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Late Pleistocene ice export events into the Arctic Ocean from the M'Clure Strait Ice Stream, Canadian Arctic Archipelago

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Abstract

Rapidly-flowing sectors of an ice sheet (ice streams) can play an important role in abrupt climate change through the delivery of icebergs and meltwater and the subsequent disruption of ocean thermohaline circulation (e.g., the North Atlantic's Heinrich events). Recently, several cores have been raised from the Arctic Ocean which document the existence of massive ice export events during the Late Pleistocene and whose provenance has been linked to source regions in the Canadian Arctic Archipelago. In this paper, satellite imagery is used to map glacial geomorphology in the vicinity of Victoria Island, Banks Island and Prince of Wales Island (Canadian Arctic) in order to reconstruct ice flow patterns in the highly complex glacial landscape. A total of 88 discrete flow-sets are mapped and of these, 13 exhibit the characteristic geomorphology of palaeo-ice streams (i.e., parallel patterns of large, highly elongated mega-scale glacial lineations forming a convergent flow pattern with abrupt lateral margins). Previous studies by other workers and cross-cutting relationships indicate that the majority of these ice streams are relatively young and operated during or immediately prior to deglaciation. Our new mapping, however, documents a large (>700 km long; 110 km wide) and relatively old ice stream imprint centred in M'Clintock Channel and converging into Viscount Melville Sound. A trough mouth fan located on the continental shelf suggests that it extended along M'Clure Strait and was grounded at the shelf edge. The location of the M'Clure Strait Ice Stream exactly matches the source area of 4 (possibly 5) major ice export events recorded in core PS1230 raised from Fram Strait, the major ice exit for the Arctic Ocean. These ice export events occur at ~12.9, ~15.6, ~22 and 29.8 ka (^{14}C yr BP) and we argue that they record vigorous episodes of activity of the M'Clure Strait Ice Stream. The timing of these events is remarkably similar to the North Atlantic's Heinrich events and we take this as evidence that the M'Clure Strait Ice Stream was also activated around the same time. This may hold important implications for the cause of the North Atlantic's Heinrich events and hints at the possibility of a pan-ice sheet response.

Keywords: ice stream; Laurentide Ice Sheet; Arctic Ocean; iceberg rafted detritus (IRD)

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1. Introduction

The growth and decay of continental ice sheets plays a significant role in the global climate system: modifying atmospheric circulation; creating large regional albedo anomalies; and modulating global sea level change (Manabe and Broccoli, 1985; Clark et al., 1999). It is also known that dynamic ice sheet behaviour can force abrupt climate change over very short (decadal–millennial) time-scales, through the delivery of icebergs and meltwater and their subsequent disruption of ocean thermohaline circulation (Overpeck et al., 1989; Bond et al., 1992; Barber et al., 1999).

In recent years, there has been an increasing awareness that rapidly flowing sectors of an ice sheet (known as ice streams) exert a profound influence on ice sheet behaviour and have the potential to issue vast amounts of icebergs (Dowdeswell et al., 1995; Marshall and Clarke, 1997). Moreover, evidence from the ocean sedimentary record supports the idea that some ice streams exhibit episodic behaviour with a short phase of rapid ice flow followed by a period of relative quiescence (Andrews and Tedesco, 1992; Marshall and Clarke, 1997). Such behaviour has been reproduced in numerical modelling experiments and it has been suggested that glaciological instabilities associated with ice stream activity may be a key mechanism in forcing abrupt climate change (Broecker et al., 1992; MacAyeal, 1993; Clarke et al., 1999; Calov et al., 2002).

The North Atlantic's Heinrich-events are, arguably, the best example of the important role of ice streams in ice sheet–ocean interactions and abrupt climate change (MacAyeal, 1993; Marshall and Clarke, 1997; Calov et al., 2002; Andrews and Barber, 2002). The provenance of iceberg rafted debris (IRD) associated with Heinrich layers has been directly linked to a source region around Hudson Strait (Bond et al., 1992; Andrews and Tedesco, 1992) where there is persuasive evidence for a large ice stream occupying the marine trough (Laymon, 1992; Andrews and MacLean, 2003). Although several mechanisms have been proposed as the cause of Heinrich events, it is most likely that ice streaming in Hudson Strait played a key role in the supply of IRD (Andrews and Tedesco, 1992; Andrews and MacLean, 2003; Hulbe et al., 2004; Alley et al., 2005).

Recently, several cores have been raised from the Arctic Ocean and which document the existence of profligate iceberg discharges and meltwater events throughout the Late Pleistocene, similar to those recorded in the North Atlantic (Bischof and Darby, 1997; Poore et al., 1999; Darby et al., 2002; Polyak et al., 2004). Provenance studies of the IRD suggest there are several source areas from the circum-Arctic but that the Canadian Arctic Archipelago is likely to have been a major contributor (Darby et al., 2002; Polyak et al., 2001, 2002). In particular, attention has been drawn to four massive ice export events between 10 and 30 ka (^{14}C yr BP) recorded in a core from Fram Strait (Darby et al., 2002). The provenance of these IRD events appears to match a till sourced from Banks Island and Victoria Island (Darby et al., 2002) but no specific ice stream has been implicated, despite geomorphological evidence for a late glacial (~10 ka ^{14}C yr BP) ice stream in M'Clintock Channel that infringed on eastern Victoria Island: the M'Clintock Channel Ice Stream (Hodgson, 1994; Clark and Stokes, 2001; De Angelis and Kleman, in press).

In this paper, we: (a) report new mapping of ice flow patterns in the vicinity of Victoria Island and Prince of Wales Island to constrain the full spatial extent of ice streaming prior to deglaciation, and (b), explicitly link the Arctic Ocean sediment record to individual ice stream events in order to explore the timing of their activity and the implications for overall Laurentide Ice Sheet dynamics.

2. Background: the late glacial (~10 ka ^{14}C yr BP) M'Clintock Channel Ice Stream

Hodgson (1994) identified three cross-cutting ice flow patterns on north-eastern Victoria Island (Storkerson Peninsula and Stefansson Island) and constrained their formation to between 11,000 and 9000 ^{14}C yr BP using radiocarbon dating of marine molluscs. One of the flow patterns (Hodgson's Flow-2) is characterised by highly elongated glacial lineaments (mega-scale glacial lineations) that exhibit a remarkably abrupt margin on central Storkerson Peninsula. Hodgson (1994) hypothesised that, during deglaciation, the marine-based ice front retreated at least 300 km from the shelf edge in M'Clure Strait to reach north-east Victoria Island around 10,400 ^{14}C yr BP.

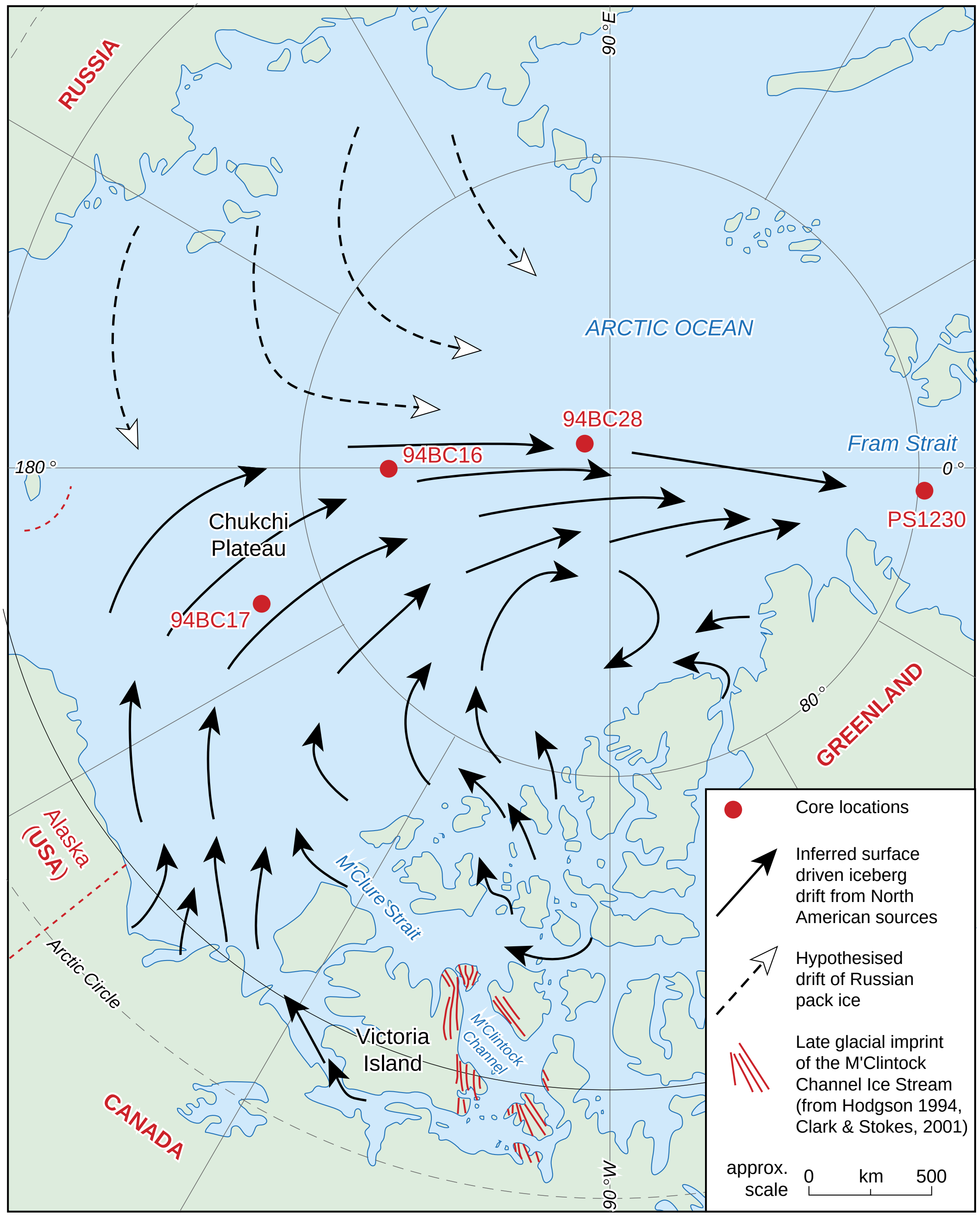

Fig. 1. Location of M'Clure Strait and the Late Glacial imprint of the M'Clintock Channel Ice Stream in the Canadian Arctic Archipelago. The inferred surface current-driven iceberg drift directions from the Canadian Arctic Archipelago (solid arrows) and concurrent hypothesised drift of Russian pack ice (broken arrows) during glacial intervals are also shown, summarised from both Bischof and Darby (1997) and Phillips and Grantz (2001). Also note the location of Arctic Ocean box cores, including core PS1230 in Fram Strait.

Subsequent to this, a large ice stream developed in M'Clintock Channel, infringing on eastern Storkerson Peninsula, and producing the spectacular array of streamlined mega-scale glacial lineations, see Fig. 1. The thick (up to 50 m), fine-grained Paleozoic carbonate till, characteristic of eastern Victoria Island, provided effective lubrication for the ice stream which surged into Viscount Melville Sound and produced an ice shelf covering around 20,000 km^2 (Hodgson and Vincent, 1984). The radiocarbon dating of Hodgson (1994) from Storkerson Peninsula suggests that it ceased to flow prior to ca. 9600 ka ^{14}C BP.

