dragged across the bed. Ridges that broke off early on in the process will have been subjected to dragging for longer periods than ridges close to where the PCS meets the bedrock/till interface. Therefore, wavelength will initially increase downstream (B). Once the PCS reaches the ice/drift interface, the ice sheet slides across the top of the ribs, thereafter the wavelength becomes regular as the ribs stop sliding across the bed (C). At this point, the ridges can become fluted and drumlinized. Further downstream, the bed is fully thawed, till deformation and lineation can take place.

locality near Arjeplog, northern Sweden, which has a morphology somewhat similar to the transition (Fig. 10.23). However, we regard Hättestrand's interpretation with caution because the wavelength pattern does not match what the theory predicts. As one can see, ribbed moraine wavelength immediately downstream of the boundary appears to be longer and becomes generally shorter further downstream, i.e. the fractures are firstly wide and then get progressively narrower. We argue that until a ribbed moraine field can be found that convincingly demonstrates the transition/progression in wavelength then the theory is somewhat weak.

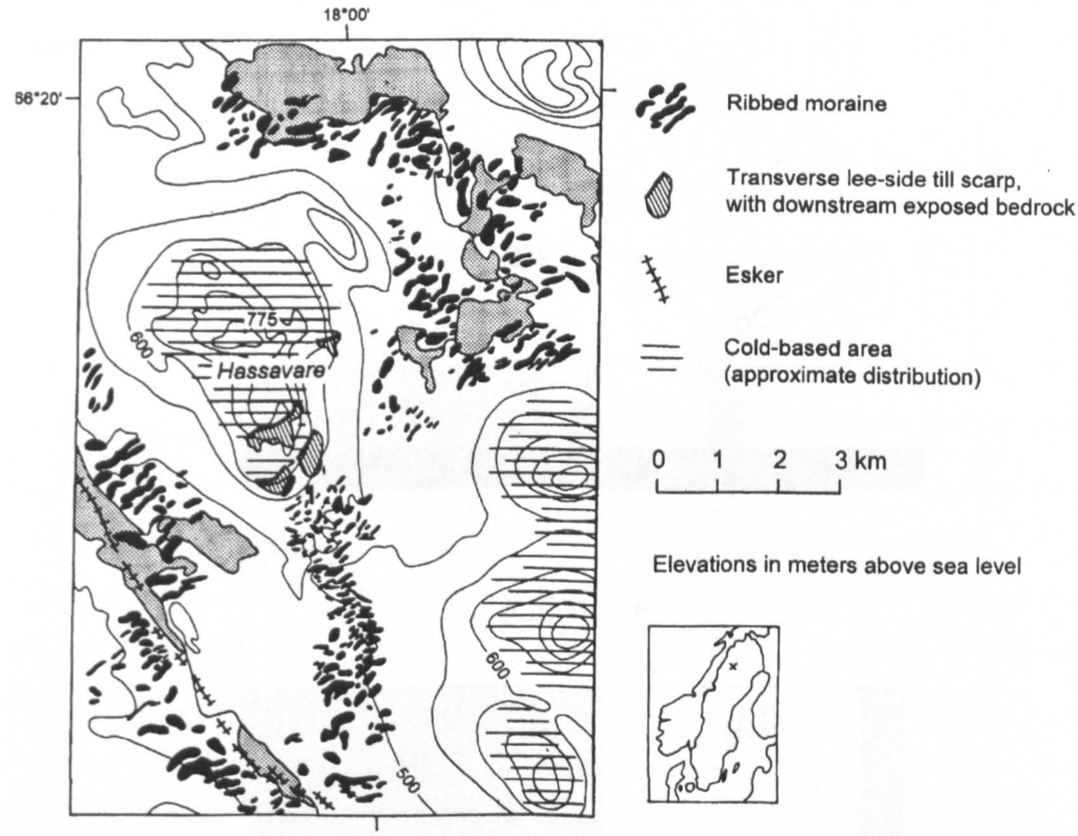

Figure 10.23. Ribbed moraine and cold-based patches (inferred from the presence of transverse lee-side till scarps), around Hassavare, 25 km north of Arjeplog in northern Sweden. The transverse lee-side till scarp is interpreted to represent the most proximal position of a retreating cold/warm-based boundary. Hättestrand (1997b) implies this area demonstrates, with cracks just distal the till scarp, then ridges becoming gradually larger downstream. Note however, that ribbed moraine wavelength decreases downstream, which is the opposite to what we would expect to see. (After Hättestrand, 1997b).

The above argument for a first-order control on wavelength assumes a constant thickness of till. However, we also recognise a second order control that must occur related to variation in till thickness. Ribbed moraine wavelength is a function of till thickness because the depth of the till influences the length of time it takes the PCS to rise to the ice/drift interface, which in turn dictates the length of time the ribs can be dragged downstream along the bed (Fig. 10.24). We therefore would expect to see ribbed moraine with shorter wavelengths formed in thin tills, with ribbed moraine wavelength gradually increasing as the till becomes thicker. Observations made during this study provide some evidence in support of this prediction. For example, in the

Lake Rogen site, large areas of exposed bedrock high up on mountain slopes indicates the till in upland areas is much thinner than in the valleys. As was discussed earlier, this is where we find minor ribbed moraines (see Section 8.5.1). These are smaller and have a much shorter wavelength than the more classical type ridges that largely restricted to valleys, where we would expect thicker accumulations of till. Similar examples are also notable

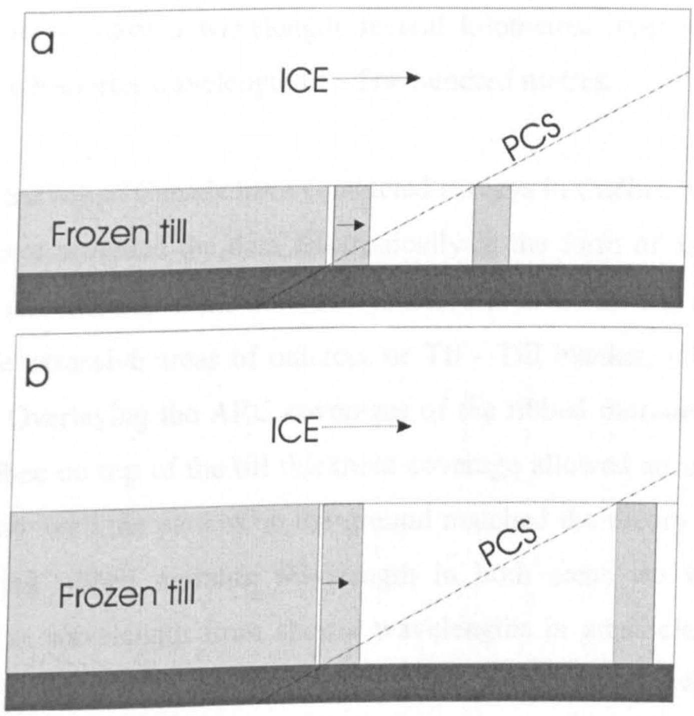

Figure 10.24. Demonstration of how drift thickness controls the wavelength of ribbed moraine ridges in the thermal fracturing model, given a steady migration of the PCS. In both cases, the PCS is inclined at exactly the same angle and hits the bedrock/drift interface at the same place. The only difference between the two scenarios is that the till sheet in **b** is twice as thick as the till sheet in **a**. Because the drift sheet is thicker in **b** it takes longer for the PCS to reach the ice/drift interface than it does in **a**. As a result, the rib will be dragged for a longer period across the bed. Because of this, the ribs in both **a** and **b** will have different wavelengths. According to the theory, ribbed moraine ridges formed in thicker drift sheet should have a longer wavelength than ridges formed in thinner drift.

in the Lac Naococane and River Kaniapiskau study sites. In both these regions, narrow tracks of small-scale ribbed moraine run through ribbed moraine fields made of much bigger ridges (see Figures 5.8 & 6.7). The ridges that make up the narrow tracks appear to be made of thinner till and have a much shorter wavelength than the surrounding ribbed moraine. Observations in Ireland are also consistent with this idea. By using the DEM to measure the height of the ridges, we can get some impression of the thickness of tills in ribbed moraine fields. The logic being that ridge height is a proxy measure of till thickness. This approach seems sound enough given that observations and seismic studies of ribbed moraine fields in Sweden indicated most of the surficial material is found within the ridges (Lundqvist, 1969, 1997; Watenson, 1983). The mega-scale ribbed moraine ridges are generally 30-45 m in height, however some are much bigger; the largest measuring 65 m (see Section 7.6.3). The classic scale ridges in the southern parts of the site are much smaller landforms and generally measure less than 12 m high. Therefore, the mega-scale ribbed moraine ridges formed in much thicker tills than the smaller scale ridges. When we examine the wavelength, we find that the mega-scale ribbed moraine has a much longer wavelength than the smaller ridges. Generally, mega-scale ribbed moraine have a wavelength several kilometres long, while the smaller ridges have a much shorter wavelength of a few hundred metres.

The Geological Survey of Canada have conducted surveys in Québec which estimate till thickness and have provided the data electronically in the form of an ARC coverage. Till thickness is classified as either **Tv** - Till veneer, which is thin and discontinuous till that may include extensive areas of outcrop, or **Tb** - Till blanket, which is thick and continuous till. Overlaying the ARC coverages of the ribbed moraine crests from the two sites in Québec on top of the till thickness coverage allowed an initial assessment be made as to how well the pattern on the ground matched the theory predictions. By visually comparing ribbed moraine wavelength in both areas we would expect to witness changes in wavelength from shorter wavelengths in areas classified as Tv to longer ones in Tb regions. The simplest way to assess whether the wavelength changed or not was to look in places where ribbed moraine fields crossed till thickness boundaries. In regions where this happened, we would expect to see a corresponding change in wavelength. However, as Figure 10.25 shows this was found no to be the case. In the examples shown here, the wavelength stayed more or less the same. Furthermore, visual inspection of both areas showed it was possible to find ribbed moraines with a similar wavelength in areas classified as Tv and Tb. We do not want to draw too many conclusions from this test because we recognise this may be too crude a method to test the idea. For example, the boundary might not be clearly defined and one area may bleed slightly into the other. There may also be patches of thicker till inside the area classified as being a till veneer and vis versa. The only way to properly resolve this issue will be to accurately survey and measure the thickness of the tills in ribbed moraine areas and then see if the wavelength changes accordingly with thickness.

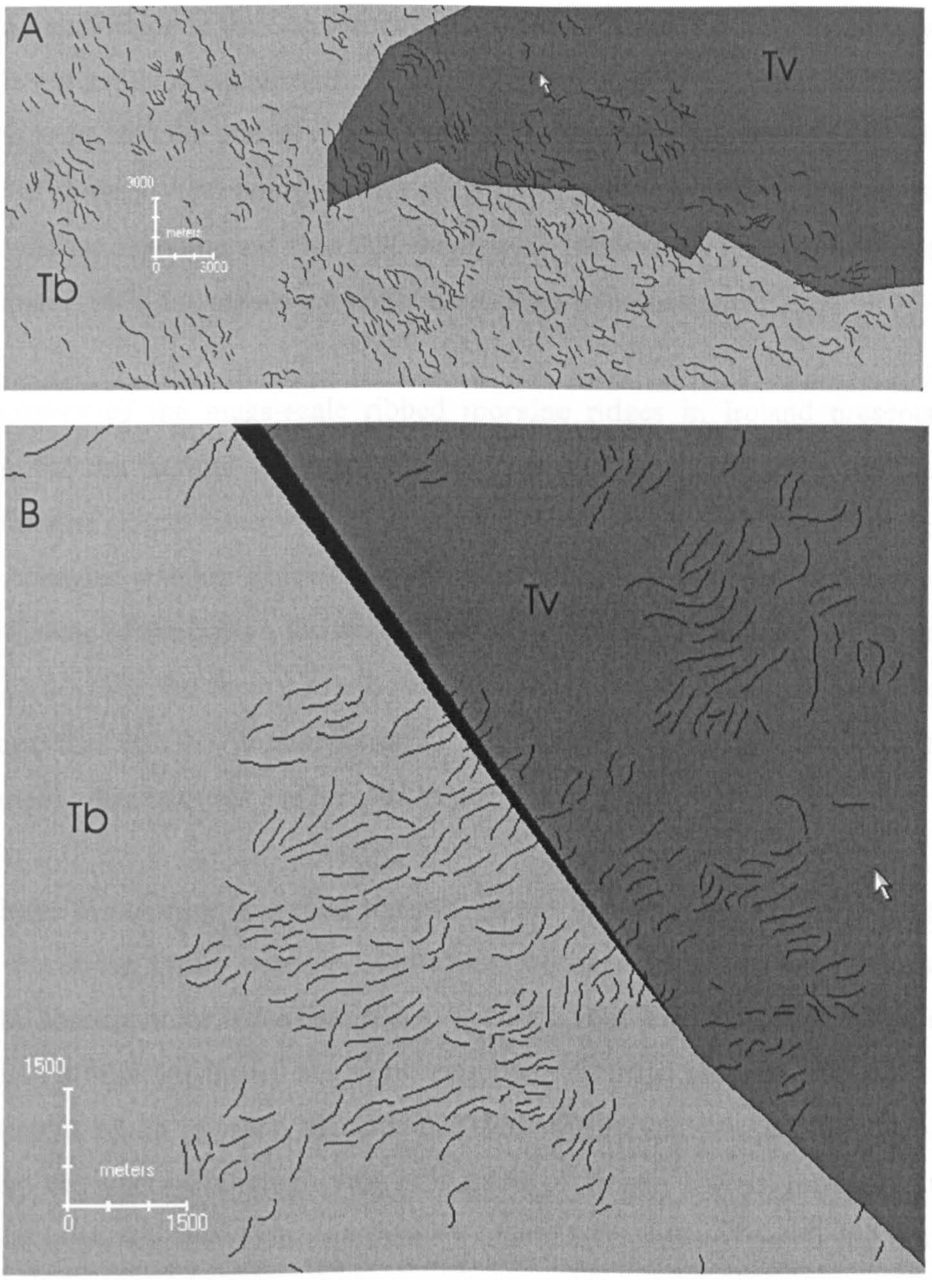

Figure 10.25. Showing ribbed moraine fields crossing over till thickness boundaries. Dark grey areas are regions that are classified as having a till veneer, light grey areas are covered in a till blanket. Note how the ribbed moraine wavelength stays more or less the same. Figure 10.25a is in the northeast portion of the Lac Naococane site (71° 06 W & 53° 28 N). Figure 10.25b is in eastern portion of the River Kaniapiskau site (66° 15 W & 57° 24 N).

