Early to Mid Wisconsin fluvial deposits and palaeoenvironment of the Kidluit Formation, Tuktoyaktuk Coastlands, western Arctic Canada

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ABSTRACT

The Kidluit Formation (Fm) is a fluvial sand deposit that extends regionally across the Tuktoyaktuk Coastlands, western Arctic Canada. It was deposited by a large river flowing north into the Arctic Ocean prior to development of a cold-climate sandy desert and later glaciation by the Laurentide Ice Sheet. Lithostratigraphic and sedimentological field observations of the Summer Island area indicate deposition of the Kidluit Fm by a braided river system. Optical stimulated luminescence (OSL) dating of Kidluit sand provides eight OSL ages of 76–27 ka, which indicate deposition during Marine Isotope Stage (MIS) 4 and MIS 3. Radiocarbon dating of well-preserved weevil remains, a willow twig, wild raspberry seeds and bulrush achenes provides non-finite ^{14}C ages of >52,200, >51,700, >45,900 and >54,700 ^{14}C BP and are assigned an age of either MIS 4 or early MIS 3. Plant macrofossils from the sand deposit indicate spruce forest conditions and climate slightly warmer than present, whereas insect fossils indicate tundra conditions slightly colder than present. The river system that deposited the Kidluit Fm was probably either a pre-Laurentide Mackenzie River or the palaeo-Porcupine River, or a combination of them.

Key words: Kidluit Formation, Early and Middle Wisconsin, optical dating, macrofossils, Summer Island

INTRODUCTION

J.R. Mackay's stratigraphic observations in the western Arctic, between Paulatuk to the east, Herschel Island to the west and Fort Good Hope to the south (Figure 1), have elucidated the Late Quaternary history of the far northwest of mainland Canada. Mackay was instrumental, with V.N. Rampton (1988), in reconstructing the Quaternary landscape evolution of the Tuktoyaktuk Coastlands, at the mouth of the Mackenzie River, Northwest Territories (Figure 1) (Mackay, 1963; Mackay *et al.*, 1972). The Late Quaternary stratigraphy of the Coastlands includes fluvial deposits that predate and postdate the last major advance of the Laurentide Ice Sheet (LIS), glacial features of the LIS and windblown sands typical of Beringia (Murton, 2009). Windblown sands and postglacial gravel in the coastlands have formed the basis of some recent studies that record the establishment of a widespread cold-climate desert, extensive sand-wedge formation and a regional erosion event due to megaflooding down the Mackenzie River (Bateman and Murton, 2006; Murton *et al.*, 2007, 2010). Earlier pre-Laurentide deposits, however, are less well understood.

Pre-Laurentide fluvial deposits of the Tuktoyaktuk Coastlands include grey sand of the Kidluit Formation (Fm). This formation is up to 11 m thick and accumulated across an area probably at least as extensive as the Tuktoyaktuk Coastlands, extending between the Mackenzie Delta and Nicholson Point, and onto the continental shelf beyond the modern shoreline (Figure 1; Rampton, 1988). The palaeoenvironmental significance and age of the Kidluit Fm are uncertain but important for understanding the development of the Mackenzie River and Delta. Plant and insect macrofossils within the Kidluit Fm have been interpreted by Mackay and Matthews (1983) to indicate summer climatic conditions as warm or warmer than at present (see also Rampton, 1988, tables 9 and 10; Dallimore *et al.*, 1997, tables 1 and 2)—a climate typical of the northern boreal forest (Rampton, 1988). Rampton attributed the Kidluit Fm to deposition by braided channels on a broad alluvial plain because of its sandy nature and paucity of floodplain facies. Since modern braided systems along the Beaufort coast have steep gradients and abundant sediment supply, he proposed that the Kidluit Fm was deposited during either *proglacial* conditions (when a glacier lay directly south of the Tuktoyaktuk Coastlands) or *interglacial* conditions (when uplands such as the Caribou Hills, north of Inuvik, were more extensive and subject to erosion; Figure 1). Rampton favoured interglacial deposition because of the scarcity of cobbles, boulders and exotic material within the Kidluit Fm.

The aims of the present study are to elucidate the palaeoenvironment and age of the Kidluit Fm. The objectives are to report field observations on its lithostratigraphy and sedimentology and to date the sand by optical stimulated luminescence (OSL), and macrofossils within it by accelerator mass spectrometry (AMS) ^{14}C dating.

