Episodic ice streams and ice shelves during retreat of the northwesternmost sector of the late Wisconsinan Laurentide Ice Sheet over the central Canadian Arctic Archipelago

DOUGLAS A. HODGSON

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A complex of glacial landforms on northeastern Victoria Island records diverse flows within the waning late Wisconsinan Laurentide Ice Sheet over an area now divided by marine straits. Resolution of this ice flow pattern shows that dominant streamlined landforms were built by three radically different ice flows between 11,000 and 9000 BP. Subsequent to the glacial maximum, the marine-based ice front retreated at least 300 km to reach northeast Victoria Island by 10,400 BP. Disequilibration at the rapidly retreating margin induced minor surges on western Storkerson Peninsula (Flow 1). Next, a readvance into Hadley Bay transported 10,300 BP shells, while a major ice stream over eastern Storkerson Peninsula (Flow 2) remoulded till into a drumlin field several hundred kilometres long and at least 80 km wide until flow ceased prior to 9600 BP. The ice stream surged into Parry Channel, covering 20,000 km^2 with the Viscount Melville Sound Ice Shelf. Finally, Flow 2 drumlins on the northwest shore of M'Clintock Channel were cross-cut *c.* 9300 BP by advance of the grounded margin of a buoyant glacier (Flow 3), possibly an analogue of Flow 2 displaced farther south.

Douglas A. Hodgson, Terrain Sciences Division, Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8, Canada; *15th January, 1993 (revised 10th November, 1993).*

New insight into deglacial events around Viscount Melville Sound and M'Clure Strait (described here collectively as western Parry Channel, Fig. 1) is provided by recent mapping of Quaternary deposits of northeast Victoria Island and adjacent islands and channels (Hodgson 1993a). Much ice entering western Parry Channel flowed over this area, including Storkerson Peninsula and Stefansson Island, east of the impediment presented by the 600 m high Shaler Mountains (Fig. 2). Deglaciation, which continued into the early Holocene, was punctuated by several rapid readvances of the northwesternmost Laurentide Ice Sheet margin, driven by ice streams debouching into ice shelves up to 20,000 km^2 in area. This paper examines (1) late-glacial events over northeast Victoria Island, and how they bear on (2) initial retreat and subsequent readvances of the northwesternmost sector of the Laurentide Ice Sheet, and (3) regional implications with respect to ice divides, ice streams and ice shelves.

Two decades of mapping by the Geological Survey of Canada of Quaternary deposits in the area formerly covered by the northwesternmost sector of the Laurentide Ice Sheet has produced a wealth of data on chronology, form and process (Dyke *et al.* 1992, for Prince of Wales Island; Hodgson 1992, for western Melville Island; Hodgson 1993a, b, for northeast Victoria Island; Hodgson *et al.* 1984, for central Melville Island; Sharpe & Nixon 1989, and Sharpe 1992, for southwest Victoria Island; Vincent 1983, for Banks Island summarized by Dyke & Dredge (1989), Hodgson (1989) and Vincent (1989). Agreement, however, has yet to be reached on the extent of the last ice sheet and on correlation of subsequent deglacial events. Of particular relevance to regional events are (a) a glacial limit along the Banks Island coast from a lobe of ice in M'Clure Strait, shown as late Wisconsinan by Prest *et al.* 1968, based on communications from J. G. Fyles; (b) Vincent's (1984, 1989, 1992) Wisconsinan glacial limits on northern Banks Island, consisting of an early Wisconsinan ice margin overlapping the Banks Island shore of M'Clure Strait and a late Wisconsinan lobe, dated by inferred glacial ice thrust sediments, which impinged only on the northeasternmost tip of Banks Island (Fig. 1); (c) an ice shelf that filled Viscount Melville Sound at *c.* 10,000 BP depositing Winter Harbour Till (Fig. 1), probably generated during an advance following retreat of grounded ice (Hodgson & Vincent 1984); (d) Dyke's (1987) reappraisal of events, based on new data from Prince of Wales Island, in which he advanced the age of the ice shelf by at least a thousand years, and returned Vincent's early Wisconsinan limit to late Wisconsinan (Dyke & Prest 1987a, b, c; Fig. 1).

Landscape of Stefansson Island and Storkerson Peninsula of Victoria Island

The height of land on Stefansson Island is over 300 m in the north, declining southwards; on Storkerson Peninsula it is slightly less than 300 m along the rugged west coast, declining to the low-lying east coast (Fig. 2). Till covers 80% of the area. The uniform, dark greyish brown, calcareous loam has a regional similarity resulting from the uniformity of the sub-

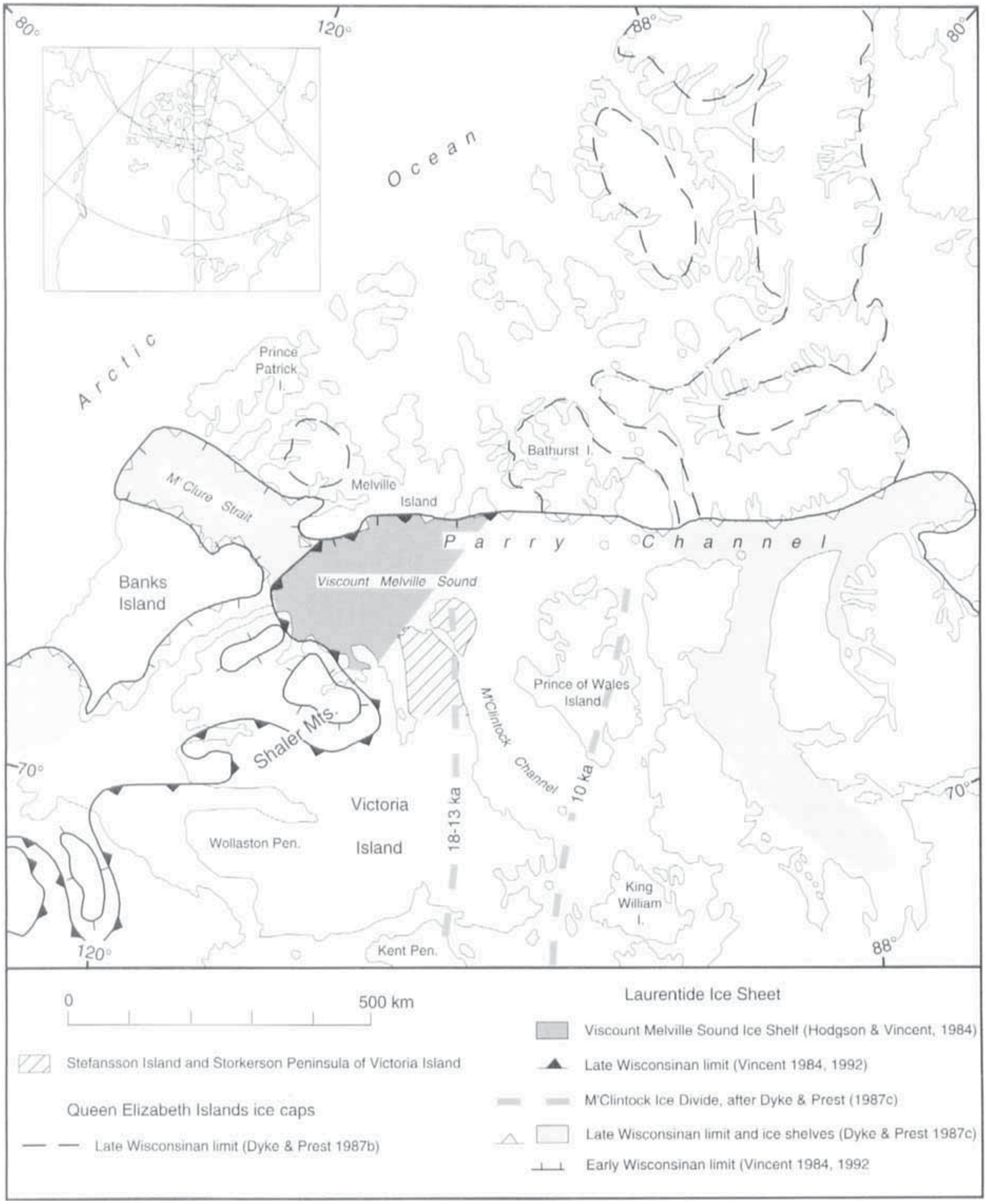

Fig. 1. Canadian Arctic Archipelago showing position of Stefansson Island and Storkerson Peninsula of Victoria Island with respect to previously proposed limits of Laurentide Ice Sheet and Queen Elizabeth Islands ice caps.

horizontal Paleozoic carbonate rocks underlying eastern Victoria Island. The till incorporates 4% exotic lithologies, mainly granitic and gneissic rocks transported north at least 400 km from the closest exposed Canadian Shield (other than a few km^2 of granodiorite in a small inlier at the head of Hadley Bay; Campbell 1981). To the west of Hadley Bay lie the Proterozoic sedimentary and volcanic rocks that reinforce the Shaler Mountains.

