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Coalescence of late Wisconsinan Cordilleran and Laurentide ice sheets east of the Rocky Mountain Foothills in the Dawson Creek region, northeast British Columbia, Canada

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ABSTRACT

Geomorphic, stratigraphic and geochronological evidence from northeast British Columbia (Canada) indicates that, during the late Wisconsinan (approximately equivalent to marine oxygen isotope stage [MIS] 2), a major lobe of western-sourced ice coalesced with the northeastern-sourced Laurentide Ice Sheet (LIS). High-resolution digital elevation models reveal a continuous 75 km-long field of streamlined landforms that indicate the ice flow direction of a major northeast-flowing lobe of the Cordilleran Ice Sheet (CIS) or a montane glacier (>200 km wide) was deflected to a north-northwest trajectory as it coalesced with the retreating LIS. The streamlined landforms are composed of till containing clasts of eastern provenance that imply that the LIS reached its maximum extent before the western-sourced ice flow crossed the area. Since the LIS only reached this region in the late Wisconsinan, the CIS/montane ice responsible for the streamlined landforms must have occupied the area after the LIS withdrew. Stratigraphy from the Murray and Pine river valleys supports a late Wisconsinan age for the surface landforms and records two glacial events separated by a non-glacial interval that was dated to be of middle Wisconsinan (MIS 3) age.

Introduction

The timing and extent of the Cordilleran (CIS) and Laurentide (LIS) ice sheets in northeastern British Columbia has been the subject of debate for several decades. One view is that the two ice sheets coalesced during the late Wisconsinan glacial interval, approximately equivalent to marine oxygen isotope stage (MIS) 2 (Mathews, 1978, 1980; Dyke and Prest, 1987; Dyke et al., 2003; Bednarski and Smith, 2007; Hartman and Clague, 2008). Others have suggested, however, that coalescence, if it did occur, happened during an earlier glaciation (MIS 4 or older) and that the CIS was of limited extent in the region during MIS 2 (Reimchen, 1980; Bobrowsky, 1989; Bobrowsky and Rutter, 1992; Catto et al., 1996). Determining if coalescences occurred or if an unglaciated corridor existed during MIS 2 has important implications. The separation of the ice sheets may have provided a significant route for the migration and spread of flora and fauna, including people, in North America (cf. Reeves, 1973; Arnold, 2002; Goebel et al., 2008). Furthermore, establishing field evidence of ice-sheet dynamics and interactions, coupled with geochronological constrains of ice-sheet extent, is essential for validating ice-sheet models (e.g. Peltier, 2004; Rutt et al., 2009). Gregoire et al. (2012), for example, implicated the collapse of the ice saddle that connected the two ice-sheets in the Dawson Creek and surrounding area as a cause of major global sea level rise and freshening of the world's oceans.

This study presents new geomorphic, stratigraphic, geochemical and geochronologic evidence from northeastern British Columbia (Fig. 1A) that helps resolve this debate. The study takes advantage of high resolution digital elevation models (DEMs) constructed from light detecting and ranging (LiDAR) surveys in the study area. These techniques have enhanced our ability to delineate glacigenic geomorphic features, e.g., streamlined landforms that record former ice sheet dynamics and flow direction (cf. Clark, 1997; Smith

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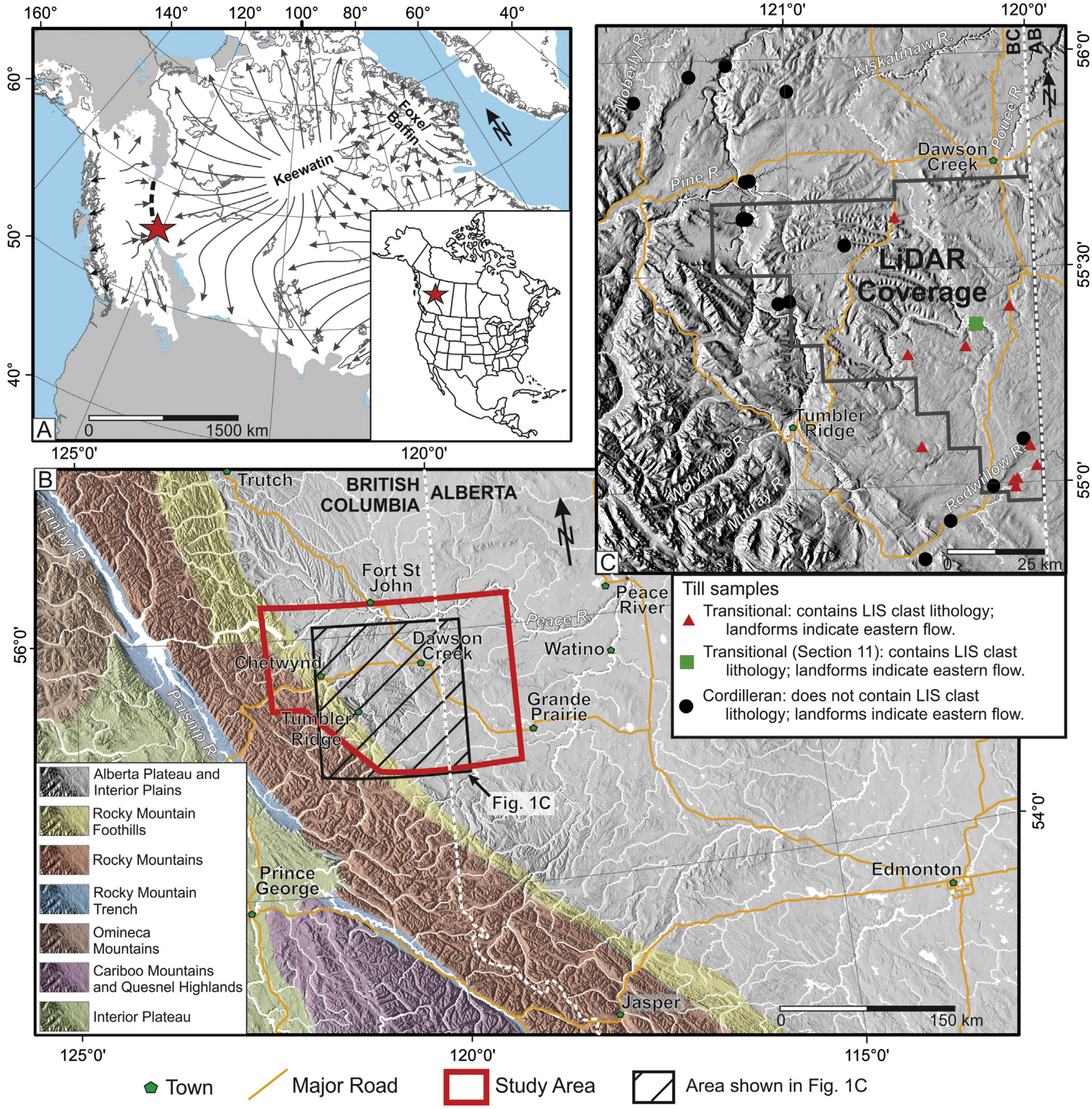

Figure 1. A) Location of the study area (red star) and the generalized ice-flow of the Laurnetide and Cordilleran ice sheets during the retreat phase of the late Wisconsinan glaciation (ice-flow modified from Prest, 1983; ice position from Dyke et al., 2003); B) regional digital elevation model (DEM; 2x vertical exaggeration) of the study area (red box) in northeast British Columbia and northwest Alberta with physiographic regions (Mathews, 1986); and C) till sample locations and LiDAR coverage within the study area (2x vertical exaggeration).

and Clark, 2005). They directly inform the model of ice-flow trajectory and ice sheet interaction that we propose here for northeastern British Columbia.

