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Reconstructing the confluence zone between Laurentide and Cordilleran ice sheets along the Rocky Mountain Foothills, south-west Alberta

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Abstract

Landform mapping near the Athabasca valley was fundamental to determining whether or not the Late Wisconsinan Laurentide and Cordilleran Ice Sheets coalesced. In this paper we examine the detailed landform record using new LiDAR digital elevation and hillshade models of the area of confluence and eventual desuturing of these ice sheets. This work reveals an earlier more extensive Cordilleran advance prior to coalescence with the LIS. When the ice sheets coalesced, the flow pattern is dominated by ice flow along the mountain front, with Cordilleran ice flowing out of major trunk valleys but Laurentide ice flowing into the Foothills up smaller valleys. This flow pattern implies that when the ice sheets coalesced the CIS was already waning, or at least was not at its maximum. Deglaciation was interrupted by several re-advances, likely related to the destabilizing effect of proglacial lakes along the ice margin.

Key Words: LiDAR, Cordilleran, Laurentide, Ice Flow, Proglacial Lakes

Introduction

The Late Wisconsinan glacial history of the eastern Rocky Mountain Foothills has long been of interest because of its association with a potential human migration pathway along the mountain front (Johnston, 1933; Mandryk, 1996). Although an ice-free corridor would have existed between the Laurentide (LIS) and Cordilleran (CIS) ice sheets during buildup and retreat, most researchers now agree that ice sheet confluence and mutual deflection did occur along the Rocky Mountain Front during the Last Glacial Maximum (LGM) (Levson and Rutter, 1996; Jackson *et al.*, 1997; Dyke, 2004; Bednarski and Smith, 2007). The Athabasca River valley area of south-west Alberta was a key location in resolving this debate, since ice-flow indicators clearly demonstrate that a major Late Wisconsinan CIS outlet glacier emerging from the valley converged with the LIS and was deflected to the south-east (Fig. 1; Roed, 1975; Levson and Rutter, 1996). This south-easterly deflection of confluent ice flows is delineated by the dispersal pattern of lithologically distinctive glacially transported debris, which includes a train of metamorphic erratics originating west of the Rocky Mountains, and the Foothills erratics train which comprises Rocky Mountains derived quartzites that extends from the Athabasca Valley as far south as the international border (Stalker, 1956; Roed *et al.*, 1967; Jackson *et al.*, 1997).

However, although it is acknowledged that the LIS and CIS converged in south-west Alberta during the last glaciation, the glaciodynamic behaviour of these ice sheets, manifest by the pattern and timing of confluence and subsequent desuturing, remains uncertain. For example, previous portrayals of the Late Wisconsinan LIS and CIS feature a generalized flow reconstruction of the confluence zone of these ice sheets at the LGM (Dyke and Prest, 1987). Recent glacigenic sediment-landform mapping in southern Alberta indicates that temporal variations in ice flow configuration during the last glacial cycle are more complex than previously recognized (Ó Cofaigh *et al.,* 2010). This is further suggested by the recent identification of subglacial lakes, likely related to deglaciation as ice thinned (Livingstone *et al.,* 2016). Additionally, regional scale deglacial reconstructions based on the distribution of radiocarbon dates portray a simplified desuturing zone evolving rapidly along a narrow corridor extending the length of the Alberta portion of the eastern Rocky Mountain Foothills (Dyke *et al*., 2003; Dyke, 2004). Recent ice-sheet modelling suggests that the 'ice saddle' along the confluence zone of the LIS and CIS collapsed rapidly during deglaciation, potentially contributing to Meltwater Pulse 1A (MWP-1A) at around 14.5 ± 0.7 cal. ka (Gregoire *et al.,* 2012; Gomez *et al.,* 2015). During deglaciation, proglacial lakes formed along with the progressive latitudinal desuturing of ice sheet margins along the Rocky Mountain Front (St-Onge, 1972; Mathews, 1980; Dyke*,* 2004; Fenton *et al.,* 2013). These proglacial lakes temporarily stored and released water, and potentially affected glaciodynamics by triggering rapid ice flow due to bed lubrication and increased calving and drawdown (Evans, 2000; Stokes and Clark, 2004; Evans *et al*., 2012; Carrivick and Tweed, 2013).

Previous examinations of the interaction between the LIS and CIS in south-west Alberta were based on extensive field mapping and traditional airphoto interpretation (Boydell, 1970, 1978; Roed, 1975; Kvill, 1984). However, the recent availability LiDAR derived bare-earth digital elevation models (DEM) across this region now enables greater resolution landform identification to augment earlier mapping, particularly in areas of dense vegetation cover. Additionally, due to the potential influence of proglacial lakes on understanding late glacial ice sheet dynamics, LiDAR mapping provides the opportunity to reassess the extent and drainage history of previously mapped glaciolacustrine features in south-west Alberta (cf. St-Onge, 1972; Boydell, 1978).

In this paper, we utilize new mapping data to assess the competing influence of the CIS and LIS on the glacial history of south-west Alberta, and reconstruct the relative timing, pattern and behaviour of these confluent ice sheets during desuturing at the end of the last glaciation, particularly the role of meltwater storage and routing. The configuration of ice retreat might be used to place currently limited deglacial ages in a glaciological context, or guide site selection for future dating.

Regional setting

We focus on a 26,500 km^2 area of the Rocky Mountains Front Ranges and Foothills and the Benchlands and Plains between the Athabasca and Red Deer river valleys (Pettapiece, 1986; Fig. 1). To the west, the study area is bounded by the Front Ranges, which comprise NW to SE striking thrust sheets of Palaeozoic carbonate and clastic rock (Pană and Elgr, 2013). Higher grade metamorphic rocks occur along the western edge of the Rockies near the Rocky Mountain Trench (Fig. 1). The study area extends eastwards across the Foothills, a 40 km wide zone of more subdued topography comprising erodible Mesozoic strata with a NW to SE strike. The Foothills descend eastwards onto the Plains which contain isolated erosional remnant benchlands, such as Mayberne Tableland caped by Palaeocene gravels (Pană and Elgr, 2013).

The area is dissected by several prominent drainage systems, including the Athabasca, McLeod, Pembina, Brazeau, North Saskatchewan, Clearwater and Red Deer rivers (Fig. 1). The headwaters of these rivers are largely bedrock controlled, flowing along strike (NW-SE) within relatively narrow valleys until they emerge from the mountains and flow north-eastwards down the regional gradient within broader valleys (Osborn *et al.,* 2006).

Previous mapping identified complex ice sheet interactions along the mountain front. For example, although coalescent LIS and CIS flow patterns were identified in the Athabasca (Roed, 1975) Brazeau (Kvill, 1984) and North Saskatchewan valleys (Boydell, 1978), similar behaviour was not observed in the Sundre and Red Deer river valleys immediately south (Fig. 1; Boydell, 1970). Ice flow patterns within the coalescence zone have also been reconstructed based on the weathering, distribution and provenance of glacial deposits. Bayrock and Reimchen (1980) mapped extensive areas of leached till in the Foothills at elevations above 1500 m asl, and suggested these deposits were pre-Late Wisconsinan in age (Bayrock and Reimchen, 1977). Boydell (1972, 1978) used the same weathering criteria to propose that the Brazeau and Ram Ranges (Fig. 1), also above 1500 m asl, were similarly unglaciated during the Late Wisconsinan. Glacial deposits across the areas mapped by Boydell (1972; 1978) also lack the higher grade metamorphic rocks (garnet talcose schist) originating west of the continental divide (Fig. 1), considered diagnostic of transport by the CIS during full glacial conditions (Boydell, 1972; 1978). Such erratics are also absent from the upper reaches of the North Saskatchewan valley (McPherson, 1970). These rocks do occur within the Athabasca Valley erratics train emerging from the Athabasca River valley, which is deflected south along the mountain front at least as far as the North Saskatchewan River valley (Roed *et al.*, 1967). The western limit of the LIS is demarcated by Shield (granite) erratics, mapped in the northern portion of the study area by Roed (1975; Fig. 2).

Methods and data sources

Uninterpreted glacial landform data were presented by Atkinson *et al.* (2014a and b). Glacial lineations, moraines, crevasse-fill ridges, meltwater channels and eskers were manually identified and mapped from 1 and 5 m resolution LiDAR digital elevation models (DEM; CGVD28 vertical datum) using criteria listed in Table 1 (also see Fig. 2). We have extended this mapping to include deltas, esker-fan deltas, hummocky moraine and kames. Meltwater channels have also been genetically classified (ice-marginal or proglacial) using standard criteria (e.g. Greenwood *et al.,* 2007; Table 1). These data were used to reconstruct the temporal evolution of ice-flow patterns across the region based on the flowset approach. In this procedure, glacial lineations are generalized into flowlines as a method of simplification. These flowlines are amalgamated into glaciologically coherent groups (flowsets) that are interpreted to have formed during the same flow phase based on similarities of morphology, length and parallelism (e.g. Clark, 1997, 1999; Livingstone *et al*., 2008; Greenwood and Clark, 2009; Hughes *et al.,* 2014).

In the study area some flow features represent partially eroded or palimpsest features and portions of some flows have been buried by glaciolacustrine sediment. Thus only patches or segments of a flowset might be preserved. Also, flows out of valleys (for example Cordilleran ice flow) might be represented by only a few bedforms because of their limited lateral extent. These were classified as "flowset components", which are interpreted as fragments of a complete flowset due to erosional and postglacial depositional gaps in the flowset record. The surface morphology of glacial lineations within flowset components were then classified as either; sharp (sharp-crested), subdued (smooth-crested, possibly draped), or unclear (likely due to later subglacial reworking). Ice-flow direction was inferred from crag-and-tails, as well as marginal features such as moraines, ice-marginal meltwater channels and beaded eskers. The directionality of beaded eskers was determined by the position of fan-deltas that indicate water flow into a proglacial lake.

Proglacial lakes formed extensively across Alberta because the LIS retreated down the regional gradient, blocking drainage and promoting the accumulation of water within a succession of ice impounded basins (St-Onge, 1972; Mathews, 1980; Fenton *et al.,* 2013). Lake levels were controlled by the elevation of spillways or outlets. As the LIS continued to retreat north-eastward, lakes would have enlarged, and progressively lower outlets would have been exposed, allowing the lake to drain to lower elevations. By identifying outlets and determining their elevation, the configuration of proglacial lakes and the associated pattern of ice retreat could be determined (e.g. Jansson, 2003; Stokes and Clark, 2004). Spillway elevations were determined from the DEM, which was then flooded to that elevation (Fig. 3A). The lake extent was estimated from local topography and an inferred ice marginal position above the next lower spillway (Fig. 3B). Time-slices for a succession of ice marginal positions and proglacial lake configurations were then produced by repeating this process for the elevation of progressively lower spillways (Figs 3C and 3D). Although topographic flooding with a horizontal water surface does not incorporate differential uplift, its influence is considered negligible for this study since these lakes had a limited aerial extent, and the pattern of ice retreat for each lake configuration time-slice typically parallels the regional isobases (Dyke, 1996).

Flowset mapping

We identify 24 flowset components in the study area (Table 2, Fig. 4), which are subdivided into 3 stages based on cross-cutting relationships and elevation ranges. Thirteen flowset components are attributed to the CIS, and 11 to the LIS (Table 2).

Stage 1

The oldest flowset components (FSc-2, 6, 8, 13 and 19; Fig. 4) comprise NW-SE oriented glacial lineations that extend obliquely across the regional topographic gradient. Morphologically, they were all classified as unclear, and have all been overridden (Table 2, Figs 5D and E). Flowset components in the northern half of the study area (FSc-2, 6, 8, 13) generally parallel the strike of the mountains, raising the potential they relate to underlying bedrock structures. However, the southern lineations (FSc-19) do not parallel strike and are therefore considered to be glacigenic features. Glacial lineations also included with this stage are oriented west-east and occur at high elevations along the flanks of the Brazeau valley (FSc-12; at 1680 m asl; Figs 6 and 7). These landforms are included in Stage 1 because they have a different orientation and are higher than Stage 2 features.

