PERGAMON

Quaternary Science Reviews 21 (2002) 33–48

QSR

The Goldilocks dilemma: big ice, little ice, or "just-right" ice in the Eastern Canadian Arctic☆

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Received 15 March 2001; accepted 30 August 2001

Abstract

Our conceptions of the NE sector of the Laurentide Ice Sheet (LIS) at the Last Glacial Maximum (LGM) have evolved through three major paradigms over the past 50 years. Until the late 1960s the conventional view was that the Eastern Canadian Arctic preserved only a simple deglacial sequence from a LIS margin everywhere at the continental shelf edge (Flint Paradigm). Glacial geologic field studies began in earnest in this region in the early 1960s, and within the first decade field evidence documenting undisturbed deposits predating the LGM led a pendulum swing to a consensus view that large coastal stretches of the Eastern Canadian Arctic remained free of actively eroding glacial ice at the LGM, and that the most extensive ice margins occurred early in the last glacial cycle. This Minimalist Paradigm dominated until the late1980s when an expanded data set from shallow marine studies indicated LGM ice at least locally reached the continental shelf. Within the past decade the marine data, coupled with new evidence from lake sediments and cosmogenic exposure dates on moraines and glaciated terrain in the Eastern Canadian Arctic has led to a new paradigm that better reconciles the terrestrial and marine evidence. Collectively, these lines of evidence indicate that all of southern Baffin Island was glaciated at the LGM, but that some coastal uplands north of Cumberland Sound remained above the limit of actively eroding glacial ice, even though outlet glaciers reached the continental shelf in front of most fiords and sounds. The most plausible explanation for the observed glacial limits is that low-gradient, relatively fast-moving outlet glaciers sliding on deformable sediments occupied marine embayments and fiords, contrasting with slower moving ice frozen to its bed on the intervening crystalline terrain. Slow-moving ice frozen to its bed would have had steeper surface gradients, hence would have terminated inland from the coast. This scenario is consistent with observations indicating high-elevation coastal terrain remained unglaciated even though outlet glaciers reached the continental shelf. LGM summer temperatures were apparently much lower than present, as lakes in the ice-free regions were permanently frozen.

1. Introduction

Everybody loves the story of a curious little girl named Goldilocks, who wandered through the Eastern Canadian Arctic and discovered differences of opinion on the limits of ice at the last glacial maximum. "Oh my, the monolithic ice sheet extended beyond the very edge of the continental shelf," exclaimed Goldilocks after talking to Big Ice advocates. But after she talked with the Minimalists she was heard to proclaim "Goodness, the tiny little ice sheet barely made it to the heads of the fiords". More recently, Goldilocks apparently reconciled these differences and she has been seen wandering the Arctic with an expression of delight, singing, "Because the ice sheet slid in the fiords and stuck on the hillsides it was bigger than small and littler than big". And it was "Just Right".

Over the past half century, our view of the Laurentide Ice Sheet (LIS) has evolved from a thick monolithic dome with a relatively stable central core, to a thinner,

☆PARCS Contribution # 161.

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0277-3791/02/$ - see front matter © 2001 Published by Elsevier Science Ltd.
PII: S0277-3791(01)00085-3

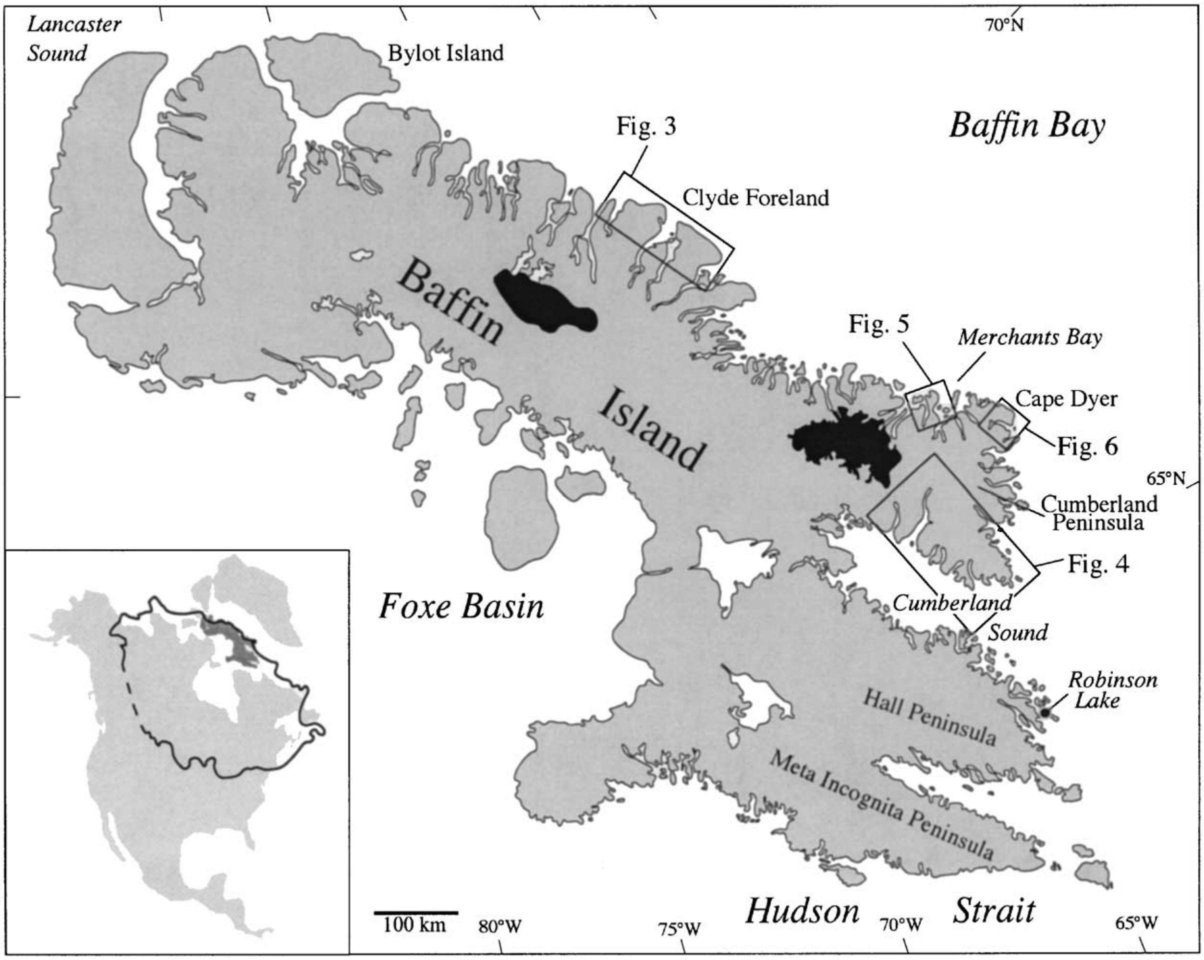

Fig. 1. Baffin Island, Arctic Canada, showing the locations of Figs. 3–6 and most place names used in the text. Large ice caps are shown in black. Inset shows Baffin Island in dark stipple relative to North America. The approximate location of the Laurentide Ice Sheet at the LGM is outlined (Dyke and Prest, 1987, as modified in Dyke et al., this volume).

multi-domed and more dynamic glacial system, with inherent instabilities. Primary field information on the timing and style of continental glaciation has played a key role in this conceptual evolution. Along the northeastern margin of the LIS (Fig. 1), nested sets of lateral and terminal moraine complexes provide a direct record of past ice-sheet behavior. Early studies of these moraine systems were limited by an inability to date the deposits directly. Consequently, one argument advanced was that all of the moraines post-date the Last Glacial Maximum (LGM) and that they simply reflect complex recessional stillstands and readvances during overall deglaciation from an ice margin that extended to the edge of the continental shelf (e.g. Ives and Andrews, 1963). The field-based interpretation of extensive glaciation throughout the NE sector of the LIS at the LGM (Flint Paradigm) is supported theoretically by some ice-sheet modeling efforts (e.g. Sugden, 1977; Hughes, 1987). Alternative arguments have also been forwarded based on relative weathering characteristics and radiocarbon-dated marine bivalve shells from ice-marginal raised-marine deposits. These interpretations postulate an LGM ice margin restricted to the inner- or mid-fiord regions, with high-elevation lateral moraines and terminal moraine complexes on the coastal forelands relating to previous glacial stages (Minimalist Paradigm: Løken, 1966; Pheasant and Andrews, 1973; Miller and Dyke, 1974; Miller et al, 1977; Dyke et al., 1982; Klassen, 1993). These opposing views have dominated discussions of the glacial history in the Eastern Canadian Arctic for more than a quarter century, but conclusive evidence for either argument has been lacking.