Stratigraphic evidence is drawn from an extensive late Quaternary sedimentary record that is exposed in sections along the Murray–Pine drainage system and the Kiskatinaw River (Fig. 2) with chronological control based on radiocarbon and optical dating. The objective of this study is to reconstruct major paleo-ice flow from geomorphic features and establish temporal context for these surface landforms.

The study area encompasses Dawson Creek, Chetwynd and Tumbler Ridge in British Columbia and extends into northwest Alberta (Figs. 1B and 2). Here, the Rocky Mountain Foothills transition to the plains of the Alberta Plateau (Holland, 1976). The area is generally agreed to have been influenced by three glacial systems (Catto et al., 1996): 1) LIS sourced from the northeast; 2) CIS sourced from west of the Rocky Mountains; and 3) montane glaciers mainly sourced from within the Rocky Mountains. LIS deposits are generally differentiated from those of other glacial systems by the presence of allochthonous red, granitic and gneissic clasts derived

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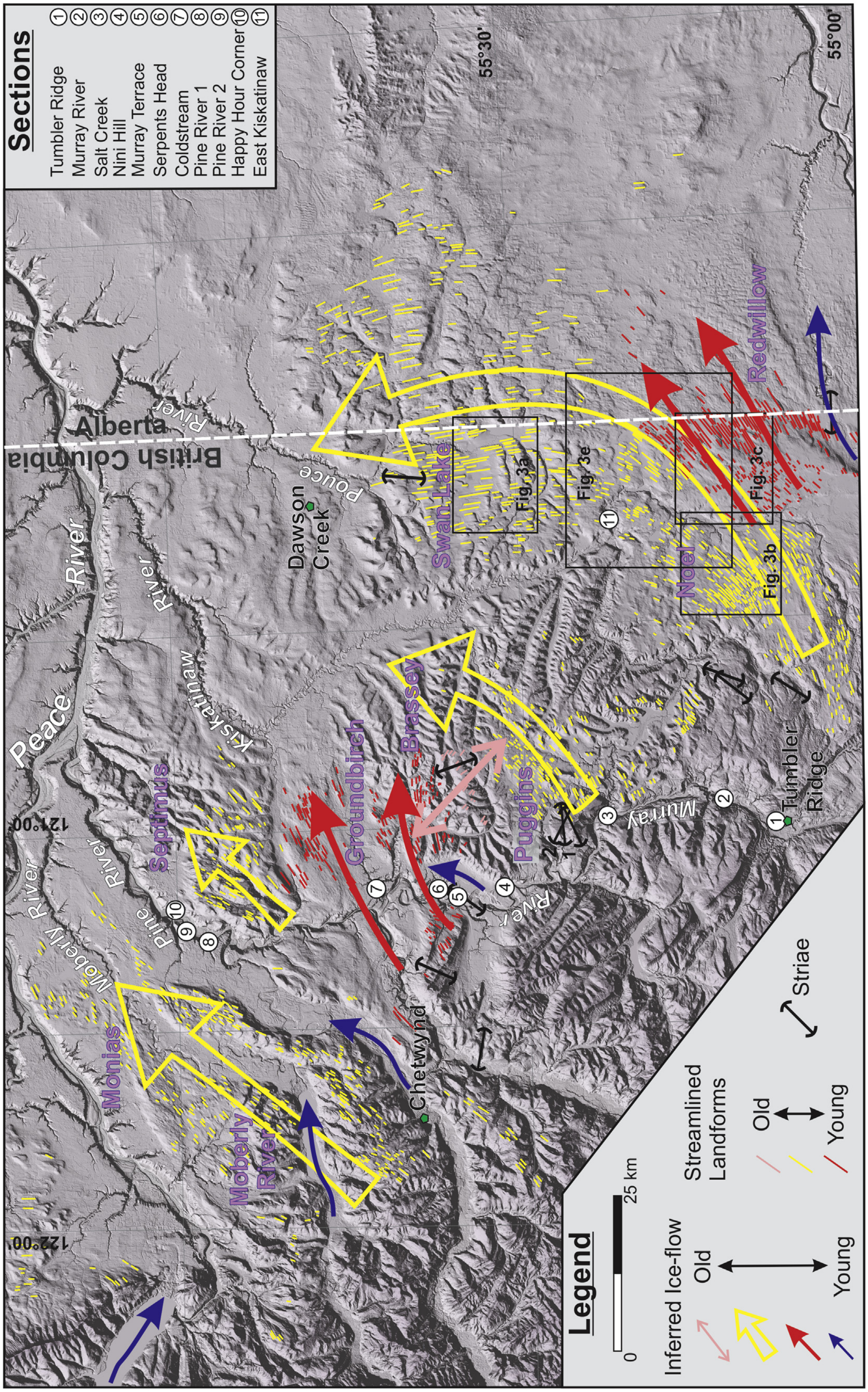

Figure 2. The mapped streamlined landforms in the study area record ice flow patterns from western sourced (CIS/montane) ice. Numbered circles refer to the lithostratigraphic sections (Figs. 5–9) along the Murray, lower Pine, and Kiskatinaw rivers.

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from Proterozoic Canadian Shield (Beach and Spivak, 1943; Mathews, 1978). The presence of these durable clasts indicates transport away from the Keewatin ice center in north–central Canada (Fig. 1A). Differentiating westerly derived CIS deposits is more problematic as both local montane and Cordilleran sediments are dominated by sedimentary clasts. The presence of low-grade schist and slate from the Rocky Mountain Trench (Fig. 1B), however, is considered diagnostic of CIS deposits (Mathews, 1978). Unfortunately, these rocks tend to be soft and may not survive subglacial transport. They will, therefore, be under-represented in till deposits sourced from distant localities. Nonetheless, the proportion of western and eastern-derived lithologies has been used by previous investigators to reconstruct the extent of former ice sheets in the area (e.g. Mathews, 1978; Hartman and Clague, 2008).

Previous work

Much of our knowledge of Quaternary history of the study area comes from Mathews (1954, 1955, 1978, 1980, 1954) who proposed a twice-repeated succession of non-glacial gravel, advance-phase proglacial lacustrine sediments, till, and retreat-phase proglacial lacustrine sediments. He assumed the till in the lower succession to be of early Wisconsinan (MIS 4) age and the till in the upper succession to have been deposited during the late Wisconsinan (MIS 2). Mathews (1978, 1980) recognized three ice sources: LIS, CIS, and montane glaciers. He suggested that there were at least two Laurentide glacial events represented (early and late Wisconsinan) and, based on the presence of shield clasts in gravel, possibly a third (pre-early Wisconsinan). He assigned three western-sourced glacial events: two Cordilleran events (early and late Wisconsinan) and one (late Wisconsinan) montane event (Portage Mountain ice advance). Rutter (1977) working along the Finlay, Parsnip, and Peace rivers (Fig. 1B) suggested that there was evidence of four western events, two representing full CIS development and two associated with later montane events. From work along the Peace River between the foothills and the Alberta boarder, Mathews (1978) noted a gradual eastward increase in the proportion of LIS clast types in the upper till and suggested that this was evidence for late Wisconsinan LIS and CIS coalescence.

