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Late Wisconsinan glaciation and postglacial relative sea-level change on western Banks Island, Canadian Arctic Archipelago

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ABSTRACT

The study revises the maximum extent of the northwest Laurentide Ice Sheet (LIS) in the western Canadian Arctic Archipelago (CAA) during the last glaciation and documents subsequent ice sheet retreat and glacioisostatic adjustments across western Banks Island. New geomorphological mapping and maximum-limiting radiocarbon ages indicate that the northwest LIS inundated western Banks Island after ~31 ^{14}C ka BP and reached a terminal ice margin west of the present coastline. The onset of deglaciation and the age of the marine limit (22–40 m asl) are unresolved. Ice sheet retreat across western Banks Island was characterized by the withdrawal of a thin, cold-based ice margin that reached the central interior of the island by ~14 cal ka BP. The elevation of the marine limit is greater than previously recognized and consistent with greater glacioisostatic crustal unloading by a more expansive LIS. These results complement emerging bathymetric observations from the Arctic Ocean, which indicate glacial erosion during the Last Glacial Maximum (LGM) to depths of up to 450 m.

Introduction

Banks Island is located in the western Canadian Arctic Archipelago (CAA) and is bounded by Amundsen Gulf to the south and M'Clure Strait to the north, two major outlets for an expansive, former ice-sheet complex that existed during late Wisconsinan glaciation (Stokes et al., 2005, 2006, 2009; England et al., 2009; Fig. 1). This dynamic ice mass was made up of the northwest Laurentide Ice Sheet (LIS), the southwest Innuitian Ice Sheet (IIS), and several local ice caps, that converged over the islands of the western CAA and included multiple ice shelves and ice streams that operated for thousands of years (Dyke and Prest, 1987; Dyke et al., 2002; Hanson, 2003; Dyke, 2004; England et al., 2006; Stokes et al., 2006; England et al., 2009; Stokes et al., 2009; MacLean et al., 2012; Nixon, 2012; Fig. 1a). Banks Island is, thus, uniquely situated to record past ice-sheet limits and glacier dynamics, that have implications for assessing former changes in paleoclimate and relative sea level, as well as the sedimentation history of the Arctic Ocean basin, where glacial bedforms at depths exceeding 1000 m have been identified (e.g. Polyak et al., 2001).

For more than 60 years, researchers investigating the Quaternary paleogeography of northern North America have hypothesized that much of Banks Island was unglaciated during the late Wisconsinan (Hobbs, 1945; Jenness, 1952; Wilson et al., 1958; Fyles, 1962; Prest, 1969; French, 1972; Vincent, 1982, 1983; Dyke, 1987; Dyke and Prest, 1987; Dyke et al., 2002, 2003). The purportedly ice-free area contrasts markedly with adjacent islands and marine channels where more recent field studies have identified thick, extensive ice cover during the Last Glacial Maximum (LGM; Dyke et al., 2002; Hanson, 2003; Dyke, 2004; Stokes et al., 2005; England et al., 2006; Stokes et al., 2006; England et al., 2009; Stokes et al., 2009; MacLean et al., 2012; Nixon, 2012; Fig. 1a). This apparent discontinuity has spurred a debate about whether Banks Island supported a refugium during the late Wisconsinan (Harington, 2005; MacPhee, 2007).

Recent investigations by England et al. (2009) and Lakeman and England (2012), addressing the timing and extent of late Wisconsinan glaciation on Banks Island, contradict previous ice-sheet reconstructions developed by Vincent (1982, 1983; Fig. 2). Vincent (1982, 1983) concluded that Banks Island was inundated by continental ice sheets during at least three separate glaciations, each successively less extensive, between >780,000 and ~20,000 yr ago (Fig. 2a). Vincent (1982, 1983) further proposed that the island was a predominantly ice-free refugium during the LGM (i.e. Harington, 2005; Fig. 2a). However, the configuration, limits, and ages of these glaciations remained unconstrained. Furthermore, the pattern and magnitude of relative sea-level change resulting from glacioisostatic crustal adjustments following ice-sheet retreat were poorly documented. On the basis of new geomorphological mapping and a robust radiocarbon chronology, England et al. (2009) and Lakeman and England (2012) demonstrated that the northwest LIS inundated the northern interior of Banks Island, well beyond the LGM margin proposed by previous workers (Fyles, 1962; Vincent, 1982, 1983; Dyke, 1987; Figs. 1a and 2). For example, England et al. (2009) and Lakeman and England (2012) demonstrated that the LIS

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Figure 1. (a) Canadian Arctic Archipelago (CAA) showing the extent of the Innuitian Ice Sheet (IIS) and Laurentide Ice Sheet (LIS) during the Last Glacial Maximum (LGM). Banks Island was bounded by the Amundsen Gulf Ice Stream (AGIS) and the M'Clure Strait Ice Stream (MSIS). The dashed line indicates the minimum extent of the LIS on Banks Island following England and Furze (2008), England et al. (2009), and Lakeman and England (2012). Ice-sheet limits elsewhere are from Dyke (2004) and England et al. (2006, 2009). Box denotes the location of b. (b) Place names and generalized bedrock geology of Banks Island and Victoria Island, western CAA.

flowed northward across north-central Banks Island during the late Wisconsinan and not only filled Castel and Mercy bays but was confluent with an ice stream in M'Clure Strait (Stokes et al., 2005, 2009; Figs. 1 and 2b). Nonetheless, the geometry, extent, and dynamics of the LIS across western Banks Island during the LGM remain undetermined. This study is an extension of recent field investigations by England et al. (2009) and Lakeman and England (2012) and is aimed at further testing the conceptual model proposed by Vincent (1982, 1983) by revisiting the paleoenvironmental record of Quaternary landforms and sediments on northwest Banks Island (Fig. 2b).

The objectives of this study are to: 1) determine the late Wisconsinan limit of the LIS on Banks Island, 2) characterize local glacier dynamics during ice-sheet retreat, and 3) document the history of postglacial relative sea level change resulting from glacioisostatic unloading of the crust following deglaciation. The study implicitly tests the hypothesis that the modern ecosystem of Banks Island evolved from its own Ice

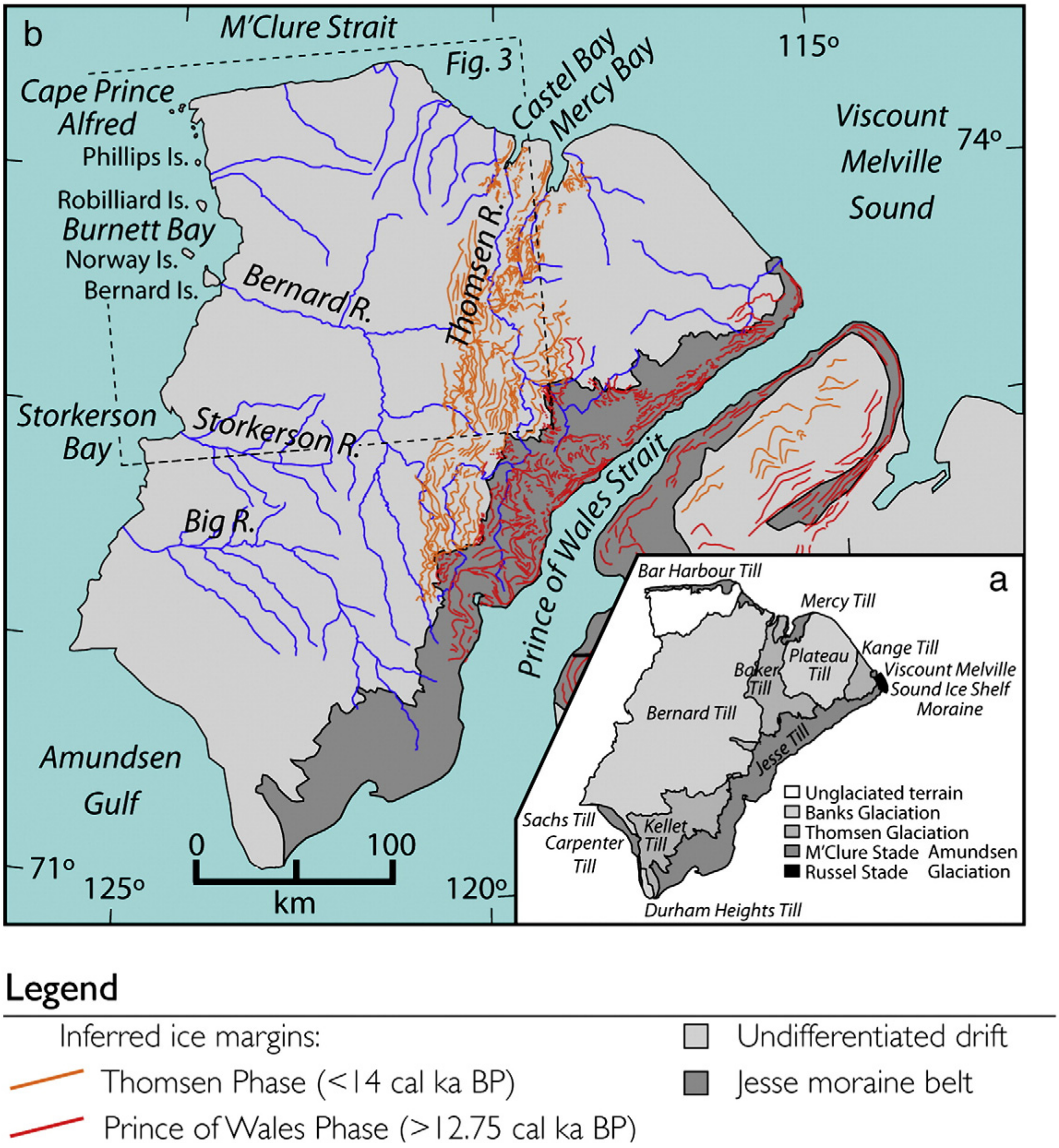

Figure 2. (a) The spatial distribution of the multiple till sheets reported by Vincent (1982, 1983), which were considered to document at least three Quaternary glaciations. Note the purportedly unglaciated plateau in the northwest. (b) Revised surficial geology of Banks Island following England et al. (2009) and Lakeman and England (2012). All the previously reported till sheets are considered to be a single, discontinuous late Wisconsinan deposit, including the Jesse moraine belt (formerly the Jesse till), which records a signficant, short-lived readvance or stillstand during deglaciation (Lakeman and England, 2012). Also shown are inferred ice margins from Lakeman and England (2012) that record two phases of ice-sheet withdrawal. The Thomsen Phase records dominantly northward ice flow and accompanying ice-sheet withdrawal to the south and east from M'Clure Strait beginning ~14 cal ka BP. The Prince of Wales Phase records deposition of the Jesse moraine belt prior to 12.75 cal ka BP. The box denotes the location of Fig. 3.

