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Résumé de l'article

Les courants glaciaires ont eu une influence déterminante sur la configuration et la stabilité de l'Inlandsis Laurentidien. Leur identification est cruciale pour la compréhension du comportement de la calotte glaciaire et l'intensification récente de la recherche sur les courants paléoglaciaires témoigne de leur importance. Dans cet article, nous présentons une vue d'ensemble des courants paléoglaciaires de l'Inlandsis Laurentidien, compilée à partir de la revue des sources publiées et de notre cartographie établie à l'aide d'imagerie satellite et de photographies aériennes. En tout, nous avons étudié 49 hypothèses de courants glaciaires. Nous les avons classées selon l'importance du témoignage de leur écoulement et la connaissance que nous avons de leur extension. Nous proposons une carte des courants paléoglaciaires laurentidiens ainsi que des tableaux décrivant la nature de la preuve permettant d'établir le comportement de l'écoulement. La répartition des courants glaciaires montre l'organisation spatiale d'un écoulement glaciaire rapide et le chevauchement des empreintes traduit les changements de l'écoulement durant son retrait. Nous notons que la taille des courants paléoglaciaires laurentidiens est plus importante que celle des courants glaciaires actuels de l'Antarctique.

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ICE STREAMS OF THE LAURENTIDE ICE SHEET

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ABSTRACT Ice streams had a major influence on the configuration and the stability of the Laurentide Ice Sheet. Their identification is crucial for an understanding of ice sheet behaviour and their importance is reflected by the recent increase in paleo-ice stream research. This paper provides a synopsis of Laurentide paleo-ice streams, compiled from published sources and our mapping from satellite imagery and aerial photography. In total, 49 hypothesised ice streams are reviewed, and categorised according to the strength of evidence for streaming and knowledge of their extent. A map of Laurentide paleo-ice streams is presented, along with tables documenting the nature of evidence on which streaming behaviour has been invoked. The distribution of ice streams demonstrates the spatial organisation of fast ice flow, and overlapping imprints document major changes in ice flow during retreat. We note that Laurentide paleo-ice streams exhibit a much greater range in size than those currently operating in Antarctica.

RÉSUMÉ Les courants glaciaires ont eu une influence déterminante sur la configuration et la stabilité de l'Inlandsis Laurentidien. Leur identification est cruciale pour la compréhension du comportement de la calotte glaciaire et l'intensification récente de la recherche sur les courants paléoglaciaires témoigne de leur importance. Dans cet article, nous présentons une vue d'ensemble des courants paléoglaciaires de l'Inlandsis Laurentidien, compilée à partir de la revue des sources publiées et de notre cartographie établie à l'aide d'imagerie satellite et de photographies aériennes. En tout, nous avons étudié 49 hypothèses de courants glaciaires. Nous les avons classées selon l'importance du témoignage de leur écoulement et la connaissance que nous avons de leur extension. Nous proposons une carte des courants paléoglaciaires laurentidiens ainsi que des tableaux décrivant la nature de la preuve permettant d'établir le comportement de l'écoulement. La répartition des courants glaciaires montre l'organisation spatiale d'un écoulement glaciaire rapide et le chevauchement des empreintes traduit les changements de l'écoulement durant son retrait. Nous notons que la taille des courants paléoglaciaires laurentidiens est plus importante que celle des courants glaciaires actuels de l'Antarctique.

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INTRODUCTION

The Laurentide Ice Sheet (LIS) was a fundamental influence on global climate during the Late Wisconsinan and therefore requires accurate representation in paleoenvironmental reconstructions and models. The extent, retreat pattern and gross flow geometry are relatively well constrained (Prest *et al.*, 1968; Dyke and Prest, 1987; Dyke *et al.*, 2003), but details of the flow dynamics are less well understood. A key component of the flow dynamics are ice streams (Clark, 1994; Andrews and Maclean, 2003) and it is essential to determine their location and timing. Once identified, their location is a valuable tool for assessing the success of numerical models which seek to reproduce changes in ice sheet configuration and the location of fast ice flow. Conversely, the location of ice streams can be used to tune models that require parameterisation of basal boundary conditions. Discovery of paleo-ice streams also provides clues to where major iceberg export events occurred, which has important implications for ocean circulation and paleoclimate (Andrews and Tedesco, 1992; Stokes *et al.*, 2005). The aim of this synopsis is to provide an up-to-date map of paleo-ice streams in the Laurentide Ice Sheet, based on published sources where authors have suggested streaming and a concerted mapping campaign, by the authors, using satellite images and aerial photography. We do not regard the map as a definitive inventory, however, it is the most comprehensive compilation to date and should provide a useful reference, resource and stimulus, for future research.

COMPILATION OF PALEO-ICE STREAMS OF THE LAURENTIDE ICE SHEET

The flow geometry and pattern of glaciation of the Laurentide Ice Sheet was reported in the Glacial Map of Canada (Prest *et al.*, 1968). Many of the flow patterns that we now recognise as paleo-ice streams, and report in this paper, are visible on the Glacial Map of Canada, but their significance was not understood at this time. The first attempt at an overview of ice streams of the LIS was undertaken by Denton and Hughes (1981) who depicted numerous ice streams, most of which correlated with topographic troughs. Their map was somewhat speculative, but was vital in recognising the importance of ice streams. More recent overviews (Patterson, 1998; Stokes and Clark, 2001) portray between 10 and 15 ice streams of the LIS, but the last few years have seen a considerable increase in paleo-ice stream research and in the number of hypothesised ice streams in the published literature (see special issue of Boreas, vol. 32, 2003 for example).

