Canadian Journal of Earth Sciences
Revue canadienne des sciences de la Terre

**The pattern and style of deglaciation at the Late
Wisconsinan Laurentide and Cordilleran ice sheet limits in
northeastern British Columbia**

Journal:	<i>Canadian Journal of Earth Sciences</i>
Manuscript ID	cjes-2016-0066.R1
Manuscript Type:	Article
Date Submitted by the Author:	25-Jul-2016
Complete List of Authors:	Huntley, David; Geological Survey of Canada Pacific Vancouver, Research Scientist Hickin, Adrian; British Columbia Ministry of Energy, Mines and Petroleum Resources Lian, Olav B.; Department of Geography,
Keyword:	Late Wisconsinan, Laurentide Ice Sheet, Cordilleran Ice Sheet, deglaciation

SCHOLARONE™
Manuscripts

1 **The pattern and style of deglaciation at the Late Wisconsinan Laurentide and**
2 **Cordilleran ice sheet limits in northeastern British Columbia**

3

4 David H. Huntley¹, Adrian S. Hickin² and Olav B. Lian³

5

6 1. Geological Survey of Canada, Pacific Division, 1500-605 Robson Street, Vancouver,
7 British Columbia, V6B 5J3 david.huntley@canada.ca

8

9 2. British Columbia Geological Survey, PO Box 9333 Station Provincial Government,
10 Victoria, British Columbia, V8W 9N3

11

12 3. Department of Geography and the Environment, University of the Fraser Valley,
13 33844 King Road, Abbotsford, British Columbia, V2S 7M8

14

15

16

Abstract

This paper reports on the landform assemblages at the northern confluence of the Late Wisconsinan Laurentide and Cordilleran ice sheets with montane and piedmont glaciers in the northern Rockies and southern Mackenzie Mountains. Recent observations in northeastern British Columbia refine our knowledge of the pattern and style of ice sheet retreat, glacial lake formation and meltwater drainage. At the onset of deglaciation, confluent Laurentide and Cordilleran terminal ice margins lay between 59°N, 124°30'W and 60°N, 125°15'W. From this terminal limit, ice sheets retreated into north-central British Columbia and Yukon Territory, with remnant Cordilleran ice and montane glaciers confined to mountain valleys and the Liard Plateau. Distinctive end moraines are not associated with the retreat of Cordilleran ice in these areas. Laurentide ice retreated northeastward from uplands and the plateaus; then separated into lobes occupying the Fort Nelson and Petitot river valleys. Ice-retreat landforms include recessional end moraines (sometimes overridden and drumlinized), hill-hole pairs, crevasse-fill deposits, De Geer-like ribbed till ridges, hummocky moraines, kames, meltwater features and glacial lake deposits that fall within the elevation range of glacial Lake Liard and glacial Lake Fort Nelson (ca. 840 to 380 m). Meltwater and sediment transport into glacial lakes Fort Nelson, Liard, Nahanni and Mackenzie was sustained by remnant ice in the Liard River and Fort Nelson River drainage basins until the end of glaciation. Optical dating of sand from stabilized parabolic dunes on the Liard Plateau indicates that proglacial conditions, lake formation and drainage began before 13.0 ± 0.5 ka (calendar years). The Petitot, Fort Nelson and Liard rivers all occupy spillways incised into glacial deposits and bedrock by meltwater overflow from glacial lakes Peace and Hay.

Keywords

Late Wisconsinan, Laurentide Ice Sheet, Cordilleran Ice Sheet, Deglaciation

Introduction

Surficial geology mapping and fieldwork in northeastern British Columbia over the last 50 years has established that meltwater spillways and glacial lakes formed along retreating margins of the Late Wisconsinan (Late Pleistocene Marine Isotope Stage 2) Cordilleran and Laurentide ice sheets (Mathews 1980; Smith 1992, 1994; Lemmen et al. 1994; Duk-Rodkin 1995; Dyke et al. 2003; Zazula et al. 2004; Teller et al. 2002, 2005; Bednarski and Smith 2007; Bednarski 2008; Hartman and Clague 2008; Trommelen and Levson 2008; Jackson et al. 2013; Hickin et al. 2015; 2016). In the context of landsystem models of past ice sheets and observations of modern dynamic ice sheet behaviour, outstanding questions remain regarding: 1) the limits of Laurentide and Cordilleran ice sheets in the region; 2) patterns and relative timing of ice retreat; 3) the sources and influences of meltwater on ice sheet dynamics during deglaciation; 4) evolution of meltwater drainage routes; and 5) elevation limits and extent of proglacial lake formation.

The Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas, British Columbia (**Fig. 1A-C**) are favorably located to provide new insight into how the Late Pleistocene Laurentide and Cordilleran ice sheets interacted and retreated from northern Canada. A landform assemblage model for Late Wisconsinan deglaciation in northeastern British Columbia is proposed that incorporates: a) recent field observations of glacial deposits and landforms; b) stratigraphic logs of drift sequences in physiographically

contrasting settings; and c) glacial lake limits constrained by optical ages obtained on proglacial dunes. Remote sensing, field observations, and optical dating provide new insight into the patterns and timing of Cordilleran and Laurentide ice sheet retreat; the influence of supraglacial and proglacial lakes on ice sheet dynamics during deglaciation; and the implications of changes in elevation limits of proglacial lake formation and meltwater drainage routes during ice retreat.

Study area

Physiography

The study area lies between 59°N and 60°N, and 122°W and 124°W (**Fig. 1C**). From east to west, relief and elevation increase. The Fort Nelson Lowland generally lying below 540 m elevation flanks the Etsho Plateau, which ranges from 600 m to 740 m elevation. The Maxhamish Escarpment, a glacially modified bedrock ridge rising above low-lying terrain, reaches a maximum elevation of 710 m. To the south of the Fort Nelson River, the Tsoo Tablelands reach a maximum elevation ca. 940 m (Bostock 1980; Mathews 1978, 1980; Huntley and Hickin 2010; Huntley et al. 2011).

West of the Liard River, the Liard Plateau is an incised peneplain that increases in elevation from prominent terraces around 540 m elevation in-filling valleys and low-lying terrain, to around 620 m elevation where it abuts against the Liard Range of the Franklin Mountains. Elevations in the Liard Range and Caribou Range of the southern Mackenzie Mountains are generally above 1200 m. South of the Liard River, and west of Toad River, elevations increase from 900 m in the northeastern Rocky Mountain Foothills, to

greater than 2000 m in the northern Rocky Mountains. Mountain and foothill ranges, plateaus and lowlands are deeply incised by post-glacial streams. The Liard, Toad, Scatter, Beaver, Crow, Dunedin, Petitot and Fort Nelson river valleys are cut into bedrock and glacial deposits, and have active flood plains at elevations generally below 320 m. The minimum elevation in the study area is ca. 220 m on the active Liard River floodplain as it crosses 60°N (Bostock 1980; Mathews 1978, 1980; Huntley and Hickin 2010; Huntley et al. 2011).

Late Wisconsinan glacial history

The glacial history of the region outlined here is constrained by ^{14}C ages of organic material, $^{230}\text{Th}/^{234}\text{U}$ isotopic ages of speleothems, cosmogenic ages of glacial erratics, and optical ages of dune fields in adjacent areas of British Columbia, Yukon and Northwest Territories (e.g., Ford 1976; Mathews 1980; Rampton 1987; Rutter et al. 1993; Lemmen et al. 1994; Duk-Rodkin and Lemmen 2000; Smith 2000; 2002; Bednarski and Smith 2007; Bednarski 2008; Hartman and Clague 2008; Trommelen and Levson 2008, Demchuk 2010; Huntley et al. 2011; Hickin et al. 2015; 2016). Radiocarbon ages are converted to approximate corresponding calendar years before present (ka) using the calibration model of Reimer et al. (2009).

Similar to much of North America and Eurasia, Late Pleistocene ice sheets advanced over permafrost-rich deposits and deranged pre-glacial fluvial landscapes in northern Canada (Dyke and Prest 1987; Johnson 1990; Ó Cofaigh et al. 2005; Hickin et al. 2008; Lajeunesse, 2014). The relatively subdued topography of northeastern British Columbia

does not reflect the irregular, buried bedrock surfaces. Mountains, foothills and high plateaus were deeply incised by pre-glacial rivers, and their paleovalleys were subsequently infilled with a succession of Pleistocene sediments during multiple cycles of glaciation (Hartman and Clague 2008; Hickin et al. 2008; Trommelen and Levson 2008, Hickin et al. 2016). For example, valley fill successions described by Trommelen and Levson (2008), 100 km south of the study area contain wood dated ca. 50 ka and evidence of a boreal forest cover similar to today. The source of fluvial and lacustrine sediments confined to the paleovalleys was an extensive pre-Late Wisconsinan Cordilleran till in the foothill ranges (Trommelen and Levson 2008). Buried paleovalley segments in the Emile Creek basin that contain sub-till successions indicate a paleo-Petitot–Muskeg river system flowed north along the eastern flank of the Maxhamish Escarpment prior to the Late Wisconsinan glaciation (Bednarski 2008; Huntley et al. 2011). Northeast-trending valleys draining the Tsoo Tablelands and southern Liard Plateau incise through pre-Late Wisconsinan sediments, suggesting these valleys may also be part of this drainage system.

Pre-existing drainage patterns were subsequently deranged during the Late Wisconsinan as the Cordilleran and Laurentide ice sheets advanced into northeastern British Columbia and southern Yukon. Regionally, the advance of montane and Cordilleran ice began before 30 ka, with the Laurentide Ice Sheet arriving at the eastern Cordilleran margin ca. 29.4 ka (Klassen 1987; Catto et al. 1996; Levson et al. 2004; Bednarski 2001, 2007). Paleovalleys of the Prophet and Peace rivers were infilled with proglacial permafrost-rich outwash and lake sediments (“glacial Lake Mathews”) then overridden by Laurentide ice

(Hartman and Clague 2008; Trommelen and Levson 2008; Huntley and Hickin 2010). Advance stage glacial lake deposits reported by Huntley et al. (2011) are equivalent in age and depositional environment to those associated with glacial Lake Mathews, but there is no evidence to suggest these water bodies were connected. The Laurentide and Cordilleran ice sheets reached their maximum extents between ca. 26.5 ka and 19 ka (Yokoyama et al. 2000; Dyke et al. 2003; Clark et al. 2009).

Elsewhere beneath Late Pleistocene continental ice sheets, bed materials were preserved, eroded, deformed and streamlined over large areas during full glacial conditions (e.g., Kleman and Borgström 1994; Stokes and Clark 1999; Clark and Stokes 2005; Shaw et al. 2009). Advancing, terminal and recessional positions of ice margins were marked by moraine ridges formed by deformation, ablation and accumulation of glacial debris and rafted bedrock blocks (Van der Wateren 1987; Andriashek and Fenton 1989; Bennett et al. 1998; Dyke and Sevelle 2000). Subglacial thermal conditions varied temporally and spatially, with frozen beds near ice sheet centres, over bedrock uplands, and at ice sheet margins flanked by thawed bed ice streams concentrated in lowlands (Moran et al. 1980; Dyke and Evans 2005; Kleman and Glasser 2007; Booth et al. 2003). Significant volumes of interior ice were discharged by ice streams and during intervals of rapid iceflow (surging) of marginal lobes (Clayton et al. 1985; Hart 1999; Boulton et al. 2001; Stokes and Clark 2001; 2002; Evans and Rea 2005).

Large volumes of meltwater stored in supraglacial lakes and subglacially were also discharged from beneath glaciers through sheet flow and networks of subglacial channels

and eskers (e.g., Brennand and Shaw 1994; Clark et al. 2004; Cutler et al. 2002; Fisher et al. 2005; Jørgensen and Sandersen 2006; Kehew et al. 2012; Burke et al. 2012; Perkins et al. 2013). Discrete, channelized drainage systems developed in association with streamlined terrain, whereas eskers more frequently formed in areas for which ice streaming has not been reconstructed (Storrar et al. 2014; Margold et al. 2015; Greenwood et al. 2016).

In the study area, it is uncertain whether Laurentide ice arrived at the mountain front ahead of Cordilleran ice, or if Cordilleran ice arrived first, or whether the ice sheets arrived at their limits around the same time (Huntley et al. 2011). Regardless, as continental ice accumulated along the foothill ranges and against the Cordilleran Ice Sheet, a divide between northwest and southwest-flowing Laurentide ice formed close to 60°N, in the vicinity of the borders of Yukon Territory, Northwest Territories and British Columbia (**Fig. 2A**). The mutual diversion of iceflow features and distribution of erratics demonstrate that Laurentide, Cordilleran and local montane ice coalesced between approximately 59°N, 124°30'W and 60°N, 125°15'W (Mathews 1980; Bednarski 2008; Huntley et al. 2011). This zone is further defined by the absence of terminal interlobate moraines and lack of stratigraphic overlaps of Cordilleran and Laurentide till (Levson and Rutter 1996; Bednarski and Smith 2007). Cirques, arêtes, hanging valleys, moraine deposits and rock glaciers indicate the highest sector of the northern Rocky Mountains was a local centre for Pleistocene alpine glaciation. The absence of Cordilleran till and glacial erosion features on mountain peaks above 1800 m elevation suggest radially out-flowing montane ice was coalescent with southwest flowing Cordilleran ice at the glacial

178 maximum, ca. 26.5 to 19 ka (Mathews 1980; Dyke et al. 2003; Bednarski and Smith
179 2007; Clark et al. 2009; Huntley et al. 2011).

180

181 Retreat of the Cordilleran and Laurentide ice sheets began sometime after 21.5 ka in
182 northeast British Columbia (Dyke et al. 2003; Clark et al. 2009; **Fig. 2A-B**). South of the
183 study area, local montane glaciers and Cordilleran and Laurentide ice occupied the Rocky
184 Mountain Foothills until ca. 17 ka (Catto et al. 1996; Bednarski and Smith 2007). With
185 the exception of some cirque basins, the northern Rocky Mountains and Liard Range
186 were probably ice-free by 12 ka; and Laurentide ice had retreated into northeastern
187 Alberta and central Northwest Territories (Mathews 1980; Dyke and Prest 1987; Dyke et
188 al. 2003; Bednarski and Smith 2007; Hickin et al. 2015; **Fig. 2E**).

189

190 As deglaciation progressed, large proglacial lake systems formed along retreating
191 margins of the Cordilleran and Laurentide ice sheets in northwestern Canada (Mathews
192 1980, Smith 1992, 1994; Lemmen et al. 1994; Dyke et al. 2003; Zazula et al. 2004; Teller
193 et al. 2002, 2005; Bednarski 2008; Hickin et al. 2015; 2016; **Fig. 2B-F**). Spillways and
194 proglacial lakes impounded along receding ice sheet margins regulated inflow of glacial
195 meltwaters to the ocean basins (Dyke and Prest 1987; Teller and Kehew 1994; Mangerud
196 et al. 2002). From ca. 17 ka to 10.2 ka, meltwater discharge, sediment erosion and
197 deposition, wind erosion, transport and deposition, permafrost activity, landslides and
198 stabilization of terrain by vegetation were conditioned by proximity to retreating
199 Cordilleran ice and valley glaciers in the northern Rocky Mountains, and Laurentide ice

masses and proglacial lakes in Alberta, Saskatchewan, Manitoba and Northwest Territories (cf. Church and Ryder, 1972; Dyke and Prest 1987; Dyke et al. 2003).