A different interpretation emerged from Reimchen and Rutter (1972), Reimchen (1980), Bobrowsky (1989), Bobrowsky and Rutter (1992) and Catto et al. (1996). They suggest that an extensive CIS in the region was restricted to an early Wisconsinan (MIS 4) or older event and that the late Wisconsinan CIS was of limited extent. Bobrowsky (1989) advocated for a limited late Wisconsinan CIS based on his work in the Finlay River area. He simplified Rutter's (1977) stratigraphy and proposed a pre-middle Wisconsinan Cordilleran event and a short late Wisconsinan event (lasting ~5000 yr) of limited extent, supported by sub-till radiocarbon ages of 15,180 ± 100 ^{14}C yr BP (18,690–18,160 cal yr BP) (calibration using OxCal 4.2 and the IntCal 13 data set; Bronk Ramsey, 2009; Reimer et al., 2013) and 18,750 ± 120 ^{14}C yr BP (22,930–22,380 cal yr BP). Based on his youngest sub-till age and the oldest available ages for post-glacial sediments above till (i.e. 10,100 ± 90 ^{14}C yr BP; 12,040–11,310 cal yr BP), Bobrowsky and Rutter (1992) argued for a diminutive and short lived CIS that did not coalesce with the LIS in the late Wisconsinan. Liverman et al. (1989) working in western Alberta, concluded that only one Laurentide glacial event is recorded at Watino in Alberta (~175 km east of the study area; Fig. 1B) and that it was of late Wisconsinan age. Bobrowsky and Rutter (1992) summarized that in the Peace River Valley: 1) Cordilleran and Laurentide events were asynchronous and maximum advance of the CIS predates the maximum extent of the LIS, which is in turn postdated by the maximum extent of mountain ice; 2) the late Wisconsinan Cordilleran event was of limited extent; 3) LIS only reached the area once in the late Wisconsinan; and 4) there was no late Wisconsinan ice sheet coalescence, i.e., an 'Ice-Free Corridor' existed throughout the late Wisconsinan.

Jackson et al. (1997, 1999) and Levson and Rutter (1996) in the southern and central Canadian Rocky Mountains, respectively, contested the late Wisconsinan ice-free corridor concept and argued that the Foothills erratic train from southwestern Alberta was evidence for CIS and LIS coalescence. These erratics were emplaced where CIS and LIS converged and deflected, flowing south along the Rocky Mountain Foothills towards what is now the United States–Canada border. Jackson et al. (1997, 1999), using cosmogenic ^{36}Cl ages, confirmed that the Foothills erratic train is late Wisconsinan in age. Levson and Rutter (1996) demonstrated that the CIS sourced from west of the continental divide, flowed through the Jasper area (Fig. 1B) and was deflected south along the mountain front by the LIS during the late Wisconsinan. Nonetheless, an ice free corridor likely did exist for a time both before and after the last glacial maximum (Dyke et al., 2003; Bednarski and Smith, 2007).

Hartman and Clague (2008) revisited the stratigraphy in the Peace River Valley and supported Mathews (1978) model of three Laurentide and two Cordilleran events. They concluded that the earliest Laurentide event (>MIS 4) was less extensive than the penultimate (possibly early Wisconsinan) event, which, in turn, was less extensive than the late Wisconsinan event. They suggest that the penultimate Cordilleran event (possibly early Wisconsinan) and the late Wisconsinan event extended east, beyond the mountain front, but they did not speculate on the extents or if the ice sheets coalesced. They reconciled their multiple Laurentide model with the single late Wisconsinan Laurentide model (Westgate et al., 1971, 1972; Catto, 1984; Liverman, 1989; Liverman et al., 1989; Young et al., 1994) by suggesting that the pre-late Wisconsinan LIS had a northwest trending ice front and southwest trajectory, so that the ice sheet entered the Peace River region but terminated before Watino and Edmonton (Fig. 1B).

Bednarski and Smith (2007) found evidence of both Cordilleran and Laurentide deposits in the foothills around the Trutch area, 300 km north of our study area (Fig. 1B). They concluded that the CIS initially retreated from the foothills around 14 ka (based on cosmogenic ^{36}Cl ages) and that the CIS and LIS were at their maximum extent around the same time. They further suggested that the CIS retreat was followed by an incursion of the LIS into the foothills around Trutch. In the southern part of their study area, however, the CIS was still present at the mountain front, preventing the LIS from advancing into the mountains. In their postulated sequence of events, the LIS then retreated and montane glaciers readvanced as far as the eastern edge of the foothills. They also argued that surface landforms that record deflection of the LIS are interpreted to be of a late Wisconsinan age and indicated that the late Wisconsinan CIS must have been present, i.e., coalescence with the LIS, beyond the foothills to deflect the ice-flow trajectory of the LIS.

The LIS retreated down the regional slope and blocked drainage during deglaciation resulting in the development of large proglacial lakes, including glacial Lake Peace (Taylor, 1960) that reached an elevation of >1100 m above sea level in the area (Mathews, 1980; Hickin et al., 2015).

Methods

Geomorphic methods

DEMs from a variety of sources were used within a geographic information system (GIS) to map streamlined glacial landforms that record former ice-flow directions. DEMs were generated from Shuttle Radar Topographic Mission (SRTM) data (~90 m resolution), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery (30 m), British Columbia Terrain Resource Information Management (TRIM) data (25 m resolution), and Light Detection and Ranging (LiDAR) data (<1 m resolution).

More than 1100 streamlined landforms were manually mapped from a combination of hill shaded (with various sun orientations and angles) and slope DEMs (Fig. 2). Where there was LiDAR coverage, hundreds to thousands of subtle (<1 m height) streamlined features are detectable but were not specifically delineated because of scale limitations (e.g., Fig 3). The results of the mapping enable clusters of landforms to be grouped together and their relative age assigned based on cross-cutting relationships (Fig. 2). The flow direction is inferred from the shape of the landforms (Menzies and Rose, 1987).

Lithostratigraphic methods

Select sections with extensive stratigraphy were examined and logged using a lithofacies system similar to that of Eyles et al. (1983). Lithostratigraphic subdivisions are established based on lithofacies association, stratigraphic position, inferred genesis, and correlation. Total clast content (>2 mm diameter fraction) was estimated in the field. Diamict samples (2–5 kg) were collected from selected units for geochemical and grain-size analysis. Clasts with diameters >100 mm were discarded in the field and as such we recognize that clast content established from sieving can only be considered an estimate.

Chronology methods

Two radiocarbon ages and four optical ages were obtained to temporally anchor the regional lithostratigraphy. The two radiocarbon samples were collected and analysed from a 0.5 cm-thick organic-rich layer at the Pine River 1 Section (Fig. 2). A flattened twig, approximately 5 cm long and 0.5 cm wide, was dated by accelerator mass spectrometry (AMS). Four common silver weed (*Potentillo anserina*) achenes were identified, extracted and dated.

Four sand samples, collected from sites where the sand was interpreted to have been deposited in an aeolian or fluvial setting, were optically dated. These settings were targeted because they are depositional environments likely to have exposed the sand grains to sufficient light so as to reset their luminescence clocks. Optical dating is a method that provides an estimate of the time elapsed since mineral grains (usually quartz or K-feldspar) were last exposed to sunlight, i.e., deposited and buried. The method requires an estimation of the dose of radiation absorbed by the mineral grains in the environment over their burial time (the equivalent dose, D_e), and a measure of the environmental dose rate. An optical age (in ka) is simply the equivalent dose (usually measured in grays, Gy) divided by the environmental dose rate (measured in Gy/ka). The specific protocols used in this study are outlined in the supplementary data from the journal's website.