Different approaches have been used to identify and confirm the location of paleo-ice streams (see Stokes and Clark, 2001 for a review); ranging from field-based investigations of subglacial sediments (Hicock, 1988), to large scale mapping of ice sheet flow patterns (De Angelis and Kleman, in press). A wide variety of evidence has been cited as indicative of ice streaming and recently we have seen the development of 'diagnostic' sedimentological (Lian *et al.*, 2003) and geomorphological criteria for identifying ice streams (Stokes and Clark, 1999). Collectively, these criteria can be grouped into a formal 'ice stream landsystem' (Clark and Stokes, 2003) which provides an observational template for identifying ice stream 'footprints' on a former ice sheet bed.

Contemporary ice streams are defined as 'regions in a grounded ice sheet in which the ice flows much faster than in the regions on either side' (Paterson, 1994: p. 301). It therefore follows that to reliably identify a paleo-ice stream requires: (1) evidence for a discrete pattern and (2) some indication of fast flow within this. Geomorphological or geological evidence can define a pattern, distinct from its surroundings, and then further evidence is required to indicate fast flow velocities within this zone. We thus regard that a pattern defined by a drumlin field, for example, is insufficient to define an ice stream unless there is other evidence for fast ice flow. This could be sedimentological indications of fast flow, or a particular erratic dispersal pattern or a systematic pattern of drumlin elongation. Conversely, whilst sedimentological fieldwork at a location might suggest fast ice flow, until we can demonstrate that such flow is a spatially-discrete unit, it is in our view, premature to define an ice stream in this location. Returning to contemporary ice streams, we note that their defining characteristic is not some threshold velocity defining fast flow, but that relatively faster flow velocities are organised into discrete arteries.

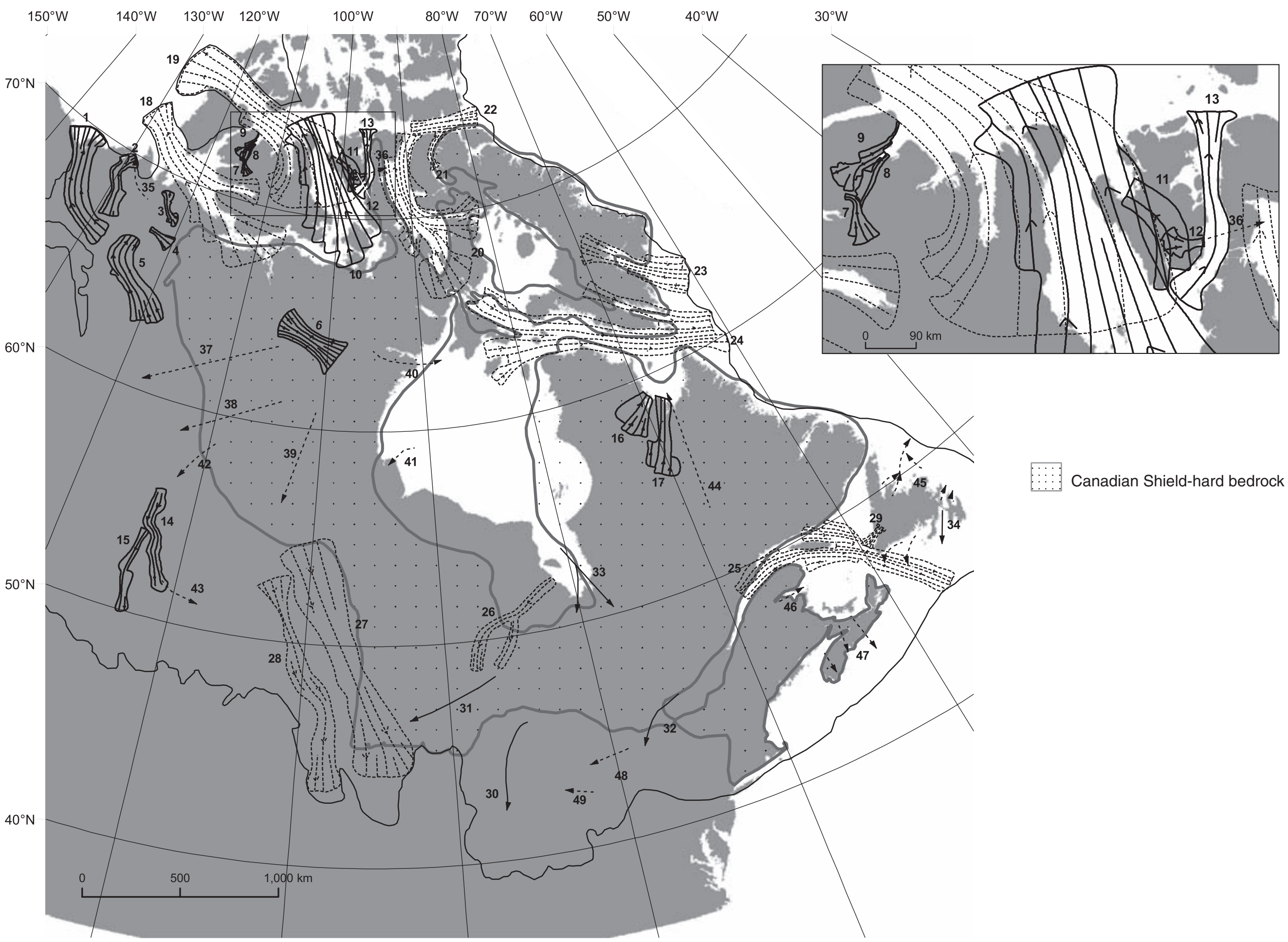
CATEGORISING PALEO-ICE STREAMS OF THE LAURENTIDE ICE SHEET

The paleo-ice stream map is shown in Figure 1. Strong evidence has been found for 34 ice streams, with a further 15 less certain. Further information on the ice streams in Figure 1 is provided in Table I-IV in Appendix, including the nature of evidence on which streaming has been inferred, the key references and, where known, the dates during which streaming