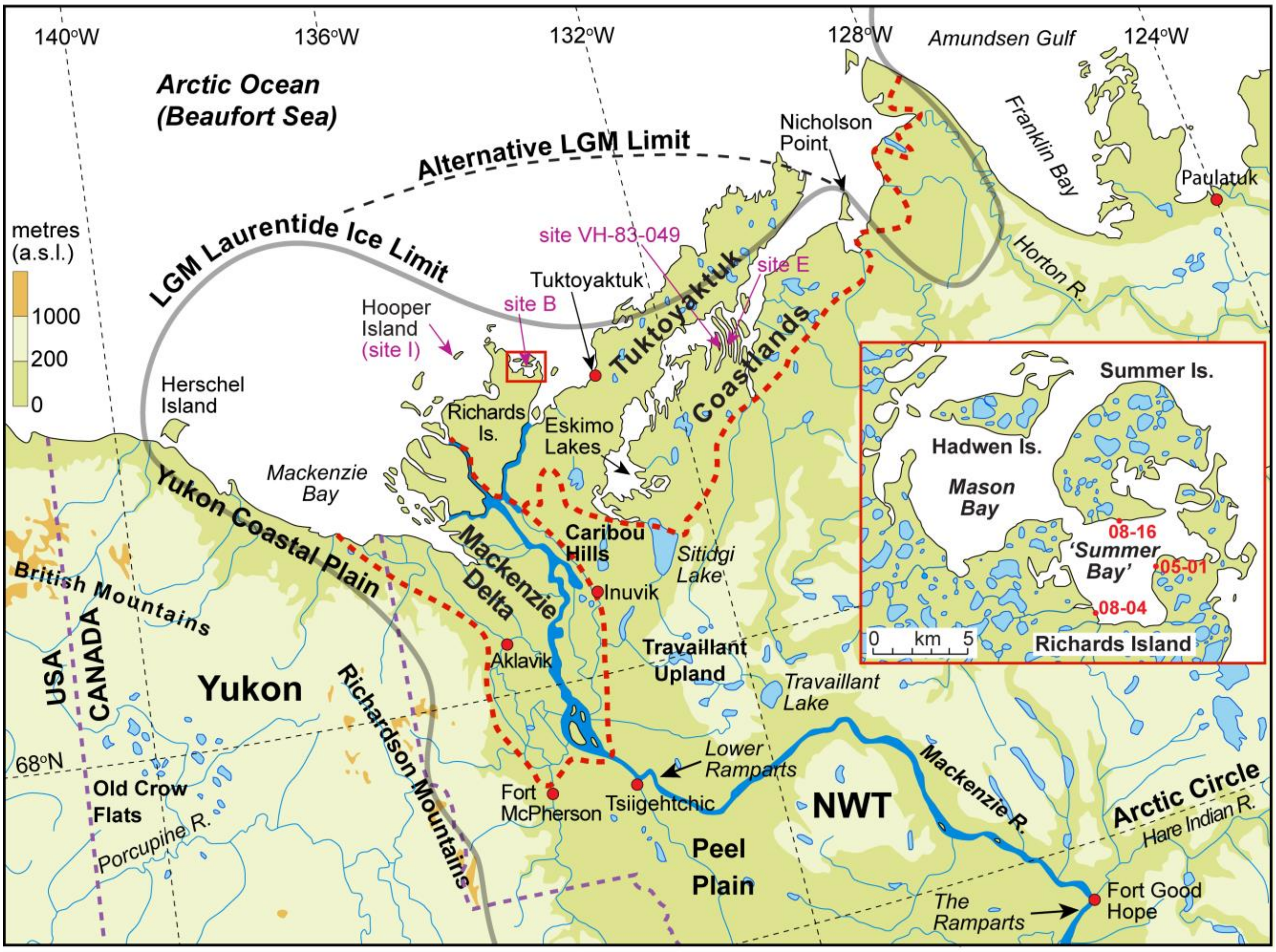

Figure 1 Location map of the lower Mackenzie valley and adjacent Beaufort Sea coastlands. Glacial limits after Rampton (1982, 1988): Toker Point Stade Glaciation of the Tuktoyaktuk Coastlands, Buckland Glaciation of the Yukon Coastal Plain, and Franklin Bay Stade Glaciation of Amundsen Gulf correspond to the Last Glacial Maximum (LGM) limit. An alternative glacial limit for the Toker Point Stade crosses the eastern Beaufort Sea Shelf north of the Tuktoyaktuk Pensinsula, indicating uncertainty about the topographic profile of the ice sheet here (Rampton, 1988). Red rectangle indicates study area. Inset map shows location of field sites in the Summer Island area.

STUDY AREA

The study area covers Summer Island and northeast Richards Island, where the Kidluit Fm is well exposed in coastal bluffs (Figure 1 inset map). The relevant onshore Pleistocene lithostratigraphy, in ascending order, comprises: (1) silty clay assigned to the 'Hooper clay', (2) grey sand of the Kidluit Fm, (3) brown sand of the Kittigazuit Fm, (4) pebbly clay (diamicton) of the Toker Point Member (Mb) of the Tuktoyaktuk Fm, (5) sand and pebbly sand of the Turnabout Mb of the Tuktoyaktuk Fm, and (6) a pebble-boulder lag (Rampton, 1988; Terrain Analysis & Mapping Services Limited, 1993).

METHODS

Logging

Stratigraphic sections through Kidluit Fm sand were examined and logged sedimentologically in the Summer Island area. Three sections were selected for dating (Figure 1 inset map). Section 08-16 is on southern

Summer Island (69° 32' 36.9"N; 133° 55' 37.9" W), where the Kidluit Fm overlies Hooper clay (Figure S1). Section 05-01 borders eastern “Summer Bay” (informal name), Richards Island (69° 31' 05.5"N; 133° 53' 08.2" W), and reveals Hooper clay beneath the Kidluit and Kittigazuit formations (Figures 2 and 3). Section 08-04 borders southern “Summer Bay” (69° 30' 20.7" N; 133° 58' 37.6" W), where sand wedges penetrate the Kidluit Fm (Figure S2).