Representative D_e values used for the age calculations were found using either the central age model (CAM) if the overdispersion (OD) is <20% or the minimum age model (MAM) if the OD is >20% (Galbraith et al., 1999). The CAM gives the weighted mean D_e and takes into account the OD in the data, which is the variation in the D_e values provided by each aliquot which is above and beyond those associated with analytical uncertainties (cf. Jacobs and Roberts, 2007). The MAM provides a statistically representative D_e from the population of aliquots with the lowest D_e values. The true burial age of the sample is therefore considered to be equal to or younger than the age value calculated using the MAM D_e. Additional information on experimental procedures are presented in Figure S7 (supplementary data).

Till matrix geochemistry methods

Diamict samples were collected from key stratigraphic sections and from a number of surface exposures to help understand the composition and origin of till units (Fig. 1C). Samples were categorized as: 1) Cordilleran if eastern provenance clast lithologies were not present; 2) Transitional if samples contained shield clasts, but the surface geomorphology suggest ice flowed from the west to the east; and 3) Laurentide when from a suite of samples from northwestern Alberta (Plouffe et al., 2006) that are known to be of LIS origin and not to have been influenced by Cordilleran ice. An additional sub-set of transitional samples (Section 11; Fig. 2) was also collected to evaluate vertical variation within the transition area. Major oxide and element abundances were determined from the silt–clay size fraction by inductively coupled plasma emission spectrometry (ICP-ES) following a lithium metaborate/tetraborate fusion and dilute nitric acid digestion (Hickin, 2013). Principal component analysis (PCA) on the major oxide data was performed using GCDkitTM to reduce and interpret the multivariate data set (cf. Davis, 2002; Grunsky, 2006; Janoušek et al., 2006).

Results

Murray-Pine River lithostratigraphy results

Eleven sections provide representative lithostratigraphy (see Fig. 2 for locations). Units are summarized (Table 1) and represented graphically (Figs. 4–7). The section from the Kiskatinaw River (Section 11; Fig 8) is described and discussed separately because it was examined to specifically evaluate vertical variations within the transitional area. Detailed lithostratigraphic subdivisions are summarized into 12 units. Each unit is assigned to a climatostratigraphic interval and, for ease of global comparison, to an approximately equivalent MIS based on the timescale of Cohen and Gibbard (2011). Detailed descriptions of the units are provided by Hickin (2013) and photographs of the units are provided in the supplementary data items (Figs. S1–S6).

The 12 units, interpreted to represent 5 stages and 2 glacial cycles, are briefly described below. We elaborate on the interpretation of the each unit in the discussion section of our paper.

Units 1–5 occur stratigraphically below the most recent glacial deposits and so are interpreted to be of pre-late Wisonsinan age (Table 1). Unit 1 (exposed at Section 2, Fig. 4B) consists of deformed non-glacial sand and gravel. Units 2–4 have characteristics that suggest they have a glacial origin and together represent the first glacial cycle. Unit 2 (exposed at Section 9, Fig. 6C) consists of pebble to cobble gravel (probably advance phase). Unit 3 (exposed at Sections 5–6, Fig. 5B–C; Sections 9–10, Figs. 6C and 7), consist of diamicts interpreted to be primary and secondary tills (c.f. Dreimanis, 1988) of a pre-late Wisconsinan glaciation. Unit 4 (exposed at Sections 8–9, Fig. 6B–C) is interpreted to be a retreat phase glaciolcustrine deposit predominantly of fine-sand, silt and clay with dropstones. Unit 5 (exposed at Sections 7–8, Fig. 6A and B) consists of non-glacial fluvial sand and gravel with an organic horizon (Section 8, Fig. 6B) that we radiocarbon and optically dated to be of middle Wisonsinan age (see Chronology results).

Units 6–11 are glaciogenic and together represent the second, and most recent, glacial cycle (Late Wisconsinan). Units 6–8 (Table 1) are interpreted to be part of the advance phase sequence. Unit 6 (exposed at Sections 3, Fig. 4C; Section 4, Fig. 5A; Section 7, Fig. 6A; Section 9, Fig. 6C; Section 10, Fig. 7) consists predominantly of sand and gravel. Unit 7 (exposed at Sections 3–6, Figs. 4C and 6; sections 8–10, Fig. 6B, C, and 7), consists of sand, silt, clay, diamict, and dropstones and is interpreted to have been deposited in advance phase glacial Lake Mathews (cf. Hartman and Clague,

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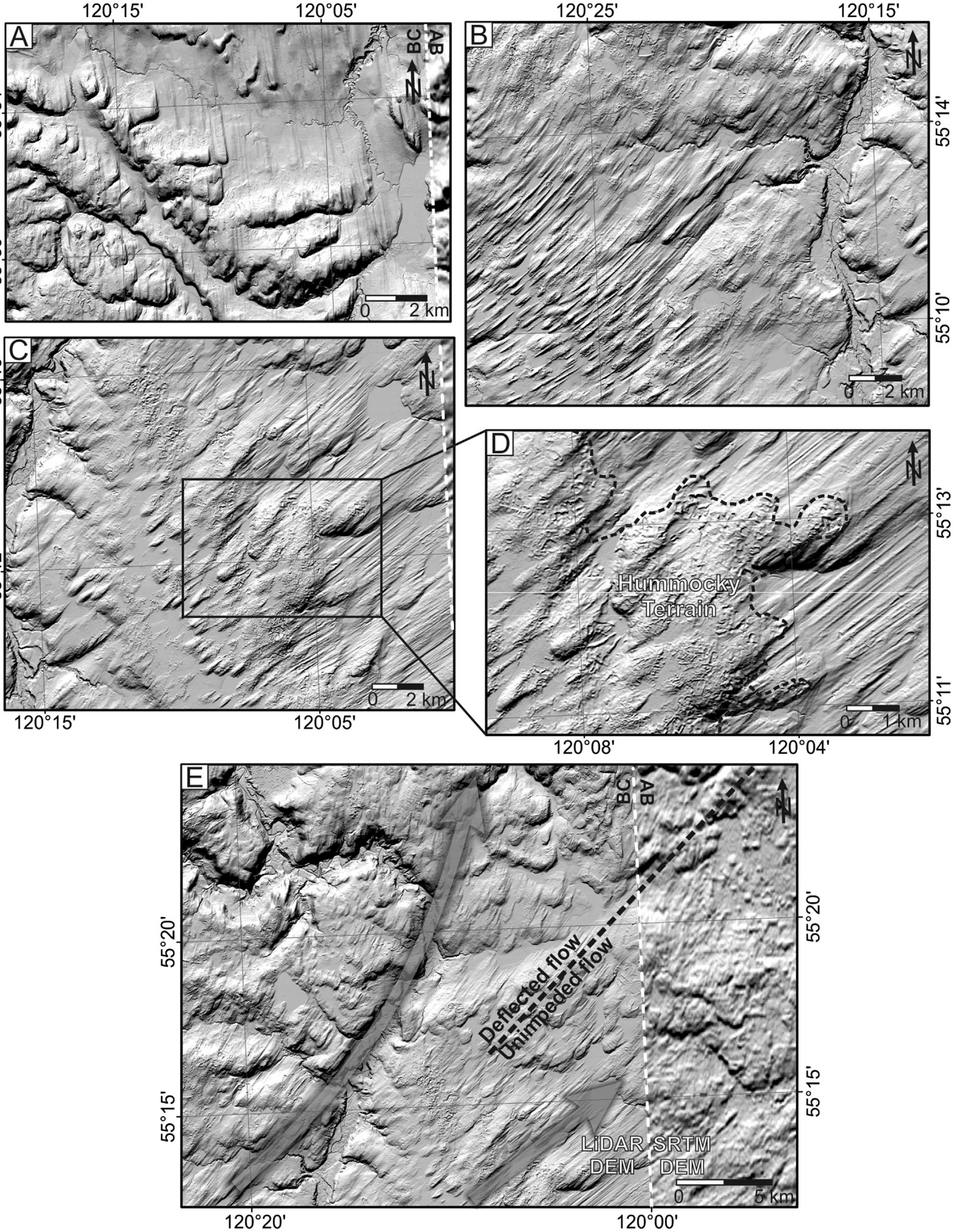