→

Figure 1. The inventory of paleo-ice streams reviewed in this paper. Ice streams are numbered and further details on each are given in Tables I-IV. Ice streams in bold have good geomorphic evidence for their margins and extent, whilst those with dashed outlines have poorly defined margins, but it is reasonable to infer extent based on topographic setting. Bold arrows represent locations where there is clear evidence for streaming, but the extent of the ice streaming is unknown. Dashed arrows indicate locations where streaming has been hypothesised but in our view further supporting evidence is required. Ice sheet extent at 18 ka is shown by the solid black line (modified from Dyke *et al.*, 2003). The inset map shows the ice streams on Victoria Island and Prince of Wales Island in more detail, the location of this is indicated by the box on the main map.

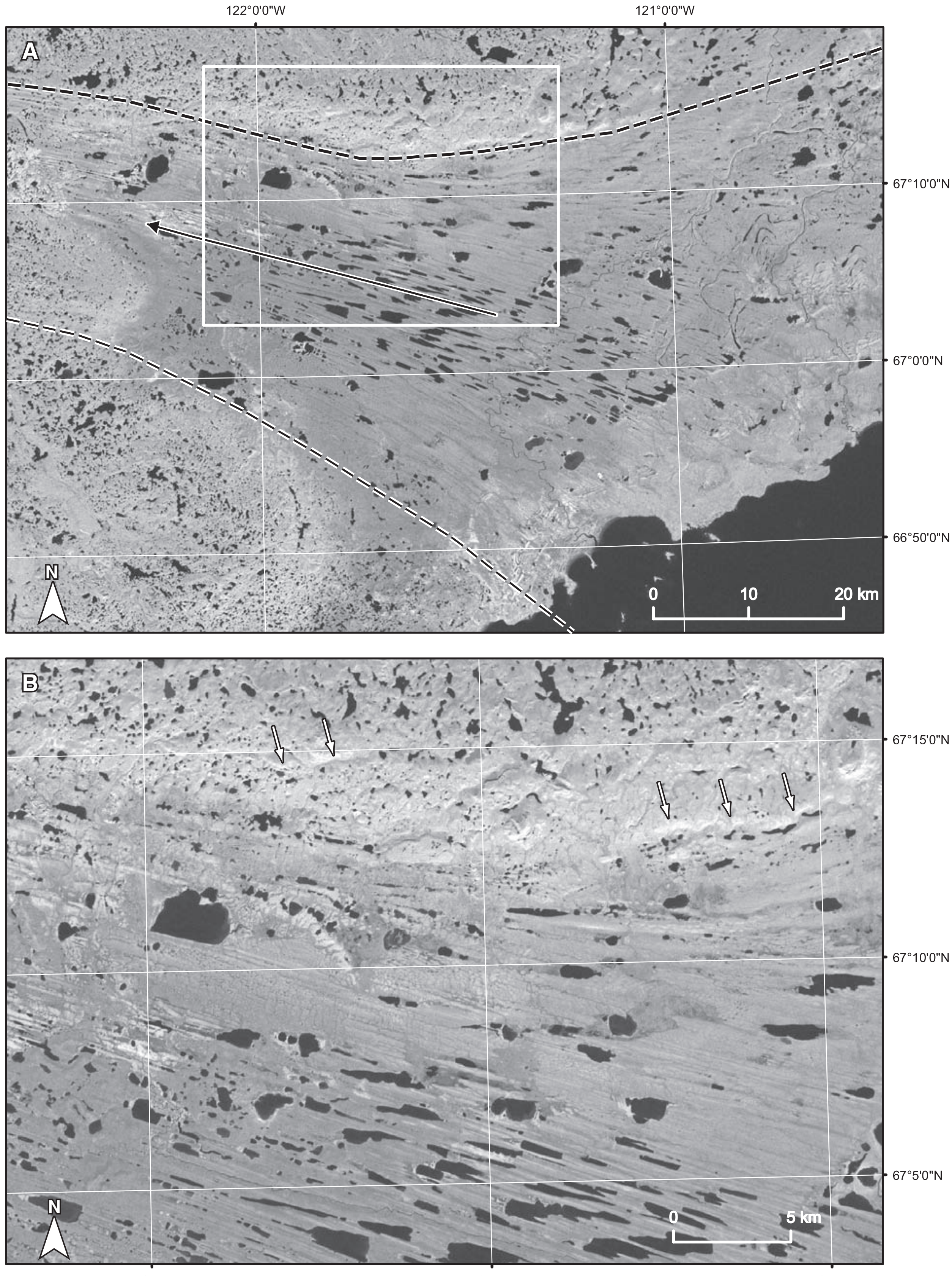
Inventaire des courants paléoglaciaires examinés dans cet article. Les courants glaciaires sont numérotés et des détails supplémentaires sur chacun d'eux se trouvent dans les tableaux I à IV. Les courants glaciaires en gras présentent une bonne preuve géomorphique de leurs bordures et de leur extension; ceux aux contours en pointillé présentent des bordures mal définies, mais il est raisonnable de déduire leur extension sur la base de la topographie. Les flèches en gras représentent les emplacements où il existe une preuve évidente d'écoulement mais dont l'extension n'est pas connue. Les flèches en pointillé indiquent des emplacements pour lesquels nous avons fait l'hypothèse d'un écoulement, mais, à notre point de vue, des preuves supplémentaires s'avèrent nécessaires. La ligne noire épaisse (modifiée d'après Dyke et al.*, 2003) détermine l'extension de l'inlandsis, il y a 18 000 ans. L'encart montre le détail des courants glaciaires sur l'Île de Victoria et l'Île du Prince-de-Galles; l'encadré sur la carte principale en indique l'emplacement.*