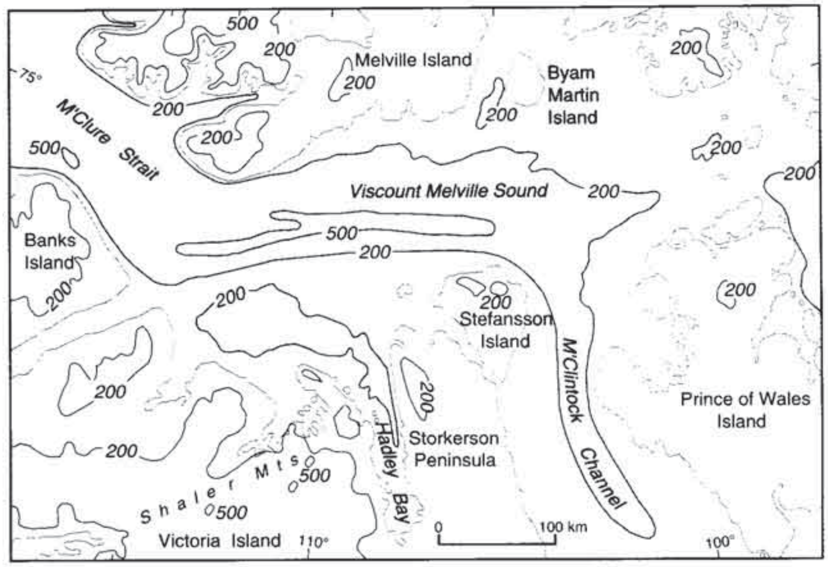

Fig. 2. Topography and bathymetry of Viscount Melville Sound and vicinity. Contours 200 m and 500 m above and below sea level.

Only a general outline of bathymetry of surrounding waters is known (Fig. 2). Hadley Bay has the form of a glacial trough, especially at the overdeepened, rough northern neck; in contrast, Goldsmith Channel is shallow, opening at each end onto extensive platforms. To the east, the floor of M'Clintock Channel declines gently to 300 m depth, whereas north from Stefansson Island the surface profile drops steeply from 300 m summits to more than 500 m below sea level in Viscount Melville Sound. Surficial seabed sediments have not been investigated because year-round sea ice cover in this sector of Parry Channel prevents passage of survey vessels. Marine geological investigations of northernmost Viscount Melville Sound adjacent to Byam Martin Island showed 5–50 m of multiple glacial drift sequences, which were subsequently scoured by grounded glacial ice or icebergs (MacLean *et al.* 1989).

Readvances and marine incursions during deglaciation

Diverse ice flows are recorded on eastern Victoria Island by streamlined till; these were outlined by Fyles (1963) and summarized on the Glacial Map of Canada (Prest *et al.* 1968). Hodgson (1987) concluded that the pattern on Storkerson Peninsula and Stefansson Island (Fig. 3) was created by three late glacial events triggered by disequilibration when the partially marine-based calving ice margin retreated into southern Viscount Melville Sound.

Flow 1

The oldest landforms are preserved on northwest Storkerson Peninsula and northern Stefansson Island in two assemblages, lenticular in plan (Fig. 3). These are composed of drumlin fields (to 500 km^2) divided by areas of hummocky till (the broad rises are described as mammilated by Hodgson 1993a) overlain by numerous kames and eskers. This till is poorly exposed in section; glacial drainage channels cut in hummocky till indicate thicknesses of 50 m over bedrock. Numerous retrogressive thaw flowslides occur uniquely on the hummocky till. Sharpe (1988) proposed that buried last-glacial ice was present under hummocky partially-failing till in a wide moraine belt on Wollaston Peninsula of southwest Victoria Island. Similarly for northeast Victoria Island it is conjectured that hummocky till includes late Wisconsinan glacial ice, although there is no evidence that it is part of a moraine belt.

It is speculated that flow within the ice sheet locally accelerated (Flow 1) when the entry of a calving bay into Hadley Bay formed an oversteepened ice front. The resulting flows on Storkerson Peninsula are recorded by drumlin fields which are flanked by higher hummocky terrain. The hummocks, whether underlain by till or relict glacial ice, were not subjected to the scouring action that left relatively thinner till in the drumlin fields. The up-ice limit of at least one drumlin field was truncated by Flow 2.

The final activity in this sector of the ice sheet was deposition of eskers and kames across both drumlins and hummocks. Some eskers drained to undated (marine?) deltas now at 120 to 140 m above sea level (a.s.l.) on the east coast of Hadley Bay. These are presumably older than shells and whalebone deposited on the same coast in a sea >81 m a.s.l. and probably $\geqslant 90$ m a.s.l. between 10,000 and 9820 BP (sites 7, 8 and 9 on Fig. 3; radiocarbon age estimates, including corrections, are given in Table 1).

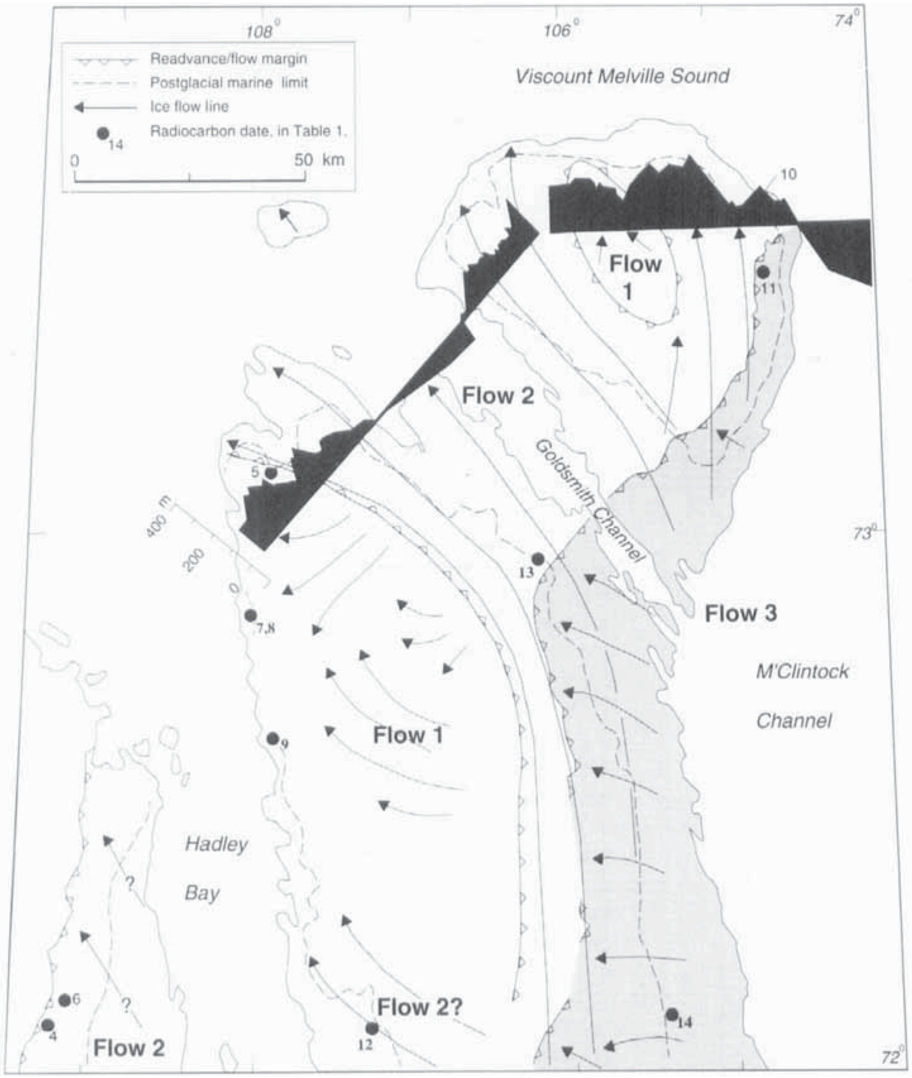

Fig. 3. Extent of late glacial flows over Stefansson Island and Storkerson Peninsula of Victoria Island; flow lines determined from drumlin and striation orientations. Topographic profile shows cross-section of base of Flow 2 ice stream.