Figure 3. Images of streamlined landforms (see Fig. 2 for locations) from high resolution DEM (4x vertical exaggeration); A) streamlined landforms in the Swan Lake area indicate a north to north-northwest ice-flow direction; B) streamlined landforms from the Noel area between the East and West Kiskatinaw rivers show a coherent arcuate and deflected flow path of Cordilleran/montane ice; C) streamlined landforms in the Redwillow area; D) hummocky and reticulate terrain overlies the streamlined landforms; E) discordant streamlined landforms indicate that unimpeded ice-flow to the northeast occurred after northern flow deflection.

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2008). Unit 8 (exposed at Sections 4–6, Fig. 5) consists of sand, gravel and diamict associated with debris flows and alluvial fan deposits. Unit 9 (Table 1; exposed at Sections 3–7, Figs. 4C, 5 and 6A; Section 9, Fig. 6C) represents the local, last glacial maximum and is predominantly tills. Units 10 and 11 are part of the deglacial cycle (Table 1). Unit 10 (exposed at Sections 3–7, Figs. 4A, 5 and 6A; Section 9, Fig. 6C) consists of sand, silt, clay, and dropstones and is interpreted to have been deposited in retreat phase glacial Lake Peace (Mathews, 1980). Unit 11 (exposed at sections 4–5, Fig. 5A and B) consists of sand and gravel and Unit 12 (exposed at Section 5, Fig. 5B; Section 7, Fig. 6A) consists of silt and sand deposited by aeolian processes in a post-glacial paraglacial environment during the early Holocene.

Section 11 – Kiskatinaw River lithostratigraphy results

The Kiskatinaw River section (Section 11; Fig. 2) is within the region occupied by both the CIS and LIS. Section 11 consists of 30 m of diamict (Unit 9) overlain by 4 m of glaciolacustrine sediments (Unit 10; Fig. 8A). Shield clasts are common in both units. Clast content (2–100 mm fraction) increases from <10% at the base of the section up to >30% at the top of the section (Fig. 8B). Matrix texture also increases in the sand size fraction from 25% at the base to 36% at the top of the section. There is a marked decrease in the proportion of shield clasts from the lowest sample (15.6% at Kisk-766) to the other samples which have proportions that range from 0.2 to 1.1%.

Chronology results

The two radiocarbon age determinations are from the Pine River 1 section (Figs. 2 and 6B; Table 2). The wood yielded a radiocarbon age of 27,760 ± 230 ^{14}C yr BP (32,230–31,120 cal yr BP). The achenes yielded a statistically older age of 30,380 ± 300 ^{14}C yr BP (34,900–33,870 cal yr BP). The minimum 1640 year discrepancy (2σ) between the calibrated radiocarbon ages suggests that the organic horizon may consist of reworked material, or that the wood may have been contaminated by younger carbon, i.e., from groundwater or modern flora.

Environmental dose rates for the optical ages were determined from laboratory analysis of the K, U, and Th from a representative subsample of the bulk sediment used for dating (Table 3). Over-dispersion in samples CS02 and PR02 is 12.5 ± 1.8 and 12.0 ± 2.3% (uncertainties are ±1σ), respectively indicating that the CAM should be used to find a representative D_e. Samples CS02 and PR02 yielded ages of 8.7 ± 0.32 and 22.7 ± 1.0 ka, respectively. Sample PR01 has an over-dispersion value of 26.1 ± 3.8%, which is higher than those for samples CS02 and PR02, but still close to the arbitrary threshold value of 20% when the analytical uncertainty is considered for applying the CAM (cf. Jacobs and Roberts, 2007; Arnold and Roberts, 2009). The CAM returned an age of 157 ± 9 ka for sample PR01 whereas the age established for it using the MAM is 128 ± 5 ka. Consequently, it is only possible to state that sediment from sample PR01 was deposited during or after MIS 6. The natural luminescence measured from many of the aliquots from sample CS03 was close to saturation, and only 34 of 58 aliquots measured were accepted. This, together with an OD value of 30.5 ± 4.3%, suggests that a significant proportion of grains were not exposed to sufficient sunlight to reset the "luminescence clock" prior to burial. The MAM age for this sample is 112 ± 25 ka, which implies that sediment sampled from CS03 was deposited during or after MIS 5.

The discrepancy between the radiocarbon ages of organic samples collected from unit 5 (Fig. 6B) is large (averaging ~3 ka), and the difference between them and the optical age for enclosing sediments (sample PR02) is even larger (~10 ka). These age differences suggest that the organic material in this unit originated from an older deposit(s) and was eroded, transported and emplaced during deposition of Unit 5. Alternatively, the optical age may be too young, which is possible if unstable components of the luminescence signal (so-called medium and/or slow components) were inadvertently sampled during construction of the samples' dose response curves, although the results of the dose-recovery experiments do not suggest that this was an issue (see discussion in Hanson et al., 2012). Additional radiocarbon sampling and analysis accompanied by more optical dating experiments could refine the age of this unit. Nonetheless, the ages together suggest deposition during late MIS 3/early MIS 2 so we are relatively confident that Unit 5 was deposited during the latter part of the middle Wisconsinan.

Till matrix geochemistry results

The PCA of major oxide data somewhat differentiates Cordilleran from Laurentide samples (Fig. 9A and B). The populations have distinct fields but they do overlap. Transition samples plot mainly in the overlap zone. The CIS diamict samples are, to some extent, geochemically distinct from LIS diamict samples from Alberta and the transition samples are intermediate. Elevated SiO_2 is associated with Cordilleran samples. Laurentide samples generally have lower SiO_2 content together with relatively high levels of several of the other oxides. Bivariate plots show that the samples associated with CIS and LIS remain somewhat distinct when plotting Al_2O_3, Fe_2O_3, CaO, K_2O and TiO_2 against SiO_2 (Fig. 9C–J). We suggest that major oxide geochemistry can be used, to a certain degree, to differentiate the geochemical signals for the two ice sheets.

Section 11 is in the transition zone (Fig. 2) making it ideally located to examine the influence that each ice sheet had on the sedimentary record. Within the section, there is no distinct stratigraphic boundary that differentiates LIS from CIS tills (Fig. 8), however, vertical changes in the composition of the till provides evidence of a shift in provenance.

Several major oxide composition trends exist from the bottom to the top of Section 11 (Fig. 10A). There is a generally increasing up-section trend in SiO_2, Al_2O_3, Fe_2O_3, Na_2O, and TiO_2. There is a slight deviation in the slope of the trend for SiO_2, Al_2O_3, Fe_2O_3, and TiO_2 in the top two samples (S2 and Kisk-789), and there is a general decreasing up-section trend in MgO, CaO, K_2O, and P_2O_5. In sample Kisk-773 there is significant composition deviation (i.e. SiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O, K_2O, P_2O_5).