Three new primary lines of evidence have emerged in the past decade that now allows us to resolve much of this debate. These are: (1) the development of cosmogenic exposure (CE) dating and its application to surfaces on Baffin Island, (2) the recovery of strategically positioned continuous lake sediment records that extend beyond the limits of radiocarbon dating, and (3) marine sediment cores from the shelves and deep sea adjacent to the Eastern Canadian Arctic. To fully exploit the first two lines of evidence requires a firm understanding of the regional surficial geology; regional seismic surveys provide a similar context for the marine evidence.

Several recent studies utilize these new strategies to better constrain the areal and elevational limits of LGM outlet glaciers over discrete sectors of eastern Baffin Island. The evidence derived from terrestrial field studies, complemented by new marine records from the adjacent seas, demonstrate that southern Baffin Island was completely inundated by actively eroding continental ice at the LGM. The footprint of continental glaciation diminished to the north, where strong contrasts in basal thermal conditions resulted in low-gradient outlet glaciers occupying fiords and sounds, separated by slower moving cold-based ice and locally ice-free areas in the inter-fiord regions. Conceptually, outlet glaciers in the fiords were connected to the main ice cap through fiord-head valleys, allowing higher velocities and thicker ice than on the inter-fiord uplands where ice was cold-based and frozen to its bed. Within the fiord systems, wet-based outlet glaciers frequently moved across deformable marine sediments, further reducing basal shear stresses, and lowering surface profiles of the outlet glaciers. We postulate that extensive inter-fiord uplands and coastal stretches remained free of actively eroding Laurentide ice throughout the LGM (Goldilocks Paradigm).

This paper traces the conceptual evolution of the glacial history for the NE sector of the LIS over the past 50 years, and summarizes recently acquired CE dating and lake sediment records that point the way toward a new model of the glacial history of this region. These ideas are then tested by new data from Cape Dyer, a portion of Baffin Island dominated by an ice complex that remained independent of the LIS. Finally, all of the available observations are combined to formulate a new generalization of the glacial style for the Eastern Canadian Arctic. Our proposed model is compatible with observations elsewhere in the Arctic, suggesting it may have pan-Arctic applicability.

2. Paradigm shifts: developing a glacial history for the Eastern Canadian Arctic

2.1. Big ice: the Flint Paradigm

Our conceptual understanding of the glacial history across the Eastern Canadian Arctic has evolved through three major paradigms over the past 50 years, beginning with the concepts championed in a seminal paper by Flint (1943). In a simplified (and not entirely correct) depiction of topography (Fig. 2a), Flint established the idea of ice-age inception over the mountainous eastern Canadian rim, with an expansion of ice northeastward to the shelf break, and a southwestward expansion across Hudson Bay and eventually into the northern USA, creating a monolithic, single-domed LIS. Although earlier observers had suggested alternative, multiple-dome ice configurations (e.g., Tyrrell, 1898; Coleman, 1920), Flint's view prevailed and this conceptual model influenced a generation of glacial geologists. The concept of a single-domed ice sheet formed the basis of most early glaciological models of the LIS (e.g., Sugden, 1977; Hughes, 1987). The Flint Paradigm, implying that the geological record of glaciation in the Eastern Canadian Arctic was restricted to the last deglaciation, strongly influenced glacial geologists working there after World War II. This influence is apparent in the reports from the major field programs of the Arctic Institute of North America (to the Barnes and Penny ice caps in the 1950s), and the former Canadian Geographical Branch (Barnes Ice Cap and Clyde region of Baffin Island in the early 1960s).

2.2. Little ice: the Minimalist Paradigm

The Flint Paradigm received its first major challenge in the Eastern Canadian Arctic with the description of an extensive, undisturbed, ice-proximal raised-marine delta at Cape Aston on the east coast of Baffin Island (Fig. 3) containing in situ marine bivalves ^{14}C-dated >50 ka (Løken, 1966). This finding initiated a pendulum swing away from the "maximum" reconstruction postulated by Flint and supported by the interpretation of the field evidence up to this point, to an increasingly restricted reconstruction of LGM ice limits. As additional field work in the Eastern Canadian Arctic was completed, evidence was presented for ice-free conditions along many of the forelands and inter-fiord mountains (Harrison, 1964; Ives and Buckley, 1969; Andrews et al., 1972; Pheasant and Andrews, 1972; Miller and Dyke, 1974; England, 1976; Miller et al., 1977; Brigham, 1983; Klassen, 1985, 1993; Miller et al., 1992; Wolfe, 1996). Weathering zones, the vertical boundaries between landscapes bearing qualitative differences in the degree of rock-surface weathering characteristics, were first used to suggest restricted LIS in the Torngat Mountains of Labrador (Ives, 1957), and subsequently used to reconstruct the profiles of former outlet glaciers from Newfoundland to the Queen Elizabeth Islands (Dyke, 1977, 1979; Grant, 1977; England, 1978; Ives, 1978; Andrews, 1987). Although profiles of weathering zone boundaries resembled glacier profiles, the boundaries could not be dated quantitatively, and some suggested that such boundaries might reflect englacial changes in basal thermal regime, rather than actual ice limits (Sugden, 1977; Sugden and Watts, 1977; Hughes, 1987). Nevertheless, for the field-based community of glacial geologists working throughout the Eastern Canadian Arctic, a minimal LGM ice margin