Hättestrand and Kleman (1999) argued that "of critical importance are the observations that the shape of individual ribbed moraine ridges match each other, like a jig-saw puzzle" (Hättestrand and Kleman, 1999, p16). Therefore, a good test would be to select various ribbed moraine fields and try to match the ridges using the same methods they employed. If the theory is correct, it should be possible to match the ridges accurately and reconstruct till sheets. An attempt was made at this earlier on in this study on some ribbed moraine fields in the Lac Naococane region (see Section 5.4.3). As was shown, the result was rather disappointing. In general, there were more gaps and miss matches than clear joins, and the overall result failed to produce anything that resembled a single coherent drift sheet. Our analysis clearly demonstrated that jigsaw matching is a much less convincing phenomenon than that thought by Hättestrand (1997b) and Hättestrand and Kleman (1999) and somewhat undermines their hypothesis.

The discovery of the mega-scale ribbed moraine ridges in Ireland presents a new challenge for the thermal fracturing theory. As was discussed, these are the largest ribbed moraine ridges discovered so far, being up to 16 km long and 65 m high. We have to consider whether fractures of this scale can be propagated in till sheets over extensive areas of the bed by the mechanism they propose. The only way to know this will be to develop the theory into a into physically-based process model that makes predictions that can be properly tested. At least we now have a comprehensive morphometric database that can be used to test such a model if ever it is made.

In the above discussion, it is clear that we do not have enough evidence to reject the thermal fracturing theory outright. However, we have found a few weaknesses that need to be accounted for if the theory is to remain a valid explanation of ribbed moraine formation. Whilst this theory has some elegance, the main problem relates to the lack of assessment of its physical plausibility. Until a physically-based numerical model (using the engineering strength and properties of frozen till) is produced it is not possible to know whether such a mechanism would be capable of producing fractures at the appropriate scale. For example, the pull-apart fracturing might only occur at the scale of metres and not the hundreds of metres required for ribbed moraine. Also Because the PCS is migrating steadily why is it that it tears off chunks of till of hundreds of metres wide rather than simply incrementally stripping off thin slices (metre-scale). The reasons for this might be rheological but they have yet to be explored.

10.6. Sediment deformation

The idea that ribbed moraines are a product of deforming subglacial sediment has been presented by Boulton (1987). The deforming bed model has since been built on by

Hindmarsh (1998a,b, 1999) who has developed the first numerical computer model of ribbed moraine formation. The next chapter describes this model in detail and discusses the results of the first quantitative tests that were conducted on it.

10.7. Summary and conclusions

This aim of this chapter was to review the competing theories of ribbed moraine formation and compare the predictions that arise from them against the observations made during this study. The first formational hypothesis reviewed was the shear and stack model due to some topographic obstruction (Minell, 1980; Sollid & Sørbel, 1984; Bouchard, 1980,1989). According to these authors, ribbed moraines were formed exclusively in topographic basins, where compressive glacial stresses in depressions promoted shearing and stacking of basal rich ice. However, detailed observations made in four ribbed moraine areas and analysis conducted using a GIS found no support for this argument. Whilst there are some associations with topographic lows, this study demonstrated that the majority of ribbed moraines do not occur in areas explained by compressive ice flow due to topography, and on this basis the hypothesis is rejected. We do acknowledge however that whilst the observations and data in this thesis require rejection of their theories as a unified model of ribbed moraine genesis, they do not preclude localised (and most likely rare) generation of some transverse ridges by compression against topographic obstructions.

The freeze-on and entrainment model of shear and stack (Solid and Sørbel, 1994) is similar to the above model because it too argues ribbed moraines are exclusive to topographic hollows and invokes similar mechanisms of shearing and stacking of basal debris into ridges. However, since we now know from our observations that topography is not the primary controlling factor of ribbed moraine formation, the hypothesis is rejected as a general theory, because it cannot account for ribbed moraines formed in other topographic settings.

The shear and stack hypothesis of Aylsworth and Shilts (1989) is more complex in that it required specific basal ice conditions and external climate forcing to explain the widespread occurrence of ribbed moraine. We argued against their formative theory on three grounds, however, probably the most compelling argument is that the theory seems glaciologically unsound. The glaciological plausibility that the Keewatin Ice Sheet re-advanced and then shattered into pieces is highly questionable. Their hypothesis invokes widespread development of thrust planes during this reactivation from presumably a more stagnant situation, and whilst there are contemporary examples of thrust plane development (e.g. Croot, 1988; Krüger, 1993) they tend to occur only at the absolute margin and on a much smaller scale than ribbed moraine ridges. We argue that until ice-rheological modelling experiments can verify thrust development at the scale of ribbed moraine (i.e. faulting at the km-scale and over wide areas) the hypothesis remains suspect.

The idea that ribbed moraines are sub-marginal features formed by compressive stresses behind a frozen outer margin has been presented by several authors (Shaw, 1979; Punkari, 1984; Bouchard & Salonen, 1989). This hypothesis was not favoured for several reasons. Firstly, the model requires that permafrost conditions be in place during deglaciation. However, we argued that this is unlikely for margins that were rapidly retreating given the length of time required for permafrost conditions to become established. If permafrost conditions were in place, we would expect to find a geomorphological signature of this process (e.g. ice wedges, patterned ground). However, Lundqvist (1962, 1981) found no evidence of permafrost conditions inside the Younger Dryas moraines in Sweden where all occurrences of ribbed moraine in this country are found. Arguably one of the biggest shortfalls of this hypothesis is the assumption that ribbed moraines are sub-marginal features. If this was the case, their large-scale distributional pattern should reflect the intricacies of a margin (see Figure 10.9). However, we argued that ribbed moraines tend to reflect broad-scale radial flow patterns (e.g. see Figure 5.3) and have never been convincingly matched to ice margin recessional patterns. We further argued that downstream transitions from ribbed moraine to glacial lineations was compelling evidence that undermined the supposition that ribbed moraines formed several kilometres behind a retreating ice margin.

Dyke *et al.* (1992) suggested several mechanisms of ribbed moraine genesis on Prince of Wales Island. Their argument is that changes in basal thermal regime induced stick-slip motion at the bed, which in turn promoted infolding and stacking of basal debris into ridges. The stick-slip hypothesis represents an interesting possibility that may be worthy of further consideration, particularly since recent discoveries indicate that basal sliding can indeed be accomplished by jumps rather than as a smooth sliding process (Annadakrishnan and Bentley, 1993; Ekström *et al.*, 2003). However, at this stage it has not been possible to address the idea fully since a mechanism has not been explicitly proposed or predictions made. As it stands, it remains as an interesting speculation rather than a general formative theory of ribbed moraine.

The idea that ribbed moraines are formed in two-steps whereby glacial processes modify pre-existing ridge structures has been presented by Boulton (1987) and Lundqvist (1989, 1997). However, an obvious failure of this hypothesis is that the origin of the primary ridges is not specified or cannot be properly explained. As it stands, their hypothesis avoids the key problem of explaining spontaneous relief development and offers only a partial explanation of formation. We contend that until the two-step hypothesis can account for the widespread creation of the initial ridges, it cannot be accepted as a general theory of ribbed moraine formation.

The megaflood hypothesis presented by Fisher and Shaw (1992) argues that ribbed moraines are the consequence of large-scale subglacial sheet floods. There are several reasons why this idea is not favoured. Their theory infers that floodwaters should interact with large-scale topographic features and we proposed that ribbed moraine patterns should reflect this (see Figure 10.17). However, mapping carried out during this thesis indicates ribbed moraine orientation patterns are more consistent with ice flow under a thick ice sheet than by subglacial floods. We also presented other arguments that we believe undermine the hypothesis, however, our greatest concern is regarding whether it is physically plausible. We argue that advocates of this hypothesis need to explain viable sources of meltwater and demonstrate that floodwaters flow as sheets and not in channels as stated by others (e.g. Walder, 1994). They are also required to demonstrate that hydrodynamic modelling of subglacial floods can produce cavities and ribbed moraine at the appropriate scales. Since these have yet to be fully addressed, the plausibility of the hypothesis remains suspect.

The thermal fracturing model is presented by Hättestrand (1997b) and Hättestrand and Kleman (1999). Their theory is elegant and its greatest strength is that it explains the regional distribution pattern very well (see Section 3.2.3.10) and can account for the specific cases of ribbed moraine formation in ice stream onsets (see Section 9.8 and

Figure 9.11.). However, our observations of ribbed moraine have highlighted some weaknesses that undermine its credibility (e.g. poor jigsaw matching), and whilst the theory has some elegance, the main problem relates to the lack of assessment of its physical plausibility. We argue that the theory needs to be extended into a physically-based process model that can be quantitatively assessed to determine whether fracturing in frozen till sheets can occur at the appropriate scale.

Finally, we briefly discussed how the qualitative deforming bed theory of bedform generation (Boulton, 1987) has been extended into a physically-based numerical ice sheet model (Hindmarsh, 1998a,b. 1999) that makes quantitative predictions of ribbed moraine wavelength. A major aim of this thesis is to use the ribbed moraine wavelength data collected during this study to attempt a falsification of this model. The next chapter describes the model in detail and discusses the results of model testing.

Chapter 11: Bed Ribbing Instability Explanation (BRIE) - Testing a Numerical Model of Ribbed Moraine Formation by Viscous Till Deformation

11.1. Introduction

As outlined in Chapters 3 and 10, there are many qualitative theories of ribbed moraine formation, which have been qualitatively tested against the data gathered and presented in this thesis. There is now a numerical model that makes quantitative predictions of ribbed moraine characteristics, which can be quantitatively tested. The aim is to use the ribbed moraine wavelength data collected during this thesis to attempt a falsification of this model. This chapter introduces the concepts that underpin the theory and outlines the main aspects of the model. Mathematical details and procedures can be found in Hindmarsh (1998a,b, 1999).

11.2. Instability theory

Investigations into ribbed moraine characteristics have clearly demonstrated (Chapters 5-8) that topography is not a primary controlling factor in the formation of ribbed moraine. The present study has not specifically investigated bedrock geology. However, the fact that ribbed moraines are underlain by a wide variety of bedrock types (Bouchard, 1989; Aylsworth and Shilts, 1989; Knight and McCabe, 1997) strongly suggests bedrock geology is also not a primary control on formation. Since there appears to be no specific topographic or geological control then we must appeal to another primary mechanism.

The fact that ribbed moraine cover extensive areas and that the ridges display systematic organisation into wavelengths suggests the primary mechanism may be an *instability* in the subglacial environment. We are essentially appealing to the fact that ribbed moraine fields look like waves in the topography of the land surface (see Figure 7.8). It is also known that ribbed moraine is generally composed of subglacial sediment (see Section 3.2.3.8 and Table 3.4) suggesting that the waves are somehow related to the flow, erosion or deposition of subglacial till. Wave pattern formation in natural systems are frequently driven by instabilities. Examples are the Kelvin Helmholtz instability that drives some cloud formations, convection plumes controlled by the Bénard instability, ripples in sand on the beach and jet contrails, (condensation trails left behind by jet aircraft) that are produced by a shear flow instability (Fig. 11.1).

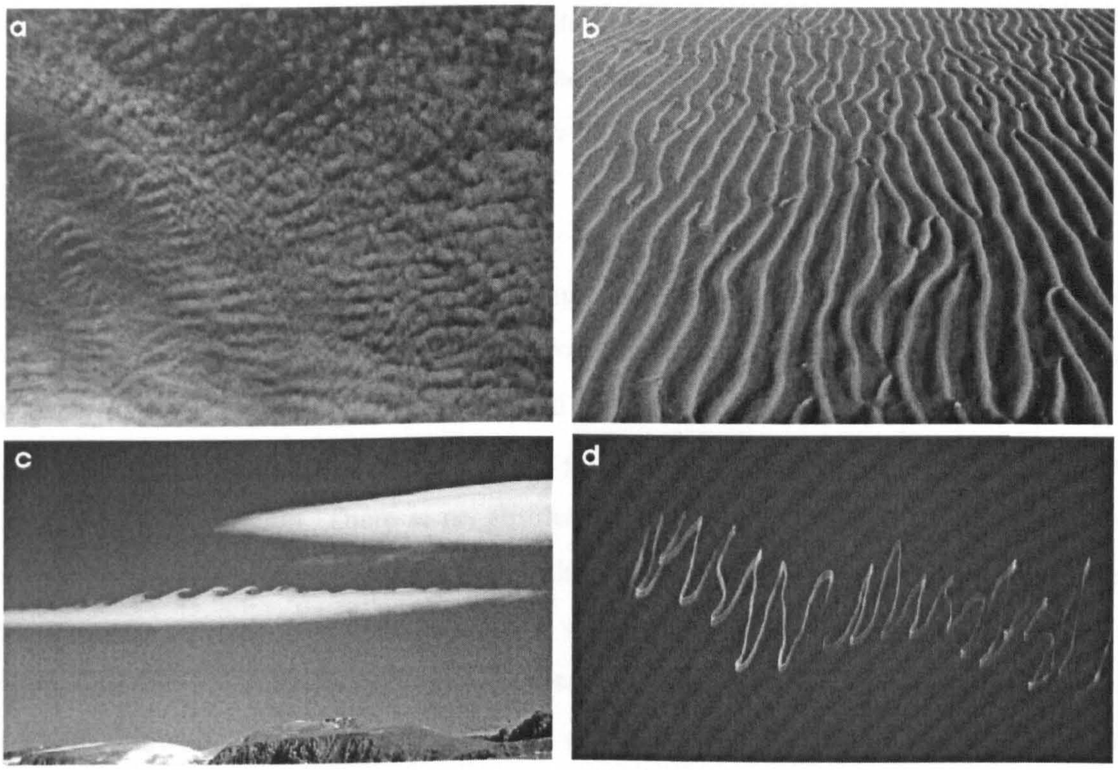

Figure 11.1. Examples of patterns in nature caused by instability mechanisms (a) Cirrus cloud formations. (b) Sand ripples on a beach. (c) The Kelvin Helmholtz instability manifested in this lenticular cloud formation is a classic flow instability. It is characterized by waves that appear between two superimposed fluids of differing densities and velocities. A familiar example are the ripples that form when wind flows over a pool of water (d) Shear-flow instability in jet contrails causes them to show undulations which become more extreme (showing larger amplitude) with time. Usually the instability undulations (or waves) last a few minutes after the airplane has created the contrail. Note the regular wave pattern in all cases.