Stage 2

A flow pattern can be traced along the mountain front, from the Mayberne Tableland to the North Saskatchewan valley (FSc-3, 5, 7, 9, 15), which then arcs south-westward (Fig. 4; FSc-21, 24). Cordilleran ice flowing out of the Athabasca valley (FSc-10) met Laurentide ice flow (FSc-3, 9) at an oblique angle, and was deflected to the south (Fig. 8). The boundary between these two flows is marked by a series of medial moraines (Fig. 8B), part of which coincides with the western limit of shield erratics mapped by Roed (1975; Fig. 2). Convergent Cordilleran and Laurentide ice flows extended south-east along the mountain front and merged with a major Cordilleran outlet glacier emerging from the North Saskatchewan valley (FSc-17).

While easterly oriented ice flow features emerge from the Athabasca and North Saskatchewan valleys, westerly oriented lineations curve towards the mountains and extend up smaller valleys (FSc-9, 10, 21, 24). These include low relief (<1–2 m) lineations along the McLeod (Figs 8 and 8A; FSc-10), Pembina (Figs 9 and 9A; FSc-9), Brazeau (Figs 7 and 7B; FSc-9), and Clearwater (Figs 6 and 6B; FSc-21) river areas. Directionality is determined from crag-and-tails indicating a SSW flow in the Pembina valley at 1430 m asl (Fig. 9A). Moreover, a pattern of subtle east-west oriented moraines in the Mercoal area likely relates to marginal positions of ice retreating to the north (Fig. 8A; FSc-10). In the south, FSc-21 and 24 terminate at ice marginal channels, near the Clearwater and Red Deer rivers, respectively.

There is a general concordance in the elevation of ice marginal features at ~1440 m asl, with associated glacial lineations at lower elevations. For example, in the McLeod River area, the highest moraine occurs at 1440 m asl, while ice stagnation features on the Brazeau Piedmont extend up to 1450 m asl (Fig. 6A). Kame terraces on the south side of the Brazeau valley occur up to 1445 m asl (Fig. 7B). Contemporaneous features occur at lower elevations towards the southern part of the study area, such as near the Clearwater River, where ice-marginal meltwater channels occur at 1370 m asl, and near the Red Deer River at 1350 m asl.

Stage 3

A prominent south-west oriented flow pattern in the Baptiste River area comprises glacial lineations (FSc-14, 16) that cross-cut Stage 1 (FSc-19) and Stage 2 (FSc-15, 19, Fig. 10B) landforms. This flow terminates at a meltwater channel at 1200 m asl (Fig. 10). Glacial lineations within this flow are overlain by crevasse-fill ridges (Fig. 10B).

In the North Saskatchewan valley area near McGregor Lake, potential palimpsest drumlins relate to an earlier eastwards ice-flow (FSc-17). These drumlins were subsequently reworked by northwards flowing ice (FSc-18, Fig. 10A). Unlike in the Obed or Baptiste River areas (Fig. 1), there is no obvious terminal position for this ice flow.

FSc-4 initiates within valleys on the southern flank of the Mayberne Tableland and extends south-westwards, across FSc-3. The north-east portion of this flow is flanked for 7.5 km by smoothed to hummocky bedrock and hill-hole pairs (Fig. 5B). The eastern boundary of this flow is sharply demarcated by a shear moraine (Fig. 5C). Discontinuous, recessional moraines lie perpendicular to the glacial lineations (Fig. 5D).

In the Obed area, glacial lineations (FSc-1, Fig. 11D) that cross cut older features (FSc-10), terminate at a discontinuous moraine (Obed ice re-advance moraine; Fig. 11). Similarly, lineations extending north-east from the Athabasca River terminate at a series of arcuate moraines (Fig. 11A). The Emerson Lake esker terminates near this position in the Athabasca valley (Fig. 11B), and likely debauched into a glacial lake based on the fan-delta at its north-east end.

Proglacial Lake Reconstructions

Many of the valleys in the study area contained proglacial lakes impounded against the retreating margins of the CIS and LIS. Sixty-two lake phases were mapped within this widening desuture zone across the study area during regional deglaciation (Fig. 12, Table 3). In general the lakes are larger in the north and east, compared to near the mountain front.

Our proglacial lake reconstructions are generally consistent with the distribution of glaciolacustrine deposits mapped by Roed (1970) and Boydell *et al.* (1974). Exceptions include the larger expanses of proglacial lakes draining through the Bingley (Fig. 6) and Lloyd (Fig. 2) meltwater channels, as well as proglacial lakes in the Brazeau valley that had not previously been mapped (cf. Bayrock and Reimchen, 1980; Fenton *et al.*, 2013). These discrepancies might be because proglacial lakes in this part of the study area were too short-lived to accumulate significant glaciolacustrine deposits, or such sediments were overlooked during pre-LiDAR mapping due to thick forest cover and limited accessibility.

A proglacial lake record is preserved in the Clearwater River area (Fig. 6), where five outlets of Glacial Lake Caroline were identified by Boydell (1978) at progressively lower elevations, including: the Crammond I (1105 m asl), Crammond II (1060 m asl), Kevisville (~1020 m asl), Stauffer (990 m asl) and Lasthill (980 m asl) channels. We could not find the geomorphic imprint of the Lasthill channel. Significantly, the Stauffer channel is deflected around the south-west end of the Evergreen moraine (Fig. 6), orthogonal to the easterly sloping topographic gradient, suggesting the moraine marks an ice marginal position that blocked the eastward drainage route. We also identified a previously unmapped channel at Bingley, which initiates at 975 m asl in the north and follows an arcuate path for approximately 60 km (Fig. 6). This channel cuts through the Evergreen moraine, suggesting Laurentide ice had retreated to the east by the time this drainage route was established.

Along the Pembina River, beaded eskers associated with multiple flat-topped fan-deltas record the north-eastward retreat of a lobe of Laurentide ice and progressive lowering of a proglacial lake impounded in this valley (Fig. 9B). Similar fan-deltas at esker termini are used to correlate eskers with outlets and lake levels (Table 4). Prominent features include the Thunder Lake esker, which records the development of a proglacial lake between the retreating margins of the CIS and LIS in the Brazeau River valley at 1405 m asl (Fig. 7A). Additionally, the flat topped portion of the eastern end of the Emerson Lake esker (Roed, 1975) is interpreted to be a fan-delta (Fig. 11B), which coincides with the elevation of the base of the prominent Sundance Creek meltwater channel (1030 m asl), along the south-west Swan Hills. Terraces on the channel flanks (up to 1110 m asl; Fig. 11C) give a maximum elevation of a lake draining through this channel. Moraines adjacent to the channel (Fig. 11C) document the position of successive ice margins while water drained through the channel, otherwise water would have drained to the south down the topographic gradient.

Glacial Reconstruction

The configuration of flowsets, proglacial lakes and ice marginal positions allows us to reconstruct the glaciodynamic history of the Cordilleran and Laurentide ice sheets in this part of south-west Alberta.

Stage 1 - Early extensive Cordilleran ice

The earliest glacial event preserved in the landform record of this region involved an extensive advance of topographically unconstrained Cordilleran ice (Fig. 13A). This advance is recorded by south-east oriented glacial lineations (FSc-2, 6, 8, 13, 19), which are cross-cut by a later LIS flow (FSc-5, 7, 9), as well as glacial lineations (FSc-9, 15, 21, 24) on summits near the mountain front (i.e. McLeod, Brazeau, Pembina, and Clearwater areas). Unlike subsequent CIS flowsets, the earliest Cordilleran ice flows do not exhibit any convergence with Laurentide ice advancing from the north. An early advance of the CIS has been documented by weathered tills (sourced from the Rocky Mountains) on the summits of the Brazeau Range (Boydell, 1978) and the distribution of Rocky Mountain derived quartzite erratics, 30-40 km east of the previously mapped Late Wisconsinan limit of coalescent Cordilleran and Laurentide ice flow (Boydell *et al.,* 1974; Roed, 1975; Fig. 2). However, our landform mapping suggests that at some point Cordilleran ice extended at least 60 km further onto the plains, 150 km from the mountain front.

The relative age of Stage 1 was determined by cross cutting relationships. We have found no geomorphic record of a gradual shift in flow direction from Stage 1 to 2, nor is it clear if there was an intervening ice-free interval, or if there was a rapid shift in ice flow patterns during a single glaciation. While these features are undated, previous work within the region provides a range of age possibilities. A pre-Late Wisconsinan age for the leached, high elevation tills was proposed by Boydell (1972, 1978). Moreover, high elevation erratics in the Rocky Mountains west of the study area have also been correlated with earlier glaciations (Levson and Rutter, 1996; Gadd, 2003). About 450 km to the south, Barendregt *et al.* (1991) used paleomagnetism on a stack of multiple Cordilleran tills to suggest that the oldest was possibly Pliocene in age. A pre-Late Wisconsinan, extensive Cordilleran advance was suggested by Moran (1986) in the Calgary area, about 300 km to the south. However, 500 km to the north-west Bednarski and Smith (2007) used cosmogenic nuclide dating to show that a pre-coalescent, extensive Cordilleran ice flow was likely Late Wisconsinan in age, although this doesn't preclude an earlier advance. Moreover, recent glacial reconstructions (e.g. Gregoire *et al.,* 2012; Gowan *et al.,* 2016) show thick ice over the study area during the LGM, which would rule out a pre-late Wisconsinan age for the leached tills. Further work is needed in the study area to assign Stage 1 an numerical age.

Stage 2 - Flow towards the mountains and deglaciation

The configuration of the CIS and LIS in Stage 2 is characterised by Cordilleran ice, flowing out of the Athabasca (FSc-10) and North Saskatchewan (FSc-17) valleys, which converged with south-easterly flowing Laurentide ice (FSc-5, 9). These convergent flows were mutually deflected south-eastwards along the mountain front (FSc-9, 15). The position of the confluence zone near the Athabasca valley is marked by medial moraines, which coincide with the western limit of Laurentide erratics (Figs 2 and 8). This erratic limit suggests Laurentide ice only reached the area after Cordilleran ice had already flowed out of the Athabasca valley, otherwise Shield erratics might have been deposited further west.

Although the main trajectory of the deflected ice flow was south-eastward along the mountain front, some ice also extended back towards the mountains along smaller valleys (i.e. McLeod, Brazeau, Pembina, and Clearwater, Fig. 13B). These ice flow patterns suggest that montane glaciers had already retreated from these valleys, or were thin enough to be overwhelmed by late stage Laurentide flows from the east. This Laurentide incursion reached similar elevations (~1440 m asl) in the northern valleys (i.e. McLeod, Brazeau, and Pembina), and progressively lower elevations in the Clearwater valley further south. The elevational consistency suggests these incursions relate to contemporaneous flows from the gently southward sloping LIS margin that trimmed the eastern flank of the Rocky Mountain Foothills.

Our work shows that during Stage 2, Laurentide ice flowed along the McLeod, Brazeau, Pembina, and Clearwater valleys. In these valleys, the LIS likely abutted Cordilleran ice based on the absence of intervening lakes, but areas above ~1450 m asl were potentially ice free during this stage. These areas correspond with the more eroded tills of Boydell (1972; 1978), suggesting that there were intervals of ice free conditions between the LIS and CIS in places along the Foothills and Front Ranges of the Rocky Mountains. Further dating of these surfaces might confirm this interpretation.

In the Baptiste (Figs. 13d), Mayberne Tableland (Fig. 14A) and Obed (Fig. 14B) areas, Laurentide and Cordilleran ice lobes experienced late glacial re-advances. The close association of these re-advances with ice-dammed lakes suggests that the lakes may have played a role in inducing ice marginal instability during regional deglaciation. Proglacial lakes and ice instability are well documented in other regions, where changes in porewater pressure and increased calving are thought to relate to surges or ice streaming (e.g. Sharpe and Cowan, 1990; Stokes and Clark, 2004; Evans *et al.*, 2012). Additionally, proglacial lakes can enhance melting leading to further glacier mass loss and increasing the flux of meltwater (Carrivick and Tweed, 2013).