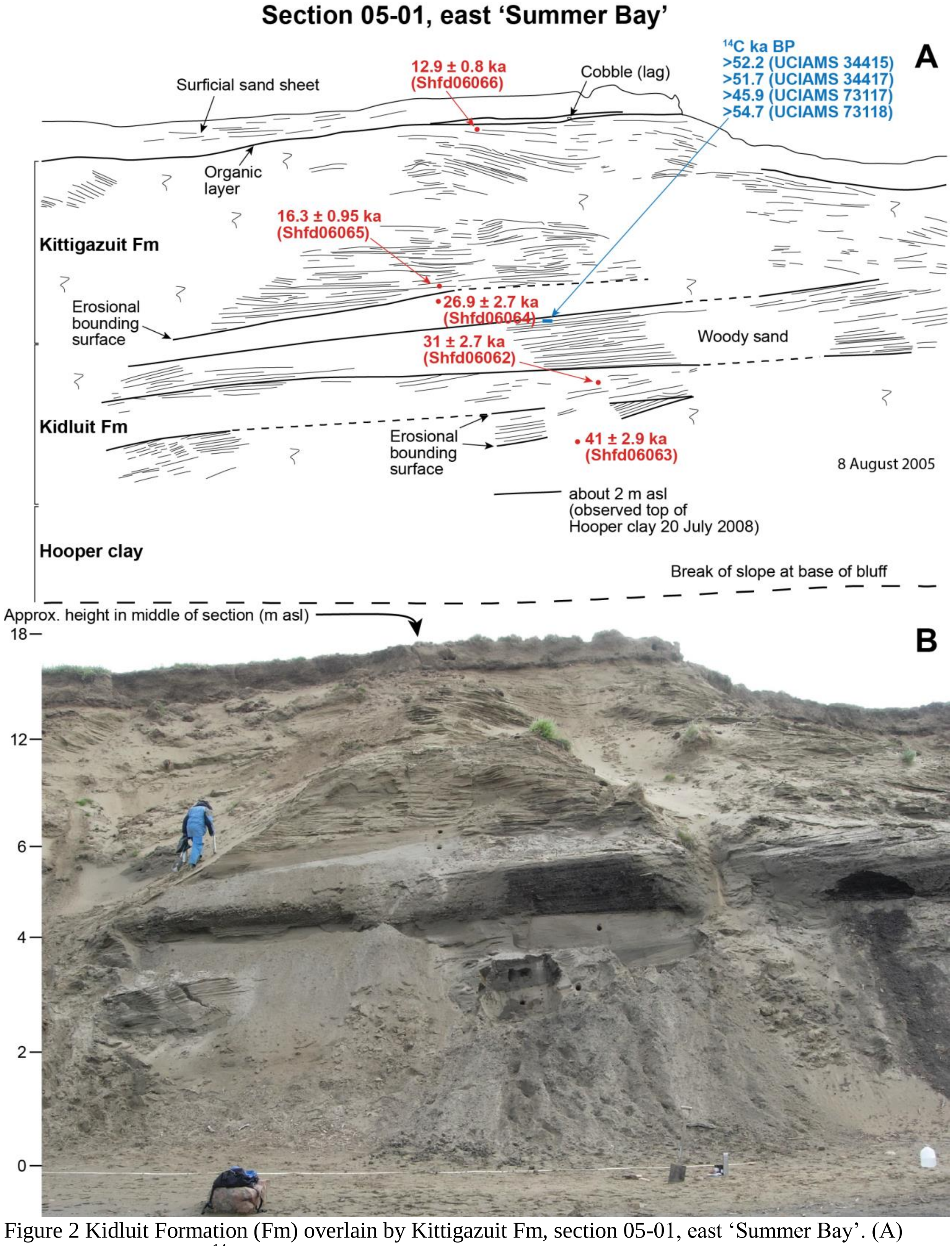

Figure 2 Kidluit Formation (Fm) overlain by Kittigazuit Fm, section 05-01, east ‘Summer Bay’. (A) Stratigraphy, OSL and ^{14}C ages. (B) Photograph of section. asl = above sea level. Person for scale. Note variable vertical scale on (B) due to inclination of the section.

