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Identifying Palaeo-Ice Stream Tracks Using Remote Sensing

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Abstract. Investigating palaeo-ice streams enhances our knowledge of Quaternary Ice Sheet dynamics and allows us to glean information about their basal processes and functioning. However, our understanding of palaeo-ice stream geomorphology is limited and they have often been postulated on a rather subjective basis, evading detailed scrutiny. In addition, many, or most palaeo-ice streams have yet to be found. To introduce more objectivity to palaeo-ice stream research, and to aid the search for new palaeo-ice stream evidence, Stokes and Clark (1999) predicted several geomorphological criteria indicative of their activity. This paper builds on that purely theoretical work by using remote sensing to identify the criteria and (i) validate the location of an already hypothesised ice stream, and (ii), find evidence for a previously undetected palaeo-ice stream

Key words: remote sensing; ice stream geomorphology

1. Introduction.

Ice streams are regions in an ice sheet which flow much faster than the surrounding ice. Most ice streams range in width from 20-30 km and reach lengths of over 300 km. Despite their large size, however, they only constitute a relatively small proportion of contemporary ice sheets, 13 % of the Antarctic coastline for example (Paterson, 1994). Their importance lies in their disproportionate ice flux and it has been estimated that they may drain as much as 90 % of the Antarctic Ice Sheet (Morgan *et al.* 1982). As such, they have a profound effect on ice sheet configuration and their activity is thought to be a key control on ice sheet stability. In recognition of this, recent research has focused on ascertaining their spatial and temporal controls, particularly in West Antarctica, an area thought to be particularly vulnerable to future climate change (Bindschadler, 1997).

Despite recent advances, ice streams still represent somewhat of an enigma. This stems from a paucity of data from the beds of contemporary ice streams, and a lack of understanding about their behaviour over longer timescales than contemporary observations permit. Both these inhibitors to ice stream research can be overcome if we investigate those ice streams which drained the now extinct ice sheets, which disappeared at the end of the last ice age. These ice sheets were also drained by ice streams and if we can find their former locations, we have an unprecedented opportunity to view their basal environment. Such research provides an enhanced understanding of the role of ice streams in Quaternary Ice Sheet dynamics. Furthermore, it may be possible to use the geomorphological products of their activity to glean information about their spatial controls and basal functioning.

Although many workers have recognised the importance of palaeo-ice stream research, they have sometimes been postulated on a rather *ad hoc* basis. A huge variety of evidence has been used to cite their former locations, but such evidence has rarely been scrutinised in detail. Put simply, their has been little theoretical work on which to base our hypotheses. This point was emphasised by Matthews (1991) who noted that the establishment of diagnostic criteria is an essential pre-requisite for finding former ice streams.

Recent work by Stokes and Clark (1999) addressed this issue by predicting several key geomorphological criteria indicative of ice streams. This theoretical work used the characteristics of contemporary ice streams as a basis for their identification in formerly glaciated areas. These criteria can be used to validate already hypothesised locations and help the search for other palaeo-ice streams yet to be identified in the geo(morpho)logical record.

Many of these diagnostic criteria are well suited to identification on satellite imagery and this paper demonstrates the suitability of this data source for palaeo-ice stream investigations. The criteria are presented and the advantages of using remote sensing to find and map them are outlined. Simple methodologies for identifying subglacial bedforms and grouping them into flow-sets are presented, and the characteristics of ice stream flow-sets are discussed. Using two case studies as examples, detection of several geomorphological criteria on satellite imagery is used to validate an already hypothesised ice stream location and identify a hitherto undetected palaeo-ice stream.

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2. Geomorphological Criteria for Identifying Palaeo-Ice Streams.

Ice sheets leave behind an array of geo (morpho) logical products, from which their former activity can be inferred. These can be broadly summarised as moraines (outlining ice sheet extent and marginal positions), flow indicators (i.e. drumlins, striae and erratics) and the distribution of till (i.e. its stratigraphy and properties). For reconstructing flow patterns, the most commonly used evidence are assemblages of subglacial bedforms, such as flutings, drumlins and mega-lineations. Their distribution is a manifestation of a number of important controls, such as the underlying lithology, the basal conditions of the ice sheet and ice velocity. Because ice streams are discrete features of an ice sheet, in general we would expect them to leave behind a suite of landforms which differ in morphometry and pattern from those produced by the slower-flowing parts of the ice sheet.

In recognition of this, Stokes and Clark (1999) predicted several geomorphological criteria thought to be indicative of former ice stream activity. This purely theoretical work used the main characteristics of contemporary ice streams as a basis for their identification in formerly glaciated areas. Put simply, how would an ice stream be manifest in the geomorphological products of an ice sheet? Table 1 shows the eight criteria suggested by Stokes and Clark (1999) and how they relate to contemporary ice stream characteristics. These criteria are not definitive, but merely introduce a theoretical framework upon which palaeo-ice stream hypotheses can be better based.

Table 1. Geomorphological criteria for identifying palaeo-ice streams.

Contemporary ice stream characteristic	*Proposed geomorphological signature*
A. Characteristic shape and dimensions	**1.** Characteristic shape and dimensions **2.** Highly convergent flow patterns
B. Rapid velocity	**3.** Highly attenuated bedforms (length:width >10:1) **4.** Boothia-type erratic dispersal trains (Dyke and Morris, (1988)
C. Sharply delineated shear margin	**5.** Abrupt lateral margins **6.** Ice stream marginal moraine
D. Deformable bed conditions	**7.** Glaciotectonic and geotechnical evidence of pervasively deformed till.
E. Focused sediment delivery	**8.** Submarine till delta or sediment fan (only marine terminating ice streams)

The criteria can be grouped together to illustrate a characteristic landsystem, produced by a former ice stream. This landsystem is shown in Figure 1 where ice streams have been classified as either marine-terminating (a) or terrestrial (b). Of greater significance is the temporal context of bedform generation, see Clark (1999). Some ice streams will operate and switch off, and their geomorphology will not be significantly modified by later ice flows or deglaciation. This represents an isochronous bedform record, or 'rubber stamped' imprint, shown in (c) and (d). Alternatively, an ice stream may operate through several cycles of activation, or remain active during deglaciation. This is known as a time-transgressive record and represents a far more complex picture, i.e. a 'smudged imprint', shown in (e) and (f). A time-transgressive record of a ice stream activity may therefore leave behind several populations of bedforms, with varying degrees of cross-cutting relationships. These have been omitted from figure 1 for clarity but are shown in more detail in figure 2. Figure 2 shows how time-transgressive ice stream activity produces a confusing array of cross-cutting relationships. It is of paramount importance to acknowledge this complication, which in the past, has led to erroneous interpretations of glacial histories.

It must be remembered that these models represent the ideal geomorphological signature of an ice stream. It would not be expected to find all of the criteria produced by a single ice stream. However, it is suggested that these landsystems models (figure's 1 and 2) represent an observational template upon which palaeo-ice stream hypotheses can be better based. It is argued that the key to finding former ice streams lies in the identification of the landsystem (composing several of the criteria) rather than individual facets. To achieve this requires a synoptic view of regional scale glacial geomorphology. This is provided by satellite remote sensing.

3. Methodology: Remote Sensing of Ice Stream Geomorphology.

3.1. Advantages of Using Remote Sensing.

Traditionally, glacial geomorphology has been mapped by intensive fieldwork and/or by aerial photography. Fieldwork is often extremely time-consuming and its use is often restricted to small areas of a former ice sheet bed. This produces detailed information from discrete regions but the scale of the investigation limits its utility for an ice sheet wide reconstruction. To overcome this problem, aerial photographs have been used to map larger areas (and even whole ice sheet beds, e.g. Prest *et al.* 1968) relatively quickly, but this mapping approach is highly dependent on the solar elevation at the time of the photo-