During earliest deglaciation, ice-marginal lakes drained north into glacial Lake Nahanni. From there, meltwater was routed through ice-free corridors in the Mackenzie Mountains into glacial lakes Hughes, Bell and Old Crow, and ultimately into the Pacific Ocean (Ford 1976; Duk-Rodkin et al. 1995; Duk-Rodkin 1999; Zazula et al. 2004; **Fig. 2A, B**). As deglaciation progressed, meltwater drainage was routed north into glacial lakes Porcupine and Eagle, then later through glacial Lake Mackenzie to the Beaufort Sea (**Fig. 2B-E**). Glacial Lake Mackenzie formed ca. 13.8 ka and, at its southern limit, had drained by 9.8 ka: duration of less than 4000 years (Mathews 1980; Smith 1992; 1994; Lemmen et al. 1994; Duk-Rodkin et al. 1995; Zazula et al. 2004; Bednarski 2008; Couch and Eyles 2008; Huntley and Duk-Rodkin 2008). Peak meltwater and sediment discharges into the Beaufort Sea occurred in pulses between 13.8 ka and 10.2 ka through glacial lakes Liard, Hay, Mackenzie and McConnell/Agassiz (Mathews 1980; Smith 1992; 1994; Lemmen et al. 1994; Teller et al. 2002, 2005; Bednarski 2008; Couch and Eyles 2008; **Fig. 2C-E**). Over this time frame, unglaciated terrain and unconsolidated deposits exposed by ice retreat and lake drainage were reworked by katabatic winds to form dune fields and widespread loess deposits supporting tundra ecosystems (David 1981; Wolfe et al. 2004; Porter 2001; Begét 2001, Dyke 2005).

Knowledge gaps

Key questions remain regarding: 1) the limits of Laurentide and Cordilleran ice sheets in northeastern British Columbia; 2) patterns and relative timing of ice retreat; 3) the evolution of glacial meltwater drainage routes; 4) the influences of meltwater on ice sheet dynamics during deglaciation; and 5) the extent, duration and controls on proglacial lake elevations. In the following sections, we address these questions based on evidence from: a) new field observations of glacial deposits and landforms; b) stratigraphic logs of drift successions; c) mapped glacial lake limits and meltwater drainage patterns; and d) an age constraint from optical ages obtained on proglacial dunes.

Methods

Surficial Geology

Surficial earth materials and landforms between latitudes 59°N and 60°N, and longitudes 122°W and 124°W were interpreted and mapped from 1:60,000 scale black-and-white stereo-pair air photos (e.g., 15BCB97010 series), an ortho-rectified RADARSAT-1 250 m mosaic of Canada (open.canada.ca 2015), free online LANDSAT-7 pan-sharpened imagery (landsat.usgs.gov 2015) and a Shuttle Radar Topography Mission 3-arc-second resolution digital elevation model (DEM) accessed through Global Mapper software between 2009 and 2011 (srtm.cigar-csi.org 2015) and used as a base map. From this DEM, a slope map was generated using Global Mapper™ software (Version 10). Base maps were generated from CANVEC shape files downloaded from the Natural Resources Canada (NRCan) GeoGratis website (Huntley et al. 2011; geogratis.cgdi.gc.ca 2015).

Surficial deposits and landforms were described at over 300 observation stations and waypoints to verify mapped interpretations (**Fig. 3**). Field observations were compiled, edited and digitally archived later in the office. Terrain polygons, landforms and other site symbols were digitized using commercially available computer software packages (Global MapperTM and ArcMapTM), edge-matched and rectified with published maps, reports and digital data (e.g., Bednarski 2003a-c; Bednarski 2005a, b; Levson and Fournier 2012). The surficial geology data model conforms to the science language for the data management component of the Geological Survey of Canada (GSC) geological map flow process (Cocking et al. 2015).

Sixteen lithostratigraphic sections provide a sedimentary record of processes occurring in the major physiographic regions of the study area (**Fig. 1C**). Logged sections along line X-X' (**Fig. 3A**) record events in the Mackenzie Mountains, Liard Range, northern Liard Plateau, Etsho Plateau, Fort Nelson Lowland and Petitot River valley (**Fig. 6A, B**, logs A-H). Logged sections along line Y-Y' (**Fig. 3A**) capture events in the North Rocky Mountains, northeastern Rocky Mountain Foothills, southern Liard Plateau, Tsoo Tablelands, Fort Nelson Lowland and Fort Nelson River valley (**Fig. 7A, B**, logs A-H). Sections were located and measured with a handheld GarminTM GPS unit and a ThommenTM altimeter during ground observations; or remotely with the aid of oblique aerial and on-site photographs.

Surficial and lithostratigraphic units were distinguished from surrounding terrain on the basis of classified landsystems (cf. Evans 2005): landform associations, earth material

genesis, sedimentology, morphology, texture, sorting, colour, thickness, degree of consolidation, mapped extent, interpreted environment of deposition, stratigraphic relationships, geological age, and other distinguishing characteristics (Huntley and Hickin 2010; Huntley et al. 2013a-c). Glacial lake limits and meltwater drainage patterns were inferred from the mapped distribution and elevation range of end moraines, glaciofluvial and glaciolacustrine terraces, outwash deposits and spillways (cf. Mathews 1980; Bednarski 2008; Huntley et al. 2011; **Fig. 4; Fig. 5A, B**).

Optical dating

Optical dating is an inherently experimental technique that provides the time elapsed since mineral grains (typically quartz and feldspar) were exposed to sunlight (Roberts and Lian 2015). Various methods for providing an optical age are discussed in, for example, Lian and Roberts (2006), Wintle (2008), and Roberts et al. (2015). For sand dunes, this usually dates the burial of eolian sediment and landform stabilization. In this study, optical dating of quartz dune sands were undertaken to provide the maximum limiting age of deglaciation and glacial lake drainage, and minimum limiting ages for stabilization by vegetation and soil formation. The morphology and age of dunes also provide new insight into the timing of wind circulation patterns associated with late-glacial climates (cf. Wolfe et al. 2004; Hickin 2013).

Three eolian sand samples were collected from forested (stabilized) parabolic dunes from the Liard Plateau, located on a glaciolacustrine plain near the confluence of Beaver, Crow and Liard rivers (**Fig. 5B; Table 1**). The dunes examined in this study occur within the

present-day boreal forest and were assumed to have remained stabilized since climate amelioration following glaciation. At each site, a sample was collected from the upper metre of a hand-dug pit. An opaque plastic cylinder, 25 to 30 cm long, was inserted into the excavation face, then removed and the ends sealed and taped to prevent grains from being exposed to light, to preserve water content, and to keep the grains from mixing.

To calculate an optical age, two measurements were required: 1) an estimate of the laboratory dose of radiation that produces the same intensity of luminescence as the dose of radiation the sample absorbed in the environment since burial (equivalent dose, D_e); and 2) a measure of the environmental dose rate. The D_e can be found using several methods (e.g., see reviews by Olley et al. 2004; Lian and Roberts 2006; Wintle 2008; Lian 2013), and for this study, quartz grains (180-250 μm in diameter) and a modified version of the standard single-aliquot regenerative-dose (SAR) method were used (Murray and Wintle 2000; 2003; Wintle and Murray 2006). Quartz grains were isolated from the bulk samples using the procedure outlined by Hanson et al. (2012), and, for each sample, 50-100 grains were mounted on each of forty 9.8 mm diameter aluminum discs. For each aliquot, the measured luminescence was likely dominated by that emitted from fewer than 10 grains (cf. Duller et al. 2000). For an accurate optical age it was necessary, but not sufficient, that all of the grains comprising a multi-grain sample aliquot be exposed to sufficient sunlight prior to burial to completely reset the luminescence signal (for quartz, a few seconds of direct sunlight is usually adequate). It is likely that this condition was met for the wind-blown samples collected for this study.

Observations, results and interpretations

Surficial geology

Nine lithostratigraphic units are identified from regional mapping and logged sections: organic, alluvial, eolian, colluvial, glaciofluvial, glaciolacustrine, Cordilleran and Laurentide tills, and bedrock (Huntley et al. 2011; Huntley et al. 2013a-c; **Fig. 4**). The distribution of glacial landforms, glaciofluvial features and glaciolacustrine deposits form distinctive landsystem terrains that together define recessional limits of the Cordilleran and Laurentide ice sheets (**Fig. 5A**), extent of proglacial lakes and changes in meltwater drainage in the study area (**Fig. 5B-E**).

Cordilleran and Laurentide tills

In the Caribou and Liard ranges, northern Rocky Mountains and Rocky Mountain Foothills (**Fig. 1C**), glacially eroded, fractured and streamlined bedrock is overlain by moderately compact, massive and stratified, silt and sand-rich clast-supported to matrix-supported diamicton, with clast contents ranging from ca. 20% to greater than 35%. Diamictons form patchy, discontinuous clast-supported veneers less than one metre thick on ridge crests and slopes; and blankets up to 14 m thick in valleys (**Fig. 6A, B** logs B and C; **Fig. 7A, B**, logs A and B). Mostly, clasts are striated, faceted, and locally derived Paleozoic and Mesozoic conglomerate, sandstone, siltstone, shale and carbonate bedrock (Stott and Taylor 1968; Ferri et al. 2011; Huntley et al. 2011). Precambrian quartzite, chert and Mesozoic granodiorite erratics with potential sources in north-central British Columbia and southeastern Yukon are less common.

East of the Liard ranges and Rocky Mountain Foothills, bedrock and buried unconsolidated channel deposits are mantled by undulating, rolling and streamlined landforms containing matrix-supported massive and stratified diamictons. Deposits vary in thickness from less than a metre in uplands; to 10 m in the lower Crow River (**Fig. 6A, B**, logs C and D); 20 m in the Dunedin and Liard river valleys (**Fig. 7A, B** logs C and D); 10 m in Fort Nelson River valley (**Fig. 7A, B**, logs E, F and H); and 10 m in the Petitot River valley (**Fig. 6A, B**, logs E and G). Near-surface diamictons are sand and silt-rich, with clast contents generally less than 20%. Precambrian granite, schist and quartzite from the Canadian Shield are the dominant lithologies. At depth, and down-ice of clay-rich bedrock and older glacial deposits, diamictons are clay-rich with less than 10% clasts that are predominantly locally sourced sub-angular Cretaceous conglomerate and sandstone erratics.

Massive and stratified clast-supported and matrix-supported diamictons are interpreted by Huntley and Hickin (2010) as tills deposited directly by basal lodgement, meltout and pervasive glaciogenic shear deformation beneath active Cordilleran and Laurentide ice sheets; and *in situ* melting from stagnant ice during deglaciation (cf. Boulton 1987; Boulton and Hindmarsh 1987; Dreimanis 1989; Alley 1991; Murton et al 2004; Menzies et al. 2006). Fractures and thrust faults with planes perpendicular to iceflow observed in the topmost sub-till units in Emile Creek (**Fig. 6A, B**, log G) suggest advancing Laurentide ice deformed partly frozen outwash (cf. Kleman and Borgström 1994; Bennett et al. 1998; Boulton et al. 1999; Bednarski 2008; Evans et al. 2008; Benediktsson et al. 2009). Ice-thrust moraine ridges formed on the down-ice side of pre-glacial or buried

valleys were subsequently overridden and streamlined by southwest- to west-flowing ice (Fig. 8A). In this study, till provenances are distinguished by lithological content: Cordilleran tills contain locally eroded Paleozoic and Mesozoic siliciclastic and carbonate rocks, and erratics of Proterozoic quartzite and chert and Mesozoic granodiorite; Laurentide tills contain Cretaceous siliciclastic and carbonate rocks and distally derived Precambrian granite, gneiss, schist and quartzite. The distribution of Laurentide iceflow features and erratics in the Liard Range suggest a minimum ice sheet elevation of 1250 m at the glacial maximum. Post-glaciation, tills were extensively winnowed by wind action and remobilized by periglacial and colluvial processes (Huntley et al. 2011).

Streamlined (drumlinized) tills

Drumlins, crag-and-tails, roche moutonnées and striae in the Caribou and Liard ranges indicate that the Cordilleran Ice Sheet flowed southeast into the Liard and Toad River valleys, where it was confluent with glaciers flowing from cirques in the northern Rocky Mountains. Laurentide ice flowed from the northeast and southeast, and then continued westward into the Liard River basin and southwest over the Tsoo Tablelands towards the northern Rocky Mountains. The distribution of Precambrian and Cretaceous erratics reflects these dispersal patterns (Fig. 5A). Drumlinized terrain is most pronounced south of the Petitot River, over the Etsho Plateau west of the Maxhamish Escarpment, and eastern Liard Plateau where ice advanced up-hill, and thick accumulations of till were deposited over soft bedrock and unconsolidated advance-phase sediments (Fig. 6A, B logs C-E and Fig. 7A, B, logs C-F; Fig. 8A). Here, drumlins, fluted till ridges and furrows are up to several tens of kilometres in length, suggesting tills were deposited

beneath a Laurentide Ice Sheet prone to sustained fast flowing and, or surging conditions (cf. Clayton and Teller 1985; Hart 1999; Stokes and Clark 1999; 2001; 2002; 2003; van der Meer 2003; Evans et al. 2008; Ross et al. 2009; Benediktsson et al. 2009; Ó Cofaigh et al. 2010; Shaw et al. 2009; Stokes and Clark 2002; 2003; Evans and Rea 2005). Impermeable, clay-rich siliciclastic bedrock likely contributed to deformable, lubricated conditions beneath Cordilleran and Laurentide ice (Mathews 1974; Boulton 1987; Boulton and Hindmarsh 1987; Alley 1991; Fisher et al. 1995; Boulton et al. 2001; Stokes and Clark 2001; 2002; 2003; van der Meer et al. 2003).

Major moraine ridges

Across the Liard and Etsho plateaus and in the Fort Nelson Lowland, multiple crested till-filled ridges, up to 12 km in length and 10 m high, often lie in a down-ice direction from depressions; an example of this can be found near Maxhamish Lake (**Fig. 4; Fig. 5A; Fig. 8B**). At least ten semi-continuous moraine ridge belts are recognized east of the mountain front, lying transverse to Laurentide ice flow. Ridges are composed of massive and stratified clay and silt-rich till diamicton with clast contents above 10%. Sub-rounded granite and gneiss erratics are relatively abundant. Their association with streamlined, sheared, folded and thrust basal tills, proximity to hill-hole pairs, proglacial outwash and lake sediments, together with melt-out and remobilization of glacial debris suggest these ridge belts are major end moraines (cf. Moran et al. 1980; Bennett et al. 1998; Boulton and van der Meer 1999; Dyke and Savelle 2000; Benediktsson et al. 2009; Dyke and Evans 2005; Ó Cofaigh et al. 2005; **Fig. 8B, C**). The distribution of major moraine belts across the study area suggests ten significant recessional still-stands of ice lobes

during retreat in the Petitot and Fort Nelson river valleys, and that ice margins retreated 10 to 20 km before stabilizing in ephemeral proglacial lakes or grounding on higher terrain (**Fig. 5A**).