Ice retreat and marine transgression permitted migration of molluscs onto northernmost hummocky till of Storkerson Peninsula by 10,350 ± 80 BP (TO-533, site 5 on Figs. 3, 4). These fragile shells were collected 110 m a.s.l. in a pocket of silt in a valley a few kilometres beyond the limit of Flow 2 landforms. Marine limit on Flow 2 landforms in this area is only 75 m a.s.l. A lower marine limit implies later deglaciation, strongly suggesting that Flow 2 is younger than Flow 1. A number of shell deposits elsewhere in the region, where slopes faced advancing ice, will be shown to have been ice transported; however, this is unlikely to have occurred at site 5, which lies down-ice (Flows 1 and 2) from extensive uplands. Meanwhile, molluscs dated 10,400 ± 90 BP (GSC-4492, site 4) and 10,300 ± 90 BP (GSC-4356, site 6) migrated into Hadley Bay (they were subsequently ice transported).

Flow 2

Flow 2 is recorded by a spectacular field of till drumlins and fluted till extending up the east side of Storkerson Peninsula to Goldsmith Channel, where it divides around central Stefansson Island (Fig. 5). The lenticular to spindle shaped drumlins have length: width ratios up to 20:1, lengths to 10 km, and heights commonly 10–25 m. The conventional interpretation of the bedforms is that they record parallel flowlines of warm-based (sliding) ice extending at least 200 km in a stream a minimum of 80 km wide, and far larger if it filled northern M'Clintock Channel. In order to overtop Stefansson Island, this glacier must have been at least 400 m thick over Goldsmith Channel between Storkerson Peninsula and Stefansson Island, and well over 600 m thick in western M'Clintock Channel.

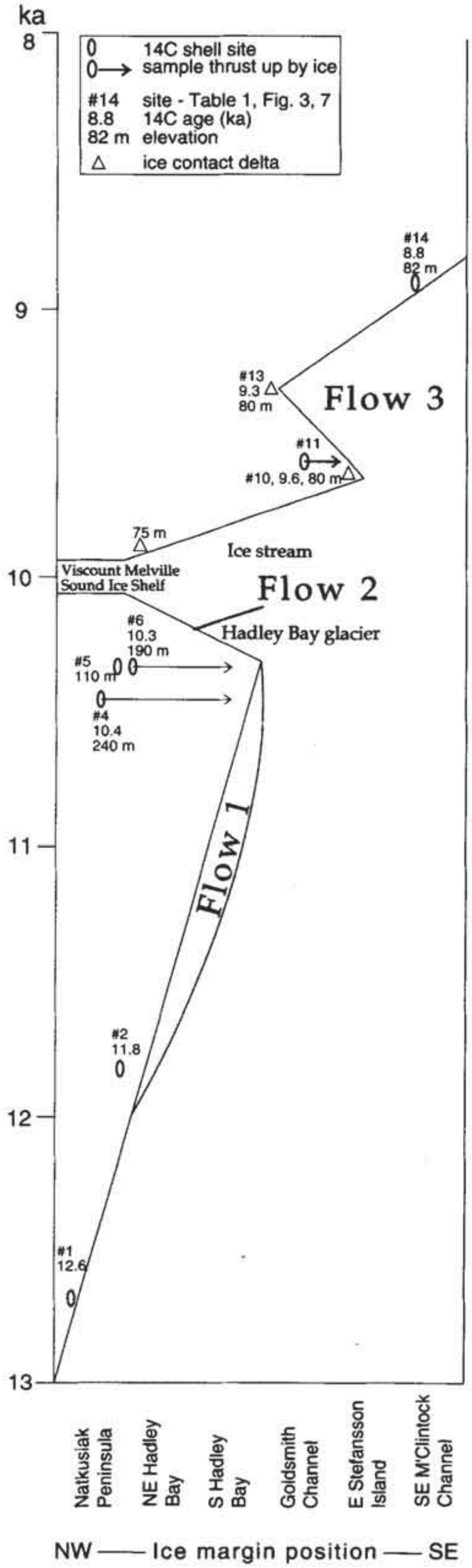

Fig. 4. Late Wisconsinan/early Holocene glacial surges and intervening marine incursions on Storkerson Peninsula and Stefansson Island. Shell dates constrain timing of glacier advances and retreats; horizontal axis plots local events, superimposed on general retreat of ice margin from northwest to southeast.

There are no indicators of the ice surface gradient. The pattern of streamlines strongly suggests that Flow 2 ice from Goldsmith Channel crossed northern Hadley Bay, where expanding flow transformed it into the Viscount Melville Sound Ice Shelf. This thin, buoyant glacier deposited Winter Harbour Till, similar to till of the Storkerson Peninsula, farther west along the north coast of Victoria Island. The flow from ice sheet into ice shelf is shown below to have lasted only a few hundred years, possibly at a rate of advance fast enough to be considered a surge (Paterson 1969).

Flow 2 till is much thinner overall than till forming the two adjacent, older, lenticular landform assemblages that include Flow 1, permitting the exposure of moulded bedrock between drumlins, especially in the north. This northward thinning, combined with the basic consistency in composition of till throughout northeast Victoria Island (Hodgson 1993a), suggests that Flow 2 deformed and eroded a widespread cover of till, leaving the drumlins as either remoulded material or erosional remnants. It is suggested that the well-defined margin of the drumlin field indicates that ice beyond the ice stream was in the process of being dragged and deformed prior to abrupt decay of Flow 2. Massive, extended drumlin ridges, flanking Flow 2 on northern Storkerson Peninsula and west-central Stefansson Island (Fig. 5), are similar to a ridge at the margin of the Crooked Lake drumlin field on Prince of Wales Island (Dyke *et al.* 1992). These were interpreted by Dyke & Morris (1988) as a lateral shear moraine contacting a cold-based ice mass; however, eskers described above on Flow 1 till of central Storkerson Peninsula indicate that there, at least, the ice mass abutting Flow 2 was temperate.

Topography below contemporary sea level generally steered this flow, as was the case in southwest Victoria Island (Sharpe 1988). However, the split in streamlines around the Stefansson Island lentil-shaped body of Flow 1 till was not solely caused by subglacial topography, for flow crossed the highest (300 m) summits without deflection (Fig. 3). On adjacent upland, inactive ice protected Flow 1 landforms and provided a plug that impeded and caused separation of the later flow, at least at the base of the flow. Possibly Flow 2 overrode inactive ice at higher levels in the glacier.

The age of Flow 2 was determined from bracketing marine deposits (Figs. 3, 4). It postdates or was possibly concurrent with deposition of 10,350 ± 80 BP shells (TO-533, site 5) at ≥110 m in an arm of the sea over Flow 1 hummocky till. This is the only date bearing on the maximum age of the main Flow 2 ice

Table 1. Radiocarbon ages, deglaciation of northern Victoria Island and Stefansson Island.