Age refugium (i.e. Harington, 2005). The synthesis also contributes to an improved understanding of long-term climatic variability in Arctic Canada and glacially-influenced sedimentation and erosion in the Arctic Ocean (i.e. Jakobsson et al., 2008b). Clarifying the Quaternary history of Banks Island is also relevant to understanding modern sea-level change, including the rate and magnitude of ongoing submergence impacting coastal communities across the western Canadian Arctic (e.g. Paulatuk, Tuktoyuktuk, Sachs Harbour; Fig. 1b). Improved knowledge of past ice-sheet extents and chronologies provides essential constraints for global geophysical modeling of modern sea-level change (i.e. Siddall and Milne, 2012).

Previous work

The earliest studies to address the Quaternary history of Banks Island were limited in extent and reconnaissance in nature (Hobbs, 1945; Washburn, 1947; Porsild, 1950; Jenness, 1952; Manning, 1956). Fyles (1962) completed the first detailed investigation of the physiography of Banks Island using aerial photographs and extensive field mapping. He recognized several distinct physiographic regions on the island, including "extensive monotonous lowlands, massive hilly moraines … and dissected uplands", that he attributed to regional differences in bedrock geology and Pleistocene history. Fyles (1962) suggested that the Jesse till that rims the east coast of the island (Fig. 2a), marked the limit of late Wisconsinan glaciation on the island. This limit was adopted by subsequent compilations addressing the size and nature of the late Wisconsinan LIS (i.e. Prest, 1969). The landscape distal to (i.e. west of) the Jesse till was interpreted by Fyles (1962) to have been ice-free during the last glaciation based on the apparent absence of "fresh" glacial landforms and the striking dominance of fluvial erosion and deposition in many catchments. However, he acknowledged the presence of glacial landforms and deposits of unknown age originating from one or more earlier continental glaciations on western Banks Island.

Vincent (1982, 1983) and Vincent et al. (1984) revisited the Quaternary geomorphic and stratigraphic records on Banks Island and applied several new correlation techniques not employed by previous researchers (i.e. paleomagnetism, amino acid geochronology). Vincent (1982, 1983) identified several formal climatostratigraphic units on Banks Island and interpreted them as a conformable succession of Quaternary glacial–interglacial environments. The oldest, most extensive glaciation was termed the Banks Glaciation and was estimated to be more than 780,000 yr old (Vincent et al., 1984; Fig. 2a). This was followed by two successively less extensive glaciations, the Thomsen Glaciation and finally the Amundsen Glaciation, which was further subdivided into the M'Clure and Russel Stades, corresponding to the early and late Wisconsinan, respectively (Fig. 2a).

The till sheets associated with these glaciations include the Bernard, Baker, Kellet, and Jesse tills, among others (Fig. 2a), which were distinguished primarily on the basis of their lithology, their relationship to inferred ice-sheet margins, and their presumed relative ages. As well, Vincent (1982, 1983) formally associated all of these till sheets with a series of proglacial lakes and postglacial marine transgressions and regressions. Vincent (1982, 1983) assigned the Jesse till to the early Wisconsinan based on amino acid ratios from shell fragments collected from the surface of a marine delta overlying the till. Tills farther west were assigned to older Quaternary glaciations following Fyles' (1962) earlier observations. Notably, the northwest plateau was purported to have been 'never glaciated' (Fig. 2a) based on an apparent absence of till and glacial erratics. The only glacial landform on the island regarded by Vincent (1982, 1983) to be late Wisconsinan is a prominent moraine on the northeast coast (Fig. 2a), which was later ascribed to a deglacial ice shelf in M'Clure Strait (the Viscount Melville Sound Ice Shelf; Hodgson and Vincent, 1984; Hodgson, 1994).

Vincent's (1982, 1983) reconstruction sought to correlate the surficial record of multiple tills and marine deposits with the subsurface record, exposed in several stratigraphic sections. These correlations were based primarily on lithostratigraphy; however, aminostratigraphy was also used but only where fossil molluscs were identified. The final reconstruction of Quaternary events proposed by Vincent (1982, 1983, 1984) represents an incomparably elaborate history of Quaternary environmental change within the CAA, one in which the subsurface record perfectly mirrors the surficial geology, despite a paucity of absolute ages for the identified deposits.

In the first major challenge to Vincent's (1982, 1983) reconstruction, Dyke (1987) reinterpreted the age of the Jesse till, reassigning it to the late Wisconsinan on the basis of an associated marine deposit dating to 12,410–11,355 calibrated years Before Present (cal yr BP; GSC-1437). Thus, Dyke (1987) reverted the late Wisconsinan ice margin back to that of Fyles (1962) and Prest (1969), but retained the previously proposed deglacial age for the Viscount Melville Sound Ice Shelf moraine (Hodgson and Vincent, 1984; Hodgson, 1994; Fig. 2a). Consequently, Dyke and Prest (1987) and later compilations (Dyke et al., 2002; Dyke, 2004) portrayed the Jesse till as the local limit of the northwest LIS during the LGM. Furthermore, England and Furze (2011) refined the deglacial age of the Viscount Melville Sound Ice Shelf moraine on Melville Island and northeast Banks Island.

England et al. (2009) and Lakeman and England (2012) reinvestigated the surficial geology and geomophology of northern and eastern Banks Island. They observed previously unreported glacial and marine deposits, many of which further revise the conceptual model proposed by Vincent (1982, 1983; Fig. 2). For example, new observations demonstrate northward ice-flow from the northern interior of Banks Island into M'Clure Strait, discounting the opposite (southward) flow direction proposed by Vincent (1982, 1983). Furthermore, Lakeman and England (2012) reconstructed the pattern and timing of ice-sheet retreat from northern and central Banks Island to Prince of Wales Strait, on the basis of newly identified moraines, meltwater channels, and radiocarbon-dated ice-contact deltas (Fig. 2b). Two phases of deglaciation were recognized. The Thomsen Phase was characterized by ice-sheet retreat from the north-central interior and from Mercy and Castel bays at approximately 13.75 cal ka BP, and the subsequent withdrawal of a predominantly cold-based ice-sheet margin to the east coast (England and Furze, 2008; England et al., 2009; Lakeman and England, 2012; Fig. 2b). Widespread withdrawal of the northwest LIS was punctuated by a readvance or stillstand during the Prince of Wales Phase, which coincided with deposition of the Jesse moraine belt (formerly the Jesse till) along Prince of Wales Strait prior to ~12.75 cal ka BP (Lakeman and England, 2012; Fig. 2b). Hence, glacial landforms and sediments that were formerly attributed to multiple, pre-Late Wiscsonsinan glaciations (Vincent, 1982, 1983; Fig. 2a) are now ascribed to a deglacial interval of ~1000 calibrated years during the late Wisconsinan (Fig. 2b). Accordingly, all the surficial tills previously reported by Vincent (1982, 1983) are considered by England et al. (2009) and Lakeman and England (2012) to be a discontinuous late Wisconsinan deposit and, as such, the formal nomenclature introduced by Vincent (1982, 1983) was abandoned. Furthermore, England et al. (2009) and Lakeman and England (2012) recognized that the unidentified LGM limit of the northwest LIS must be located west of Castel Bay, possibly lying offshore on the adjacent Beaufort Sea shelf (Stokes et al., 2005, 2006, 2009; England et al., 2009; Fig. 1).

Despite exhaustive field surveys throughout northern and eastern Banks Island, England et al. (2009) and Lakeman and England (2012) did not observe any of the raised marine deposits and shorelines reported by Vincent (1982, 1983). For example, on the east coast, marine sediments and landforms associated with the *Big Sea* (120–215 m above sea level (asl)), the *East Coast Sea* (120 m asl), and the *Schuyter Point Sea* (<25 m asl), which purportedly record three separate deglaciations (Vincent, 1982, 1983), are all absent. Similarly, sedimentary evidence for *Lake Ivitaruk*, shown to extend more than 300 km along the Thomsen River valley, and the *Investigator Sea* (<30 m asl) in Mercy and Castel bays are also absent. In contrast, England et al. (2009) and Lakeman and England (2012) surveyed ice-contact shorelines marking the marine limit in Mercy and Castel bays at 41 and 37 m asl, respectively, and dated them to ~13.75 cal ka BP. These data document a previously unrecognized amount of glacioisostatic unloading by the northwest LIS on northern Banks Island following the late Wisconsinan, which is consistent with new geomorphic observations indicating a thicker and more expansive northwest LIS (England et al., 2009; Lakeman and England, 2012).

Methods

New surficial mapping of landforms and sediments across western Banks Island permits a detailed reconstruction of ice-sheet retreat. Glacial and marine landforms and sediments were mapped and investigated in the field using aerial photography (scale 1:100,000), satellite imagery, and widespread surveys by foot, ATV, canoe, and helicopter. Fieldwork was concentrated along the west coast which was surveyed entirely. The extent and pattern of retreat for the LIS were determined using cross-cutting relationships among mapped glacial landforms. The elevation of deglacial, raised marine deltas and beaches was measured by digital altimetry that has an accuracy of ±2 m to 100 m asl when measurements span short intervals (5–10 min), thereby eliminating the effects of atmospheric pressure changes. Critical elevations were confirmed by multiple, consistent measurements on the same landform.