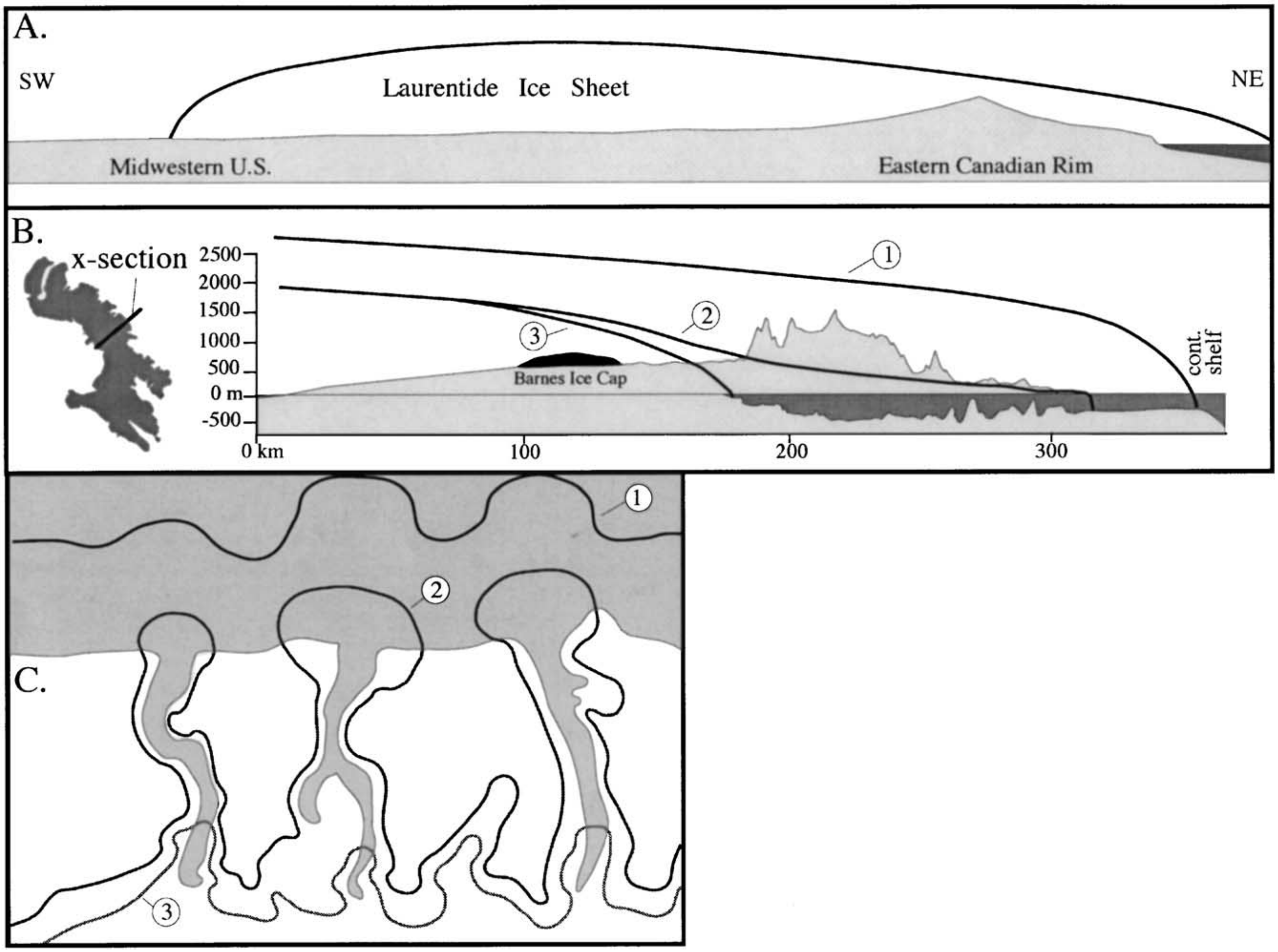

Fig. 2. Schematic summary of the conceptual development of ice-sheet profiles for the NE Sector of the LIS. (A) The Flint Paradigm (modified from Flint, 1943). (B) A cross-section of Baffin Island (as shown on inset at left) illustrating the inferred ice-sheet profiles of the Flint Paradigm (1), the Minimalist Paradigm (3), and the Goldilocks Paradigm (2). Land elevations are taken from a transect just north of Clyde Inlet; bathymetry is based on unpublished soundings from a transect up Clyde Inlet (J. Syvitski, unpubl. data). (C) A conceptual map view of the terminal margins for the three paradigms using the same numbering scheme. Land is white; ocean and fiords are stippled.

became the dominant new paradigm. Probably the most widely cited version of this paradigm is the LIS reconstruction of Dyke and Prest (1987). Similar conclusions were postulated for Svalbard (Boulton, 1979; Andersson et al., 1999) and parts of Greenland (Funder, 1990), suggesting a pan-Arctic minimalist LGM ice extent, a concept supported in principle by inferred LGM aridity in the Arctic (e.g., Alley et al., 1993).

2.3. *The pendulum swings back toward big ice*

Cracks began to appear in the Minimalist Paradigm by the mid-1980s. Seismic stratigraphy from the Baffin Shelf (MacLean et al., 1986; Praeg et al., 1986) and the record preserved in marine sediment cores recovered from Cumberland Sound (Jennings, 1993; Jennings et al., 1996) could only be reconciled with occupation of these regions by grounded ice during the LGM, in direct conflict with the favored interpretation of evidence from the adjacent terrestrial realm (e.g., Miller, 1980; Dyke et al., 1982). In northern Labrador, a study combining marine and terrestrial evidence also suggested LGM ice was more extensive than previously mapped, with the LGM ice limit extending onto the continental shelf (Clark and Josenhans, 1990). Similar marine evidence from Svalbard and Greenland suggested that extensive LGM ice in the Arctic might be the dominant pattern (e.g., Funder, 1989, and summary articles in Elverhøi et al., 1998). These studies signaled the beginning of a swing away from the Minimalist Paradigm and back toward the Flint Paradigm. Debate over the limits of LGM ice in the Arctic, and by inference, the overall behavior of Pleistocene ice sheets, was rekindled with renewed vigor.

At the core of the debate lies the difficulty in dating specific moraines. Most early terrestrial studies were dependent on tracing moraines to meltwater-fed raised-

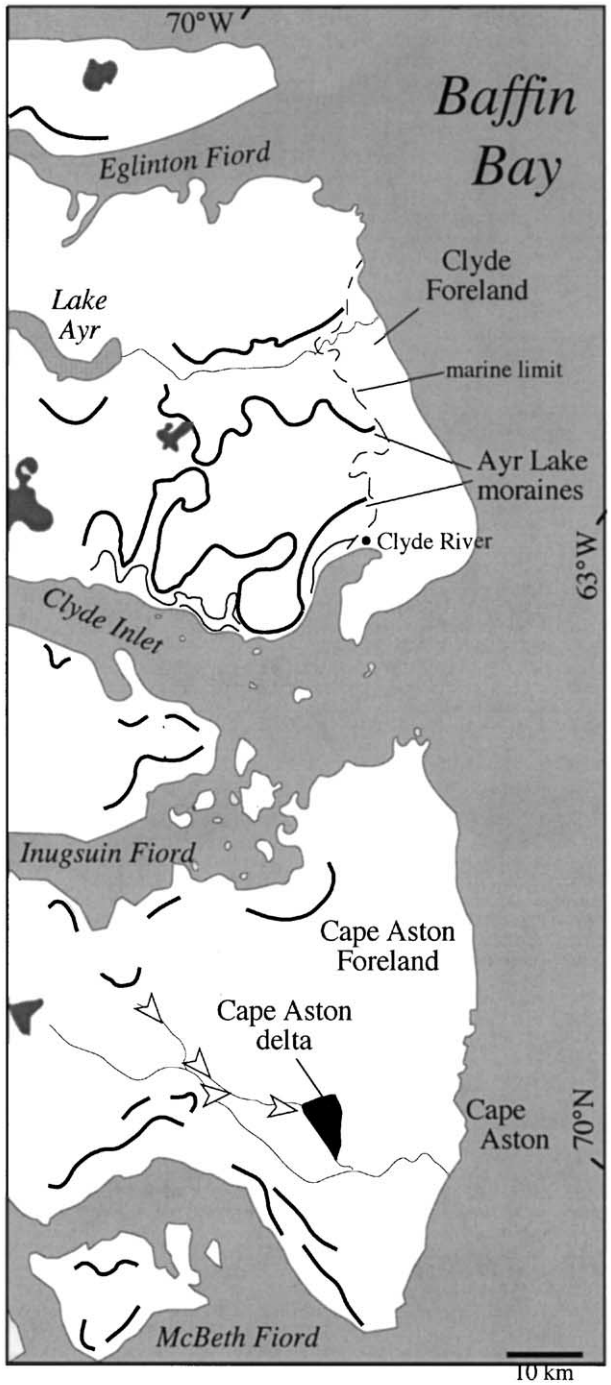

Fig. 3. The Clyde and Cape Aston forelands, showing the distribution of mapped moraines. The Ayr Lake moraines, thought to pre-date the LGM, are represented by heavy lines; younger moraines that might represent the LGM margin are lighter. The path of meltwater required to deposit the Cape Aston delta is shown by means of open arrows and can be traced to the Ayr Lake moraines in McBeth and Inugsuin fiords.

marine deltas. These deltas sometimes contained in situ marine bivalves that could be dated by radiocarbon, thereby dating the associated moraine system. In situ marine shells from raised-marine deposits demonstrably associated with moraines provide reliable constraints on times of moraine formation; we know of no exceptions to this principle on Baffin Island. However, the criterion for demonstrably in situ bivalves was relaxed over the years, and whole, but not paired valves, and even shell fragments were at times used to constrain the ages of associated moraines. The consequence was that some moraines, such as the Duval Moraine described in the next section, were assigned ages based on reworked shells, hence the ages were too old. If we maintain the rigorous criterion for in situ bivalves then this approach reliably differentiates LGM from older moraine systems. However, no moraines in the Eastern Canadian Arctic are associated with datable raised-marine deposits between about 12[1] and 30 ka, leaving the question of the LGM marginal position unresolved.

Relative weathering criteria have been widely applied to constrain moraine ages (e.g. Pheasant and Andrews, 1973; Boyer and Pheasant, 1974; Locke, 1987). However, these criteria involve a level of subjectivity, are rarely calibrated, and weathering differences depend on climate and bedrock type as well as age. Hence, they are of uncertain reliability.