Consistent trends are observed when Section 11 samples are shown in bivariate plots (Fig. 10B–G) using the same classification field established for the surface sample matrix geochemical plots (Fig. 9). All samples plot in the Laurentide and/or in the overlap fields and generally show an up-section trend from the Laurentide field toward the overlap field in the direction of the Cordilleran fields. Sample Kisk-773, however, plots farthest toward the Cordilleran field. Silica content remains the most significant control on the displacement of each sample toward the Cordilleran field. An up-section trend is poorly developed in Al_2O_3 and Fe_2O_3 (Fig. 10B–C). There is a well-developed decreasing trend in MgO, CaO and K_2O from the bottom of the section to the top (Fig. 10D, E, and 10G). Na_2O has an increasing up-section trend that is directed away from all three discrimination fields, an unexplained trend that is inconsistent with those of the other major oxides.

Discussion

This study provides evidence that, in the Dawson Creek area, an extensive late Wisconsinan CIS coalesced with a contemporaneous LIS. This evidence on which this assertion is based includes: 1) a

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Table 1
Generalized description and interpretation of the regional stratigraphy from the Murray and Pine river valleys.

Climato-stratigraphic interval and MIS[a]	Unit	Description	Interpretation
Non-glacial – MIS 5 (?)	Unit 1	Bedded sand and gravel overlain by laminated sand and silt, indurate and oxidized. Sediment is over-consolidated with significant large-scale deformation including folding and subsequent high angle normal faults (Fig. S1). Clasts are well-rounded and predominantly resistant lithologies such as quartzite and siliceous sedimentary rocks of western affinity. Neither eastern provenance, nor striated and faceted clasts were observed. The basal contact is obscured below river level.	Fluvial gravel deposits overlain by overbank deposits (cf. Miall, 2006)
Early Wisconsinan glacial event – MIS 4 (?)	Unit 2	Poorly sorted and massive to weakly horizontally stratified pebble to cobble-sized gravel. Matrix content increases upwards from clast-supported to matrix-supported. Poorly developed beds are 1–2 m thick and are distinguished by subtle variation in modal clast-size. Clasts are sub- to well-rounded and many are striated and faceted. Clasts are of western provenance likely from local sources and from the main ranges of Rocky Mountains. The lower contact is covered and the unit grades conformably upward into Unit 3 (Fig. S2a and S2b).	Advance-phase glaciofluvial gravel deposits (cf. Miall, 2006; Eyles and Eyles, 2010)
	Unit 3a	Massive to weakly stratified diamict with abundant sand and gravel lenses. Diamict is matrix supported, dense and blocky with well-developed fissility. The matrix is silt- and clay-rich. Clasts range in size from pebbles to large boulders and are generally sub-rounded to well-rounded and contain abundant faceted and striated clasts. No clasts of eastern provenance are present. Sedimentary rocks of local and western provenance predominates the clasts lithologies. Within the diamict there are large rafts of sand and gravel bodies, often deformed (folded and thrusted; Fig. S2c). The rafts likely have a mixed genetic origin (i.e. alluvium and colluvium) and have likely been incorporated in the diamict by thrusting (Occhiette, 1973; Aber and Ber, 2007). At Section 10 (Fig. 7) the base of the unit consists of a mélange of local bedrock incorporated at the lower contact (Fig. S2d).	Glacial diamict deposits modified by gravitational and glaciotectonic processes (ie secondary till, cf. Dreimanis, 1988; Elson, 1988).
	Unit 3b	Massive, matrix supported diamict that has only rare, thin lenses (<1 cm) of sand (Fig. S2e and S2f). Matrix silt- and clay-rich. Clasts range in size from pebbles to large boulders and are generally sub-rounded to well-rounded and contain abundant faceted and striated clasts. No shield lithologies of eastern provenance are present and clasts lithologies are predominantly sedimentary rocks (local and western sources)	Subglacial till deposit (cf. Dreimanis, 1988)
	Unit 4	Massive to laminated fine-sand, silt and clay with abundant, isolated, pebble sized clasts. Where exposed the lower contact is sharp.	Retreat-phase glaciolacustrine deposits (cf. Powell, 1981).
Middle Wisconsinan non-glacial - MIS 3	Unit 5	1) Heavily oxidized, partially cemented, massive to trough crossed-stratified (troughs 1 –2 m wide and 0.5–1.0 m thick), open and closed-framework sand and poorly-sorted pebble to cobble gravel (Fig. S3a); or 2) a massive to imbricated, clast-supported, moderately-sorted, cobble-sized gravel overlain by fining-upward, laminated sand, silt and clay (at Section 8 unit capped by a thin (0.5 cm) organic horizon (Figs. S3b) that was dated (See Chronology Section).	Fluvial gravel deposits and overbank deposit (cf. Miall, 2006).
Late Wisconsinan glacial event – MIS 2	Unit 6a	Oxidized, massive to subhorizontally-stratified, imbricated, moderate to poorly-sorted, clast-supported, gravel with rare planar cross-bedding and minor subhorizontal sand beds (Fig. S3c). No eastern provenance clasts. Matrix is coarse to medium sand. Major fluvial architectural elements (Miall, 2006) are sheeted gravel deposits. The lower contact is erosional.	Advance-phase glaciofluvial deposits (cf. Eyles and Eyles, 2010)
	Unit 6b	Oxidized, weakly imbricated, massive to poorly stratified, poorly sorted, clast-supported pebble to cobble gravel with fine sand, silt and clay matrix (Fig. S3d). Clasts are well-rounded and predominantly durable siliceous western provenance lithologies. No eastern provenance clasts present. Facets and striations common. The lower contact is sharp and erosional.	Advance-phase glaciofluvial deposits (cf. Eyles and Eyles, 2010)
	Unit 7	Ranges in thickness from < 1 m (south) to > 200 m (north). Murray River Valley: Horizontally bedded, medium sand (no dropstones; Fig. S3e). Typically coarsens-up, commonly grades into gravel or diamict (Fig. S3f). Pine River Valley: Initially fines-up (laminated sand - laminated silt and sand - laminated silt and clay). Above 550 m asl, coarsens upward (laminated silt and sand). Toward the top, dropstones and thin intercalated lenses of diamict (0.1–0.4 m thick) common. Eastern provenance clasts are common. Unit can be pervasively deformed (Sections 5 and 6; Fig. 6a-b). The lower contact is conformable and gradational over ~1 m.	Advance-phase glaciolacustrine deposits (referred to as glacial Lake Mathews in this area; Hartman and Clague, 2008).
	Unit 8a	Low angle to subhorizontally-stratified, pebble to cobble-sized, poorly sorted gravel with minor sand interbeds (Figs. S4a-c). In places, open framework though typically has a coarse to fine sand matrix. Major beds are massive or normally graded (sand). Clasts are typically, flat-lying to slightly imbricated and are a mix of well-rounded to angular fragments. Many tabular clasts are local sandstone, but well-rounded quartzite and siliceous mudstone clasts are common. The lower contact is gradational over 5–10 m, often intercalated with unit 7 (Fig. S3f).	High energy non-cohesive debris flows deposits likely from an alluvial fan to subaqueous fan setting (cf. Levson and Rutter, 2000).