Stage 3 –Deglaciation

Ice flow patterns during deglaciation were strongly influenced by the glaciodynamic effects of desuturing between the CIS and LIS. The pattern is discernible primarily from proglacial lakes, since the distribution of moraines and stagnant ice deposits is limited. For example, progressively lower proglacial lakes formed in the North Saskatchewan and Ram river valleys as deglaciation progressed. These lakes drained through meltwater channels between 1355 and 1240 m asl across the northern Brazeau Piedmont (Fig. 10). This succession of channels likely records recession of a lobe of Laurentide ice impounding a lake in the North Saskatchewan and Ram river valleys. Phases of this lake relate to glacial lake sediments and pitted deltas in these valleys (Fig. 10). The lowest these lake phases decanted through the North Prairie Creek meltwater channel (Fig. 5), into an early stage of Glacial Lake Caroline (Fig. 13C). This channel merges downstream with the Strachan meltwater channel (cf. Boydell, 1978), which likely flowed into the Crammond II phase of Glacial Lake Caroline since it terminates at the same elevation (1060 m asl) as that lake's outlet (Fig. 6). The ice margin for this lake level is estimated to have been between the head of the North Prairie Creek channel and the flat topped terminus of the Cow Lake esker (Fig. 6).

Although the earliest phases of Glacial Lake Caroline could have been dammed by Laurentide ice to the north-east (e.g. Fig. 13C), the topography requires an ice dam on both the south and north sides of this basin during the enlarged Stauffer phase (Boydell *et* *al.*, 1974; Fig. 13D). To the south, this ice margin is delineated by the Evergreen moraine which related to ice flow from the south-east (FSc-20). To the north, ice flow is recorded by glacial lineations in the Baptiste River area (FSc-16). Based on cross-cutting relationships and bedform elevation (features are limited to 1200 m asl), FSc-16 is younger than FSc-15, and likely occurred as a surge into Glacial Lake Caroline.

As ice retreated on the southern side of Glacial Lake Caroline (Fig. 13D), the Bingley meltwater channel (Fig. 6) opened, causing the lake to drain. However, a lower basin would have been exposed as the LIS continued to retreat north, enabling a lower lake stage to form, which continued to drain through the Bingley meltwater channel (Fig. 12). There are no lower channels in this part of Glacial Lake Caroline, although a sequence of progressively lower meltwater channels are present to the north-east. These include the Lloyd meltwater channel (~950 m asl) 50 km to the north-east (Fig. 2), and an unnamed channel at ~820 m asl further to the north-east (Andriashek *et al.*, 1979). Collectively, these meltwater channels document a locally extensive proglacial lake that experienced successive lowering's associated with large drainage events (Fig. 12) during the north-east retreat of the LIS.

As Laurentide ice, extending westwards along the Pembina and Brazeau valleys, began to retreat towards the Plains, it left imprints of proglacial lakes in the valleys. In the Pembina valley, the most westerly (earliest) fan-delta (1414 m asl; Fig. 9B) was deposited into a lake that drained southwards through the Crooked Creek valley forming terraces (1420 m asl), en route to the Brazeau Valley to the south (Fig. 9). A subsequent lake stage at 1380 m asl is recorded by a fan-delta further to the east (Fig. 9B). However, this lake stage would have been too low to drain through the Crooked Creek valley and no outlets relating to its drainage have yet been mapped. Potentially this lake level drained along or across the ice margin without leaving a geomorphic imprint.

The landform record in the Brazeau valley not only supports the interpretation of Laurentide ice flow and meltwater drainage towards the mountains, it also reveals the pattern of westward retreat of the CIS. Easterly subglacial drainage under Cordilleran ice in the Brazeau Valley is recorded by the Thunder Lake esker, which terminates at a fan-delta (1400 m asl; Fig. 7A). The surface of this delta occupies a similar elevational range as an abandoned outlet channel to the south-east (1385-1405 m asl; Fig. 7B), suggesting both features relate to the same proglacial lake level. However, as the LIS continued to retreat to the north, this lake progressively drained through successively lower meltwater channels formed along its margin (Fig. 7).

We suggest glacial lineations from the Mayberne Tableland (FSc- 4) region formed during a late stage of deglacial ice flow when a proglacial lake became dammed in the Edson area (Fig. 14A). The sharp eastern boundary of this flowset is interpreted as a shear moraine formed between more rapidly flowing ice within the flowset and slower moving ice along its flank (Stokes and Clark, 2002). Angular hill-hole pairs at the northern end of this flowset likely correspond to where the faster flow initiates.

Glacial Lake Miette (St-Onge, 1972) was impounded in the Athabasca River valley by the LIS to the north-east; geomorphic indicators and stratigraphic data suggest the lake was also impounded by the Obed re-advance of the CIS to the south-west (Roed, 1975) (Fig. 14B). The lake's outlet was the Sundance Creek meltwater channel, which drained into Glacial Lake Edson at the Edson delta (St-Onge, 1972; Roed, 1975) (Fig. 14B). Cordilleran ice must have abutted the Sundance Creek meltwater channel (marked by moraines on Fig. 11C), thereby preventing water from draining to the south. Based on their position and orientation, these moraines likely relate to the Obed re-advance of CIS as postulated by Roed (1975), based on the stratigraphic relationship of till overlying glaciofluvial outwash deposits. Additional geomorphic evidence for the Obed re-advance includes small lineations that cross-cut FSc-10. Furthermore, the Emerson Lake esker probably drained into Glacial Lake Miette (Fig. 11B), as the elevation of the fan-delta is similar to the Sundance Creek meltwater channel, further suggesting the Obed re-advance was positioned at the margin of Glacial Lake Miette. Collectively, these landform associations suggest that Glacial Lake Miette was contemporaneous with the Obed re-advance. Glacial Lake Miette finally drained along ice marginal channels when Laurentide ice had retreated north-eastwards down the Athabasca Valley (Utting, 2013).

Our work confirms that meltwater accumulated in a succession of spatially and temporally transgressive proglacial lakes within the desuturing zone of the Cordilleran and Laurentide ice sheets. In some cases, these lakes were relatively extensive (Fig. 12). Ice sheet modelling simulations also suggest rapid melting occurred in the desuture zone of the LIS and CIS, which resulted in a meltwater pulse to the oceans – a process termed saddle-collapse (Gregoire *et al.,* 2012; Gomez *et al.*, 2015). However, the volume and drainage history of these lakes is insufficient to explain a eustatic sea level equivalent rise of ~10 m in <500 years (cf. Gomez *et al.,* 2015). The loss of ice between Stage 1 and Stage 2 could have contributed a substantial volume of water to the oceans, although the timing of this, if it occurred, is unknown. Similarly, while these lakes would have accelerated thermally induced melting and ice marginal retreat, creating a positive feedback that could enhance ice saddle drawdown, geomorphic indicators suggest that these processes occurred progressively along the desuturing zone throughout the last deglaciation of south-west Alberta.

Conclusions

We examined the landform record in an area of complex former ice flow within the confluence zone of the Cordilleran and Laurentide ice sheets. The landform record of this area has represented a key line of evidence in recognising the confluence and mutual deflection of the Late Wisconsinan Laurentide and Cordilleran ice sheets (Roed, 1975; Bednarski and Smith, 2007), although detailed evidence relating to the build-up, confluence and subsequence desuturing and retreat of these two ice sheets has hitherto remained uncertain.

Using a two pronged approach of flowset interpretation and reconstruction of former proglacial lake extents, we have recognized three distinctive glaciodynamic stages within the fragmentary and overprinted landform record of this area. The earliest of these stages is identified by flowset components consisting of lineations on the foothills and plains, and high flutings on the summits. These landforms are overprinted by younger flow-set components and document a stage of unconstrained flow of Cordilleran ice out onto the Alberta Plains which was significantly more extensive than previously recognised in south-west Alberta. Although establishing the numerical age of this event was beyond the scope of the present study, this finding lends support to other reconstructions in the foothills (Moran, 1986; Bednarski and Smith, 2007) which have previously recognized evidence of an extensive Cordilleran Ice Sheet developing prior to the arrival of the Laurentide Ice Sheet in the region.

The second glaciodynamic stage relates to Cordilleran ice flowing out of the Athabasca Valley and deflecting to the south-east upon encountering the Laurentide ice. The general pattern of flow identified in this study is broadly similar to that recognized by previous workers, however additional complexities have been revealed based on the examination of high-resolution imagery and bare-earth LiDAR imagery. We find evidence that the along-the-mountain-front-flow (FSc-9, 15, 21) moved up into some of the smaller valleys, which suggests that some areas west of this flowset were ice free during this time.

The third glaciodynamic stage is represented by the retreat of ice from the mountain front, which is manifested in the development of a sequence of proglacial lakes created by glacial ice blocking the regional drainage. Localized flow-set components demonstrate that overall ice sheet recession was interrupted by re-advances or surges, such as in Baptiste River (FSc-14, 16), North Saskatchewan River (FSc-18), Edson (FSc-4) and Obed (FSc-1) areas. All of these re-advances are closely associated with proglacial lakes, suggesting the lakes induced instability in the ice sheet.

The three phases of former ice-sheet flow documented by the geomorphological and proglacial lake extent record represent a framework for further ice sheet reconstruction studies. Another line of research expanding from the current study would be to establish the numerical ages of the flow-set components and associated proglacial lake stages within the LIS and CIS interaction zone. Such an approach is essential in order to more broadly investigate how proglacial lake drainages correspond with deglaciation events, including whether the drainage events involved are sufficient to account for rapid deglacial global sea level rises as invoked by recent ice sheet modelling simulations (Gregoire *et al.,* 2012).

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Figures and Captions

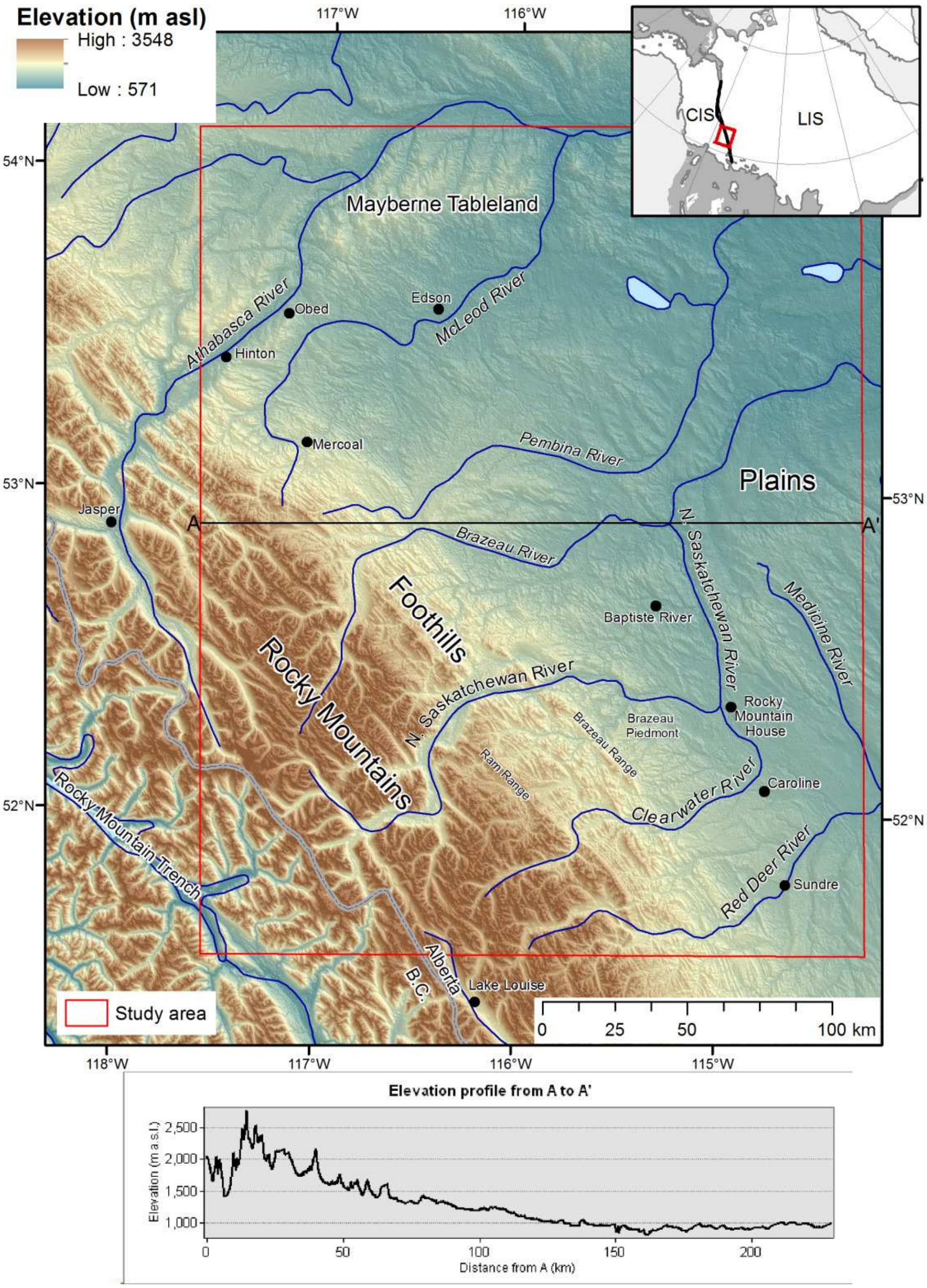


Figure 1. Study area location. Dashed line demarcates the border between Alberta and British Columbia, along the continental divide. Inset map shows the extent of the Laurentide and Cordilleran ice sheets at the Last Glacial Maximum (c.f. Dyke, 2004; Kleman *et al.,* 2010).