A conclusive resolution to the debate requires a new category of evidence capable of placing quantitative constraints on the ages of moraines and on the maximum limits of ice during the LGM.

2.4. New constraints from cosmogenic exposure dating

The Cosmogenic exposure dating (Kurz, 1986; Lal, 1991; Nishiizumi et al., 1991; Bierman, 1994; Cerling and Craig, 1994) provides a new tool by which moraines can be dated directly. The first application of CE dating in the Baffin sector was by McCuaig et al. (1994), who argued that modern glaciers on Bylot Island are close to their LGM limits, and that Laurentide ice did not inundate the region. Although this initial study supported the Minimalist Paradigm, subsequent studies in southern Baffin Island showed that LGM ice there was much more extensive than previously proposed.

The Duval Moraine is a conspicuous lateral moraine complex deposited by ice flowing out Pangnirtung Fiord into Cumberland Sound (Figs. 1 and 4), and postulated under the Minimalist Paradigm to pre-date the LGM (Dyke, 1977; Dyke et al., 1982). But, with the new marine evidence from Cumberland Sound (Jennings et al., 1996), the age of the moraine became a matter of renewed debate. Six erratics from the type locality of the Duval Moraine, each dated by both ^{10}Be and ^{26}Al, confirm an LGM age (Fig. 4); this is supported by ^{10}Be and ^{26}Al dates on another 10 erratics from correlative moraine segments in the area (Bierman et al., 1999; Marsella et al., 2000).

[1] All ages are in calendar years. Radiocarbon dates have been calibrated following Stuiver and Reimer (1993).

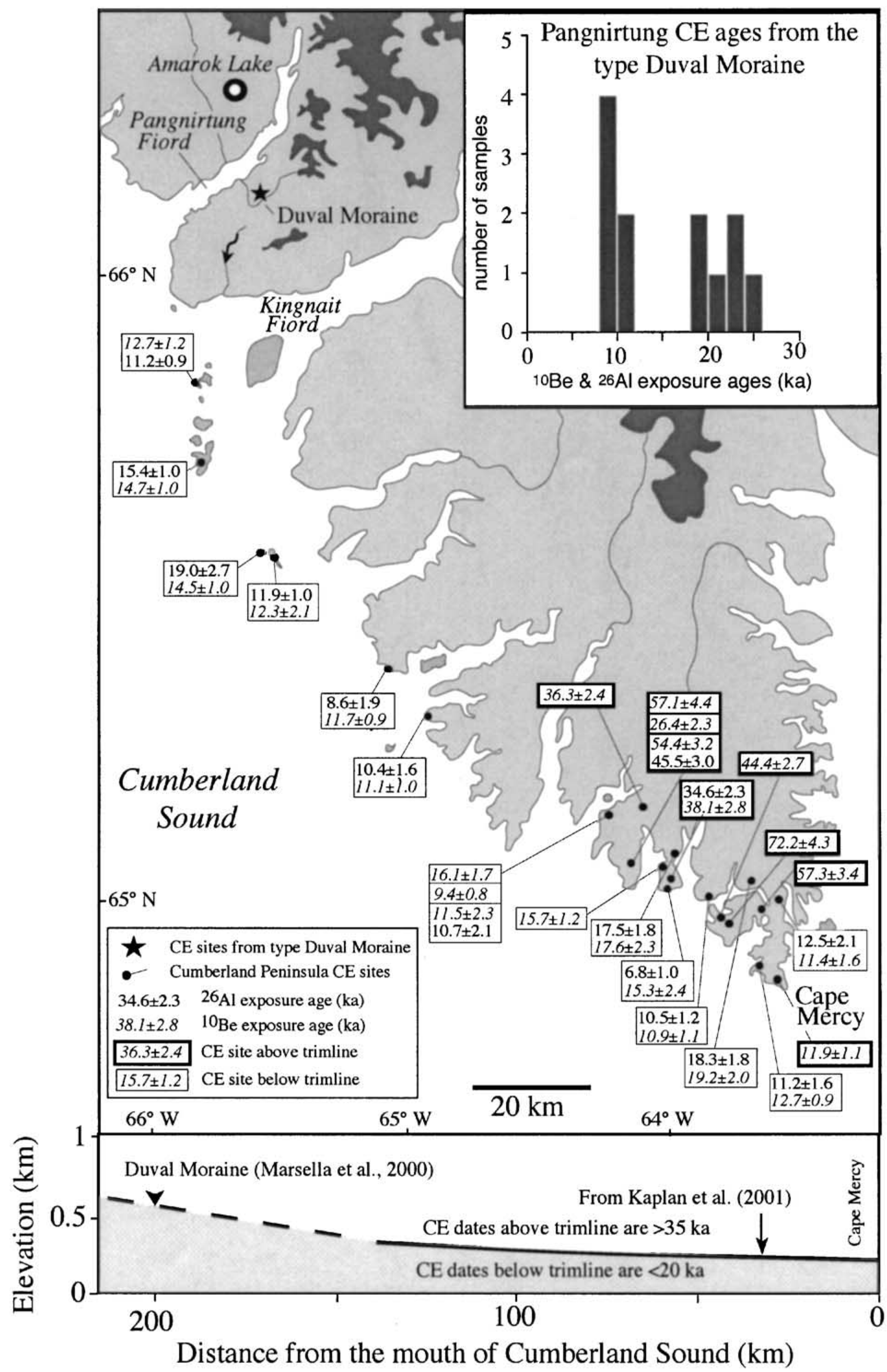

Fig. 4. Cumberland Sound and southern Cumberland Peninsula, showing the location and ages of CE dating samples that are above (dark boxes) and below (lighter boxes) a conspicuous glacier-erosional trimline. Bedrock and boulder ages above the trimline pre-date the LGM, with only two exceptions (each of which is dated by only one isotope). The two younger ages may be related to emplacement by local ice sources or periglacial processes. Map and exposure ages are modified from Kaplan et al. (2001). A large series of CE ages are available from the Pangnirtung region (Marsella et al., 2000). Six boulders from the type locality of the Duval moraine (shown by a star) all have CE ages within the LGM, but their ages (inset) show a pronounced bimodal distribution. Three erratics have ^{10}Be and ^{26}Al ages between 8 and 12 ka; ^{10}Be and ^{26}Al ages on the other three erratics are between 21 and 27 ka. A more extensive series of CE ages from correlative deposits in the same region show a similar bimodal age distribution (Marsella et al., 2000).

While the CE dates from the Duval Moraine are from the last glaciation, the frequency distribution is strongly bimodal, suggesting a two-part delivery of boulders: an early advance centered on 24 ± 3 ka, and a later advance about 10 ± 2 ka. A bimodal distribution of erratic CE ages for the Duval Moraine suggests that the behavior of the ice sheet is modulated at sub-Milankovitch timescales. Whether this modulation is related to downdraw of the LIS during Heinrich events in Hudson Strait (Andrews et al., 1998) or stochastic processes yet to be determined, awaits further investigation.

To further test the evidence for extensive LGM glaciation in Cumberland Sound, a field campaign was mounted at the mouth of the sound. A prominent glacier-erosional trimline was traced along the outer half of Cumberland Sound. CE ages of striated bedrock surfaces and erratics below the trimline are exclusively of the last glaciation, whereas erratics above the trimline indicate long, complex exposure histories, with no glacial erosion for more than 50 ka (Kaplan et al., 2001). The trimline's low surface gradient ($\sim 0.03^{\circ}$) suggests a driving stress between 2 and 7 kPa, similar to stresses observed for ice streams that dominate the dynamics of the West Antarctic Ice Sheet today. The glacial geology of SE Cumberland Peninsula is discussed by Kaplan et al. (2001), who conclude that ice flow off Cumberland Peninsula was minimal; most of the ice there was frozen to its bed and slow moving, and its contribution to the Cumberland Sound outlet glacier was negligible. These results, combined with the work of Bierman et al. (1999), Davis et al. (1999), and Marsella et al. (2000), and the earlier marine evidence (Jennings et al., 1996) converge in support of a low-gradient outlet glacier of the LIS extending the length of Cumberland Sound during the last glaciation. Recession from this maximum extension appears to have been delayed until ca. 11 ka (Fig. 4).