occurred. We categorised the ice streams according to our confidence in the evidence used to invoke streaming, and the current availability of data on their location and extent. This was a difficult task and we acknowledge that it introduces some subjectivity, but we felt it necessary given that some paleo-ice streams are well-established and robust, but for others there are only hints that fast flow existed. For example, some paleo-ice streams have excellent imprints with well defined trunks and onset zones, mega-scale glacial lineations recording fast ice flow and clear shear margin moraines (*e.g.* Haldane Ice Stream in Fig. 2). In contrast, paleo-ice streams have been hypothesised in the absence of supporting geomorphic or sedimentary evidence, for example those suggested by Denton and Hughes (1981) along the western margins of the ice sheet (#37-39 in Fig. 1). To differentiate between such a range of paleo-ice streams they were categorised as: (1) Paleo-ice streams for which there is strong evidence and a well defined footprint; (2) Paleo-ice streams for which there is strong evidence and their extent can be inferred based on topography; (3) Paleo-ice streams for which evidence exists but their extent remains undefined, and (4) Ice streaming has been hypothesised but more evidence is needed to confirm this.

Many of the readily identifiable paleo-ice stream imprints are along the northern margins of the ice sheet (Fig. 1), whilst those along the southern margin tend to have a more smudged record which is often difficult to unravel. This may reflect the more dynamic nature of the southern margin, which is thought to be characterised by episodic advance and retreat (Mickelson and Colgan, 2003), leaving a geomorphic and sedimentary record which is a composite of multiple events. In concert with Jennings (2006) we contend that ice streaming played a dominant role in controlling the southern margin fluctuations, and anticipate that further paleo-ice streams will be identified here.

The distribution of paleo-ice streams provides a valuable tool for assessing the controls on fast ice flow within ice sheets. The marine troughs along the northern and eastern margins of the LIS are intuitive locations for fast flow, given topographic focusing of ice and the presence of a marine calving front. In total, ten ice streams are found in such locations, but it is interesting to note that ice streaming is by no means restricted to these situations. Fourteen ice streams have neither a calving margin nor a topographically constrained location. Ice streaming is also reported on the hard bed geology of the Canadian Shield (*e.g.* Dubawnt Lake number 6 in Figure 1 and Appendix), Albany Bay (#26) and Ungava Bay (#16-17). These examples demonstrate that fast flow is not solely restricted to topographic troughs, calving bays or areas of soft deformable sediments.


122°0'0"W
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A
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66°50'0"N
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B
67°15'0"N
67°10'0"N
67°5'0"N
N
0 5 km
122°0'0"W
121°40'0"W
121°20'0"W

FIGURE 2. Landsat satellite image of the Haldane Ice Stream (#4 on Figure 1), an extremely well defined paleo-ice stream imprint. (A) shows ice stream extent with abrupt lateral margins (dashed black) displaying a characteristic broad onset zone converging into a narrow trunk. Direction of flow is indicated by the arrow. (B) is an enlargement of the boxed area in (A) and demonstrates many of the characteristic geomorphic features used to identify paleo-ice streams. In the very north of the image there is hummocky terrain outside the ice stream margin and below this a transition to the streaming area, marked by a suite of shear margin moraines (two examples are indicated by the white arrows). The ice stream bed is much smoother and is characterised by mega-scale glacial lineations and associated streamlined bedforms. These are highly elongate (with length:width well in excess of 10:1) and show a high degree of parallel conformity.

Une empreinte très bien définie de courant paléoglaciaire : l'image satellite Landsat du courant glaciaire Haldane (#4 sur la Figure 1). (A) montre l'extension du courant glaciaire avec des bordures latérales abruptes (pointillé blanc) affichant une zone caractéristique, large à son début, convergeant en un tronc étroit. Une flèche indique la direction de l'écoulement. (B) est un agrandissement de l'aire encadrée en (A) et révèle beaucoup des traits caractéristiques géomorphiques utilisés pour identifier les courants paléoglaciaires. À l'extrême nord de cette image, un terrain accidenté délimite la bordure externe du courant glaciaire. En dessous, une suite de moraines de bordure de cisaillement souligne une transition vers l'aire d'écoulement. Le lit du courant glaciaire est beaucoup plus lisse; il est caractérisé par des lignes de coulées glaciaires à grande échelle et est associé à des formes de lit dans le sens de l'écoulement. Celles-ci sont excessivement allongées (avec un rapport de longueur/largeur supérieur à 10) et présentent un parallélisme important.