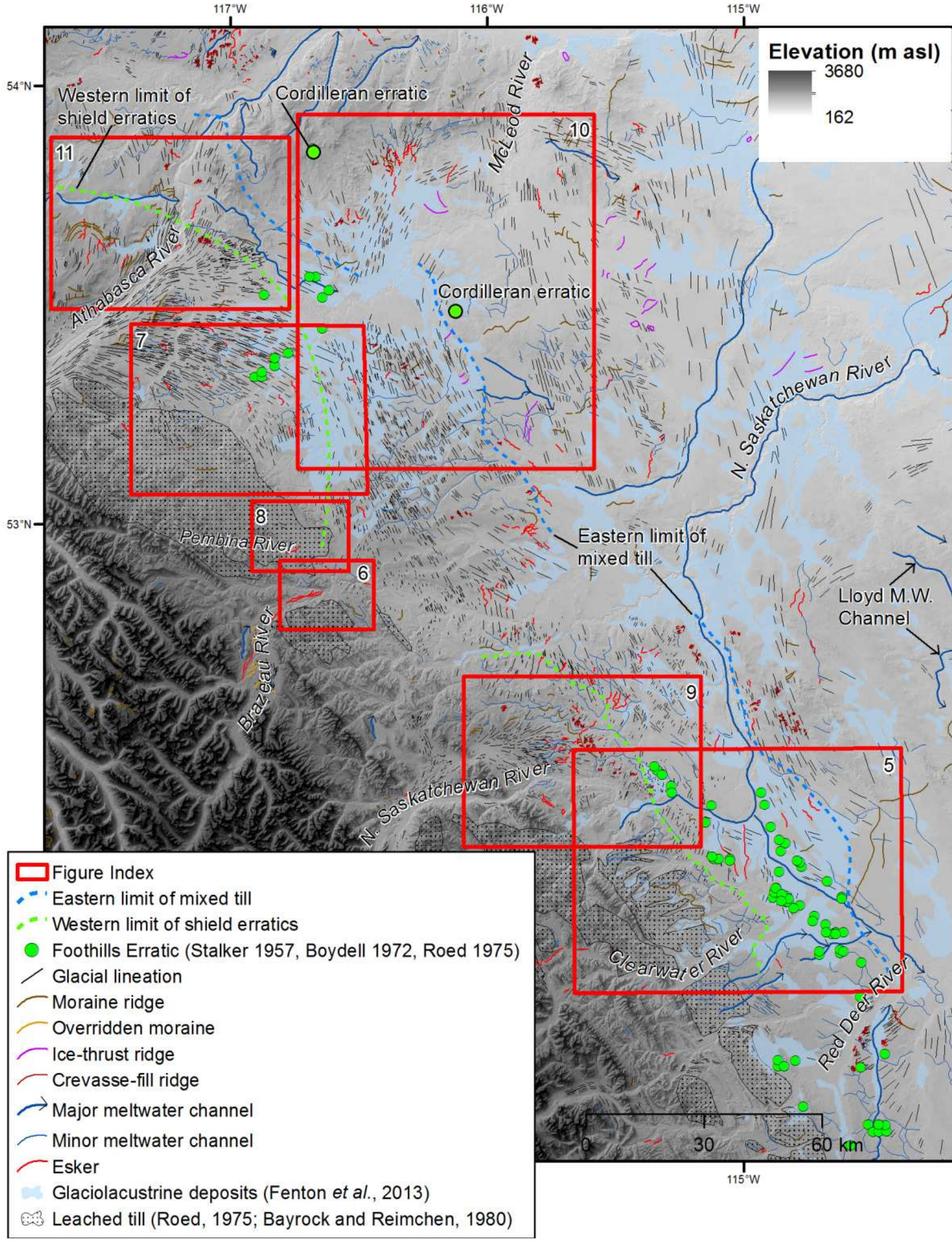


Figure 2. DEM of study area, with glacial landforms depicted after Atkinson *et al*. (2014a). Boxes indicate location of more detailed figures. Western limit of shield erratics and eastern limit of mixed till from Boydell *et al.* (1974) and Roed (1975). Areas of leached till generalized from Roed (1975) and Bayrock and Reimchen (1980).

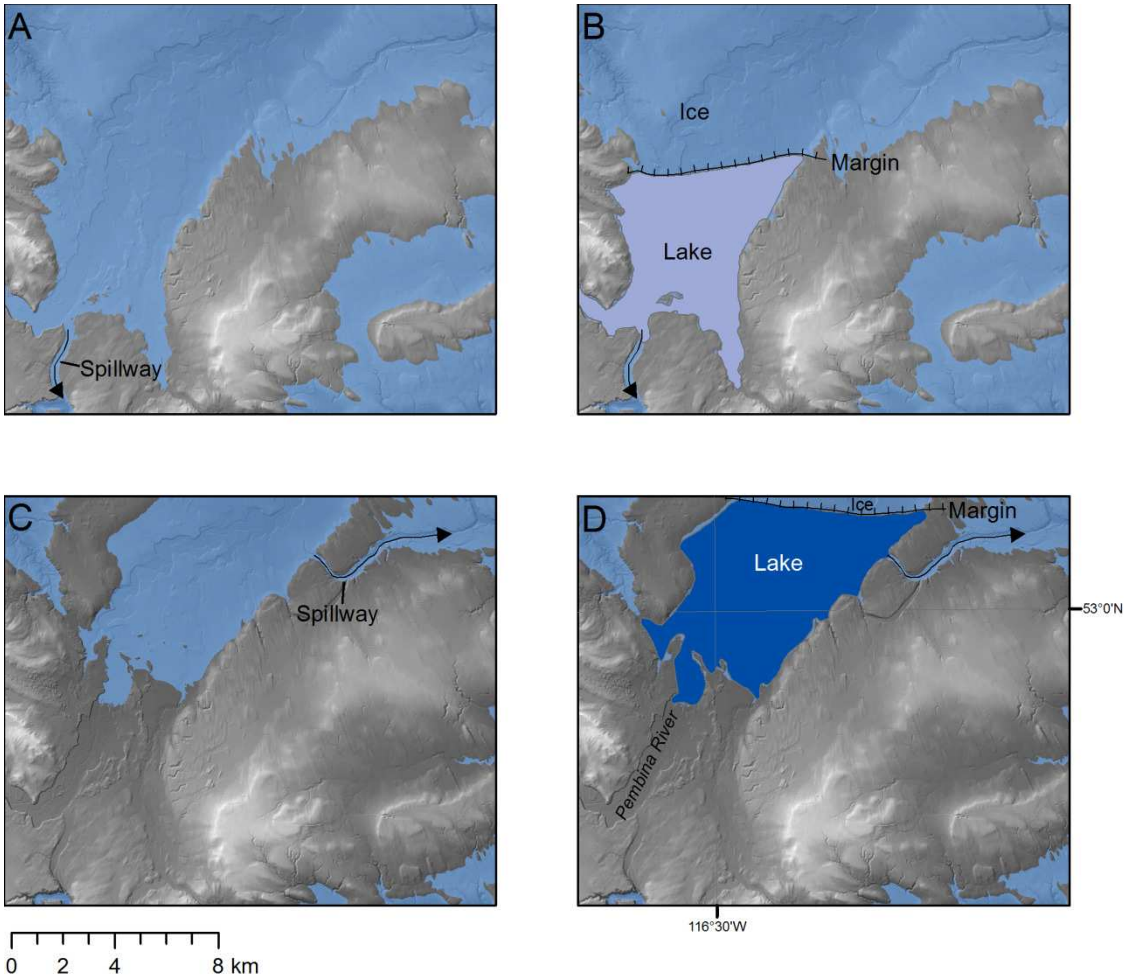


Figure 3. Method for reconstructing lake levels involved flooding the DEM to the level of a spillway (A), in this case 1305 m asl. The lake was digitized to the extent where it was contained within a basin (B). The next lower spillway was identified, and the DEM flooded to that elevation (C). The next lake was then digitized to a maximum extent within the basin blocking lower outlets by ice (D).

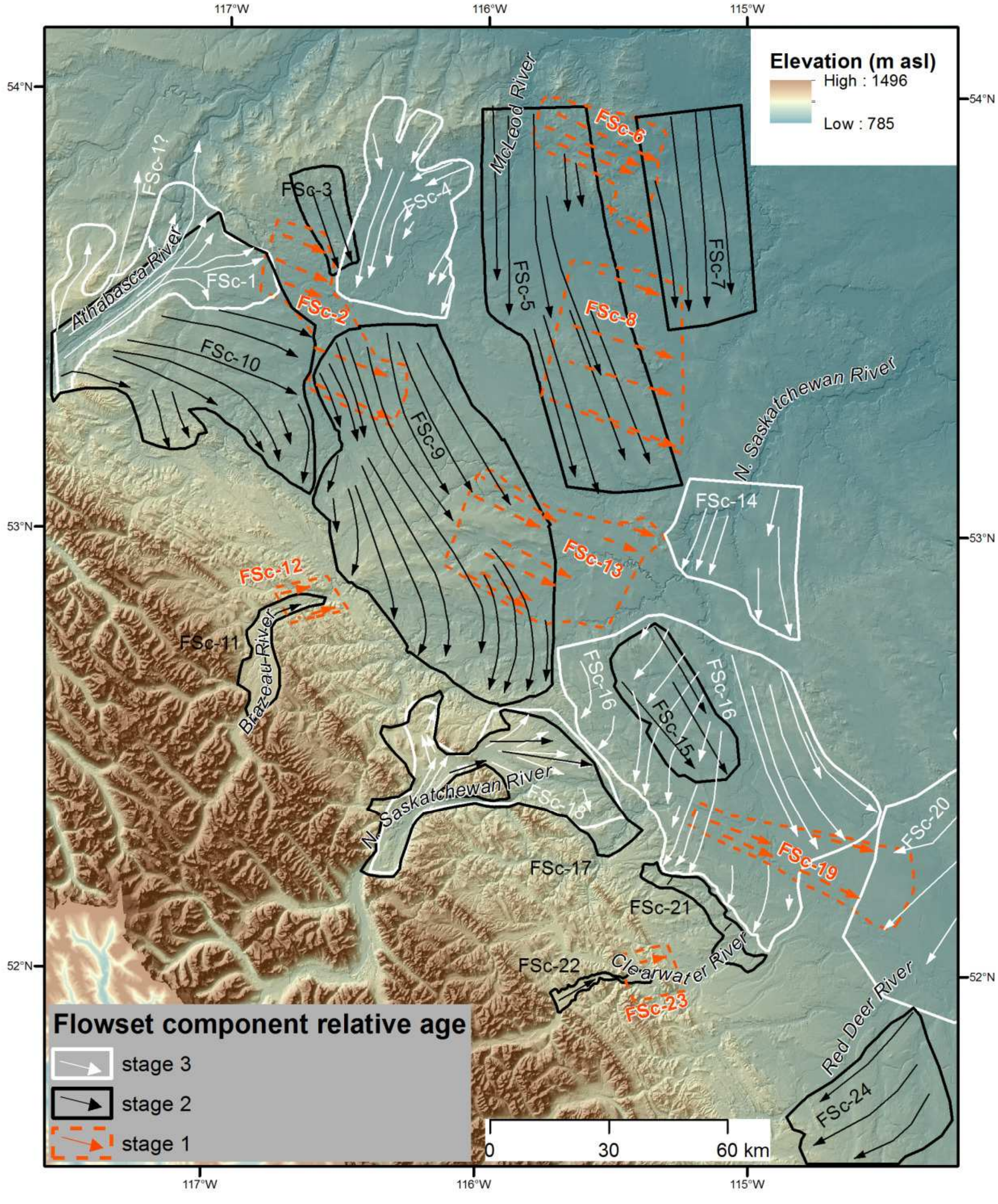


Figure 4. Patterns of glacial lineations grouped into flowset components (Table 2). The flowset components were given relative ages in the study area based on cross-cutting relationships, discussed in the text.