Site on Figs. 3 &/or 6	^{14}C age (years BP)[a]	$\delta^{13}C$ ‰	Laboratory No. Collector No.	Material Wt.; pairs/whole/ fragmented valves	Elevation (m)	Related sea level (m)	Geological environment	Location (NTS, Lat., Long.)	Collector	References
1	12,600 ± 140	+2.4	**GSC-1707**[b] FG-59-87b	*Portlandia arctica* 22 g pairs & whole	67–70	82–85	Clay over silt & sand	88D/6, 73°18′N, 114°30′W	J. G. Fyles, 1959	Lowdon & Blake (1976)
2	11,800 ± 100	+0.2	**GSC-3511** HCA-82-5.7.4	*Hiatella arctica* 47 g whole	105	≥120	On till under >10 m silt	78B/13, 72°52′N, 110°20′W	D. A. Hodgson & J. Bednarski, 1982	Hodgson & Vincent (1984)
3	10,900 ± 100	+1.2	**GSC-3519** HCA-82-22.7.18	*Hiatella arctica* 46 g whole	91	130?	Base of fine sand & silt, 15 m thick, adjacent to 130 m a.s.l. outwash delta	78B/6, 72°22′N, 110°05′W	D. A. Hodgson & J. Bednarski, 1982	This report
4	10,400 ± 90	+1.8	**GSC-4492** HCA-86-10.7.1	*Hiatella arctica* 34 g whole	240	(90 m marine limit)	Shelly, stony (striated) stratum in >2 m silt; ice thrust from Hadley Bay	78B/2, 72°05′N, 109°13′W	D. A. Hodgson, 1986	This report
5	10,350 ± 80	–	**TO-533** HCA-86.19.7.9	*Portlandia arctica* pairs	110	≥110	Shelly stratum in 6 m thick silt	78D/4, 73°06′N, 107°43′W	D. A. Hodgson, 1986	This report
6	10,300 ± 90	−0.4	**GSC-4356** HCA-86-8.7.6	*Hiatella arctica* 48 g whole	190	(90 m marine limit)	Shelly, stony stratum in >2 m thick silt; ice thrust from Hadley Bay	78B/2, 72°08′N, 109°08′W	D. A. Hodgson, 1986	This report
7	10,000 ± 110	+0.5	**GSC-4445** HCA-86-18.7.6	*Hiatella arctica* 46 g whole	70	>75	Shelly, stony stratum under >5 m silt	78D/4, 73°06′N 107°43′W	D. A. Hodgson, 1986	This report
8	9935 ± 190	–	**S-2954** HCA-86-18.7.7	Bowhead whale	68	>68	Embedded in silty gravel beach	78B/16, 72°51′N, 108°01′W	D. A. Hodgson, 1986	This report
9	9820 ± 100	+0.6	**GSC-4403** HCA-86-10.8.6	*Hiatella arctica* 34 g whole	81	>81	On silt; nearby outwash deltas 90 m a.s.l.	78A/12, 72°37′N, 107°53′W	D. A. Hodgson, 1986	This report
10	9640 ± 110	+2.0	**GSC-4377** HCA-86-1.8.4	*Hiatella arctica* 25 g whole	70–75	≥80	On till, under 5 m silt, adjacent to 75 m a.s.l. outwash delta	78D/9, 73°35′N, 104°40′W	D. A. Hodgson, 1986	This report
11	9560 ± 100	+0.7	**GSC-4336** HCA-86-30.7.2A	*Hiatella arctica* 22 g whole	120	(75 m marine limit)	In 10 m thick silt; some strata of *P. arctica*; ice thrust from M'Clintock Ch	78D/8, 73°29′N, 104°47′W	D. A. Hodgson, 1986	This report
12	9400 ± 150	–	**GSC-269**	*Mya truncata*	104?	124?	On silt	78A/4, 72°07′N, 107°15′W	R. Thorsteinsson, 1959	Dyck & Fyles (1964)
13	9340 ± 100	+1.2	**GSC-4316** HCA-86.24.7.4	*Hiatella arctica* 32 g pairs	75	≥80	On till, under 10 m silt forming an outwash delta	78A/14, 72°58′N, 106°08′W	D. A. Hodgson, 1986	This report
14	8840 ± 120	+1.6	**GSC-4409** HCA-86-8.8.4	*Hiatella arctica* 14 g whole & frags	80	≥82	Surface of washed till adjacent to 82 m washing limit	78A/1, 72°08′N, 105°27′W	D. A. Hodgson, 1986	This report

[a] **GSC** (Geological Survey of Canada) dates: error represents 95% probability; where ages are corrected for isotopic fractionation, standard value for marine shells is $\delta^{13}C = 0.0‰$; for wood $\delta^{13}C = -25‰$. **TO** (IsoTrace) dates: error represents 68.3% probability; marine shells corrected for isotopic fractionation to a $\delta^{13}C = 0‰$. **S** (Saskatchewan) shell and bone dates: error represents 68% probability; dates uncorrected for isotopic fractionation. To 'correct' marine shell dates listed above to a $\delta^{13}C$ of $-25‰$, add 400–410 years.

[b] I(GSC)-18, 12,400 ± 320 determined from the same collection (Walton *et al.* 1961).

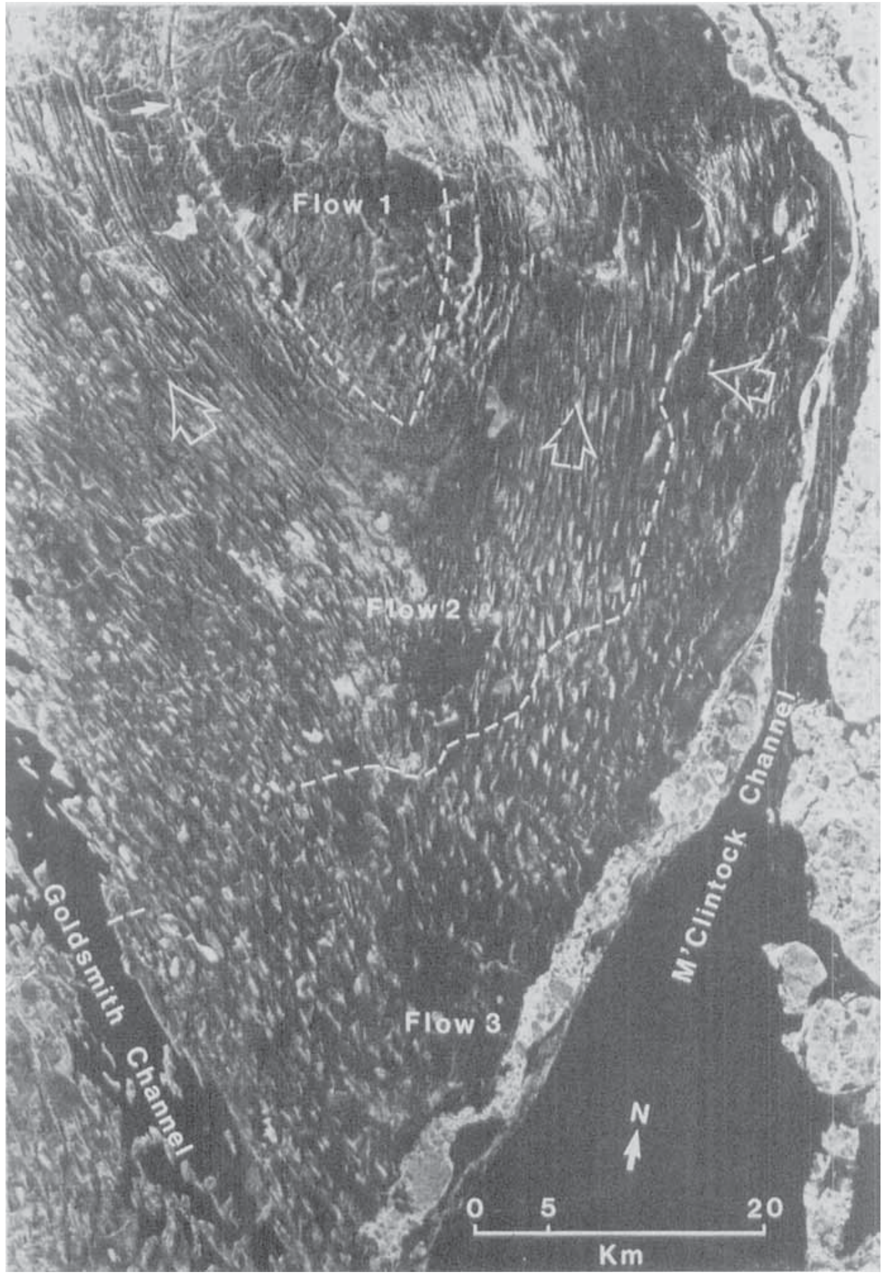

Fig. 5. Landforms outlining late glacial Flows 1, 2 and 3 (open arrows) on eastern Stefansson Island; the record here is dominated by drumlins left by the short-lived Flow 2 ice stream. Arrow in northwest corner indicates massive extended drumlin. Synthetic aperture radar image courtesy of Canarctic Shipping Co. Ltd.

stream. As shown above for Storkerson Peninsula, the marine limit on Flow 2 drumlins is significantly lower than the marine limit on adjacent Flow 1 till, therefore Flow 2 is likely to have been younger than Flow 1. Outwash deltas 75 m a.s.l. record initial decay of ice at the margin of the ice stream on northwest Storkerson Peninsula. At site 7, 35 km to the south, the sea level was higher than 75 m at $10,000 \pm 110$ BP (GSC-4445), indicating that Flow 2 was still active at that time. Flow certainly had ceased and disintegration of the glacier and the Viscount Melville Sound Ice Shelf had occurred by the time of deposition of shells dating 9640 ± 110 BP at site 10 (GSC-4377) and 9560 ± 100 BP (GSC-4336) at site 11. Hence Flow 2 lasted no more than 800 years, and probably only a few hundred years.