Later work by Clark and Stokes (2001) used satellite imagery and aerial photographs to map the extent of the late glacial ice stream imprint and examine its basal characteristics in detail. They reconstructed the ice stream at 720 km long and 140 km wide, with a cross sectional area of 100 km^2 (Fig. 1). The surface area of the ice stream was estimated to be around 162,000 km^2 and it had a likely catchment area of 400,000 km^2. Clark and Stokes (2001) postulated that the ice stream infringed on western Prince of Wales Island (Fig. 1) and used the additional dating control from the cross-cutting flow patterns there (Dyke et al., 1992) to constrain the final ice stream activity to between 10,400 and 10,000 ^{14}C BP but more likely for only 200 years. If the ice stream operated with a velocity of 4 km per year (the estimated velocity of the similarly sized Hudson Strait Ice Stream: Dowdeswell et al., 1995), it could have drained 80,000 km^3 of ice (400 km^3 a^{-1}) and delivered a sediment flux of up to 73,000 m^3 a^{-1} per metre width of terminus (Clark and Stokes, 2001).

More recently, De Angelis and Kleman (in press) produced a detailed map of palaeo-ice streams further east in Northern Keewatin and Boothia Peninsula. They identified at least three generations of ice streaming in the vicinity of the late glacial M'Clintock Channel and concluded that more than one ice stream configuration existed in this area.

3. Methods

Satellite remote sensing is ideal for detecting and mapping terrestrial palaeo-ice stream beds (e.g., Jansson et al., 2003; Stokes and Clark, 2003; De Angelis and Kleman, in press). As part of a larger mapping project, we acquired 50 Landsat Enhanced Thematic Mapper Plus scenes (spatial resolution 30 m; 15 m in the panchromatic band) to map ice flow patterns on Victoria Island, Banks Island and Prince of Wales Island. Spatially coherent flow patterns of glacial lineaments were grouped into distinct 'flow-sets' relating to specific ice flow events and each was incorporated into a GIS database (cf. Clark, 1997, 1999). In addition, eskers and moraines were mapped to ascertain the approximate direction of ice margin retreat and relative ages were obtained from cross-cutting flow-sets (cf. Clark, 1993, 1999). Given the unique suite of subglacial bedforms that ice streams produce (i.e., parallel patterns of large, highly elongated mega-scale glacial lineations) and their potential for preservation beneath younger ice flow patterns (Clark, 1993), we were able to search for evidence of older flow patterns in the palimpsest glacial landscape.

Complementing this remote sensing approach, is field mapping and vertical airphoto interpretation by the Geological Survey of Canada, which has provided much information relating to Quaternary history of the north-westernmost sector of the Laurentide Ice Sheet (LIS) in the Canadian Arctic Archipelago (see Dyke et al., 1992; Hodgson, 1994; Sharpe, 1992; Dyke and Dredge, 1989). Ice flow patterns on Victoria Island were first mapped by Fyles (1963) and generally portrayed on the Glacial Map of Canada (Prest et al., 1968). Greater detail is shown on, for example, Hodgson (1993a,b) and Hodgson and Bednarski (1994). The deglaciation of the LIS is illustrated by Dyke et al. (2003a), and shown in detail for southwest Victoria Island by Dyke et al. (2003b). In the course of these and other studies, glacial tills and shallow marine sediments derived from nearby bedrock formations have been sampled. Of greatest significance for this study is the lithological 'finger-print' of marine sediments and glacial tills from Banks and Victoria Island (Darby, 2003; Darby and Bischof, 1996). If a large ice stream, in the position we hypothesise, delivered significant amounts of IRD into the Arctic Ocean, the Banks and Victoria Island lithology should be recognisable in the ocean sedimentary record. In addition to our new mapping, we report and discuss previous provenance studies of Arctic Ocean sediment cores (Bischof and Darby, 1997; Darby et al., 2002; Darby, 2003; Polyak et al., 2004) to explore the potential activity of ice streaming on north-western

Victoria Island, with a particular focus on box core PS1230 recovered from Fram Strait which records at least four massive ice export events (e.g., Darby et al., 2002).

4. Results

4.1. Identification of palaeo-ice streams on Victoria Island and Prince of Wales Island

A total of 88 flow-sets were identified in the complex glacial landscape on Victoria Island, Banks Island and Prince of Wales Island, shown in Fig. 2 (coloured arbitrarily). It is clear that the glacial landscape depicts several generations of 'cross-cutting' ice flow patterns (cf. Clark, 1993) and that although flow was predominantly focussed into the inter-island channels, ice flow and subsequent retreat in this area was highly complex. There are numerous areas where younger ice flows cross older ice flows at right angles, attesting to major reorganisation of the ice sheet in this region (Fig. 2).

The first task was to extract all flow-sets that were potentially formed by ice streams. In order to do this objectively, we compared the characteristics of each

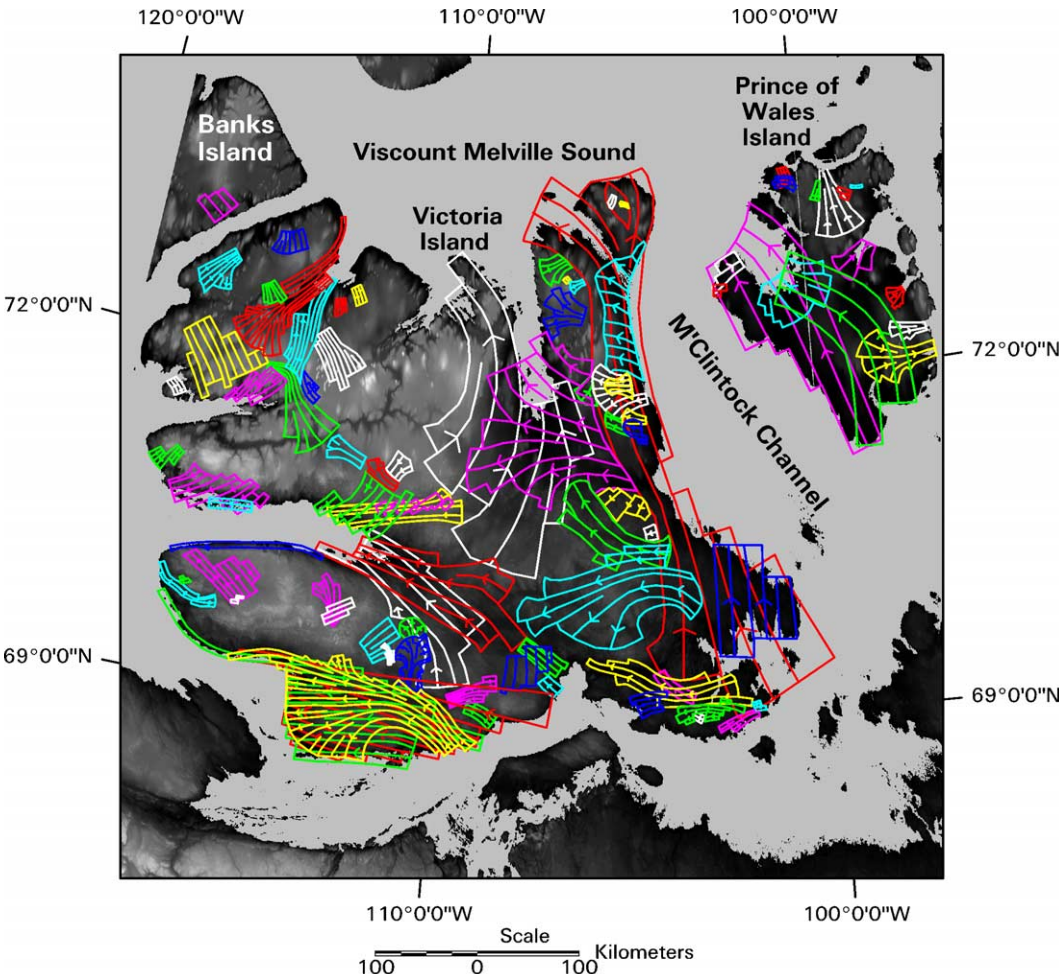

Fig. 2. Flow-sets mapped on Banks Island (top left), Victoria Island (centre) and Prince of Wales Island (top right). Although ice flow was predominantly directed into and along the inter-island channels, the rapid changes in the configuration of the ice sheet produced a highly complex pattern of cross-cutting landscapes. Flow-sets are coloured arbitrarily.

flow-set against the geomorphological criteria we would expect a palaeo-ice stream to produce (Stokes and Clark, 1999; Clark and Stokes, 2003). Table 1 lists several criteria for identifying palaeo-ice streams and indicates how they are derived from the characteristics of contemporary ice streams (cf. Clark and Stokes, 2003). Based largely on these criteria we identified thirteen flow-sets as strong candidates for palaeo-ice streams, shown in Fig. 3. Other flow-sets may also be potential candidates for ice streaming but we focus on those that are preserved well enough to be confident that they were produced by a discrete zone of fast flowing ice bordered by slower flowing ice.

Some of the flow-sets in Fig. 3 have previously been recognised as ice streams. Flow-set 10 on Prince of Wales Island corresponds to the Transition Bay Ice Stream (Dyke et al., 1992). Flow-set 15 (the 'Crooked Lake drumlin field': cf. Dyke et al., 1992) has also been recognised as part of an ice stream that was diverted by cold based ice on western Prince of Wales Island (Dyke et al., 1992; De Angelis and Kleman, in press). Flow-set 9 is part of an older ice stream imprint preserved underneath this cold-based patch and Clark and Stokes (2001) speculated that it formed part of the late-glacial (~10 ka BP) M'Clintock Channel Ice Stream, labelled as flow-set 16 (see also Fig. 1). Further west on Victoria Island, Sharpe (1992) hypothesised that flow-set 53 (the 'Read Island drumlin field) was produced by a late glacial (11–10 ka BP) surge/ice stream and that a similar situation could have occurred in Prince Albert Sound to the north, possibly related to flow-set 20 and/or 21. More recently, Stokes et al. (submitted for publication) identified the two older flow-sets beneath flow-set 53, labelled flow-set 54 and 55, and related them to the reorganisation of a major ice stream in Amundsen Gulf and Dolphin and Union Strait.

Flow-sets 17, 74, 76 and 80 (Fig. 3) have not been previously recognised as palaeo-ice streams. Flow-sets 74, 76 and 80 are relatively minor ice streams, around 80–100 km long and 20–30 km wide. It is likely that flow-set 76 and 80 formed through reorganisation of an ice stream converging into Richard Collinson Inlet (here named 'Collinson Inlet Ice Stream').

Flow-set 17 is a major flow pattern, around 330 km long and over 140 km wide, converging into Hadley Bay and turning to the west in Viscount Melville Sound. Its orientation is very similar to the late glacial M'Clintock Channel Ice Stream (flow-set 16) but cross-cutting landforms indicate that they could not have operated at the same time (see discussion below).