To test whether the reconstructed outlet glacier is consistent with glaciological theory, a finite-element ice-flow model (Fastook and Chapman, 1989) was used to simulate a Cumberland Sound outlet glacier (Kaplan et al., 1999). The advance of an outlet glacial across the central deep (1200 m) and grounded on the shelf at the mouth of the sound (400 m) could only be simulated if three conditions were satisfied: (1) the outlet glacier was derived from an ice-dispersal center in Foxe Basin of at least 2 km thickness, (2) ice was allowed to slide on its bed in the sound and upstream into Foxe Basin, and (3) ice over the crystalline terrain of adjacent Cumberland and Hall peninsulas remained frozen to its bed. This contrast in glacial style, between regions with low-surface-slope outlet glaciers for which ice flow is controlled primarily by sliding and deformable sediment and adjacent regions characterized by higher slope ice profiles where the ice sheet is thinner, cold-based, and resting on crystalline terrain, bears similarities to previous studies along other LIS margins where dramatic changes in ice characteristics over short distance due to contrasting basal regimes have been postulated (e.g., Boulton and Jones, 1979; Clark et al., 1996).

2.5. New constraints from lake sediment records

A second new line of terrestrial evidence that provides direct constraints on glacial limits is the record of sedimentation in lake basins. Although efforts to use lake sediment to test the Minimalist Paradigm have been attempted at several Arctic sites postulated to have been ice free at the LGM (e.g., Svendsen et al., 1988; Blake, 1989), in situ lacustrine sediments that clearly pre-date the LGM have remained elusive. A small lake on northern Devon Island contains primary lacustrine sediments underlying transgressive and regressive marine facies (Wolfe and King, 1999). Although the dating of the sediment core from this lake is tentative, it does not appear to have been glacially overridden, and thus possibly constrains the extent of glaciation on the coastal lowlands. More compelling pre-LGM lacustrine sediments were reported for Amarok Lake, a small, high-elevation (848 m a.s.l.) cirque lake on southern Cumberland Peninsula (Fig. 4), where a thick interglacial sequence is overlain by postglacial gyttja without an intervening diamict (Wolfe, 1994; Wolfe and Härtling, 1996). Problems in dating the original cores complicated their interpretation, but the lake was re-cored in 1998 and new AMS ^{14}C dates confirm a major depositional hiatus between about 10 and >40 ka (APW unpublished data). There is no evidence on an intervening glacier-erosional/depositional event.

The first demonstrably stratified pre-LGM lacustrine sediment was recovered beneath till and glacial-lacustrine mud in Robinson Lake, Brevoort Island, just off southeastern Baffin Island (Fig. 1; Miller et al., 1999). Although this site confirmed the presence of ancient lacustrine deposits, it also confirmed an expanded LGM ice sheet in this area. The lake sits at the drainage divide on Brevoort Island where regional ice-flow features, primarily striae, indicate the last glacial event was from a continental ice sheet moving off adjacent Hall Peninsula. Till and glacial-lacustrine mud that overlie pre-LGM lacustrine units in sediment cores from Robinson Lake are consistent with geomorphic evidence of continental glaciation in the catchment.

More recently, Wolfe et al. (2000) reported a 90-ka record of lacustrine sedimentation resting on a basal diamict at Fog Lake, a moraine-dammed lake 460 m a.s.l. on northern Cumberland Peninsula (Fig. 5). Stratified interglacial sediments in the lowest lacustrine sediments are >52.2 ka (^{14}C on plant macrofossils). A closer limiting age of the interglacial sediment is about 90 ka based on paired optical and thermal luminescence dating. The interglacial sediments are overlain by non-glacial sediment. Both Amarok and Fog lakes lack stratigraphic evidence and sedimentary structures indicative of glacial over-riding, as was apparent in the Robinson Lake sequence, or meltwater from regional deglaciation that produces diagnostic sedimentary

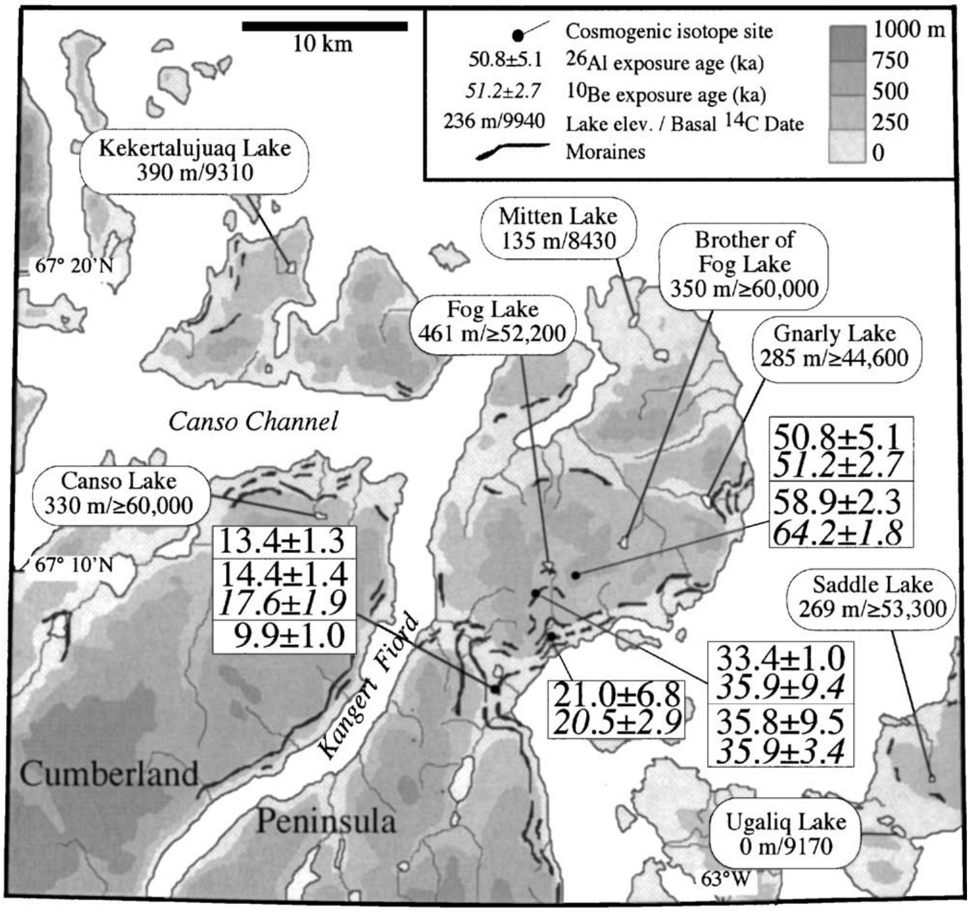

Fig. 5. Summary of moraine distribution, basal ^{14}C dates from lake sediment cores, and erratic/bedrock CE ages in the Merchants Bay region of northern Cumberland Peninsula (Fig. 1). ^{14}C ages are given in radiocarbon years; CE dates are in calendar years. Modified from Steig et al. (1998) and Wolfe et al. (2000). Moraines from an early and late phase of the LGM are preserved; higher moraines pre-date the LGM, consistent with the old ages of basal lake sediment.

signatures in lower-elevation lakes in the same region. Instead, these upland lakes preserve primarily sediments associated with interglacial conditions, with an apparent cessation of sediment beginning well before the LGM, and only reinvigorated at the end of the Pleistocene. Little or no sedimentation occurred during the 10–35 ka time window, presumably because lakes in this region were permanently frozen.