In the somewhat restricted technical sense used in this thesis, a system is unstable when it acts to amplify small disturbances. This means that some sort of positive feedback is operating.

In this chapter we use the term 'field' to represent a property of the system which varies with position – for example till thickness, sand thickness, air moisture content. In nature, any nearly uniform (i.e. not changing much with position) field is subject to random forcing. Consider sand ripples which are created where sand is being transported by currents. The current is never constant, but varies in time as a result of wave action and wind action. This means that the rate of sediment transport varies in time. The variability of the rate of sediment transport is complicated and we can consider it to be a random process.

If the system is unstable, then small natural variations (perturbations) that occur as a result of the forcing become larger and larger, through the operation of positive feedback, eventually disrupting the near uniformity of the field. For example, on an initially flat sand surface on a beach, a small protuberance (i.e. variation in the sand thickness) encourages local sediment accretion and the protuberance consequently grows.

If a pattern or wave is to form, these disturbances must have a preferred horizontal scale, i.e. the wavelength. The instability grows with time, and in practice grows fastest at a particular preferred wavelength, called the wavelength of maximum growth rate (Fig. 11.2). The wavelength of maximum growth rate is determined by the physical operation of the system. There is no absolute principle which says that there must be such a wavelength, but in practice there almost always is – otherwise we would not observe any patterns. For example, if the wavelength of maximum growth rate of a ripple was larger than the beach, we would see no ripple. In other words, the system has not been allowed to operate freely without a constraint imposed by the size of the beach.

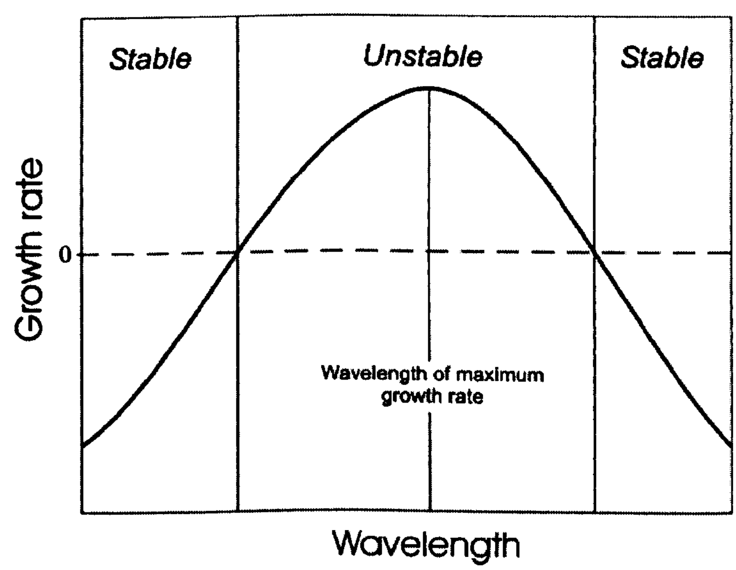

Figure 11.2. Schematic illustration of the wavelength dependency of instabilities. Graph shows growth rate of instability plotted against wavelength of a small perturbation. Where the growth rate is negative, a small perturbation will decay. If there are wavelengths where the growth rate is positive (as illustrated in this example) small perturbations grow in size and the system is unstable. In general the system evolves into a pattern state with a dominant wavelength round about the wavelength of maximum growth rate. The reason why it grows fastest at a particular wavelength depends upon the detailed physical operation of the system.

It is a very general property of small perturbations that they grow exponentially with time (see any textbook on dynamics of physical systems). This is true in all the examples presented in Figure 11.1. As a consequence of the exponential growth, perturbation with the preferred wavelength soon comes to dominate, and a pattern forms with scales around this wavelength. Eventually processes that prevent further growth of the instability start to operate, and a new steady patterned form is reached (see examples in Figure 11.1). Of course, waves grow at wavelengths other than the wavelength of maximum growth rate, but the net effect of all these waves combined is a wave with wavelength around the wavelength of maximum growth rate (Fig. 11.3).

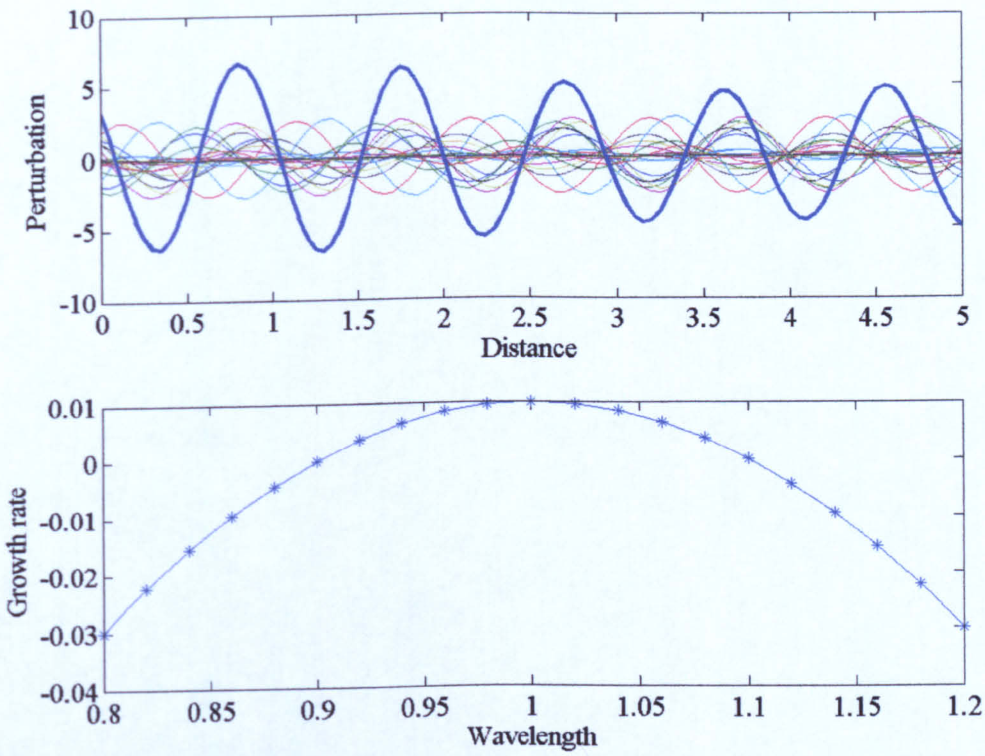

Figure 11.3. Illustrating the fact that growth of perturbations at closely related wavelengths produces a net perturbation at a well defined wavelength. The heavy blue line in the upper panel represents a computed perturbation to an initially flat till surface. Note that the wavelength is around one. The lower panel shows the growth rate as a function of wavelength. Waves at each of these wavelength are plotted in the upper panel (multi-coloured) with amplitude given by exp(100 × Growth Rate), representing their evolution after say one hundred years. The heavy blue line in the upper panel represents the sum of all the multi-coloured waves. The multi-coloured smaller waves are not physically observable; only the heavy blue line is directly observable.

Hindmarsh (1998a,b,c), Fowler (2000) and Schoof (2002) demonstrated mathematically that instabilities can be generated in subglacially deforming till. The physical basis of this instability stems from the fact that the rheology of till depends upon the effective pressure (the difference between the ice pressure and the water pressure (see Section

2.2.1). The effective pressure is affected by the pressure exerted on the till by the flowing ice. This theory joins a large volume of instability theories that have successfully explained patterns in nature (e.g. Philips, 1993; Murray *et al.*, 2001; Ashton *et al.*, 2001; Yamamoto *et al.*, 2003).

Hindmarsh (1998a,b,c) and Fowler (2000) suggested that drumlins were formed as the result of the instability, but this was a somewhat optimistic extrapolation of their theories, which had only considered two-dimensional plane flow (i.e. unidirectional flow in the direction of the main ice flow or longitudinal flow). In fact, they had only demonstrated that the instability operated for transverse features, i.e. ribbed moraine. Schoof (2002) explicitly demonstrated that transverse features, i.e. ribs transverse to flow grow faster than any other shape, for example, drumlinoid features. The conclusion from this is that as the instability starts to operate (till waves start to form), transverse features should form at around the wavelength of maximum growth rate. In short Hindmarsh (1998a,b,c) and Fowler (2000) were premature to regard the instability as a likely cause of drumlins (more work required) and the mathematical analysis by Schoof (2002) demonstrates that the instability *might* be an explanation for ribbed moraine.

The model of Hindmarsh (1998a,b, 1999) predicts the dominant wavelength of the instability, i.e. the wavelength of ribbed moraine ridges. Morphometric analysis of ribbed moraines conducted during this study has ensured we now have an extensive suite of ribbed moraine wavelength data that can be used to test this theory. We argue that a crucial test is whether the model produces ribbed moraine ridges at the correct wavelength. This chapter is concerned primarily with testing the Hindmarsh numerical computer model of ribbed moraine genesis. It describes the model and introduces the style of model test and discusses the results of model runs, compared against measured ribbed moraine wavelength data summarised in Chapter 9.

11.3. Description of the Hindmarsh numerical models

Chapter 3 introduced the Hindmarsh theory of ribbed moraine and drumlin formation. It is a development of the conceptual theory of landform generation by a deformable bed mechanism (Boulton, 1987) and quantitatively models the behaviour of a viscously deforming subglacial till. As was discussed, Hindmarsh produced two physicaly-based models, which for technical reasons have yet to be combined (see Section 3.2.2.3). The first model, referred to as the Bed Ribbing Instability Explanation (BRIE) takes a linearised approach and predicts under which conditions sediment amplification can be initiated in viscously deforming subglacial till. Since it uses a linearised approach, this model applies to small perturbations from uniform fields, which in this instance is a flat till sheet. The second model, the Shock Formation Model is a non-linear model and predicts under which circumstances drumlins can be formed in a viscously deforming till after amplification has occurred. This model is not restricted to small perturbations. Since this thesis is concerned with ribbed moraine formation, we are focussing solely on testing BRIE. The following section discusses this model in more detail.

As was discussed, BRIE is a physically-based ice sheet model, which models the behaviour of an ice mass coupled to a viscously deforming till. The physical environment considered is a viscous layer of ice overlying a layer of viscous till which in turn overlies bedrock. Deformation can occur both within the ice and the till, and sliding can also occur at the ice/bed and till/bedrock interface (Fig. 11.4). The bedrock cannot deform. It has been demonstrated that the coupled flow of ice and till is conditionally unstable (Hindmarsh, 1998b,c; Fowler, 2000) if bumps exist in the till surface. This means that under certain conditions, small undulations in till thickness can grow, causing relief to appear spontaneously. This has been shown to occur over a range of wavelengths (Hindmarsh, 1998a). Here, wavelength refers to the horizontal scale of a disturbance in the till thickness. As explained above, since the instability grows exponentially with time, the growth at the preferred wavelength soon comes to dominate, and a wave forms with length scales characterised by this wavelength.

BRIE accurately computes stress and velocity fields in ice and till, ensuring that mass is conserved and that forces (momentum) balance – in other words, Newton's Laws are respected. For example, the till pushes back on the ice with a force equal to that which the ice exerts on the till. Conservation of mass simply means that material is neither created or destroyed. BRIE uses these principles along with the viscous relationships for till and for ice to predict the variation of velocities and stresses in relation to bump geometry within the ice and the till. The velocities within the till determine whether till bumps grow or decay. Intuitively one can expect physical parameters such as the ice velocity to affect the rate of growth or decay of bumps and even whether the bumps grow or decay.

These equations are non-linear and difficult to solve. To get round this, BRIE assumes that deviations from uniformity in the till and the ice are small compared to till thickness. This is why it can only be used to predict the wavelength at which subglacial landforms are "seeded" i.e. creating an obstacle that generates a feedback, which leads to further growth of the obstacle. Once the bumps become large the predictions of BRIE become inaccurate and the results can be no longer relied upon. In more technical terms the non-linear equations are linearised, and this linearisation is no longer valid when bumps become large. Such a linearised model deals with a restricted range of bump amplitudes, over which the rate of growth or decay of the height of the bump is linearly proportional to the bump amplitude. For example, if the system is unstable then a bump with twice the amplitude will grow twice as fast. With such a methodology, BRIE can predict the dominant wavelength of the amplified perturbations. However, it is unable to predict the maximum size to which these bumps can grow. To summarise, this theory interprets ribbed moraine as being a wave-like phenomenon caused by this ribbing instability and offers the first quantitative explanation of ribbed moraine genesis.