At the same time, a smaller glacier branched west into Hadley Bay (Fig. 3), though the head of this flow on southern Storkerson Peninsula appears to have been partly truncated by the main Flow 2 (see Fyles 1963, Fig. 1). The eastern margin of this lobe lay at or close to a chain of kames and eskers descending from 180 m to 140 m a.s.l. subparallel to the eastern shore of the bay. These interlobate deposits abutted static, wasting ice in the Flow 1 assemblage. The western margin of the Hadley Bay lobe is better

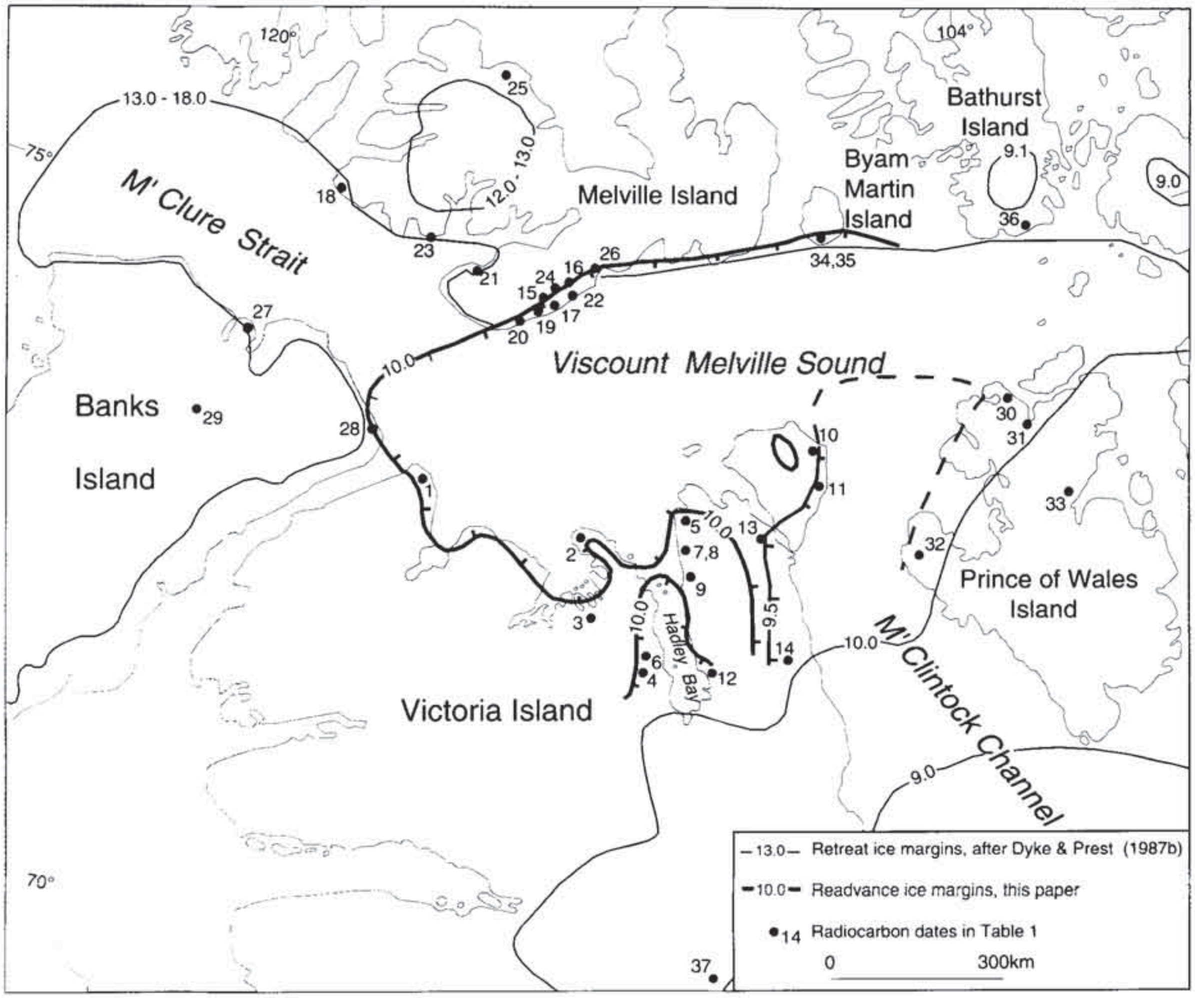

Fig. 6. Limits of major late glacial readvances in western Parry Channel, compared with sequential retreat model for deglaciation. Ice margin ages shown in thousands of years.

defined: a thick till (and buried glacier ice?) blanket overlaps discontinuous till and scoured rock left by the earlier northwesterly regional flow. The margin descends from 300 m a.s.l. abreast of the south end of Hadley Bay, to less than 150 m at the northern neck. Shells dating 10,400 ± 90 BP (GSC-4492, site 4) and 10,300 ± 90 BP (GSC-4356, site 6), originally deposited in Hadley Bay during the earlier marine incursion, were glacially transported to 240 m and 190 m a.s.l., respectively. This is far higher than any known sea level on Victoria Island; heights of more than 200 m are reported only from the mainland (Dyke & Dredge 1989). Outwash from the northwesternmost sector of this lobe drained west, 20 km beyond Hadley Bay, into a sea lying 85 m above the present level. This is 45 m lower than the 130 m sea level dated 10,900 ± 100 BP (GSC-3519) at site 3 (Fig. 6), a further 30 km to the west. No emergence curves have been constructed for this area; however, it can be assumed on the basis of other Arctic emergence data (Dyke *et al.* 1991) that the sea level fall of 45 m occurred over 500–1000 years: i.e. the readvanced glacier still occupied Hadley Bay at *c.* 10,000 BP.

The final marine reincursion of Hadley Bay is recorded by the 75 m outwash deltas that drained the main Flow 2 ice in the northeast, and by glaciomarine sediments and outwash deltas around 100 m a.s.l. on the southeast and southwest shores of the bay. Shells in the southeast from approximately 104 m dated 9400 ± 150 BP (GSC-269, site 12). On northern Stefansson Island, a few outwash deltas that drained wasting Flow 2 ice lie at 90 m a.s.l. – the same elevation as the highest beaches. A 75 m a.s.l. delta that drained the northwest extremity of the subsequent Flow 3 contained shells that dated 9640 ± 100 BP (GSC-4377, site 10).

Flow 3

The sheet of till deposited or modified by Flow 3 extends 5–50 km inland from M'Clintock Channel to a margin 100–120 m a.s.l. (Fig. 3). On parts of Stefansson Island this till was observed to be of lighter colour than adjacent Flow 2 and to include ice-transported marine deposits, but otherwise is of similar composition. Ice occupied at least western M'Clintock Channel and flowed onshore in a west or northwest direction; the glacier was grounded over present land and probably buoyant in the several hundred metres of water farther east. Low drumlins, drumlinoid ridges and smears of till are oriented orthogonally to the distal (inland) till margin, overriding and crosscutting older and larger north–south aligned Flow 2 drumlins. The few exposures of rock within this area commonly show strong north-trending striations (from Flow 2) lightly overscored by onshore striations (Flow 3). Eskers are scattered near the limit of this flow. In southern Storkerson Peninsula, decaying Flow 2 ice coexisted with Flow 3 long enough for several eskers to extend from the later flow into ice of the earlier flow. Subsequently, however, Flow 2 ice completely melted, permitting terrestrial or subaqueous fans to issue from the Flow 3 ice front onto Flow 2 till.

On northeast Stefansson Island, Flow 2 had decayed and the sea had entered M'Clintock Channel before Flow 3 readvanced to form two ridges, 30 m high and several kilometres long. Shells from shelly strata 110–120 m a.s.l. within one ridge (site 11, Fig. 3) yielded an age of 9560 ± 100 BP (GSC-4336). These shells are much higher in altitude than outwash deltas draining from the Flow 3 margin into the sea, therefore the ridges are inferred to be ice thrust blocks of till interleaved with shell-bearing marine deposits (cf. Mackay 1959). Shells from one of the marginal deltas at the northeast tip of Stefansson Island, at 75 m a.s.l., dated 9640 ± 110 BP (GSC-4377, site 10). This date appears anomalously older than the shells from an earlier marine incursion transported to site 11, until the 110-year overlap of the two sigma error terms is taken into account. Two deltas flank Goldsmith Channel 80 m a.s.l.; glaciomarine sediments under the southernmost delta yielded shells dating 9340 ± 100 BP (GSC-4316, site 13). The east coast postglacial marine limit lies about 80 m a.s.l. on southeast Storkerson Peninsula, where the highest shells, just below the washing limit, dated 8840 ± 120 BP (GSC-4409, site 14). This limit declines northward to 68 m on eastern Stefansson Island.