Our group cored four additional high-elevation lakes on northern Cumberland Peninsula that reflect a similar sedimentary sequence. Saddle (305 m a.s.l.), Gnarly (285 m a.s.l.), Brother-of-Fog (360 m a.s.l.), and Canso (330 m a.s.l.) lakes (Fig. 5) all record lacustrine sedimentation beyond the limits of radiocarbon dating (>60 ka in two cases, >40 ka in all others; Table 1), without any evidence of an intervening diamict or ice-proximal sedimentation. Ice-proximal sediments are differentiated from postglacial muds by their coarser grain-size, dominance of mineral constituents, and fine, varve-like laminations lacking evidence of bioturbation. In three of these lakes (Saddle, Canso, Brother-of-Fog) there is also evidence for a depositional hiatus between about 10 and ⩾40 ka; too few dates have been obtained from Gnarly Lake to test for an hiatus. In all lower-elevation lakes from the same area, the basal lacustrine sediments reflect a brief interval of rapid ice-proximal sedimentation, followed by postglacial gyttja. These sequences confirm the erosion of pre-existing sediment by LGM ice in the lower lakes, followed by a simple deglacial/postglacial sedimentation cycle. The presence of diagnostic deglacial sediment of the last glacial cycle in these lakes, and its absence in lakes at higher elevations, reinforces our assertion that the high-elevation lakes provide reliable vertical constraints on LGM ice limits. We interpret the depositional hiatus in these lakes to be a consequence of cold, arid conditions, under which lake ice did not seasonally melt, with greatly reduced geomorphic processes in their catchments. These conditions require summer temperatures at least 4°C lower than present (Freeman, 2000).

Table 1
Physical characteristics of lakes and the basal ^{14}C dates obtained from sediment cores recovered from these lakes in the Merchants Bay Region. All radiocarbon dates are ^{13}C-corrected conventional radiocarbon ages

Lake (Fig. 5) and core ID	Elev. (m a.s.l.)	Water depth (m)	Thickness of post-LGM sediment (cm)	Thickness of pre-LGM lac. Sediment (cm)	Sample depth (cm)	Material dated	Radiocarbon age (yr BP)	Lab-ID
Fog 96FOG-05	461	9	82	34	111–112	Aquatic moss	>52,200	CAMS-28652
Brother-of-Fog 98BRO-05	350	16	65–140[b]	185	86–87	Aquatic moss	60,000±1900	OS-18064
Saddle 96SAD-04	269	3	63	165	82–83 138–139	*Salix* Aquatic moss	53,300± >52,800	 CAMS-28654
Gnarly 96GNR-01	~285	9	149	114	182–183	Aquatic moss	44,600±1500	CAMS-28655
Amarok 98AKL-02	848	14	121	89	124–125 170–171	Aquatic moss Aquatic moss	46,000±640 47,900±780	OS-18067 OS-18066
98AKL-04		14	87	74	149–150	Humic acids	49,000±1900	OS-20402
Canso 98CAN-06	330	9	55	134	114–150	Aquatic moss	>60,000	OS-17672
Mitten 96MTN-08	135	43	109	0	105–106	Humic acids	8430±50	CAMS-28656
Ugaliq 96OGL-01	0[a]	31	90 postglacial 63 deglacial	0	88–89	Humic acids	9170±60	CAMS-28657
Kekertalujuaq 98KLJ-03	390	50	160	0	148–149	Bulk sediment	9310±40	CAMS-47421

[a] Ogaliq Lake was initially above sea level, but late Holocene submergence dropped the outlet below sea level so that it now has marine water in the main basin. The dated level is from the initial freshwater phase (confirmed by diatom analyses by APW). The marine transgression occurs at 30 cm depth in the core.

[b] Thickness of post-LGM sediment includes 65 cm of Holocene gyttja, and up to 75 cm of stratified minerogenic sediment that may represent runoff into the lake from extensive LGM snowfields in the drainage. Core 98BRO-05 was designed to bypass the Holocene gyttja, so only recovered the minerogenic unit and deeper interglacial sediment. The dated acquatic moss comes from near the top of the interglacial unit, at a sediment depth of 151–152 cm; its depth in the core is less because the core bypassed the Holocene gyttja.

To test the implications of our lake sediment records, we initiated a complementary CE dating effort in the Fog Lake valley (Steig et al., 1998). During periods of continental glaciation, large outlet glaciers occupied adjacent Merchants Bay, and back-filled the Fog Lake valley, leaving a nested series of terminal and lateral moraine complexes in the valley below Fog Lake (460 m a.s.l.; Fig. 5). Erratic boulders from two of these moraines have been dated by CE. The older of the moraines (450 m a.s.l.) is $\geqslant$35 ka (^{10}Be and ^{26}Al), whereas a prominent lower moraine (256 m a.s.l.) is about 20 ka (^{10}Be and ^{26}Al; Fig. 5). Glaciated summits above Fog Lake were last glaciated $\geqslant$60 ka. In contrast, three boulders from the crest of a lower-elevation (120 m a.s.l.) moraine just 5 km south of Fog Lake have an average CE age of 13 ka (^{10}Be), and the lake dammed by this moraine contains only a single deglacial/postglacial sedimentary sequence.

The concordance of the two independent lines of evidence (^{14}C dating of lake sediment and CE dating of moraines) provides additional confidence in both methods, and by inference in our ability to constrain the limits of LGM ice in this region.

3. Cape Dyer: a paradigm testing ground

Cape Dyer lies at the eastern limit of Cumberland Peninsula (Fig. 1). The high alpine core of the peninsula deflected Laurentide ice through adjacent troughs and sounds, leaving an independent ice-dispersal center over the Cape Dyer highlands (Dyke et al., 1982). It is also currently the wettest area on Baffin Island, receiving almost twice the precipitation that most other coastal sites receive. Consequently, the region allows an independent assessment of regional glacier style and timing. If the glacial history of Cape Dyer is similar to that of the LIS in nearby Merchants Bay (Fig. 1), then ice margins in both areas likely reflect regional climate patterns. If the two areas differ strongly in their glacial histories it is probable that glacier advance and retreat in one area is constrained by aclimatic processes. This would limit the broader implications of the moraine record.

A series of nested lateral moraines at Cape Dyer, the Sunneshine Moraines (Fig. 6), can be mapped along both sides of Sunneshine Fiord between 300 and 500 m a.s.l. (Locke, 1987). A broad undulating upland

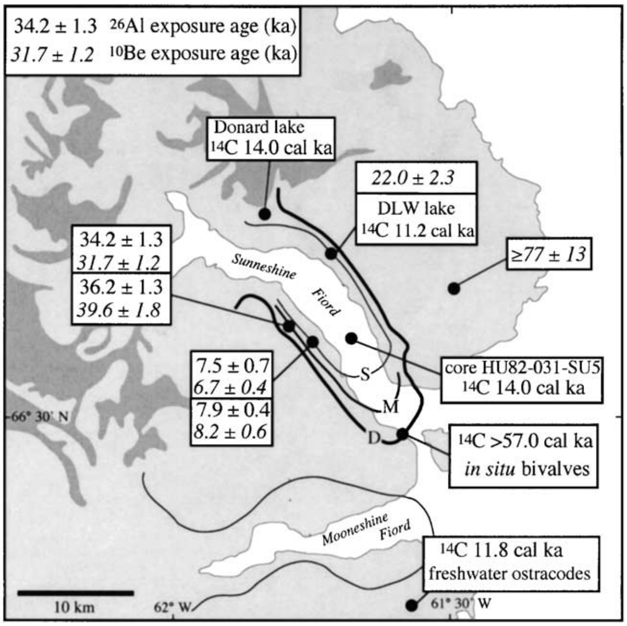

Fig. 6. Moraines of the Sunneshine (S), Monneshine (M), and Dyer (D) drift in the Cape Dyer region (Fig. 1), showing CE dates and ^{14}C dates (cal. yr) in basal lake sediment and marine bivalves in an ice-contact delta. The Sunneshine Moraine marks the apparent maximum LGM ice limit. Glacier advances in this region are derived from an ice-dispersal center immediately to the NW that remained independent of the LIS at least through the last glacial cycle. Advances of this independent ice-dispersal center occur at similar times to advances from the LIS-dominated Merchants Bar area, just 100 km to the north. Moraines modified from Locke (1987).

plateau (400–600 m a.s.l.) of considerable antiquity extends above these moraines. Weathering of tors on the plateau is exceptionally advanced. Toward the interior, the plateau is backed by highly dissected mountains reaching over 1500 m a.s.l. The eastern coast of the Cape Dyer region is composed of flat-lying Tertiary basalts that lack erratics of Canadian Shield origin or evidence of glacial erosion, hence are thought to have escaped continental glaciation (Clarke and Upton, 1971).