4.2. Relative ages of palaeo-ice streams on Victoria Island and Prince of Wales Island

It is clear from looking at Fig. 3 that not all of the ice streams can have operated at the same time. Ideally, it would be possible to constrain the formation of each flow-set from dating techniques and build a full reconstruction of ice stream activity through to deglaciation. Although previous workers (e.g., Sharpe, 1992; Dyke et al., 1992; Hodgson, 1994) have used radiocarbon dating to constrain the

Table 1
Criteria for identifying palaeo-ice streams (modified from Clark and Stokes, 2003)

Contemporary ice stream characteristic	Proposed geomorphological signature of flow-set
A. Characteristic shape and dimension with convergent onset zone and/or tributaries feeding a main trunk >20 km wide and >150 km long	1. Characteristic shape and dimensions (>20 km wide and >150 km long) of distinct flow pattern
	2. Highly convergent flow patterns leading into a main trunk
B. Rapid velocity	3. Bedform signature of fast flow; mega-scale glacial lineations and highly attenuated drumlins (length:width >10 : 1)
	4. Boothia-type erratic dispersal plume
C. Distinct velocity field (plug flow; general increase in velocity through the onset zone)	5. Spatial variation elongation ratios of mega-scale glacial lineations and drumlins should mimic expected ice velocity
D. Sharply delineated shear margin	6. Abrupt lateral margins (<2 km) to the flow-set
	7. Ice stream shear margin moraines
E. Spatially focussed sediment delivery	8. Submarine till delta or sediment fan (marine-based ice streams only)

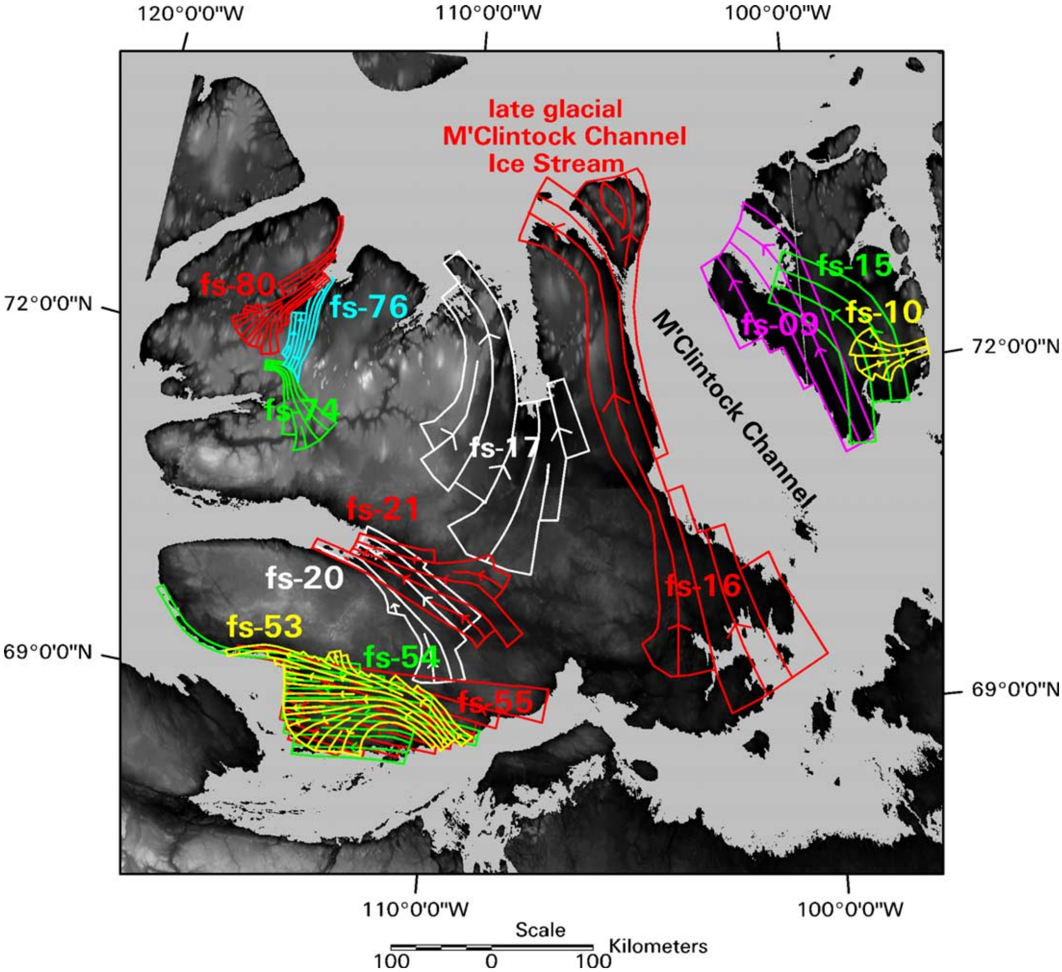

Fig. 3. Location of major flow-sets fulfilling several geomorphological criteria for palaeo-ice streams. Note the location of the late glacial M'Clintock Channel Ice Stream in red (Hodgson, 1994; Clark and Stokes, 2001). Flow-set colours correspond to Fig. 2.

formation of some of the ice streams (e.g., fs-10, fs-15, fs-16, fs-53) to a late glacial age (11–10 ka BP), such a precise chronology is not available everywhere. It is possible, however, to ascertain relative ages of neighbouring flow-sets based on cross-cutting landforms.

On Prince of Wales Island, the three ice stream imprints cross-cut each other (Fig. 3). The Transition Bay Ice Stream (fs-10) is the youngest, clearly superimposed on flow-set 15. It is also clear that flow-set 15 is superimposed on flow-set 09 on western Prince of Wales Island. De Angelis and Kleman (in press) and Dyke et al. (1992) noted that preservation of flow-set 09 and the deviation of flow-set 15 requires a cold-based patch on western Prince of Wales Island. De Angelis and Kleman (in press) concluded that flow-set 09 is, therefore, a remnant of a relatively older ice stream and speculated that the location of the cold-based patch that protected it may have resulted from a switch in the basal thermal regime of this ice stream during stagnation (i.e., basal freeze-on: Christofferson and Tulaczyk, 2003).

Flow-set 16 relates to the late-glacial M'Clintock Channel Ice Stream and Clark and Stokes (2001) linked this flow-set across the channel to flow-set 09 on Prince of Wales Island, thus reconstructing an ice stream occupying the whole of M'Clintock Channel.

From its position and compatible flow configuration, flow-set 17 appears that it might also belong to the M'Clintock Channel Ice Stream (flow-set 16 and 09), see Fig. 3. Relative age determinations from overlapping non-ice stream flow-sets, however, preclude this possibility and demonstrate a different age, with flow-set 17 clearly older than flow-set 16. Fig. 4 shows all of the flow-sets, including non-ice streaming events, in the vicinity of flow-set 16 and 17. It depicts a general picture of ice streaming (fs-16 = red and fs-17 = white) flowing from south to North into Viscount Melville Sound, punctuated by non-ice stream flow patterns flowing from east to west. Fig. 5 shows satellite imagery from the onset zone of flow-set 17 where it is cross-cut by a younger flow pattern (fs-27). Mega-scale glacial lineations can be clearly seen underneath the fresher east to west drumlins on the right hand side of Fig. 5. Thus, the flow-set 17 ice stream must be older than flow-set 27.

Fig. 6 shows that the M'Clintock Channel Ice Stream (flow-set 16), has completely 'beheaded' flow-set 27 (note the abrupt margin of flow-set 16 in centre of image). Thus, flow-set 27 has to be older

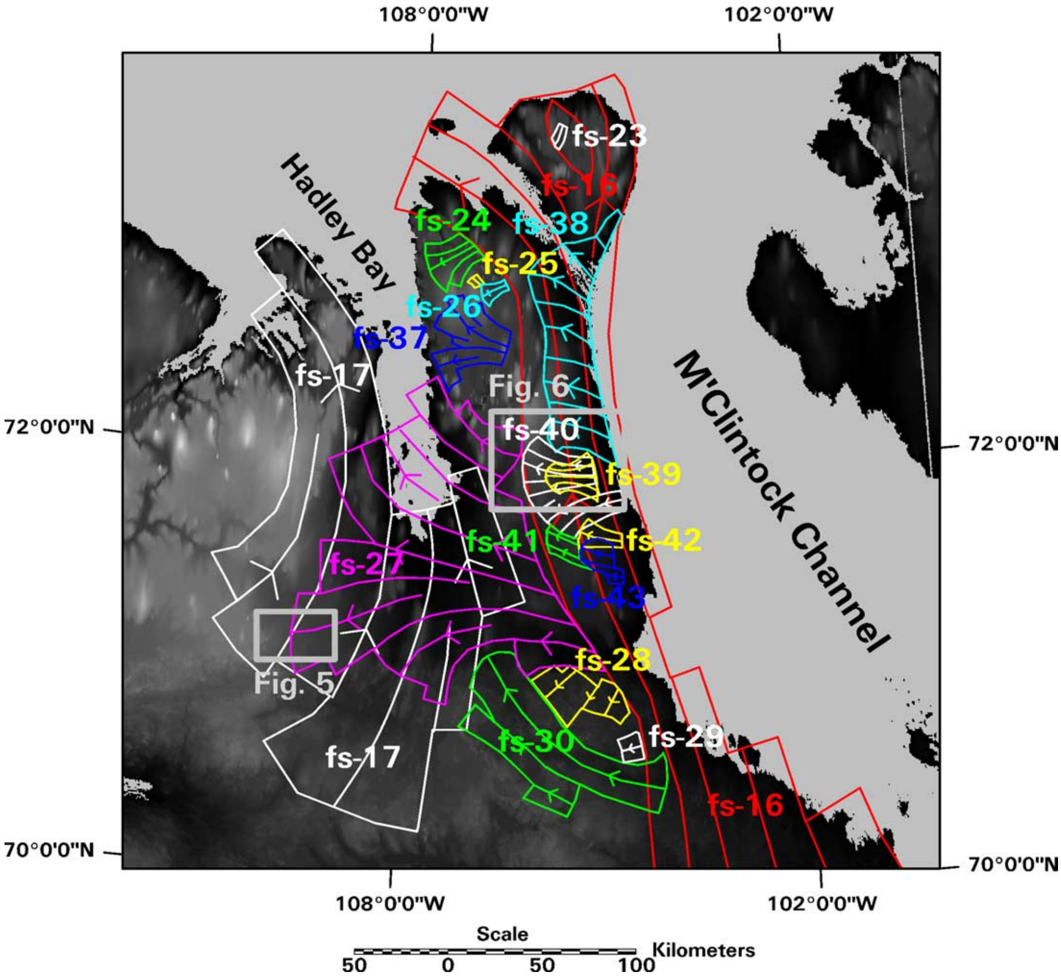

Fig. 4. Flow patterns in the vicinity of Storkerson Peninsula, eastern Victoria Island. The major ice stream flow-sets from south to north in M'Clintock Channel (fs-16: red) and Hadley Bay (fs-17: white) are cross-cut by younger flow patterns flowing from east to west. Flow-set colours correspond to Figs. 2 and 3.