Minor moraine ridges

A variety of smaller ridges, less than 1 km in length and less than 5 m high, formed over Laurentide drumlins, flutes and major moraines across the Etsho and Liard plateaus and the Fort Nelson Lowland. Low relief ridges that drape drumlins and flutes lie transverse or oblique to the direction of iceflow inferred from underlying streamlined bedforms (**Fig. 8A-C**). These ridges are composed of sand and silt-rich till diamicton with clast contents up to 20%, including relatively abundant sub-rounded granite erratics. Minor moraine ridges also form splaying and reticulate patterns adjacent to eskers and subglacial meltwater channels (**Fig. 8B**). Low relief ridges are interpreted to be crevasse fill or crevasse squeeze deposits produced by glacier lobes undergoing cycles of surging and stagnation. Subsequent preservation of small ridges and their close association with eskers and meltwater channels implies iceflow ceased after formation and that post-surge crevassed ice masses became separated from retreating active margins to form stagnant bodies of dead debris-rich ice that melted *in situ* on the glacier forefields (cf. Sharp 1985; Harper et al. 1998; Evans et al. 1999; Bennett et al. 2000).

Corrugated, or ribbed ridges in contact with, or overlain by glaciolacustrine deposits (**Fig. 8B, C**) may have been produced by annual calving at grounded ice fronts in a manner similar to De Geer-moraines, while others may have formed by transpression and

shearing of discontinuously frozen sediment during seasonal advances along retreating ice fronts after lake drainage. Behind grounding lines, iceflow was likely accommodated mostly through bed deformation, basal sliding and streamlining of clay-rich bedrock and subglacial deposits (cf. Boulton et al. 2001; Stokes and Clark 2001; 2002; 2003; van der Meer et al. 2003; Lindén and Möller 2005; Bednarski 2008; Benediktsson et al. 2009; Clayton et al. 2008).

Hummocky moraine

Hummocky terrain occurs in proximity to ice-thrust moraine ridges, hill-hole pairs, kettle holes, eskers, kame deposits, meltwater channels and spillways over the Fort Nelson Lowland and Etsho Plateau, to the west of the Maxhamish Escarpment and in most mountain valleys (**Fig. 8A, B**). Hummocks have irregular planform and less than 5 m relief. Internally, hummocks are composed of massive and stratified sand and silt-rich diamictos with clast contents above 20%, including sub-rounded granite erratics. Slump structures in stratified diamictos and irregular topography are evidence of debris melt-out from stagnant ice bodies (cf. Dyke and Savelle 2000; Murton et al. 2004; Dyke and Evans 2005; Clayton et al. 2008).

Glaciofluvial deposits

In the valleys of Scaffold Creek, and Crow, Bear, Liard, Trout and Toad rivers, the retreat of the Cordilleran Ice Sheet and montane glaciers was marked by the accumulation of outwash fans and terraces (**Fig. 6A, B**, logs A and B; **Fig. 7A, B**, logs A and B). Within these landforms massive, planar-stratified, trough cross-bedded or foreset-bedded

451 boulders, cobbles, pebble-gravel, sand, silt and diamicton deposits, between 2 m and 80
452 m thick, are found in contact with, or in close proximity to tills and glaciolacustrine
453 deposits (**Fig. 6A, B**, logs D-H; **Fig. 7A, B**, logs A, D). These sequences are interpreted
454 as glaciofluvial in origin, with sediments deposited by rivers and streams flowing
455 subglacially, or in contact with glacial ice in forefield settings (cf. Eyles and Eyles 1992;
456 Brennand and Shaw 1994; Ó Cofaigh 1996; Boulton et al. 2009; Kehew et al. 2012;
457 Burke et al. 2012; Perkins et al. 2013).

458

459 Meltwater channels incised into dip slopes of escarpments east of Liard and Toad river
460 valleys imply that Cordilleran ice was confined to the Rocky Mountain Foothills early
461 during deglaciation. Ice-proximal meltwater channels cross drainage divides in the
462 mountains, uplands and across the crests of escarpments (**Fig 8A**). At lower elevations,
463 the distribution of kame deposits and relict channels indicates ice-contact meltwater
464 drainage and sediment transportation parallel to receding glacier margins and interlobate
465 areas (**Fig. 5B-E; Fig. 8B**).

466

467 Over the eastern Liard Plateau, the Etsho Plateau and Fort Nelson Lowland, eskers and
468 subglacial meltwater channels lie sub-parallel to, and in places cut across drumlins, flutes
469 and topographic highs, for example the Maxhamish Escarpment. Eskers and minor
470 channels have widths generally less than 500 m, and range in length from less than 500 m
471 to 30 km. This network coalesces to form major westward draining subglacial meltwater
472 channels, 3 to 5 km wide and up to 100 km in length (**Fig. 5B-E; Fig. 8B, C**). Subglacial
473 channels contain little sand and gravel, suggesting either channel flow velocities were too

high for deposition to occur, limited duration for aggradation, or that draining meltwater contained fine sediments only (cf. Clark and Walder 1994; Brennand and Shaw 1994; Boulton et al. 2001; Cutler et al. 2002; Fisher et al. 2005; Jørgensen and Sandersen 2006; Boulton et al. 2009; Kehew et al. 2012; Burke et al. 2012; Perkins et al. 2013). Diamicton, gravel and sand-filled eskers are draped by hummocky moraines, suggesting preservation beneath stagnant, debris-rich ice during deglaciation. Many subglacial channels exposed by ice retreat functioned as proglacial spillways draining proglacial lakes and stagnant ice bodies until infilled by fine-grained outwash, alluvial and organic deposits (**Fig. 8A**). Major subglacial meltwater channels are now occupied by modern drainage systems, for example significant reaches of the Petitot River and Fort Nelson River.

Glaciolacustrine deposits

In major valleys across the study area, an abrupt transition is observed from Cordilleran and Laurentide tills, ice-contact colluvium and glaciofluvial outwash to massive or rhythmically interbedded and laminated silt and clay with subordinate amounts of stratified diamicton, gravel and massive, planar, ripple-bedded sand (**Fig. 6A, B**, logs B-D; **Fig. 7A, B**, logs B-F). Clay-rich units contain cobble to boulder clasts dispersed throughout. Fine-grained sediments, generally thicker than 2 m and up to 35 m thick, form terraced plains when incised by meltwater channels and postglacial streams (**Fig. 6A, B**, logs B-D; **Fig. 7A, B**, logs B-F; **Fig. 8C**).

496 Silt, clay, diamicton, gravel and sand units are interpreted as deposited in ice-contact
497 subaqueous settings from debris-rich meltwater overflows, interflows and underflows
498 discharging subaqueously at glacier margins grounded along proglacial lakes. Massive
499 silt and clay beds are attributed to rapid deposition of suspended sediment from meltwater
500 overflows and interflows entering a quiet basin floor setting free of current activity and
501 below wave base (i.e., deep water). Rhythmically laminated and massive silt and clay are
502 also indicative of ice-distal deposition from underflows and overflows in deep water.
503 Clasts in clay-rich units are interpreted as glacially transported dropstones released by
504 meltout from icebergs. The presence of icebergs is consistent with episodic discharge of
505 crevassed ice into proglacial lakes, for example, during surge events (cf. Sharp 1985;
506 Smith 1992; 1994; Evans et al. 1999; Bennett et al. 2000; Mangerud et al. 2002).
507 Stratified diamictons are interpreted to be deposited by meltwater-sourced underflows
508 and subaqueous gravity flows triggered by thermal melting of ice, during intervals of lake
509 drainage, or melt-out of massive ice-rafted debris during surge and calving events (cf.
510 Mathews 1980; Cowan and Powell 1991; Eyles and Eyles 1992; Evans and Rea 2005;
511 Bednarski 2008; Couch and Eyles 2008).

512

513 Glaciolacustrine deposits record seasonal and longer-term fluctuations in the volume of
514 meltwater and suspended sediment entering proglacial basins; and also changes in water
515 depth within outwash-dammed and ice-bound basins (cf. Ashley 1975; Teller 1987; Fyfe
516 1990; Bednarski 2008; Couch and Eyles 2008; Hickin 2013; Hickin et al. 2015).
517 Glaciolacustrine (and glaciofluvial) deposits have generally planar surfaces that are

graded to elevations ca. 840 m, 720 m, 640-620 m, 540 m, 460-420 m and 380-320 m (Fig. 4).

Eolian deposits

Glacial sediments throughout the study area are draped by beds of massive, well-sorted silt and sand forming discontinuous veneers less than a metre thick; undulating blankets up to 3 m in thickness; and parabolic dunes with crest heights up to 5 m above surrounding terrain (Fig. 6A, B, logs B-H; Fig 7A, B, logs B-H; Fig. 8C). Silt and sand deposits are interpreted as eolian in origin and derived from the deflation of exposed clay, silt and sand-rich glacial lake sediments, glaciofluvial outwash, till and alluvial sediments (cf. David 1981; Wolfe et al 2004; Hickin et al 2015). The orientation of parabolic dunes on the Liard Plateau and Fort Nelson Lowland indicate southeast katabatic wind flow (Fig 5B=E; Fig 6A, B, log D; Fig 8C).

Optical dating

Dune samples collected on the Liard Plateau consisted of medium-grained, well-sorted sand. Of the 40 aliquots measured from each sample, 26, 29, and 26 were accepted from samples BRD-01, BRD-02 and BRD-03 respectively (Table 1). Aliquots that were rejected were those that did not show a distinct fast component in their shine down curves, or displayed significant thermal transfer (luminescence measured after a zero Gy regenerative dose was >5% of the natural signal), and/or failed the recycling test (the sensitivity corrected luminescence measured after a repeat of the 15 Gy regenerative dose is different by more than 10% of the initial measurement at this dose). The utility of the

SAR protocol used was further tested through a dose recovery experiment (Roberts et al. 1999; Murray and Wintle 2003) on sample BRD-02. The ratio of measured dose to given dose was 1.12 ± 0.04 , which indicates that the protocol used is satisfactory. D_e values from accepted aliquots were plotted on radial plots, and for each sample the distribution indicates only one population. Moreover, over-dispersion (OD) values for each sample, which indicates the variance in D_e values in addition to that resulting from analytical uncertainties, is relatively low for all three samples ($\leq 10\%$; **Fig. 9**) suggesting the weighted mean D_e values would be appropriate for the age calculation (cf. Jacobs and Roberts 2007); these were found using the central age model (Galbraith et al. 1999) and are listed in **Table 2**.

The D_e s for all the samples are remarkably similar, as might be expected for samples collected from heterogeneous sediments deposited in an eolian environment in one region, and that likely means that the analytical uncertainties in the ages are mainly from the dosimetry (measurement of U, Th, and K). The optical ages for BRD-01, -02, and -03 are 13.7 ± 0.9 ka, 12.6 ± 0.8 ka, and 12.7 ± 0.8 ka respectively. These ages are statistically identical at only one standard deviation (**Fig. 9; Table 2**), and give a weighted mean age of 13.0 ± 0.5 ka. They are significant since they provide a northern extension to, and are consistent in age with the existing chronology of dune activity in British Columbia and Alberta (e.g., Wolfe et al. 2004; Hickin et al. 2015; 2016).

Landscape Model: Paleogeographic Reconstructions

Paleogeographic reconstructions are framed in the context of a series of diachronous subglacial, ice-marginal and proglacial landsystems comprising landforms, their sediments, and associated geomorphic processes observed in the Toad River and Maxhamish Lake map areas (cf. Evans 2005; **Fig. 4**; **Fig. 10**). The distinctive landscapes of the study area are largely a product of underlying bedrock type and geological structures, with modification by the action of Late Wisconsinan ice sheets and valley glaciers (equivalent to those that existed during the Fraser Glaciation in British Columbia and the McConnell Glaciation in the Yukon). Montane, Cordilleran and Laurentide landform assemblages are recognized that allow for the reconstruction of ice sheet margins, glacial lake limits and meltwater drainage patterns in northeastern British Columbia (**Fig. 11A-M**).

Glacial maximum phase I (>21.5 ka)

Cordilleran Ice Sheet and montane subglacial terrains

In the mountains and upland areas, Cordilleran till forms discontinuous veneers or blankets overlying a glacially streamlined clastic and carbonate bedrock below a Late Wisconsinan glacial limit of 1850 m elevation. Streamlined terrain (**Fig. 10**), including drumlins, crag-and-tails and striae on bedrock in the Caribou and Liard ranges indicate that at its maximum extent, Cordilleran ice flowed southeast into the Liard and Toad River valleys, where it was confluent with glaciers flowing from cirques in the northern Rocky Mountains and with northwest-flowing Laurentide ice along the mountain front between approximately 59°N, 124°30'W and 60°N, 125°15'W (**Fig. 11A**). The distribution of Precambrian and Cretaceous erratics reflects these dispersal patterns

(Huntley et al. 2011). At the last glacial maximum, Cordilleran ice prevented the Laurentide Ice Sheet from penetrating into the northern Rocky Mountains and southern Mackenzie Mountains. Conversely, Laurentide ice inundating the mountains to a minimum elevation of 1250 m prevented the Cordilleran Ice Sheet from advancing eastward from the mountain front over the Liard Plateau. This zone is further defined by the absence of terminal interlobate moraines and lack of stratigraphic overlaps of Cordilleran and Laurentide till (cf. Mathews 1980; Levson and Rutter 1996; Bednarski and Smith 2007; Bednarski 2008).

Laurentide Ice Sheet subglacial terrains

East of the mountain front, sand-rich Laurentide till form discontinuous veneers on glacially streamlined clastic and carbonate bedrock exposed along ridge crests in the eastern Liard Plateau, the Maxhamish Escarpment and Tsoo Tablelands (**Fig. 10**). Dissected pre-Late Wisconsinan terrain lies buried beneath a clay-rich till blanketing the low relief Liard Plateau, Etsho Plateau and Fort Nelson Lowland (**Fig. 6A, B**, log G; **Fig. 10**). Deformed sub-till deposits and over-ridden ice thrust-ridges (**Fig. 8A**) are indicative of initial advance of ice margins over sand and clay-rich bed materials containing permafrost (cf. Dyke and Prest 1987; Johnson 1990; Kleman and Borgström 1994; Bennett et al. 1998; Boulton et al. 1999; Ó Cofaigh et al. 2005; Bednarski 2008; Evans et al. 2008; Hartman and Clague 2008; Hickin et al. 2008; Trommelen and Levson 2008; Lajeunesse 2014; Benediktsson et al. 2009; Hickin et al. 2016).