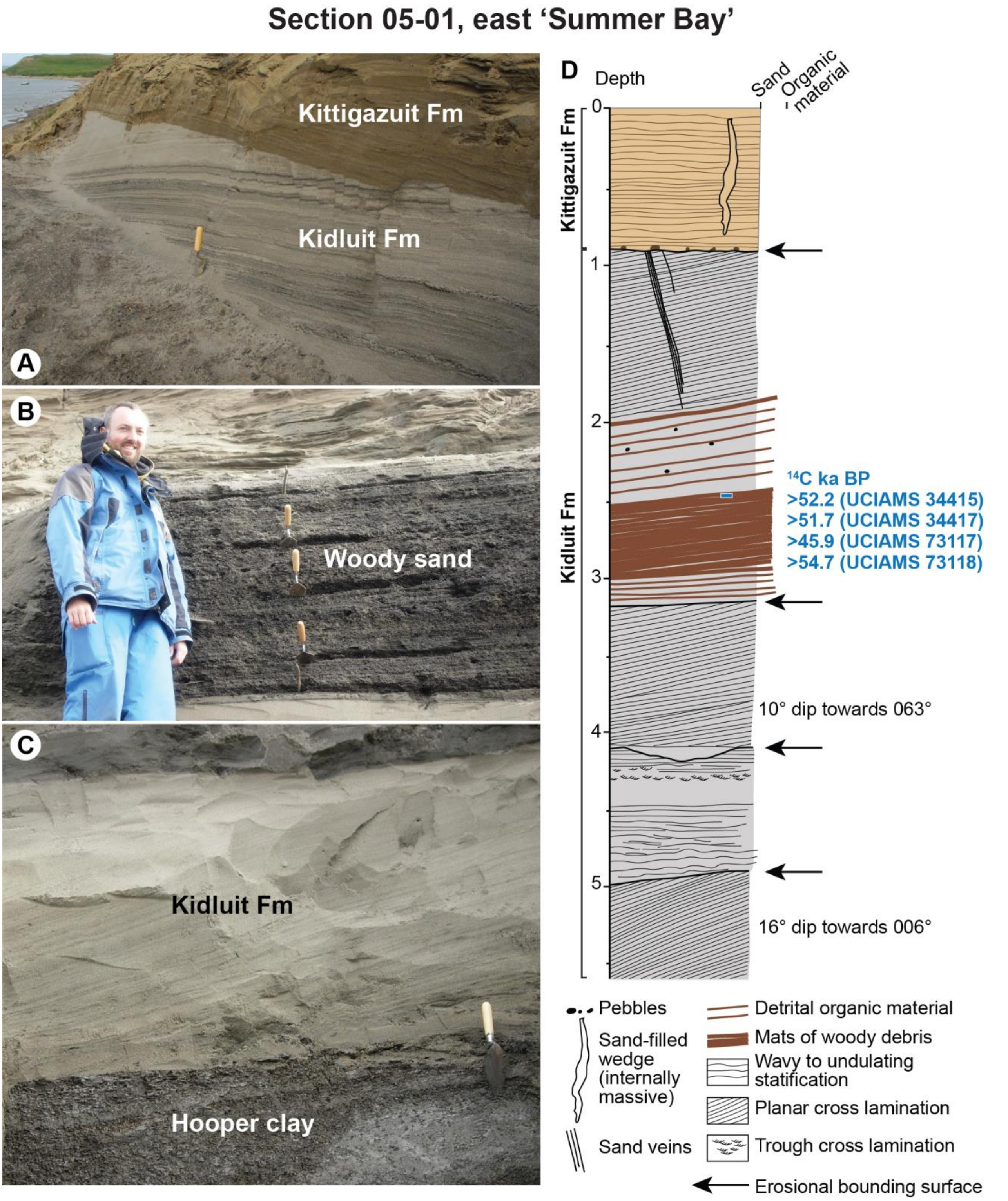

Figure 3 Kidluit Fm in section 05-01, east 'Summer Bay'. (A) Upper contact of Kidluit Fm with overlying Kittigazuit Fm. Comminuted organic detritus occurs as dark grey laminae within the Kidluit Fm. (B) Woody sand facies. 14C samples collected from highest of the five sample sites (marked by a stick). (C) Lower contact of the Kidluit Fm with underlying Hooper clay. Trowel for scale in each photograph. (D) Sedimentological log.

Macrofossils

The procedure for isolating macrofossils for analysis involved the standard technique of wet sieving with warm tap water (Birks, 2001). The sample was soaked in warm water and the organic material floating on the surface was gently decanted into a 100 mesh Tyler sieve (mesh opening 0.15 mm). The remaining sample was sieved through nested 20 and 40 Canadian Standard Tyler series sieves (mesh opening 0.85 and 0.425 mm, respectively) using a swirl technique to separate the organic fraction from the sand component. The float fraction (>0.15 mm) and all material >0.425 mm were examined using a binocular microscope, and plant and insect fossil remains were isolated for identification and potential AMS ^{14}C dating.

OSL Dating

Samples for OSL were collected in opaque PVC tubes from freshly exposed sediments, prepared as per Bateman and Catt (1996) and measured as outlined in Murton *et al.* (2015). Dose rates were calculated from *in situ* gamma spectrometry measurements with palaeomoisture based on those measured at present and a calculated cosmic dose contribution as per Prescott and Hutton (1994). Multiple replicate measurements of the palaeodose (De) per sample were carried out. The final ages are calender years before 2005 and 2008 (when samples were collected).

OSL dating can be subject to problems such as partial bleaching prior to burial or dim quartz (e.g. from the northern Cordillera; Demuro *et al.*, 2008, 2013). Thus, we have carried out checks to establish the accuracy of the OSL ages. First, we have previously used OSL in conjunction with ^{14}C dating of *in situ* plant material and peaty units in aeolian sand sheet deposits of Wisconsin Lateglacial age and found them to be in stratigraphic agreement and within analytical errors for the site examined in most detail (Bateman and Murton, 2006). Second, OSL quartz ages obtained by Bateman and Murton (2006) on the Kittigazuit Fm are broadly similar (within MIS 2) to ages on different dosimeters (feldspar) using different luminescence techniques (thermoluminescence and infrared stimulated luminescence) obtained at an independent laboratory by Murton *et al.* (2007). Third, our OSL-derived chronology for the last major advance of the LIS into the study area (between about 17.5 and 15 ka; Murton *et al.*, 2015) is consistent with chronologies based on ^{14}C and U/Th disequilibrium dating of material on and near the Richardson Mountains, to the south (Figure 1) (Kennedy *et al.*, 2010; Lacelle *et al.*, 2013; Lauriol *et al.*, 2010). Fourth, the present study involves internal luminescence checks to optimise preheating for the single aliquot regeneration (SAR) protocol through a dose-recovery preheat test (Murray and Wintle, 2003) and through dose-recovery tests that show the used SAR protocol can recover known laboratory doses. Fifth, we have previously dated aeolian sand from a modern dune on Hadwen Island to establish bleaching likelihood at such high latitudes, and found the sand to be fully bleached (Bateman and Murton, 2006). Finally, efforts were taken using multiple values of dose equivalent (De) measured per sample to establish whether samples had been fully bleached (reset) prior to deposition. Where De distributions for a sample were normally distributed with a low over-dispersion (OD; <25%), sediment was assumed to have been well bleached prior to burial and ages are based on a mean De. Where De distributions were scattered (OD>25%) and/or skewed, partial bleaching could not be ruled out and so final De values for ages were derived using the finite mixture model (FMM; Roberts *et al.*, 2000). In all cases where FMM was applied the component identified with the lowest De, which is assumed to have the greatest number of fully bleached grains, was selected for age calculation purposes.

^{14}C Dating

Four samples of organic material collected from the top of a wood-rich unit in the Kidluit Fm in section 05-01 (Figures 2 and 3B) were ^{14}C dated by AMS at the Keck Carbon Cycle AMS Facility, University of California, Irvine. This is the first attempt to AMS date macrofossil remains from the Kidluit Fm; all other published Kidluit ages are conventional ^{14}C ages on wood. Sample kd1 beetle comprised heads, prothoraces, prosterna, sternites and elytra of the weevil *Lepidophorus lineaticollis* (Figure S3). Sample kd1 twig comprised a willow (*Salix*) twig with bark and one persistent bud intact (Figure S4). Sample 08-001 berry included macrofossils seeds of wild raspberry (*Rubus idaeus*) (Figure S5) and sample 08-001 bulrush contained macrofossil achenes of bulrush (*Schoenoplectus tabernaemontani*) (Figure S6). The samples were chosen based on their abundance and excellent preservation. The selection of spruce macrofossils and wood for dating in kd1 was avoided, based on results obtained by Kennedy *et al.* (2010) from deltaic sediments of the Eagle River spillway, northern Yukon. In their study, non-finite ^{14}C ages on robust materials such as spruce needles, bark and wood showed problems of reworking, which consistently overestimated ages of the enclosing host sediments. Instead, they chose fragile macrofossils representative of their ecological requirements such as herbaceous xerophilic taxa from glacial environments and pill beetle (*Morychus* sp.) indicative of a steppe-tundra environment, which provided finite ages ranging from 21,600 ± 1,300 to 15,840 ± 90 ^{14}C BP, with the youngest thought to indicate a depositional age of about 16–15 ^{14}C ka BP. In terms of the Kidluit samples, the weevil remains, willow twig, wild raspberry seeds and bulrush achenes were well-preserved and delicate, which also suggested that they were more likely to provide ^{14}C ages contemporaneous with deposition rather than dating of material that was poorly preserved, such as rounded, reworked, allochthonous wood and spruce remains.