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Table 1 (*continued*)

Climato-stratigraphic interval and MIS[a]	Unit	Description	Interpretation
	Unit 8b	Massive to weakly normally graded, clast-supported pebble to boulder-sized diamict (Fig. S4d). Clasts are angular to sub-rounded and include a variety of lithologies. Faceted and striated clasts common. No eastern provenance clasts present. Matrix is clay, silt and sand and the lower contact is sharp and erosional.	Hyperconcentrated stream flow deposits in part, from a subaqueous setting (cf. Levson and Rutter, 2000).
Late Wisconsinan glacial event – MIS 2	Unit 9a	Stratified diamict, interbedded with horizontally laminated or massive sand. Diamict is poorly sorted, silt to clay-rich, and matrix supported (Fig. S5b). Clasts are generally subangular to well-rounded and commonly striated and faceted. Sand horizons range from a few mm up to >10 cm thick. Bedforms: subhorizontal stratification and ripples. Intensely deformed at Section 6 (Fig. 5)c where laminated sand, silt, diamict and pebble-gravel are folded and often merge into subhorizontal to low angle shear planes (Fig. S5c). The lower contact is indistinct and gradational over 5–10 m.	Waterlain glaciogenic diamict (cf. Dreimanis, 1988)
	Unit 9b	Massive, poorly-sorted, fissile diamict (Fig. S5a, e, f). Silt- to clay-rich matrix with granules to boulders sized clasts. Clasts are sub-angular to well-rounded, commonly striated and faceted. Clasts are a mix of local and western sedimentary lithologies. The lower contact is generally sharp and erosional but is conformable and intercalated over unit 8.	Subglacial till (cf. Dreimanis, 1988)
	Unit 10	Ranges in thickness from ~2 m to >200 m. Stratified and massive clay, silt, and sand. South: Unit coarsens-up from rhythmically-laminated silt and clay to horizontally stratified and rippled sand. Local dewatering structures and turbidite (Bouma) sequences common (lower unit). Small pebble sized dropstones are sparse. Upper part of the unit is sandy with well-developed Type A and Type B climbing ripples (Ashley et al., 1982). North: Lower unit dominantly sand with climbing ripples and some gravel. Fines upward to rhythmically-bedded silt and sand with abundant thinly-bedded diamict and common dropstones (become rare towards the top).	Retreat-phase glaciolacustrine sediments (referred as glacial Lake Peace; Mathews, 1980; Hickin et al., 2015).
	Unit 11a	Moderate to well sorted sand and gravel. Clasts are moderately to well-rounded and commonly faceted. Striations are common on larger cobble to boulder clasts. Clasts have western provenance. Large scale (2–4 m thick) planar tabular crossbeds distinguishes this unit (Fig. S6a).	Foreset beds of glaciofluvial deltas (cf. Bogen, 1983)
	Unit 11b	Pebble to cobble gravel with interbedded sand, overlain by horizontally stratified silt and sand. Gravel is massive or crudely bedded, poorly to well-sorted, has open and closed frameworks, and is poorly to well-imbricated (Fig. S6b). Clasts are moderately to well-rounded and facets are common. Planar and trough cross-bedding is common. The upper silt and sand is typically 1–2 m thick but can exceed 4 m (e.g. Section 4; Fig. 5a, S6c) and is horizontally laminated to thinly bedded.	Retreat-phase glaciofluvial deposits (cf. Eyles and Eyles, 2010).
Holocene – MIS 1	Unit 12a	Massive to poorly stratified, moderately sorted silt and fine sand (Fig. S6d and S6e).	Leoss and aeolian deposits (cf. Roberts and Cunningham, 1992)
	Unit 12b	Oxidized, uniform medium sand associated with parabolic sand dunes.	Aeolian deposits (cf. Pye, 1982)

[a] MIS boundaries are globally diachronous but are included here for general worldwide correlation.

continuous field of streamlined landforms indicates that a major lobe of east flowing ice was deflected by the LIS; 2) the ice lobe post-dates the maximum advance of the LIS and is, therefore, of late Wisconsinan age; and 3) stratigraphy from the Murray and Pine river valleys support a late Wisconsinan age for the surface glacial sediments and landforms.

Before further discussion, clarification of the terms *montane ice* and *CIS* is necessary. During the last glacial maximum, the CIS flowed across the Rocky Mountains from British Columbia's interior (Clague, 1989; Kleman et al., 2010). Mathews (1980) and Catto et al. (1996) differentiate the CIS (originating west of the Rocky Mountain trench) from montane ice (sources from the Rocky Mountains). This distinction becomes problematic east of the mountains, i.e., in the Alberta Plateau physiographic region (Fig. 1B). For example, Catto et al. (1996) infer that the Redwillow streamlined features are from a montane source, yet the scale and extent of the Redwillow streamlined field and the large flow tract depicted in the Noel and Swan Lake areas (Fig. 2) imply a glacier or ice lobe more than 100 km in width. These ice lobes may have been sourced from the main Rocky Mountain range, i.e., they are montane, but it is equally probable that they are part of the CIS. Since diagnostic low-grade metamorphic schist and slate till clasts have limited preservation potential in far-travelled subglacially transported till, it is difficult to equivocally assign landforms to the CIS or montane glaciers. Consequently, in this study we can only imply a general western ice source and do not attempt to differentiate montane ice sources from the CIS.

Streamlined landforms in the Noel and Swan lake areas (Figs. 2 and 3B) form a continuous field that track more than 75 km. These features indicate that a substantive western sourced lobe of ice flowed to the northeast but was deflected to a north-northwest flow trajectory. Since eastern flow is down the regional slope and there are no significant topographic barriers, this deflection is only possible if the LIS impeded the flow of western-sourced ice. Reimchen (1980) indicated that streamlined landforms within and between the Puggins and Noel areas (CIS origin) are 'truncated' by landforms from south flowing late Wisconsinan LIS (the same areas as shown in Fig. 3A) and that this truncation implies that an extensive CIS pre-dated the maximum extent of the LIS. We argue that there is no geomorphic evidence of south-flowing ice in this area and mapped features in fact indicate a northerly flow (Fig. 3A) and that truncation has not occurred.

The LIS only reached the Watino area once during the late Wisconsinan (Liverman et al., 1989). This implies that the Laurentide till in the Dawson Creek area must also be of late Wisconsinan age. Although Hartman and Clague (2008), on the basis of the presence of shield clasts in pre-late Wisconsinan gravel suggest