Large tracts of the Liard Plateau, Etsho Plateau and Fort Nelson Lowland are covered in till blankets and drumlinized terrain (**Fig. 10**), suggesting extensive subglacial erosion, bed deformation, material transport and lodgement of till by warm-based ice (cf. Mathews 1974; Clayton et al. 1985; Boulton 1987; Boulton and Hindmarsh 1987; Boulton 1987; Dreimanis 1989; Alley 1991; Fisher et al. 1995; Boulton et al. 2001; Stokes and Clark 2001; 2002; 2003; van der Meer et al. 2003; Murton et al 2004; Evans and Rea 2005; Menzies et al. 2006; Evans et al. 2008; Ross et al. 2009; Benediktsson et al. 2009; Ó Cofaigh et al. 2010; Shaw et al. 2009). At the glacial maximum, elongated (mega-scale) drumlins and flutes were formed by fast-flowing Laurentide ice from the northeast coalescing, then deflecting northwest along a southeast flowing portion of the Cordilleran Ice Sheet between 59°N, 124°30'W and 60°N, 125°15'W (**Fig. 11A**).

Deglaciation phases II-XII (ca. 21.5 to 12.9 ka)

Cordilleran Ice Sheet and montane ice-contact terrains

The retreat history of the Cordilleran Ice Sheet and montane glaciers after 21.5 ka is recorded in the accumulation of hummocky till, outwash fans and terraces in the valleys of Scaffold Creek, and Crow, Bear, Liard, Trout and Toad rivers (**Fig. 6A, B**, logs A and B; **Fig. 7A, B**, logs A and B; **Fig. 11B-L**). Like other regions covered by the Cordilleran Ice Sheet, recessional end moraines similar to those formed by the retreat of the Laurentide Ice Sheet are not observed in mountain valleys of the study area (Mathews 1980; Klassen 1987; Catto et al. 1996; Levson et al. 2004; Bednarski 2001, 2007). In contrast, hummocky till associated with glaciofluvial outwash and glaciolacustrine deposits are evidence of stagnant ice bodies confined to valley floors melting *in situ* (**Fig.**

10). As ice retreated from mountain valleys and uplands, Cordilleran tills were extensively modified by wind action, cryoturbation and colluviation along ridge crests and steep slopes in the Liard Range, Rocky Mountain Foothills and Tsoo Tableland. Rapid incision of deglaciated valleys triggered large bedrock landslides and rock falls, for example Scatter River and Tsoo Tableland. Sediment from these exposed areas was redeposited in lowlands and valleys or transported by meltwater through the upper levels of glacial Lake Liard, then northward toward glacial Lake Nahanni and glacial Lake Mackenzie (Ford 1976; Mathews 1980; Smith 1992; 1994; Duk-Rodkin et al. 1995; Duk-Rodkin 1999; Teller et al. 2002, 2005; Dyke et al. 2003; Zazula et al. 2004; Bednarski 2008; Couch and Eyles 2008).

Laurentide Ice Sheet ice-contact terrains

Laurentide ice-contact terrains are characterized by till ridges and stagnation features superimposed upon bedrock, till plains and older drumlinized terrain (cf. Van der Wateren 1987; Andriashek and Fenton 1989; Bennett et al. 1998; 2000; Dyke and Sevelle 2000). Changes in iceflow directions during deglaciation are recorded by younger generations of drumlins that are superimposed on older streamlined terrain and till ridges (**Fig. 8A; Fig. 11B-I**). Although the Laurentide Ice Sheet retreated from the mountain front after 21.5 ka (**Fig. 2A**), ice lobes confined to the Petitot River valley and over the Etsho Plateau continued to flow southwest and west; while to the south, a separate lobe occupied the Fort Nelson Lowland and flowed northwest (**Fig. 11B-J**). It is possible that rapid ice flow was episodically maintained in receding lobes by a combination of high basal pore pressures and storage of meltwater in the subglacial zone, with deformation

and ice-thrusting of permafrost-rich glacial deposits in the ice-marginal zone. Crevasse ridges with transverse or oblique orientations indicate transtensional conditions within a rapidly flowing ice sheet (**Fig. 8A**). The network of channels and eskers that crosscut drumlins and crevasse deposits suggest that ice streaming and, or surging conditions terminated with meltwater discharge through a subglacial drainage system developed beneath intensely crevassed ice masses (**Fig. 5B**).

Ten major recessional end moraine belts mark stable positions of these ice lobes as they retreated eastward across forefields and proglacial lake basins in the study area (**Fig. 4; Fig 5A**). Terrain dominated by hummocky till and a variety of low relief till ridges indicate stagnation of debris-rich and heavily crevassed ice behind these end moraine complexes (**Fig. 8B, C**). Drumlinized, hummocky and corrugated terrain behind individual moraine belts suggests end moraine formation was accompanied by deformation of frozen ice-marginal sediments and reorganization in flow trajectories of individual ice lobes (cf. Moran et al. 1980; Bennett et al. 1998; Boulton and van der Meer 1999; Dyke and Savelle 2000; Murton et al. 2004; Benediktsson et al. 2009; Dyke and Evans 2005; Ó Cofaigh et al. 2005 Clayton et al. 2008). The distribution of glaciolacustrine and outwash deposits in contact with or proximal to end moraines indicates falling proglacial lake elevations and reorganization of meltwater drainage routes also accompanied ice retreat (**Fig. 11B-J**).

The presence of low-relief crevasse fills and De Geer-like ribbed moraines (**Fig. 8B, C**) indicates portions of receding Laurentide Ice Sheet terminated in proglacial lakes

677 confined to major valleys and low lying terrain (cf. Harper et al. 1998; Boulton et al.
678 1999; Boulton et al. 2001; Stokes and Clark 2001; 2002; 2003; van der Meer et al. 2003;
679 Lindén and Möller 2005; Bednarski 2008; Benediktsson et al. 2009; Clayton et al. 2009).
680 Hydrological and iceflow conditions in the ice-marginal and subglacial zones were likely
681 influenced by fluctuating supraglacial, subglacial and proglacial lake levels. At high lake
682 levels, buoyant glacier lobes would have decoupled from the bed, leading to rapid
683 discharge of crevassed ice and subglacially stored meltwater into proglacial water bodies.
684 After lake drainage, or during low lake stages, iceflow behind the grounding line was
685 accommodated through deformation of partly frozen sediments and basal sliding where
686 subglacial meltwater accumulated as suggested by the association of subglacial meltwater
687 channels and eskers with ice-thrust features and streamlined landforms. Meltwater
688 drainage was maintained by seasonally functioning conduits incising and eroding clay-
689 rich bedrock and subglacial deposits (cf. Sharp 1985; Evans et al. 1999; Bennett et al.
690 2000). Laurentide ice had retreated east of the study area by deglaciation phase XI, ca.
691 12.9 ka (**Fig. 2D**; **Fig. 11K**). Once abandoned, end moraines and low-relief till ridges
692 were modified by debris flows, meltwater incision and eolian action until stabilized by
693 vegetation and soil formation.

694

695 *Laurentide subglacial meltwater drainage terrains*

696 Subglacial drainage terrain is confined to areas formerly beneath the Laurentide Ice
697 Sheet, and is superimposed upon till plains and drumlinized terrain (**Fig. 10**).
698 Channelized drainage channels are most frequently found in association with streamlined
699 terrain (**Fig. 8A**) suggesting discrete meltwater drainage accompanied fast iceflow

conditions. In contrast, eskers formed in areas where ice streaming has not been reconstructed, for example in association with hummocky moraines deposited from stagnant ice masses (**Fig. 8B**). Networks of subglacial meltwater channels and eskers over the Etsho Plateau, Maxhamish Escarpment and Fort Nelson Lowland (**Fig. 5B-E; Fig. 11B-J**) are evidence of the transition from rapid iceflow conditions and formation of drumlinized terrain in the subglacial zone to terrain produced by debris melt-out from stagnant, heavily crevassed ice masses in the ice-marginal zone (cf. Eyles and Eyles 1992; Clark and Walder 1994; Brennand and Shaw 1994; Harper et al. 1998; Boulton et al. 2001; Cutler et al. 2002; Clark et al. 2004; Fisher et al. 2005; Jørgensen and Sandersen 2006; Boulton et al. 2009; Kehew et al. 2012; Burke et al. 2012; Perkins et al. 2013; Storrar et al. 2014; Margold et al. 2015; Greenwood et al. 2016). Subglacial channels and eskers running upslope over clay-rich basal till plains and bedrock terrain imply phreatic meltwater flow under recessional ice masses. Subglacial drainage routes, for example along the Maxhamish Escarpment and Etsho Plateau, were abandoned as ice stagnated and conduits infilled with silt, sand, debris flow diamicton and melt-out till (**Fig. 8A, B**). It remains unclear whether eskers and subglacial meltwater channels were rapidly formed during discharge of stored supraglacial and subglacial water bodies; or developed gradually through erosion and depositional cycles involving ice creep and low discharge flows generated through frictional melting and dewatering of saturated basal sediments.

Cordilleran and Laurentide proglacial meltwater terrains

Proglacial outwash deposits occur in proximity to till ridges and ice stagnation terrain throughout the study area (**Fig. 10**). Significant northward meltwater drainage was

established as Cordilleran and Laurentide ice retreated from terminal limits along the foothill ranges of northern British Columbia and Alberta (**Fig. 5B-E; Fig. 11B-L**). Early during deglaciation, Cordilleran ice confined to the Rocky Mountain Foothills was drained by meltwater spillways incised into dip slopes of escarpments east of Liard and Toad rivers (**Fig. 5B**). Meltwater drainage patterns changed significantly as Cordilleran and Laurentide ice retreated from terminal limits in the Liard Range and Rocky Mountain Foothills (**Fig. 5C-E**). Subaerial outwash fans and kame terraces formed at the discharge points of subglacial meltwater channels. Proglacial spillways maintained their subglacial channel morphology, but were infilled to varying degrees with diamicton, gravel, sand and silt outwash (**Fig. 8A-C**). Spillways connected receding glacier margins to proglacial lakes with surface elevations ca. 840 m, 720 m, 620 m, 540 m, 460-380 m and 320 m occupying the Liard, Fort Nelson and Petitot river valleys (**Fig. 4; Fig. 5B-E; Fig. 8C; Fig. 11B-L**). From ca. 13.8 ka to 10.2 ka, peaking during deglaciation phases VI to XII, large volumes of meltwater and fine-grained sediment drained northward through spillways and proglacial lakes confined to the eastern foothill ranges, uplands, plateaus and lowlands (**Fig. 2D-F; Fig. 6A, B, logs A-H; Fig. 7A, B, logs A-H**). The Liard, Toad, Fort Nelson, Petitot and other major rivers all occupy meltwater spillways incised into recessional end moraines, landslide debris and bedrock (**Fig. 5B-E**). Post-glacial underfit streams have incised this outwash to form glaciofluvial terraces between 300 and 280 m elevation (**Fig 8A, C; Fig. 11M**).

Proglacial lake terrains

Glacial lake terrain occurs in proximity to outwash deposits in all major valleys and low-lying areas, where it is generally superimposed upon ice-marginal and subglacial terrains (cf. Mathews 1980; Sharp 1985; Dyke and Prest 1987; Cowan and Powell 1991; Eyles and Eyles 1992; Smith 1992; 1994; Lemmen et al. 1994; Evans et al. 1999; Bennett et al. 2000; Mangerud et al. 2002; Teller et al. 2002, 2005; Dyke et al. 2003; Zazula et al. 2004; Evans and Rea 2005; Bednarski 2008; Couch and Eyles 2008; Hickin et al. 2015, 2016; **Fig. 10**). Together with the mapped distribution of end moraines and glaciofluvial features (**Fig. 5A, B**; **Fig. 8A-C**), logged sections (**Fig. 6A, B** logs A-H; **Fig. 7A, B** logs A-H) record the formation of succession of extensive, interconnected proglacial lakes in the major valleys of the Caribou Range, Liard Range, northern Rocky Mountains, Tsoo Tablelands, Liard Plateau and Etsho Plateau (**Fig. 4**; **Fig. 11B-L**). Glaciofluvial and glaciolacustrine deposits observed in this study lie within the elevation range and geographic limits of the precursors to glacial Lake Liard (Mathews 1980; Smith 1992; 1994; Lemmen et al. 1994; Bednarski 2008).

The highest interlobate proglacial lakes were impounded to elevations of 840 m, 720 m, and 620 m by ice sheets, valley glaciers, glacial deposits and landslide debris at the onset of regional deglaciation in the mountains and foothill ranges: deglaciation phases II to IV (**Fig. 4**; **Fig. 11B-D**). As the Laurentide Ice Sheet thinned and retreated to the northeast and east of the study area, proglacial lakes extended eastward, inundating ice-free portions of the Liard Plateau, Tsoo Tablelands and Fort Nelson Lowland. Glacial lakes in the Liard and Fort Nelson valleys were connected by meltwater spillways incising the Tsoo Tablelands and Maxhamish Escarpment. A progressive, but episodic lowering of

spillway outlet elevations and proglacial lake levels from 540 m to 380 m elevation was accompanied by decreasing areal extent during deglaciation phases V-XI (**Fig. 11E-K**). Shallower water depths and shorter lake stand durations are suggested by thinner accumulations of glacial lake sediment in the Fort Nelson Lowland, deposited in “glacial Lake Fort Nelson” (**Fig. 4; Fig. 7 logs F, H; Fig. 11G-K;**).

The proglacial lake system in the Liard, Petitot and Fort Nelson river valleys likely functioned from deglaciation phases II to XI, ca. 18 ka to 13 ka (**Fig. 11B-K**). Meltwater and sediment sources included: proglacial, supraglacial and subglacial debris in the study area; early overflow from glacial Lake Peace, 300 km to the south; and later overflow events from glacial Lake Hay, 100 km to the east. Early ice-marginal lakes (elevations ca. 840 m; **Fig. 11B**) and glacial lakes Liard and Fort Nelson (elevations of 720 m to 380 m; **Fig. 11C-K**) drained north into glacial Lake Nahanni before being routed through the ice-free Mackenzie Mountains into glacial Lake Mackenzie and the Beaufort Sea (**Fig. 2B-D**). As outlets elevations in the study area fell below 380 m (**Fig. 11K-M**), meltwater drainage was routed northeast into directly into glacial Lake Mackenzie and the Beaufort Sea. This latter proglacial lake had drained by 9.8 ka (**Fig. 2F**). Peak meltwater and sediment discharges through the study area occurred between deglaciation phases V to XI as glacial lakes Nahanni, Liard, Fort Nelson, Hay, Peace and Mackenzie drained into the Beaufort Sea (**Fig. 2B-E; Fig. 11B-L; Mathews 1980, Smith 1992, 1994; Lemmen et al. 1994; Dyke et al. 2003; Teller et al. 2002, 2005; Bednarski 2008; Hickin et al. 2015; 2016**).