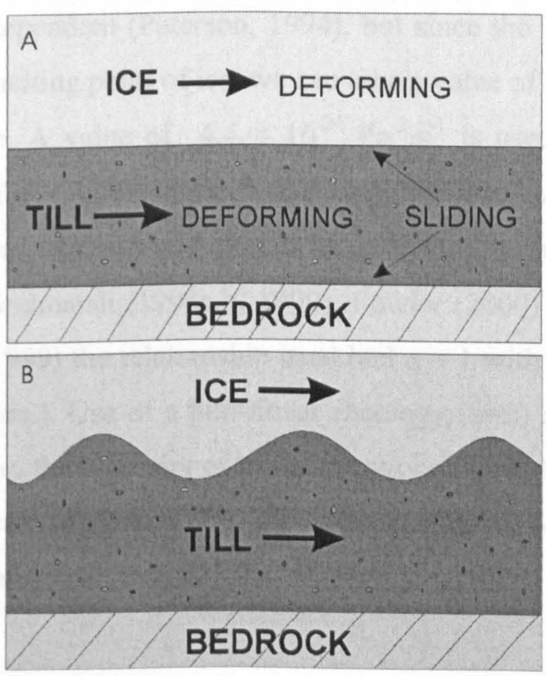

Figure 11.4. (A) Showing ice/till coupling, deformation occurs within the ice and till and sliding can occur at the ice/bed and till/bedrock interface. (B) Within ranges of parameter space, perturbations can preferentially grow and a wave is initiated in the till.

11.4. BRIE model; parameters and outputs

As was discussed previously, Hindmarsh (1998a,b,c, 1999) argues for a viscous rheology. In the BRIE these parameters are effective pressure at the surface (P_{e0}), shear stress (τ_0), ice velocity (U_0) and till thickness (D_0), rheological index b and the proportion of slip velocity due to till deformation (as opposed to slip over the till). Some of these parameters occur in the rheological relationship

$$\dot{\varepsilon} = A\frac{\tau^b}{p_e^b}, \qquad (11.1)$$

where $\dot{\varepsilon}$ is the strain rate, A is the viscous coefficient, τ is the shear stress, p_e is the effective pressure and b is the rheological index. The viscous coefficient A and the index b are properties of the till, while the shear stress and the effective pressure are determined by the flow of ice and the flow of water in the sub-glacial system.

The rheology of ice is also given by a viscous relationship, the major difference being that there is no dependence upon the effective pressure because in common with nearly every other glaciological model, it is assumed that there is no water within the ice. The relationship is of the form

$$\dot{\varepsilon} = B\tau^n, \qquad (11.2)$$

where B is the viscous coefficient for ice and n is another index. The coefficient B is strongly temperature-dependent (Paterson, 1994), but since the BRIE assumes that the bed is at the pressure melting point of ice, we can take a value of B appropriate to that of ice at this temperature. A value of 4.4×10^{-24} $Pa^{-3}.s^{-1}$ is used along with the usual glaciological choice of $n = 3$. This is an as yet unpublished development of the BRIE model (Hindmarsh, pers. comm.) and should be compared with the linear rheological relationship used in Hindmarsh (1998a,b, 1999), Fowler (2000) and Schoof (2002). In Hindmarsh (1998a,b, 1999) the relationship used had $n = 1$ with $B = 4.4 \times 10^{-14}$ $Pa^{-1}.s^{-1}$ (Hindmarsh, pers. comm.). Use of a non-linear rheology (n=3) adds greater realism to the studies. In particular, the viscosity of ice is strongly affected by the shear stress, and this makes a significant difference to the wavelength of maximum growth rate (Hindmarsh, pers. comm.)

The viscous coefficient A for subglacial till is poorly known. However, it has easily computed effects on the mean ice velocity, which is much better constrained. The ice velocity is simply proportional to the parameter A, if this is doubled the ice velocity also doubles. Thus, rather than using the viscous coefficient as a parameter, the ice velocity U_0 is used as a parameter and the viscous coefficient computed from the specified ice velocity, effective pressure, shear stress and rheological index b.

The index b is equally poorly known. This index determines whether the till deforms viscously or plastically. If b is very large (>10) then the till is effectively plastic. If b is relatively small ($b < 5$) then the till can be regarded as viscous. Since one of the wider aims of the study is to use glacial landforms to infer rheological properties of till, the value of b will be varied between 1 and 10 to determine its effect on the results.

Apart from the parameters defining the till rheology, other parameters which affect the characteristics of subglacial instabilities are the till thickness D_0. Account is also taken of the fact that some of the ice motion can be accommodated by slip at the ice-till interface and also at the till-bed interface. This is represented in the system by specifying the proportion of the ice-sliding velocity taken up by sliding at the ice-bed interface, within the till and at the ice-till interface. Further details may be found in Hindmarsh (1999).

As mentioned previously, when the model is run, bumps, or instabilities, in the system begin to grow. The instability grows fastest at the preferred wavelength or wavelength of maximum growth rate. The BRIE predicts this dominant wavelength and the results are conveniently displayed in graphical form (Fig. 11.5). In this case, the model predicts a maximum wavelength of 300 m under the specified parameter settings.

This is gratifying because the data from Section 9.3 and Figure 9.5 indicate that 90 % of ribbed moraine wavelengths lie between 100 m and 1000 m, so the computed wavelength would appear to be very typical. However, this value was obtained for a particular parameter set with $D_0 = 10\,\text{m}$, $U_0 = 100$ m/a, $\tau = 50$ kPa, $p_e = 50$ kPa, $b = 3$, and with all the ice velocity accommodated by internal deformation. These are just one set of a very wide range of plausible parameters. In order to be convinced that the theory *can* explain ribbed moraine wavelengths, one needs to determine whether ribbed moraines of the correct wavelength are produced by other plausible parameter values.

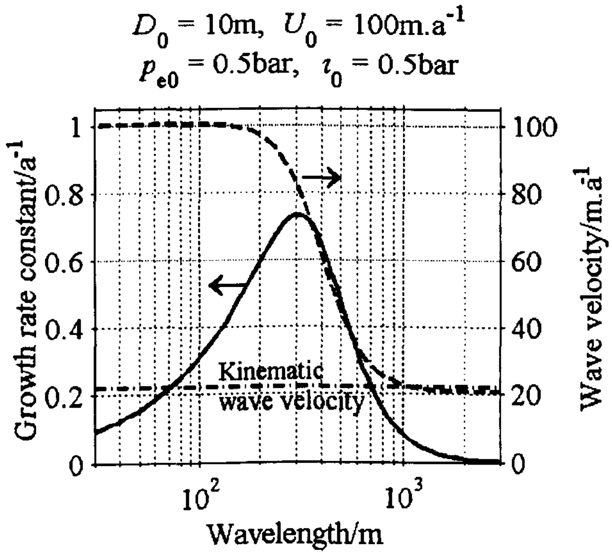

Figure 11.5. Graphical output of the BRIE showing the dominant wavelength of the instability. In this model run a wavelength of 300 m is obtained when the till thickness, D_0 =10 m, effective pressure p_{e0} = 50 kPa, shear stress, τ_0 is 50 kPa and the sliding velocity, U_0 is 100 m.a-1. (After Hindmarsh, 1999).

To understand the effect that each parameter has on the model output a sensitivity study was performed. Sensitivity analysis is normally conducted by assessing the affect of a percentage change in each model parameter whilst holding all the other parameters constant. Thus, a base line is required to allow for comparison of results between model runs. In this study, I used the default parameter values given by Hindmarsh (1999) as a baseline, which were used to produce the graph shown in Figure 11.5. The sensitivity tests began by making changes in single parameters and then progressed to examine joint interactions in parameter space. The main conclusions of this study was that all of the parameters effected the wavelength and in a way that would be expected. For example, there is a negative relationship between effective pressure and wavelength. That is, as effective pressure increases, the wavelength decreases. One would expect this to happen in a deforming bed system since increasing values of effective pressure increase the shear strength of the till, which in turn inhibits the deformation process (Fig 11.6a). Increasing values of till thickness showed there is a positive relationship with wavelength (Fig 11.6b). At the thinner end of the till values the wavelength initially increases quite sharply between till thickness of 1 and 8 m. After this, the trend does not continue and although the wavelengths get longer, large increases in till thickness do not produce very long wavelengths. This is expected, because as the till thickens the extra weight of the till causes effective pressures to increase at the base of the till sheet, meaning only the upper layers will undergo deformation. The joint sensitivity tests indicated that there were no complex interactions occurring in the model when more than one parameter was changed. The parameters behaved in a manner more or less expected given the results of the single parameter tests (Fig. 11.6c).

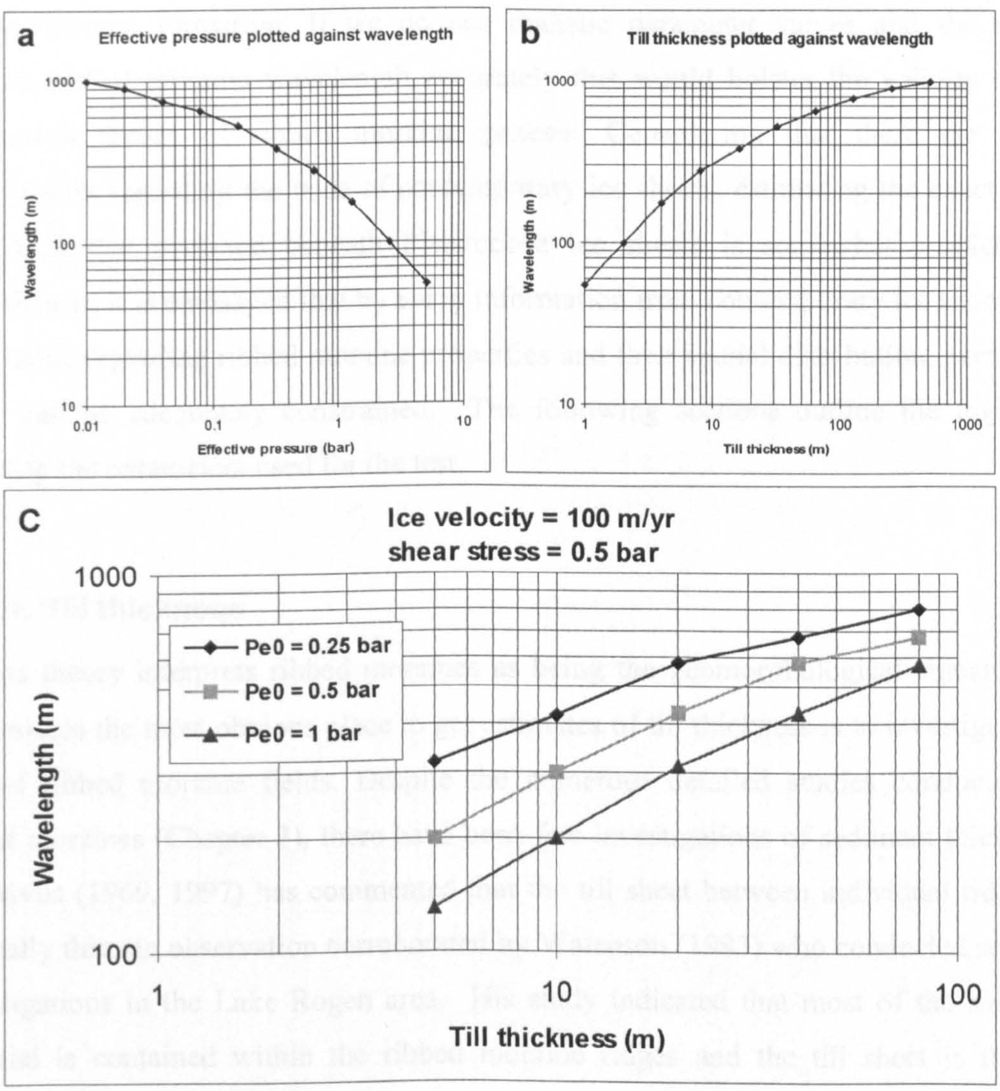

Figure 11.6. Some examples of sensitivity analysis. (a) Shows there is a negative relationship between increasing values of effective pressure and wavelength. As effective pressures rise the wavelength decreases. This would be expected given that increasing effective pressure increases the shear strength of the till, which makes it more able to withstand shear stresses and less able to deform. (b) Demonstrates the effect of increasing till thickness. As can be seen, there is a positive relationship between till thickness and wavelength. That is, as till thickness increases so also does the wavelength. (c) Showing joint sensitivity between effective pressure and till thickness. The single parameter tests showed there was a negative relationship between wavelength and effective pressure (a) and a positive one with till thickness (b). In the joint sensitivity tests between these parameters, we can see that this relationship still holds.

11.5. Model test and parameter table

A key test of the BRIE is whether it can predict ribbed moraine ridges at the right wavelength. The objective of the test is to attempt to falsify the model using the wavelength data gathered earlier in this thesis. The model test is based on whether the model can simulate nature given a set of realistic parameter ranges for each of the parameters. If the model produces realistic wavelengths under unrealistic parameter settings it is of no use as a tool in understanding the nature of the subglacial environment and will be rejected. It is consequently necessary to constrain parameter ranges in order that the values used approximate those that occurred in nature during ribbed moraine formation. If we do use realistic parameter values and the model predicts ribbed moraine wavelength accurately this would bolster the validity of the Hindmarsh theory of ribbed moraine genesis. Considering that there are many uncertainties regarding the beds of contemporary ice sheets, estimating the exact basal conditions that occurred beneath Pleistocene ice sheets is somewhat problematic. Nonetheless, it is envisaged that by using information from contemporary ice sheets and knowledge regarding ribbed moraine properties and their spatial distribution, parameter space can be adequately constrained. The following sections outline the logic for choosing the parameters used for the test.

11.5.1. Till thickness

As this theory interprets ribbed moraines as being the geomorphological signature of this process the most obvious place to get estimates of till thickness is to investigate the tills of ribbed moraine fields. Despite the numerous detailed studies conducted on ribbed moraines (Chapter 3), there have been few investigations of sediment thickness. Lundqvist (1969, 1997) has commented that the till sheet between individual ridges is generally thin, an observation corroborated by Watenson (1983) who conducted seismic investigations in the Lake Rogen area. His study indicated that most of the surficial material is contained within the ribbed moraine ridges and the till sheet is thin or lacking in between. These are important observations and help provide some diagnostic clues as to the original thickness of the till sheet before it was deformed.

If it is assumed that the situation is similar in the other regions, i.e. that ribbed moraines contain most of the till, then ribbed moraine ridges are approximately twice as thick as the till sheet that they originated from. This is actually a controversial assumption, because it assumes that the instability theory is correct and that waves are being produced. The Hättestrand theory for example makes no strong prediction about the relative dimensions of ridge width and the spacing between the ridge.