Summary

Three phases of late glacial ice flow are recorded by landforms and dated by intervening marine incursions:

Flow 1. Ice flow within the late Wisconsinan ice sheet was locally accelerated when disequilibration was induced by marine-based ice margin retreat. This event was completed *c.* 10,400 BP, by which time the sea had penetrated to the head of Hadley Bay.

Flow 2. A surge, recorded by a drumlin field 200 km long by 80 km wide, occurred after *c.* 10,400 BP. The main ice stream responsible was actively expanding laterally and eroding Flow 1 deposits immediately before flow ceased, which was earlier than 9600 BP.

Flow 3. A buoyant ice mass, grounded on the western shore of M'Clintock Channel, thrust older marine sediments and smeared the till composing Flow 2 drumlins sometime between 9600 and 8800 BP.

Deglaciation of western Parry Channel

Late Wisconsinan maximum ice flow and initial retreat, including Flow 1

Till emplaced from a seaward direction overlaps much of the shore of Viscount Melville Sound and segments of the coast of M'Clure Strait. A dearth of dateable materials bracketing these deposits has led to equivocation over their age. Thus most deposits were shown as late Wisconsinan in age by Prest *et al.* (1968, based on communication from J. G. Fyles) and by Dyke & Prest (1987a), whereas Vincent (1983, 1984, 1989, 1992) limited late Wisconsinan ice to Viscount Melville Sound, and indicated an early Wisconsinan age for till adjacent to M'Clure Strait (Figs. 1, 6).

The Bolduc and Winter Harbour tills present on the southern shore of central Melville Island are notable for their lack of glacial landforms and for the presence of carbonate and Shield erratics indicating southern provenance (Hodgson *et al.* 1984). Bolduc Till was deposited by slightly more extensive ice than the younger Winter Harbour Till. Several samples of marine shells that were either in original location of deposition or erratics on the surface of Bolduc Till yielded middle Wisconsinan or greater ages (sites 15 and 16, Fig. 6, Table 2). A minimum age for Bolduc Till is provided by several shell collections in and under Winter Harbour Till, of which the oldest is 11,700 ± 100 BP (GSC-3249, site 17).

Isolated coastal deposits of till with similar characteristics to Bolduc Till are present on southwest Melville Island. Shells from marine deposits directly overlying the till yielded ages between 11,700 and 10,600 BP (sites 18, 20, 23). Hodgson (1992) provided circumstantial evidence of a late Wisconsinan ice sheet on western Melville Island, but noted the absence of evidence of confluence between it and continental ice responsible for the coastal deposits. No till has been observed farther west on the southern shores of Eglinton and Prince Patrick islands. In contrast, the

Table 2. Representative radiocarbon ages, deglaciation of western Parry Channel (ex. Victoria and Stefansson Islands).

Site on Figs. 3 &/or 6	^{14}C age (years BP)[a]	$\delta^{13}C$ ‰	Laboratory No.	Material	Elevation (m)	Related sea level (m)	References
Melville Island							
15	42,400 ± 1900	–	**GSC-787**	*Hiatella arctica*	85	?	Lowdon & Blake (1968); Hodgson *et al.* (1984)
16	>33,000	–	**GSC-727**	*Hiatella arctica*	79	?	Lowdon & Blake (1968); Hodgson *et al.* (1984)
17	11,700 ± 100	+0.5	**GSC-3249**	*Hiatella arctica*	58	>82	Hodgson *et al.* (1984)
18	11,700 ± 110	+0.6	**GSC-4167**	*Hiatella arctica*	6	>15	Hodgson (1992)
19	11,590 ± 90	–	**TO-247**	*Portlandia arctica*	10	>20	This report[b]
20	11,550 ± 90	–	**TO-2405**	*Hiatella arctica*	124	?	This report[b]
21	11,500 ± 260	+0.5	**GSC-3113**	*Hiatella arctica*	56	>56	Hodgson *et al.* (1984)
22	11,400 ± 130	+1.4	**GSC-3111**	*Hiatella arctica*	82	>82	Hodgson *et al.* (1984)
23	10,600 ± 150	–	**GSC-324**	*Hiatella arctica*	40	>40	Lowdon *et al.* (1967); Hodgson *et al.* (1984)
24	10,340 ± 150	–	**GSC-278**	*Hiatella arctica*	55	>55	Fyles (1963); Hodgson *et al.* (1984)
25	10,200 ± 120	−27.1	**GSC-5002**	*Salix* sp. twigs	22	>30	Hodgson (1992)
26	9620 ± 150	–	**GSC-665**	*Hiatella arctica*	20	>28	Lowdon & Blake (1968)
Banks Island							
27	11,300 ± 190	+1.0	**GSC-5096**	*Hiatella arctica*	1.75	20?	Vincent (1992)
28	10,600 ± 270	–	**GSC-1437**	*Hiatella arctica*	85–88	?	Lowdon & Blake (1973); Hodgson & Vincent (1984)
29	10,200 ± 130	−26.2	**GSC-2673**	Moss fragments	120	–	Lowdon & Blake (1980)
Prince of Wales Island							
30	11,005 ± 170	–	**S-2708**	*Hiatella arctica*	133	⩽188	Dyke (1987)
31	10,435 ± 160	–	**S-2709**	*Hiatella arctica*	120	133	Dyke (1987)
32	10,070 ± 150	–	**S-2683**	*Mya truncata*	70	>70	Dyke (1987)
33	9470 ± 100	+0.5	**GSC-3679**	*Hiatella arctica*	85–90	>95	Dyke (1987)
Byam Martin and Bathurst Islands							
34	9800 ± 150	–	**GSC-315**	*Hiatella arctica*	66	>66	Lowdon *et al.* (1967); Hodgson & Vincent (1984)
35	9500 ± 100	+1.5	**GSC-3740**	*Hiatella arctica*	74	>74	This report[b]
36	9070 ± 190	–	**GSC-353**	*Hiatella* sp., *Balanus* sp.	104	>104	Lowdon *et al.* (1967)
Mainland							
37	9190 ± 210	–	**GSC-125**	*Mya truncata*	186	?	Dyck & Fyles (1964)

[a] **GSC** (Geological Survey of Canada) dates: error represents 95% probability; where ages are corrected for isotopic fractionation, standard value for marine shells is $\delta^{13}C = 0.0‰$; for wood $\delta^{13}C = -25‰$. **TO** (IsoTrace) dates: error represents 68.3% probability; marine shells corrected for isotopic fractionation to a $\delta^{13}C = 0‰$. **S** (Saskatchewan) shell and bone dates: error represents 68% probability; dates uncorrected for isotopic fractionation. To 'correct' marine shell dates listed above to a $\delta^{13}C$ of $-25‰$, add 400–410 years.

[b] Additional information on unpublished dates reported here. Site 19, **TO-247** collected by J.-S. Vincent (1980) from marine/deltaic silt & clay at 74°29.5′N, 111°57′W (78F/12). Site 20, **TO-2405** collected by D. A. Hodgson and J.-S. Vincent (1980) from sand under gravel (a delta?) at 74°29.5′N, 112°05′W (88E/9). Site 35, **GSC-3740** collected by D. A. Hodgson (1980) from silty sand surface of Winter Harbour Till at 75°04′N, 104°24′W (78H/1).

northwest Banks Island shore of M'Clure Strait is overlapped by Bar Harbour Till, which pre-dates marine shells dated 11,300 ± 190 BP (GSC-5096, site 27). Vincent (1984, 1989, 1992) has presented plausible arguments for M'Clure Stade ice (which includes the Prince Alfred Lobe that deposited Bar Harbour Till) advancing sometime between Sangamonian *sensu lato* and middle Wisconsinan time. Retreat occurred possibly in the late Wisconsinan, more likely earlier, since shells in marine deposits laid down during or after the ice advance yield 'old' radiometric ages (Vincent 1992).

The oldest firm record of late Wisconsinan marine incursion is a collection of shells dated 12,600 ± 140 BP (GSC-1707, site 1) from marine sediments at Peel Point on northwest Victoria Island. The sea had reached Natkusiak Peninsula by 11,800 ± 100 BP (GSC-3511, site 2) where abundant shells occur at the base of marine silt directly overlying unweathered till and striated bedrock. The ice margin lay in the eastern Shaler Mountains when shells dating 10,900 ± 100 BP (GSC-3519, site 3) grew in glaciomarine silt; the first record of shells migrating into Hadley Bay is 10,400 BP (sites 4 and 6), after Flow 1 but before Flow 2.