Proglacial eolian terrains

Eolian terrain (**Fig. 10**) is predominantly superimposed upon glacial lake deposits and outwash, reflecting the nearby source materials and remnant ice masses required to generate katabatic winds. Dune formation began in regional proximity to retreating Cordilleran and Laurentide ice after glacial Lake Liard fell below 540 m elevation, exposing clay, silt and sand over a significant portion of the Liard Plateau (**Fig. 4; Fig. 11F-K**).

Parabolic dune orientations and optical ages obtained on eolian sands in the study area indicate dune fields are relict Late Wisconsinan landforms (**Table 2; Fig. 5B-E; Fig. 9**). The maximum limiting age of the Liard Plateau dune field is a function of the timing of deglaciation, subsequent drainage of proglacial lakes, then stabilization through vegetation and soil formation. The ages reported here constrain the timing of deglaciation events and surface wind patterns. The first dunes record transportation directions from the west, suggesting katabatic winds from the Cordilleran Ice Sheet were funneled between receding ice sheet masses. Ice-distal dunes with an east-southeast orientation formed in the Fort Nelson Lowland as glacial lake levels fell below 380 m elevation after deglaciation phase XI (**Fig 5B; Fig. 8C; Fig. 11K-L**). Dunes stabilized around 13.0 ± 0.5 ka with the establishment of tundra vegetation on deglaciated terrain, and as the climate became increasingly influenced by the Pacific air mass (cf. David 1981; Wolfe et al 2004; Hickin et al. 2015).

Deglaciation phase XIII to post-glaciation (ca. <11.5 ka - present)

814 *Non-glacial terrains*

815 Retreat of the Laurentide Ice Sheet and remnant montane ice from the study area,
816 combined with changes in regional base level after 11.5 ka, led to episodes of channel
817 incision and aggradation, resulting in the formation of drift terraces along most streams
818 and river valleys (cf. Lemmen et al. 1994; Duk-Rodkin et al. 1995; Duk-Rodkin 1999;
819 Zazula et al. 2004; Huntley and Duk-Rodkin 2008). In the early Holocene, pulses of
820 fluvial terrace building followed initial valley incision by the Liard, Toad, Fort Nelson,
821 Petitot and other major rivers (**Fig. 8A, C; Fig. 11M**). In these valleys, prominent alluvial
822 terraces consisting of gravel overlain by silt and sand, form less than 5 m above active
823 floodplains. Many smaller rivers and streams occupy meltwater channels and have silt
824 and organic-rich floodplains. Other poorly organized streams on the plateaus and in
825 lowland areas drain extensive postglacial peat deposits and fens blanketing clay-rich till
826 and glaciolacustrine sediments containing sporadically discontinuous permafrost (**Fig.**
827 **8A-C**).

828

829 **Summary and concluding remarks**

830 Lithostratigraphic sections observed in the Toad River (NTS 094N) and Maxhamish Lake
831 (NTS 094O) map areas are a record of retreating ice sheet margins; infilling of meltwater
832 channels by glaciofluvial debris derived from retreating glaciers; inundation of valleys by
833 proglacial lakes; followed by rapid drainage, incision and terracing of outwash; and then
834 resumption of glacial lake conditions at progressively lower elevations (**Fig. 6A, B** logs
835 **A-H; Fig. 7A, B** logs **A-H**). Surficial deposits and landforms provide new insight into the
836 nature and pattern of the retreating of Late Wisconsinan (MIS-2) Cordilleran and

Laurentide ice sheets, specifically the influence of proglacial lakes on ice dynamics and reorganization of iceflow during deglaciation, the evolution of meltwater drainage routes, and elevation limits and spatial extent of proglacial lake formation in northeastern British Columbia (**Fig. 4; Fig. 5A-E; Fig. 8A-C; Fig. 11A-M**).

Landsystem (landscape process-form) model

Similar to other glaciated regions of Canada, topography and changing basal thermal regimes of the Late Wisconsinan Laurentide and Cordilleran ice sheets were important controls on the distribution of glacial landsystems in northeastern British Columbia (**Fig. 10**). Glacial advance landsystems include eroded and streamlined bedrock terrain common to both the Laurentide and Cordilleran ice sheets; and dissected and buried pre-Late Wisconsinan terrain restricted to areas overridden by Laurentide ice. Deformation structures in sub-till deposits suggest predominantly cold-based conditions beneath and around the advancing ice sheet margins. The widespread deposition of subglacial tills east of the mountain front is an indication of a later change to warm-based conditions beneath the Laurentide Ice Sheet.

Glacial maximum landsystems include drumlinized terrain common to both ice sheets, and subglacial drainage terrain confined beneath Laurentide ice. Streamlined impermeable bedrock and till deposits cross-cut by subglacial channels indicate widespread warm-based conditions, rapid ice flow and channelized subglacial meltwater drainage at the glacial maximum.

Glacial retreat landsystems are more numerous, reflecting the transition from warm-based glacial maximum conditions to cold-based (or polythermal) ice-marginal conditions, then proglacial and periglacial conditions. Ice-marginal landsystems evolved from late glacial maximum terrains. Ice stagnation terrain is common to both Laurentide and Cordilleran ice sheets, and indicates that streamlining of till was followed by down-wasting of debris-rich crevassed ice masses drained by a network of eskers and subglacial channels. Ice-contact till ridge terrain is associated with the Laurentide Ice Sheet only. Regional moraine belts define the eastward recession of ice lobes and periodic local re-advance of thin, crevassed ice margins across exposed till plains, proglacial outwash and glacial lake terrain.

Proglacial outwash, glacial lake and eolian terrains are superimposed on older Cordilleran and Laurentide landsystems. Subglacial drainage networks remained connected to proglacial spillways and ice-proximal lakes confined to major valleys and low-lying areas throughout deglaciation. As ice retreated, glacial lake levels lowered and spillways were abandoned or incised. Exposed glacial deposits were reworked by fluvial, mass-wasting, periglacial and eolian processes conditioned by their proximity to receding margins of Laurentide and Cordilleran ice sheets, and glacial lake elevations in the South Nahanni and Mackenzie valley watersheds north of the study area.

Patterns of ice retreat and ice sheet dynamics

Deglaciation began with Cordilleran and Laurentide ice sheets retreating from a confluence zone between approximately 59°N, 124°30'W and 60°N, 125°15'W in the

Liard Range and Rocky Mountain Foothills sometime after 21.5 ka (glacial maximum phase I). Cordilleran and montane ice retreated into the north-central British Columbia and northwest into the Yukon. Laurentide ice retreated northeastward from uplands and the Liard and Etsho plateaus, separating into lobes occupying the Fort Nelson Lowland and Petitot River valley. In the study area, retreat of Laurentide ice from upland, plateau and lowland areas involved at least 10 intervals of major end moraine formation, accompanied by short-lived surges, ice stagnation, reorganization in flow trajectories of individual ice lobes, changes in meltwater drainage routes, and a progressive lowering of proglacial lake elevations.

Meltwater drainage and proglacial lake systems

Laurentide meltwater drainage was focused westward toward ice margins through an evolving, interconnected system of subglacial topographic basins, channels and eskers. The meltwater drainage system revealed by this study drained increasing volumes of supraglacial, englacial and subglacial meltwater during deglaciation. Proglacial lakes and spillways formed in major valleys as Laurentide and Cordilleran ice sheets retreated from their terminal Late Wisconsinan limits along the foothill ranges of northern British Columbia and Alberta. During deglaciation, meltwater and sediment were routed northward into glacial Lake Nahanni through ice-marginal spillways and lakes formed ca. 840 m elevation; then through glacial lakes Liard and Fort Nelson with stable elevations at 720 m, 620 m, 540 m, and 460-380 m. Receding continental and montane ice, glacial deposits and landslide debris in the Mackenzie Mountains to the north controlled lake levels in the study area during deglaciation phases II-XI. Below 320 m elevation,

meltwater and sediment from receding Laurentide ice margins and glacial lakes Peace and Hay drained through the Fort Nelson, Liard and Petitot spillways to glacial Lake Mackenzie, and thence into the Beaufort Sea. Remnant montane and Cordilleran ice in the Liard River drainage basins likely sustained glacial meltwater and sediment transport into this system during deglaciation phases XII-XIII.

Proglacial dune fields

This study provides the first ages for relict dune fields along the Laurentide and Cordilleran ice sheet margins in this part of northeastern British Columbia. Optical ages from stabilized parabolic dunes on the Liard Plateau imply that extensive tracts of exposed glacial sediments on the Liard Plateau were reworked by katabatic winds sourced from the Pacific Ocean and retreating Cordilleran ice masses. Dunes stabilized ca. 13.0 ± 5 ka with retreat of the Cordilleran and Laurentide ice sheets from the area.

Future research directions

The spatial and temporal relationships of streamlined, ridged, hummocky and meltwater drainage landforms identified by this regional study suggest linkages with the mass balance of retreating Late Wisconsinan ice sheets in northwestern Canada that require further investigation (cf. Storrar et al. 2014; Margold et al. 2015; Greenwood et al. 2016). For future in-depth studies, combining satellite image analysis with geophysical surveys and geochemical sampling in these terrains will further refine the working knowledge of the landforms and functioning of the Laurentide and Cordilleran ice sheets. Terrain analysis of high resolution multispectral imagery from satellites (e.g., Landsat 8) and

airborne light detection and ranging (LiDAR) surveys using conventional aircraft (or drone technologies) would be suitable for the detailed mapping of overlapping iceflow, stagnation, and meltwater landforms (cf. Hickin 2013; Hickin et al. 2013; 2015; 2016). Insight into the composition, internal structure and relative age relationships of till veneers, till plains, drumlins, moraine ridges, hummocky till and permafrost terrain may be gained through the application of electrical resistivity tomography, frequency-domain electromagnetic terrain conductivity, ground penetrating radar, seismic surveys (cf. Hickin 2013; Huntley et al. 2016). Borehole logging of natural gamma, conductivity and magnetic susceptibility can also provide information on the geophysical properties of glacial deposits at depth (cf. Hickin et al. 2008; Huntley et al. 2016). These geophysical techniques will also provide insight into the structure, composition and functioning of eskers, subglacial meltwater channels, kames, outwash plains and terraces, and glaciolacustrine deposits. Regional-scale geochemical mapping and sampling would provide additional information on the compositional variation of glacial sediments, ice sheet dynamics and meltwater drainage systems, for example by delineating erratic transport paths, distinguishing ice lobes, and the extent of glacial lake deposits in lowland areas (cf. Huntley et al. 2011). Lastly, greater resolution of the timing for glacial lake drainage and stabilization of eolian deposits in northwestern Canada would be achieved with further sampling of dune fields identified by this study (cf. Hickin et al. 2015; 2016).

Acknowledgements

Fieldwork and mapping (2009-2013), and preparation of the manuscript (2013-2016) were undertaken as part of Natural Resources Canada (NRCAN) Geo-mapping for

Energy and Minerals (GEM) Program projects managed by Larry Lane (GSC Calgary) and Roger Paulen (GSC Ottawa). Our work in the region has benefitted from past collaboration with Jan Bednarski (GSC-Pacific), Alejandra Duk-Rodkin and Rod Smith (GSC-Calgary), and Alain Plouffe (GSC-Ottawa); and Travis Ferbey, Tania Demchuk and Holly Arnold (BCGS). Derek Brown, Catherine Sidwell, Lauren Wilson and Lisa Fodor were professional assistants during reconnaissance fieldwork in 2009 and 2010. Libby Griffin and Jordan Bryce prepared and measured the optical dating samples at University of the Fraser Valley. Thanks also to Great Slave Helicopters and the hamlet of Fort Liard, Northwest Territories for logistical support during the 2009 and 2010 field seasons. OBL acknowledges support from a Discovery Grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada. The authors greatly appreciate the critical reviews by Jeff Bond (Yukon Geological Survey) and Martin Margold (University of Alberta / Stockholm University).

References

- Alley, R.B. 1991. Deforming-bed origin for southern Laurentide till sheets? *Journal of Glaciology*, **37**: 67-77
- Andriashek, L.D. and Fenton, M.M. 1989. Quaternary stratigraphy and surficial geology of the Sand River Area 37L. *Alberta Research Council, Bulletin*, **57**: 1-154
- Ashley, G.M. 1975. Rhythmic sedimentation in Glacial Lake Hitchcock, Massachusetts Connecticut; in Jopling, A.V. and McDonald, B.C. Editors; *Glaciofluvial and*

- 975 Glaciolacustrine Sedimentation. Society of Economic Paleontologists and
976 Mineralogists, Special Publication, **23**: 304-320
977
- 978 Bednarski, J.M. 2001. Drift geochemistry and surficial geology of Trutch (94G),
979 northeastern British Columbia; Geological Survey of Canada, Open File **D3815**, scale
980 1:50 000
981
- 982 Bednarski, J.M. 2003a. Surficial geology of Fort Liard, Northwest Territories-British
983 Columbia; Geological Survey of Canada, Open File **1760**, scale 1:50 000
984
- 985 Bednarski, J.M. 2003b. Surficial geology of Lake Bovie, Northwest Territories-British
986 Columbia; Geological Survey of Canada, Open File **1761**, scale 1:50 000
987
- 988 Bednarski, J.M. 2003c. Surficial geology of Celibeta Lake, Northwest Territories-British
989 Columbia; Geological Survey of Canada, Open File **1754**, scale 1:50 000
990
- 991 Bednarski, J.M. 2005a. Surficial Geology of Etsine Creek, British Columbia; Geological
992 Survey of Canada, Open File **4825**, scale 1:50 000
993
- 994 Bednarski, J.M. 2005b. Surficial Geology of Gote Creek, British Columbia; Geological
995 Survey of Canada, Open File **4846**, scale 1:50 000
996

- 997 Bednarski, J.M. 2008. Landform assemblages produced by the Laurentide Ice Sheet in
998 northeastern British Columbia and adjacent Northwest Territories – constraints on
999 glacial lakes and patterns of ice retreat; Canadian Journal of Earth Sciences, **45**: 593-
1000 610
1001
- 1002 Bednarski, J.M. and Smith, I.R. 2007. Laurentide and montane glaciation along the
1003 Rocky Mountain Foothills of northeastern British Columbia; Canadian Journal of
1004 Earth Sciences, **44**: 445-457
1005
- 1006 Begét, J.E. 2001. Continuous Late Quaternary proxy climate records from loess in
1007 Beringia. Quaternary Science Reviews, **20** (1): 499-507
1008
- 1009 Benediktsson, Í.Ö., Ingólfsson, Ó, Schomacker, A. and Kjær, K. 2009. Formation of
1010 submarginal and proglacial end moraines: implications of ice-flow mechanisms during
1011 the 1963-64 surge of Brúarjökull, Iceland. Boreas, **38**: 440-457
1012
- 1013 Bennet, M.R., Hambrey, M.J. Huddart, D. and Glasser, N.F. 1998. Glacial thrusting and
1014 moraine-mound formation in Svalbard and Britain: the example of Coire a'Cheud-
1015 chnoic (Valley of a Hundred Hills). Quaternary Proceedings, **6**: 17-34
1016
- 1017 Bennett, M.R., Huddart, D. and Waller, R. 2000. Glaciofluvial crevasse and conduit fills
1018 as indicators of supraglacial dewatering during a surge, Skeiðarárjökull, Iceland.
1019 Journal of Glaciology, **46**: 25-34