The chronology of late Wisconsinan glaciation was established by accelerator mass spectrometry (AMS) radiocarbon dating of marine molluscs collected from marine sediments. A total of eleven radiocarbon ages are reported from nine samples across the field area (Table 1) and augment those (>100) published by England and Furze (2008), England et al. (2009), and Lakeman and England (2012). For this study, radiocarbon ages were obtained from the W.

M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (UCIAMS), University of California at Irvine and the National Ocean Sciences Accelerator Mass Spectromety Facility (NOSAMS), Woods Hole Oceanographic Institute. Unless otherwise stated, all radiocarbon ages are reported in ^{14}C yr Before Present (1950) (^{14}C yr BP) and are not corrected for marine reservoir effects (Coulthard et al., 2010) because they exceed 30,000 ^{14}C yr BP.

In addition, two optically stimulated luminescence (OSL) ages were obtained from a raised marine deposit on Phillips Island off the west coast of Banks Island (Fig. 2b and Table 2). These ages were obtained from quartz sand (90–180 μm) at the Sheffield Centre for International Drylands Research (SCIDR) Luminescence Laboratory. The dose rate for the samples was determined by thick source beta counting using a Riso Multi-channel beta counter and by inductively coupled plasma mass spectrometry at SGS Laboratories, Ontario, Canada. Elemental concentrations were converted to annual dose rates using data from Aitken (1998), Adamiec and Aitken (1998), and Marsh et al. (2002). Samples underwent quartz extraction and cleaning following the procedure of Bateman and Catt (1996) and were preheated to 260°C for 10 s. The palaeodose determinations were derived using the single-aliquot regenerative (SAR) approach (Murray and Wintle, 2000) and measurements made on a Riso TL DA-20 luminescence reader with radiation doses administered using a calibrated ^{90}Sr beta source.

Glacial landforms and sediments

Western Banks Island is primarily an extensive lowland incised by broad, west-draining valleys flanked by isolated hills. A prominent plateau in the northwest corner of the island comprises the highest terrain. The region is underlain by poorly lithified sandstone and shale of the Palaeocene Eureka Sound Formation and unlithified sand and gravel of the Pliocene Beaufort Formation (Miall, 1979; Fig. 1b). These Cenozoic clastic sediments are mantled by scattered erratics and by discontinuous thin till commonly composed of unsorted sand and gravel of local origin with rare erratic clasts, including boulders. Proglacial and ice-lateral meltwater channels developed during former glaciation(s) are the most widespread glacial landforms and are distinguished on the basis of their morphology and location. Ice-lateral meltwater channels are situated on interfluves and valley sides, oriented oblique to slope, and presently occupied by ephemeral misfit streams. They are commonly nested or paired and have steep channel sides and gradients. Proglacial meltwater channels are similarly occupied by misfit streams and occur in association with ice-lateral meltwater channels or in isolation, where they record the pattern of proglacial meltwater drainage from ice-lateral and supraglacial meltwater streams, respectively.

The pattern of glacial meltwater channels in the study area (Fig. 3) comprises an undisrupted succession of former ice margins that document eastward ice sheet retreat from the Beaufort Sea coast across western Banks Island (Fig. 4). On the west coast, ice-lateral meltwater channels terminate at the marine limit, less than 5 km from the Beaufort Sea (Fig. 3). These channels delineate a formerly digitate, terrestrial ice margin that was characterized by multiple glacier lobes occupying the primary river valleys (Fig. 4). Younger ice-lateral meltwater channels lying farther inland (Fig. 3a) delineate a nested sequence of multi-lobate ice margins, recording subsequent ice-sheet withdrawal up the major river valleys (Fig. 4). In the central interior, meltwater channels outline a large curvilinear ice front, which contrasts markedly with the highly digitate ice margin farther west (Figs. 3 and 4). Geomorphological relationships indicate that this curvilinear ice front is contemporaneous with widespread ice-lateral meltwater channels and lateral moraines along Castel and Mercy bays (Figs. 3 and 4), which document northward ice-flow to M'Clure Strait via the Thomsen River valley (Lakeman and England, 2012). Ensuing ice withdrawal from M'Clure Strait into Castel and Mercy bays is constrained by minimum-limiting radiocarbon ages of ~13.75 cal ka BP for the deglacial marine limit (England et al., 2009; Lakeman and England, 2012). Therefore, the curvilinear ice margin in the central interior marks the position and geometry of the northwest LIS at ~14 cal ka BP (Fig. 4), when westerly ice-flow across western Banks Island was inhibited by dominant northward ice-flow to M'Clure Strait via the Thomsen River valley (Lakeman and England, 2012).

Several, prominent proglacial meltwater channels emanating from various mapped ice margins are also present in the study area (Fig. 3). These channels further delineate the evolution of the retreating ice front and, like adjacent ice-lateral channels, commonly descend into

Table 1
New radiocarbon ages cited in this study.

	Laboratory number[a]	Age[b]	Lab error[c]	Dated material	Location	Coordinates	Sample elevation	Site description
		(^{14}C yr BP)	(^{14}C yr BP)				(m asl)	
West coast, Banks Island	NOSAMS-79535	49,900	550	*A. borealis* (fragment)	First Point	73° 17′ 14.8″ N 124° 32′ 58.7″ W	5	Surface: stony sand and silt
	NOSAMS-79536	30,700	140	*A. borealis* (whole valve)	Adam River	73° 25′ 12.2″ N 124° 23′ 11.2″ W	2	Surface: stony sand and silt
	NOSAMS-79539	34,700	200	*H. arctica* (fragment)	Liot Point	73° 05′ 16.4″ N 124° 51′ 24.4″ W	3	Surface: stony sand and silt
	NOSAMS-79612	45,600	480	*A. borealis* (whole valve)	*South Bluff* Burnett Bay	73° 49′ 54.3″ N 123° 52′ 13.5″ W	6	Stratigraphic section: organic-rich, stony mud
	NOSAMS-79613	33,600	240	*A. borealis* (fragment)	*North Bluff* Burnett Bay	73° 50′ 12.1″ N 123° 53′ 24.2″ W	4	Surface: sandy gravel on top of the bluff
	NOSAMS-79614	45,500	600	*A. borealis* (whole valve)	*North Bluff* Burnett Bay	73° 50′ 17.7″ N 123° 53′ 56.4″ W	5	Stratigraphic section: stony sand
	NOSAMS-79615*	35,100	220	*A. borealis* (whole valve)	*North Bluff* Burnett Bay	73° 50′ 29.8″ N 123° 54′ 09.4″ W	6	Surface: sandy gravel on top of the bluff
	UCI-77838*	38,540	330	*A. borealis* (whole valve)	*North Bluff* Burnett Bay	73° 50′ 29.8″ N 123° 54′ 09.4″ W	6	Surface: sandy gravel on top of the bluff
Norway Island	NOSAMS-79616	44,800	770	*A. borealis* (fragment)	Norway Island	73° 42′ 11.2″ N 124° 35′ 51.5″ W	5–30	Stratigraphic section: sandy gravel delta foresets
Phillips Island	NOSAMS-79617*	>52,000		*H. arctica* (whole valve)	Phillips Island	74° 05′ 06.1″ N 124° 33′ 16.5″ W	7	Stratigraphic section: glaciotectonized stony sand
	UCI-77839*	>57,300		*H. arctica* (whole valve)	Phillips Island	74° 05′ 06.1″ N 124° 33′ 16.5″ W	7	Stratigraphic section: glaciotectonized stony sand

[a] NOSAMS (National Ocean Sciences Accelerator Mass Spectrometry Facility, Woods Hole Oceanographic Institute); UCI (University of California at Irvine).
[b] no marine reservoir correction.
[c] 1-sigma.
* indicates redate on the same valve.

Table 2
Optically stimulated luminescence ages from Phillips Island.

Laboratory number[a]	Elevation (m asl)	Depth (cm)	Palaeodose (De) (Gy)	Dose rate (μGy/a)	Age (ka)	Material	Coordinates
Shfd11043	7	150	92.1 ± 1.93	784 ± 34	118 ± 5.7	Glaciotectonized gravelly sand	74° 05′ 05.5″ N 124° 33′ 13.7″ W
Shfd11071	7	150	88.8 ± 2.40	810 ± 22	110 ± 4.2	Glaciotectonized gravelly sand	74° 05′ 05.5″ N 124° 33′ 13.7″ W

[a] Shfd (Sheffield Centre for International Drylands Research).

the major valleys comprising the modern fluvial drainage network. These valleys contain expansive terraces that are several kilometers wide and composed of glaciofluvial sand and gravel (Fig. 3), which is poorly drained and characterized by widespread kettles, low-centered ice-wedge polygons, and myriad shallow ponds. These terraces are, therefore, interpreted as deglacial sandurs, which transported large volumes of glaciofluvial sediment to the Beaufort Sea. Sandurs within the Bernard and Storkerson river valleys are traceable across the island to the Jesse moraine belt on the east coast of the island (Fig. 2b), indicating that they remained active until the northwest LIS retreated fully from the island's east coast ~12.75 cal ka ago (Lakeman and England, 2012; Fig. 2b).