Table 9.2 shows the range of ridge heights that were measured using DEM's during this study. If we consider that the smallest ribbed moraine ridges are estimated to be 1 m in height and the largest 64 m, then on the basis that the original till thickness was half the moraine height, the lower limit for the till thickness parameter is taken as 0.5 m and the upper value 30 m.

11.5.2. Shear Stress

The Hindmarsh theory requires the mean stress to be a parameter. This should not be confused with the local stress, which fluctuates around any subglacial obstacle. This mean stress can be equated with the basal shear stress as commonly defined in glaciology. In simple terms, basal shear stress in glacial systems is due to both the weight of the overlying ice and the slope of the ice surface. For small bed slopes, the shear stress at a point can be calculated from the following equation:

$$\tau = \rho_i g h \sin \alpha \qquad (11.3)$$

where τ is the shear stress, ρ is the density of ice, g is gravitational acceleration, h is the ice thickness and α is the surface slope of the ice. Regarding Pleistocene ice sheets, it is difficult to see how this formula can be of much use as a method for estimating basal shear stress, as all of the components necessary for making the calculation are effectively unknown. Using contemporary ice sheets as an analogue is probably a better way of determining the range of shear stress that can occur in nature at the ice sheet scale as all the components of the equation can be measured.

By using equation (11.3), the basal shear stresses for many valley glaciers have been calculated and estimates show that values vary typically between 50 and 150 kPa (Patterson, 1994). More recent investigations conducted on ice streams resting on deformable sediment show that the driving stresses can be much lower. For example, the driving stress of Ice Stream B in the Siple Coast, Antarctica has been estimated to be about 20 kPa (Alley *et al.*, 1989). In contemporary ice sheets the lowest shear stresses are located in fast moving ice streams such as those that drain the Siple Coast. Within these arteries of fast flowing ice, typical driving stresses are small and have been estimated to be as low 10 kPa (Jackson and Kamb, 1997). Moreover, the flanks of ice streams can support much of this stress, so that the basal stress can be much lower than the driving stress in ice streams (Whillans and Van der Veen, 1993). Values as low as 2 kPa (the cohesive strength of till) have been suggested (Jackson and Kamb, 1997). Inside the main body of the ice sheet shear stresses are much higher with the maximum shear stress being estimated to be 100 kPa (Paterson, 1994). To test the model the shear stress values will range from 2 kPa to 100 kPa.

11.5.3. Effective pressure

The effective pressure enters the Hindmarsh model through the rheological relationship (equation 11.1). The effective pressure is a measure of the overall strength of the sediment, with high values indicating that the sediment is strong and more able to withstand shear stresses, and low values signifying the opposite, with yield stresses significantly less than that of the overlying ice (Patterson, 1994). Since the Hindmarsh ribbed moraine formation theory presupposes that the till is deforming, there is an implied upper limit to effective pressures, as we need not consider those that increase the strength of the sediment to the point where the till can no longer deform. As a rough approximation to the upper value of effective pressure, we can use Coulomb's Law (equation 2.2) to state that $\tau = \eta p_e$, where η is the coefficient of friction. A typical value for η is 0.5, but it can be as low as 0.25, taking this with the maximum value of the shear stress discussed above (100 kPa) then the largest effective pressure that permits deformation is given by $p_e = \tau / \eta$. This gives a maximum effective pressure of 400 kPa. Even though an argument based on plasticity is being used here, this is consistent with the view of Hindmarsh (1997) who argues that viscous deformation is the aggregate of many plastic events (see Section 2.2.3). Plastic failure must occur for deformation to occur. Evidence for ponds beneath Ice Stream C implies that the effective pressure can be as low as zero. The Hindmarsh model must have effective pressures greater than zero, so somewhat arbitrarily the lowest effective pressure is taken as 1 kPa. Thus, a realistic range of effective pressures for a deforming system will range somewhere between 1 to 400 kPa and these values are used to test the model.

This effective pressure is the value at the ice till interface. Under the assumptions of the Hindmarsh model, the effective pressure increases with depth as the weight of the sediment presses the grains harder together. The increase of effective pressure with depth is taken as 10 $Pa.m^{-1}$. This value is justified in Hindmarsh (1998a). It can be seen from equation (11.2) that the strain rate will depend on the depth of the point being considered beneath the ice-till interface. The shear stress can be considered to be constant over the depth of the till (Hindmarsh 1998a; Fowler, 2000). The ice velocity is given by summing (integrating) the strain rates over the depth of the till.

11.5.4. Ice velocities

Within an ice sheet, ice velocities will vary significantly depending on the position that is being measured. Generally speaking, the slowest moving ice will be found in the interior of the ice sheet with ice velocities at the ice divide being close to zero. The fastest velocities within an ice sheet (excluding ice streams) occur just up-glacier from the margin (Hart, 1999). The present Greenland Ice Sheet at this point has been estimated by Dahl-Jensen (1989) to be flowing at 90 ma^{-1} and 100-150 ma^{-1} by Bamber *et al.* (1997). The fastest moving ice is located within ice streams where speeds of up to 8360 ma^{-1} have been recorded (Lingle *et al.*, 1981). Typical values however for these features are normally in excess of 300 ma^{-1} (Stokes, 2000). From these estimates, it is clear that the range of ice velocities that exist within an ice sheet vary between the streaming and sheet flow modes.

Although ribbed moraines have now been identified within palaeo-ice stream tracks (see 9.8), their location in the onset zone (Figures 9.11 & 9.12) and superimposition on top of the ice stream bedforms (Fig. 9.13) indicates they were formed at slower velocities typical of ice streams. Stokes and Clark (1999) also exclude them from being part of their geomorphological criteria for identifying palaeo-ice streams and argued that only highly attenuated bedforms with elongation ratios >10:1 are indicative of fast flowing ice. Thus, ribbed moraines appear unlikely to be formed under ice flowing at velocities typically found in fully functioning ice streams and are more likely to be associated with ice velocities that operate in sheet-flow mode. Figure 11.7 shows the spatial distribution of ribbed moraines in Sweden and Canada, clearly demonstrating that they are restricted to regions that are close to the ice divide. Bouchard (1989) also noted this distribution and stated that in Keewatin and Quebec ribbed moraines are spatially restricted to a zone that lies between 50 to 350 km from the former ice divide and 350 to 400 km behind the margin. In Ireland, Clark and Meehan (2001) the ribbed moraine belonging to rm-1 (see 7.3) is estimated to lie between 30 km and 140 km from the former ice divide. Because the distribution of ribbed moraines appears spatially confined beneath the ice sheet, all that is required for the velocity parameter is to work out the velocities that would be typically found in these regions. One method of doing this is to use a simple mass balance equation to estimate the mass flux across a given point along the ice sheet.

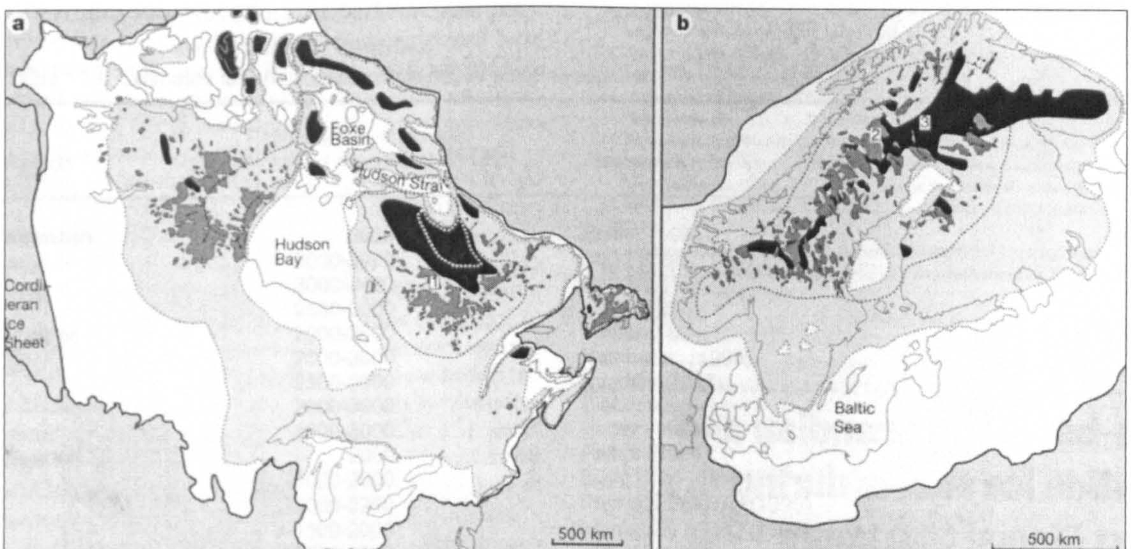

Fig.11.7 Ribbed moraine distribution in Sweden and Canada. The dashed line marks the ice margin during deglaciation, dark grey areas are ribbed moraines. (After Kleman and Hättestrand, 1999)

Under an assumption of steady state, the mean velocity can be found if three quantities are known; the accumulation rate, the distance the point of interest is from the ice divide and the thickness of the ice sheet:

$$\text{Velocity} = \frac{\text{Accumulation rate} \times \text{distance from the ice divide}}{\text{Ice thickness}}$$

It will be seen that we are dealing with order-of-magnitude estimates, so the assumption of steady state is not expected to introduce significant errors. For palaeo-ice sheets, obtaining the input values is complicated by the fact the ice sheet has gone and the climate has changed. To obtain estimates of how thick the Pleistocene ice sheets were during the last glaciation a literature search of ice sheet models that predict ice thickness was conducted, Table 11.1 summarises the findings. As can be seen, ice thickness predictions for Sweden range between 1000 m and 3250 m; in the Keewatin sector of the Laurentide Ice Sheet is estimated to range from 1500 m to 3000 m; and in Québec the ice thickness is estimated to be between 1500 m to 3000 m. The full range of ice thickness for these regions therefore ranges from 1000 m to 3250. There is a paucity of data for the Irish Ice sheet, however, a reasonable estimate would be to put it between 1000 m and 1500 m thick as it was much smaller than the continental scale Fennoscandian and Laurentide ice sheets.

Table 11.1. Estimated ice sheet thickness in ribbed moraine regions

Region	Estimated ice thickness in ribbed moraine region (m)	Reference
Keewatin	3000	Peltier (1994)
	2000-3000	Budd *et al.* (1998)
	3000-3400	Sugden (1977)
	2500-3000	Clark (1996)
Québec	2000-3000	Peltier (1994)
	2000-3000	Budd *et al.* (1998)
	2500-3000	Sugden (1977)
	2000-3000	Clark (1996)
	1500-3000	Peltier (1994)
Sweden	2000	Peltier (1994)
	1000-2000	Budd *et al.* (1998)
	2000-3250	Payne & Baldwin (1999)
	1500-2000	Letréguilly & Ritz (1993)
	1800-2500	Høydal (1993)

The accumulation rates were based on present day estimates of the Greenland ice sheet and West and East Antarctica, these are 0.3 ma $^{-1}$ for Greenland and 0.1 ma $^{-1}$ and 0.03 ma $^{-1}$ for the west and east Antarctica respectively. To calculate the maximum and minimum distances that ribbed moraines occur from the former ice divides, glacial geomorphology maps of Canada and Sweden were used (Prest *et al.*, 1968; Hättestrand, 1997a). Firstly, the ice divide was located by carefully studying the pattern of glacial lineations. Once this was done, measurements were taken to the furthest and closest ribbed moraine fields. This assumes that the ice divide position is known and that the ribbed moraines formed contemporaneously with the divide in this position. The minimum and maximum distances for Ireland were estimated using the maps published by Clark and Meehan (2001). Table 11.2 shows the measured distances for the three regions and Table 11.3 summarises the results obtained from the calculations made using the mass balance equation. The minimum ice velocity calculated is 0.15 ma $^{-1}$ and the fastest velocity is 130 ma $^{-1}$. These values are rounded off so that the lower and upper velocity limits that will be used to test the model will be 0.1 to 100 ma $^{-1}$.

There is an issue as to whether all the ice basal velocity is due to internal deformation of the till, and there is evidence for ice sliding over till (Iverson *et al.*, 1995). Obviously if all the basal ice velocity is due to sliding, no internal deformation of the till can happen and no landforms generated. To consider the effect of ice-till sliding on the ribbing instability, two cases were considered, one where all the ice basal velocity was due to the internal deformation of till, and the other where half the velocity was due to the internal deformation of till and half due to ice-till sliding.

Table 11.2. The minimum and maximum distance that ribbed moraine occur from the former ice divide

Region	Min distance of ribbed moraine from ice divide (km)	Max distance of ribbed moraine from ice divide (km)
Sweden	5	325
Ireland	30	140
Keewatin	25	475
Canada	10	650

Table 11.3. The minimum and maximum calculated palaeo ice velocities for the Laurentide, Fennoscandian and Irish ice sheets using the mass conservation equation.