1020

1021 Booth, D. B., Troost, K.G., Clague, J.J. and Waitt, R.B. 2003. The Cordilleran Ice Sheet.

1022 Development in Quaternary Science, **1**: 17-44

1023

1024 Bostock, H.S. 1970. Physiographic regions of Canada; Geological Survey of Canada,

1025 Map **1254A**, scale 1:5 000 000

1026

1027 Boulton, G.S. 1987. A theory of drumlin formation by subglacial deformation; in

1028 Drumlins: A Symposium, Menzies, J. and Rose, J. Editors, Balkema: 25-80

1029

1030 Boulton, G.S. and Hindmarsh, R.C.A. 1987. Sediment deformation beneath glaciers:

1031 rheology and geological consequences; Journal of Geophysical Research, **92**: 9059-

1032 9082

1033

1034 Boulton, G.S. and van der Meer, J.J.M. 1999. The sedimentary and structural evolution of

1035 a recent push moraine complex: Holmstrømbreen, Spitsbergen; Quaternary Science

1036 Reviews, **18**: 339-371

1037

1038 Boulton, G.S., Dobbie, K.E. and Zatsepin, S. 2001. Sediment deformation beneath

1039 glaciers and its coupling to the subglacial hydraulic system. Quaternary International,

1040 **86**: 3-28

1041

- 1042 Boulton, G.S., Hagdorn, M., Maillot, P.B. and Zatsepin, S. 2009. Drainage beneath ice
1043 sheets: groundwater-channel coupling, and the origin of esker systems from former ice
1044 sheets; *Quaternary Science Reviews*, **28**: 621-638
1045
- 1046 Brennand, T.A., and Shaw, J. 1994. Tunnel Channels and associated landforms, south-
1047 central Ontario: their implications for ice-sheet hydrology. *Canadian Journal of Earth*
1048 *Sciences* **31**: 505–522
1049
- 1050 Burke, M.J., Brennand, T.A., and Perkins, A.J. 2012. Evolution of the subglacial
1051 hydrologic system beneath the rapidly decaying Cordilleran Ice Sheet caused by ice-
1052 dammed lake drainage: implications for meltwater-induced ice acceleration.
1053 *Quaternary Science Reviews* **50**: 125–140
1054
- 1055 Catto, N.R., Liverman, D.G.E., Bobrowsky, P.T., Rutter, N. and Mandryk, C.A.S. 1996.
1056 Laurentide, Cordilleran and Montane glaciation in western Peace River – Grande
1057 Prairie region, Alberta and British Columbia, Canada. *Quaternary International*, **32**:
1058 21-32
1059
- 1060 Church, M. and Ryder, J.M. 1972. Paraglacial sedimentation: a consideration of fluvial
1061 processes conditioned by glaciation. *Geological Society of America Bulletin*, **83**:
1062 3059-3071
1063

- 1064 Clark, C.D., Evans, D.J.A., Khatwa, A., Bradwell, T., Jordan, C.J., Marsh, S.H., Mitchell,
1065 W.A. and Bateman, M.D. 2004. Map and GIS database of glacial landforms and
1066 features related to the last British Ice Sheet. *Boreas*, **34** (4): 359-375
1067
- 1068 Clark, C.D. and Stokes C.R. 2005. Palaeo-Ice Stream Landsystem. In D.J.A. Evans (ed.),
1069 Glacial Landsystems, Chapter 9: 204-227 Hodder Arnold
1070
- 1071 Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica,
1072 J.X., Hostelter, S.W. and McCabe, A.M. 2009. The Last Glacial Maximum. *Science*;
1073 325: 710-714
1074
- 1075 Clark, P.U. and Walder, J.S. 1994. Subglacial drainage, eskers and deforming beds
1076 beneath the Laurentide and Eurasian ice sheets; Geological Society of America
1077 Bulletin; **106**: 304-314
1078
- 1079 Clayton, L., Teller, J.T. and Attig, J.W. 1985. Surging of the southwestern part of the
1080 Laurentide Ice Sheet. *Boreas*, **14**: 235-241
1081
- 1082 Clayton, L., Attig, J.W., Ham, N.R., Johnson, M.D., Jennings, C.E., Syverson, K.M.
1083 2008. Ice-walled-lake plains: implications for the origin of hummocky glacial
1084 topography in middle North America. *Geomorphology*, **97**: 237-248
1085

- 1086 Cocking, R.B., Deblonde, C., Kerr, D.E., Campbell, J.E., Eagles, S., Everett, D., Huntley,
1087 D.H., Inglis, E., Laviolette, A., Parent, M., Plouffe, A., Robertson, L., St-Onge, D A.,
1088 Weatherston, A. 2015. Surficial Data Model, version 2.1.0: Revisions to the science
1089 language of the integrated Geological Survey of Canada data model for surficial
1090 geology maps Geological Survey of Canada Open File **7741**: 1-276
1091
- 1092 Couch A.C. and Eyles, N. 2008. Sedimentary record of glacial lake Mackenzie,
1093 Northwest Territories, Canada: Implications for Arctic freshwater forcing.
1094 Paleogeography, Paleoclimatology, Paleoecology, **289**: 26-38
1095
- 1096 Cutler, P.M., Colgan, P.M. and Mickelson, D.M. 2002. Sedimentologic evidence for
1097 outburst floods from the Laurentide Ice Sheet margin in Wisconsin, USA: implications
1098 for tunnel-channel formation. Quaternary International, **90** (1): 23-40
1099
- 1100 David, P.P. 1981. Stabilized dune ridges in northern Saskatchewan. Canadian Journal of
1101 Earth Sciences, **18**: 286-310
1102
- 1103 Demchuk, T.E. 2010. Surficial Geology of the Komie Creek area (NTS 94P/05); British
1104 Columbia Ministry of Energy, Mines and Petroleum Resources, Open File **2010-08**;
1105 Geological Survey of Canada Open File **6568**, scale 1:50 000
1106

- 1107 Dreimanis, A. 1989. Tills: their genetic terminology and classification; in Goldthwait,
1108 R.P. and Matsch, C.L. Editors; Genetic classification of glacial deposits; Balkema:
1109 17-93
1110
- 1111 Duk-Rodkin, A. 1999. Glacial limits map of Yukon Territory. Geological Survey of
1112 Canada Open File **3694**, Indian and Northern Affairs Geoscience Map **1999-2**, scale 1:
1113 1000 000
1114
- 1115 Duk-Rodkin, A., Barendregt, R.W., Tarnocai, C. and Phillips, F.M. 1995. Late Tertiary
1116 to late Quaternary record in the Mackenzie Mountains, Northwest Territories, Canada:
1117 stratigraphy, paleosols, paleomagnetism and chlorine-36; Canadian Journal of Earth
1118 Sciences, **33**: 875-895
1119
- 1120 Duk-Rodkin, A. and Lemmen, D.S. 2000. Glacial history of the Mackenzie region; in The
1121 Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line
1122 for the Assessment of Environmental Change. Dyke, L.D. and Brooks, G.R., Editors,
1123 Geological Survey of Canada, Bulletin **547**: 11-20
1124
- 1125 Duller, G.A.T, Bøtter-Jensen, L., and Murray, A.S. 2000. Optical dating of single sand-
1126 sized grains of quartz: sources of variability: Radiation Measurements, **32**: 453–457.
1127

- 1128 Dyke, A.S. 2005. Late Quaternary Vegetation History of Northern America Based on
1129 Pollen, Macrofossil, and Faunal Remains. *Géographie physique et Quaternaire*, **59**:
1130 211-262
1131
- 1132 Dyke, A.S. and Evans, D.G. 2005. Ice-marginal Terrestrial Landsystems: Northern
1133 Laurentide and Innuitian Ice Sheet Margins. In D.J.A. Evans (ed.), *Glacial*
1134 *landsystems*, Chapter 7: 143-165 Hodder Arnold
1135
- 1136 Dyke, A.S. and Prest, V.K. 1987. Paleogeography of northern North America, 18,000 –
1137 5000 years age. Geological Survey of Canada Map **1703A**, scale 1:12 500 000
1138
- 1139 Dyke, A.S., Moore, A. and Robertson, L. 2003. Deglaciation of North America.
1140 Geological Survey of Canada, Open File **1574**
1141
- 1142 Dyke, A.S. and Savelle, J.M. 2000. Major end moraines of Younger Dryas age on
1143 Wollaston Peninsula, Victoria Island, Canadian Arctic: implication for paleoclimate
1144 and for formation of hummocky moraine. *Canadian Journal of Earth Sciences*, **37**:
1145 601-619
1146
- 1147 Evans, D.J.A. 2005. Introduction to glacial landsystems. In D.J.A. Evans (ed.), *Glacial*
1148 *Landsystems*, Chapter 1: 1-11 Hodder Arnold
1149

- 1150 Evans, D.J.A. and Rea, B.R. 2005. Surging Glacier Landsystem. In D.J.A. Evans (ed.),
1151 Glacial Landsystems, Chapter **11**: 259-288 Hodder Arnold
1152
- 1153 Evans, D.J.A., Clark, C.D. and Brice, R. R. 2008. Landform and sediment imprints of fast
1154 glacier flow in the southwest Laurentide Ice Sheet. Journal of Quaternary Science, **23**
1155 (3): 249-272
1156
- 1157 Eyles, N and Eyles, C. 1992. Glacial depositional systems; in Walker, R.G. and James,
1158 N.P. Editors, Facies Models, Geological Association of Canada: 73-100
1159
- 1160 Ferri, F., Hickin, A. and Huntley, D. 2011. Bedded massive sulphide horizons (SEDEX)
1161 in upper Besa River Formation, western Liard Basin, British Columbia. Geoscience
1162 Reports 2011, B.C. Ministry of Energy and Mines: 19-36
1163
- 1164 Fisher, D.A., Reech, N. and Langley, K. 1995. Objective reconstruction of Late
1165 Wisconsinan Laurentide Ice Sheet and the significance of deformable beds;
1166 Géographie physique et Quaternaire, **39**: 229-238
1167
- 1168 Fisher, T.G., Jol, H.M. and Boudreau, A.M. 2005. Saginaw Lobe tunnel channels
1169 (Laurentide Ice Sheet) and their significance in south-central Michigan, USA.
1170 Quaternary Science Reviews, **24**: 2375-2391
1171

1172 Ford, D.C. 1976. Evidences of multiple glaciation in South Nahanni National Park,
1173 Mackenzie Mountains, Northwest Territories; Canadian Journal of Earth Sciences,
1174 **13**:1433-1445
1175
1176 Fyfe, G.J. 1990. The effect of water depth on ice-proximal glaciolacustrine
1177 sedimentation: Salpausselkä I., southern Finland. *Boreas*, **19**: 147-164
1178
1179 Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., and Olley, J.M. 1999. Optical
1180 dating of single and multiple grains of quartz from Jinmium rock shelter, northern
1181 Australia. Part I: Experimental design and statistical models: *Archaeometry*, **41**: 339–
1182 364.
1183
1184 Greenwood, S.L., Clason, C.C. Helanow, C. and Margold, M. 2016. Theoretical,
1185 contemporary observational and palaeo-perspectives on ice sheet hydrology: processes
1186 and products. *Earth Science Reviews*, **155**: 1-27
1187
1188 Hanson, M.A., Lian, O.B., and Clague, J.J. 2012. The sequence and timing of large late
1189 Pleistocene floods from glacial Lake Missoula: *Quaternary Science Reviews*: **31**: 67–
1190 81.
1191
1192 Harper, J.T., Humphrey, N.F. and Pfeffer, W.T. 1998. Crevasse patterns and the strain
1193 tensor: a high resolution comparison; *Journal of Glaciology*, **44**: 68-76
1194

- 1195 Hart, J.K. 1999. Identifying fast ice flow from landform assemblages in the geological
1196 record: a discussion; *Annals of Glaciology*, **28**: 59-68
1197
- 1198 Hartman, G.M.D. and Clague, J.J. 2008. Quaternary stratigraphy and glacial history of
1199 the Peace River valley, northeast British Columbia; *Canadian Journal of Earth*
1200 *Sciences*, **45**: 549-564
1201
- 1202 Hickin, A.S., Kerr, B., Turner, D.G. and Barchyn, T.E. 2008. Mapping Quaternary
1203 paleovalleys and drift thickness using petrophysical logs, northeast British Columbia,
1204 Fontas map sheet, NTS 094I; *Canadian Journal of Earth Sciences*, **45**: 577-591
1205
- 1206 Hickin, A.S. 2013. Late Quaternary to Holocene geology, geomorphology, and glacial
1207 history of Dawson Creek and surrounding area, Northeast British Columbia, Canada.
1208 Unpublished Ph.D. Thesis: 1-369, University of Victoria
1209
- 1210 Hickin, A.S., Lian, O.B., Levson, V.M. and Chui, Y. 2015. Pattern and chronology of
1211 glacial Lake Peace shorelines and implications for isostasy and ice-sheet configuration
1212 in northeastern British Columbia, Canada. *Boreas*, **10** 1111/bor.12110
1213
- 1214 Hickin, A.S., Lian, O.B., Levson, V.M. 2016. Coalescence of late Wisconsinan
1215 Cordilleran and Laurentide ice sheets east of the Rocky Mountain Foothills in the
1216 Dawson Creek region, northeast British Columbia, Canada. *Quaternary Research*. In
1217 press

- 1218
- 1219 Huntley, D.J., Godfrey-Smith, D.I., Thewalt, M.L.W. 1985. Optical dating of sediments.
- 1220 Nature, **313**: 105–107
- 1221
- 1222 Huntley, D.H. and Duk-Rodkin, A. 2008. Field recognition, inventory, and analysis of
- 1223 landslides in the Camsell Bend map area, southern Mackenzie River watershed,
- 1224 Northwest Territories; Geological Survey of Canada, Current Research **2008-10**: 1-14
- 1225
- 1226 Huntley, D.H. and Hickin, A.S. 2010. Surficial deposits, landforms, glacial history and
- 1227 potential for granular aggregate and frac sand: Maxhamish Lake Map Area (NTS
- 1228 94O), British Columbia; Geological Survey of Canada, Open File **6430**: 1-17
- 1229
- 1230 Huntley, D.H., Hickin, A.S. and Ferri, F. 2011. Provisional surficial geology, glacial
- 1231 history and paleogeographic reconstruction of the Toad River (NTS 094N) and
- 1232 Maxhamish Lake map areas (NTS 094O), British Columbia in Geoscience Report
- 1233 **2011**: 37-56
- 1234
- 1235 Huntley, D., Hickin, A., Chow, W. and Mirmohammadi, M. 2013a. Surficial Geology of
- 1236 Stanolind Creek, B.C. (preliminary), Canadian Geoscience Map **107**: 1:50,000-scale
- 1237 map
- 1238
- 1239 Huntley, D., Hickin, A., Chow, W. and Mirmohammadi, M. 2013b. Surficial Geology of
- 1240 Trail Lake, B.C. (preliminary), Canadian Geoscience Map **123**: 1:50,000-scale map