Few moraines occur in the study area. Those that are present are narrow, discontinuous, ice-thrust moraines. Furthermore, many of the islands off the west coast of Banks Island, (i.e. Phillips Island), are composed of marine sediment with glaciogenic faults and overturned folds (Fig. 5a). These glaciotectonized sediments record former ice-sheet margins beyond the Banks Island coast, possibly constituting remnants of former moraines deposited on the Beaufort Sea shelf. Kettles and kames, primarily composed of sand and gravel that is possibly reworked from the underlying Beaufort Fm. also occur within the study area. Kames often occur as concentrations of flat-topped mounds and conical hills, although isolated deposits are also present. Kettles are widespread in the low-lying areas of western Banks Island. Higher surfaces within the study area, including the northwest plateau, generally lack kettles but are nonetheless covered by discontinuous thin till and scattered erratics resting on bedrock. Basalt and gabbro erratics are most abundant, likely sourced from

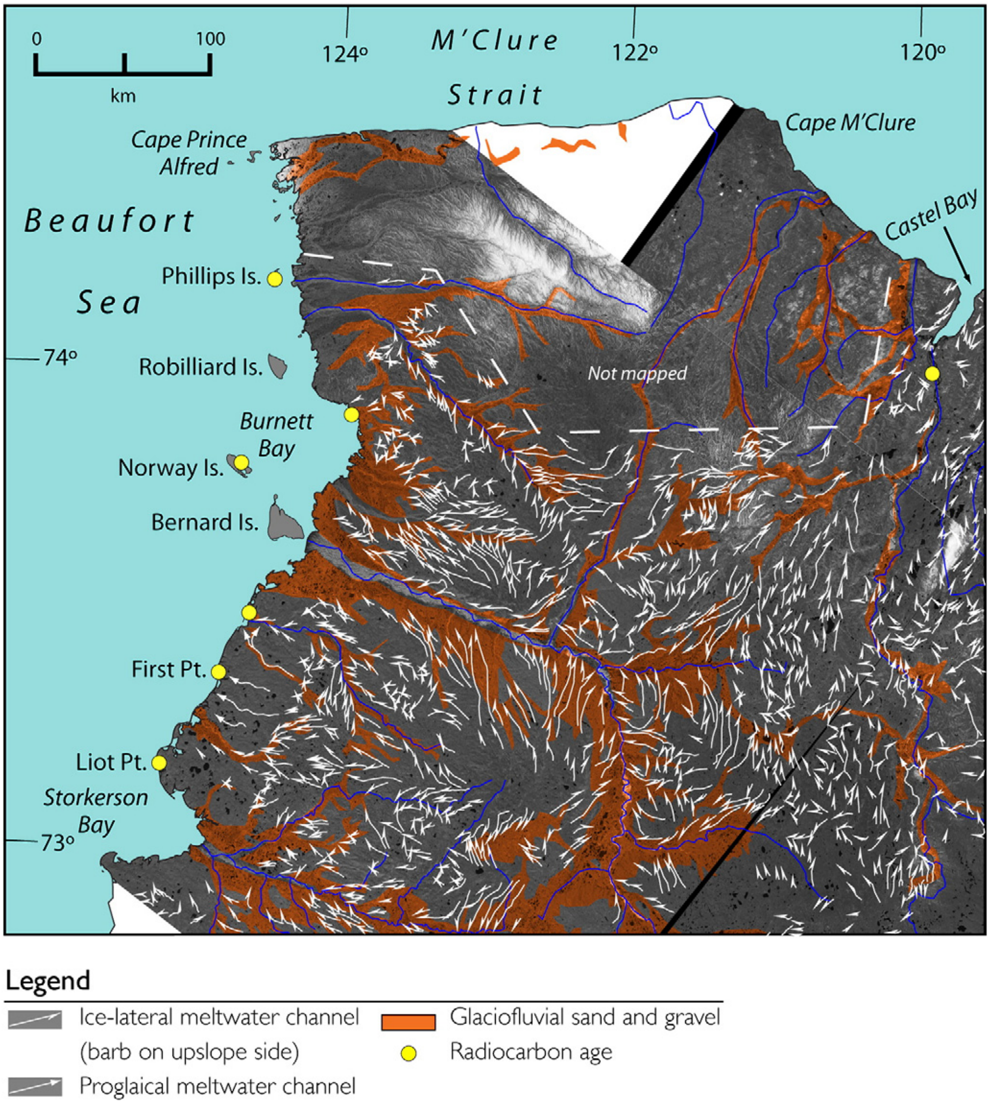

Figure 3. The distribution of meltwater channels, glaciofluvial sand and gravel, and radiocarbon sample locations in the study area, shown on a composite Landsat 7 orthoimage (band 8) of western Banks Island.

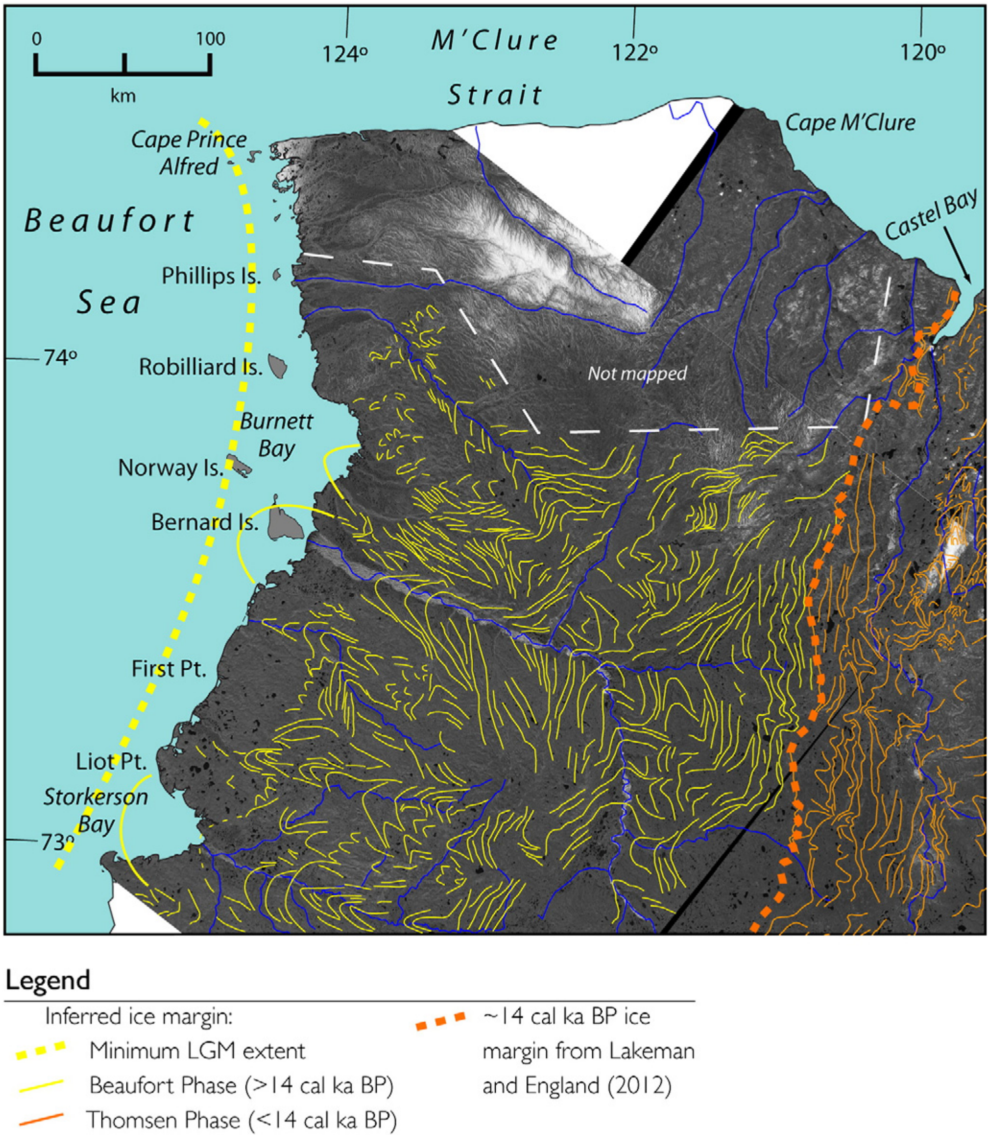

Figure 4. Inferred deglacial ice margins in the study area, shown on a composite Landsat 7 orthoimage (band 8) of western Banks Island. During the Beaufort Phase, ice-sheet withdrawal proceeded from the Beaufort Sea coast to the central interior. During this interval, the geometry of the northwest LIS was generally constrained by the major west-draining river valleys. During the early Thomsen Phase, the northwest LIS was characterized by dominantly northward ice-flow to M'Clure Strait via the Thomsen River valley. The inferred ~14 cal ka BP ice margin from Lakeman and England (2012) marks the transition from dominantly westward to northward ice flow.

the Shaler Mountains, Victoria Island, approximately 400 km to the east (Fig. 1b). Sandstones and granites are less abundant compared to mafic erratics on the west coast, as well as to the concentration of sandstones and granites in the Jesse moraine belt (Lakeman and England, 2012).

Raised marine deposits and radiocarbon ages

Well-preserved raised beaches, ice-contact deltas, and glacier-fed deltas record former relative sea level on western Banks Island (Fig. 6). The beaches discontinuously rim the coastline and trim till upslope (Fig. 6). Ice-contact and glacier-fed deltas are accordant with the uppermost beaches, and emanate from broad, ice-lateral and proglacial meltwater channels (Fig. 6). Because these channels comprise part of the network of meltwater channels that outlines ice-sheet retreat across the study area (Figs. 3 and 4), the raised marine landforms are interpreted to mark the marine limit and are attributed to deglaciation of the west coast.

Below the marine limit, in low-lying areas adjacent to the coast, sand and silt with rare molluscs is widespread. Available stratigraphic exposures in these deposits reveal 0.5 to 2 m of stony, planar-laminated sand and silt overlying clayey, matrix-supported diamict (Fig. 5b). The sand and silt has a sharp contact with the underlying diamict and in some exposures a well-sorted gravel lense occurs between the diamict and the sand and silt (Fig. 5b). In all exposures, the uppermost ~0.5 m of stony sand and silt is massive (Fig. 5b). Despite exhaustive field surveys, only three surface collections of whole valves and fragments of *Astarte borealis* and *Hiatella arctica* (2–5 m asl) were obtained from the widespread stony sand and silt that is situated below and seaward of the marine limit. These samples yielded ages of 30,700 ± 140 (NOSAMS-79536), 34,700 ± 200 (NOSAMS-79539), and 49,900 ± 550 (NOSAMS-79535) ^{14}C yr BP (Table 1 and Fig. 5b).