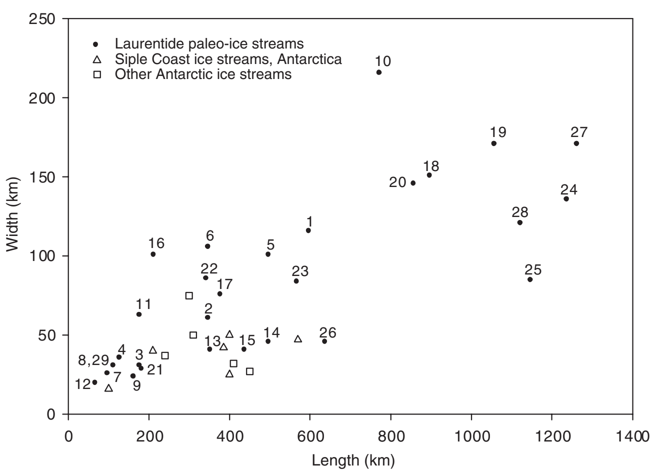

FIGURE 3. Comparison of the dimensions of Laurentide paleo-ice streams with contemporary Antarctic ice streams, demonstrating the much larger variation in length and width of the Laurentide paleo-ice streams. All Laurentide paleo-ice streams whose dimensions are known are included and numbered as in Figure 1. Antarctic examples used are as follows: Lambert Glacier, Bailey Ice Stream, Recovery Glacier, Rutford Ice Stream, Blackwall Ice Stream, and the five Siple Coast ice streams. Dimensions of Antarctic ice streams were measured from the RAMP SAR imagery produced by Jezek and RAMP product team (2002).

Comparaison des dimensions des courants paléoglaciaires laurentidiens avec celles des courants glaciaires contemporains de l'Antarctique; les courants laurentidiens témoignent de plus grandes variations en longueur et en largeur. Cette figure comprend tous les courants paléoglaciaires laurentidiens aux dimensions connues et sont numérotés comme dans la Figure 1. Les exemples antarctiques sont les suivants : glacier de Lambert, coulée de Bailey, glacier de Recovery, coulée de Rutford, coulée de Blackwall et les cinq courants glaciaires de la Côte Siple. Nous avons mesuré les courants glaciaires antarctiques à partir de l'imagerie RAMP SAR élaborée par Jezek et l'équipe de produits de RAMP (2002).

Other conditions must be capable of triggering and sustaining fast ice flow; possibilities include meltwater distribution and geothermal heat flux. Further research into potential controlling factors is needed and this map provides a useful sample of ice streams to test such theories.

The paleo-ice stream map also provides insights into the temporal controls on ice streaming and the interaction between neighbouring ice streams. For example, on Victoria Island and Prince of Wales Island at least three generations of ice streams are revealed by overlapping imprints, each having a different size, shape and flow direction (see inset in Figure 1). Of these, the oldest and largest is the M'Clure Strait Ice Stream (#19) which extended to the shelf edge at the LGM (Last Glacial Maximum). During retreat, the M'Clintock Channel hosted a second ice stream (#10) of slightly reduced dimensions. As retreat progressed, flow ceased in the marine channel and the Transition Bay Ice Stream (#12) flowed perpendicular to earlier events, calving along the east coast of Prince of Wales Island. This example clearly demonstrates the high degree of spatial and temporal variability of Laurentide ice streams and provides a useful context with which to compare the ongoing changes taking place in contemporary ice streams in West Antarctica (Conway *et al.*, 2002).

Finally, we note that Laurentide ice streams show a much wider range of dimensions than those currently operating in Antarctica (Fig. 3). Laurentide paleo-ice streams operating at the LGM are much larger than contemporary ice streams. During retreat, many ice streams are comparable in size to contemporary examples, but some exist below the size normally associated with streaming. This variability suggests that ice stream configurations are highly variable and that contemporary ice streams represent a relatively narrow part of the wider spectrum (Fig. 3).

CONCLUSIONS

This brief synopsis provides an up-to-date map (and associated information) on the location of known and hypothesised paleo-ice streams of the Laurentide Ice Sheet. It is compiled from previous overviews (Patterson, 1998; Stokes and Clark, 2001), a review of new published material, and synoptic mapping using satellite imagery and aerial photographs. In total, 49 hypothesised ice streams are reviewed and categorised according to the strength of evidence for streaming and knowledge of their extent. Ice streaming is found to be widespread and it is noted that several exist in areas not thought to be conducive to fast ice flow. The location of ice streams also reveals highly dynamic (perhaps unpredictable) interactions between neighbouring ice streams. The map provides a useful dataset to test theories concerning the spatial and temporal controls on streaming within ice sheets. The map should also assist in reconstructing and modelling the Laurentide Ice Sheet. Knowledge of ice stream location is valuable for testing numerical models and, alternatively, could be used as input data to parameterise areas of fast flow. In addition to discoveries of new ice streams, a crucial advance will be to improve the dating controls on ice streaming in order to gain a better understanding of the rates of change and duration of fast flow events.