- 1241
- 1242 Huntley, D., Hickin, A., Chow, W. and Mirmohammadi, M. 2013c. Surficial Geology of
1243 Emile Creek, B.C. (preliminary), Canadian Geoscience Map **119**: 1:50,000-scale map
1244
- 1245 Huntley, D., Bobrowsky, P., Parry, N., Bauman, P., Candy, C. and Best, M. 2016. Ripley
1246 Landslide: the geophysical properties of a slow-moving landslide near Ashcroft,
1247 British Columbia, Canada; Geological Survey of Canada, Open File 8062, 64 pages
1248
- 1249 Jacobs, Z., and Roberts, R.G. 2007. Advances in optically stimulated luminescence
1250 dating of individual grains of quartz from archeological deposits. *Evolutionary*
1251 *Anthropology*, **16**: 210–223.
1252
- 1253 Johnson, W.H. 1990. Ice-wedge casts and relict patterned ground in central Illinois and
1254 their environmental significance. *Quaternary Research*, **33** (1): 51-71
1255
- 1256 Jørgensen, F. and Sandersen, P.B.E. 2006. Buried and open tunnel channels in Denmark-
1257 erosion beneath multiple ice sheets. *Quaternary Science Reviews*, **25**: 1339-1363
1258
- 1259 Kehew, A.E., Piotrowski, J.A. and Jørgensen, F. 2012. Tunnel valleys: concepts and
1260 controversies – a review. *Earth Science Reviews*, **113**: 33-58
1261
- 1262 Klassen, R.W. 1987. The Tertiary-Pleistocene stratigraphy of the Liard Plain,
1263 southeastern Yukon. Geological Survey of Canada; Paper **86-17**

1264

1265 Kleman, J. and Borgström, I. 1994. Glacial landforms indicative of a partly frozen bed.

1266 Journal of Glaciology, **40**: 255-264

1267

1268 Kleman, J and Glasser, N.F. 2007. The subglacial thermal organization (STO) of ice

1269 sheets. Quaternary Science Reviews, **26**: 585-597

1270

1271 Lajeunesse, P. 2014. Buried preglacial fluvial gorges and valleys preserved through

1272 Quaternary glaciations beneath the eastern Laurentide Ice Sheet. Geological Society of

1273 America Bulletin, **126** (3-4): 447-458

1274

1275 Lemmen, D.S. Duk-Rodkin, A. and Bednarski, J.M. 1994. Late glacial drainage systems

1276 along the northwestern margin of the Laurentide Ice Sheet; Quaternary Science

1277 Reviews, **13**: 805-828

1278

1279 Levson, V.M. and Rutter, N.W. 1996. Evidence of Cordilleran Late Wisconsinan glaciers

1280 in the "Ice-free Corridor". Quaternary International, **32**: 33-51

1281

1282 Levson, V.M., Ferbey, T., Kerr, B., Johnsen, T., Bednarski, J., Smith, I.R., Blackwell, J.

1283 and Jonnes, S. 2004. Quaternary geology and aggregate mapping in northeast British

1284 Columbia: application for oil and gas exploration; in Summary of Activities, BC

1285 Ministry of Energy, Geoscience and Natural Gas Development Branch: 29-40

1286

- 1287 Levson, V.M. and Fournier, M. 2012. Surficial geology, Fort Nelson, NTS 94-J/NE
1288 Geological Survey of Canada, Open File **7041**, 1 sheet, 1:50,000-scale map
1289
- 1290 Lian, O.B. and Roberts, R.G., 2006. Dating the Quaternary: progress in luminescence
1291 dating of sediments. *Quaternary Science Reviews* **25**, 2449–2468.
1292
- 1293 Lindén, M. and Möller, P. 2005. Marginal formation of De Geer moraines and their
1294 implications to the dynamics of grounding-line recession; *Journal of Quaternary*
1295 *Science*; **20**: 113-133
1296
- 1297 Mangerud, J., Astakhov, V., Jakobsson, M. and Svendsen, J.I. 2002. Huge ice-age lakes
1298 in Russia. *Journal of Quaternary Science*, **16**: 773-777
1299
- 1300 Margold, M., Stokes, C.R. and Clark, C.D. 2015. Ice streams in the Laurentide Ice Sheet:
1301 identification, characteristics and comparison to modern ice sheets. *Earth-Science*
1302 *Reviews*, **143**: 117-146
1303
- 1304 Mathews, W.H. 1974. Surface profiles of the Laurentide Ice Sheet in its marginal areas;
1305 *Journal of Glaciology*, **13**: 37-43
1306
- 1307 Mathews, W.H. 1978. Quaternary stratigraphy and geomorphology of Charlie Lake
1308 (94A) map area, British Columbia; Geological Survey of Canada, Paper **76-20**: 1-25
1309

- 1310 Mathews, W.H. 1980. Retreat of the last ice sheets in northeastern British Columbia and
1311 adjacent Alberta; Geological Survey of Canada, Bulletin **331**: 1-22
1312
- 1313 Menzies, J., van der Meer, J.J.M. and Rose, J. 2006. Till- as a glacial “tectomict”, its
1314 internal architecture, and the development of a “typing” method for till differentiation.
1315 Geomorphology, **75**: 172-200
1316
- 1317 Moran, S.R., Clayton, L., Hooke, R. LeB., Fenton, M.M. and Andriashek, L.D. 1980.
1318 Glacier-bed landforms of the Prairie region of North America. Journal of Glaciology,
1319 **25**: 457-476
1320
- 1321 Murray, A.S., and Wintle, A.G. 2000. Luminescence dating of quartz using an improved
1322 regenerative-dose protocol. Radiation Measurements, **32**: 57–73.
1323
- 1324 Murray, A.S., and Wintle, A.G. 2003. The single aliquot regenerative dose protocol:
1325 potential for improvements in reliability. Radiation Measurements **37**: 377–381.
1326
- 1327 Murton, J.B., Whiteman, C.A., Waller, R.I., Pollard, W.H. and Dallimore, S.R. 2004.
1328 Basal ice facies and supraglacial melt-out till of the Laurentide Ice Sheet, Tuktoyaktuk
1329 Coastlands, Western Arctic Canada. Quaternary Science Reviews, **24** (5): 681-708
1330
- 1331 Ó Cofaigh, C. 1996. Tunnel valley genesis; Progress in Physical Geography, **20**: 1-19
1332

- 1333 Ó Cofaigh, C., Evans, D.J.A. and England, J. 2005. Ice-Marginal Terrestrial
1334 Landsystems: Sub-Polar Glacier Margins of the Canadian and Greenland High Arctic.
1335 In D.J.A. Evans (ed.), *Glacial Landsystems*, Chapter **11**: 259-288, Hodder Arnold
1336
- 1337 Ó Cofaigh, C., Evans, J.A. and Smith, I.R. 2010. Large-scale reorganization and
1338 sedimentation of terrestrial ice streams during late Wisconsinan Laurentide Ice Sheet
1339 deglaciation; *Geological Society of America Bulletin*, **122**: 743-756
1340
- 1341 Olley, J.M., Pietsch, T., and Roberts, R.G. 2004. Optical dating of Holocene sediments
1342 from a variety of geomorphic settings using single grains of quartz. *Geomorphology*,
1343 **60**: 337–358.
1344
- 1345 Perkins, A.J., Brennand, T.A. and Burke, M.J. 2013. Genesis of an esker-like ridge over
1346 the southern Fraser Plateau, British Columbia: implications for paleo-ice sheet
1347 reconstruction based on geomorphic inversion. *Geomorphology*, **190**: 27-39
1348
- 1349 Porter, S.C. 2001. Chinese loess record of monsoon climate during the last glacial-
1350 interglacial cycle. *Earth-Science Reviews*, **54** (1): 115-128
1351
- 1352 Rampton, V.N. 1987. Late Wisconsin deglaciation and Holocene river evolution near
1353 Fort Nelson, northeastern British Columbia; *Canadian Journal of Earth Sciences*, **24**:
1354 188-191
1355

- 1356 Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk
1357 Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M.,
1358 Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F.,
1359 Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A.,
1360 Southon, J.R., Talamo, S., Turney, C.S.M., van der Flicht, J. and Weyhenmeyer, C.E.
1361 2009. IntCal09 and Marine 09 radiocarbon age calibration curves 0-50,000 years cal.
1362 BP. Radiocarbon, **51** (4): 1111-1150
1363
1364 Roberts, R.G., Galbraith, R.F., Olley, J.M., Yoshida, H., and Laslett, G.M. 1999. Optical
1365 dating of single and multiple grains of quartz from Jinmium rock shelter, northern
1366 Australia: Part II, results and implications. Archaeometry, **41**: 365–395.
1367
1368 Roberts, R.G. and Lian, O.B. 2015. Illuminating the past. Nature, **520**: 438–439.
1369
1370 Roberts, R.G., Jacobs, Z., Li, B., Jankowski, N.R., Cunningham, A.C., and Resenfeld,
1371 A.B. 2015. Journal of Archaeological Science **56**, 41–60.
1372
1373 Ross, M., Campbell, J.E., Parent, M. and Adams, R.S. 2009. Paleo-ice streams and the
1374 subglacial landscape mosaic of the North American mid-continental prairies. Boreas,
1375 **38**: 421-439
1376

- 1377 Rutter, N.W., Hawes, R.J. and Catto, N.R. 1993. Surficial Geology, southern Mackenzie
1378 River valley, District of Mackenzie, Northwest Territories; Geological Survey of
1379 Canada, GSC A-Series Map **1683A**, scale 1:500 000
1380
- 1381 Sharp, M. 1985. Crevasse-fill ridges – a landform type characteristic of surging glaciers?
1382 *Geografiska Annaler*, **67A**: 213-220
1383
- 1384 Shaw, J., Sharpe, D., and Harris, J., 2009. A flow-line map of glaciated Canada based on
1385 remote sensing data; *Canadian Journal of Earth Sciences*, **47**: 89-101
1386
- 1387 Smith, D.G. 1992. Glacial Lake Mackenzie, Mackenzie Valley, Northwest Territories,
1388 Canada; *Canadian Journal of Earth Sciences*, **29**: 1756-1766
1389
- 1390 Smith, D.G. 1994. Glacial Lake McConnell: paleogeography, age, duration and
1391 associated river deltas, Mackenzie River basin, Western Canada. *Quaternary Science*
1392 *Reviews*, **13**: 829-843
1393
- 1394 Smith, I.R. 2000. Preliminary report on surficial geology investigations of La Biche River
1395 map area, southeast Yukon Territory; Geological Survey of Canada, Current Research
1396 **2000-B3**: 1-9
1397

- 1398 Smith, I.R. 2002. Surficial geology, Mount Martin (95C/1), Yukon Territory – Northwest
1399 Territories – British Columbia; Geological Survey of Canada, Open File **4260**, 1 map,
1400 scale 1:50 000
1401
- 1402 Stokes, C. R. and Clark, C.D. 1999. Geomorphological criteria for identifying Pleistocene
1403 ice streams. *Annals of Glaciology*, **28**: 67-74
1404
- 1405 Stokes, C.R. and Clark, C.D. 2001. Palaeo-ice streams; *Quaternary Science Reviews*, **20**:
1406 1437-1457
1407
- 1408 Stokes, C.R. and Clark, C.D. 2002. Are long subglacial bedforms indicative of fast ice
1409 flow? *Boreas*, **31**: 239-249
1410
- 1411 Stokes, C.R. and Clark, C.D. 2003. Laurentide ice streaming on the Canadian Shield: a
1412 conflict with the soft-bedded ice stream paradigm; *Geology*, **31**: 347-350
1413
- 1414 Storrar, R.D., Stokes, C.R. and Evans D.J.A. 2014. Increased channelization of subglacial
1415 drainage during deglaciation of the Laurentide Ice Sheet. *Geology*, **42**: 239-242
1416
- 1417 Stott, D.F. and Taylor, G.C. 1968. Geology of Maxhamish Lake; Geological Survey of
1418 Canada, Map **2-1968**, scale 1:250 000
1419

1420 Teller, J.T. 1987. Proglacial lakes and the southern margin of the Laurentide Ice Sheet. In
1421 W.F. Ruddiman and H.E. Wright (eds.), North American and adjacent oceans during
1422 the last deglaciation. Geological Society of America, Decade of North American
1423 Geology, **K-3**: 39-69

1424

1425 Teller, J.T. and Kehew, A.E. (eds.) 1994. Late glacial history of proglacial lakes and
1426 meltwater runoff along the Laurentide Ice Sheet. Quaternary Science Reviews, **13**:
1427 795-981

1428

1429 Teller, J. T., Leverington, D.W. and Mann, J.D. 2002. Freshwater outbursts to the oceans
1430 from glacial Lake Agassiz and their role in climate change during the last deglaciation.
1431 Quaternary Science Reviews, **21**: 879-887

1432

1433 Teller, J. T., Boyd, M., Yang, Z., Kor, P.S.G. and Fard, A.M. 2005. Alternative routing of
1434 Lake Agassiz overflow during the Younger Dryas: new dates, paleotopography, and a
1435 re-evaluation. Quaternary Science Reviews, **24**: 1890-1905

1436

1437 Trommelen, M. and Levson, V.M. 2008. Quaternary stratigraphy of the Prophet River,
1438 northeastern British Columbia; Canadian Journal of Earth Sciences, **45**: 565-575

1439

1440 van der Meer, J.J.M., Menzies, J. and Rose, J. 2003. Subglacial till: the deforming
1441 glacier bed. Quaternary Science Reviews, **22**: 1659-1685

1442

- 1443 Van der Wateren, F.M. 1987. Processes of Glaciotectonism. In J. Menzies (ed.), Glacial
1444 environments: processes, sediments and landforms. Butterworth-Heinemann, Oxford:
1445 309-335
1446
- 1447 Wolfe, S.A., Huntley, D.J. and Ollerhead, J. 2004. Relict Late Wisconsinan Dune Fields
1448 of the Northern Great Plains, Canada. *Géographie Physique et Quaternaire*, **58**: 323-
1449 336
1450
- 1451 Wintle AG., 2008. Luminescence dating: where it has been and where it is going. *Boreas*
1452 **37**: 471–482
1453
- 1454 Wintle, A.G., and Murray, A.S. 2006. A review of quartz optically stimulated
1455 luminescence characteristics and their relevance in single aliquot regeneration dating
1456 protocols. *Radiation Measurements*, **41**: 369–391
1457
- 1458 Yokoyama, Y., Lambeck, K., De Dekker, P., Johnston, P. and Field, K.L. 2000. Timing
1459 of the Last Glacial Maximum from observed sea-level minima; *Nature*, **406**: 713-716
1460
- 1461 Zazula, G.D., Duk-Rodkin, A., Schweger, C.E., Morlan, R.E., 2004. Late Pleistocene
1462 chronology of glacial lake Old Crow and the north-west margin of the Laurentide Ice
1463 Sheet. In *Quaternary glaciations – extent and chronology. Part II*. Edited by J. Ehlers
1464 and P.L. Gibbard. Elsevier: 347-362
1465

List of Figures (Huntley et al. 2016)

Fig. 1. Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas, northeastern British Columbia: **A.** Location of study area in northeastern British Columbia. **B.** Major drainage patterns of northwestern Canada: *MR* – Mackenzie River; *HR* – Hay River; *PR* – Peace River; *LR* – Liard River; *FNR* – Fort Nelson River; *FN* – Fort Nelson; base map - ortho-rectified RADARSAT-1 250 m mosaic of Canada (open.canada.ca 2015). **C.** Major physiographic elements (after Bostock 1970; Mathews 1980) and rivers of the study area (blue rectangle in A and B); base map - LANDSAT-7 pan-sharpened imagery (landsat.usgs.gov 2015) draped over Shuttle Radar Topography Mission 3-arc-second resolution DEM (srtm.cigar-csi.org 2015).