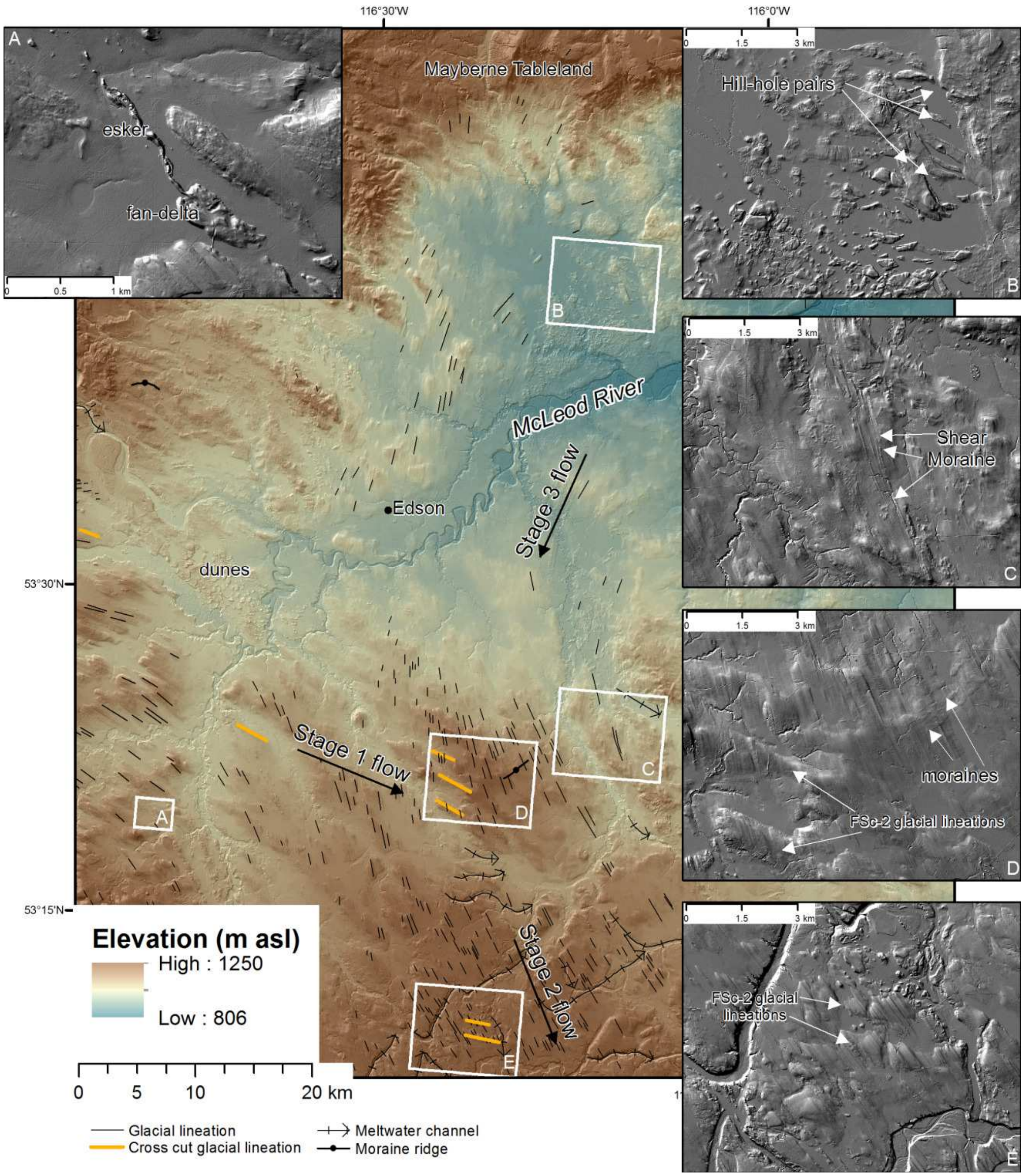


Figure 5. Glacial geomorphology of the Edson area, overlain on LiDAR bare-earth image. North-south Edson flow (FSc-4, Stage 3) merges with FSc-9 (Stage 2) from north-west near centre of image. Some earlier steamlined bedforms (FSc-2; Stage 1) have been cross cut by the north-south flow. Inset A shows an esker terminating at a fan-delta at 1020 m asl at its south-east end. Inset B is an example of hill-hole pairs along the margin of FSc-4. Inset C provides a detailed view of a shear moraine along the eastern boundary of FSc-9. Inset D shows the recessional moraines marking retreat of this flow pattern, as well as FSc-2 (Stage 1) glacial lineations, crosscut by FSc-9 landforms (Stage 2). Inset E shows further examples of the oldest features (FSc-2) trending WNW-ESE and crosscut

by FSc-9. The area on the main image marked “dunes” is the Edson delta of Roed (1970) and St-Onge (1972), which has been reworked by eolian processes, and relates to meltwater flow through the Sundance Creek outlet channel in Glacial Lake Edson.

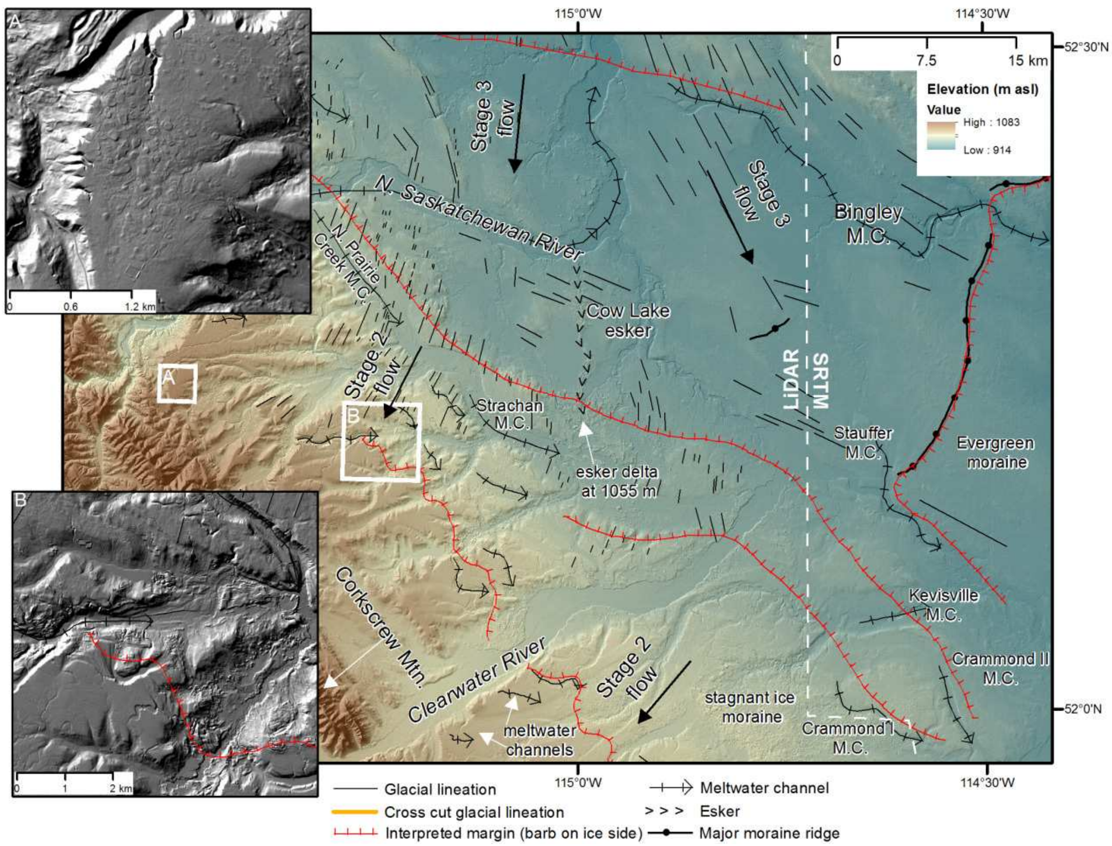


Figure 6. LiDAR bare-earth image and SRTM hillshade of Brazeau Piedmont and Clearwater River area (white dashed line indicates LiDAR coverage to the west). Ice stagnation features (Inset A) on the Brazeau Piedmont, suggesting ice at least to that position. FSc-21 (Stage 2) flowed towards the mountains in this area from the north-east (Inset B); ice marginal meltwater channels mark the ice retreat pattern in the south of the image. Inferred margins are based on the positions of the Crammond I, Crammond II, Kevisville, Stauffer, and Bingley meltwater channels, which drained Glacial Lake Caroline (Boydell 1978), as well as the orientation of ice flow features and eskers.

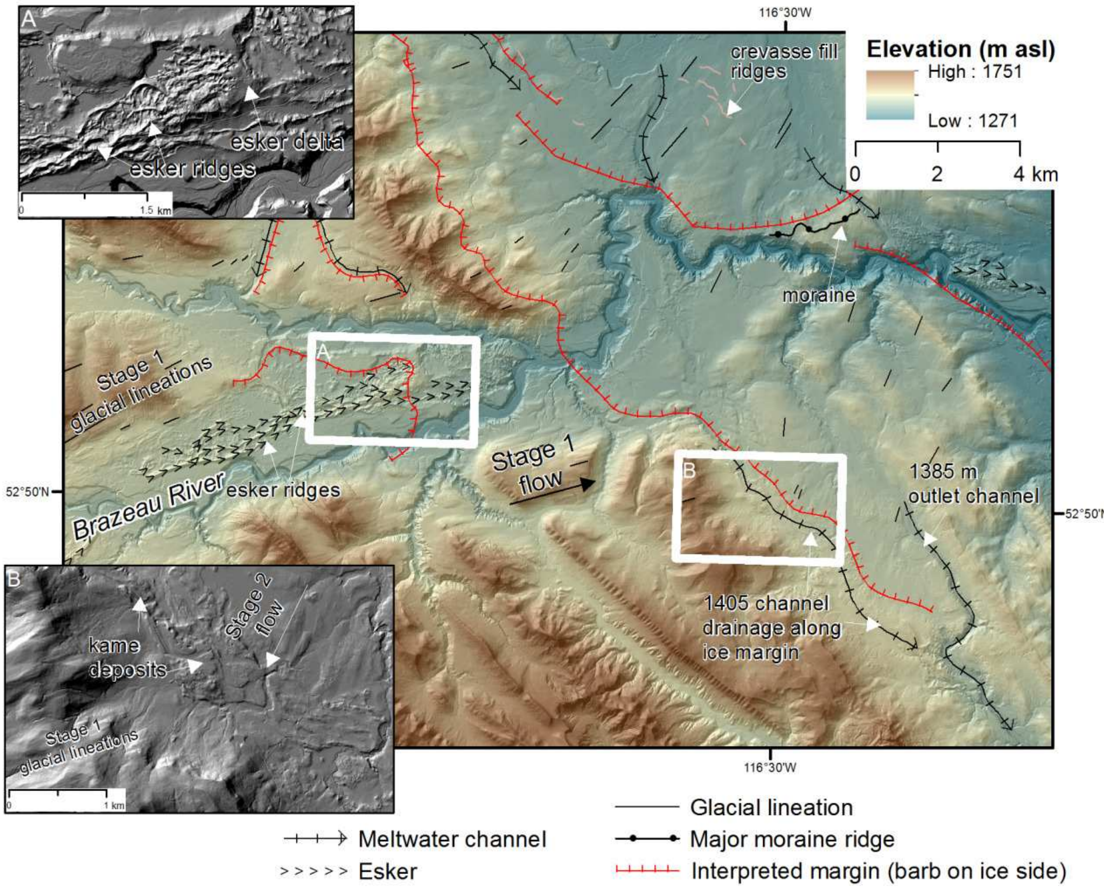


Figure 7. LiDAR bare-earth image of Brazeau River area. Flutings on the mountain peaks likely relate to earlier, more extensive Cordilleran ice flow (Stage 1). FSc-9 (Stage 2) flowed from the north-east, to the mountain front (interpreted margin). A proglacial lake formed between this ice and retreating Cordilleran ice in the west. The Thunder Lake esker debauched into the intervening lake, forming a flat topped surface, likely a delta (Inset A). The lake initially drained along the coalesced ice margin towards the south-east, forming kames (Inset B). As the ice margin retreated, the lake began draining through the outlet channel in SE portion of map. A succession of terraces flanking the channel between 1405 and 1385 m asl record 20 m of incision during lake drainage.