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APPENDIX

TABLE I

Paleo-ice streams for which there is strong evidence and a well defined footprint

Ice stream	References	Nature of evidence	Timing
Mackenzie (1)	Clark (unpublished)	Mega-scale glacial lineations in a major topographic trough.	Unknown
Anderson (2)	Clark (unpublished)	Mega-scale glacial lineations form a coherent flow-set with abrupt lateral margins.	Unknown
Horton (3)	Clark (unpublished)	Mega-scale glacial lineations, characteristic flow-set shape and shear margin moraines.	Deglacial
Haldane (4)	Clark (unpublished)	Topography and bedforms indicate a convergent onset zone feeding the main trunk. Elongate bedforms create a coherent flow-set with abrupt lateral margins marked by a suite of shear margin moraines.	Deglacial
Great Bear (5)	Clark (unpublished)	Mega-scale glacial lineations and characteristic flow-set shape.	Deglacial
Dubawnt Lake (6)	Stokes and Clark (2003)	Well-preserved geomorphic record showing convergent onset zone, mega-scale glacial lineations and abrupt lateral margins. Lineations have a mean length of 1 808 m, a maximum of 12 743 m and a maximum length: width of 48:1. Spatial variation in bedform elongation matches expected velocity patterns, i.e. the most elongate bedforms are in the ice stream centre where velocities would have been highest.	9-8.2 ka
Saneraun Hills (7)	Stokes *et al.* (2005)	The relatively small flow-set (100 km length, 25 km width of trunk) displays a characteristic shape. Its imprint shows a coherent pattern of highly elongate drumlins (length:width greater than 10:1) with a convergent onset zone and abrupt lateral margins.	Younger than ice streams 8 and 9
Collinson (8)	Stokes *et al*. (2005)	Highly elongate drumlins with length:width greater than 10:1. These form a coherent flow-set with a convergent onset zone and abrupt lateral margins. At 97 km by 25 km this ice stream is unusually small.	Younger than ice stream 9, older than 7

TABLE I (continued)

Paleo-ice streams for which there is strong evidence and a well defined footprint

Ice stream	References	Nature of evidence	Timing
Flow set 76 (9)	Stokes *et al.* (2005)	Coherent flow-set of highly elongate drumlins (length:width greater than 10:1) and abrupt margins. This might be a different configuration of the Collinson Ice Stream.	Older than ice streams 7 and 8
M'Clintock Channel (10)	Hodgson (1994), Clark and Stokes (2001), De Angelis and Kleman (in press)	Convergent onset zone leading into main trunk centred in a marine trough. Mega-scale glacial lineations with a mean length:width of 8:1 and a maximum of 30:1. Abrupt lateral margins with associated shear margin moraines. Sharp contrast between smoothed ice stream bed and adjacent hummocky terrain.	10.4-10 ka, but likely operated only for 200 years.
Crooked Lake (11)	Dyke *et al.* (1992), Stokes *et al.* (2005), De Angelis and Kleman (in press)	Bedform flow-set with abrupt lateral margins and associated shear margin moraines. The Crooked Lake drumlin field is part of the ice stream footprint. There is some uncertainty as to whether this flow-set is a separate ice stream or a fragmentary record of a larger M'Clintock Channel Ice Stream.	Younger than ice streams 10 and 12.
Transition Bay (12)	Dyke and Morris (1988), Dyke *et al.* (1992), De Angelis and Kleman (in press), Stokes *et al.* (2005)	The imprint has a convergent onset leading into a trunk with highly elongate drumlins. Glacial lineations show a maximum length of 3 356 m and maximum length:width of 14:1. The flow-set has abrupt lateral margins marked by shear margin moraines. Variations in bedform elongation mimic expected ice velocity pattern. A Boothia-type erratic dispersal plume marks the ice stream location. Unusually small (76 km length, 20 km width of trunk).	Younger than ice stream 10, older than 11.
Peel Sound (13)	De Angelis and Kleman (in press)	Mulitbeam sonar survey data show streamlined glacial landforms on the sea floor, the size and morphology of which are indicative of streaming flow.	Unknown
Central Alberta Ice Stream (14)	Evans *et al.* (in review), Evans (2000)	Flutings and fluted ridges are observed within a corridor of smoothed topography. Bedforms show a spatial coherency in morphology and orientation and a splayed terminus. The corridor of smoothed topography has abrupt lateral margins with adjacent rough topography. Thin tills along the ice stream centreline suggest that basal sliding may have been more important than soft sediment deformation in sustaining fast ice flow.	Unknown
High Plains Ice Stream (15)	Evans *et al.* (in review), Evans (2000)	Glacial lineations within a corridor of smoothed topography. The lineations show similar orientation and morphology. The area of smoothed topography has abrupt lateral margins with adjacent rough topography.	Unknown
Ungava Bay fans (16, 17)	Jansson *et al.* (2003)-fans b and i, Clark *et al.* (2000)-flow sets 21 and 22	Complex suite of drumlins, mega-scale glacial lineations and flutes. Two ice stream footprints are identifiable by their highly elongate bedforms which form distinctive flow-sets These have abrupt lateral margins. Our own mapping reveals areas of exceptionally long and broad lineations over 100 km in length.	Unknown

TABLE II

Paleo-ice streams for which there is strong evidence and their extent can be inferred based on topography