The elevation of the marine limit on the west coast ranges from 22 to 40 m asl (Fig. 6). In Storkerson Bay, the marine limit is marked by a prominent beach terrace at 30 m asl, which is traceable for more than 30 km (Fig. 6). Between Liot Point and First Point, the elevation of the same beach together with accordant deltas falls progressively from 28 to 22 m asl (Fig. 6). North of First Point, the beach terrace rises in elevation and is accordant with a well-preserved glacier-fed delta at

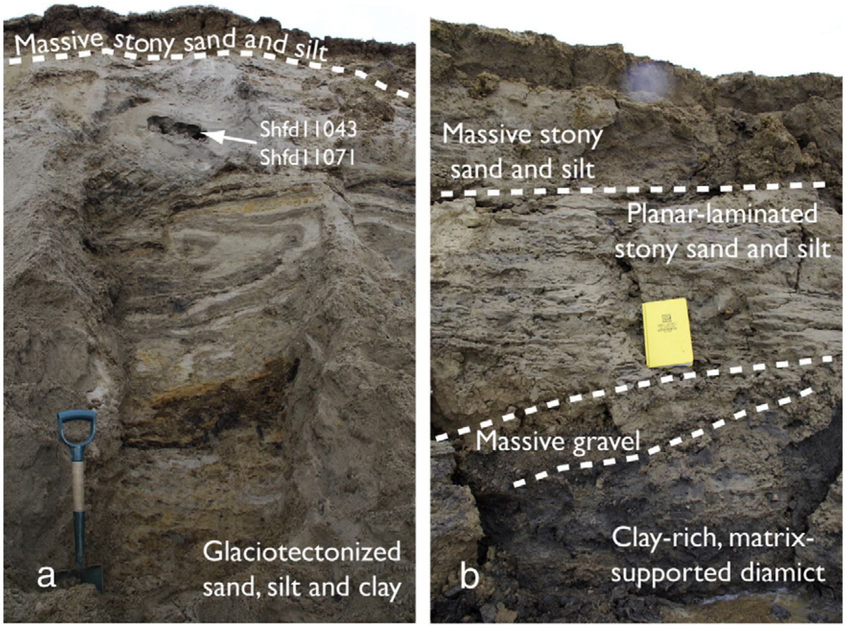

Figure 5. (a) Glaciotectonized nearshore marine sediments on Phillips Island (Fig. 3). Most evident is an overturned fold outlined by interbedded sand and silt. Additional folds and faults occur in the overlying gray sand. The upper gray sand contains whole valves of *H. arctica* in growth position that yielded non-finite radiocarbon ages (Table 1). Two optically stimulated luminscence ages from the gray sand (arrowed) yielded ages of 118 ± 5.7 (Shfd11043) and 110 ± 4.2 (Shfd11071) ka BP (Table 2). (b) Coastal exposure at First Point (Fig. 3) showing planar-laminated stony sand and silt sharply overlying massive gravel and clayey diamict. The uppermost ~0.5 m is massive stony sand and silt. Rare mollusc fragments from the massive stony sand, capping the exposure, yielded a radiocarbon age of 49,900 ± 550 ^{14}C yr BP (NOSAMS-79535; Table 1). Additional mollusc samples collected from the surface of the same deposit elsewhere on the coast (Table 1 and Fig. 3) yielded ages of 34,700 ± 200 ^{14}C yr BP (NOSAMS-79539) and 30,700 ± 140 ^{14}C yr BP (NOSAMS-79536; Table 1).

25 m asl near the mouth of the Adam River (Fig. 6). In the Bernard River valley, several proglacial and ice-lateral meltwater channels terminate at small fan deltas (composed of gravelly sand) that attain a maximum elevation of ~30 m asl (Fig. 6). Farther north, the marine limit rises to 38–40 m asl between Burnett Bay and the Davies River, marked by well-preserved beaches, ice-contact deltas, and glacier-fed deltas (Fig. 6). On the small islands just offshore from western Banks Island, raised marine landforms are present but sparse, probably due to widespread Holocene coastal erosion. On Norway Island, an ice-contact delta remnant (32 m asl) composed of sandy gravel foresets records a former ice-sheet margin west of Banks Island as well as a former relative sea level to at least this elevation (Fig. 6). Similarly, raised beaches on Robilliard Island and Phillips Island attain elevations of 22–29 m asl (Fig. 6).

In addition, the study area includes several coastal exposures of fossiliferous littoral and deltaic sediments. In section, these sediments commonly contain abundant organic matter (including locally high concentrations of woody detritus redeposited from the Beaufort Fm.) and a diverse molluscan fauna. For example, two bluffs at the head of Burnett Bay are composed of deltaic and littoral sediments with abundant valves of *H. arctica*, *A. borealis*, and *Portlandia arctica* (Fig. 7). The *North Bluff* rises to 10 m asl and is composed of planar-laminated and rippled, fossiliferous stony sand (Fig. 7b). The *South Bluff* rises to 7 m asl and is composed of planar-laminated stony sand interbedded with fossiliferous, organic-rich mud (Fig. 7c). Paired, whole valves of *A. borealis* collected at 5–6 m asl in growth position from both bluffs provided ages of 45,600 ± 480 (NOSAMS-79612) and 45,500 ± 600 (NOSAMS-79614) ^{14}C yr BP (Table 1 and Fig. 7). Younger ages were obtained from the uppermost 0.5–1 m of sediment at both bluffs where fossiliferous, massive stony sand has a gradational contact with underlying stratified sediment (Fig. 7). These uppermost sediments extend laterally across the top of the bluffs onto adjacent, low-lying areas (Fig. 7a). Surface collections of whole valves and fragments of *A. borealis* from these massive sediments yielded ages of 33,600 ± 240 (NOSAMS-79613), 35,100 ± 220 (NOSAMS-79615), and 38,540 ± 330 (UCI-77838) ^{14}C yr BP that we regard to be finite (Table 1 and Fig. 7).

A glaciotectonized exposure on Phillips Island, ~35 km to the northwest, reveals similar, interbedded sand, silt, and clay with abundant fossil molluscs; however, glaciotectonism has disrupted the stratigraphy (Fig. 5a). Whole valves of *H. arctica* and *A. borealis* from this deposit yielded non-finite radiocarbon ages (Table 1). Two OSL ages of 118 ± 5.7 ka (Shfd11043) and 110 ± 4.2 ka (Shfd11071; Table 2 and Fig. 5a) from a single stratigraphic horizon, which immediately overlies the radiocarbon-dated stratum, provide an estimate for the age of the sediments as well as a maximum-limiting age for the subsequent glaciogenic deformation. The sedimentological and biostratigraphic affinity between this OSL-dated deposit and the bluffs in Burnett Bay (with radiocarbon ages of ~46 ^{14}C ka BP) raises further uncertainty regarding whether these older mollusc ages are indeed finite.

Discussion

Chronology

The widespread coastal stratigraphy constituting clay-rich diamict overlain by gravel and planar-laminated, stony sand and silt (Fig. 5b) is interpreted to record the transition from glacial to postglacial sedimentation. The diamict is inferred as a till because it is massive and widespread along the coast; however many inaccessible and slumped exposures along the coast likely mask local facies variability (i.e. ice-marginal debris-flows). The stratigraphic position of the stony sand and silt, and its absence of interbedded organic matter imply that it was deposited following deglaciation of the coast. Furthermore, the stony sand and silt has no sedimentological affinity to deposits with molluscs in growth position that yielded radiocarbon ages of ~46 ^{14}C ka BP and older. The uppermost, massive stony sand and silt (Fig. 5) is traceable upslope to the marine limit (22–40 m asl) and is, thus, inferred to relate to postglacial relative sea-level regression. Subsequent, additional reworking of these massive sediments, which comprise the dominant outcrop along the west coast, was likely achieved through cryoturbation.

The mollusc samples collected from the surface of the massive stony sand and silt are interpreted to be redeposited because their

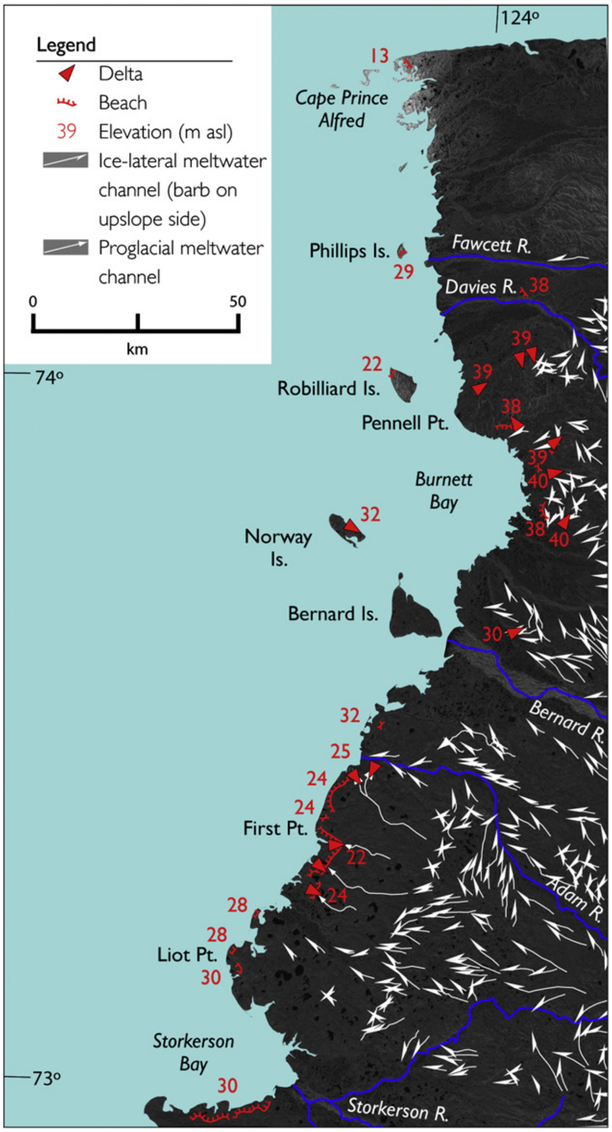

Figure 6. The location and elevation of raised marine beaches, ice-contact deltas, and glacier-fed deltas on western Banks Island. Note the 13 m marine-limit shoreline at Cape Prince Alfred (J.H. England and M.F.A. Furze, pers. comm., 2010).

occurrences are exceedingly rare and the few identified sample sites consist of predominantly small, sub-angular and sub-rounded fragments. The same interpretation was made by Lakeman and England (2012) on eastern Banks Island for rare mollusc fragments (55–32 ^{14}C ka BP in age) collected from till, outwash, glaciolacustrine deltas, and marine-limit deltas, which were all unequivocally deposited during late Wisconsinan deglaciation.