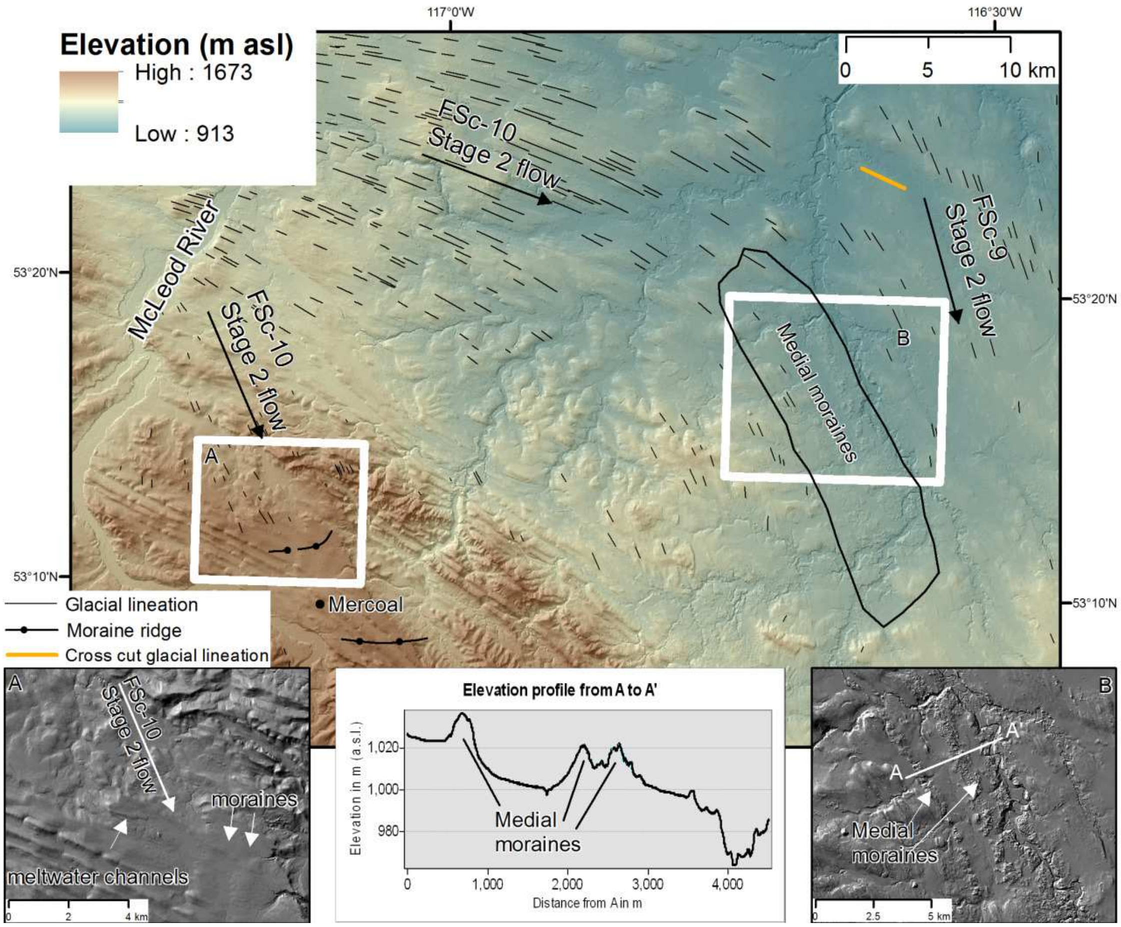


Figure 8. LiDAR bare-earth image of the McLeod River valley area near Mercoal. Cordilleran ice flow from the Athabasca valley (FSc-10) was deflected south-east by convergent Laurentide ice (FSc-9). This ice flow pattern was deflected towards the mountain front, ending at low relief moraines (inset A). Medial moraine marks the boundary between Laurentide and Cordilleran ice (inset B).

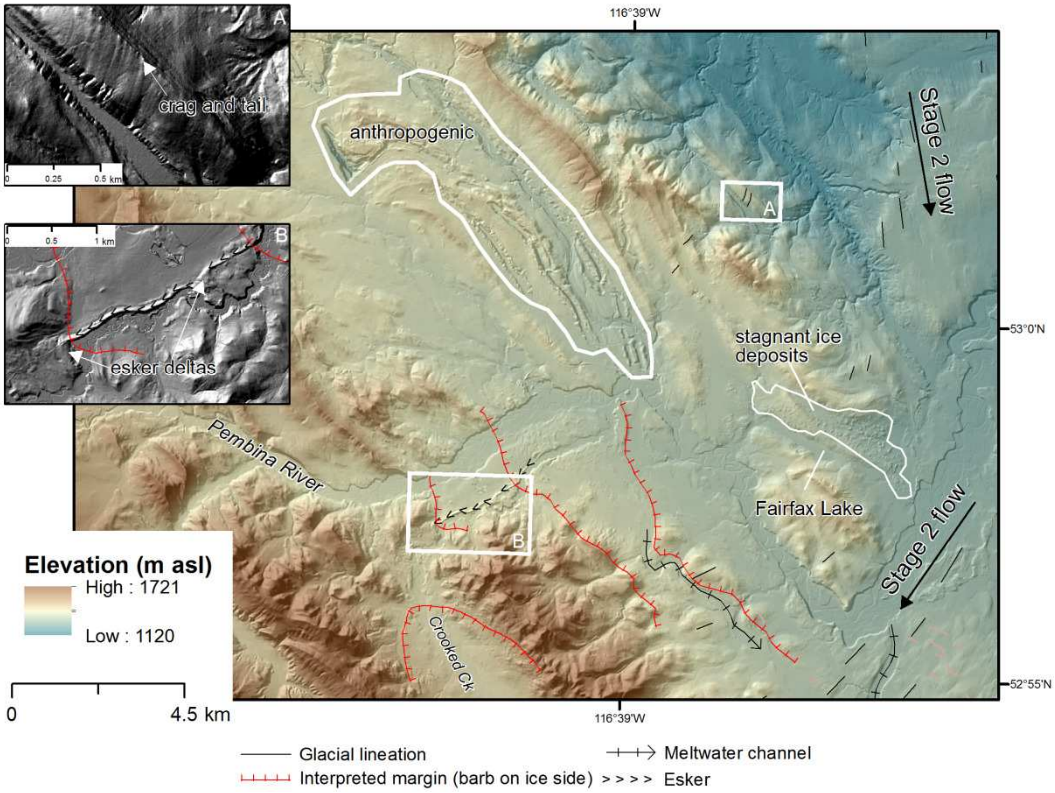


Figure 9. LiDAR bare-earth image of Pembina River area. FSc-9 (Stage 2) ice flow is from the north in the north-east portion of figure and arcs towards the valley. Inset A shows crag and tails relating to this flow. Inset B is of a beaded esker, suggesting FSc-9 flowed into the valley from the north-east, damming a lake as it retreated.

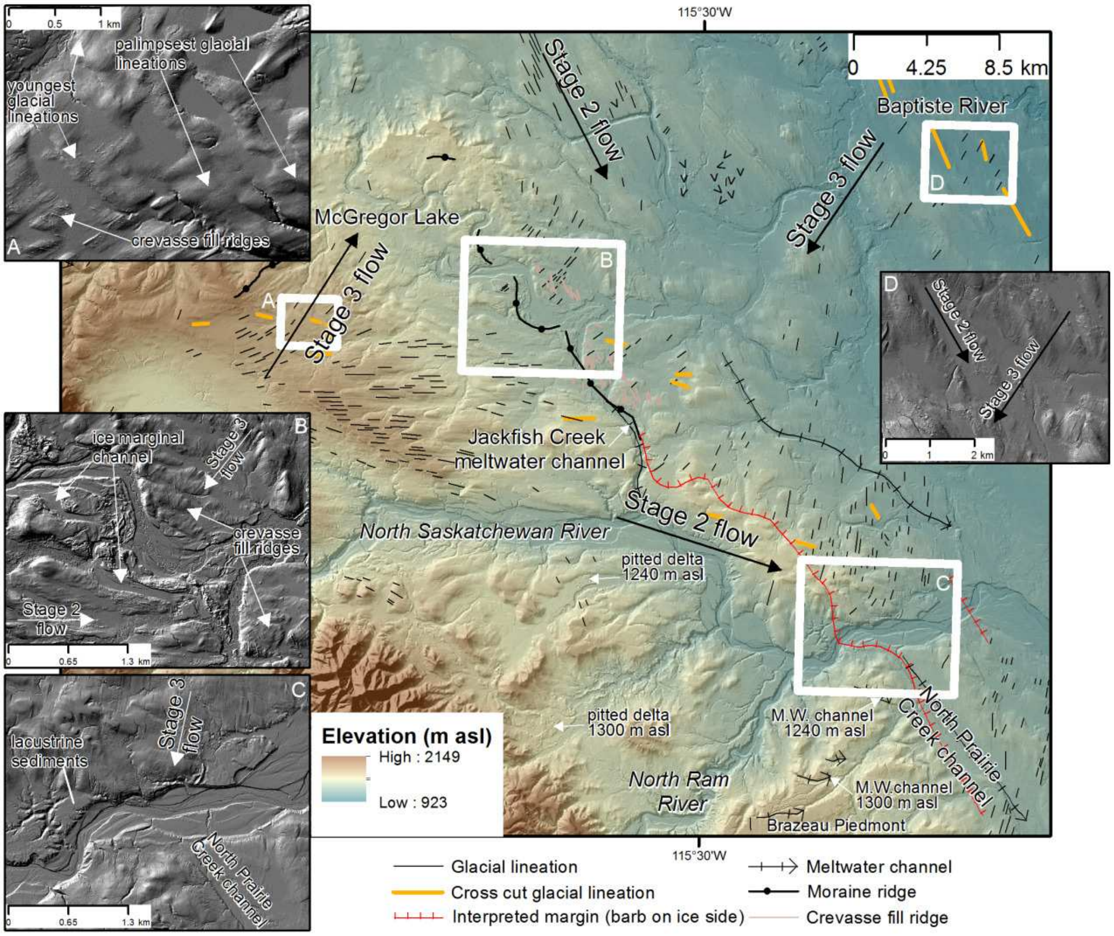


Figure 10. LiDAR bare-earth image of the North Saskatchewan River valley. Potential palimpsest drumlins (FSc-17; Stage 2) oriented WNW-ESE are cross-cut by NE oriented flutings (FSc-18; inset A). A late south-west flow of Laurentide ice (FSc-16; Stage 3) cross-cut south-south-easterly flowing ice (FSc-15; Stage 2) along the Foothills (north-eastern portion of image and inset B and D). This flow blocked drainage of the North Saskatchewan and North Ram rivers, indicated by terraces and meltwater channels (south-eastern portion of image and inset C). The inferred terminus of the ice margin during this re-advance is based on the extent of glacial lineations and the position of meltwater channels. Once ice retreated from this position, impounded water flowed down the North Prairie Creek channel (south-eastern portion of image). Inset D shows FSc-16 landforms cross-cutting FSc-15.