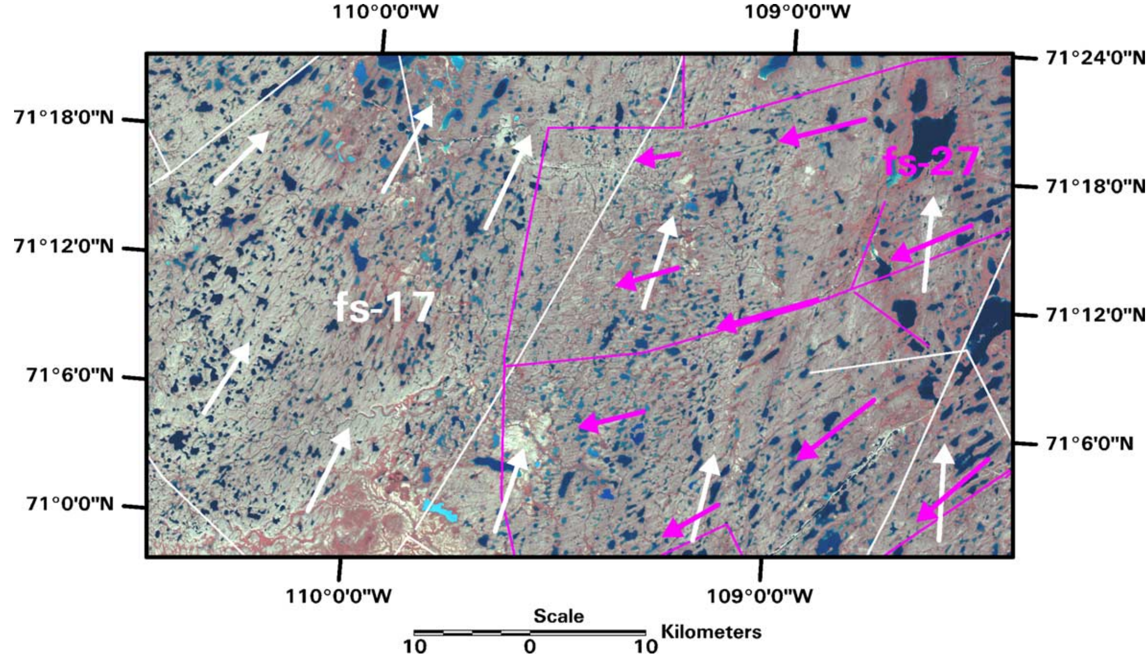

Fig. 5. Landsat satellite imagery illustrating the cross-cutting relationship between the older ice stream mega-scale glacial lineations (fs-17) flowing from south to north and a younger flow pattern (fs-27) flowing from east to west. Mega scale glacial lineations can clearly be seen underneath the fresher east to west drumlins on the right hand side of the image. Flow-set colours correspond to Figs. 2–4.

than flow-set 16 and, therefore, the ice stream associated with flow-set 17 is definitely older than the M'Clintock Channel Ice Stream (flow-set 16). Furthermore, flow-set 16 has itself been cross-cut by even younger flow events (fs-38, fs-39 and fs-40), again flowing in an east to west direction from M'Clintock Channel (Fig. 6). These younger flow patterns are aligned with eskers and outwash fans that indicate that they were probably produced during final deglaciation. The overall picture is of an oscillation between ice streaming from south to north in the marine trough, punctuated by non-ice stream flow from east to west. Ground-based observations show deglaciation of the marine-based portion of flow-set 17 was completed between 11.8 and 10.9 ka ^{14}C BP, up to 1500 yr earlier than flow-set 16 (Hodgson, 1994; Hodgson and Bednarski, 1994).

On north-western Victoria Island, the mapping reveals that flow-set 74 is clearly younger than the two northward flowing patterns into Richard Collinson Inlet (Fig. 3). Although not as conclusive, subtle cross-cutting relationships are suggestive that flow-set 76 is the older of the two north-ward flowing ice stream imprints. Preliminary construction of a deglacial chronology indicates these flows were approximately concurrent with the final activity of flow 17. Table 2 depicts the relative age relationship (where known) for each of the palaeo-ice streams shown on Fig. 3.

In summary, thirteen palaeo-ice stream imprints have been identified on Victoria Island and Prince of Wales Island (Fig. 3). Published radiocarbon dates (e.g., Sharpe, 1992; Dyke et al., 1992; Hodgson, 1994) and cross-cutting relationships indicate that most of these palaeo-ice streams operated immediately prior to deglaciation which occurred between 12 and 10 ka ^{14}C BP. The clear exceptions to this rule are flow-set 09 on western Prince of Wales Island and a very large (330 km long × 140 km wide) flow-set 17, converging into Hadley Bay and flowing north-westward into Viscount Melville Sound (Fig. 3). These flow-sets indicate the presence of a relatively large older ice stream(s) flowing parallel to M'Clintock Channel into Viscount Melville Sound

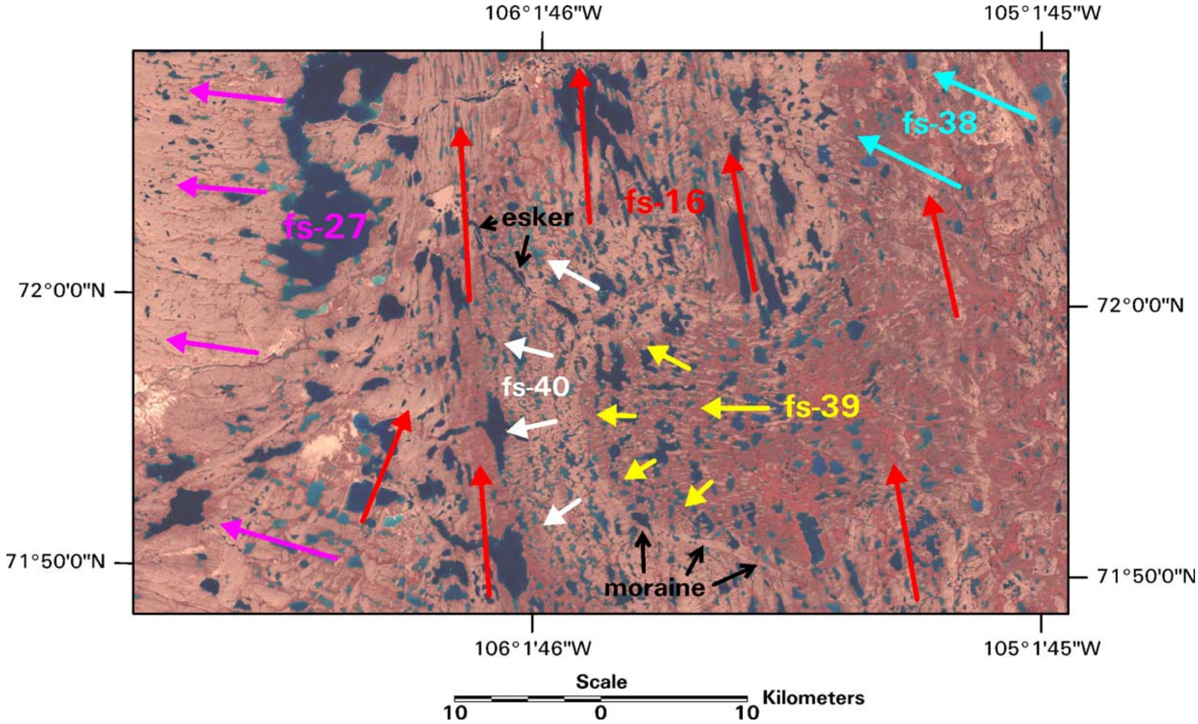

Fig. 6. Landsat satellite imagery showing the complex cross-cutting ice flow relationships on Storkerson Peninsula. The older flow-set (fs-27) can be seen on the left of the image flowing from east to west. This flow pattern has been beheaded by the late glacial M'Clintock Channel Ice Stream (fs-16 = red) flowing from south to north. This flow-set has also been cross-cut by even younger (deglacial) flow-sets (fs-38, 39 and 40) aligned with eskers and again, originating from the channel and flowing from east to west. The lobate patterns of flow-sets 38, 39 and 40, and their association with eskers and outwash fans, demonstrates that they are the youngest ice flow events.

prior to the deglacial imprints. Moreover, episodes of ice streaming within the marine channels were punctuated by non-ice stream flow patterns that appear to have originated in the channels and regressed perpendicular to the ice streams.

Table 2
Relative age relationships between palaeo-ice streams on Victoria and Prince of Wales Island

Pre-LGM	LGM–12 (ka BP)	11.9–11 (ka BP)		10.9–10 (ka BP)		
Fs-17?	Fs-17	Fs-15?	Fs-16?	**Fs-15**	**Fs-16**	**Fs-10**
Fs-09?	Fs-09					
	Fs-20?	Fs-20?	Fs-21?	Fs-21		
	Fs-55?	Fs-55?	Fs-54	Fs-54?	**Fs-53**	
	Fs-80?	Fs-76	Fs-74			

The location of each ice stream flow-set is shown on Fig. 3. Age relationships are based on radiocarbon dating from previous workers (marked in bold), see text, and cross-cutting relationships identified in this paper. Question marks denote uncertainty.

5. Discussion: linking ice stream activity to the Arctic Ocean sediment record

5.1. Evidence for a major ice stream in M'Clure Strait

Our mapping indicates at least three episodes of ice streaming approximately parallel to M'Clintock Channel (fs-15, fs-16, fs-17) possibly four if flow-set 09 is not related to the flow-sets west of M'Clintock Channel (Fig. 3). This suggests that several episodes of ice streaming occurred within the marine trough at different times and with different widths (cf. De Angelis and Kleman, in press).

The location and extent of a relatively old ice stream imprint (flow-set 17) converging into Hadley Bay and Viscount Melville Sound is intriguing. The extent of this flow-set is shown in Fig. 7, with Landsat satellite imagery illustrating the mega-scale glacial lineations that characterise the flow-set and which

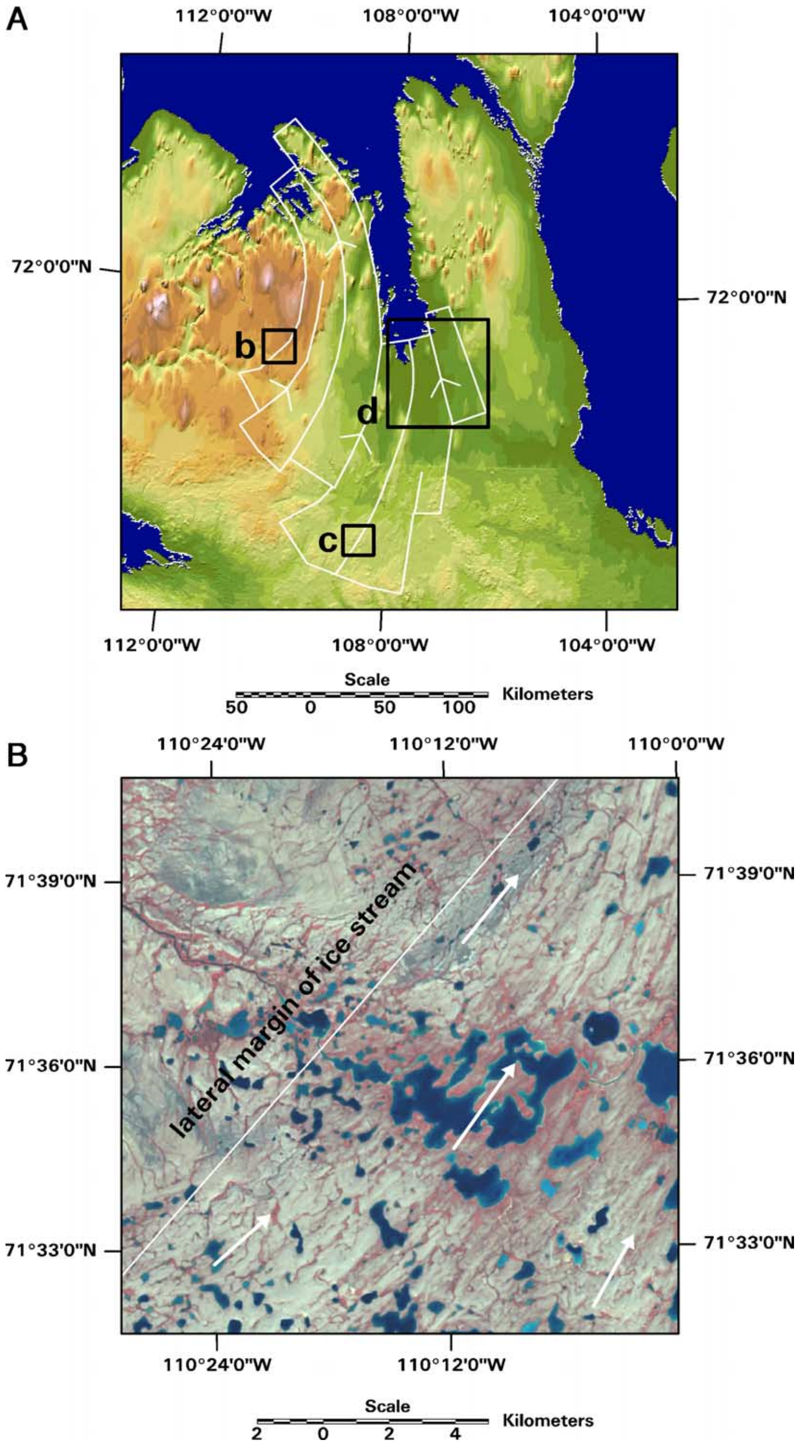

Fig. 7. Extent of flow-set 17 converging into Hadley Bay. The abrupt lateral margin of this flow-set can be seen in (b). This flow-set is characterised by mega-scale glacial lineations (c) which have, in places, been cross-cut by younger flow patterns emanating from the east (d). Note that the south to north flow can be seen beneath the younger flow pattern in (d).