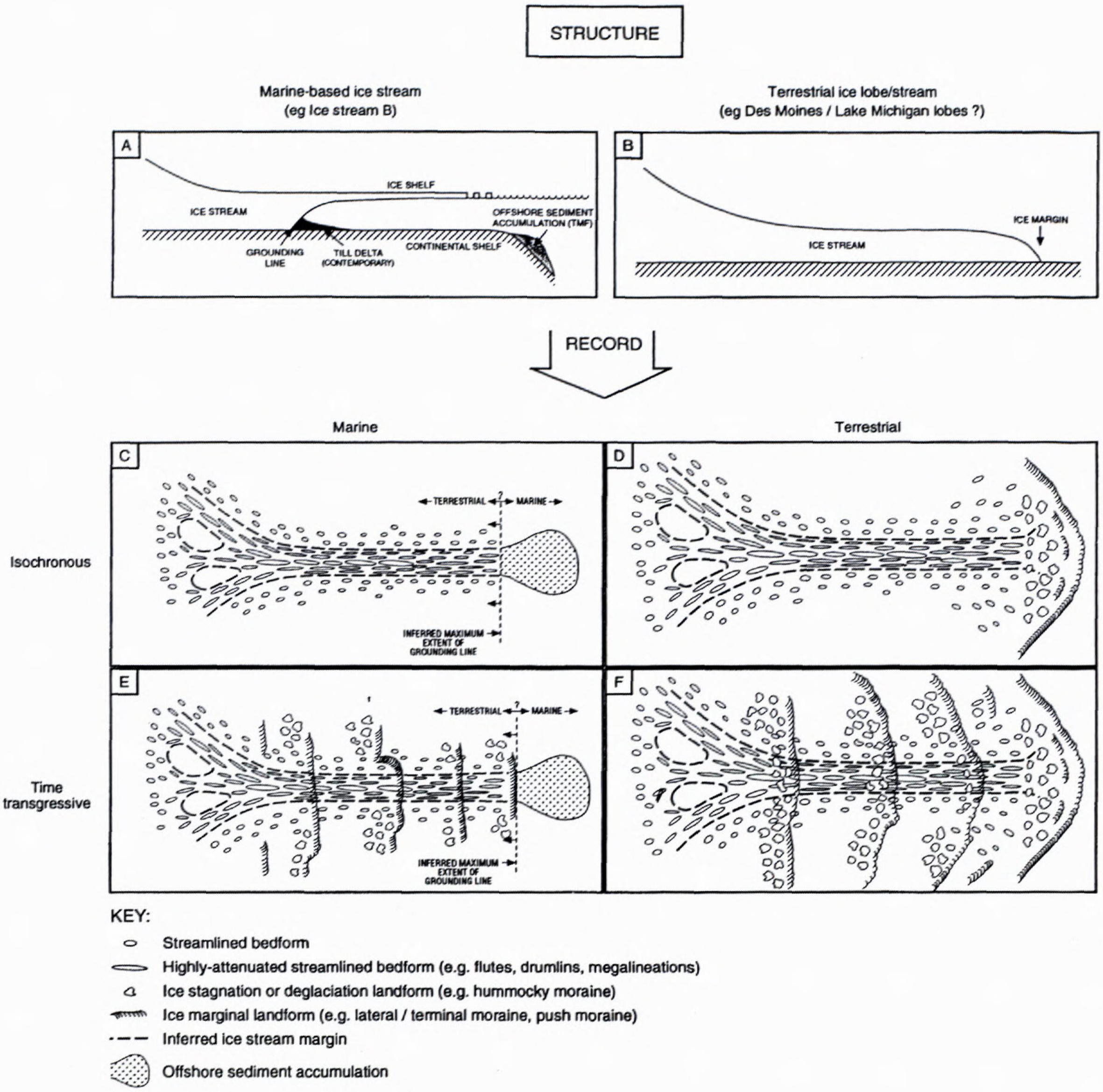

Fig. 1 Conceptual landsystems of palaeo-ice stream geomorphology (from Stokes and Clark, 1999).

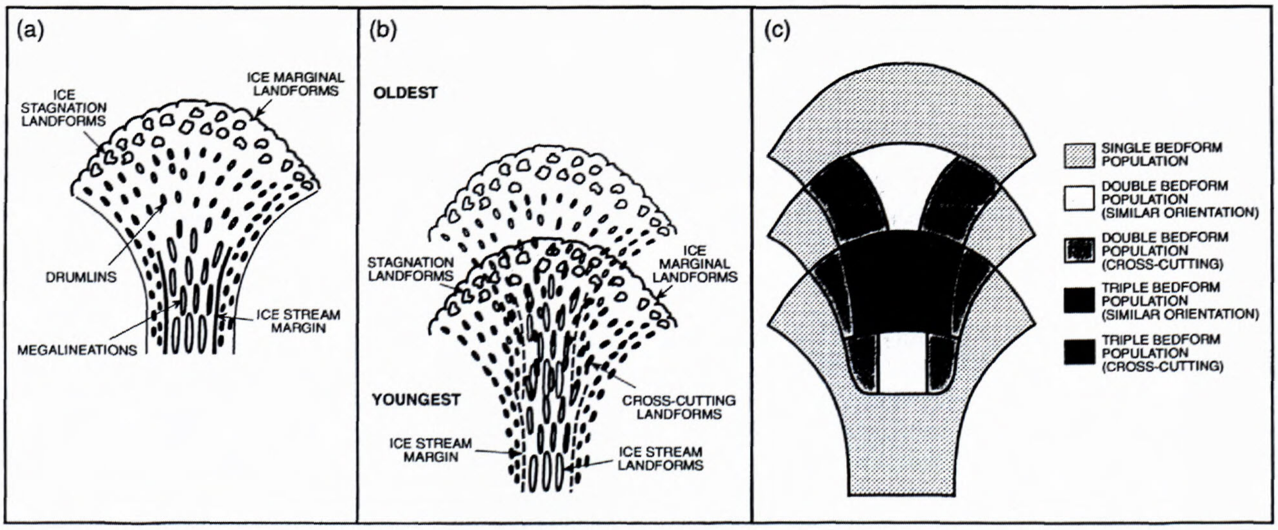

Fig. 2 Simplified bedform imprint of isochronous (a) and time-transgressive (b) ice stream activity. Note that the time-transgressive ice stream activity creates a complex assemblage of bedforms of different ages and orientations (c).

graph, the vegetation cover and the quality of the photographs (cf. Clark, 1997). Furthermore, the scale of the mapping is fixed by the resolution of the photographs, typically 1:30,000.

More recently, the use of satellite remote sensing has revolutionised the identification and mapping of glacial geomorphology and has greatly improved our knowledge of the dynamic behaviour of whole ice sheets. This is largely due to the numerous advantages it holds over fieldwork and air photograph mapping, of which Clark (1997) outlines five main benefits:

1. Satellite imagery covers large areas and this allows a single user to map geomorphology over very large regions, including whole ice sheets.

2. It is far quicker to map glacial landforms using satellite imagery than by aerial photography or fieldwork.

3. Most glacial landforms can be detected far more easily on satellite imagery than by aerial photography or fieldwork.

4. Satellite imagery allows the user to work at a range of scales.

5. The large area view of satellite imagery allows the user to discover previously unseen landforms and patterns.

For these reasons alone, satellite remote sensing is ideal for identifying palaeo-ice stream tracks. More importantly, satellite remote sensing is suited to identifying the individual geomorphological products of their activity, outlined in section 2 (table 1). The following sections briefly outline the methodology/techniques for detecting six of the geomorphological products of a palaeo-ice streams. The final two criteria in table 1 can not be identified using remote sensing. Glaciotectonic and geotechnical evidence of pervasively deformed till require identification in the field and offshore sediment accumulations can only be detected by specialised sub-marine sonar equipment.

3.2. The identification and mapping of flow-sets.

Having obtained imagery at a suitable resolution for the investigation, the flow patterns of former ice sheets can be reconstructed from an assemblage of subglacial bedforms. Most subglacial bedforms are formed parallel to ice flow (the exception being transverse ridges such as ribbed moraine) and are collectively known as 'lineations'. Using satellite imagery, these features can be mapped at a variety of scales and digitised on screen, whereby they are incorporated into a Geographic Information System (GIS).

Lineations are usually mapped by drawing a line representing the long axis of the bedform. Once identified, the length, width (and therefore elongation ratio and approximate surface area), and orientation can be measured. Overlaying a sampling grid of suitable resolution (or reconstructing a flow band) makes it possible to calculate bedform density (number of bedforms per unit area), packing (surface area of bedforms per unit area) and parallel conformity (usually calculated from the standard deviation of a sample of bedform orientations).

According to their morphometric characteristics, clusters of individual lineations can be grouped into flow-sets, which Clark (1990) defines as „integrated groups of flow lines revealing a widespread pattern of flow". The grouping of individual landforms into a flow-set is usually based on some combination of the following (cf. Clark, 1999);

a) Parallel concordance (i.e. similar orientations)
b) Close proximity to each other
c) Similar morphometry (length, width, elongation ratio)
d) Similar spacing (density)
e) Glacial plausibility

These criteria apply to any set of lineations, including a flow-set produced by an ice stream. The major challenge therefore, lies in demonstrating *why* a specific flow-set was produced by an ice stream. Here lies the importance of the diagnostic criteria outlined in section 2.

3.3. Characteristics of Ice Stream Flow-sets.

According to the criteria outlined in section 2, the flow-set needs to be large enough to have been produced by an ice stream. It would therefore be expected to be greater than 20 km wide and over 200-300 km long. However, it is acknowledged that some palaeo-ice streams may have been smaller than their present day counterparts. On the other hand, during deglaciation, ice streams may have been considerably larger than contemporary ice streams.

A flow-set produced by an ice stream would also be expected to exhibit a large degree of flow convergence in the inferred onset zone, see figure 1. The spatial extent of the transition from slow sheet flow to fast stream flow is still under debate (see Hodge and Doppelhammer, 1996), but it is suggested here, that the convergent transition zone would be expected to represent at the most one third of the ice stream length, usually less.

Most flow-sets are large and inherently convergent. Therefore, perhaps the most important criteria for identifying a palaeo-ice stream flow-set is the extremely abrupt margin to the bedform pattern. This is a unique characteristic of ice streams and it would be expected that their bedform pattern would display an abrupt margin as a result of the change in ice velocity and possibly basal thermal regime. This may be manifest as an abrupt margin with no bedforms outside it, or, a sharp zonation of landforms at the margin, as shown in figure 1. However, it must be remembered that an abrupt margin to a bedform pattern may arise from differential preservation, or abrupt changes in the underlying sedimentology. For example, Aylsworth and Shilts (1989) mapped a large area of the Keewatin Sector of the Laurentide Ice Sheet and concluded that the observed landform assemblages may be a result of the changes in underlying lithology, rather than invoking discrete ice dynamics. A major challenge therefore, lies in demonstrating why the abrupt margin is solely related to ice velocity. Questions to be answered include; what bedforms lie beyond the margin and how is their morphometry different from ice stream bedforms? Is their a change in lithology or topography which coincides with