Meanwhile, by *c.* 11,000 BP, the ice front had retreated to shallow water over what is now northwest Prince of Wales Island (Dyke 1987; Dyke *et al.* 1992). Here it maintained equilibrium and formed several large moraine systems, while sea level at the moraines fell from 188 m to 133 m between 11,050 ± 170 BP (S-2708, site 30) and 10,435 ± 160 BP (S-2709, site 31). Ice had withdrawn from the westernmost moraine system by 10,070 ± 150 BP (S-2683, site 32). These events are corroborated by numerous other dates collected by Dyke. Ice streams were postulated for this area by Dyke & Morris (1988) during the late Wisconsinan maximum or earlier.

Readvance of an ice stream and ice shelf into Viscount Melville Sound, and deposition of the Winter Harbour Till (Flow 2)

The short-lived Flow 2 ice stream over Storkerson Peninsula and Stefansson Island clearly forced a large volume of ice into Viscount Melville Sound *c.* 10,000 BP. For this period, Hodgson & Vincent (1984) suggested Winter Harbour Till was deposited on the northern and southern shores of Viscount Melville Sound by the Viscount Melville Sound Ice Shelf. An unambiguous maximum age for Winter Harbour Till is provided by shell collections from marine sediments stratigraphically lower than the till and ranging in age between 12,600 and 11,400 BP (sites 1, 2, 17, 19, 20 and 22). The minimum age, as Dyke (1987) pointed out, is not so well constrained; therefore the critical site will be discussed here in some detail. A sample of shells that yielded an age of 10,340 ± 150 BP (GSC-278, site 24) was collected by J. G. Fyles from a 1 m thick silty shelly stratum in silt 55 m a.s.l., 1 km beyond the distal margin of Winter Harbour Till on southern Melville Island (Fyles 1963; Hodgson *et al.* 1984). This abundance of shells is unusual but not extraordinary for marine deposits pre-dating Winter Harbour Till, but far exceeds concentrations found at any site clearly overlying the till. As Hodgson & Vincent (1984: 25) pointed out, the site elevation is much higher than the uppermost evidence of postglacial marine overlap (<35 m a.s.l.) on Winter Harbour Till on this stretch of coast. Hence, the evidence strongly suggests that the shells pre-date the till. The oldest shells clearly overlying that till in the Winter Harbour area are 9620 ± 150 BP (GSC-665, site 26, sea level ⩾28 m). The postglacial marine limit declines to the west and rises to the east to a maximum of at least 74 m on southern Byam Martin Island, where shells from the surface of Winter Harbour Till dated 9500 ± 100 BP (GSC-3740, site 35), which is not substantially different from 9800 ± 100 BP shells collected 8 m lower (GSC-315, site 34) after applying the margin of error.

Shells dated 10,600 ± 270 BP (GSC-1437, site 28) on or in deposits categorized by Hodgson & Vincent (1984) as Winter Harbour Till at Parker Point, on the northeast tip of Banks Island, have been the subject of several discussions (Vincent 1983; Dyke 1987). The assessment that the shells were raised by glacial ice (Vincent 1983; Hodgson & Vincent 1984) is retained here, rather than the suggestions of Barnett (the collector, in Lowdon & Blake 1973) and Dyke (1987) that they were deposited in a high postglacial sea. There is evidence of ice thrusting on that coast and ice-thrust blocks of marine sediment were identified in a similar topographic position at the margin of the Flow 3 grounded ice shelf on northeast Stefansson Island (site 11). Furthermore, numerous shells yielding 11,000–12,000 BP dates have been collected from opposing shores of Banks and Victoria islands, all at lower elevations than the Parker Point sample.

Winter Harbour Till has not been observed on shores flanking eastern Viscount Melville Sound, including southern Bathurst Island (Barnett *et al.* 1976; Blake 1964). However, undated till of Laurentide provenance occurs on islands of central Parry Channel; Barnett *et al.* (1976) and Dyke (1993) suggest this is of late Wisconsinan age. Blake (1964) suggested the last glaciation of Bathurst Island was by a local ice cap, which is shown by Dyke & Prest (1987b) as finally wasting between 10,000 and 9000 BP. The oldest finite date yielded by marine or terrestrial deposits from southern Bathurst Island is 9070 ± 190 BP (GSC-353, site 36) from shells 104 m a.s.l. (highest beaches 108 m a.s.l.). Thus, it is likely that an ice cap on the island blocked external glaciers at and prior to 10,000 BP.

Less readily explained is the lack of evidence of latest Pleistocene/early Holocene till deposition on the eastern shore of M'Clintock Channel opposite Storkerson Peninsula. Dyke (1987) predicated his reinterpretation of the age of Winter Harbour Till on the deglaciation chronology of northern Prince of Wales Island (Figs. 6, 7). However, this area appears to be an anomaly in western Parry Channel and adjacent areas of Victoria Island (Sharpe 1988). Ice retreated landward from coastal end moraines that apparently show no modification by the later ice flows in northwest M'Clintock Channel described here, even though Flow 2 was strong enough to overtop 300 m summits on Stefansson Island. Possibly landforms resulting from a glacier or ice shelf in the channel are relatively much weaker than those left by earlier land-based ice on Prince of Wales Island.

Readvance of an ice shelf in M'Clintock Channel (Flow 3)

Flow generally orthogonal to Flow 2, onto shores of northwesternmost M'Clintock Channel, occurred after 9640 BP (sites 10 and 11); a proglacial delta was still being built at 9340 BP (site 13). The grounded/buoyant ice appears to have been an analogue of that responsible for Winter Harbour Till, though with the

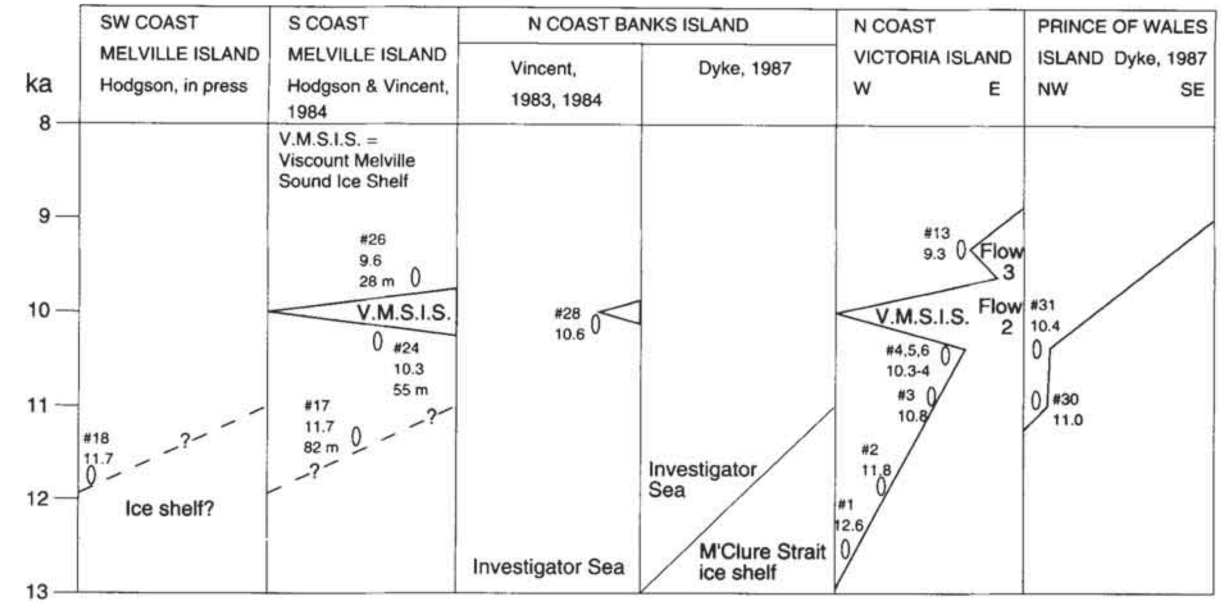

Fig. 7. Correlation of last glacial events around western Parry Channel. Symbols same as in Fig. 4.

ice front displaced several hundred kilometers farther south (Fig. 6). This event has not been reported from the eastern shore of M'Clintock Channel. To the south on King William Island, an ice margin fluctuation of at least 40 km was recorded (Dyke & Dredge 1989; Hélie 1984). The ice front still was over central Prince of Wales Island at 9470 ± 100 BP (GSC-3679, site 33), but retreated across Boothia Peninsula, southeast of M'Clintock Channel between 9300 and 8800 BP (Dyke 1984) and had left Kent Peninsula, on the mainland southwest of the channel, by 9120 ± 210 BP (GSC-125, site 37).