Three distinct lateral moraines within the Sunneshine Moraines have sufficient along-fiord preservation that their terminal positions can be reconstructed with reasonable certainty. Locke (1987) named these, from youngest to oldest, the Sunneshine, Mooneshine, and Dyer drifts (Fig. 6). Locke (1987) used differences in relative weathering to suggest that all of the Sunneshine Moraines pre-date the LGM and that local glaciers are currently similar in size to their LGM limits. Sediment and faunal changes recorded in marine cores from the fiord could be reconciled with this interpretation (Andrews et al., 1996). However, this interpretation differs greatly from the revised glacial history of Merchants Bay summarized above (Steig et al., 1998), just 100 km to the north.

Our goal in revisiting Cape Dyer was to test the chronological interpretation of Locke (1987) using CE dating and lake sediment cores. We sampled erratic boulders on crests of the right and left lateral Sunneshine Moraine, the left lateral Monneshine Moraine and tors from the adjacent plateau for CE dating, and collected in situ bivalve mollusks from an ice-contact raised-marine deposit near the mouth of Sunneshine Fiord for AMS ^{14}C dating. We also recovered sediment cores from several lakes, including one dammed by a moraine of the Sunneshine drift.

The Sunneshine drift lateral moraines are sharp-crested with abundant quartz-rich erratic boulders. One boulder from the crest of the lowest (300 m a.s.l.) left lateral Sunneshine Moraine has a ^{10}Be age of 22 ka (Fig. 6). Two boulders about 10 m apart on the right lateral Sunneshine Moraine gave ^{10}Be and ^{26}Al ages of about 8 ka. The CE ages of these two samples suggest deglaciation slightly later than nearby marine core evidence (see below) that indicates ice withdrew from the Sunneshine terminal moraine 11 ka ago. Possibly the erratics at this particular site on the moraine were shielded by snow cover during deglaciation, resulting in reduced cosmic radiation and the younger ages. Higher (older) moraine segments are best preserved as right laterals; two boulders from the crest of the Mooneshine Moraine have ^{10}Be and ^{26}Al ages $\geqslant 35$ ka. Hence, the Mooneshine drift pre-dates the LGM, and the Dyer Moraine (Fig. 6) must be even older. Tors from the plateau above and inland from the moraine systems exhibit no obvious evidence of glaciation. A ^{10}Be age from one tor is $\geqslant 77$ ka (Fig. 6).

A small ice-contact delta is situated at the projected terminus of the Dyer Moraine near the mouth of Sunneshine Fiord (Fig. 6). Dramatic changes in the sediment character of this delta, alternating between well sorted, stratified coarse sands, and poorly sorted layers with striated clasts to > 1 m diameter, and the lack of any alternative sediment source, attest to the ice-marginal interpretation. We collected paired valves of juvenile *Hiatella arctica* in growth position from one of the finer grained units. We interpret these mollusks to reflect brief intervals of ice recession allowing mollusk colonization before the ice margin returned to the site and buried the horizon with poorly sorted, rapidly deposited sediment. The shells have an AMS ^{14}C age of > 57 ka (CAMS-11337), consistent with the Dyer drift being older than Mooneshine drift, now dated at $\geqslant 35$ ka.

We cored several lakes in the Cape Dyer area. Dye Lower Water Lake (Fig. 6; 305 m a.s.l., 7 m deep; it provided drinking water for the Dye Main DEW Line Station's lower camp) is dammed by a segment of the left-lateral Sunneshine Moraine dated by CE at 22 ka (see above). We recovered five piston cores that bottom in diamict; all exhibit a simple postglacial sediment accumulation. The oldest basal ^{14}C age is about 11 cal ka BP. Because the cores lack characteristic deglacial sediments and are 9 ka younger than the moraine, we conclude that ice recession from the Sunneshine Moraine occurred before the lake formed. Donard Lake (460 m a.s.l.; 21 m deep) is situated well above the upper limit of the Sunneshine Moraine (Fig. 6). Cores from the central deep have a basal date of ca. 14 cal ka (Moore, 1996), also suggesting early deglaciation.

In light of these new results, we can revisit the marine evidence from core HU82-031-SU5, collected close to the reconstructed terminus of the Sunneshine Moraine (Fig. 6). The 8.4-m-long core spans 14 ka (Andrews et al., 1996). Almost 5 m of the core was deposited rapidly between about 12 and 11 ka. The foraminiferal assemblages for much of this interval are dominated by *Elphidium excavata* forma *clavata*, a taxon characteristic of ice-proximal environments. The high sedimentation rates and faunal characteristics are consistent with an LGM outlet glacier at the reconstructed Sunneshine Moraine terminus as late as 11 ka, followed by rapid deglaciation.

Collectively, our data confirm that a large outlet glacier occupied, but did not reach the mouth of Sunneshine Fiord at the LGM, and that higher moraine segments in the fiord relate to pre-LGM expansions. This differs from the conclusions of Locke (1987) who argued that modern glaciers are as extensive as they were at the LGM, but this conclusion relied primarily on relative weathering characteristics. All observers agree that the upland plateau may not have been glaciated for an even longer time, if ever.

The glacial histories of Cape Dyer and Merchants Bay are internally consistent, even though outlet glaciers in the two regions were derived from independent ice-dispersal centers. Similar glacial histories for these independent ice masses suggest the moraine records reflect regional climate as a primary forcing mechanism.

4. A new paradigm for the glacial style across the Eastern Canadian Arctic

Recent studies and new evidence summarized above have forced a substantial re-evaluation of the glacial limits for Baffin Island outlined by Dyke and Prest (1987), the last major synthesis of the LIS. The consensus view now is that all of southern Baffin Island was inundated at the LGM. Lake cores (Williams, 1990; Miller et al., 1999), marine cores (Andrews et al., 1990), and glacial geology (Stravers et al., 1992; Kaufman et al., 1993) demonstrate that all of SE Baffin Island, including small islands off the SE coast previously thought to have remained outside the LGM limit (Miller, 1980; Dyke and Prest, 1987), were inundated by the last glaciation. By inference, we might expect that all of Labrador, including the highlands, was glaciated at the LGM. On-going cosmogenic dating programs can be expected to provide important new constraints for this region. In the Queen Elizabeth Islands, where a similar debate on LGM ice extent has persisted for several decades, recent field observations imply a large Innuitian Ice Sheet (Dyke, 1999) and subsequent CE dating and re-evaluation of other primary field data support this contention (England, 1998, 1999; Zreda et al., 1999). An Innuitian Ice Sheet inundated most of the archipelago at the LGM, and was contiguous with, although independent from, the Greenland Ice Sheet in the northeast and the LIS to the south, although ice-free areas persisted in the western portion of the archipelago (Dyke et al., this volume). These studies demonstrate that throughout the Eastern Canadian Arctic the LGM ice limits were substantially more extensive than defined by the Minimalist Paradigm.

On the other hand, the pendulum swing away from the Minimalist Paradigm has been checked long before it returned to the Flint Paradigm. Despite firm new evidence for a more extensive LGM margin than proposed by Dyke and Prest (1987), there is equally strong new evidence from Baffin Island to suggest that both LGM ice margins and ice dynamics were very different from the original "Big Ice" model. This evidence is derived from recent studies in Cumberland Sound, Merchants Bay, Cape Dyer, and Bylot Island, summarized above, and older studies conducted at Clyde and adjacent forelands (Fig. 1). For these small segments we have sufficient evidence to constrain the ice limits and to draw initial inferences on ice-sheet dynamics. As a working hypothesis we can extrapolate these results over much of the NE sector of the LIS.

4.1. "Just-Right" ice: the Goldilocks Paradigm

Collectively, the new evidence suggests that ice-sheet profiles and ice velocities were strongly dependent on basal thermal regime and substrate, and that these conditions exhibited strong spatial variability. Local variations in basal thermal regime are overprinted with a strong N–S gradient in glacial style, presumably reflecting regional glacial-age gradients of precipitation and temperature, resulting in more extensive continental glaciation over southern Baffin Island than farther north. The new field evidence, coupled with regional marine evidence and recent glaciological modeling, suggests a dynamic LIS; inherent instabilities characterized outlet glaciers in major marine troughs and embayments (e.g., Hudson Strait, Cumberland Sound, and possibly Home Bay and Lancaster and Jones sounds; Fig. 1).