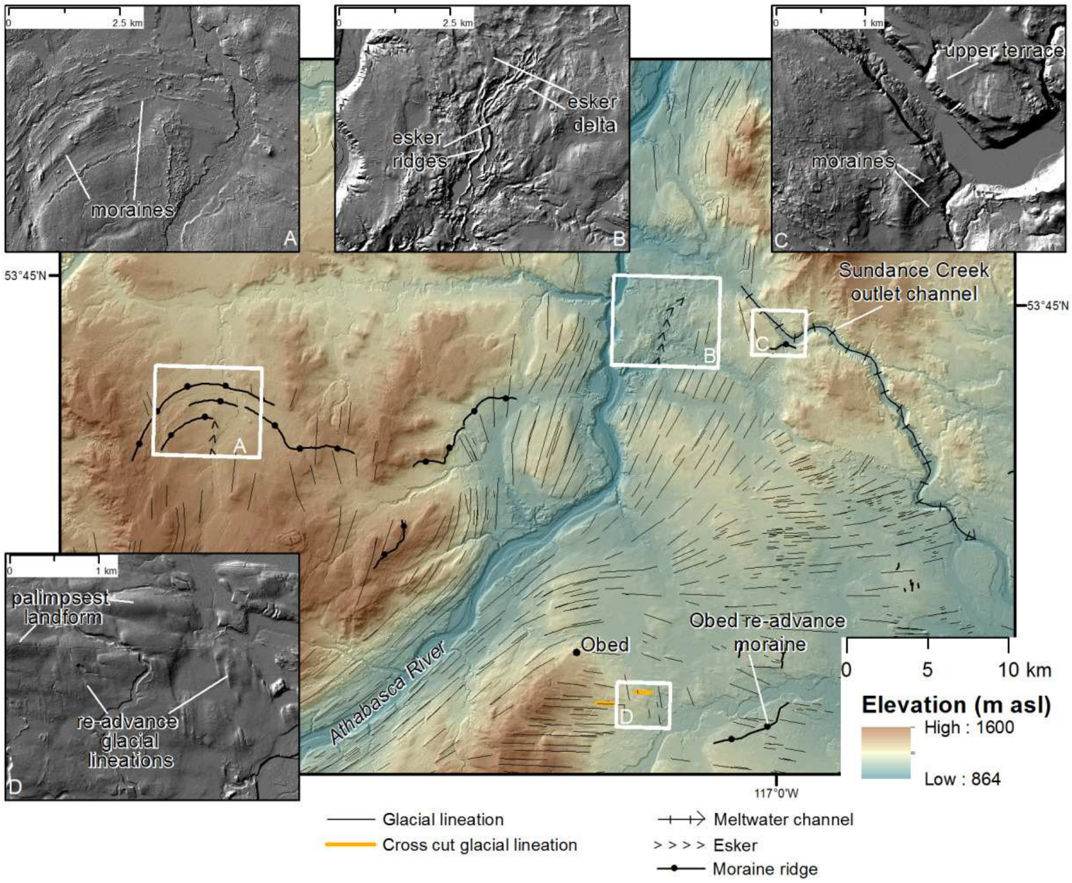


Figure 11. LiDAR bare-earth image of the Athabasca River valley in the Obed area, north of Hinton. Arcuate moraines mark a recessional position of Cordilleran ice (FSc-1, Inset A). The Emerson Lakes esker (Roed, 1975) terminates at a flat topped delta at 1030 m asl (Inset B). The flanks of the Sundance Creek outlet channel are terraced up to 1110 m asl (Inset C), suggesting an initial higher lake level drained through this channel, which likely had ice abutting the channel, as indicated by a moraine adjacent to the channel (Inset C). Glacial lineations (FSc-1) in the southern portion of the image relate to the Obed re-advance (Roed, 1975), which cross-cut older flutings (Inset D).

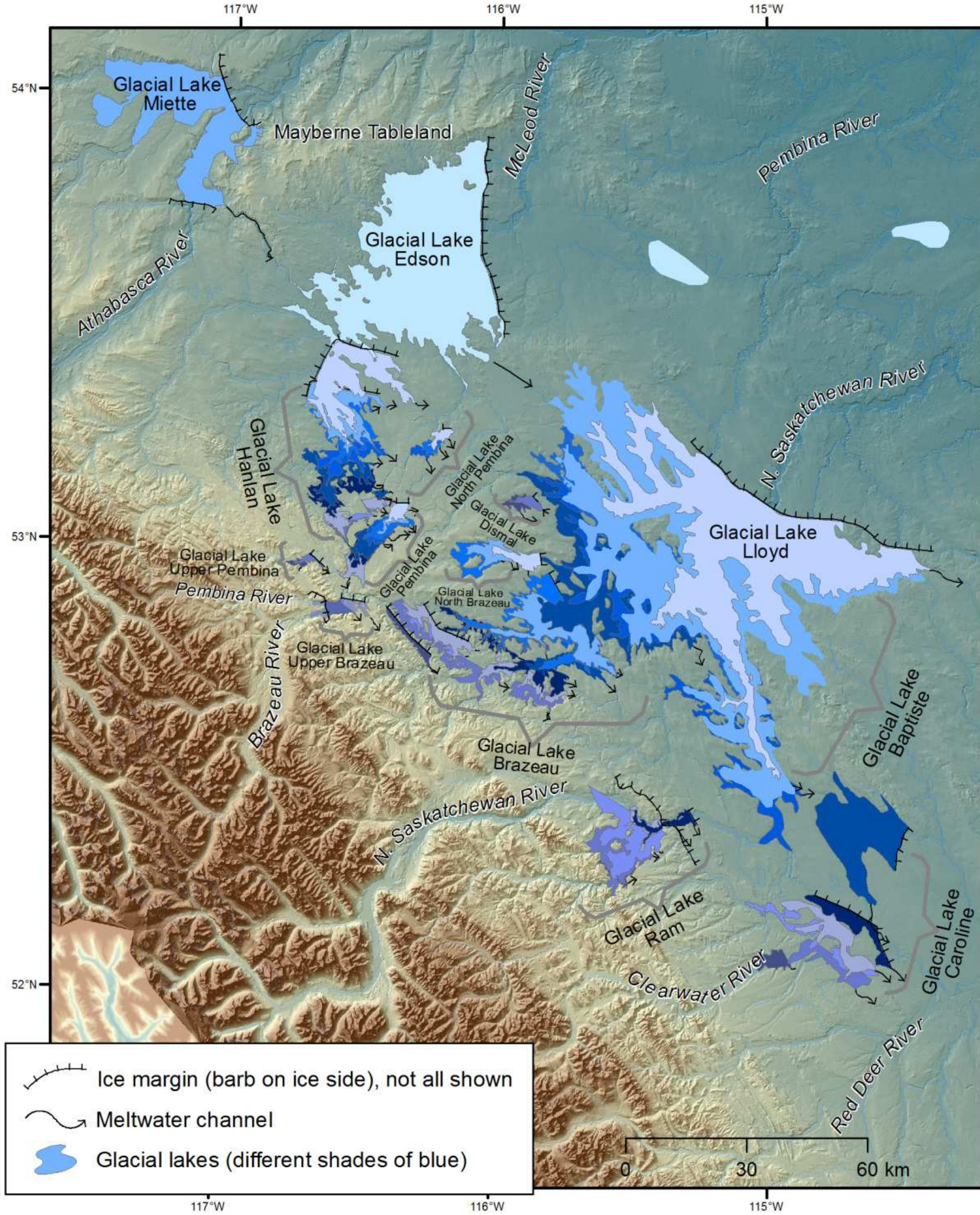
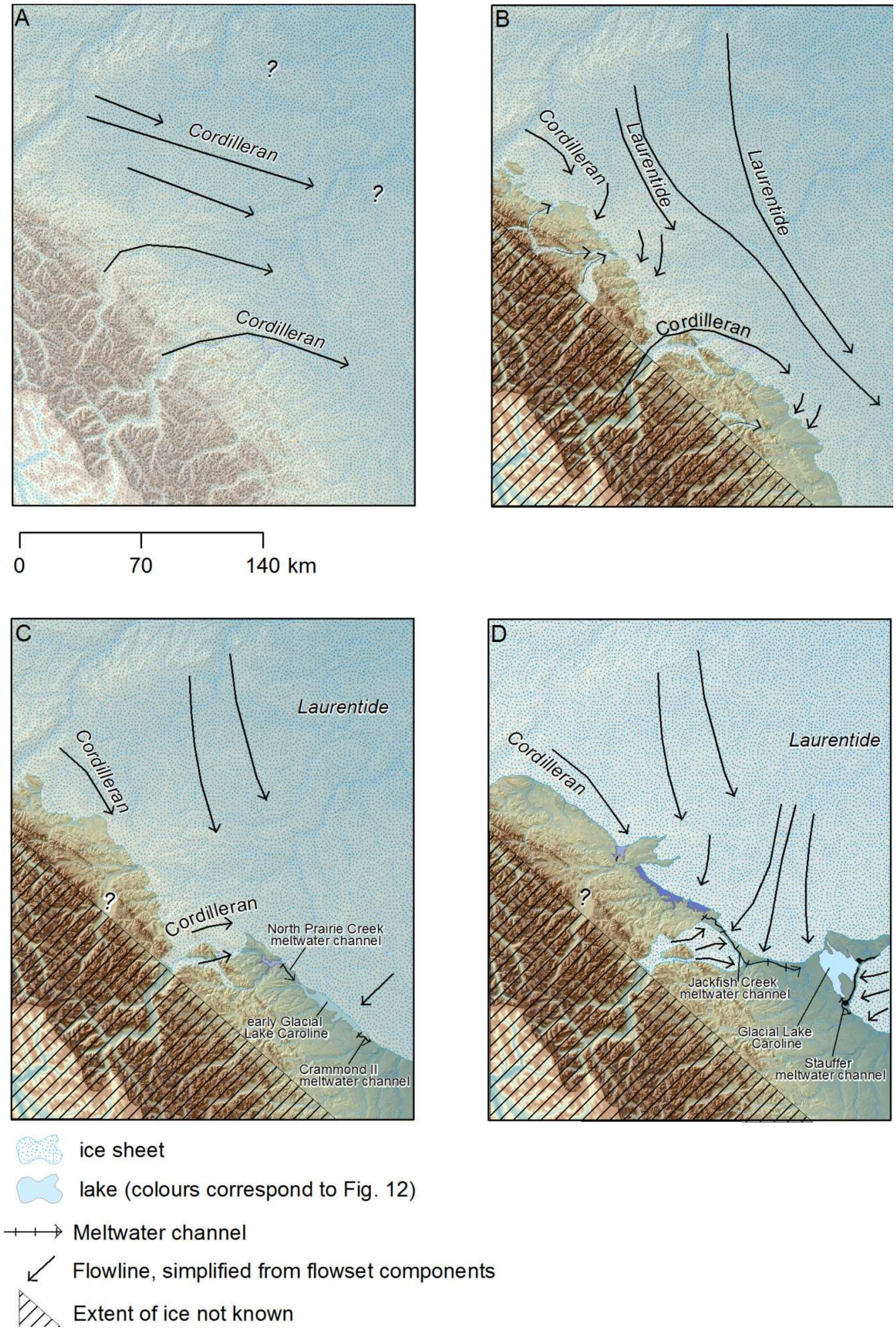


Figure 12. Reconstruction of a succession of proglacial lakes in the study area based on outlet elevations and meltwater channels. All lakes were formed at the margin of the LIS, except one the most westerly in the Brazeau River valley, which was in contact with both the LIS and CIS. Ice marginal positions are not all shown because of overlapping configurations, but occur on the downslope side.