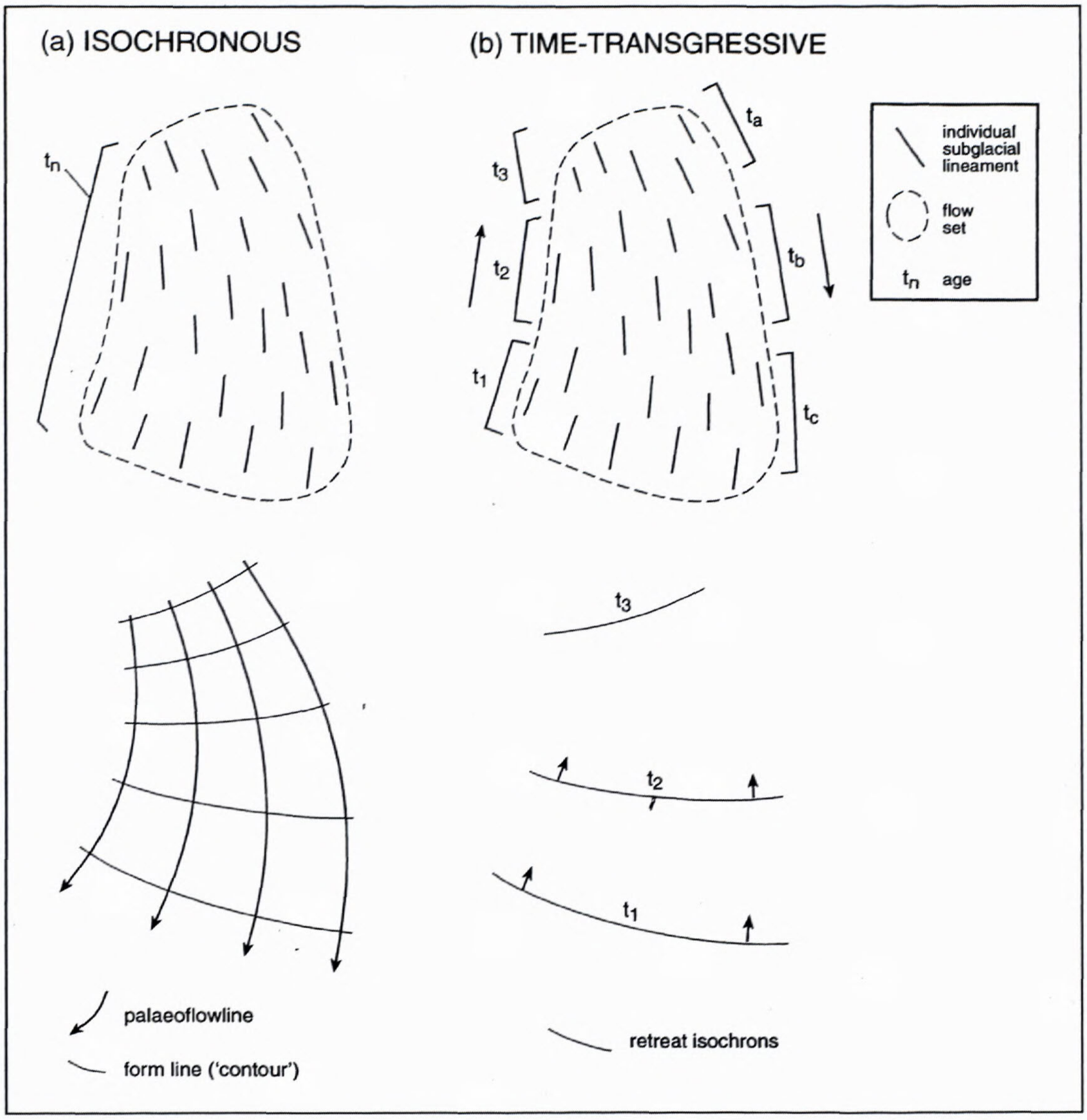

Fig. 3 Simplified diagram showing how similar bedform patterns may be produced isochronously (a) or time-transgressively (b), (modified from Clark, 1999).

the inferred ice stream margin? How has the ice stream flow-set been modified by later ice flows? Was the flow-set produced isochronously or time-transgressively?

3.4. Deciphering between isochronous and times-transgressive flow-sets.

The landsystems models in section 2 (figures 1 and 2) make a clear distinction between an isochronous record of ice stream activity and that produced time-transgressively. It is of paramount importance to make this distinction, because erroneous assumptions can lead to grave misinterpretations pertaining to the glacial dynamics. For example, a key criteria for an ice stream flow-set is a highly convergent onset zone. However, apparently convergent flow patterns can be produced isochronously or time-transgressively. This is demonstrated in figure 3 which shows how a similar flow-set can be produced by one ice flow episode, or by three separate flow events as the margin retreats.

Clark (1999) suggests several differences between an isochronous and time-transgressive bedform record. These characteristics are shown in table 2, where it can be seen that isochronous bedform patterns are generally more coherent, show a high degree of parallel conformity and display no cross-cutting relationships. This is in contrast to time-transgressive flow-sets which are generally more divergent, show abrupt discontinuities and will often exhibit cross-cutting relationships. Some of these criteria are also illustrated in the landsystems models in figure 2. In theory therefore, it should be possible to use the within flow-set variations in lineament morphometry, orientation and parallel conformity to ascertain whether the ice stream flow-set was generated incrementally (i.e. time-transgressive) or at an instant (i.e. isochronously).

If a flow-set is large enough to be considered an ice stream, and if it exhibits a convergent onset zone and abrupt lateral margins, then it may represent a good candidate for a palaeo-ice stream track. However, further

Table 2: Criteria for distinguishing between a time-transgressive and isochronous bedform record (modified from Clark, 1999).

Time-transgressive record	*Isochronous record*
Predominantly lobate or splaying flow patterns	Predominantly parallel flow patterns
Correspondence to local topography	Little or no correspondence to local topography
Likely to contain cross-cutting relationships	Unlikely to contain cross-cutting relationships
Low parallel conformity between lineations	High parallel conformity between lineations
Spatial variations in lineament morphometry abrupt	Spatial variations in lineament morphometry gradual
Probable landform association with end moraines	No landform association with moraines
Probable landform association with eskers	No landform association with eskers

evidence of ice stream activity may be found in the nature of the flow-set geomorphology. Characteristics of ice stream geomorphology are discussed below.

3.5. Characteristics of ice stream geomorphology.

It is a long held assumption in glacial geomorphology that long bedforms equal fast ice flow. Although this has never been demonstrated unequivocally, several studies report a correlation between elongated bedforms and fast ice flow (e.g. Boyce and Eyles, 1991; Clark 1994; 1997; Hart, 1999). Therefore, the rapid velocity of ice streams would produce subglacial bedforms which are highly attenuated. It could be the case that highly-attenuated bedforms may form by slow flowing ice over long time periods. However, since the discovery that the flow geometry of ice sheets are known to vary rapidly (see Boulton and Clark, 1990), it is argued that this scenario is highly unlikely.

Elongation ratio is a useful way of quantifying the degree of attenuation of subglacial bedforms (such as flutes, drumlins and mega-lineations). In theory, ice stream bedforms should exhibit high elongation ratios (>10:1), and these would be expected to be (statistically) significantly higher than neighbouring flow-sets. However, elongation ratio's within the flow-set may vary both across and within the ice stream flow-set. For example, if elongation ratio is taken as crude proxy for strain at the bed and therefore ice velocity, we would expect to find the elongation ratio's increasing from the onset zone into the main ice stream channel. Likewise, we may observe elongation ratios to decrease towards the terminus of terrestrial ice streams, where ice may be expected to slow down as it diverges (see figure 2).

In terms of the lateral variations in elongation ratio across an ice stream, we would expect little differences. This is because in contemporary ice streams fast ice flow is maintained across their whole width, a characteristic described as 'plug flow'. However, if significant drag is imparted by the margins, such as on topographic ice streams, we may expect elongation ratio to decrease slightly, reflecting the decrease in ice velocity. Examining the within stream variations in elongation ratio may provide a wealth of information pertaining to shear strain at the bed and hence ice velocity. Thus, patterns in elongation ratio can be used to support or refute the ice stream hypothesis.

The rapid velocity of an ice stream may also transport any available sediment in a distinctive pattern. Boothia-type dispersal trains form when an abrupt lateral variation in ice velocity transports distinctive sediment from a large source area, see figure 4. Such an abrupt lateral variation in velocity is a characteristic of ice streams and Boothia-type dispersal trains can be considered to be indicative of their activity. Figure 4 shows that a very similar pattern can be produced by a Dubawnt-type dispersal plume, but because the source area is localised, this implies no lateral variation in velocity. Hence, the spectral characteristics of some sat-

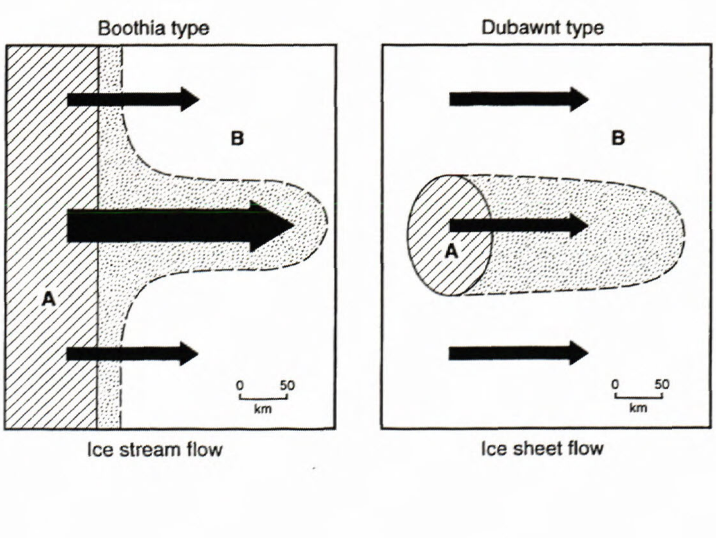

Fig. 4 Boothia-type and Dubawnt-type dispersal plumes. Only the Boothia-type dispersal plume is indicative of ice stream activity because it implies an abrupt lateral variation in ice velocity (from Dyke and Morris, 1988).