The precise origin of redeposited mollusc fragments collected from the surface of the massive stony sand and silt is uncertain. However, because they occur in deglacial sediment, they were likely redeposited from glacier ice and till (i.e. Lakeman and England, 2012). Alternatively, these mollusc fragments could have been redeposited from autochthonous marine sediment, however, no such marine deposits containing molluscs of similar age (i.e. ~31 ^{14}C ka BP) and in growth position were observed in the study area. Furthermore, such sediments would have to have been deposited when relative sea level was >6 m higher than present, which we consider unlikely because eustatic sea level at that time was ~50 to 100 m *below* modern (Clark et al., 2009). As well, the northwest margin of the mid Wisconsinan LIS was restricted to Victoria Island (Dyke et al., 2002), likely rendering western Banks Island beyond the limit of significant peripheral glacioisostatic depression (i.e. >200 km from the margin; Andrews, 1970). Indeed, ages for redeposited mollusc fragments collected from the Jesse moraine belt, which was deposited between ~13.75 and 12.9 cal ka BP, indicate that ice-free conditions extended at least as far east as Prince of Wales Strait ~33 ^{14}C ka BP (Lakeman and England, 2012). Regardless, the redeposited molluscs provide maximum-limiting ages for the widespread and generally unfossiliferous stony sand and silt (Fig. 5), and the youngest age of 30,700 ± 140 ^{14}C yr BP (NOSAMS-79536; Table 1) provides the closest constraint on the age of the surveyed marine limit.

The maximum-limiting ages for the marine limit along western Banks Island constrain the timing of the last deglaciation to some time after ~31 ^{14}C ka BP. Therefore, it is inferred that the study area was inundated by the northwest LIS during the late Wisconsinan (Fig. 4). This is consistent with England et al. (2009) and Lakeman and England (2012), who demonstrated that Vincent's (1982, 1983) till sheets and associated raised marine deposits on northern and eastern Banks Island constitute a single late Wisconsinan deglacial sequence. Similarly, widespread ice-lateral meltwater channels extending from the Beaufort Sea to the Thomsen River valley comprise an undisrupted succession (Fig. 3), recording a single phase of ice recession prior to the withdrawal of the LIS from Castel and Mercy bays ~13.75 cal ka BP (England and Furze, 2008; England et al., 2009; Lakeman and England, 2012; Fig. 4). Consequently, there is no geomorphological evidence to invoke a readvance to the ~14 cal ka BP ice margin on north-central Banks Island (Fig. 4), thereby requiring the more distal meltwater channels extending westward of the Thomsen River valley (Fig. 3) to record a separate glaciation. Hence, we support regional deglaciation of the northwest LIS that progressed eastward from the Beaufort Sea across northern and central Banks Island during the late Wisconsinan (Fig. 4).

There are currently no collections of deglacial mollusc samples to closely constrain the timing of initial ice sheet retreat from the Beaufort Sea coast of western Banks Island. Likewise, reliable, closely limiting deglacial ages from marine molluscs are unavailable from the westernmost part of the CAA, from Prince Patrick Island to the Arctic mainland west of Baillie Island (Hodgson et al., 1994; Dyke et al., 1996; Dyke et al., 2003; Dyke, 2004; R.D. Coulthard pers. comm., 2012; Fig. 1). This regional absence of marine molluscs older than ~14 cal ka BP is attributed to the full disappearance of a marine molluscan fauna from the western CAA during the LGM (Kaufman et al., 2004; England and Furze, 2008). Thus, the earliest phase of deglaciation along terrestrial margins of the northwest LIS and southwest IIS, predated the reestablishment of a marine molluscan fauna from the north Pacific, which coincided with the resubmergence of Bering Strait (Kaufman et al., 2004; England and Furze, 2008).

Stratigraphic exposures of fossiliferous sediments in Burnett Bay and on Phillips Island provide evidence of non-glacial marine sedimentation ≥46 ^{14}C ka BP. The prevalence of *A. borealis* in these deposits implies that local nearshore marine conditions resembled those of the southwest Canadian Arctic during the Holocene (Dyke et al., 1996). As well, sediments comprising the bluffs in Burnett Bay, rising up to 10 m asl, display no apparent glaciotectonism, suggesting that relative sea level was higher than present at the time of their deposition.

Our interpretation of new data presented here is incompatible with the longstanding hypothesis purporting the existence of an ice-free refugium on Banks Island during the LGM (Fyles, 1962; French, 1972; Vincent, 1982, 1983; Dyke, 1987; Harington, 2005). Additionally, these new results falsify previous correlations proposed by Vincent (1982, 1983, 1984) and Vincent et al. (1984) between the stratigraphic record and the surficial geology. For example, Vincent (1982, 1983, 1984) and Vincent et al. (1984) correlated magnetically reversed tills (i.e. >780,000 yr old) exposed in multiple stratigraphic exposures with the Bernard till (Fig. 2a), which is now ascribed to the late Wisconsinan on the basis of multiple maximum- and minimum-limiting radiocarbon ages of ~31 ^{14}C ka BP and ~13.75 cal ka BP, respectively (England and Furze, 2008; England et al., 2009; Lakeman and England, 2012; this study; Fig. 4).

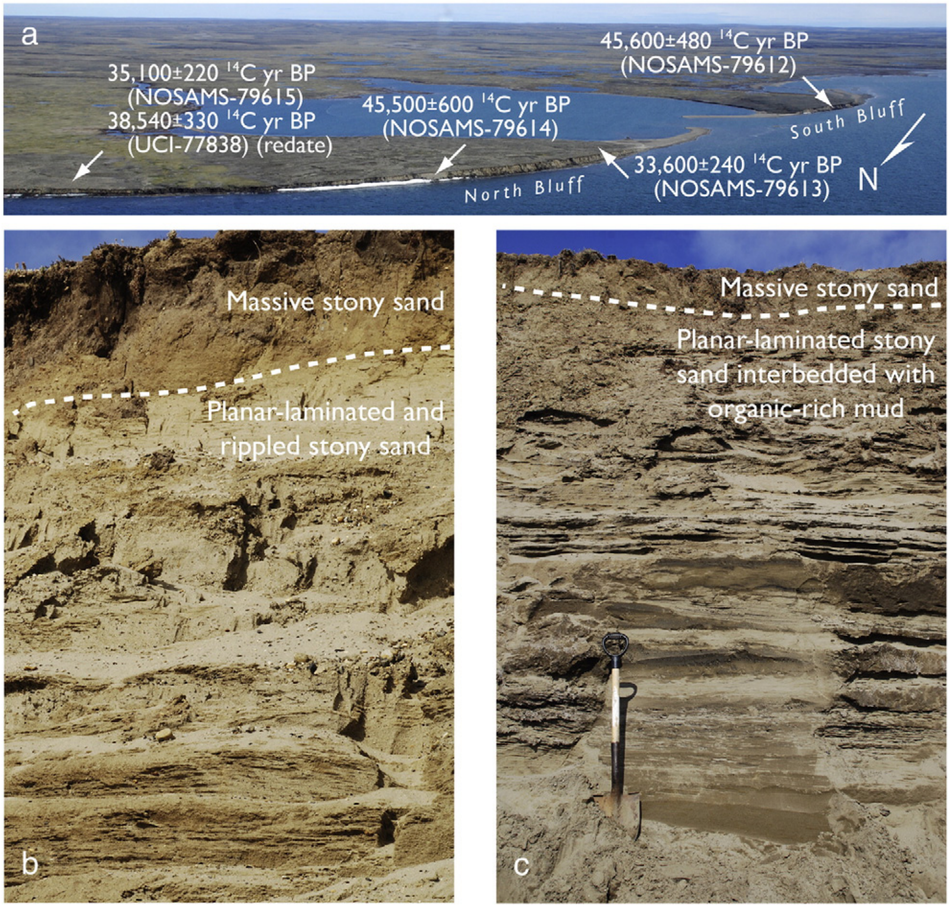

Figure 7. (a) Oblique photograph of two bluffs at the head of Burnett Bay (Fig. 3), looking southeast. Locations of radiocarbon sample locations are shown. NOSAMS-79614 and —79612 (Table 1) are from paired, whole valves of *A. borealis* collected at 5–6 m asl from the *North* and *South Bluff*, respectively. NOSAMS-79615, UCI-77838, and NOSAMS-79613 (Table 1) are surface collections of whole valves and fragments of *A. borealis*. (b) The *North Bluff* rises to 10 m asl and is composed of planar-laminated and rippled, fossiliferous stony sand. Massive stony sand with a gradational lower contact comprises the uppermost 1 m of sediment in the exposure. (c) The *South Bluff* rises to 7 m asl and is composed of interbedded stony sand and fossiliferous, organic-rich mud. Similarly, the capping 0.5 m of sediment is massive stony sand with a gradational lower contact. These upper, massive sediments extend laterally across the top of the bluffs onto adjacent, low-lying areas and are correlative to massive stony sand and silt pictured in Fig. 5.