Ice stream	References	Nature of evidence	Timing
Amundsen Gulf (18)	Stokes *et al.* (2006), Sharpe (1988)	Multiple flow-sets indicate several ice stream configurations in the marine channel. Mega-scale glacial lineations form several flow-sets with abrupt lateral margins and convergent onsets. These flow-sets are seen to enter Dolphin and Union Strait (including the Read Island drumlin field) and Amundsen Gulf from both SW Victoria Island and the mainland, all show orientation consistent with along channel flow. Bedforms on both sides of the marine channel show a strong similarity of elongation and orientation, with mean lengths of ~5 km and length:width of 10:1. Bathymetric data reveals a fan-shaped erosional footprint at Amundsen Gulf shelf edge and mega-scale glacial lineations in Amundsen Gulf.	LGM
M'Clure Strait (19)	Stokes *et al.* (2005), De Angelis and Kleman (in press)	Flow-sets of mega-scale glacial lineations with coherent morphology and orientation have been identified on Victoria Island and Prince of Wales Island. The main trunk of the ice stream is inferred based on the extent of the underlying marine channel. A large trough mouth fan exists at its terminus.	LGM
Gulf of Boothia (20)	Dredge (2000, 2001), Dyke and Dredge (1989), De Angelis and Kleman (in press)	A Boothia-type carbonate dispersal train on Melville Peninsula indicates a discrete zone of ice flowing over a soft carbonate till bed. This forms part of the onset of the ice stream. Carbonate dispersal trains are also noted on Boothia Peninsula, which may relate to the onset of streaming. Bedforms indicative of fast flow (mega-scale glacial lineations, elongate drumlins and flutes) form several flow-sets feeding into Committee Bay and north through the Gulf of Boothia. These provide robust evidence for the ice stream's onset and tributaries, the topography of the channel allows reconstruction of the main ice stream trunk. The very large area of convergent flow suggests that this was one of the main drainage routes of the Laurentide Ice Sheet. In Figure 1 the most conservative extent is shown, but convergent drumlins on King William Island may be associated with a larger onset.	Older than 9 ka
Admiralty Inlet (21)	De Angelis and Kleman (in press)	Multibeam sonar survey data show mega-scale glacial lineations forming a coherent flow-set along the floor of the sound. The size and morphology of these are indicative of fast ice flow. Topography of the channel is used to infer ice stream extent.	Unknown
Lancaster Sound (22)	De Angelis and Kleman (in press)	Multibeam sonar survey data show mega-scale glacial lineations on the floor of the sound. Channel topography determines ice stream extent.	Unknown
Cumberland Sound (23)	Jennings (1993), Kaplan *et al.* (1999, 2001)	Marine acoustic and core data from the Sound demonstrate that it was occupied by grounded ice, suggested to be an ice stream. Geomorphic mapping shows a shallow trim-line gradient consistent with low driving stresses as noted on contemporary ice streams. Numerical modelling results and cosmogenic nuclide dating support the geologic evidence of low gradient ice and low driving stresses. The presence of soft deforming sediment is favourable to ice streaming.	Unknown
Hudson Strait (24)	Laymon (1992), Marshall and Clark (1997), Dowdeswell *et al.* (1995), Andrews and MacLean (2003), Bond *et al.* (1992)	Ice-rafted debris (Heinrich layers) spread over a large portion of the North Atlantic is said to have originated from Hudson Strait, consistent with occupation by an ice stream. Estimates of sedimentation rate necessary to produce these Heinrich layers require high balance velocities (4-7.2 kma-1) indicative of streaming flow. Till lithology shows that very distant and wide ranging ice sources converged on Hudson Strait, consistent with occupation by an ice stream. Outcrops on islands in the mouth of Hudson Strait show striae indicating flow along the axis of the trough. Numerical ice sheet modelling indicates highly convergent ice flow within Hudson Strait. Seismic sections show large scale crag-and-tail features at the mouth of Hudson Strait. Thick accumulations of ice-contact sediments and meltwater channels on the shelf indicate that ice streaming extended to the shelf break.	Heinrich events associated with streaming date to ~20.5 ka and ~14.5 ka.

TABLE II (continued)

Paleo-ice streams for which there is strong evidence and their extent can be inferred based on topography

Ice stream	References	Nature of evidence	Timing
Gulf of St. Lawrence (25)	Occhietti (1989)	Till fabrics and striae indicate convergent ice flow down St. Lawrence Valley. Deep marine trough is highly suggestive of streaming flow. A calving bay in the Gulf of St. Lawrence would have been favourable to ice streaming.	LGM
Albany Bay (26)	Hicock (1988)	Thick deposits of far-travelled calcerous tills are found north of Lake Superior. These show an abundance of distal lithologies and minimal local erosion suggesting extending ice flow and low ice pressure, consistent with streaming. The high sediment flux, low rates of dilution of this sediment, and source area far to the north in the James Bay Lowlands are all consistent with streaming. A prominent trough is conducive to focused, fast ice flow.	Pre-9.4 ± 150 ka, probably LGM
Des Moines Lobe (27)	Patterson (1997, 1998), Jennings (2006), Clark (1992)	Location within trough-shaped lowland is conducive to focused ice flow. Ice marginal hummocky deposits indicate active ice readvance into stagnant ice, with radiocarbon dates demonstrating that this was a rapid readvance. Crevasse-fill ridges are consistent with ice flow above the rate of internal deformation. A series of tunnel valleys are located around the margins suggesting large subglacial meltwater discharge. Low reconstructed ice surface slope and driving stresses (0.7-4.3 kPa) are similar to the ice plains of contemporary West Antarctic ice streams. Our own observations revealed relatively few bedforms, but where present they showed a smudged footprint, suggesting that there were several different ice stream configurations in this area.	Around 14 ka
James Lobe (28)	Patterson (1997), Clark (1992)	Located in a trough within lowlands which would have encouraged focusing of ice. Where sediment cover is present, till streamlining is noted. A low reconstructed ice surface slope and driving stresses (0.9-1.2 kPa) are consistent with contemporary West Antarctic ice streams.	Around 14 ka
St Georges Bay (29)	Shaw (2003)	Evidence for streaming flow into Laurentian Channel based on drumlins, crag-and-tails and roches moutonnées. A large submarine moraine marks the maximum extent of the ice stream. Reconstructions indicate that it would have had a relatively large catchment area and experienced strong marine draw-down.	LGM