RESULTS

Sedimentology and Stratigraphy

The Kidluit Fm consists of well-stratified sand that is locally pebbly and rich in organic detritus (Figure 3; Tables S1–S3). The formation varies from fine- to medium-grained sand to pebbly sand containing granules, pebbles and cobbles up to 100 mm in maximum dimension. Clasts are commonly subrounded to subangular. Occasional striated and/or facetted clasts within the Kidluit Fm were observed along the southwest coast of Mason Bay (Figure 1 inset). Planar to curved erosional bounding surfaces are common within the sand, many defining tabular cross sets about 0.5–2 m thick (Figures 2 and 3). Planar cross lamination is the most common stratification type, although trough cross lamination and wavy to undulating stratification occur in some sections. Cross sets measured at section 05-01 dipped towards the north and east-northeast (Figure 3D). Organic detritus is typically concentrated in discrete laminae or beds, and much is finely comminuted. A prominent unit of woody sand occurs in section 05-01 (Figure 2; Table S2). Cut-and-fill structures and infilled channels are common within the formation. The lower and upper contacts of the formation are sharp and erosional. Intraclasts of clay or organic-rich silt occur above the lower contact, and sand veins and sand wedges extend down into the Kidluit Fm from the upper contact and from the basal part of the overlying Kittigazuit Fm

Macrofossils

Macrofossils in sample kd1 from the Kidluit Fm in section 05-01 are similar to those from Hooper Island (Mackay and Matthews, 1983), site VH-83-049 on the 'outer fingers' of the Eskimo Lakes (Figure 1; Rampton, 1988) and from Hooper and Summer islands and Eskimo Lakes (Figure 1, sites I, B and E; Dallimore *et al*., 1997). The floral and faunal assemblages are rich (Tables S4 and S5), and include conifer remains of spruce (*Picea* sp., seeds, cone scales, and needles) and shrubs of birch (*Betula nana/glandulosa* type), willow (*Salix*) and alder (*Alnus alnobetula*). Freshwater aquatic plants are prevalent in kd1, with submergents of pondweed (*Potamogeton* spp.), bur-reed (*Sparganium*), naiad (*Najas flexilis*) and emergent plants of mare's-tail (*Hippuris vulgaris*), spike rush (*Eleocharis palustris*), and buckbean (*Menyanthes trifoliata*).

Fossils of aquatic invertebrates reveal an environment similar to that suggested by the aquatic plant macrofossils. They include freshwater sponges (*Spongilla* sp.), bryozoans (*Cristatella mucedo*), water fleas (*Daphnia* sp.), tadpole shrimp (*Lepiduris* sp.), ostracodes (Ostracoda) and freshwater mollusks (snails (Gastropoda) and clams (Pelecypoda)) (Table S5). Aquatic insects include larvae midges (Chironomidae) and predaceous diving beetles (*Hydroporus* sp. and *Agabus moestus*). Of significance is *A. moestus*, the most northerly species of *Agabus* found frequently along the Arctic coast and lower Arctic islands (Larson *et al*., 2000). It has been collected in small tundra ponds and appears to be one of the more common aquatic beetles in northern tundra (Kuzmina and Telka, unpublished data).

Among the terrestrial insects, fossils of beetles dominate and include mostly ground beetles (Carabidae), weevils (Curculionidae) and pill beetles (Byrrhidae). According to Lindroth (1961–1969) all the ground beetles listed in Table S5 are tundra beetles. *Diacheila polita* has been collected in plant debris near rivers in tundra and forest-tundra. *Pterostichus agonus* inhabits moist tundra; *P. pinguedineus* and *P. ventricosus* occupy wet meadows with rich vegetation in tundra and riverbanks in northern forest; and *P. tareumiut* inhabits tundra on wet peaty soil. *P. brevicornis* lives in tundra mostly on dry meadow-like spots with rich vegetation and in forested areas near the timber limit. *P. parasimilis* and *Amara alpina* are true Arctic tundra species, living on dry peaty sites with grasses and low shrubs, having a southern distribution coinciding with the limit of polar conifers. The ecological requirements of the weevil *Lepidophorus lineaticollis* are broad: from wet to dry tundra, south-facing slopes and river shorelines, to steppe patches and disturbed ground in boreal forest (Anderson, 1997; Kuzmina and Telka, unpublished data). Another species of this weevil, *L. thulius*, occurs in dry tundra and south-facing slopes (Anderson, 1997). The pill beetle *Simplocaria metallica* is mostly found in tundra but also occurs in forested areas (Majka and Langor, 2011). This species lives in sandy areas near water and feeds on mosses. Another pill beetle, *Morychus* aff. *aeneolus* (LeC.), whose status as a fossil species is uncertain, likely represents a new, non-described species of the genus *Morychus* or subspecies of *M. aeneolus*. *M. aeneolus* is commonly collected in dry sandy areas along riverbanks (Johnson, 1986). We have collected numerous *Morychus* (which closely resembles the non-described fossil beetle) on relict steppe near Kluane Lake, Yukon Territory (Kuzmina and Telka, unpublished data).

Most of the species listed in Table S5 are cold-adapted Arctic beetles. The ground beetles *Pterostichus agonum, P. brevicornis, P. pinguedineus, P. ventricosus, P. tareumiut, Amara alpina*, predaceous diving beetle *Agabus moestus,* pill beetle *Simplocaria metallica*, and weevil *Isochnus arcticus* are recorded as the species living most northerly in the tundra (Chernov and Makarova, 2008). Two of the beetles, *Pterostichus pinguedineus* and *Isochnus arcticus*, are known from polar deserts.