An alternative interpretation of our evidence might be that the marine limit on western Banks Island, together with its associated moraines and meltwater channels, dates from a pre-late Wisconsinan glaciation. However, we argue that such a model, involving multiple glaciations across the field area (i.e. Vincent, 1982, 1983), clearly lacks geomorphological or chronological voracity. Indeed, it is considered untenable because several finite ages spanning 39–31 ^{14}C ka BP are related to the local deglacial marine limit. Additionally, the pattern of meltwater channels extending from the Beaufort Sea coast to the ~14 cal ka BP ice margin in the interior of Banks Island is incompatible with the argument for a separate and earlier glaciation, as there are no significant cross-cutting relationships nor associated landforms or deposits marking a long-lived ice margin (Fig. 3). Furthermore, there is no indication that the raised marine deposits marking the marine limit were formerly inundated by a cold-based ice sheet, as they lack the meltwater channels, thin till and erratics that are widespread above the marine limit, nor are these marine deposits glaciotectonized. The lack of minimum-limiting radiocarbon ages for the marine limit distal to the ~14 cal ka BP ice margin is fully consistent with a barren Arctic Ocean prior to this date throughout the westernmost CAA. Therefore, a pre-late Wisconsinan age for the last deglaciation of western Banks Island is rejected.

Late Wisconsinan ice-sheet dynamics

The glacial geomorphology of western Banks Island permits the development of a detailed reconstruction of the northwest LIS during the last deglaciation, including former ice margins and past dynamics (Fig. 4). The maximum limit achieved by the LIS cannot be ascertained in the study area. The occurrence of ice-lateral meltwater channels extending to the marine limit and widespread evidence for glaciotectonism on many of the small islands west of Banks Island, imply that the ice sheet terminated on the Beaufort Sea shelf during the late Wisconsinan (Fig. 4). Due to the lack of deglacial molluscs from the study area, the absolute age of deglaciation along the west coast of Banks Island remains imprecise. Furthermore, deglaciation was apparently time-transgressive along the west coast of Banks Island where ice-contact deltas, glacier-fed deltas, and beaches occur at variable elevations (Fig. 6). Nevertheless, the general accordance among these landforms, the gradient of which is compatible with dated marine limits in Castel and Mercy bays, suggests that they are contemporaneous.

The period of ice-sheet retreat across western Banks Island is herein termed the *Beaufort Phase* (Fig. 4) and is well-recorded by widespread ice-lateral meltwater channels (Fig. 3). The *Beaufort Phase* was characterized by the westward withdrawal of a predominantly cold-based ice margin and is distinguished from the younger, *Thomsen Phase*, which was coincident with southeastward ice-sheet withdrawal from northern and central Banks Island (Lakeman and England, 2012; Figs. 2b and 4). The westernmost (i.e. oldest) ice-lateral meltwater channels on western Banks Island delineate a multilobate ice front conforming to the major river valleys (Fig. 4). This pattern demonstrates that the geometry of the retreating ice front was topographically controlled and confirms that the ice sheet was locally thin (Fig. 4). This contrasts with evidence from M'Clure Strait, where grounded ice was at least 635 m thick (England et al., 2009; Lakeman and England, 2012;

Fig. 1a). This evidence for a thin terrestrial ice cover during deglaciation across western Banks Island possibly reflects diminished westward ice flow from an LGM ice divide located on Victoria Island (Dyke, 1983, 1984; Dyke et al., 1992; England et al., 2009; Lakeman and England, 2012), which formerly supplied ice terminating on the Beaufort Sea shelf. Thus, it is possible that ice divides within the northern LIS were beginning to thin at this time or that dynamical changes within the ice sheet (i.e. greater ice flux to calving margins in the adjacent marine channels) reduced ice flow to western Banks Island.

Following initial withdrawal of the northwest LIS from the Beaufort Sea shelf, ice-sheet retreat proceeded eastward across the study area (Fig. 4). Widespread ice-lateral meltwater channels and the general paucity of moraines indicate that the ice-sheet margin remained cold-based and proceeded without any regionally significant readvances or stillstands. Where rare moraines occur, these are likely the product of ice thrusting of frozen sediments along the ice margin where convergent ice flow generated sufficient strain or where minor, local readvances occurred. By ~14 cal ka BP, the ice-sheet margin was situated in the central interior and was still dominantly cold-based (Fig. 4). The position of the ice margin at ~14 cal ka BP is documented by radiocarbon ages on molluscs collected from ice-contact glaciomarine deltas deposited in Castel and Mercy bays (England and Furze, 2008; England et al., 2009; Lakeman and England, 2012). Subsequently, the ice-margin retreated southward and eastward to Prince of Wales Strait (*Thomsen Phase*, England et al., 2009; Lakeman and England, 2012; Fig. 2b).

Perhaps the oldest evidence for deglaciation of the west coast is recorded by beaches and ice-contact deltas north of the Bernard River (Fig. 6). These deposits rise in elevation from 30 m asl near the Bernard River to 40 m asl in Burnett Bay, well above the 13 m asl marine limit at Cape Prince Alfred, which borders M'Clure Strait (J.H. England and M.F.A. Furze pers. comm., 2010; Fig. 6). If these shorelines are of similar deglacial age, then they would provide a maximum estimate for differential emergence (i.e. 27 m over ~50 km). However, the LIS was thicker and faster-flowing in M'Clure Strait relative to western Banks Island. Specifically, M'Clure Strait supported a major ice stream that likely terminated at a floating ice shelf for much of the last deglaciation (Stokes et al., 2005, 2009; England et al., 2009; Fig. 1a). This dynamical distinction could have resulted in a significant offset in the timing of final deglaciation of the north and west coasts; with the west coast becoming ice-free earlier due to diminished ice flow resulting from enhanced ice-sheet drawdown (via calving) in the adjacent marine channels. Thus, deglaciation of Cape Prince Alfred was likely delayed in relation to areas farther south, and the development of the marine limit was exacerbated by the repeated occupation of the strait by deglacial ice shelves following removal of the grounded ice stream.

Postglacial relative sea-level change

The elevation of the marine limit on western Banks Island significantly exceeds estimates based on geophysical modeling (Tarasov and Peltier, 2004), which were derived using ice-sheet reconstructions with no LGM glaciation of western Banks Island (Dyke et al., 2002; Dyke, 2004). Thus, in addition to the geomorphological observations outlined above, our new relative sea-level data provide further support for an extensive LIS in the southwest CAA during the LGM, as hypothesized by Tarasov and Peltier (2004) to account for the divergence of their geophysical modeling estimates from previously reported field observations. Similarly, on Melville and Prince Patrick islands, where recent geomorphological mapping indicates more extensive late Wisconsinan glaciation than previously recognized, new relative sea-level data (England et al., 2009; Nixon, 2012; R.D. Coulthard, pers. comm., 2012) does not match model-derived estimates based on limited late Wisconsinan ice cover (Tarasov and Peltier, 2004).

Elsewhere across Banks Island, the marine limit rises in elevation from west to east along M'Clure Strait (England et al., 2009) and from southwest to northeast along Prince of Wales Strait (Lakeman and England, 2012; Fig. 8). The age of the marine limit on the north coast varies from >14 cal ka BP west of Cape M'Clure to ~13.75 cal ka BP at Castel Bay, Mercy Bay, and Parker Point (England et al., 2009; Lakeman and England, 2012). On the east coast of Banks Island, the marine limit is isochronous, ~12.75 cal ka BP (Lakeman and England, 2012). Collectively, this new deglacial dataset provides an important constraint for ongoing geophysical modeling of the last glaciation of northern North America (i.e. Tarasov et al., 2012).

Outwash in several major west-draining valleys on western Banks Island (e.g. adjacent to the Bernard and Storkerson rivers; Figs. 2b and 3) is graded to a base level that is similar to modern sea level. As these sandurs remained active until ~12.75 cal ka BP, when the LIS retreated entirely offshore (Lakeman and England, 2012; Fig. 2b), it is provisionally inferred that the ~13 cal ka BP shoreline on the west coast of Banks Island had regressed to a position similar to modern. Cessation of meltwater delivery to these sandurs ~12.75 cal ka BP would have fundamentally altered the hydrology and sediment supply of the major west-draining valleys of western Banks Island, favoring subsequent preservation of widespread terraces.

Observations of the modern coastline include widespread examples of drowned tundra, including ice-wedge polygons undergoing thermal and mechanical erosion; coastal microcliffs; submerged deltas; estuaries; barrier beaches; washover fans; and extensive sea-ice push ridges. These features unequivocally document a modern transgression progressing from a lowstand of unknown age and depth. Similar observations from elsewhere on Banks Island (Lakeman and England, 2012) indicate that modern coastal submergence characterizes its entire coastline. Indeed, Andrews and Peltier (1989) as well as recent relative sea-level reconstructions from Melville and Eglinton islands (Lajeunesse and Hanson, 2008; Nixon, 2012) place Banks Island on the submergence side of the zero isobase (a theoretical line separating submergent from emergent coastlines). It is possible that the lowstand on the west coast of Banks Island was achieved in the latest Pleistocene or early Holocene if the chronology of deglaciation is comparable to that of the southeast margin of the LIS in Atlantic Canada (e.g. Shaw and Forbes, 1995; Stea et al., 2001; Bell et al., 2003). The lowstand elsewhere on Banks Island (e.g. the east coast) was likely achieved later because deglaciation there was delayed until ~12.75 cal ka BP (Lakeman and England, 2012). Relative sea-level rise across Banks Island from the time of the lowstand to present can be attributed to eustatic sea-level rise (i.e. Peltier and Fairbanks, 2006), the eastward migration and collapse of a glacioisostatic forebulge (i.e. Dyke and Peltier, 2000), and steric sea-level rise (i.e. Antonov et al., 2005). Similar conclusions and provisional calculations regarding Holocene relative sea-level lowstands on Eglinton and Melville islands have been further elaborated by Nixon (2012).