Fig. 2. Generalized configuration for the Cordilleran and Laurentide ice sheets and major proglacial lakes in northwestern Canada between *ca.* 21.5 ka and 10.2 ka (from Duk-Rodkin 1999 and Dyke et al. 2003; radiocarbon calendar calibration after Reimer et al. 2009); basemap - ortho-rectified RADARSAT-1 250 m mosaic of Canada (open.canada.ca 2015).

Fig. 3. Toad River (NTS 094N) and Maxhamish Lake (NTS 094O) map areas: distribution of observations (white circles); logged sections (yellow dots, with figure numbers); erratics (red triangles – Laurentide granites, blue triangles – Cordilleran granodiorites, white triangles – Cordilleran quartzite); optical ages on dune sand samples (BRD-01, 02, 03); X-X' line of section (see **Figs. 6A** and **6B**); Y-Y' line of section (see **Figs. 7A** and **7B**). Basemap - LANDSAT-7 pan-sharpened image (landsat.usgs.gov 2015) draped over Shuttle Radar Topography Mission 3-arc-second resolution DEM (srtm.cigar-csi.org 2015).

Fig. 4. Master legend for **Fig. 5** to **Fig. 7**: **A, B.** Distribution of iceflow indicators, Laurentide and Cordilleran glacial limits and recessional ice margins inferred from the distribution of erratics, moraines, drumlins and meltwater features (see **Fig. 5**, **Fig. 11**). Approximate correspondence of ^{14}C age to calendar year (ka) after Reimer et al. (2009).

C, D. Facies codes, textures, lithostratigraphic units and paleoflow indicators to graphic logs of sections (see **Fig. 6**, **Fig. 7** and **Fig. 8**).

Fig. 5. A. Distribution of iceflow indicators, Laurentide and Cordilleran erratics, glacial limits and recessional ice margins inferred from the distribution of moraines, drumlins and meltwater features. Cordilleran (blue, yellow, brown) and Laurentide erratics (red, pink) distinguished by U/Pb isotopic ages (in millions of years) mineral composition and geochemistry (unpublished data). **B.** Meltwater spillways, glaciofluvial deposits and glaciolacustrine terraces graded to >840 m (red arrows) and 720 m (orange arrows); active ice margins I-III. **C.** Meltwater spillways, glaciofluvial deposits and glaciolacustrine terraces graded to 620 m (yellow arrows) and 540 m (light green arrows); active ice margins IV-V. **D.** Meltwater spillways, glaciofluvial deposits and glaciolacustrine terraces graded to 460 m to 380 m (green arrows); active ice margins VI-X; dune deposits, weighted mean optical age 13.0 ± 0.5 ka (tan circle with arrow indicating katabatic wind direction). **E.** Meltwater spillways, glaciofluvial deposits and glaciolacustrine terraces graded to 320 m (blue arrows) and <300 m (purple arrows); active ice margins XI-XII (montane); dune deposits, weighted mean optical age 13.0 ± 0.5 ka (tan circle with arrow indicating katabatic wind direction). See **Fig. 4** for legend.

Fig. 6. A. Station photographs for stratigraphic sections in the Crow River in the Mackenzie Mountains, Liard Range and Liard Plateau; and the Petitot River and tributaries dissecting the Fort Nelson Lowland and Etsho Plateau. **B.** Graphic logs for stratigraphic sections in the Crow River in the Mackenzie Mountains, Liard Range and Liard Plateau; and the Petitot River and tributaries dissecting the Fort Nelson Lowland and Etsho Plateau. Logged profiles are measured from the base up, and each log shows the station identifier and surface elevation. Locations of logs A-H are shown in **Fig. 3**. See **Fig. 4** for surficial geology legend.

Fig. 7. A. Station photographs for stratigraphic sections in tributaries to the Liard River in the Northern Rocky Mountains and southern Liard Plateau; and along the Fort Nelson

River dissecting the Fort Nelson Lowland. **B.** Graphic logs for stratigraphic sections in tributaries to the Liard River in the Northern Rocky Mountains and southern Liard Plateau; and along the Fort Nelson River dissecting the Fort Nelson Lowland. Logged profiles are measured from the base up, and each log shows the station identifier and surface elevation. Locations of logs A-H are shown in **Fig. 3**. See **Fig. 4** for surficial geology legend.

Fig. 8. Surficial geology and representative landforms of the Maxhamish Map Areas (NTS 92O): **A.** northwest quadrant of Emile Creek map sheet (CGM 119). **B.** southwest quadrant of Trail Lake (CGM 123). **C.** northeast quadrant of Stanolind Creek (CGM 107); inset map showing location of map fragments (maps modified from Huntley et al. 2013a-c).

Fig. 9. **A.** Example of a luminescence decay curve (main graph) and a dose-response curve (inset graph) typical of those accepted for aliquots of all the samples; the example shown is for sample BRD-01. The initial part of the luminescence decay curve is dominated by the desired fast component. The dose-response of each sample was constructed using the luminescence measured over the first 0.4 s of stimulation using the standard SAR protocol (Wintle and Murray 2006), but with the inclusion of an infrared wash to eliminate any luminescence resulting from any K-feldspar contamination (Olley et al. 2004). For each sample, the preheat was 240 °C for 10 s, and the heat treatment following the test dose (~15 Gy) was 220 °C for 10 s. The open circle on the dose-response plot is a duplicate point used to check for sensitivity change, while the zero-dose point is used to check for thermal transfer (recuperation) incurred during the SAR procedure. The equivalent dose (D_e) value is found by interpolating the signal of the undosed ("natural") aliquot onto the dose-response curve as shown in A (inset). **B**, **C**, and **D** show radial plots of D_e values for samples BRD-01, -02, and -03, respectively. Data points (D_e values) that fall within the shaded region on the radial plots (solid points) represent values that are within two standard deviations of the mean, found using the central age model (CAM) (Galbraith et al. 1999). The SAR experiments were performed using a Risø TL/OSL DA-20 reader. Irradiations were made using a calibrated $^{90}\text{Sr}/^{90}\text{Y}$ β -

1558 source mounted on the reader that delivered 5.59 ± 0.10 Gy/min to sample aliquots.
1559 Aliquots were stimulated by 45 mW/cm^2 of blue ($470 \pm 20 \text{ nm}$) light and the ultraviolet
1560 ($\sim 350 \text{ nm}$) luminescence emitted in response was detected by an Electron Tubes Ltd.
1561 9235QB photomultiplier tube placed behind a 7.5 mm-thick Hoya U-340 optical filter.

1562 **Fig. 10.** Landform assemblage model accounting for the Laurentide and Cordilleran ice
1563 sheets and proglacial terrain in the Toad River and Maxhamish Lake map areas,
1564 northeastern British Columbia.

1565

1566 **Fig. 11 A.** PHASE I: upper limit to the Cordilleran Ice Sheet approximately 1850 m,
1567 upper limit to Laurentide Ice Sheet approximately 1250 m elevation. **B.** PHASE II: early
1568 deglaciation, ice-marginal glacial lake still-stand elevation approximately 840 m. **C.**
1569 PHASE III: glacial Lake Liard (GLL) still-stand elevation approximately 720 m. **D.**
1570 PHASE IV: glacial Lake Liard (GLL) still-stand elevation approximately 620 m. **E.**
1571 PHASE V: glacial Lake Liard (GLL) still-stand elevation approximately 540 m. **F.**
1572 PHASE VI: glacial Lake Liard still-stand elevation approximately 460 m. **G.** PHASE
1573 VII: glacial Lake Liard (GLL) and glacial Lake Fort Nelson (GLF) still-stand elevation
1574 approximately 450 m. **H.** PHASE VIII: glacial Lake Liard (GLL) and glacial Lake Fort
1575 Nelson (GLF) still-stand elevation approximately 440 m. **I.** PHASE IX: glacial Lake
1576 Liard (GLL) and glacial Lake Fort Nelson (GLF) still-stand elevation approximately 430
1577 m. **J.** PHASE X: glacial Lake Liard (GLL) and glacial Lake Fort Nelson (GLF) still-stand
1578 elevation approximately 420 m. **K.** PHASE XI ($13.0 \pm 0.5 \text{ ka}$): glacial Lake Liard (GLL)
1579 and glacial Lake Fort Nelson (GLF) still-stand elevation approximately 380 m. **L.**
1580 PHASE XII: Liard and Fort Nelson spillways approximate surface elevation 320 m,
1581 draining into glacial Lake Mackenzie. **M.** PHASE XIII: modern drainage network
1582 established, less than 300 m elevation. MG – Montane glaciers; CIS – Cordilleran Ice
1583 Sheet; LIS – Laurentide Ice Sheet; CG – cirque glaciers.

1584

1585

1586

List of Tables (Huntley et al. 2016)

Table 1 Sample depths, K, U and Th contents, and water content.

¹ d : sample depth beneath the ground surface

² K, U, and Th contents found using neutron activation analysis (NAA) of a dried and milled subsample of the bulk material sampled for dating

³ Δ^w : water content (water mass) / (mineral mass); for each sample, the average of the as-collected and saturated water contents was used, with an uncertainty that is thought to account for any reasonable variation at 2σ

Table 2 Dose rates, equivalent doses, and optical ages

¹ Dose rate, D_c due to cosmic rays, calculated using present burial depths and the relationship of Prescott and Hutton (1994)

² Total dose rates, D_T (that due to cosmic rays plus that due to α , β , and γ radiation); for α radiation, only an internal dose rate applies and an estimate of 0.03 Gy/ka was used (e.g., Olley *et al.* 2004)

³ Equivalent doses, D_e found using the central age model

⁴ Apparent optical ages and their analytical uncertainties at $\pm 1\sigma$

Tables (Huntley et al. 2016)

Sample	Location	d (m) ¹	K (%) ²	U (μg/g) ²	Th (μg/g) ²	Δ^w ³
BRD-01	N59° 49' 41"	0.70	1.31 ± 0.07	1.78 ± 0.13	4.89 ± 0.17	0.16 ± 0.02
	W124° 25' 35"					
BRD-02	N59° 49' 38"	0.70	1.39 ± 0.06	2.07 ± 0.15	5.27 ± 0.18	0.15 ± 0.02
	W124° 25' 42"					
BRD-03	N59° 49' 45"	1.00	1.41 ± 0.06	2.08 ± 0.16	5.15 ± 0.18	0.16 ± 0.02
	W124° 25' 26"					

Table 1 Sample depths, K, U and Th contents, and water content.

¹ d : sample depth beneath the ground surface

² K, U, and Th contents found using neutron activation analysis (NAA) of a dried and milled subsample of the bulk material sampled for dating

³ Δ^w : water content (water mass) / (mineral mass); for each sample, the average of the as-collected and saturated water contents was used, with an uncertainty that is thought to account for any reasonable variation at 2 σ

Sample	D_c (Gy/ka) ¹	D_T (Gy/ka) ²	D_e (Gy) ³	Optical age (ka) ⁴
BRD-01	0.186 ± 0.009	1.93 ± 0.13	26.5 ± 0.5	13.7 ± 0.9
BRD-02	0.186 ± 0.009	2.11 ± 0.13	26.6 ± 0.4	12.6 ± 0.8
BRD-03	0.176 ± 0.009	2.09 ± 0.13	26.6 ± 0.6	12.7 ± 0.8

Table 2 Dose rates, equivalent doses, and optical ages

¹ Dose rate, D_c due to cosmic rays, calculated using present burial depths and the relationship of Prescott and Hutton (1994)

² Total dose rates, D_T (that due to cosmic rays plus that due to α , β , and γ radiation); for α radiation, only an internal dose rate applies and an estimate of 0.03 Gy/ka was used (e.g., Olley *et al.* 2004)

³ Equivalent doses, D_e found using the central age model

⁴ Apparent optical ages and their analytical uncertainties at $\pm 1\sigma$

A. Ice sheet retreat and proglacial lake phases

* Elevations are upper limits to glaciation ** Local base-level for meltwater drainage *** Approximate ages only

B. Erratics and ice flow indicators

Cordilleran provenance

- ▲ granodiorite
- ▲ quartzite
- ▼ dropstone

Laurentide provenance

- ▲ granite
- ▲ conglomerate

Ice flow indicators

- drumlins, flutes crag-and-tails
- striae, chatter marks, rat-tails, roches moutonnées

C. Facies codes and textures

- Fm silt and clay, massive
- Fl silt and clay, laminated
- Fd silt and clay, with dropstones

- Sm sand, massive
- Sp sand, planar-bedded
- Sr sand, ripple-bedded
- St sand, trough-cross-bedded

- Gm gravel, massive
- Gp gravel, planar bedded
- Gt gravel, trough-cross-bedded
- Bm boulder, massive

- Dmm diamicton, matrix-supported, massive
- Dms diamicton, matrix-supported, stratified
- Dcm diamicton, clast-supported, massive
- Dcs diamicton, clast-supported, stratified

Texture

- d mixed fragments
- b boulders
- g gravel
- s sand
- z silt
- c clay

D. Lithostratigraphic units and paleoflow indicators

- Organic
- Alluvial
- Eolian
- Colluvial

- Glaciolacustrine
- Glaciofluvial
- Laurentide till
- Cordilleran till
- Bedrock

Paleocurrent indicators

- Iceflow (Cordilleran)
- Iceflow (Laurentide)
- Meltwater drainage
- Katabatic wind