Sample kd1 includes some old organic material reworked from ancient deposits. The presence of Tertiary-aged amber and abundant coal in kd1 suggests reworking of Tertiary material within organic lenses of Kidluit Fm sands, as reported by Rampton (1988). He noted that major reworking of older Quaternary or Tertiary formations could lead to erroneous conclusions of fossil evidence in Kidluit Fm macrofossil assemblages. In contrast, the good to excellent preservation of intact scales on beetle remains (weevils, *Lepidophorus lineaticollis* (Figure S3) and *Isochnus arcticus*) within kd1 suggests they have been minimally transported. Such preservation, it can be argued, precludes the possibility that these macrofossils are derived from older Quaternary or Tertiary deposits.

OSL Dating

Eight OSL ages obtained from the Kidluit Fm ranged from 76 ± 6 ka to 26.9 ± 2.7 ka, with a mean of 52 ± 17 ka (Table 1). All of the ages were in correct stratigraphic order at the three sections sampled. The Kittigazuit Fm provided a new OSL age of 16.3 ± 0.95 ka at 0.3 m (Shfd06065) above the Kidluit Fm in section 05-01, east 'Summer Bay'. Two sand wedges penetrating Kidluit Fm sand at section 08-04, southern 'Summer Bay', provided ages of 58 ± 4.6 ka and 14.3 ± 0.81 ka (Shfd08146 and Shfd08144; Figure S2). Pebbly sand infilling a channel incised into the latter sand wedge returned an age of 52 ± 3.1 ka (Shfd08145). Bluff-top dune deposits 0.75 m above the Kidluit Fm in section 08-16, southern Summer Island, provided an age of 1.76 ± 0.08 ka (Shfd08153).

Table 1 OSL-related data for samples from the Summer Island area

Section	Stratigraphic unit	Lab. code	Depth from surface (m)	Palaeodose, De (Gy)	OD (%)[c]	Dose Rate (Gy/ka)	Age (ka)
08-16 (south coast of Summer Island)	Bluff-top sand dune deposits (0.75 m above base)	Shfd08153	3.4	2.98 ± 0.05	18	1.689 ± 0.072	1.76 ± 0.08
	Kidluit Fm (0.35 m below top)	Shfd08152	4.5	90.59 ± 2.59	23	1.707 ± 0.068	53.1 ± 2.6
	Kidluit Fm (middle of unit)	Shfd08151	6.6	101.56 ± 2.92	21	1.780 ± 0.093	57.1 ± 3.4
	Kidluit Fm (0.35 m above base of Kidluit Fm / top of Hooper clay)	Shfd08150	9.0	99.26 ± 2.8 [a]	28	1.353 ± 0.071	73.4 ± 4.3
05-01 (east coast of Summer Bay)	Kittigazuit Fm (0.2 m below top)	Shfd06066	1.5	22.0 ± 0.79	17	1.700 ± 0.086	12.9 ± 0.8 [b]
	Kittigazuit Fm (0.3 m above base / top of Kidluit Fm)	Shfd06065	11.55	26.55 ± 0.64	18	1.630 ± 0.086	16.3 ± 0.95
	Kidluit Fm (0.25 m below top)	Shfd06064	12.05	44.92 ± 3.81 [a]	33	1.685 ± 0.087	26.9 ± 2.7
	Kidluit Fm (2.5 m below top)	Shfd06062	13.7	46.97 ± 2.28 [a]	27	1.509 ± 0.080	31 ± 2.7
	Kidluit Fm (4 m below top)	Shfd06063	15.2	51.67 ± 2.40 [a]	27	1.256 ± 0.065	41 ± 2.9
08-04 (south coast of Summer Bay)	Centre of 0.7 m-wide sand wedge 1, 0 m mark	Shfd08146	3.1	83.2 ± 4.99 [a]	35	1.425 ± 0.071	58 ± 4.6
	Pebbly sand in channel incised into top of sand wedge	Shfd08145	1.15	70.65 ± 2.00 [a]	25	1.370 ± 0.065	52 ± 3.1
	Sand wedge penetrating Kidluit Fm	Shfd08144	1.85	22.02 ± 0.60	22	1.537 ± 0.076	14.3 ± 0.81
	Kidluit Fm	Shfd08143	1.65	86.73 ± 6.6 [a]	45	1.631 ± 0.079	53 ± 5
	Kidluit Fm	Shfd08142	4.85	106.95 ± 5.79 [a]	28	1.415 ± 0.071	76 ± 6

[a] De based on finite mixture modelling. [b] Reported in Murton *et al.* (2010). [c] Overdispersion

^{14}C Dating

All ^{14}C ages obtained from the woody sand facies in the Kidluit Fm in section 05-01 were non-finite. The weevil fragments provided a ^{14}C age of >52,200 ^{14}C BP (UCIAMS 34415), willow twig, >51,700 ^{14}C BP (UCIAMS 34417), wild raspberry seeds, >45,900 (UCIAMS 73117), and bulrush achenes, >54,700 (UCIAMS 73118) (Table S6).

DISCUSSION

Palaeoenvironment

We concur with Rampton (1988) that a sandy braided river system deposited the Kidluit Fm. The well-stratified sand, tabular cross sets and shallow infilled channels record braided channels on a sandy plain, unlike the meandering channels on the silt-clay delta of the modern Mackenzie River (see Hill *et al.*, 2001). Flow towards the north and east-northeast is recorded by cross sets in section 05-01. The aquatic plant and arthropod assemblages in this section support the interpretation of deposition on a broad alluvial plain characterised by braided stream channels and ephemeral ponds.