TABLE III

Paleo-ice streams for which evidence exists but their extent remains undefined

Ice stream	References	Nature of evidence	Timing
Lake Michigan Lobe (30)	Whittecar and Mickelson (1979), Kehew *et al*. (2005), Clark (1992), Breemer *et al*. (2002)	The Waukesha drumlin field and related streamlined bedforms suggest fast ice flow out of Lake Michigan basin. Associated with the drumlins is sedimentary evidence of subglacial and/or marginal deformation and tunnel valleys indicating abundant meltwater discharge. Reconstructed ice surface slope and driving stresses (1.8-2.9 kPa) consistent with contemporary West Antarctic ice streams. Groundwater flow modelling indicates that the aquifers beneath Lake Michigan Lobe would have been insufficient to excavate basal water. Such conditions would have created high basal water pressure beneath the lobe, decreasing frictional resistance to ice flow.	15-14 ka
Lake Superior Lobe (31)	Jennings (2006)	Deep topographic trough and weak sedimentary substrate conducive to streaming. Elongated drumlins and flutes are common. Tunnel valleys are observed perpendicular to the margins, similar to the subglacial drainage features of contemporary West Antarctic ice streams.	Unknown
Simcoe Lobe (32)	Boyce and Eyles (1991)	Geomorphological and sedimentary evidence from the Peterborough drumlin field (over 3 000 drumlins). Drumlins show elongate form (length:width greater than 6:1) which decreases down stream as till thickness increases. Drumlins show a consistent orientation. Authors regard drumlin form and undisturbed internal stratigraphy is consistent with formation by deforming bed conditions beneath an ice stream.	Less than 13 ka
James Bay (33)	Veillette (1997)	Authors regard the presence of crag-and-tails and other glacial lineations indicative of fast ice flow. Mapping of lineations and striations indicates changing ice flow directions and sedimentological data show marked changes in sediment source. These suggest a significant change in ice flow dynamics during deglaciation consistent with ice streaming.	~9 ka
Placentia Bay (34)	Shaw (2003)	There is relatively weak geological evidence because off-shore deposits are buried under glaciomarine and post-glacial muds, but multibeam bathymetry imagery reveals flow features (drumlins and crag-and-tails) showing highly convergent flow. Strong marine draw-down has been suggested. Topographic setting conducive to streaming flow.	LGM

TABLE IV

Locations where paleo-ice streams have been hypothesised but more evidence is needed to confirm this

Ice stream	References	Nature of existing evidence
North Great Bear Lake (35)	Vincent (1989)	Evidence limited to a few isolated streamlined features.
Extension of Transition Bay Ice Stream across Peel Sound (36)	Dyke and Morris (1988) Dyke and Dredge (1989)	Streamlined landforms of Transition Bay Ice Stream (#12) are suggested to extend across Peel Sound. A larger dispersal train on Somerset Island may be related to extended streaming, but further evidence is needed before the flow-sets can be confidently linked.
37, 38, 39	Denton and Hughes (1981)	Ice streaming inferred due to the presence of lake basins and topographic lows. No further evidence in support of streaming.
West Hudson Bay (40, 41)	Patterson (1998)	Two dispersal trains identified by Dyke and Dredge (1989) and suggested to be ice streams by Patterson (1998). 41 is a Dubawnt-type dispersal train therefore not considered indicative of ice streaming (Dyke and Morris, 1988). 40 is a carbonate dispersal train therefore may indicate a discrete zone of flow but further evidence for fast velocities is needed.
Extension of Central Alberta Ice Stream (42, 43)	Patterson (1998)	Mega-scale glacial lineations and highly elongate drumlins are noted in the region of the Central Alberta Ice Stream (#14), but upstream and downstream of these (#42-43) only small drumlin swarms have been mapped.
Ungava Bay (44)	Clark *et al.* (2000) Jansson *et al.* (2003)	In addition to the two ice streams in Table I (#16-17) it has been suggested that up to 6 more operated in this area. But due to the complexity of the landform record evidence for these remains inconclusive.
Newfoundland (45)	Shaw (2003)	Streaming hypothesised due to deep fjords and presence of submarine moraines at their mouths, but as yet there is insufficient evidence to conclude whether these valleys hosted outlet glaciers or ice streams.
Chaleur Bay (46)	Grant (1989) Patterson (1998)	Smeared till across Gaspésie considered by authors to indicate streaming flow into Chaleur Bay, as is the presence of sediment sourced from Chaleur bay in southern Gulf of St. Lawrence. Argument for streaming is uncertain and further supporting evidence is required.
Nova Scotia (47)	Grant (1989) Patterson (1998)	Drumlin fields on Nova Scotia but little sign of bedform elongation or coherent flow sets.
Lake Ontario basin (48)	Hicock and Dreimanis (1992) Lian *et al.* (2003) Patterson (1998)	Drumlin field attributed to mega-floods (Shaw and Gilbert, 1990) but reinterpreted by Patterson (1998) as a paleo-ice stream. Sedimentological evidence for wet ductile deformation in some locations.
Lake Erie basin (49)	Hicock (1992) Lian *et al*. (2003) Karrow (1989)	Sedimentological evidence for wet ductile till deformation in some locations. A drumlin field has been noted in this area by Karrow but streaming was not suggested.