Summary

The extent of the late Wisconsinan Laurentide Ice Sheet in western Parry Channel is equivocal. It probably entered M'Clure Strait as an ice shelf, but possibly did not extend to the Beaufort Sea. The ice margin had retreated to north-central Victoria Island by 11,800 BP, to northwest Prince of Wales Island by 11,000 BP and to the head of Hadley Bay by 10,400 BP. A surge is recorded by an ice stream at least 200 km by 80 km wide over easternmost Victoria Island and M'Clintock Channel at *c.* 10,000 BP. The glacier expanded over Viscount Melville Sound as an ice shelf grounded at the margins where it deposited the Winter Harbour Till. Following retreat into M'Clintock Channel by 9600 BP, an ice shelf readvanced onto the western shores of the channel, probably fed by an ice stream from the south.

Dynamics of the northwesternmost ice sheet

M'Clintock Ice Divide

The widespread presence of erratics of southern provenance suggests that a north- or northwest-directed flow of continental ice dominated the last glaciation of northeast Victoria Island (Fyles 1963). But late in the last glaciation, flow directions shifted. The M'Clintock Ice Divide was conceived by Dyke (1984; anticipated by Dyke *et al.* 1983) to explain some indicators of westward ice flow over Victoria Island and a better-defined eastward flow over Prince of Wales and Somerset islands and Boothia Peninsula. This topographic high of the northwest Laurentide Ice Sheet is portrayed by Dyke & Prest (1987c) as a ridge extending north from the mainland to M'Clintock Channel (Fig. 1). A shift to northwest flow in Prince of Wales Island suggested to Dyke & Prest (1987a) that the divide migrated from the west side of the channel to the east between 13,000 and 10,000 BP, after which it shortened as the ice margin retreated to the south. For northeast Victoria Island there are no particular indicators of the divide, and an intuitive argument is that the 300 m deep M'Clintock Channel should function as a conduit of more rapid flow under a temperate ice sheet rather than a divide. Certainly, by 10,000 BP the occurrence of a major ice stream flowing north in the axial direction of the presumed divide indicates that no vestiges of the divide remained in M'Clintock Channel.

Ice streams

Ice streams have been proposed to explain some dispersal trains and concentrations of drumlins within the northern Laurentide Ice Sheet (Dyke 1984; Dyke *et al.* 1992). Dyke & Morris (1988) argued that these streams, which in places cross the topographic grain, were flanked by cold-based ice. On northeast Victoria Island, the general occurrence of subglacial, englacial or supraglacial landforms indicates the unlikelihood there of cold-based ice coexisting with ice streams. Sharpe (1985) suggested subglacial meltwater was responsible for some fluted landforms composed of stratified deposits on southern Victoria Island. On northeast Victoria Island, no stratified deposits were observed within drumlins, which challenges a cavity-fill meltwater origin, though not necessarily an erosional origin for these landforms (Shaw & Sharpe 1987). However, the mass of striations on till-protected bedrock observed locally between and even beneath drumlins strongly indicates to this author that they formed under a sliding glacier, rather than by sheet flood erosion and scouring. Furthermore, although inter-island channels steered flows, Flow 2 disregarded local relief of 400 m on Stefansson Island to a degree unlikely from a basal flood (Fig. 3). Meltwater, though under the same hydrostatic pressure as basal glacier ice, would likely respond more readily to local relief.

The consistent field of drumlins records smooth flows throughout the ice stream, leading to the zone where flow expanded out of Goldsmith Channel into western Viscount Melville Sound (Fig. 3). A minor exception is the narrow zone where ice alternated between taking east and west routes over Stefansson Island. The thickness of the ice stream was a minimum of 400 m, taking the unlikely case of ice thinning completely over northern Stefansson Island. This provides a minimum cross-section area of 35 km^2 over Goldsmith Channel. Adding to this an ice stream occupying at least the western side of M'Clintock Channel, then Flow 2 would be perhaps 100 km^2 in section.

The trigger for ice stream flow was suggested above to be instability resulting from oversteepening of the ice sheet profile following rapid retreat of the marine-based ice margin by calving in Parry Channel and the other major straits that underlay this sector of the ice sheet. Why retreat of this margin started is equally speculative. Whatever the mass balance flux of the ice sheet (positive or negative), calving behind the grounded margin may have been initiated by a eustatic rise in sea level. Buoyancy forces at this point would be sufficient to initiate and continue break-up, even though by 11,000 BP shorelines around Viscount Melville Sound were emerging due to isostatic rebound. Such stepped or non-linear behaviour of an ice sheet is reviewed by Sugden (1991). At the same time, climate had warmed in this region – probably rapidly. Although proxy temperature and precipitation data are rare for the Late Pleistocene in the western Arctic Archipelago, there is evidence that summers were as warm as at present at the time of the Viscount Melville Sound Ice Shelf (i.e. Flow 2). *Salix arctica* was growing at $10{,}200 \pm 120 \pm 120$ BP (GSC-5002, site 25) in northwest Melville Island, at a site shown by Edlund & Alt (1989) to be at the present limit of the shrub. Similarly, plant material was already accumulating in a lake basin in northeast Banks Island at $10{,}200 \pm 130$ BP (GSC-2673, site 29). Several rapid fluctuations of the eastern margin of the Laurentide Ice Sheet at this time are documented by Miller & Kaufman (1990) and Stravers *et al.* (1992). In contrast to central archipelago, these flows apparently cross-cut the main topographic depression that forms Hudson Strait, culminating at *c.* 11,000, 9900 and 8500 BP. Sea-level and oceanic-atmospheric changes are believed to have destabilized this sector of the ice sheet.

Ice shelves

Ice shelves have been proposed at the northern margin of the Laurentide Ice Sheet to explain coastal till sheets with low gradient or horizontal margins extending tens or hundreds of kilometres (Hodgson & Vincent 1984; Dyke & Prest 1987a). They were apparently constrained by island shores, but were open at the east and west ends of Parry Channel. Shelves in Viscount Melville Sound and M'Clintock Channel were short lived. The Flow 2 ice stream discharged into the recently deglaciated central and western Viscount Melville Sound, which is a basin of about 20,000 km^3 (60,000 km^2 area, 250 m mean depth at present, increased to 350 m at 10,000 BP). Given a Flow 2 ice stream moving at 500 m $year^{-1}$, as in West Antarctic ice stream B (Whillans *et al.* 1987), flowing into water where basal friction is eliminated by buoyancy, a closed sound would fill entirely in 400 years. Deep outlets from the sound represented 25% of the perimeter at 10,000 BP, hence some ice escaped by calving, at a rough estimate doubling the filling time to not more than 800 years.

It might be reasoned that this 'shelf' was composed of a disordered mass of blocks rapidly calved from ice streams; therefore iceberg fluting and scouring would be expected on underlying rain-out diamicton. Side-scan sonograms of the seafloor at a present water depth of 100 m in northernmost Viscount Melville Sound off Byam Martin Island show intense scouring of glacial drift (MacLean *et al.* 1989, Fig. 46; the closest marine data). However, no such evidence is found onshore on Winter Harbour Till, where there is the possibility that scars were eradicated by periglacial processes, though iceberg scour marks are well preserved on southwest Victoria Island (Sharpe & Nixon 1989), Prince of Wales Island (Dyke *et al.* 1992), King

William Island (Hélie 1984) and south of Hudson Bay where a surging ice lobe occurred (Dredge & Cowan 1989).

Conclusions

Maps of surficial materials and landforms of northeast Victoria Island and Stefansson Island show a pattern of several ice flows, including ice streams that are correlated by chronostratigraphy with retreats and readvances of the northwesternmost sector of the late Wisconsinan Laurentide Ice Sheet between *c.* 13,000 and 9000 BP. At the end of initial retreat onto Victoria Island at 10,400 BP, Flow 1 drained ice into Hadley Bay. A readvance of as much as 400 km between 10,400 and 9600 BP is recorded by bedforms of the Flow 2 ice stream and the resultant Viscount Melville Ice Shelf, which deposited the Winter Harbour Till. A final readvance onto northeast Victoria Island occurred between 9600 and 8800 BP. It is speculated that ice margin fluctuations occurred when the eustatic sea-level rise destabilized ice fronts that stood in present inter-island channels. Although oceanic-atmospheric changes were likely factors, there is no record of such events from northern Victoria Island.

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