Region	Ice thickness (m)	Accumulation Rate (m)	Min Distance (m)	Max Distance (m)	Min Velocity (ma^{-1})	Max Velocity (ma^{-1})
Sweden	1000	0.03	5000	325000	0.15	9.75
	1000	0.1	5000	325000	0.50	32.50
	1000	0.3	5000	325000	1.50	97.50
	3250	0.03	5000	325000	0.05	3.00
	3250	0.1	5000	325000	0.15	10.00
	3250	0.3	5000	325000	0.46	30.00
Ireland	1000	0.03	30000	140000	0.90	4.20
	1000	0.1	30000	140000	3.00	14.00
	1000	0.3	30000	140000	9.00	42.00
	1500	0.03	30000	140000	0.60	2.80
	1500	0.1	30000	140000	2.00	9.33
	1500	0.3	30000	140000	6.00	28.00
Keewatin	1500	0.03	25000	475000	0.50	9.50
	1500	0.1	25000	475000	1.67	31.67
	1500	0.3	25000	475000	5.00	95.00
	3000	0.03	25000	475000	0.25	4.75
	3000	0.1	25000	475000	0.83	15.83
	3000	0.3	25000	475000	2.50	47.50
Québec	1500	0.03	10000	650000	0.20	13.00
	1500	0.1	10000	650000	0.67	43.33
	1500	0.3	10000	650000	2.00	130.00
	3000	0.03	10000	650000	0.10	6.50
	3000	0.1	10000	650000	0.33	21.67
	3000	0.3	10000	650000	1.00	65.00

11.6. Model runs

As was stated earlier in Section 11.4, the main objective of this part of the study is to try and falsify the BRIE using the wavelength data gathered in the four ribbed moraine localities. As explained, the BRIE makes predictions of wavelength in perturbations generated in a deforming till under given a combination of the parameters described above. We went to some lengths to give motivation and justification for likely ranges of these parameters, but in our present state of knowledge, it is not possible to constrain them any further. However, we cannot assert that this particular range of parameters would have been found at any given ribbed moraine field. For example, during the formation of a particular ribbed moraine field, ice velocities may have been 30 ma^{-1}, effective pressure 10 kPa, shear stress 50 kPa and till thickness 10 m, whilst in another field the parameters may have been completely different. We thus might expect a much more restricted range of parameters to have been found during the lifetime of formation of a ribbed moraine field. It is unlikely that during the few centuries taken to create a ribbed moraine field that ice velocities varied from 1 ma^{-1} to 100 ma^{-1}, and conservatively one should assume that the velocities were more or less constant. In the same way, one might expect that during the period of formation of a ribbed moraine field, the mean shear stress to be constant, because the ice thickness and surface slope would not change much during this period. We can be confident in asserting this because we have specifically said that ribbed moraine is not associated with ice velocities typical of a fully functioning ice stream (see Section 9.8), which are known to fluctuate widely over relatively short time periods (Patterson, 1994). It is harder to argue that the effective pressure was constant in view of the large fluctuations in water pressure observed in alpine glaciers (Paterson, 1994). However, this is largely a consequence of connection to the outside world (e.g. through crevasses and moulins) and is unlikely to have been true for features formed some distance back from the margin, for example in the onset zone of ice streams (Chapter 9) or in locations even more distant from the margin, as the ice would be too thick (greater than 1000 m) for water to reach the bed via these portals.

We now proceed to ask whether the BRIE always, sometimes, rarely or never predicts the formation of ribbed moraine under the range of parameters outlined above. Clearly, if it never predicts the formation of ribbed moraine then the model is wrong, however other possibilities are more complicated. For example, the BRIE may not only predict the range of wavelengths observed, but also might predict ribbed moraine to occur at many other wavelengths not found in nature. Does this mean that the BRIE is wrong, or that the chosen range of subglacial parameters is wrong?

The global histogram (Fig. 9.5) suggests that ribbed moraine are most frequent at wavelengths of around 100 m, with wavelengths less than 50 m being somewhat uncommon, and wavelengths greater than 1500 m also being atypical.

The BRIE model is run for an extensive range of combinations of all the parameters described above. Two parameter studies were carried out, one for the range of parameters discussed above (referred to as the "extended range"), and one for a more restricted range of stresses. The various combinations are listed in Table 11.4, and together create several hundred thousand cases. The parameter ranges were of necessity sampled at selected values. Where the parameters ranged over several orders of magnitude (for example, velocities ranged from 1 to 100 ma^{-1}), the parameter range was sampled approximately logarithmically; for example, the velocities in the extended parameter were (1, 2, 3, 6, 10, 20, 30, 60, 100) ma^{-1}. The extended range study comprised 283140 model runs, while the restricted range study comprised 119790 model runs.

Table 11.4. Parameter values used in extended range and restricted range studies

Parameter	Logarithmic sampling	Extended range Study	No. of samples	Restricted range Study	No. of samples
Ice velocity (ma^{-1})	Yes	1 - 100	9	1 – 100	9
Till thickness (m)	Yes	0.5 – 30	11	0.5 – 30	11
Shear stress (kPa)	No	2 – 100	11	2 – 50	11
Effective pressure (kPa)	No	2 – 100, 200, 400	13	2 – 50	11
Rheological exponent (*b*)	No	1 – 10	10	1 – 10	10
Deformational velocity proportion	No	0.5, 1	2	1	1

For each of these model runs, the wavelength of maximum growth can be computed. Given that there are more than one hundred thousand cases in each study, a convenient way of plotting the results of the parameter studies are as histograms (Figures 11.8 and 11.9). One should not expect the model histograms to be identical to the data histogram because this would imply that the parameter ranges we somewhat arbitrarily chose are similar to the ranges of conditions found during the formation of the ribbed moraine fields in the four study areas. Figures 11.8 and 11.9 assume that the parameters are equally probable, and generate histograms on this basis, meaning that there is equal likelihood of parameters being at the extreme range of the scale as at the middle range.

Figures 11.8 and 11.9 are binned logarithmically, as this distributes results more evenly amongst the bins. The bin centres are at (10, 18, 32, 56, 100, 180, 320, 560, 1000, 1800, 3200, 5600, 10000) m. The global data set for ribbed moraine wavelengths (Figure 9.5) has been replotted in Figure 11.10 using this logarithmic binning. The BRIE model, using the extended parameter range, predicts Figure 11.8, and that the modal value of the wavelength of maximum growth rate is around 100 m. The distribution is asymmetric. Wavelengths from the mode down to around 10 m are reasonably common and wavelengths between 100 m and 1000 m are equally frequent. Wavelengths between 1000 m and 10000 m are less frequent. As compared with the data, the BRIE model with the extended parameter range predicts ribbed moraine formation between

100 m and 1000 m, as is observed, but also predicts ribbed moraine between 10 m and 100 m to be very common which is not observed.

There are a number of possible reasons for this mismatch, which will be discussed below, but one is simply the choice of the range of parameters. To illustrate the kind of effects that this might have, a restricted parameter range was chosen (Table 11.4), where the maximum value of the effective pressure and the shear stress were reduced to 50 kPa (Fig. 11.9). The motivation for this was to demonstrate the match between model and data histograms could be improved. This restricted choice of parameters increases the modal value from 100 m to around 300 m providing a close match with the observations, although the tails in the BRIE restricted range model are fatter than in the observation. In principle, the ranges could be selected more precisely to fit the data even better, but the value of such an exercise is not clear. The meaning of the present results is discussed in the next section.

As discussed previously in Chapter 2 there is uncertainty regarding whether subglacial till deforms as a plastic or viscous material. This problem was not fully addressed by this study however we note that the shape of the histogram is affected by the value used for the rheological index. This dependence is illustrated in Figure 11.11, which shows the histogram for the sampled values of the rheological exponent b. It can be seen that as b changes from 1 to 10, (i.e. from viscous to plastic) the histogram becomes more concentrated around its mean value. It is not really possible to say whether a low value or a high value of b better represent the data, and attempting to infer evidence about the rheology of till from wavelength distributions may not be a fruitful avenue of enquiry.

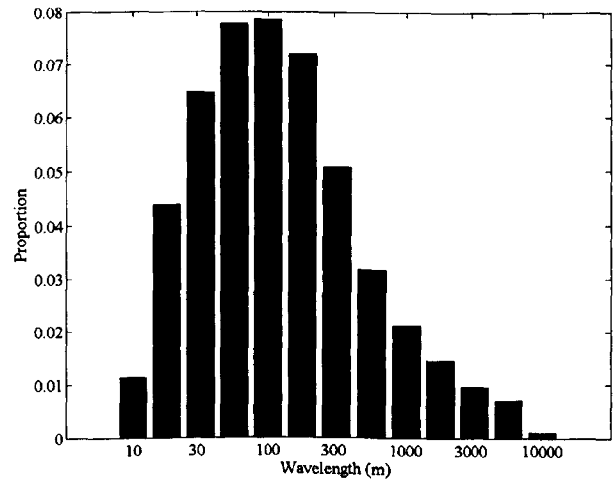

Figure 11.8. Histogram of BRIE results for extended range parameter study. Horizontal axis is wavelength of maximum growth rate. Note that bins are logarithmic. In other words bin size increases with wavelength. Vertical axis is proportion of total number of calculations in each bin. Note that total proportion does not sum to one because not all cases are unstable.

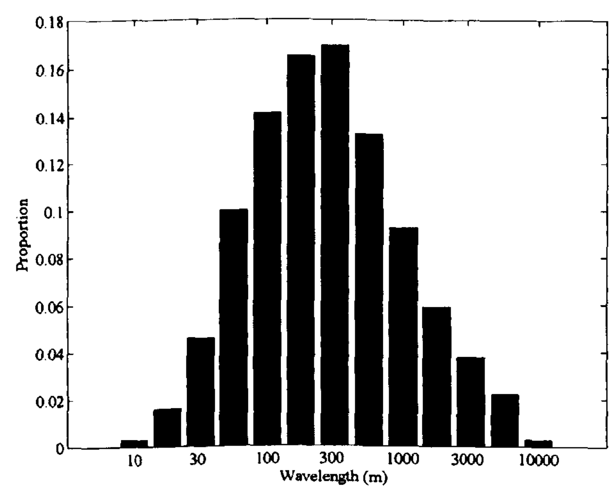

Figure 11.9. Histogram of BRIE results for restricted range parameter study. Details as for Figure 11.8.

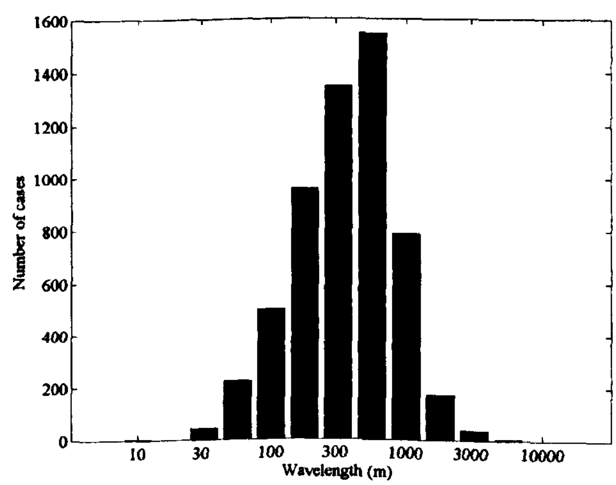

Figure 11.10. Global histogram of ribbed moraine observations (see Figure 9.5) plotted with logarithmic bins for comparison with results from BRIE model.

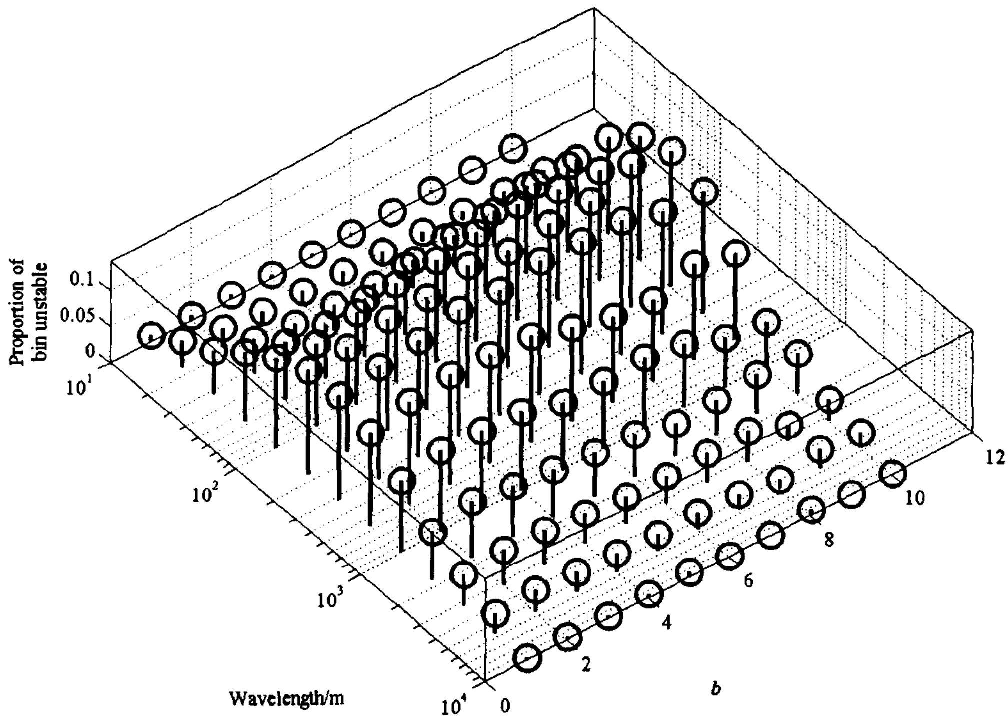

Figure 11.11. Histogram of BRIE results for restricted range parameter study, showing dependence of histogram shape on the rheological exponent *b*. Details as for Figure 11.8.

11.7. Discussion and conclusions

A physically-based model for ribbed moraine formation (BRIE) has been presented and used to compare predicted results with those obtained from the global data set of observations. BRIE requires knowledge of the physical conditions under which the ribbed moraine formed. A direct comparison between the predictions of the model and the data gathered is not possible because the physical conditions are not well known. If laboratory experiments or distinct observation of ribbed moraine generation beneath existing ice sheets were possible, then a more direct and robust validation could be attempted because we would be able to control or measure the parameters. An attempt to circumvent this problem has been made by defining glaciologically plausible ranges for the physical parameters, and assuming that all the ribbed moraine observed were formed under this same range of conditions. This, perhaps not surprisingly, gives a range of ribbed moraine wavelengths somewhat broader than those observed (compare Figures 11.8 and 11.10). The choice of a more restricted range of parameters (Fig. 11.9) restricts the histogram of computed results, which becomes more comparable with the histogram of observed results. In principle and undoubtedly in practice, one could constrain the search range further and achieve a yet better fit between the BRIE histogram and the histogram of the global data set.

On this basis, one cannot say that the BRIE model has been falsified on account of its over prediction of ribbed moraine formation at short and long wavelengths. The fact that it predicts ribbed moraine formation at wavelengths between 100 m and 1000 m is a major point in its favour. Remember that the instability may have produced completely unrealistic wavelengths such as 10 – 1000 km.