A
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Cordilleran
?
Cordilleran
B
Cordilleran
Laurentide
Laurentide
Cordilleran
0
70
140 km
C
Laurentide
Cordilleran
?
Cordilleran
North Prairie Creek meltwater channel
early Glacial Lake Caroline
Crammond II meltwater channel
D
Cordilleran
Laurentide
?
Jackfish Creek meltwater channel
Glacial Lake Caroline
Stauffer meltwater channel
ice sheet
lake (colours correspond to Fig. 12)
Meltwater channel
Flowline, simplified from flowset components
Extent of ice not known

Figure 13. Glacial reconstruction discussed in text of A: Stage 1, with extensive Cordilleran ice flow, although eastern extent is not known. B: Stage 2, Cordilleran ice emanating from Athabasca and North Saskatchewan valleys coalesces with Laurentide ice. Ice flow direction is along the mountain front, with ice flow towards the mountains in the smaller valleys. Ice extent in mountains not known. C: an early phase of Glacial Lake Caroline, the lake extent is based on the Crammond II meltwater channel. A lake in the North Saskatchewan valley flowed into Glacial Lake Caroline through the North Prairie Creek meltwater channel. D: the last phase of Glacial Lake Caroline, the lake extent is based on the Stauffer meltwater channel, and ice at the Evergreen moraine.

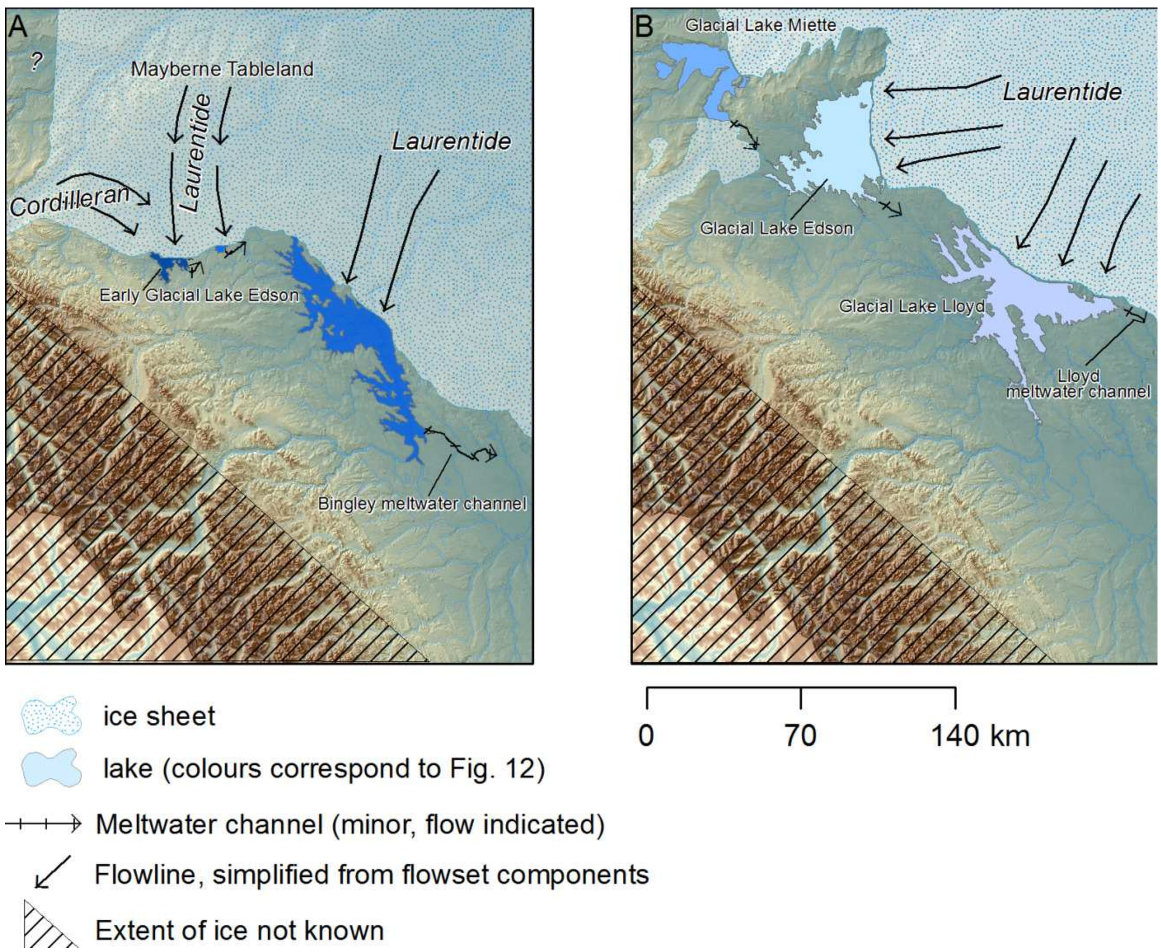

Figure 14. Glacial reconstruction discussed in text of A: following drainage of Glacial Lake Caroline, a lake would persist in the North Saskatchewan valley (Fig. 1), draining through the Bingley meltwater channel until Laurentide ice retreated further to the NE, opening lower terrain and forming the Lloyd meltwater channel (Fig. 14B). B: a late phase of Glacial Lake Edson, probably draining into Glacial Lake Lloyd. Glacial Lake Miette is based on 1040 m elevation, the lake ranged in elevation from 1110 m to 1032 m, until it finally drained following the continued north-eastward retreat of the LIS margin.

Tables

Landform	Identification criteria	Significance
Glacial lineation	Includes flutes, drumlins and streamlined bedrock (Clarhäll and Jansson, 2003). Inferred to be parallel to former ice flow direction. Directionality was noted from crag-and-tail features.	Indicates former ice flow direction. Elongate features (high L/W ratios) may indicate faster ice flow (e.g. Briner, 2007).
Moraine	Arcuate ridge of till or displaced bedrock.	Indicates ice marginal position.
Shear moraine	Elongate ridge of till; sub-parallel glacial lineations on one side.	Marks the boundary between slow and fast moving ice (Stokes and Clark, 2002).
Medial moraine	A band of ridges and/or meltout deposits.	Marks an interlobate position (Eyles and Rogerson, 1978).
Meltwater channel (ice-marginal)	Channel are sub-parallel to slope with a gentle gradient; potentially represented by a series of parallel channels.	Indicates ice marginal position and drainage route (Greenwood *et al.,* 2007).
Meltwater channel (proglacial)	Channel with a consistent gradient, and exhibiting regular meanders.	Shows drainage route of subaerial glacial meltwater or from a proglacial lake (Greenwood *et al.,* 2007).
Esker	Sinuous ridge of glaciofluvial material.	Remnant of wet-based deglacial drainage (Banerjee and McDonald, 1975).
Dune	Parabolic feature.	Formed by reworking of glacial sediment by eolian activity (Wolfe *et al*., 2004). Obscures earlier glacial landforms.
Crevasse-fill-ridge	Cross-cutting ridge typically overlying glacial lineations.	Inferred to indicate ice stagnation following a surge (Sharp, 1985; Evans and Rea, 2003).
Esker fan-delta	Triangular in plan-view, and deposited at the efflux of a subglacial channel within a proglacial lake. Also known as esker beads (Banerjee and McDonald 1975)	Represent sub-aqueous to sub-aerial sedimentation depending on water depth. Horizontal to gently sloping upper surface comprise deltaic topsets coincident with the former lake level (Banerjee and McDonald. 1975).
Delta	Gilbert-type delta (flat-topped, triangular in plan view) are present at the terminus of a meltwater channel flowing in to a proglacial lake. Some deltas (pitted deltas) have kettles or pits on the surface.	The upper surface (delta topsets) inferred to be coincident with the associated lake level (Postma, 1995). Pitted deltas indicate ice-proximal formation, pits relate to meltout of blocks of ice (Maizels, 1977)
Hummocky till	Irregular mounds of till, sometimes in the form of 'prairie-doughnuts' (circular features with central depressions).	Inferred to indicate stagnant ice (Eyles *et al.,* 1999).
Kame terrace	Terrace along hill slope.	Inferred to indicate meltwater flow, similar to meltwater channels but are constructional landforms (Benn and Evans, 2010).

Table 1: Landforms mapped in this study.

Flowset component	Morphology, general observations	L/W ratio	Form	Ice sheet	Inferred flow direction
FSc-1	Sharp, many features	11.0	Flute	CIS	Piedmont
FSc-2	Unclear, overridden	--	n/a	CIS	NW-SE
FSc-3	Subdued	5.4	Flute/drumlin	LIS	N-S
FSc-4	Subdued	5.0	Drumlin	LIS	N-S
FSc-5	Subdued	9.2	Flute	LIS	N-S
FSc-6	Unclear, but sharp between FSc-5 and 7	9.4	Flute	CIS	NW-SE
FSc-7	Subdued, a few sharp	11.5	Flute	LIS	N-S
FSc-8	Unclear, overridden	--	n/a	CIS	NW-SE
FSc-9	Sharp, many features	9.1	Flute	LIS	N-S
FSc-10	Sharp, many features	10.9	Flute	CIS	Fan
FSc-11	Sharp, many features	4.1	Drumlin	CIS	Along valley
FSc-12	Sharp	--	n/a	CIS	W-E
FSc-13	Unclear, overridden	--	n/a	CIS	NW-SE
FSc-14	Subdued	13.6	Flute	LIS	N-S
FSc-15	Subdued, unclear where overridden by FSc-16	7.9	Drumlin/flute	LIS	NW-SE
FSc-16	Sharp, many features	6.3	Drumlin/flute	LIS	E-W
FSc-17	Sharp, except where cross cut by FSc-17	11.8	Drumlin	CIS	W-E
FSc-18	Sharp, many features	6.2	Drumlin/flute	CIS	Piedmont
FSc-19	Unclear, overridden	10.2	Flute	CIS	NW-SE
FSc-20	Unclear, beyond LiDAR coverage	--	n/a	LIS	NE-SW
FSc-21	Sharp	9.9	Flute	LIS	NE-SW
FSc-22	Subdued, limited landforms	4.1	Flute	CIS	Along valley
FSc-23	Subdued, limited landforms	--	n/a	CIS	W-E
FSc-24	Sharp, many, limited coverage of LIDAR	9.6	Flute	LIS	NE-SW

Table 2: Flowset components identified during mapping. Length to width ratio (L/W) calculated for landforms in the flowset components from the DEM. Form classified according to Rose (1987).

Lake Name	Outlet Elevation (m asl)	Associated Flowset
Glacial Lake Caroline	1155, 1105, 1070, 1060, 1020, 970	FSc-16, 20
Glacial Lake Ram	1375, 1325, 1250, 1125, 1100	FSc-16
Glacial Lake Baptiste	980, 960	FSc-14 and 16
Glacial Lake Lloyd	930	FSc-14
Glacial Lake Brazeau	1260, 1200, 1170, 1120, 1085, 1080, 1070, 1050, 1015	FSc-16
Glacial Lake North Brazeau	1172, 1126, 1075	FSc-16
Glacial Lake Dismal	1075, 1035	FSc-16
Glacial Lake Upper Brazeau	1405, 1385	FSc-11, FSc-9
Glacial Lake Upper Pembina	1395, 1365	FSc-9
Glacial Lake Pembina	1300, 1280, 1260, 1245, 1230, 1210, 1200	FSc-9
Glacial Lake North Pembina	1205, 1200, 1180, 1170, 1120, 1100, 1080	FSc-9
Glacial Lake Hanlan	1240, 1230, 1140, 1110, 1075, 1045, 1025, 1015	FSc-9
Glacial Lake Edson	960	FSc-3, 4
Glacial Lake Miette	1040	FSc-1

Table 3: Glacial lakes mapped in this study, with various lake phases defined by outlet channel elevations (Fig. 12).

Esker	Delta elevation (m asl)	Correlative channel	Channel elevation (m asl)	Associated Lake (Table 3)	Figure
Thunder Lake	1400	kame terrace	1405 m	Glacial Lake Upper Brazeau (1405 m asl)	8A
S. Edson	1020	Unnamed channel	1024 m	Glacial Lake Hanlan (1025 m asl)	5A
Cow Lake	1055	Crammond II channel	1060	Glacial Lake Caroline (1060 m asl)	6
Emerson Lake	1031	Sundance Creek	1110 m	Glacial Lake Miette (1040 m asl)	11B
Pembina Esker	1420, 1390	Crooked Creek	1395	Upper Pembina (1395 m asl)	9B

Table 4: Fan-deltas used for lake reconstruction in this study.