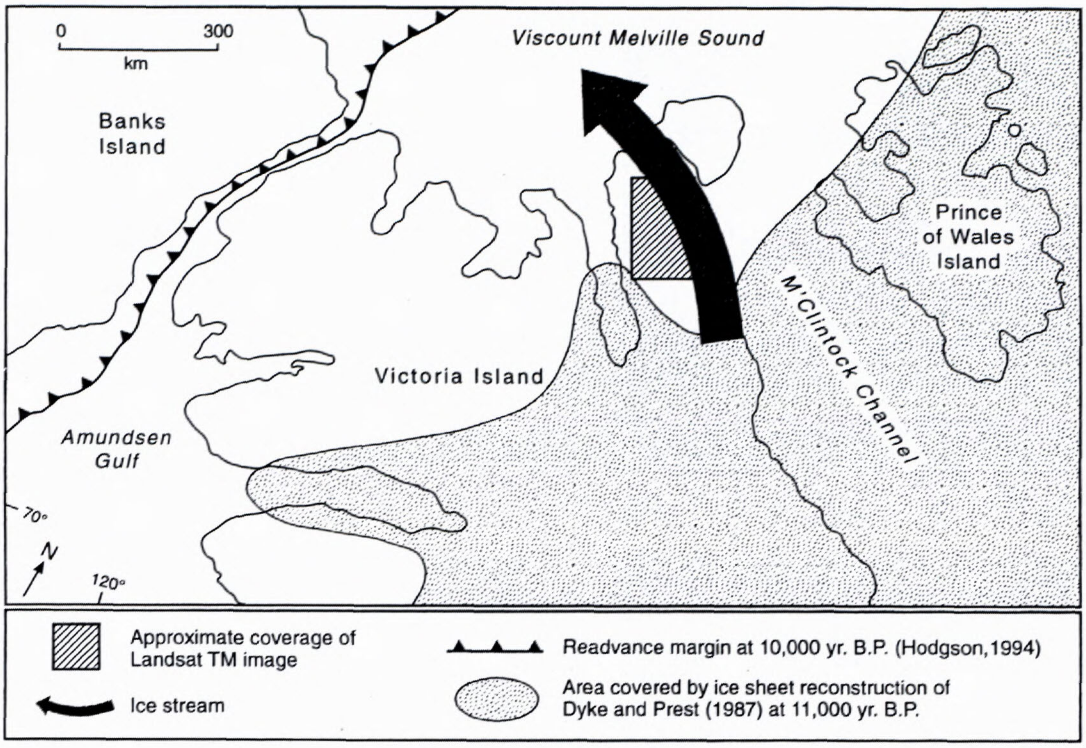

Fig. 5 Inferred location of the M'Clintock Channel Ice Stream (from Stokes, 2000).

ellite imagery (e.g. Landsat TM) can be used to identify erratic dispersal plumes and the spatial extent of the source area from which the till is transported (e.g. Dyke and Morris, 1988; Dyke *et al*., 1992).

The marginal area of an ice stream may be characterised by unique landforms, here termed ice stream marginal moraines. Dyke and Morris (1988) were the first to identify such a feature, bordering a drumlin field on Prince of Wales Island, Arctic Canada. This feature represented a smoothly curved ridge parallel to the drumlin field. The continuity of the ridge could only be appreciated at the smaller scale on the satellite imagery and reached over 68 km in length but less than 1 km wide. Dyke and Morris (1988) suggested that it marks the boundary between fast flowing (streaming) ice and slow flowing ice and thus termed it a 'lateral shear moraine'. Hodgson (1994) also identified a similar ridge on Victoria Island (Arctic Canada) and suggested that it too marked the boundary if an ice stream. Although these features are the only documented cases of ice stream marginal moraines, further investigations using satellite imagery may reveal their occurrence to be far more widespread than these isolated cases.

3.6. Application of the Geomorphological Criteria.

The criteria outlined above and in more detail in Stokes and Clark (1999) are applicable to palaeo-ice stream research in two main ways. Firstly, the criteria can be used to provide an objective validation of already-hypothesised palaeo-ice stream locations. Once a palaeo-ice stream track has been inferred, the presence of the criteria can be used to support the hypothesis for ice stream activity. If the criteria are absent, it does not imply that ice stream activity did not take place. Some ice streams signatures may have been modified or even obscured altogether. However, explanations as to why some criteria are absent may provide fruitful answers regarding the glacial history prior to and post ice stream activity.

Secondly, the criteria can be used to search for 'new' palaeo-ice streams from previously glaciated areas. Many ice streams have yet to be identified from former ice sheets and the criteria can be used as a predictive tool to aid the search for their identification.

The following two case studies demonstrate how the criteria have been used to validate the location of an already hypothesised ice stream (the M'Clintock Channel Ice Stream) and find a new palaeo-ice stream from the Keewatin Sector of the Laurentide Ice Sheet (the Dubawnt Lake ice stream). The case studies are not intended to be exhaustive, but demonstrate the suitability of remote sensing for identifying and investigating palaeo-ice streams.

4. Application of the Criteria to Palaeo-Ice Streams Locations.

4.1. The M'Clintock Channel Ice Stream.

The M'Clintock Channel Ice Stream was first postulated by Hodgson (1994) who carried out field investigations on Storkerson Peninsula, Victoria Island in the Canadian Arctic. Figure 5 shows the location of the hypothesised ice stream as the north-western margin of the

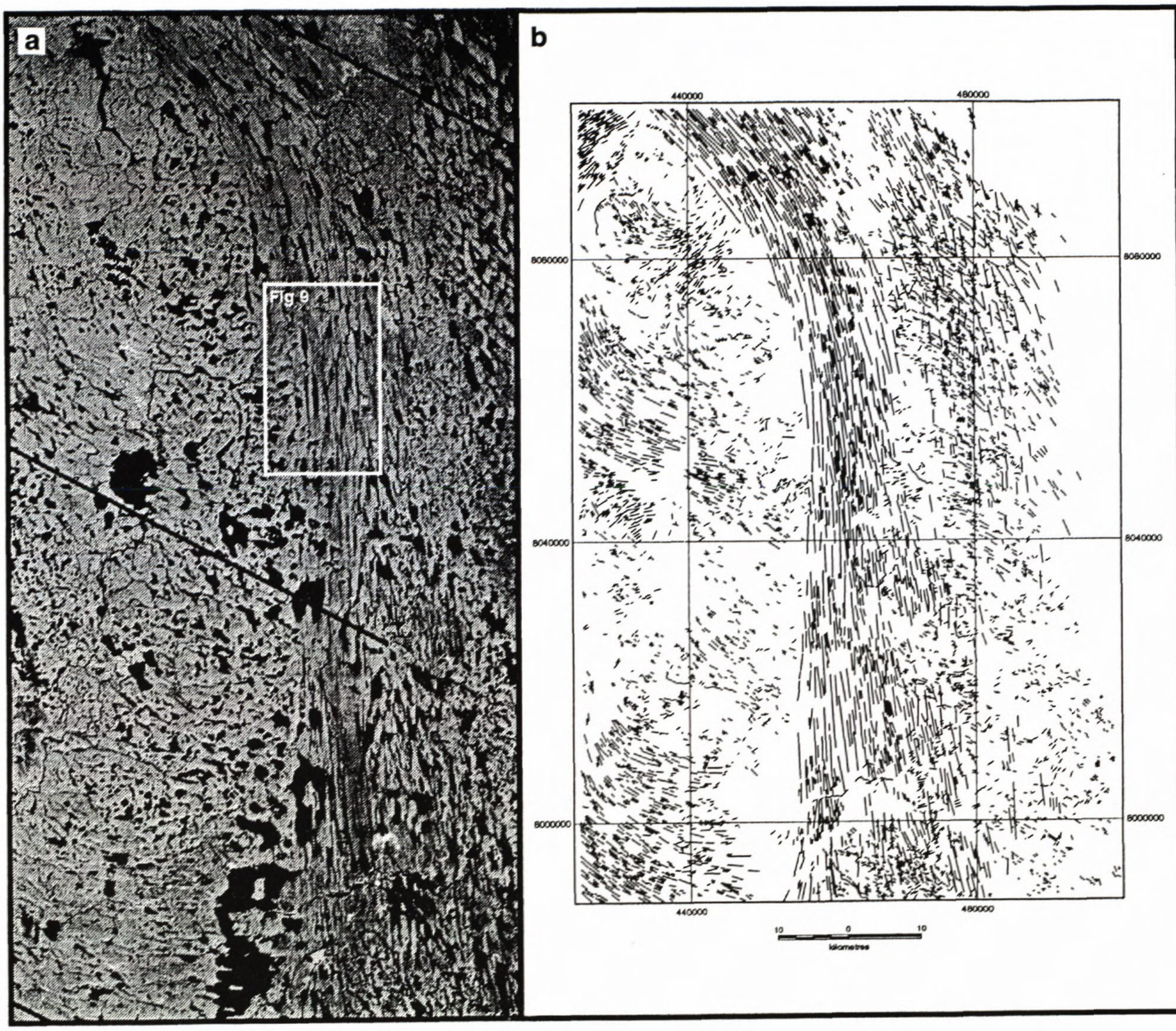

Fig. 6 Landsat TM image (band 5) of Storkerson Peninsula (a) and associated lineation map (b).

Laurentide Ice Sheet advanced between 11 and 10 ka. To assess the validity of this ice stream location and to search for the criteria outlined in section 2, a variety of imagery was obtained. A Landsat Thematic Mapper (TM) image (shown on figure 5) and four Synthetic Aperture Radar scenes were purchased covering a large part of Storkerson Peninsula and Prince of Wales Island. In addition, thirty Landsat Multi-Spectral Scanner (MSS) positives (band 4) were obtained and developed into photographs at 1:250,000. Mapping from this imagery was verified by samples of air photographs and photomaps at 10 m contour intervals.