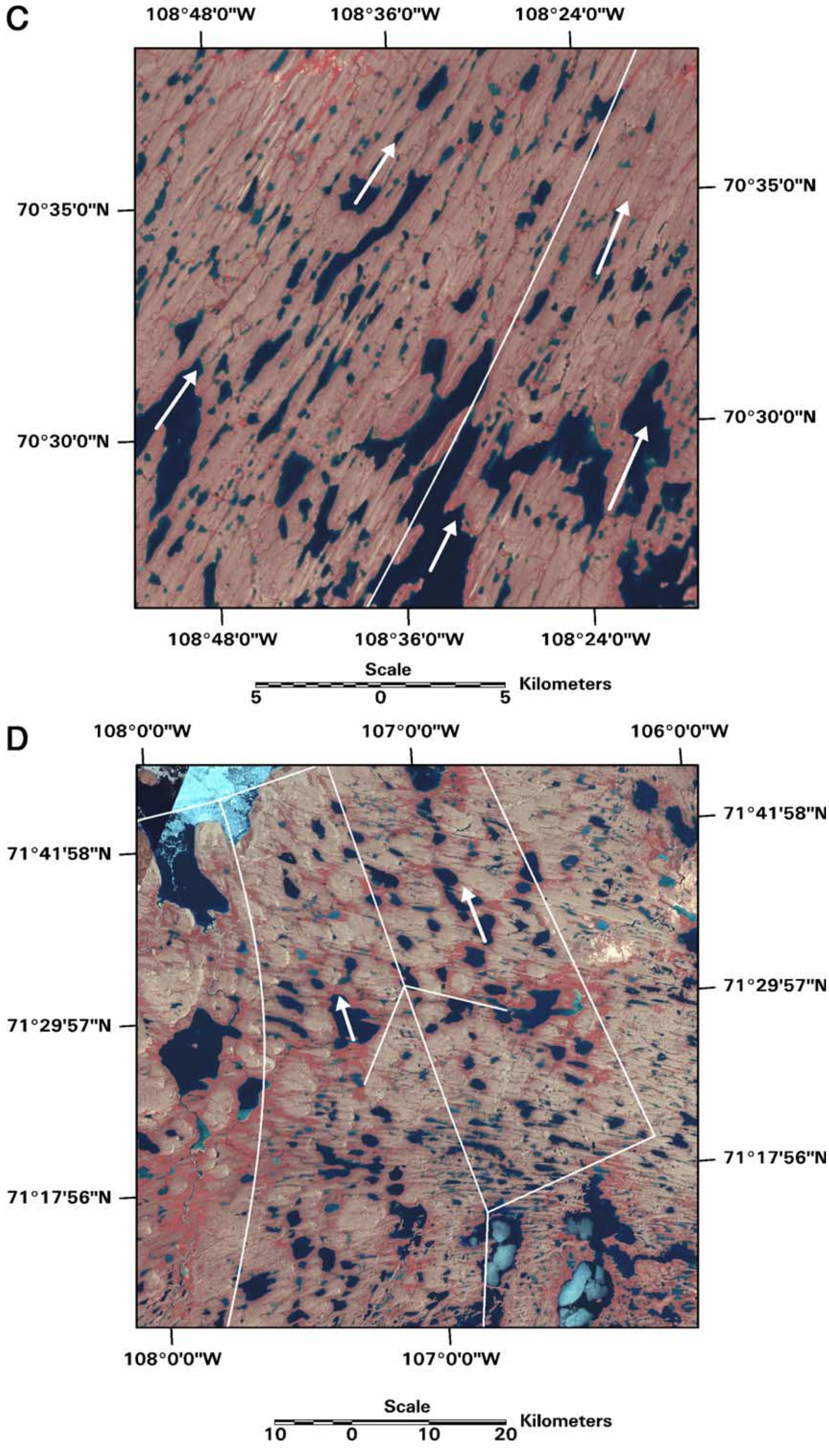

Fig. 7 (*continued*).

have been overprinted in places by younger ice flows (see Fig. 7D).

The margin of the flow-set is very abrupt at its westernmost extent, where it crosses the northeast end of the Shaler Mountains (Fig. 7B). Here, it reaches an elevation of 450 m. Given that the highest point on Storkerson Peninsula to the east is only around 290 m in height, it is very likely that the ice stream extended much further east than can be confidently mapped (Fig. 7). Moreover, to the west, northwest flowing non-streaming ice overtopped all the Shaler Mountains (maximum elevation 640 m).

There are indications of a fragmented older flow on Storkerson Peninsula underneath the younger flow patterns and hummocky topography. Fig. 8 shows satellite imagery from Storkerson Peninsula, to the east of Hadley Bay, and it is possible to discern a north-westerly 'grain' beneath the generally hummocky topography, especially towards the western coast. This grain matches with flow-set 17 and we suggest that flow-set 17 extended much further east across the lower elevations and probably overtopped the whole of Storkerson Peninsula.

We also note that the old ice stream imprint on Prince of Wales Island, flow-set 09 (Fig. 3), also matches the orientation of flow-set 17. Given that both flow-sets are relatively 'old' ice stream imprints (i.e., pre-deglacial) and that they depict a coherent parallel pattern of ice flow into Viscount Melville Sound, we argue that they are entirely consistent with a large ice stream that flowed from M'Clintock Channel and into M'Clure Strait (hereon termed the 'M'Clure Strait Ice Stream' in order to distinguish it from the late glacial M'Clintock Channel Ice Stream). This interpretation breaks from Clark and Stokes (2001) who linked the old ice stream imprint on Prince of Wales Island (flow-set 09) to the smaller M'Clintock Channel Ice Stream (fs-16). Our new mapping indicates that the orientation and relative age of flow-set 09 is far more consistent with a larger

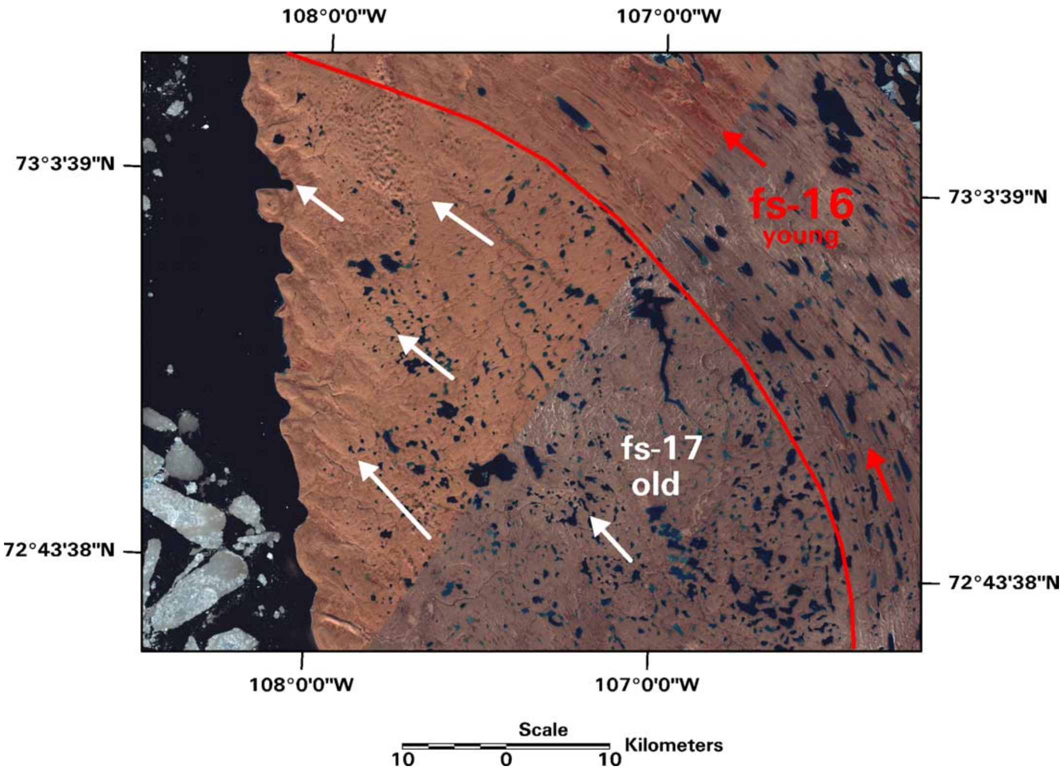

Fig. 8. Satellite imagery of western Storkerson Peninsula indicating a persistent 'grain' of north-westward orientated landscape features beneath the hummocky topography. Note that the features disappear further east where the late glacial M'Clintock Channel Ice Stream imprint dominates the landscape.

older ice stream, see Fig. 9. This revised interpretation explains the apparent anomaly between the fresh-looking late glacial landforms on Storkerson Peninsula (flow-set 16) and the much older and more fragmented landforms on Prince of Wales Island (flow-set 09).