Some of the plant macrofossils indicate a climate as warm as or warmer than present. Similar to the findings of Mackay and Matthews (1983) and Rampton (1988), sample kd1 contains shrubs and plants with northern distributional limits near or slightly south of the collection site, e.g. wild raspberry (*Rubus idaeus*), buttercups (*Ranunculus macounii/pensylvanicus* type) and niad (*Najas flexilis*) (Porsild and Cody, 1980). Kd1 also contains abundant spruce remains, as seen in Kidluit Fm organic lenses by Mackay and Matthews (1983), Rampton (1988) and Dallimore *et al*. (1997). The northern limit of spruce at present is about 50 km south of the study site (Hultén, 1968). The presence of warm or warmer-than-present plant macrofossils in kd1 may represent a time of transition: the warmer climate of MIS 5 had ended, with the ensuing cooler climate of MIS 4 allowing relict spruce forest to exist in some protected areas in the river valley. Or it could be the result of fluvial transport of these warm/warmer plant indicators to the north from southern sources, explaining their existence in an otherwise treeless environment.

Climatic conditions inferred from the plant macrofossils and insect fossils in section 05-01 differ. Plant macrofossils suggest that the climate was as warm or slightly warmer than present, with a spruce forest typical of northern forested regions today. In contrast, the insect fossils reflect a quite cold environment containing a mixture of dry and mesic tundra taxa similar to that at present in the Summer Island area. The presence of the High Arctic weevil *Isochnus arcticus* suggests the environment may have been colder than present. This weevil is not found on the mainland coast of Tuktoyaktuk, having a northern distribution reaching Ellesmere Island (80^{o} 10'N; 85^{o} 20' W) (Anderson, 1989).

The Kidluit and Kittigazuit formations show close stratigraphic and genetic relationships. The sharp contact between them, which truncates stratification in the Kidluit Fm, indicates erosion of the top of this formation before deposition of the Kittigazuit Fm. Genetically, the Kidluit Fm sand is thought to have been partially reworked by wind to form the Kittigazuit Fm because the particle-size distribution and mineralogy of both are similar, and the sedimentary structures within 3–15 m high sets of cross-stratified beds of the Kittigazuit Fm indicate deposition in aeolian dunes (Dallimore *et al.*, 1997).

Continuous permafrost was likely present in the study area and adjacent exposed Beaufort shelf during deposition of the Kidluit and Kittigazuit formations. The large sand wedge in the Kidluit Fm in section 08-04, OSL dated to 58 ± 4.6 ka (Shfd08146, Figure S2), suggests that thermal contraction cracking of permafrost and infilling with aeolian sand occurred during the interval when the Kidluit Fm accumulated (see below) but when fluvial processes were limited or inactive at this site. We attribute interformational sand veins and sand wedges that extend down from the Kidluit-Kittigazuit contact at section 05-01 (Figure 3 and Table S2) to thermal contraction cracking beneath a palaeo-land surface developed on the eroded top of the Kidluit Fm, after Kidluit deposition had ceased. Mackay and Matthews (1983) reported ice wedges and sand wedges in a similar interformational setting between grey [Kidluit] and brown [Kittigazuit] sand on Hooper Island (Figure 1), inferring that the ice wedges developed in the grey sand before deposition of the brown sand. They noted that a $\delta^{18}O$ value of –20.6‰ from ground ice within grey sand there is similar to that from pore water within the present-day active layer. Continuous permafrost conditions during deposition of the Kittigazuit Fm have been inferred from tall intraformational syngenetic sand wedges and rejuvenated sand wedges on Richards and Summer islands (Murton and Bateman, 2007). Continuous permafrost was likely present during deposition of both formations, because heat-flow calculations suggest that the time required to grow 500–600 m or more of permafrost in the study area probably exceeds 50,000 years (Mackay 1979), consistent with ice-free conditions and subaerial exposure for most of the Wisconsin (Taylor *et al.,* 1996a, 1996b).

Age

Deposition of the Kidluit Fm occurred during the Early to Mid Wisconsin. Deposition during the Sangamonian interglacial (MIS 5e) is discounted by eight OSL ages between 76 and 27 ka. The 50,000 year spread of ages implies that the river system was active for a long period of time and that the age differences reflect preservation in an aggrading braided system. Aggradation during MIS 3 may record, in part, glacio-isostatic depression of the crust to the northwest of the LIS margin, assuming that the western extent of the

LIS during MIS 3 approximately followed the margin of the exposed Canadian Shield (see Dyke *et al.*, 2002, figure 3). Deposition finished when fluvial activity ceased. River discharge may have been blocked or disrupted by the advancing LIS, as discussed below. Additionally, this region probably became more arid in MIS 2 than in MIS 4–3 because of increasing rainshadow effects from the expanding Cordilleran Ice Sheet to the southwest. As a result, aeolian processes replaced fluvial processes, reworking some of the Kidluit Fm sand into dunes and sand sheets of the Kittigazuit Fm (Murton, 2009). The age of the Kittigazuit Fm on Hadwen and northeast Richards islands is thought to be within MIS 2 (Late Wisconsin), based on 11 OSL ages of between 25.6 ± 1.3 and 12.7 ± 0.8 ka (Bateman and Murton, 2006; Murton *et al.*, 2010; this study).