The location of the TM image is shown in figure 5 and figure 6 shows this image (a) and all the lineations mapped from it (b). The inferred ice stream flowset runs from south to north and dominates the lineation assemblage on Storkerson Peninsula. These landforms are typically longer, closer together and show a high degree of parallel conformity. Of greatest note is the extremely abrupt western margin of the flow-set, which can be seen on the image itself (figure 6a) but is far clearer on the lineation map (figure 6b). Using the wider coverage provided by the SAR imagery and numerous MSS hard copies, this margin could be traced for several hundred kilometres upstream. Moreover, bedforms of a similar size, spacing and orientation were found further south on Victoria Island and Prince William Island and further east (across the channel) on Prince of Wales Island and Boothia Peninsula. It is suggested that these bedform patterns surrounding the M'Clintock Channel are consistent with a large ice stream which operated in the present day M'Clintock Channel but infringed on islands to the south, west and east. Figure 7 shows the reconstructed ice stream flowset which fulfils all three of the criteria for ice stream activity; it displays the characteristic shape and dimensions, exhibits a convergent onset zone in the upstream portion and displays a remarkably abrupt margin. The ice stream is thus reconstructed at around 720 km in

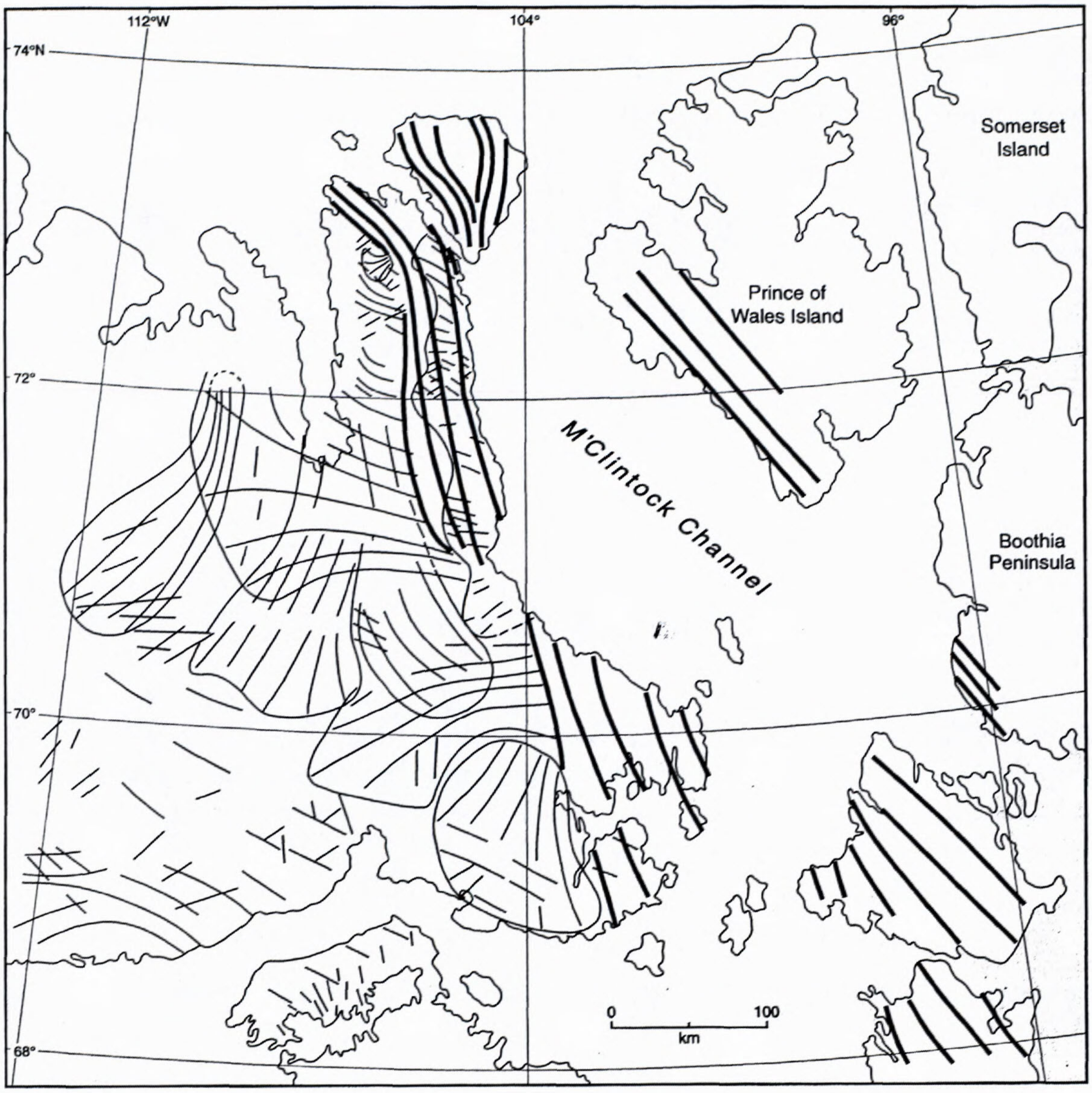

Fig. 7 Reconstructed flow-set (bold) of the M'Clintock Channel Ice Stream. Note that the ice stream is far larger than was originally inferred by Hodgson (1994) (from Clark and Stokes, in press)

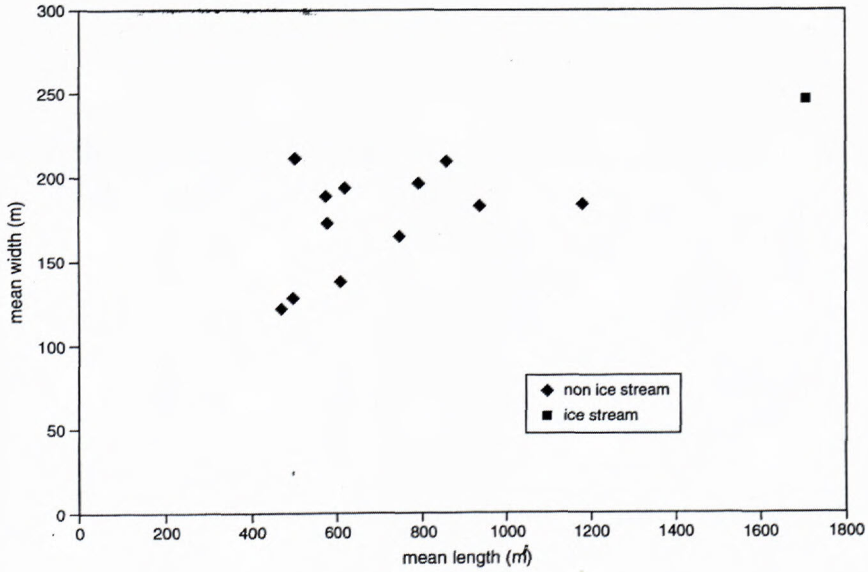

Fig. 8 Plot of mean lineament length versus mean width for each flow-set.

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length which narrowed from around 330 km in the onset zone to 140 km near the terminus. This is far bigger than was first hypothesised by Hodgson (1994) (compare figure's 5 and 7) and this ice stream would have had a profound effect on the dynamics of the whole ice sheet.

The flow-set displays all of the characteristics of an isochronous bedform pattern, outlined in table 2. Compared to neighbouring flow-sets on Victoria Island, it displays a remarkably parallel pattern which lies irrespective of local topography, see figure 6b. There are no within-stream cross-cutting relationships but rather, spatial variations in lineament morphometry are gradual. It is thus inferred that the ice stream flow-set is an isochronous record which represents a snapshot view of the bed prior to shutdown.

On average, ice stream bedforms are far more elongated than neighbouring flow-sets. Figure 8 plots mean lengths against mean widths for a number of flow-sets identified on Storkerson Peninsula and it can be seen that the ice stream flow-set represents a unique population. Moreover, mean values of ice stream bedforms indicate that they are longer, wider and more elongated than any other flow-set identified. Lengths approach 8 km, with widths of up to 750 m and elongation ratios are some of the highest in the literature (approaching 30:1). The morphometry of these bedforms fulfils a fourth criteria for ice stream activity outlined in section 2. Figure 9 shows a TM image of a typical population of elongated ice stream landforms juxtaposed to the remarkably abrupt ice stream margin.

Not only is the ice stream margin abrupt, but in places it is also demarcated by ice stream marginal moraines on Storkerson Peninsula. Figure 10 shows one of these features on the TM imagery. The ice stream marginal moraines differ from the ice stream bedforms in a number of ways. Firstly, they are far longer than the largest ice stream bedforms. For example, the southern-most moraine, shown in figure 10, is over 23 km in length. In addition, the ice stream marginal moraines maintain a fairly constant width of around 500-800 m along their length. This is in contrast to the ice stream bedforms which usually taper in the downstream direction. Furthermore, unlike the ice stream bedforms which are usually straight, the ice stream marginal moraines display a degree of sinuosity. Finally, the relief of these ridges tends to be higher than the adjacent bedforms. This is shown by a transect across the ridge which indicate elevations which are typically 10 to 40 m above the surrounding terrain. The identification of these ice stream marginal moraines represents a fifth geomorphological criteria for ice stream activity.