As well as the persuasive terrestrial evidence for this large ice stream, Clark and Stokes (2001) noted that at the mouth of M'Clure Strait there is a significant bulge in the outline of the continental shelf break (Zarkhidze et al., 1991). They interpreted this feature as a large glacially-fed fan deposit (trough mouth fan: cf. Ó Cofaigh et al., 2003). Fig. 10 provides a visualisation of this feature, from which the key morphological characteristics of trough mouth fans can be seen. The bulge at the continental break is indicative of a large deposit draped on the continental slope. Numerous gullies and lobes on the continental slope are interpreted as evidence of debris-flow activity down the slope and we note that these are most abundant distal to the axis of M'Clure Strait, in comparison with either side of the Strait. An erosional splayed footprint is evident on the continental slope, resembling the shape of a 'duck-foot'. Together, these

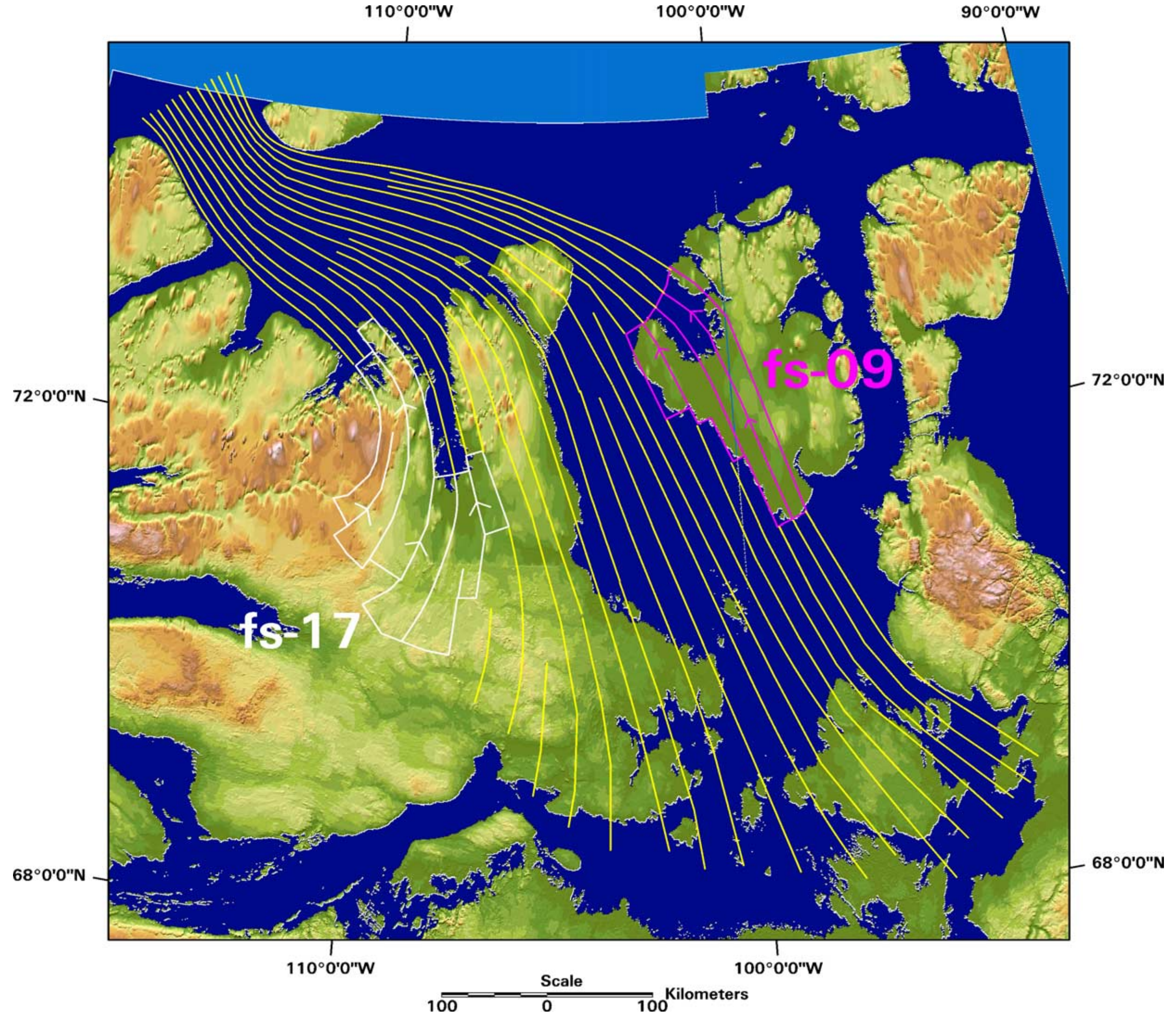

Fig. 9. Reconstructed configuration of the M'Clure Strait Ice Stream as recorded by flow-sets 17 and 09. The configuration was guided by the topography of the marine troughs (see also Fig. 10).

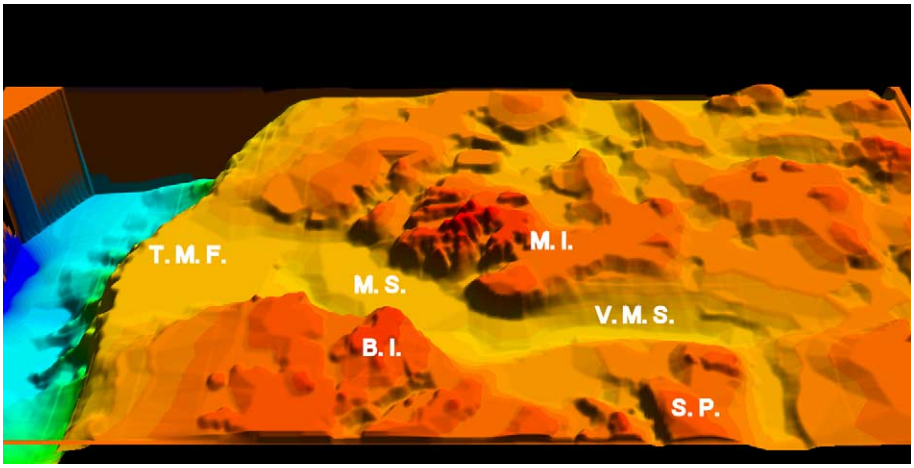

Fig. 10. Oblique visualisation of a digital elevation model of M'Clure Strait (M.S.) and the location of a large trough mouth fan (T.M.F.) and 'duck-foot' feature at the edge of the continental shelf. Image width approximately 1000 km. Banks Island = B.I.; Melville Island = M.I., Storkerson Peninsula = S.P.; Viscout Melville Sound = V.M.S. Bathymetric data derived from the International Bathymetric Chart of the Arctic Ocean (IBACO) see Jakobsson et al. (2000) for details, and terrestrial topography from the GTOPO30 data set distributed by the United States Geological Survey.

observations fit with trough mouth fans observed elsewhere (e.g., Ó Cofaigh et al., 2003; Sejrup et al., 2003) and which are widely regarded as compelling evidence for the existence of an ice stream grounded at the shelf edge. It is envisaged that rapid ice velocities across a deforming bed advects large volumes of sediment from the trough floor, discharging at the shelf break to produce the trough mouth fan (Alley et al., 1989; Vorren and Laberg, 1997; Ó Cofaigh et al., 2003). We thus infer that the M'Clure Strait Ice Stream extended along M'Clure Strait to the shelf edge. Recently-discovered mega-scale glacial lineations on the floor of Viscount Melville Sound, south of Melville Island (Blasco et al., 2005) confirm that rapidly-flowing ice was grounded in M'Clure Strait.

The hypothesised configuration of the 'M'Clure Strait Ice Stream' (Fig. 9) is reconstructed at around 1000 km in length and narrows from around 440 km in the onset zone, in southern M'Clintock Channel, to around 110 km towards its terminus between Banks and Melville Island.

5.2. Linking ice stream activity to Arctic Ocean IRD events

Previous work (Darby and Bischof, 1996) utilised discriminant function analysis (DFA) and clustering to trace IRD in Arctic Ocean glacial marine sediments back to their source areas. Results of this analysis indicate 38 distinct circum-Arctic source areas with unique petrographic and chemical signatures (see Fig. 1 in Darby et al., 2002). Of greatest significance to this study is the unique signature of marine sediments and glacial tills from Victoria Island, over which the M'Clure Strait Ice Stream would have operated (source area 8 in Darby et al., 2002). The trough mouth fan at the mouth of M'Clure Strait (Fig. 10) attests to significant mobilisation of subglacial sediment by the ice stream. If the ice stream also delivered significant amounts of IRD into the Arctic Ocean, the unique Banks and Victoria Island source area should be recognisable in the ocean sedimentary record.

The core of most relevance to this study is box core PS1230 located in 1235 m water depth at 78.9°N, 4.8°W in Fram Strait (see Darby et al., 2002 for a detailed description of the core composition and analysis). Previous analysis of core PS1230 indicates that a multitude of sources contributed to the ocean-floor sediments in Fram Strait but there is a strong and pervasive signal from detrital carbonate fragments (Darby et al., 2002). This is taken to indicate delivery of coarse IRD from the north-western margin of the Laurentide Ice Sheet, where vast expanses of carbonates exist, e.g., Victoria Island (Darby et al., 2002).

In contrast, the Eurasian side of the Arctic has only few, small carbonate exposures. Further discrimination reveals that the coarse carbonate IRD was sourced from several specific areas in the Canadian Arctic including the south-western Canadian Arctic Archipelago (primarily Victoria Island and Banks Island); the Queen Elizabeth Islands (primarily Axel Heiburg, Ellesmere, and Ellef Ringnes Island) and the Mackenzie region on the Arctic mainland (Darby et al., 2002). It is no coincidence that these areas were occupied by ice streams, at least during late glacial times (cf. Beget, 1987; Hodgson, 1994; Clark and Stokes, 2001; Atkinson, 2003).

In addition to the coarse IRD fraction, the weighted percentage of Fe oxide grains fluctuates rapidly throughout the last 30,000 years (^{14}C yr) (Darby et al., 2002). Of greatest significance for this study are four (possibly five) major IRD events indicated by detrital Fe oxide mineral grain peaks which precisely match the Banks/Victoria Island source area (labelled source area 8 in Darby et al. (2002)). Fig. 11 shows these IRD events from Banks/Victoria Island based on the detrital Fe oxide mineral grains compositions, labelled Arctic Laurentide: AL1, AL2, AL3, AL4 and AL5? It can be seen that all of the Fe oxide grain peaks in PS1230 occur in intervals with ≥4% detrital, light coloured carbonate, and two peaks coincide with peaks of >8% detrital carbonate. The combination of the light coloured Palaeozoic carbonates and the matching Fe oxide grains clearly points to Banks/Victoria Island as the major source of the Arctic Laurentide IRD spikes in core PS1230 (Fig. 11).

The new mapping of palaeo-ice stream imprints on Victoria Island in this paper (Figs. 3, 9, and 10) demonstrates that their could only have been one possible candidate for a large ice stream that operated over this source area earlier than the immediate time of deglaciation: the M'Clure Strait Ice Stream (Fig. 9). It is thus argued that it was the major contributor of the IRD events in PS1230 and that they attest to vigorous but episodic activity of an ice stream in this location during the Late Pleistocene.

The palaeo-ice stream mapping (Fig. 3) indicates that the only other location where a large ice stream existed near this IRD source area was in Amundsen Gulf, related to flow-sets 53, 54 and 55 (cf. Stokes et al., submitted for publication). The Amundsen Gulf Ice Stream was similar in size to the M'Clure Strait Ice Stream and extended from Coronation Gulf, south of Victoria Island, through Dolphin and Union Strait and out to the shelf edge through Amundsen Gulf. However, there are several reasons why this ice stream is unlikely to be contributing to the Fe oxide grain peaks in core PS1230.