Another factor worth considering that may account for the lack of short wavelengths in the data histogram, is that the resolution of the imagery may have led to an under-sampling of small-scale ribbed moraine. Ridges smaller than the pixel resolution would have been missed in those areas mapped using satellite imagery. For example, the Lac Naococane region was mapped using a Landsat MSS image that has a pixel resolution of 80 m, clearly this type of image would be too coarse to pick up small ribbed moraine ridges such as minor ribbed moraine, or smaller if indeed they exist. It might also be that numerous small wavelength (10 m) ribbed moraine are produced in nature, but that post-formational processes (e.g. subsequent overriding ice flow or solifluction) may have partially destroyed them (see Section 9.4).

Shorter, atypical wavelengths are predicted by BRIE to occur at relatively high shear stresses and high effective pressures. If we suppose BRIE to be essentially correct, this would be an indication that ribbed moraine forms at relatively low shear stresses and effective pressures. This could be addressed by using more realistic ice sheet models and computing the stress and effective pressure in regions where ribbed moraines form. This would help us understand better the physical conditions under which this occurs and thereby constrain the parameter ranges under which ribbed moraines form in reality.

The sensitivity study of the shape of the histogram on the rheological index b (Fig. 11.11) is inconclusive. Increasing b (towards values at the plastic end of the spectrum) reduces the spread of wavelengths, in line with the observed data, but on the other hand the modal value is more realistic for low b (the viscous end of the spectrum).

In summary, the BRIE theory remains a viable candidate for explaining ribbed moraine formation. The problems faced in this chapter regarding the verification of BRIE stem from our ignorance of the physical conditions under which ribbed moraine forms. A major plus for the BRIE theory is that it has been quantitatively shown that it can predict ribbed moraine of appropriate wavelength particularly regarding the modal value, which can be regarded as the strongest measure. It remains to be seen whether quantitative formulations of the other theories can achieve the same success.

Chapter 12: Summary and Conclusions

Context and thesis aims

At the beginning of this thesis, it was argued that subglacial bedforms are intrinsic to ice sheet motion, and that a clear understanding of their formational processes is critical if we are to fully appreciate their role in ice sheet dynamics. Since ribbed moraines are known to cover sizable portions of the beds of former ice sheets, we argued their role must have been significant. Chapter 3 reviewed a range of formational hypotheses that claim to explain the genesis of ribbed moraine. It was clear from the current literature that the formation of this landform is placed in a wide range of glaciodynamic settings, such as subglacial versus submarginal. This has obvious implications regarding the accuracy of ice sheet reconstructions. For example, if the Hättestrand (1997b) model of formation is favoured, then ribbed moraines signify that frozen-bed conditions were widespread during the previous glaciation, and that ice sheets were high-domed and stable during the last glacial maximum (Kleman and Hättestrand, 1999). However, if one favours the deforming bed model (Boulton, 1987; Hindmarsh, 1998a,b, 1999), then areas of ribbed moraine indicate the ice sheet was warm-based, sliding and the ice sheet was much thinner, which is quite different to the previous reconstruction.

In order to resolve such contradictions, we argued it was essential to rigorously test the various formational theories in an effort to understand the environmental conditions under which ribbed moraine are formed. An obvious way of doing this was to gather information on ribbed moraine characteristics from the literature, and then use this to determine whether the various theories could convincingly explain their unique properties. However, it became apparent that this approach was not viable since most observations of ribbed moraine in the literature are restricted to small areas and are based on small sample sizes. This presented obvious difficulties, as the data could not be considered representative of ribbed moraines in general. This thesis set out to address this shortfall and its specific aims were to;

1. Map a large and representative sample of ribbed moraines and record their spatial, morphological and morphometric characteristics.

2. Produce the first morphometric database on ribbed moraine ridge length, height, width and wavelength.

3. Use these data to examine each formational theory and make an assessment regarding whether or not they could be considered valid in light of the data gathered during this thesis.

4. Use the wavelength data to specifically test the Hindmarsh (1998a,b, 1999) numerical computer model of ribbed moraine formation based on instabilities in the coupling of ice and deforming sediment.

Using remote sensing to study ribbed moraines proved to be a practical solution for addressing the first two aims of this thesis. This approach allowed mapping of 81,000 km^2 of ribbed moraine terrain and assessment and measurement of the spatial, morphological and morphometric characteristics of large numbers of ribbed moraine from the beds of the former Laurentide, Fennoscandian and Irish ice sheets (see Chapters 5 to 8). The sample included ribbed moraines from a wide variety of ice dynamical and topographical settings, and the spatial resolution of the imagery ensured the study captured the known scale range of ribbed moraine (i.e. minor to mega-scale ribbed moraine). In total, approximately 36,000 individual ribbed moraine ridges were recorded, which makes this the largest sample of ribbed moraine ridges mapped to date. Since the sample included;

- Ribbed moraines formed beneath three separate ice sheets.
- The known scale range of ribbed moraine.
- Ribbed moraine from a wide range of ice dynamical and topographic settings.
- Large numbers of ribbed moraine ridges (i.e. tens of thousands).

we are confident that the data can be considered as being representative of the global population and argue that the results are applicable to ribbed moraines in general.

Summary of ribbed moraine characteristics

A variety of ribbed moraine characteristics were investigated at four separate localities; two in Québec, Canada (The Lac Naococane and River Kaniapiskau regions, Chapters 5

& 6 respectively), one in Ireland (The northeast midlands, Chapter 7) and one in Sweden (The Lake Rogen area, Chapter 8). These observations were then compared against ribbed moraine characteristics reported in the literature, which clearly showed many of them to be either inaccurate or untrue (Chapter 9). The key discoveries made during this section of the thesis are summarised as follows;

- Ribbed moraine *fields* (i.e. continuous tracts of ribbed moraine) are formed at a wide range of scales and can vary anywhere between a few square kilometres to extremely large expanses of continuous ribbed moraine, measuring several thousand square kilometres in extent.

- At a regional level the distributional pattern of ribbed moraine can be classified into one of the following categories;

    - Extensive continuous fields of large size.
    - Elongate ribbons and narrow tracks.
    - Densely packed or dispersed clusters of ribbed moraine.
    - Isolated fields.
    - Cross-cutting ribbed moraine.

- This thesis established that the morphology of ribbed moraine ridges is more complex than the "classic" description normally given in the literature (Section 5.4.1). Detailed observations of ribbed moraine at the four study sites demonstrated that ridge morphology is quite diverse. Ribbed moraine fields can contain ridges that are arcuate and concave up ice (opposite to what is usually stated), straight ridges that are not curved at all, barchan shaped ridges, broad rectangular ridges and many poorly developed ridges that lack a distinct morphology. The diversity in form is illustrated in Figure 12.1 which shows the various forms encountered during this thesis.

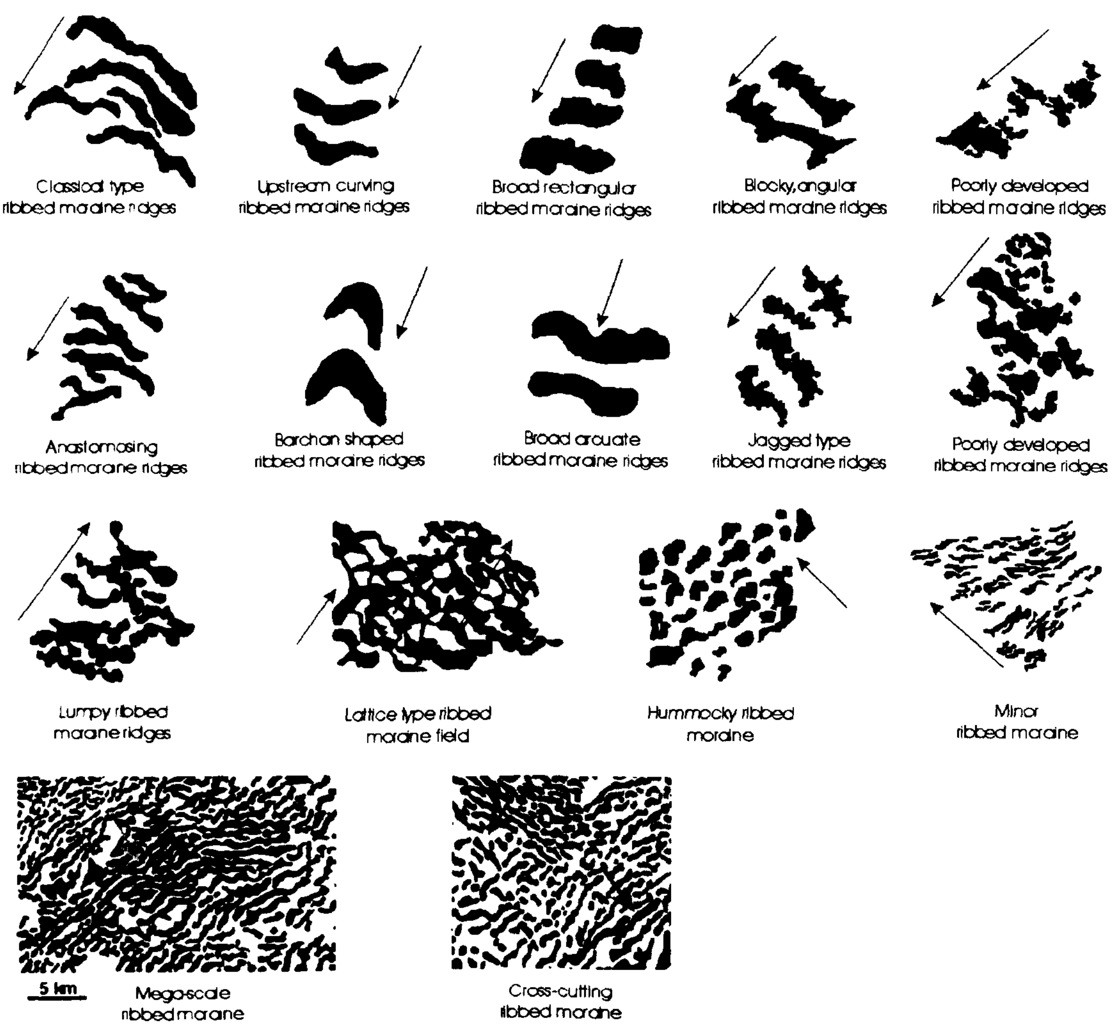

Figure 12.1. Classification of ribbed moraine ridges based on morphological distinctions. Each ridge type is discussed in more detail in the chapters 5 to 8. Arrows show the direction of ice flow.

- Ribbed moraine ridges are nearly always asymmetric in cross-section. However, unlike the usual reports in the literature which state they are normally steeper on their distal side (Shilts *et al.*, 1987; Aylsworth and Shilts, 1989; Bouchard, 1989; Hättestrand and Kleman, 1999), this study established they are just as likely to have steeper proximal slopes.

- A commonly held assumption about ribbed moraines is that over large areas of terrain the ridge crest heights are remarkably accordant (Bouchard, 1989; Menzies and Shilts, 1996; Hättestrand and Kleman, 1999). This claim was tested using regression analysis on transect data totalling 565 km in length from ribbed moraine fields in the Lac Naococane region and in Ireland (Sections 5.4.2 &

7.4.2). This analysis established that the accordant summit characteristic is no longer applicable to ribbed moraines.

- Some reports in the literature state ribbed moraine ridges are often tabular in appearance (Hättestrand and Kleman, 1999). This assertion was not supported by investigations conducted during this thesis. Both longitudinal profiles and 3-D surface plots of ribbed moraine ridges in Ireland and in the Lac Naococane region revealed they normally have undulating crests and resemble waves (Section 5.4.2 & 7.4.2).

- Detailed morphometric measures made during this study on ribbed moraine ridges have significantly extended the known size range (Table 12.1). As a result of this work, we now have the first representative morphometric database of ribbed moraine characteristics (Section 9.3).

Table 12.1. Morphometric measures of ribbed moraine ridges made during this study and comparison with "typical dimensions" from the literature. Values were obtained by combining data from the four study sites (see chapters 5-8). Ridge length was estimated using a combined sample of 31,247 individual ridges, ridge width estimated from a sample of 1000 ridges, height from 800 ridges and wavelength was derived from transect data totalling approximately 15,000 km in length.

Parameter	Mean (m)	Range (m)	"Typical dimensions" reported in literature (m)
Length	688	32-16214	300-1200
Width	278	17-1116	150-300
Height	17	1-64	10-30
Wavelength	505	12-5800	30-1925 - see Table 3.3

- Several authors argue that ribbed moraine ridges fit together like a jigsaw puzzle (Lundqvist, 1969; Bouchard, 1989; Hättestrand, 1997b; Hättestrand and Kleman, 1999). As was discussed earlier (Section 10.5) this observation inspired the Hättestrand (1997b) model of ribbed moraine genesis, however our analysis of ridge matching (Section 5.4.3) was not convincing enough to support the above assertion and we argue that it is not a common trait of ribbed moraine.

- A long held view of ribbed moraines is that they tend to be a feature associated with topographic depressions and hollows (see Table 5.2). Observations conducted during this thesis demonstrated that this assertion is no longer valid since ribbed moraines clearly form independent of topographic influences. Yes, they do form in hollows, and are particularly easy to observe in these settings as they are often highlighted by surrounding water, but they are equally found on slopes and hilltops. Analysis conducted using a GIS also demonstrated there was no preferential relationship between ribbed moraine occurrence and compressive glacial stresses arising from topography. The fact that topography appears not to be a primary controlling factor in the formation of ribbed moraine indicates the primary mechanism is due to conditions within the ice sheet itself.

- It is common to find glacial landforms, such as drumlins and mega-scale glacial lineations in close spatial association with ribbed moraines. The various relationships observed during this study are summarised schematically in Figure 12.2. As this diagram clearly illustrates, ribbed moraines and drumlins are strongly linked, which suggests they may share a common origin and supports the argument that they are part of a bedform continuum.