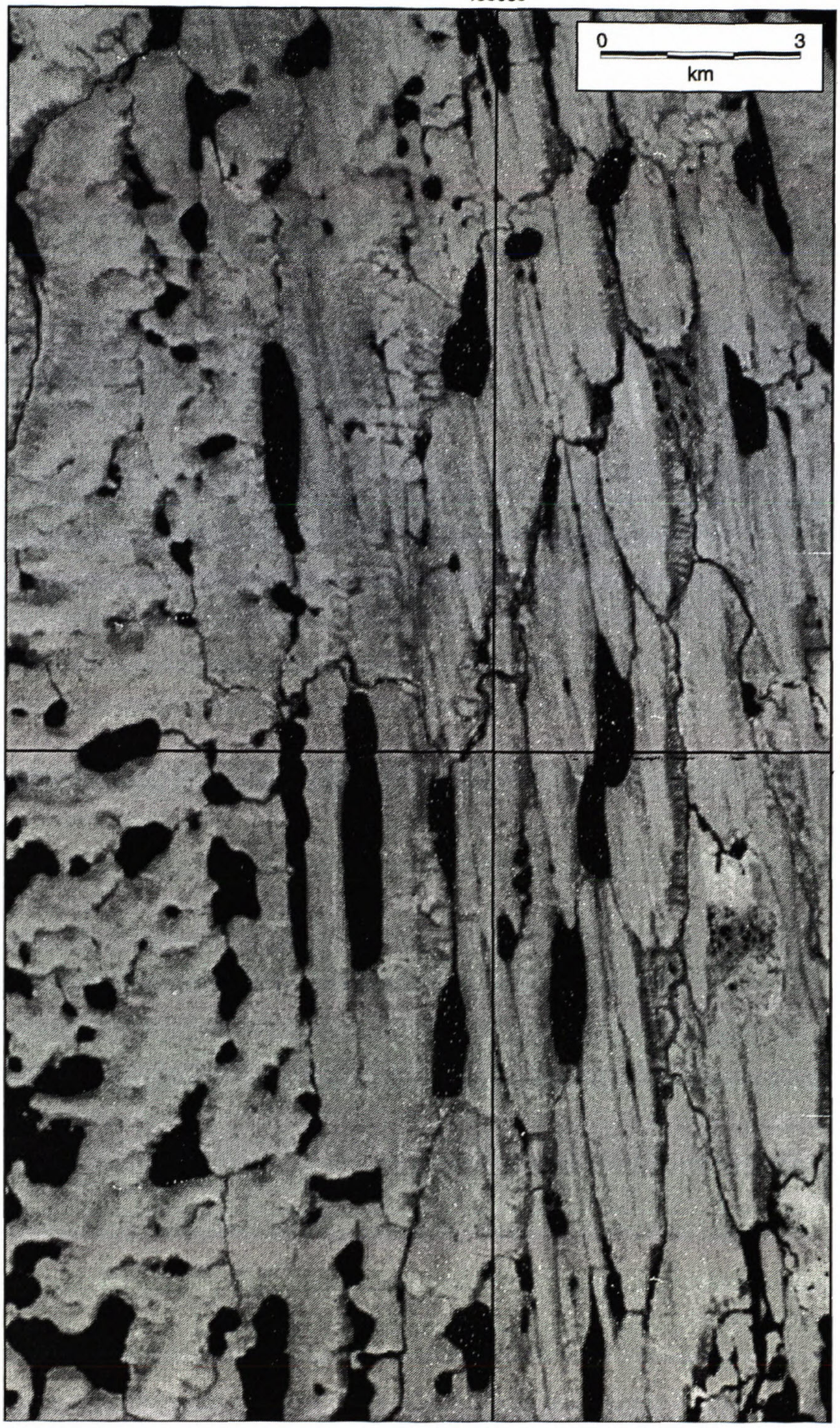

Fig. 9 Landsat TM image (band 5) of the abrupt margin of the ice stream flow-set. The location of this figure is shown on figure 6a.

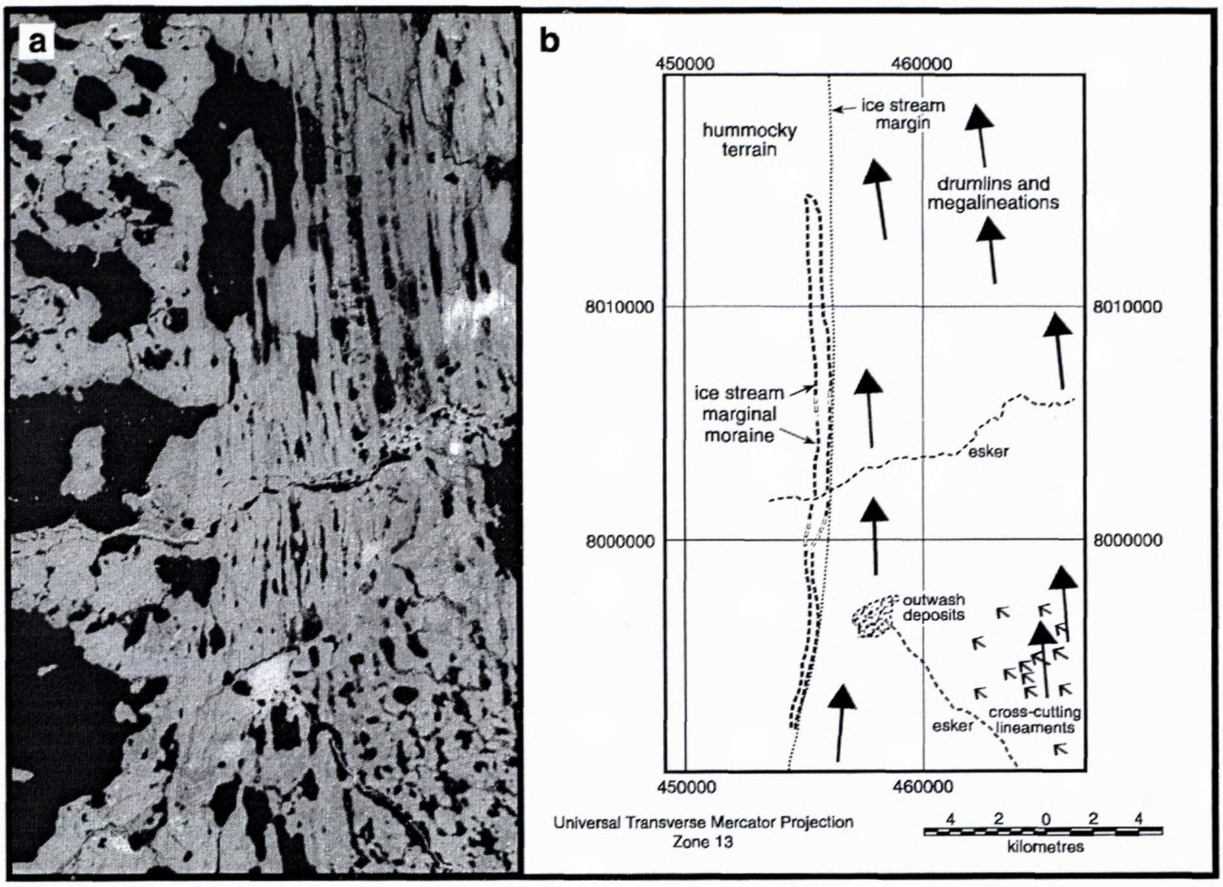

Fig. 10 Landsat TM image (band 5) of an ice stream marginal moraine on southern Storkerson Peninsula (a) and interpretation (b) (from Clark and Stokes, in press)

Of all of the criteria identifiable on satellite imagery, only the Boothia-type dispersal train is absent. The geology of the area is predominantly 'soft' carbonate sediments with only around 4% exotic lithologies incorporated from the Canadian Shield. An erratic dispersal plume was not produced because the carbonate sediments are pervasive throughout the whole region, underlying both the ice stream bed and the areas outside its margins.

Evidence of pervasively deformed till and offshore sediment accumulations may not be absent, but rather, it is suggested that they haven't been identified yet. Further investigations regarding the basal functioning of this ice stream (Clark and Stokes, in press) suggest that it may have operated by deforming the soft sediments under high pore water pressures. From his field investigations, Hodgson (1994) also commented that the ice stream „deformed and eroded a widespread cover of till". If this is the case, then a sixth criteria for ice stream activity may be identified from field evidence regarding the deformation history of the ice stream sediments. In addition, it is predicted that this deforming bed mechanism would have delivered huge amounts of sediment to the grounding line of the ice stream and that offshore sediment accumulations in Viscount Melville Sound may be present. It is noted that a distinctive sediment bulge has been identified on the continental margin at the mouth of M'Clure Strait (Zarkhidze *et al.*, 1991) and this may fulfil a possible seventh criteria for ice stream activity. Detailed examination of the architecture of this sediment fan will provide a first order test of the hypotheses regarding the ice stream flow mechanisms and sediment flux.

In summary, the M'Clintock Channel Ice Stream displays at least five (and possibly seven) out of a possible eight criteria thought to be indicative of ice stream activity. It is thus concluded that the M'Clintock Channel ice stream is one of the securest palaeo-ice stream locations ever identified. This ice stream was a considerable size and undoubtedly imparted a significant impact on the dynamics of the Laurentide Ice Sheet during deglaciation. Moreover, its bedform record is remarkably well preserved and presents an unprecedented opportunity to glean information about its basal processes and functioning. The bedform signature is described in more detail in Clark and Stokes (*in press*) where implications for ice stream operation and sediment fluxes are explored and its ice sheet wide significance is discussed.