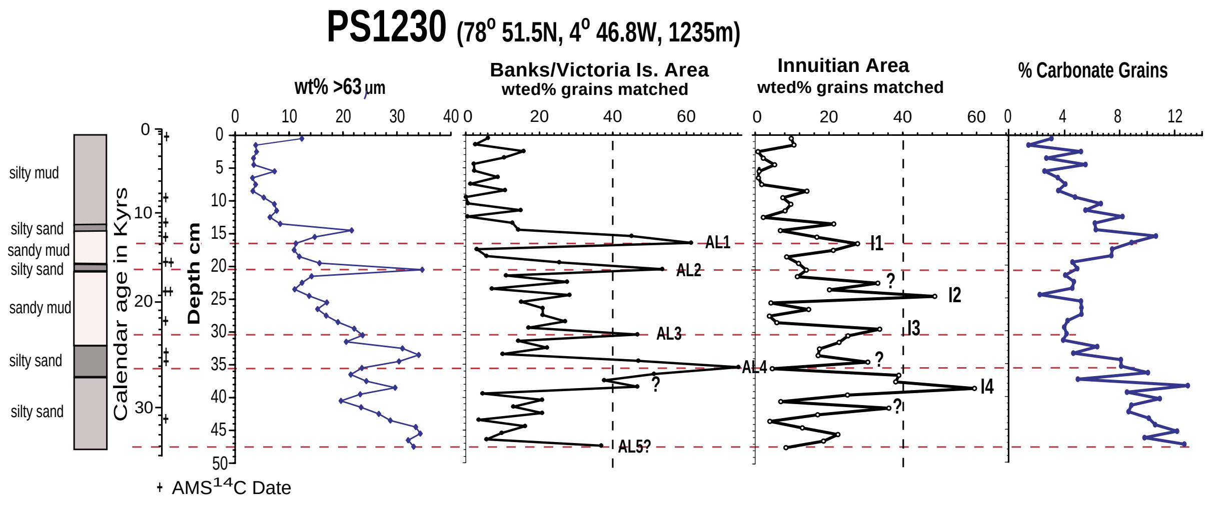

Fig. 11. Arctic Laurentide IRD events labelled 'AL1 to AL5?' based on detrital Fe oxide mineral grain compositions matched to a source on Banks and Victoria Islands (i.e., M'Clure Strait Ice Stream). Note the correspondence with similar IRD events from sources occupied by the Innuitian Ice Sheet, labelled 'I1 to I4 (modified from Darby et al., 2002).

Firstly, the Amundsen Gulf Ice Stream extent does not appear to directly infringe on the Victoria/Banks Island source area (source area 8 in Darby et al. (2002)). Rather, it is more likely to be related to the source area 9 of Darby et al. (2002) (see their Fig. 1) because it captured ice from the adjacent Arctic mainland to the south (cf. Stokes et al., submitted for publication). This source area never shows any significant mineral grain contributions in PS1230.

Secondly, given the large size of these two ice streams and the fact that they shared the same catchment area to the south-east of Victoria Island, it is unlikely that they operated at the same time. On south-western Victoria Island (Wollaston Peninsula) there is clear evidence of the retreat phases of this ice stream through deglaciation of Amundsen Gulf by 10.8 ka ^{14}C BP to final deglaciation around 10 ka (cf. Dyke et al., 2003b; Sharpe, 1992; Stokes et al., submitted for publication). This is in marked contrast to the M'Clure Strait Ice Stream flow-sets (fs-17 and fs-09), which are clearly relatively old and considerably pre-date deglaciation.

Thirdly, we note that the Amundsen Gulf Ice Stream had a major tributary in Prince Albert Sound (Stokes et al., submitted for publication), marked by two converging flow-sets (fs-20 and 21: Fig. 3). These flow-sets are superimposed on flow-set 17 (Fig. 3) and are, therefore, younger than the M'Clure Strait Ice Stream. All the available evidence, therefore, suggests that the Amundsen Gulf Ice Stream operated during deglaciation (cf. Stokes et al., submitted for publication), whereas the M'Clure Strait Ice Stream operated a number of times *prior to* deglaciation.

A further test of this hypothesis is to investigate whether different Fe grains from beneath the exact locations of the Amundsen Gulf and M'Clure Strait Ice Streams show up in Arctic deep sea cores, i.e., we may expect the M'Clure Strait Ice Stream source area (Storkerson Peninsula, north-east Victoria Island) to contribute to the Fe oxide grain peaks, but not necessarily the Amundsen Gulf Ice Stream source area (Wollaston Peninsula, south-west Victoria Island).

In order to investigate whether Fe grains from Storkenson and Wollaston Peninsulas can be discerned in Arctic deep-sea cores and thus related to the ice stream events in these areas, five surface samples from drumlin and till deposits on eastern Storkenson Peninsula (between 72° 41′ to 73° 31′N and 105° to 106° 23′W), two similar samples (one till and one drumlin) from northwest Storkenson Peninsula (north of 72° 56′N and near 108°W), and two samples from south Wollaston Peninsula from tills (68° 38′N, 110° 24′W and 69° 15′N, 110° 41′W), were analysed for characterisation of Fe oxide grain geochemistry (Darby, 2003). The Fe grains from four cores across the Arctic Ocean were then matched to these potential source areas, which were clustered into tight, unique compositional groups, see Fig. 12. Core locations are shown in Fig. 1.

Grain matches to Storkerson Peninsula and Wollaston Peninsula in our new analysis are few and far between in all cores. We note that there are no significant grain matches to Wollaston Peninsula, suggesting that any ice stream in this location did not contribute significant IRD to the Arctic Ocean. However, rather unexpectedly, there are very few matches to Storkerson Peninsula and of the three Arctic cores in Fig. 12, only the Northwind Ridge core shows any significant contribution. The peak near 10 ka in 92BC17 corresponds well with the estimated age of the late glacial M'Clintock Channel Ice Stream (flowset 16) which overtopped this peninsula. It is interesting to note that this 10 ka event is diminished in cores farther down-drift (see core locations on Fig. 1) and this suggests that this event was rather small compared to the larger events recorded in PS1230 and from the M'Clure Strait Ice Stream. This ties in very well with our mapping which demonstrates that the deglacial M'Clintock Channel Ice Stream was much smaller than the larger M'Clure Strait Ice Stream. The only other tentative match between the Banks/Victoria Island peaks and Storkerson Peninsula peaks is the large event labelled AL1 (12–15 ka) in core 1230 at Fram Strait (>3000 km drift distance), which contains a small amount of grains from Storkerson Peninsula.

Although the original Banks/Victoria Island source area (Darby et al., 2002) shows strong peaks throughout the last glacial (Fig. 11), our new analysis is unable to link these events specifically to Storkerson Peninsula. This is likely to be a result of the limited samples available for the new analysis and the complex history of successive ice stream erosion, entrainment and deposition events in and around M'Clintock Channel, i.e., the surface samples from drumlins on Storkerson Peninsula are ultimately derived from sources up-ice and different ice stream configurations

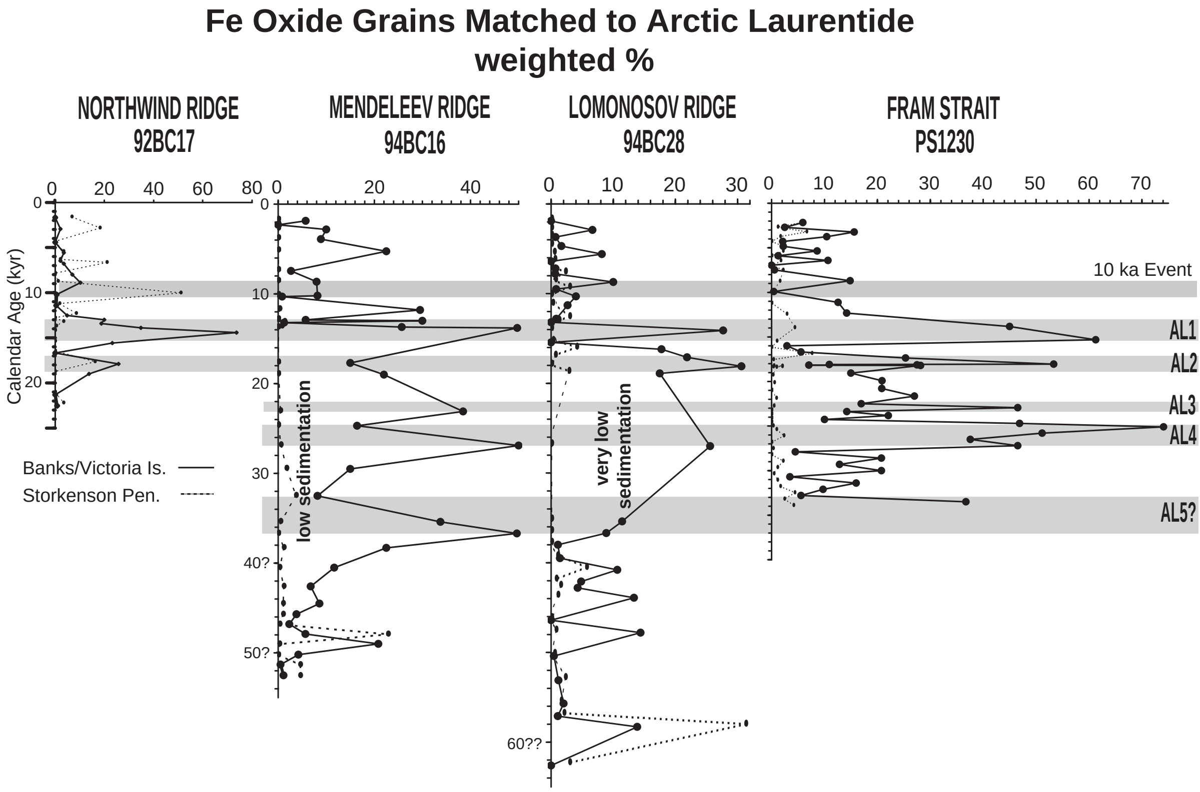

Fig. 12. Correlation of M'Clure Strait Ice Stream Fe oxide peaks from Banks/Victoria Island and Storkerson Peninsula in box cores across the Arctic Ocean (from Darby et al., 2002). Core locations are shown in Fig. 1. Radiocarbon age models used for these correlations are previously published in Darby et al. (1997) and Poore et al. (1999). Core 92BC17 has 12 dates every 2 cm and the ages are in order except for one reversal around 9 kyr. Core 94BC16 had 9 dates and no age reversals. Core 94BC28 had 15 dates with 6 dates older than 35 kyr. Although the age data used to constrain the stratigraphy across these cores is tentative (apart from core PS1230) we argue that this does not detract from the fact that several cores appear to indicate peaks in the Fe oxide grains which broadly match the events in PS1230. Ages for the period 20–25 kyr should be treated with more caution and have been denoted by question marks.

may have sourced rocks from different catchment areas. We do note, however, that there are very large peaks of Fe grains from Storkenson Peninsula in cores 94BC16 and 94BC28 prior to circa 45 ka (Fig. 12). This suggests that a large ice stream in this area (M'Clure Strait Ice Stream?) was also active during this poorly constrained earlier glacial time.

Another important but secondary source of Fe oxide grains is from the Queen Elizabeth Islands; the area occupied by the Innuitian Ice Sheet (IIS) where other smaller ice streams have been hypothesised in the inter-island channels (Bischof and Darby, 1999; Atkinson, 2003). Peaks in detrital Fe oxide mineral grains from this source area are also shown in Fig. 11. It can be seen that the weighted percentage of grains matched to the Arctic Laurentide source area (M'Clure Strait Ice Stream) are higher than those identified from the Innuitian Ice Sheet source and we conclude that whilst the M'Clure Strait Ice Stream was the dominant contributor of the IRD, other ice streams from the Innuitian Ice Sheet (and possibly elsewhere) contributed smaller amounts of IRD.