Glacial erosion of the Arctic Ocean seafloor

During the past decade, substantial advances in the acquisition of multibeam bathymetric echo sounder data and chirp sonar subbottom profiler data have provided widespread, high-resolution surveys of the Arctic Ocean seafloor (Vogt et al., 1994; Jakobsson, 1999; Polyak et al., 2001; Kristoffersen et al., 2004; Jakobsson et al., 2005; Polyak et al., 2007; Engels et al., 2008; Jakobsson et al., 2008a,b). These data reveal conspicuous glacial bedforms reaching depths of approximately 1000 m on the Lomonosov Ridge (Polyak et al., 2001), 900 m on the Chukchi Borderland (Jakobsson et al., 2005, 2008a, 2008b), and 850 m on the Yermak Plateau (Vogt et al., 1994).

Glacial bedforms are most abundant on the Chukchi Borderland (Jakobsson et al., 2008b; Fig. 9) where multiple episodes of ice grounding are recognized and provisionally attributed to Marine

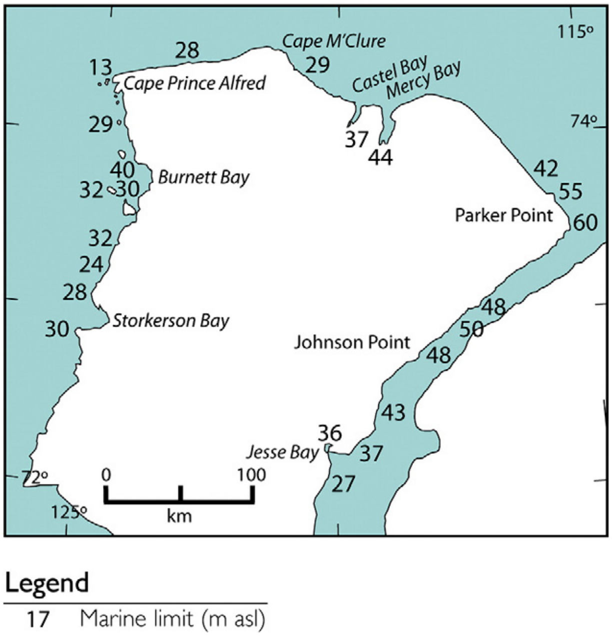

Figure 8. The elevation (m asl) of the postglacial marine limit across Banks Island. The age of the marine limit on the west coast is unknown. Data from the north coast is from England and Furze (2008) and England et al. (2009). Data from Castel Bay and the east coast is from Lakeman and England (2012).

Oxygen Isotope Stages (MIS) 6, 4, and 2 (Darby et al., 2005; Polyak et al., 2007; Jakobsson et al., 2010). On the Northwind Ridge, one of several north-trending ridges comprising the Chukchi Borderland, glacial bedforms oriented east–west and occurring to depths of ~450 m (Fig. 9) have been radiocarbon dated to the late Wisconsinan (Polyak et al., 2007). These bedforms constitute multiple, parallel, low-relief lineations reaching tens of kilometers in length. At shallower depths (<300–400 m) lineations and ridges are crosscut and obscured by abundant, randomly oriented iceberg plowmarks. Lineations are interpreted as flutes, recording the grounding of glacier ice shelves or the grounding of coalescent iceberg armadas (Polyak et al., 2001; Jakobsson et al., 2005; Polyak et al., 2007). Subbottom sonar records confirm that the flutes are composed of unstratified, glaciogenic diamicts and are capped by postglacial mud (Polyak et al., 2007). These records also document an erosional unconformity beneath the flutes (Jakobsson et al., 2005; Polyak et al., 2007). This observation confirms that the flutes document the passage of glacier ice sufficiently thick to ground in the Arctic Ocean during the last glaciation. Grounding may have been augmented by thick, pervasive sea ice across the Arctic Ocean during the LGM (i.e. Bradley and England, 2008), the evidence for which lies in sedimentary records containing abiotic intervals with very low sedimentation rates, including a possible hiatus between approximately 20 and 13 ^{14}C ka BP (Poore et al., 1999; Polyak et al., 2004, 2009).

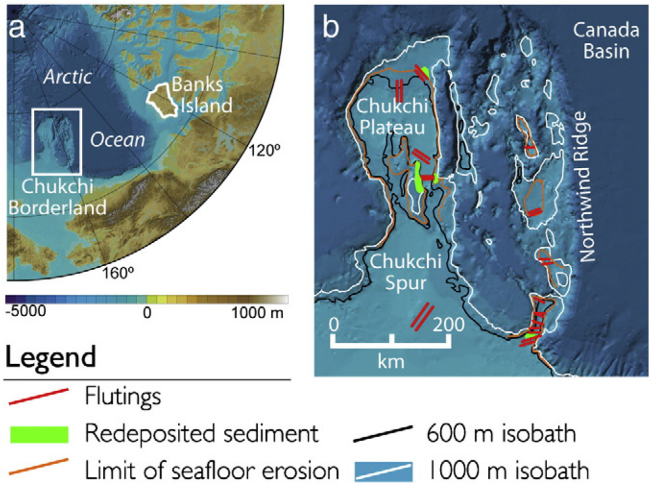

Figure 9. (a) International Bathymetric Chart of the Arctic Ocean (IBCAO) showing the location of Banks Island (outlined in white) and the Chukchi Borderland (white box) within the Arctic Ocean (Jakobsson et al., 2008a). (b) Glacial bedforms on the Chukchi Borderland. From Jakobsson et al. (2008b).

The western CAA has been tentatively invoked as the source of a glacier ice shelf or coalescent iceberg armadas that eroded the Chukchi Borderland to depths of ≤450 m during the last glaciation (Polyak et al., 2001; Jakobsson et al., 2005; Polyak et al., 2007). The extent of the northwest LIS on and around Banks Island serves as a direct measure for the thickness and extent of grounded ice in Amundsen Gulf and M'Clure Strait, where the existence of large ice streams during the LGM was proposed using satellite imagery (Stokes et al., 2005, 2006, 2009) and later documented by terrestrial and marine fieldwork (England et al., 2009; MacLean et al., 2012; respectively). Indeed, England et al. (2009) demonstrated a minimum LGM ice thickness of 635 m in M'Clure Strait. Furthermore, two piston cores from western Amundsen Gulf and the adjacent Beaufort Sea slope record several episodes of significant ice rafting between 14 and 11 cal ka BP (Scott et al., 2009), confirming that the marine channels of the western CAA served as primary conduits for icebergs entering the Arctic Ocean during the LGM. Recognition that the northwest LIS inundated western Banks Island and terminated on the Beaufort Sea shelf further clarifies the magnitude and dynamics of late Wisconsinan ice cover in the western CAA. These new results are fully consistent with the Arctic Ocean seafloor observations and demonstrate the need for additional offshore mapping on the Beaufort Sea shelf and slope to properly expand upon these new terrestrial observations from the western CAA.

Conclusions

This study revises the late Wisconsinan extent and dynamics of the northwest LIS on western Banks Island. During the LGM the ice margin was located an unknown distance west of Banks Island, on the Beaufort Sea shelf where former grounding lines and other submarine ice-marginal deposits have yet to be identified. These results complement those of England et al. (2009) and Lakeman and England (2012) from northern and eastern Banks Island, and contradict the hypothesis that the modern ecosystem on Banks Island evolved from an Ice Age refugium (Harington, 2005). Additionally, recognition of a thicker and more expansive ice sheet during the LGM verifies the suitability of the regional paleoclimate to ice-sheet buildup during the late Pleistocene. The LGM extent of the LIS west of Banks Island further complements the recognized thickness and extent of former ice streams disharging from Amundsen Gulf and M'Clure Strait (Stokes et al., 2005, 2006; England et al., 2009; Stokes et al., 2009; MacLean et al., 2012). Thus, these results bear on the geomorphic and sedimentary history of the adjacent continental shelf and Arctic Ocean basin where widespread evidence for LGM scouring of the seafloor by glacier ice has been reported (Polyak et al., 2001; Jakobsson et al., 2005; Polyak et al., 2007).

Ice-sheet withdrawal across western Banks Island following the LGM is termed the *Beaufort Phase* and was characterized by a predominantly cold-based ice margin that deposited few moraines. However, abundant ice-lateral and proglacial meltwater channels allow the pattern of ice-sheet retreat to be reconstructed. These landforms delineate a thin, multilobate ice margin, the geometry of which followed preexisting fluvial valleys. The succession of nested, ice-lateral meltwater channels extends from the Beaufort Sea coast eastward across the island and does not record any significant readvances or pauses in ice-sheet retreat. The timing of initial deglaciation of the west coast of Banks Island is currently undetermined because all raised marine deposits west of Castel Bay were deposited prior to the resubmergence of Bering

Strait and the restablishment of molluscan fauna (Kaufman et al., 2004; England and Furze, 2008).

The elevation of the deglacial marine limit on western Banks Island is greater than previous model estimates and, thus, documents greater glacioisostatic unloading of the crust by a thicker, more extensive ice sheet than formerly recognized (Vincent, 1982, 1983). As well, differences in the elevation of the marine limit partly indicate local variability in the timing of deglaciation, which was occassioned by spatial heterogeneities of varying magnitude in ice dynamics (i.e. ice streams and ice shelves in M'Clure Strait and cold-based ice sheet margins of variable thickness and velocity on western Banks Island). Collectively, these marine-limit observations provide important new constraints for glacioisostatic ajustment models of former and ongoing relative sea-level change in the western CAA. Thus, this study will help improve estimates of future coastal submergence, which is already impacting coastal communities across the western CAA, such as Paulatuk, Tuktoyuktuk, and Sachs Harbour.

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