4.2. The Dubawnt Lake Ice Stream.

Many investigations concerning the Keewatin Sector of the Laurentide Ice Sheet, west of Hudson Bay, have identified and mapped a distinct flow pattern approximately parallel to the northern shores of Dubawnt Lake and trending in a north-westerly direction (see for example,

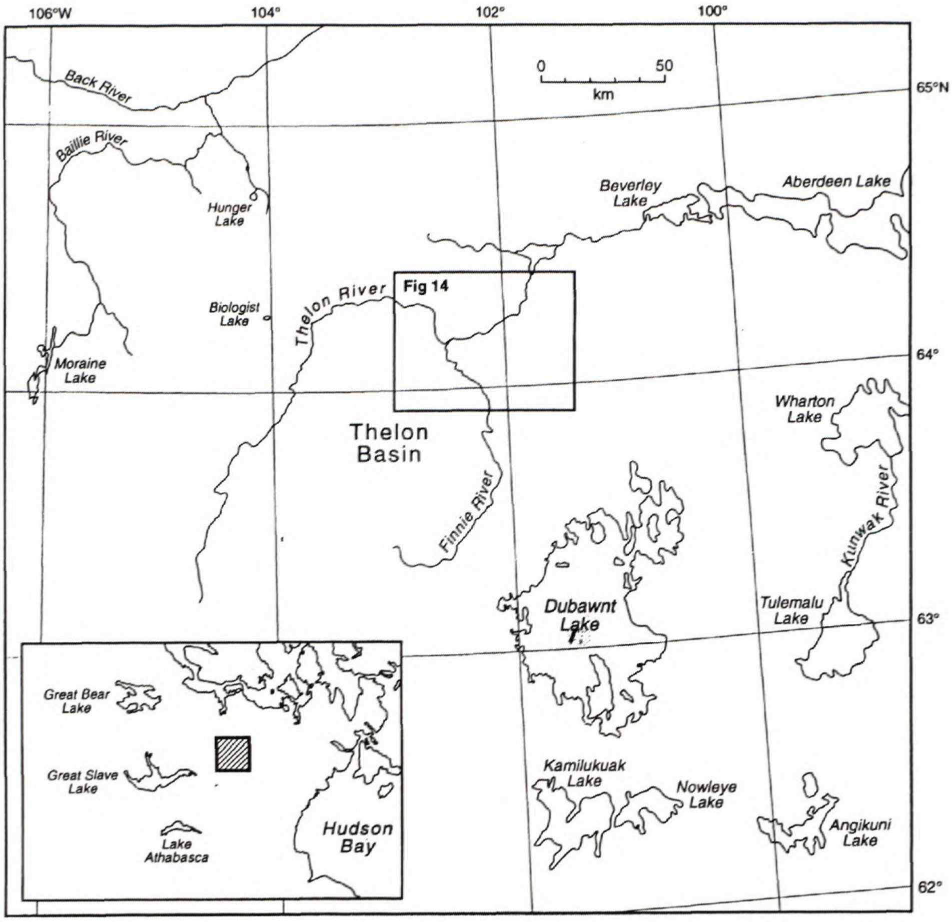

Fig. 11 Location map of the study area covered by the Keewatin sector of the Laurentide Ice Sheet.

Bird 1953; Lee, 1959; Shilts *et al.*, 1979; Aylsworth and Shilts, 1989). This highly convergent flow-set is also represented on the Glacial Map of Canada (see Prest *et al.*, 1968). Bird (1953) was the first to note the unique nature of the drumlins in the area which totally control the shape of the lakes and the pattern of stream drainage. Indeed, this spectacular fluting led Aylsworth and Shilts (1989) to speculate on the possible role of ice streaming in shaping the drumlins but they refused to postulate on the exact location of an ice stream.

To investigate this flow-set as a potential candidate for a palaeo-ice stream track, fifteen Landsat MSS positives (band 4) were obtained and developed into 1 : 250,000 hard copy photographs. This produced a complete coverage of the study area, which is shown in figure 11. Figure 12 shows the preliminary mapping of flow patterns from this area, which is totally dominated by the Dubawnt Lake flow-set, trending from the south-east to the north-west. Cross-cutting relationships with other flow-sets indicate that this flow-set is the youngest in the area. It was almost certainly fed by the Keewatin Ice Divide which migrated to its final position between 11 and 8.4 ka (Dyke and Dredge, 1989).

To investigate the Dubawnt Lake flow-set in detail and assess its validity as an ice stream track, three adjoining digital Landsat MSS images were obtained for half of the flow-set. This allowed a more refined mapping approach and the measurement of bedform characteristics. Figure 13 shows the coverage of the digital imagery and all of the lineations detected. It can be seen from Figures 12 and 13, that the ice stream flow-set is large enough to be considered an ice stream and displays a characteristically convergent onset zone. Unlike the marine-based M'Clintock Channel Ice Stream, this ice stream had no way of effectively removing ice. A result of this, was a lobate margin characterised by divergent ice flow at the terminus (see figures 12 and 13). The maximum length of the flow-set is 450 km and the width varies from 140 km at its narrowest point to over 190 km at the terminus.

It can be seen from the lineation map (figure 13) that the southern margin to the flow-set is extremely abrupt (<1 km). Outside of this margin, bedforms are scarce, but do occur further south displaying a variety of contrasting orientations, presumably from older ice flows. The abrupt ice stream margin does not coincide with a change in geology or topography. Rather, the Thelon Sedimentary basin actually traverses the margin, and it is inferred that it did not exert an influence on the width of this ice stream. Instead, it is argued that ice velocity was the only controlling factor on the position of the abrupt margin, which fulfils a third criteria for ice stream activity. The northern margin is far more difficult to define because older flow-sets have been cross-cut, with only subtle variations in orientation, see figure 12.

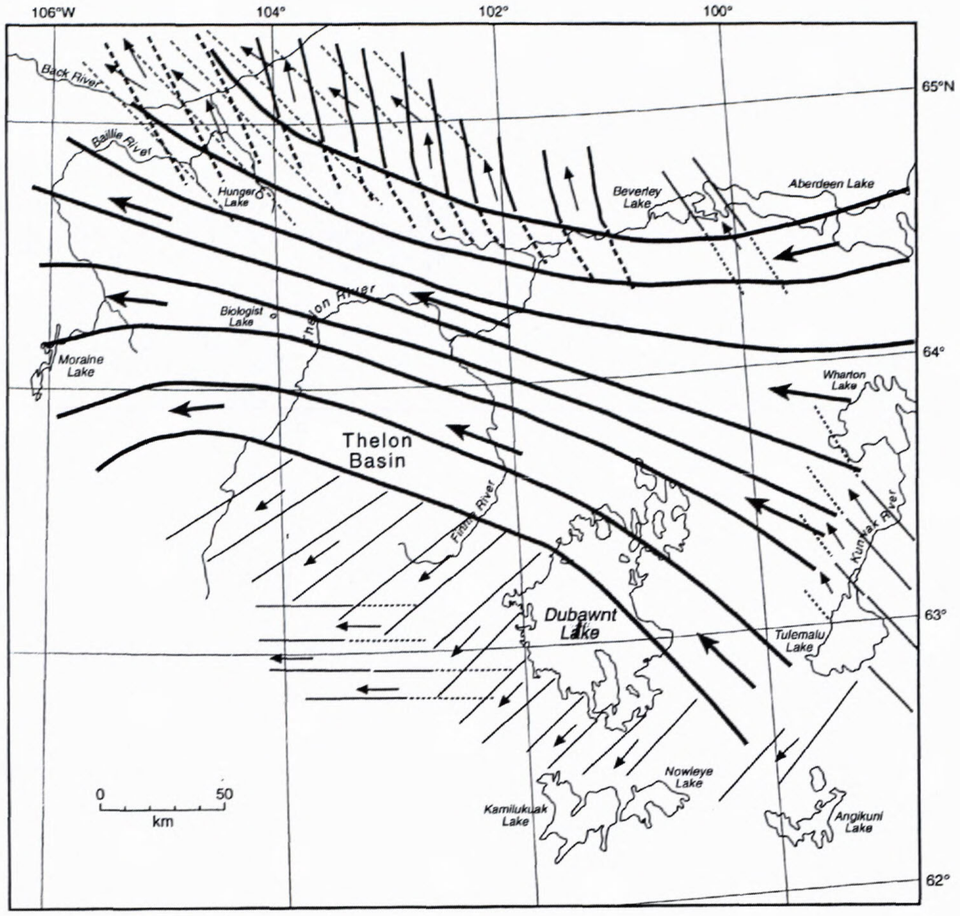

Fig. 12 Flow patterns identified on the Landsat MSS imagery. Note that the Dubawnt Lake Ice Stream (bold) dominates the regional pattern of flow.

The Dubawnt Lake flow-set meets the three criteria characteristic of an ice stream flow-set. It has the characteristic shape and dimensions, exhibits a highly convergent onset zone, and has an abrupt lateral margin.

Like the M'Clintock Channel Ice Stream imprint, it is inferred that the Dubawnt Lake ice stream record was isochronously generated. In figure 13 the lineations depict a remarkably coherent pattern, despite the convergence in the onset zone and divergence at the terminus. For the central portion of the ice stream the remarkable parallel conformity between individual lineations is so strong, that the bedform orientations only deviate by 5° along a flow-band 40 km wide and 220 km long. In addition, there are no within-stream cross-cutting relationships but rather, spatial variations in lineament morphometry are gradual. This suggests that the flow-set was generated rapidly, and was not modified during deglaciation. A result of this, is an isochronous bedform pattern which largely resembles the conceptual model outlined in figure 2.

The ice stream bedforms are exceptionally attenuated. The maximum length of the bedforms reach over 12 km in length and elongation ratios are as high as 48:1. The high parallel conformity of these drumlins and their extreme attenuation resembles a ridge/groove pattern on the satellite imagery. This is shown in figure 14 which shows lineations from a central portion of the ice stream north-west of Dubawnt Lake. These highly attenuated bedforms fulfil a fourth criteria for ice stream activity.

It is argued that these four criteria of the ice stream flow-set; characteristic shape and dimensions; highly convergent onset zone; abrupt lateral margin and highly attenuated bedforms, provide substantial evidence to invoke ice stream activity. Of the other possible criteria, there is no evidence of ice stream marginal moraines, or, Boothia-type dispersal plumes. The availability of soft sediments on the Canadian Shield is sporadic, and although major Dubawnt-type dispersal trains have been found to trend towards Hudson Bay (cf. Shilts *et al.*, 1979), Boothia-type dispersal trains are absent throughout the area. It may also be the case that ice stream marginal moraines rely on large supplies of soft sediments and the coarse grained lithology of the Dubawnt region may not be conducive to their development. Likewise, the underlying geology is unlikely to have facilitated a deforming bed mechanism for fast ice flow and pervasively deformed till is not an expected criteria.