5.3. Iceberg production and drift

Given that the M'Clure Strait Ice Stream is the primary contributor of the IRD spikes in core PS1230 (Fig. 11) and possibly during earlier glacial intervals (Fig. 12), we now investigate the implications for iceberg production and drift. The routing of the icebergs from the M'Clure Strait Ice Stream is a critical control on the likely impact of the freshwater influx. Present day circulation in the Arctic Ocean is characterised by two main patterns. The Beaufort Gyre is a clockwise circulation in the western Arctic Ocean and ice can remain in the Gyre for several decades before leaving the Arctic basin. In contrast, in the eastern Arctic Ocean the Transpolar drift carries icebergs directly into the Greenland Sea in generally less than 3 years (Bischof and Darby, 1997). Currently, the Beaufort Gyre tends to homogenise the IRD across the western Arctic basin. Phillips and Grantz (2001) have argued that the modern gyre-like circulation pattern of the western Arctic Ocean also controlled both sea-ice and iceberg drift during the Late Pleistocene but other evidence (cf. Bischof and Darby, 1997) suggests that the Ocean circulation may have been different and that the Beaufort Gyre may have resembled more of a dislocated Transpolar Drift. The reason for this change in drift pattern is becoming clear now that evidence for large ice masses grounded on the Chukchi Borderland to the west (near core 92BC17, Fig. 1) have been reported (Polyak et al., 2001). Thus, ice was diverted northward by this ice-jam and did not reach this Borderland area until the grounded ice there moved again. The significance of this is that icebergs issued from the M'Clure Strait Ice Stream may have been carried northward towards Fram Strait and would exit the Arctic Ocean relatively rapidly, without the multiple rotations in the western Arctic Ocean, which characterise present-day conditions. Fig. 1 shows a possible circulation of the Pleistocene Arctic Ocean (incorporating a semblance of the Beaufort Gyre (cf. Phillips and Grantz, 2001) and indicates how icebergs issued from the vicinity of M'Clure Strait could have exited the Arctic Ocean relatively rapidly.

In terms of iceberg production, the peaks in Fe oxide grains begin suddenly (Fig. 11), as indicated by a steep rise in the number of grains, and this suggests rapid purges of icebergs through Fram Strait (Darby et al., 2002). Based solely on core PS1230 (i.e., not the other cores) and assuming that the Fe oxide grain peaks from the Arctic LIS are proportional to the increase in iceberg flux through Fram Strait (allowing for 20% melting), Darby et al. (2002) provided a conservative estimate of 350 km^3 a^{-1} for the annual flux of fresh water bound in glacial icebergs through Fram Strait during each IRD event. If ice sheet growth rates were larger, however, and the duration of iceberg pulses shorter, the amount of ice drifting through Fram Strait could have been as much as 1000 km^3 a^{-1} (Darby et al., 2002). Textural (IRD) data for the other Arctic Ocean cores is presented in Darby et al. (1997) but these were not used for the iceberg discharge estimates.

Independent of these estimates, Clark and Stokes (2001) estimated ice discharge for the late glacial M'Clintock Channel Ice Stream based on the terrestrial evidence of the ice stream's dimensions. They estimated a cross-sectional area of 100 km^2 for the late-glacial ice stream and assuming a velocity of 4 km a^{-1}, and a life-span of 200 years, calculated an ice flux of 400 km^3 a^{-1}. Given the similar width of the M'Clure Strait Ice Stream but in deeper water further along the shelf edge, we take this flux as a minimum estimate for the larger ice stream.

We note the similarity of these independent estimates with the range of estimates for the iceberg flux through Hudson Strait during a Heinrich event, calculated at 312–2800 km^3 a^{-1} (Dowdeswell et al., 1995; MacAyeal, 1993). Table 3 illustrates the similarity in configuration and potential iceberg production between the Hudson Strait Ice Stream and the M'Clure Strait Ice Stream. Given the comparatively similar IRD fluxes for a Heinrich event, it is evident that the icebergs from the M'Clure Strait Ice Stream would have introduced a significant amount of freshwater into the Arctic Ocean.

5.4. Timing of IRD events and implications for Laurentide ice sheet dynamics

Taking the previously published mean ages from all four Arctic Ocean sediment cores (from Darby et al., 2002), the IRD events from the M'Clure Strait Ice Stream occur at approximately ~12.9, ~15.6, ~22 and 29.8 ka (^{14}C yr BP). Each event contains around 3–5 times the background level of Fe oxide grains and the steep rise in the number of grains (see Fig. 11) suggests that they begin suddenly, although only lasting for a relatively short duration (< 1–4 kyr) (Darby et al., 2002).

The timing of the events may reveal intriguing insights into the dynamics of the Laurentide Ice

Table 3
Comparison between the dimensions and iceberg production of the Hudson Strait and M'Clure Strait Ice Streams

	Hudson Strait Ice Stream	M'Clure Strait Ice Stream
Length (km)	~770	700
Width (km)	~150	110
Ice thickness (km)	0.5–1	~0.8
Cross sectional area (km^2)	~150	~100
Surface area (km^2)	?	162,000
Estimated catchment area (km^2)	1,560,000–2,700,000	400,000
Estimated ice discharge during a major ice export event ($km^3\ a^{-1}$)	312 (Dowdeswell et al., 1995) 388 (Matsumoto, 1997) 23.8–310.8 (Marshall and Clarke, 1997)	>400 (cf. Clark and Stokes, 2001) ‡350–1000 (Darby et al., 2002) ‡180–530 (Bischof, 2000)
Estimated subglacial sediment discharge ($m^3\ a^{-1}\ m^{-1}$)	800–37,300 (Dowdeswell et al., 1995)	73,000 (cf. Clark and Stokes, 2001)

‡from Arctic Laurentide Ice Sheet margin.

Sheet, particularly with respect to the North Atlantic's Heinrich events. Currently, the extent to which other ice streams participated in Heinrich events is largely unknown and this raises several important questions (Dokken et al., 2003). For example, did Heinrich events involve reorganisation of the whole ice sheet or just the eastern sector around Hudson Strait? What processes triggered the episodic ice stream activity?

The new information reported here on the timing of the M'Clure Strait Ice Stream from the ocean sedimentary record may shed some light on such questions. Previous work on these IRD events (Darby et al., 2002) suggests that they occurred at very similar intervals to Heinrich events. For example, AL1 appears to correspond to H-0 and so forth for the other Arctic LIS events (see Fig. 8 in Darby et al., 2002). This hints at the possibility that Heinrich events may have involved a reorganisation of other sectors of the LIS, rather than a more local response from the eastern sector. Support for this is documented at the southern margin of the LIS where complex glacial stratigraphy and geomorphology indicate the possibility of rapid advance and subsequent retreat of ice lobes during Heinrich events (Mooers and Lehr, 1997). Other workers have investigated the phasing of ice stream activity at the eastern margin of the LIS (e.g., Cumberland Sound Ice Stream) and noted possible responses of ice streams that post-date the Heinrich events (e.g., Andrews et al., 1998a,b).

Although the Arctic IRD events appear at similar times to H-events, Darby et al. (2002) noted that the mean age of each Arctic LIS event appears to precede the mean age of the corresponding H-events in the North Atlantic. While there is a large range of age dates for each H-event in different cores, the ages of the Arctic LIS events in the Arctic Ocean always occur at the older end of these Heinrich event ages (cf. Darby et al., 2002). The alternative is that the M'Clure Strait Ice Stream events lag the H-events by a much greater periodicity, which would be more in line with the work of Andrews et al. (1998a,b) who found IRD events from Baffin Bay that lagged Heinrich events by around 2 ka after H-1. Clearly, the large range of ages for Heinrich events and the low resolution of the Fram Strait and other Arctic Ocean cores currently precludes the precise nature of possible lags or precursor events from the Northern margin of the LIS. Higher-resolution cores could fruitfully test some of these hypotheses.

A plausible mechanism for episodic ice streaming such as that identified from the M'Clure Strait Ice Stream has been proposed by MacAyeal (1993) and Alley and MacAyeal (1994) and termed the 'binge/purge model'. This theory invokes changes in the basal temperature of the ice sheet and has been applied to the region around Hudson Strait to explain the timing of Heinrich events. It is proposed that as the ice sheet thickens and increases the pressure and temperature at the base of the ice, it will eventually reach a critical threshold that causes a switch to warm-based ice and provides effective lubrication for ice streaming. According to their modelling, this purge phase of ice streaming occurs very rapidly (~750 years) and thins the ice sheet to such an extent that the base of the ice reverts to cold-based conditions. This marks the beginning of the binge phase, which lasts approximately 7000 years before warm-based conditions are triggered again. Alley and MacAyeal

(1994) suggest that the freeze-on process at the end of the purge phase is a valid mechanism for incorporating sediment into the basal ice layers which eventually melts out during the Heinrich events.

With respect to the M'Clure Strait Ice Stream, there is evidence that cold-based conditions have preserved a part of its bed on western Prince of Wales Island (flow-set 09: Figs. 3 and 9). Indeed, De Angelis and Kleman (in press) have suggested that this imprint may have been protected by cold-based ice because the ice stream shut-down through a process of basal freeze-on (e.g., Christofferson and Tulaczyk, 2003). Given that flow-set 09 forms part of the M'Clure Strait Ice Stream described in this paper, we suggest that it may have shut-down through a process of basal freeze-on and that this would have led to a large cold-based patch (ice divide) in central M'Clintock Channel. This would then account for the east to west flows that overprint the M'Clure Strait Ice Stream imprint (i.e., flow-set 27, see Figs. 4 and 5). Furthermore, it would then appear that the cold-based patch reverted to warm-based conditions and triggered the smaller M'Clintock Channel Ice Stream (flow-set 16). Thus, the terrestrial evidence appears to support the idea of transitions in the basal thermal regime of the ice sheet in M'Clintock Channel and we speculate that it may have played an important role in the episodic behaviour of the M'Clure Strait Ice Stream, recorded in the Fram Strait core. We also note that these transitions from cold to warm-based ice and vice versa can explain the apparent conflict between evidence of ice streaming in M'Clintock Channel and the location of an ice divide, as proposed by Dyke (1984). Both happened, but at different times.

6. Conclusions

Ice streams not only exert a profound influence on ice sheet mass balance and stability but they also have the potential to disrupt the ocean–climate system through profligate iceberg discharge and subsequent melting. In recent years, much research has focussed on the North Atlantic's Heinrich events and our current understanding suggests that the Hudson Strait Ice Stream is likely to have played a crucial role in iceberg production (Andrews and Tedesco, 1992; Dowdeswell et al., 1995). To date, however, the extent to which other Laurentide ice streams influenced ocean circulation and climate (or even Heinrich events) is largely unknown.

Recently, several cores have been raised from the Arctic Ocean which document massive ice export events, similarly to those recorded in the North Atlantic. Provenance studies of this ice-rafted debris (Darby et al., 2002) has been traced to several distinct sources areas in the Canadian Arctic Archipelago but no specific ice streams have been implicated. In this paper, we report new mapping of ice flow patterns in the vicinity of Victoria Island and Prince of Wales Island and demonstrate that a large ice stream (the M'Clure Strait Ice Stream), originating from M'Clintock Channel and south-eastern Victoria Island, extended along M'Clure Strait to the edge of the continental shelf, as indicated by the presence of a large trough mouth fan. The discovery of this massive ice stream (1000 km long > 100 km wide) in the Canadian Arctic Archipelago is entirely consistent with provenance studies of Arctic Ocean sediment cores (Darby et al., 2002) which point towards north-western Victoria Island and Banks Island as a major source area for four massive ice export events between 10 and 30 ka (^{14}C yr BP). We thus conclude that episodic activity of the M'Clure Strait Ice Stream played a major role in their production. The timing of these events (at approximately ~12.9, ~15.6, ~22 and 29.8 ka ^{14}C yr BP) appear to be similar to the North Atlantic's Heinrich events but it is unclear whether they immediately precede Heinrich events (cf. Darby et al., 2002) or lag behind them by a much greater periodicity. Notwithstanding this, the apparently episodic behaviour of the M'Clure Strait Ice Stream hints at the possibility that Heinrich events may have involved a reorganisation of other sectors of the LIS (cf. Mooers and Lehr, 1997; Andrews et al., 1998a), rather than a more local response from the eastern sector.

Acknowledgements

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