The four non-finite ^{14}C ages of >52,200, >51,700, >45,900 and >54,700 ^{14}C BP from section 05-01 are older than all three of the finite OSL ages from the host Kidluit Fm sand (41.6 ± 2.9, 31.4 ± 2.7 and 26.9 ± 2.7 ka). If the finite OSL ages truly reflect the depositional age of the Kidluit Fm sand, they imply that some well-preserved, delicate organic material (Figures S3–S6) has been reworked from older material and re-deposited in the Kidluit Fm sands. The four ^{14}C ages are consistent with three non-finite ages obtained from rounded wood fragments in the Kidluit Fm on Hooper Island (Figure 1) by Mackay and Matthews (1983) (>37,000, >37,000 and >40,000 ^{14}C BP). A fourth age they obtained was 35,800 +5,400 –3,200 ^{14}C BP (GX-4579); the sample barely contained detectable radioactivity (Mackay and Matthews, 1983). Reworking of organic material may explain the AMS ^{14}C ages of 37,400 ± 810 and 33,710 ± 460 ^{14}C BP obtained by Dallimore *et al.* (1997) on detrital seeds and moss fragments within the Kittigazuit Fm on Summer Island, given their discrepancy with our OSL ages (discussed above) obtained from this formation. Underestimation of the depositional age of the Kidluit Fm based on the OSL ages cannot be ruled out but is thought to be unlikely given the checks we have carried out (see Methods) as well as the stratigraphic consistency of the ages obtained from three different sites. In addition, there is a strong geochronological consistency between the OSL ages from the Kidluit Fm (76–27 ka) and those from the overlying Kittigazuit Fm (26–13 ka). More generally, it is difficult to explain age underestimation from OSL in well-bedded undisturbed sediment unless the grains are near their saturation level, which the Kidluit Fm grains are not.

We agree with Rampton's (1988) interpretation that some of the plant macrofossils from the organic lenses within the Kidluit Fm record a warm/warmer-than-present climate. We attribute their presence in a treeless environment in the Summer Island area to northward fluvial transport. We also agree with Rampton (1988) that amber and coal were eroded from Tertiary sediments in uplands south of the Tuktoyaktuk Coastlands. Based upon macrofossil evidence in kd1, we believe that the macrofossils are of early MIS 3 or MIS 4 age and the fine lenses they occur in represent 'pulses'of depositional activity. Given the different climatic conditions inferred from the plant macrofossils and insect fossils, mixing of organic material from two or more periods within MIS 3 and 4 may have occurred.

River system

Two hypotheses need testing to determine the river system that deposited the Kidluit Fm. The first hypothesis envisages deposition by a pre-Laurentide Mackenzie River flowing along a route broadly similar to that at present. Mackay and Mathews (1973) provided evidence for such a pre-Laurentide route—based on tills interbedded within a sedimentary sequence whose top surface is glacially fluted, and which must therefore predate the last glaciation—within the Mackenzie Valley between Fort Good Hope and the Lower Ramparts (Figure 1). Meander scarps along the walls of the elongate trench 8–20 km wide occupied by the Hare Indian and Mackenzie rivers to the east of and downstream of Fort Good Hope indicate that running water, perhaps aided by glacial erosion, played a major part in cutting of the trench (Mackay and Mathews, 1973). Such running water would probably have flowed into the Arctic Ocean, routed northward along the lowland to the east of the Richardson Mountains and west of the Travaillant Upland, which now includes the southern Mackenzie Delta (Figure 1).

A second hypothesis is that the palaeo-Porcupine River system deposited the Kidluit Fm (Murton, 2009). This assumes that the palaeo-Porcupine River drained from northern interior Yukon across the Richardson Mountains and into the Arctic Ocean, near the location of the modern Mackenzie Delta, until its path was blocked by the Mackenzie lobe of the LIS during the Late Wisconsin (Kennedy *et al.*, 2010; Lauriol *et al.*, 2010; Lacelle *et al.*, 2013), diverting it into the Yukon River system (Duk-Rodkin and Hughes, 1994, fig. 2; Duk-Rodkin and Lemmen, 2000). A combination of the palaeo-Mackenzie and palaeo-Porcupine hypotheses might also apply. A sediment provenance study might test these hypotheses.

CONCLUSIONS

We draw the following conclusions:

1. A braided river system deposited the Kidluit Fm on the emergent Beaufort Shelf during the Early to Mid Wisconsin (MIS 4–3), based on eight OSL ages from Kidluit Fm sand that range from 76 to 27 ka.
2. Plant and insect macrofossils within organic lenses in the Kidluit Fm are thought to be of early MIS 3 or MIS 4 age, based on four non-finite ^{14}C ages of >52,200, and >51,700 ^{14}C BP on well-preserved weevil remains and a willow twig and >45,900 and >54,700 ^{14}C BP on wild raspberry seeds and bulrush achenes. The presence of warm/warmer-than-present plant macrofossils in a treeless environment is explained by fluvial transport, from south to north, from deposits of the same age.
3. Continuous permafrost persisted in the study area and adjacent exposed Beaufort shelf during deposition of the Kidluit and overlying Kittigazuit formations, as indicated by sand wedges and permafrost thicknesses of several hundred metres.
4. The river system that deposited the Kidluit Fm was probably a pre-Laurentide Mackenzie River flowing northward through the NWT along a route broadly similar to that at present or the palaeo-Porcupine River flowing northeastward from northern interior Yukon, or a combination of both rivers.

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SUPPORTING INFORMATION

Additional supporting information can be found in the online version of this article at the publisher's web site.

Supporting Figures

Figure S1 Kidluit Fm in section 08-16, south Summer Island.
Figure S2 Kidluit Fm in section 08-04, south 'Summer Bay'.
Figure S3 Remains of the weevil *Lepidophorus lineaticollis* from section 05-01, east 'Summer Bay'.
Figure S4 Willow (*Salix*) twig with bark and one persistent bud intact from section 05-01, east 'Summer Bay'.
Figure S5 Wild raspberry (*Rubus idaeus*) seeds from section 05-01, east 'Summer Bay'.
Figure S6 Bulrush (*Schoenoplectus tabernaemontani*) achenes from section 05-01, east 'Summer Bay'.

Supporting Tables

Table S1 Lithostratigraphy and sedimentology of section 08-16, south Summer Island
Table S2 Lithostratigraphy and sedimentology of section 05-01, east 'Summer Bay'
Table S3 Lithostratigraphy and sedimentology of section 08-04, south 'Summer Bay'
Table S4 Plant macrofossils from sample kd1, section 05-01, east 'Summer Bay'
Table S5 Insect fossils from sample kd1, section 05-01, east 'Summer Bay'
Table S6 ^{14}C ages and sample details from woody sand, section 05-01, east 'Summer Bay'

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