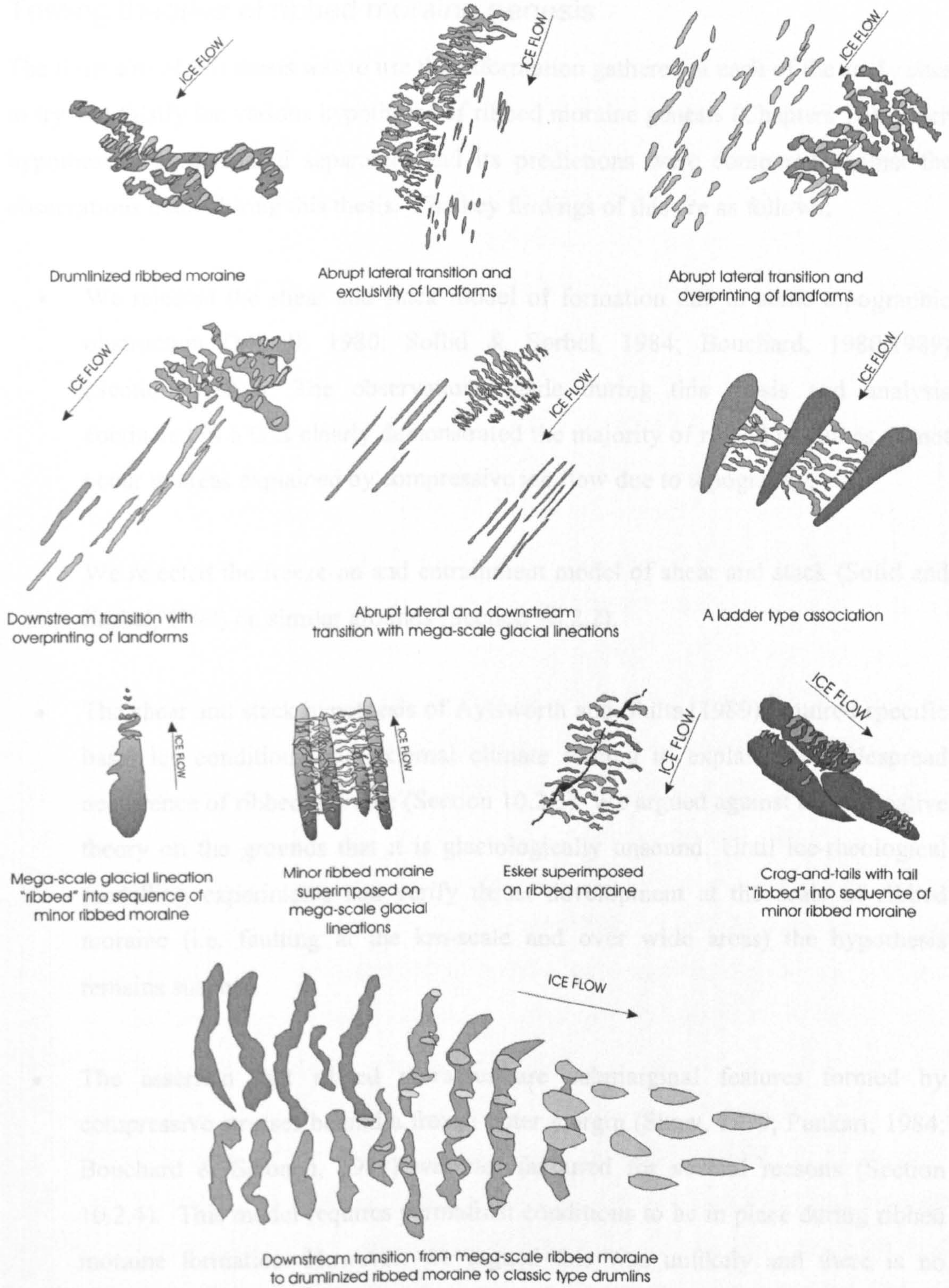

Figure 12.2. Schematic diagram illustrating the spatial relationships observed between ribbed moraine and other glacial landforms.

Testing theories of ribbed moraine genesis

The third aim of this thesis was to use the information gathered at each of the study sites to try and falsify the various hypotheses of ribbed moraine genesis (Chapters 10). Each hypothesis was discussed separately and its predictions were compared against the observations made during this thesis. The key findings of this are as follows;

- We rejected the shear and stack model of formation due to some topographic obstruction (Minell, 1980; Sollid & Sørbel, 1984; Bouchard, 1980,1989) (Section 10.2.1). The observations made during this thesis and analysis conducted in a GIS clearly demonstrated the majority of ribbed moraines do not occur in areas explained by compressive ice flow due to topography.

- We rejected the freeze-on and entrainment model of shear and stack (Solid and Sørbel, 1994) on similar grounds (Section 10.2.2).

- The shear and stack hypothesis of Aylsworth and Shilts (1989) required specific basal ice conditions and external climate forcing to explain the widespread occurrence of ribbed moraine (Section 10.2.3). We argued against this formative theory on the grounds that it is glaciologically unsound. Until ice-rheological modelling experiments can verify thrust development at the scale of ribbed moraine (i.e. faulting at the km-scale and over wide areas) the hypothesis remains suspect.

- The assertion that ribbed moraines are submarginal features formed by compressive stresses behind a frozen outer margin (Shaw, 1979; Punkari, 1984; Bouchard & Salonen, 1989) was not favoured for several reasons (Section 10.2.4). This model requires permafrost conditions to be in place during ribbed moraine formation. However, we argued this was unlikely and there is no evidence that this was the case (e.g. Lundqvist, 1962, 1981). We also presented convincing evidence that undermines the claim that ribbed moraines are submarginal features, based on the commonly observed downstream transition into streamlined bedforms.

- Dyke *et al.* (1992) suggested that ribbed moraines were formed as a consequence of stick-slip behaviour of basal ice (Section 10.2.5). We argued that this hypothesis represents an interesting possibility, particularly since recent discoveries infer this type of motion is possible (Annadakrishnan and Bentley, 1993; Ekström *et al.*, 2003). However, we could not address the idea fully since a mechanism has not been explicitly proposed or predictions made. As it stands, it remains as an interesting speculation rather than a general formative theory of ribbed moraine.

- Boulton (1987) and Lundqvist (1989, 1997) proposed that ribbed moraines are formed in two-steps whereby pre-existing ridge structures are modified by glacially related processes (Section 10.3). We argued that until the two-step hypothesis can account for the widespread creation of the initial ridges, it cannot be accepted as a general theory of ribbed moraine formation.

- We presented several arguments that we believe undermined the megaflood hypothesis of formation (Fisher and Shaw, 1992) (Section 10.4). Our greatest concern centred on whether the theory can be considered physically plausible. We argued that supporters of this theory need to explain viable sources of meltwater and demonstrate that floodwaters can flow as sheets and not in channels as stated by others (e.g. Walder, 1994). They are also required to demonstrate that hydrodynamic modelling of subglacial floods can produce cavities and ribbed moraine at the appropriate scales. Until these issues are fully addressed, we regard the hypothesis as suspect.

- The thermal fracturing model presented by Hättestrand (1997b) and Hättestrand and Kleman (1999) has several points in its favour. It explains the regional distribution pattern very well and can account for the specific cases of ribbed moraine formation in ice stream onsets. We were unable to reject the theory, however our observations did highlight several weaknesses that undermine its credibility (Section 10.5). Our main problem with the theory however centres on the fact that it is difficult to assess its physical plausibility. We argued that the theory needs to be extended into a physically-based process model that makes quantitative predictions of the fracturing process. This is essential if we are to determine whether fracturing in frozen till sheets by glacial stresses can occur at the appropriate scale.

- The fourth aim of this thesis was to test the Hindmarsh (1998a,b, 1999) numerical computer model of ribbed moraine formation (Chapter 11). This theory regards ribbed moraines as signatures of an instability in a viscously deforming subglacial till. It differs significantly from the aforementioned theories because it makes predictions of ribbed moraine that we could quantitatively test. The model specifically predicts the wavelength of ribbed moraine ridges, and we argued that a key test of the theory was whether it could predict ribbed moraine ridges at the correct wavelength. The model was run using justified ranges of parameter values (Section 11.5) and histograms showing the modelled results were compared against a histogram of ribbed moraine wavelengths measured in nature. This showed that the model predicts ribbed moraine of appropriate wavelength. This was particularly true regarding the modal value, which can be regarded as the strongest measure. Our test failed to falsify the model and as such, the Hindmarsh Bed Ribbing Instability Explanation remains a viable candidate for ribbed moraine generation.

Ribbed moraine and instabilities

In the context of this thesis, the term "ribbed moraine" is a morphological term rather than a genetic one implying we know the process of formation. We therefore need to consider whether all subglacially formed transverse ridges are ribbed moraines. It is conceivable that various processes, for example localised compressive stresses, might produce some form of transverse ridge. However, it seems reasonable to assume that the morphology of such ridges would reflect the localised conditions under which they were generated. Therefore, we would expect a variety of different independent processes to create ridges that were morphological unique to that specific environment and process. Since it seems unlikely that several independent processes could produce ridges that are morphologically similar over wide areas, we conclude that the morphological properties of ribbed moraine strongly suggest that they were formed by a single mechanism, and that ribbed moraines are an expression of this process. We recognise, however, that there might be other mechanisms for producing transverse ridges and that once understood it would not be appropriate to call them ribbed moraines. For a general theory to be credible, it must be capable of explaining ribbed moraine occurrence over the wide range of settings observed during this thesis, without local-scale special conditions. Our investigations of ribbed moraine indicated that the primary controlling mechanism of formation was not due to factors, such as topography, but rather was the result of conditions within the ice sheet itself. Wave pattern formation in natural systems are frequently driven by instabilities (see Figure 11.1) and because ribbed moraines ridges display systematic organisation into wavelengths, we argue the primary mechanism is an instability in the subglacial environment. This is an appealing idea because it eliminates the requirement for specific localised conditions to be in place before ribbed moraines can be generated. If the system is inherently unstable, then one would expect the instability to operate over large areas of that system. This would help account for the widespread generation of ridges beneath ice sheets. An instability mechanism is also appealing on the grounds that it helps explain why ribbed moraine morphology is generally consistent over wide areas and between different ice sheets (Chapters 5-8). A characteristic feature of instabilities is that they produce the same pattern repeatedly (see Figure 11.1). We would therefore expect the instability to manifest itself repeatedly, and in a similar fashion in various ice sheets, which may explain why ribbed moraines in different areas look similar.

Arising from this study, we now have a more realistic understanding of the characteristics of ribbed moraine, and the rejection of several longstanding theories also means we are a step closer in determining their role in ice sheet dynamics. On the basis that ribbed moraine patterns are repetitive, organised into dominant wavelength and are widespread it is strongly argued that *some form of instability mechanism must have created them*. The Bed Ribbing Instability Explanation of Hindmarsh (1998a,b, 1999), which is based on a natural instability in the flow of coupled ice and till, has failed to be falsified by comparison with extensive observations. It is therefore concluded, that this represents the most likely explanation for ribbed moraine genesis. If future tests, theoretical insights or observations do manage to falsify the BRIE model, then we conclude that it will be another instability mechanism that will finally emerge as being successful in explaining the genesis of this unique landform.

Suggestions for future work

One aspect of ribbed moraines that was not directly investigated during this thesis was the internal composition and structure of the ridges. We acknowledge that such observations are an important part of ribbed moraine research because investigations can certainly yield important diagnostic clues about the subglacial conditions during formation. If investigations of composition and structures were conducted properly, (i.e. using large sample sizes from different localities and with descriptions of entire ridge stratigraphy) then the data would be extremely useful. Chapter 3 summarised what is currently known (Table 3.4) and indicates that the internal composition of the ridges is quite variable. However, at present it is best to be cautious regarding the general applicability of these studies since the descriptions are based on small sample sizes (i.e. probably <50 ridges) and on shallow excavations (i.e. 1-2 m) rather than through the entire ridge. Clearly, this outstanding problem needs to be addressed and can only help in determining the exact formative processes.

Recent investigations in Antarctica has yielded some important information on the formation of mega-scale glacial lineations (e.g. Shipp *et al.*, 1999; Canals *et al*, 2000; O Cofaigh *et al.*, 2002). An important aspect of the above discoveries is that they were able to confirm the previously inferred association that mega-scale glacial lineations formed under fast ice flow (Clark, 1993). In this case, observations in Antarctica were able to verify theories developed from observations of the bed of palaeo ice sheets. Increased use of geophysics beneath the Antarctic Ice Sheet might eventually yield important results relating to ribbed moraine genesis. Recent high-resolution seismic reflection profiling of the bed of the Rutford Ice Stream in West Antarctica (King *et al.* unpublished) has produced evidence that may support the deforming bed model of drumlin formation. These authors argue that the acoustic properties of basal till indicates it is dilatant, deforming and the morphology of streamlined bedforms imaged at the bed are consistent with drumlins. Since drumlins and ribbed moraine appear to be linked, it seems reasonable to assume that ribbed moraines too were (or are being) formed somewhere beneath the Antarctic Ice Sheet. If they can be located it would certainly help increase our understanding of the formative processes that generate this landform, especially if we could observe them forming *in situ* beneath the ice sheet.

As was previously discussed, Hindmarsh (1998a,b,c, 1999) produced two numerical computer models that he argued might explain the characteristics of ribbed moraine and drumlins (Section 3.2.2.3). This thesis tested the BRIE model and demonstrated it can predict ribbed moraine at the appropriate wavelength (Section 11.6). Hindmarsh (1999) sees ribbed moraines as being part of a bedform continuum and argues that BRIE is a "seeding" process that represents the first stage in drumlin formation. An obvious extension of the work carried out during this thesis would be to link BRIE with the Shock Formation Model (SFM) to try and determine whether the Hindmarsh theory can grow realistic drumlins from perturbations created by the BRIE model. Plans are currently underway to do this and it is envisaged that both models will soon be combined (Hindmarsh and Clark, pers. comm).

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