In summary, the Dubawnt lake ice stream displays four out of a possible seven criteria for a terrestrially terminating ice stream. It has the characteristics shape and dimensions, exhibits a highly convergent onset zone and is characterised by a very abrupt lateral margin. In addition, the ice stream bedforms are some of the longest ever identified in the literature. The high parallel conformity of

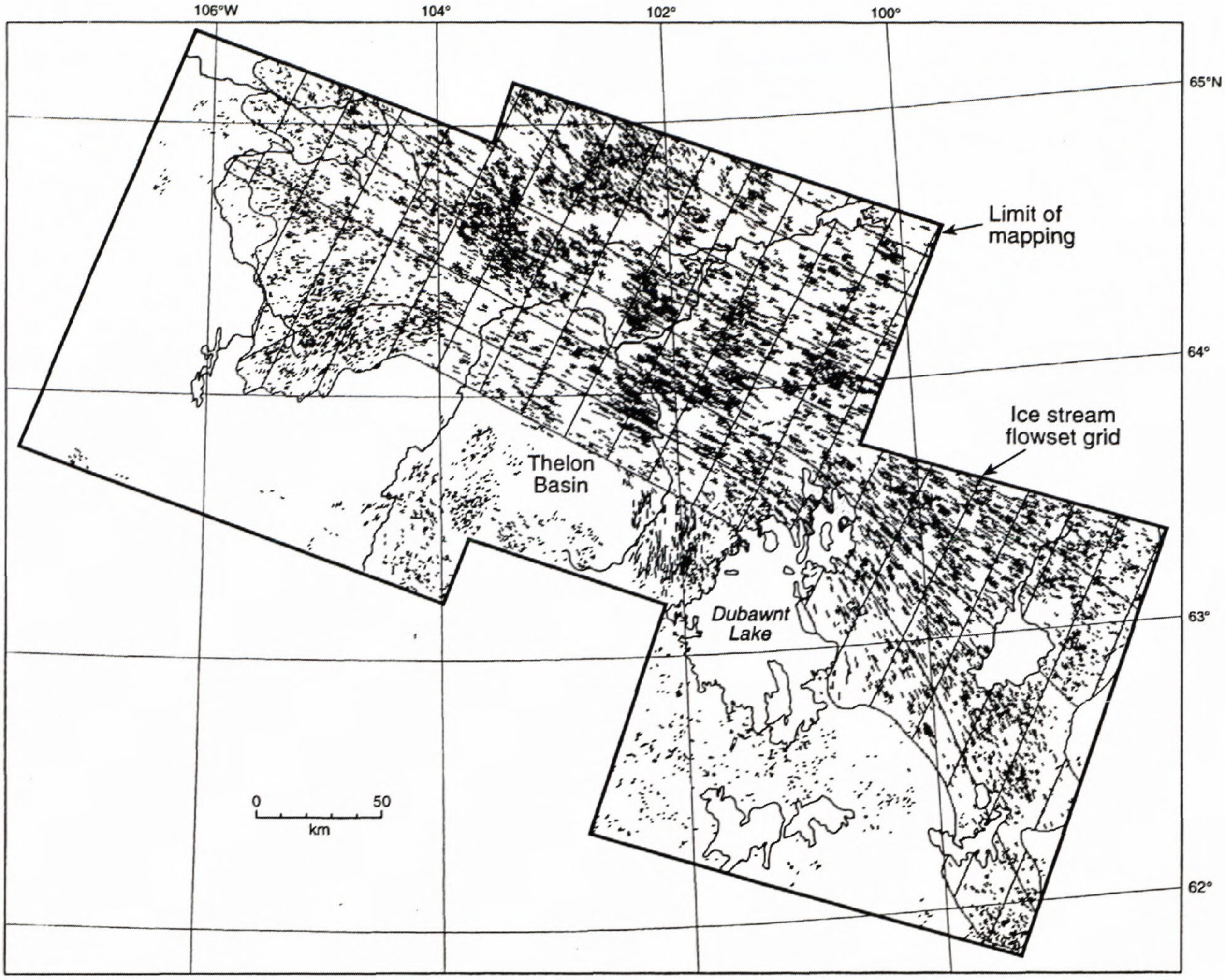

Fig. 13 Lineation map produced from three digital Landsat MSS images of the Dubawnt Lake Ice Streams.

the bedforms and the lack of cross-cutting relationships within the flow-set indicate an isochronous bedform generation. It thus represents a snapshot view of the bed, prior to ice stream shutdown. Ongoing work suggests that the well preserved bedform pattern is a useful proxy for ice velocity and may provide several insights as to the functioning of the ice stream. The ice stream probably had a significant impact on the last remnants of the Laurentide Ice Sheet west of Hudson Bay, possibly obliterating the Keewatin Ice Divide. Whether this ice stream activity was linked to that of the M'Clintock Channel Ice Stream further north and was part of a pan-ice sheet destabilisation during deglaciation is a question that deserves attention.

6. Summary and Conclusions.

Finding palaeo-ice stream locations enhances our understanding of Quaternary ice sheet dynamics and many workers have hypothesised their locations from a number of former ice sheets. Traditionally, this work has been hampered by a lack of understanding regarding the geomorphological products of ice streams, and many palaeo-ice stream hypotheses have evaded detailed scrutiny. Stokes and Clark (1999) addressed this problem by predicting diagnostic geomorphological criteria for identifying palaeo-ice streams. These criteria can be grouped into an ice stream landsystem which provides an observational template of a former ice stream signature. The identification of this landsystem requires a synoptic view of the ice sheet bed, something which is provided relatively cheaply by satellite imagery. Moreover, satellite imagery allows a single user to efficiently map geomorphology over relatively large areas very quickly. This is advantageous over field-work and aerial photograph mapping which are generally more expensive, more time-consuming and introduce a scale dependent bias.

This paper demonstrates the applicability of satellite remote sensing for identifying the diagnostic geomorphological products of palaeo-ice streams. Using the geomorphological criteria predicted by Stokes and Clark (1999) as a basis, satellite remote sensing has been used to;

- validate the location of an already hypothesised marine-based ice stream in the M'Clintock Channel, which drained the north-western margin of the Laurentide Ice Sheet between 11 and 10 ka BP.

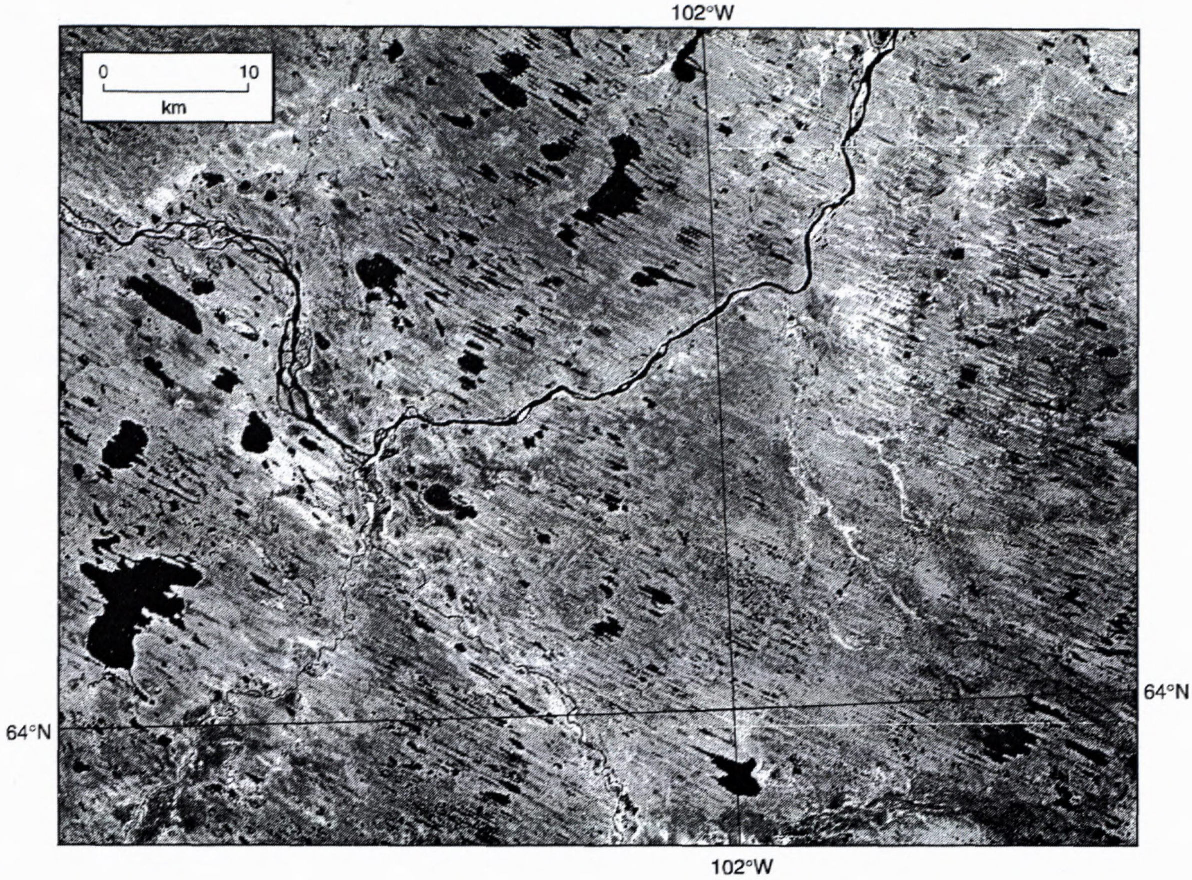

Fig. 14 Landsat MSS image of typical lineations inscribed by the Dubawnt Lake Ice Stream. The exceptional length and parallel conformity give the landscape a ridge/groove structure when viewed at this scale. The location of this figure is shown on figure 11.

- find a hitherto undetected terrestrially terminating ice stream which drained the last remnants of the Keewatin sector of the Laurentide Ice Sheet between 11 and 8.4 ka BP.

It is anticipated that this paper will go some way in helping the objective identification of ice streams from formerly glaciated areas. This will provide an enhanced understanding of Quaternary Ice Sheet dynamics which will begin to unravel the enigmatic nature of ice stream behaviour in both contemporary and Quaternary Ice Sheets.

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