LGM ice sheets everywhere overwhelmed southern Baffin Island and presumably Labrador. But north of Hall Peninsula, LIS outlet glaciers were apparently restricted to the fiords and sounds, where they maintained relatively low gradients and terminated at the coastline or on the continental shelf. Once outside the confines of the troughs, calving rates accelerated, preventing the relatively thin outlet glaciers from expanding to the shelf edge. We hypothesize that low-gradient outlet glaciers sliding on deformable sediment were also characterized by relatively high velocities, in contrast with slower-moving, cold-based flow where ice crossed topographically rough crystalline terrain between the major fiord systems. A consequence of these contrasting basal regimes is that many coastal reaches of the inter-fiord highlands remained above the limit of LGM ice, and at least some low-elevation forelands may have been free of actively eroding ice throughout the LGM. GCM simulations of the LGM climate (e.g. Pollard and Thompson, 1997), and temperature and precipitation records for the LGM from nearby Greenland (Alley et al., 1993; Cuffey et al, 1995) suggest that much of Baffin Island was up to 20°C colder, and precipitation reduced by 50% at the LGM. These conditions must have played a role in controlling the observed glacial style.

The new paradigm postulates more extensive LGM ice over Baffin Island than previously suggested from the terrestrial evidence, but reconstructed outlet glacier gradients are low and ice sheet profiles are expected to be much lower. For example, the CLIMAP maximum model (CLIMAP, 1981) has a similar ice margin, but assumes a relatively steep parabolic ice-sheet profile over most of the area, resulting in substantially thicker ice over Foxe Basin. The differences in ice-sheet profiles for these models are illustrated in Fig. 2b.

4.2. Complementary evidence consistent with the Goldilocks Paradigm

Coincident with a re-evaluation of the LGM ice margin across the Eastern Canadian Arctic has been the reassessment of LIS ice dynamics and the ice sheet's role in the global climate system. High-resolution records from the Greenland Ice Sheet (e.g., Johnsen et al., 1992; Taylor et al., 1993; Grootes et al., 1993) and the deep sea (e.g., Sachs and Lehman, 1999) document unexpected rapid reorganizations of the global climate system. Repetitive clastic layers in the North Atlantic reflect episodic outbursts of debris-laden continental ice (Heinrich (H) events; Heinrich, 1988; Andrews and Tedesco, 1992; Bond et al., 1993) that may trigger these reorganizations (Broecker and Denton, 1989). Massive ice-discharge events suggest that inherent instabilities in continental ice sheets are a major determinant of the climate system. Most H-events thicken toward Hudson Strait (Andrews and Tedesco, 1992; Dowdeswell et al., 1995), suggesting that the LIS impacts ice-age climate through iceberg discharge to the North Atlantic.

Glaciological theory supports the inherent instability of the LIS. Clark (1994) summarized evidence for strong spatial variability in basal conditions along the southern LIS terrestrial margin, depending on the nature of the underlying substrate. MacAyeal (1993) proposed an aclimatic binge–purge cycle that includes a long interval of thickening and increasing thermal isolation of the glacier bed until melting occurs, accelerating ice flow. Faster flow adds additional heat to the bed, resulting in rapid downdraw from the interior and the transfer of large masses of ice to the North Atlantic (Alley and MacAyeal, 1994). Foxe Basin would be impacted by any major downdraw of the LIS interior, suggesting that outlet glaciers along eastern Baffin Island might be expected to fluctuate repeatedly during the last glacial cycle in response to surging in Hudson Strait (or Cumberland Sound; Jennings, 1989), a process that may explain the bimodal distribution of CE dates for LGM moraines in the Pangnirtung region (Fig. 4).

5. Conclusions

Direct field observations of glacial geology, ^{14}C-dated in situ marine bivalves from meltwater-fed raised-marine deposits, lacustrine sedimentary records dated by AMS ^{14}C and luminescence, and CE dating of scoured bedrock and erratic blocks on moraine crests collectively constrain the limits of LGM Laurentide ice along eastern Baffin Island, Arctic Canada. From these constraints, we offer a new paradigm to describe the style of glaciation across this region. LGM glaciation inundated all land on southern Baffin Island, including both Meta Incognita and Hall peninsulas and their offshore islands. A fast-moving, low-gradient outlet glacier fed dominantly by ice centered over Foxe Basin occupied Cumberland Sound; there was minimal contribution to this glacier by ice flow off Cumberland Peninsula. Farther north, basal shear stress (low in fiords, where thick, wet, deformable sediments dominate; high on adjacent crystalline terrain where drift cover is thin, ice-velocities low, and frozen to the bed), and width/height ratios of troughs controlled LGM ice limits. In narrow, deep fiords (e.g., Sunneshine Fd.), frictional resistance to flow provided by the fiord walls results in slower moving ice with steeper surface slopes than in wide sounds (i.e., Home Bay, Cumberland Sound; Fig. 1) where the lateral resistance is less significant. Interfiord highlands and some coastal forelands apparently remained ice-free, or under permanent snowfields lacking basal flow throughout the LGM, and were effectively geomorphically inert. Consequently, "glacial" times are represented in lakes in ice-free terrain as periods of non-deposition.

There is suggestive evidence for a two-part local LGM; an early advance culminating between 30 and 20 ka, and a later advance of almost the same extent late in the last glacial cycle (ca. 12–10 ka). Both of these events are apparent in the CE ages in Merchants Bay (where they occur as separate moraines) at Pangnirtung (where the Duval Moraine has a bimodal erratic clast age) and at Cape Dyer (where CE dates on 3 erratics from the Sunneshine Moraine and radiocarbon dates from a fiord core exhibits a similar pattern). A possible explanation is that the Foxe Dome was drawn down during Heinrich events H2 and H1, resulting in minor contraction of outlet glaciers along the Baffin Island margin or that the peak LGM climate was so dry in the eastern Canadian Arctic that ice margins receded slightly. These hypotheses require testing at other sites with LGM terminal moraines. Prior to the LGM, Baffin Island remained under persistent cold and presumably arid conditions at least back to 60 ka. During this period multiple glacial advances occurred, although chronological controls remain too sparsely distributed and too imprecise to delimit regional patterns.

The LGM ice margins predicted by the Goldilocks Paradigm are substantially more advanced than in the Minimalist Paradigm. The northeastern Laurentide ice margin is characterized by a series of outlet glaciers terminating near the mouths of fiords and sounds, rather than at the shelf edge, and these outlet glaciers had lower ice-sheet profiles than predicted by the Flint Paradigm.

Acknowledgements

Field and analytical work were primarily supported by the National Science Foundation through grants EAR-9510063, OPP-9807066, and ATM-9708414. We thank Nunavut Research Institute (Nunavummi Qaujisaqtulirijikkut), Iqaluit, for logistical assistance, the Inuit people of Pangnirtung and Qikiqtarjuaq (formerly Broughton Is.) for permission to work in these areas and for logistical assistance in the field. For assistance and companionship in the field we thank Chance Anderson, Obadiah Miller and Luke Miller.

We thank Drs. Edward J. Brook (Washington State University), Grant Raisbeck and Francoise Yiou (Gif-sur-Yvette, France) for providing two of the CE ages at Cape Dyer. The CE-dating program and field collecting around Pangnirtung was a collaboration between Kimberley Marsella, Paul Bierman (both at University of Vermont) and P.Thom Davis (Bentley College). Except for two of the Cape Dyer samples, all CE-samples were analyzed at the LLNL AMS facility with the assistance of Marc Caffee and Robert Finkel. Ideas presented here benefited from discussions with John Andrews, Art Dyke, Anne Jennings, Jan Mangerud, Tad Pfeffer, John England, Kimberley Marsella and Thom Davis. The manuscript was clarified and strengthened by reviews from Kimberley Marsella, Thom Davis, Art Dyke, Eiliv Larsen and Geoffrey Boulton.

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