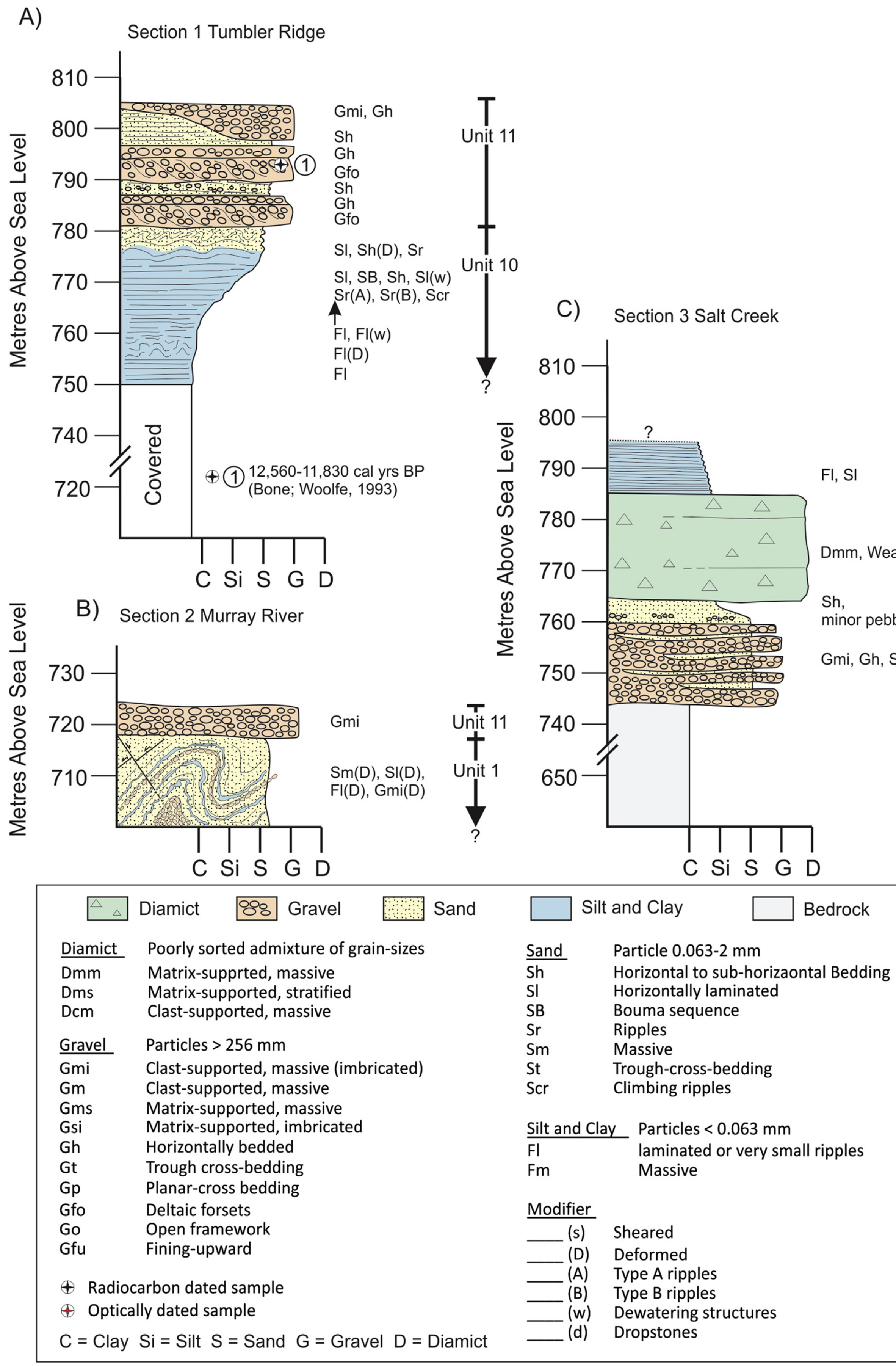

Figure 4. Stratigraphy of A) Section 1: Tumbler Ridge; B) Section 2: Murray River; and C) Section 3: Salt Creek (see Fig. 2 for section locations).

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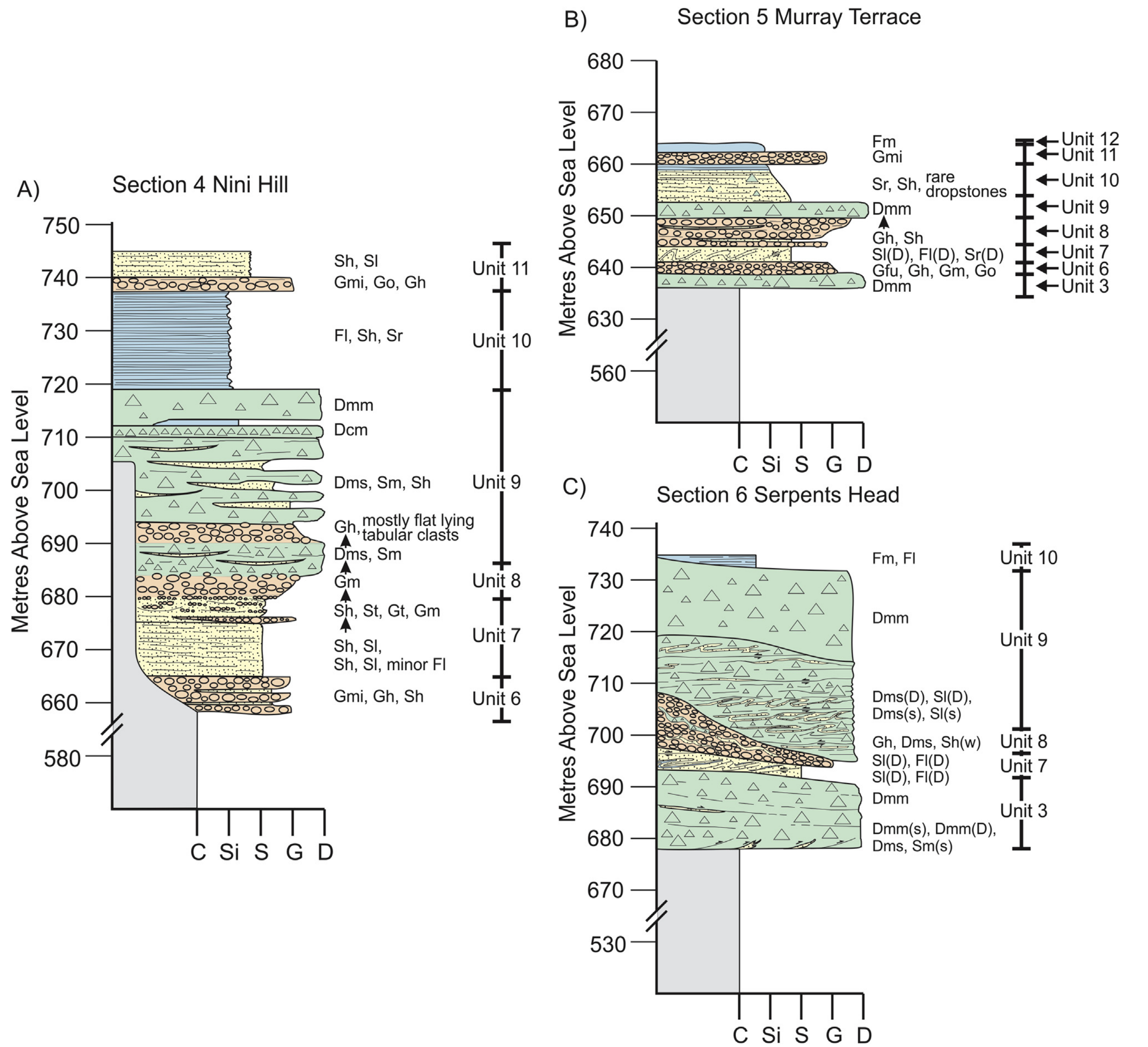

Figure 5. Stratigraphy of A) Section 4: Nini Hill; B) Section 5: Murray Terrace; and C) Section 6; Serpents Head (see Fig. 2 for section locations; legend is the same as for Fig. 4).

three Laurentide events in the Fort St. John area of the Peace River valley, they only have evidence of Laurentide till for what they interpreted to be of late Wisconsinan age. Surface diamict samples (Fig. 1C) and the absence of Laurentide till in the Murray and Pine river sections indicate that the LIS did not extend into the foothills in this area, consistent with the observations of Bednarski and Smith (2007) for the southern portion of their study area. Ice-rafted debris in the lower Pine River valley demonstrates that the Laurentide ice margin was supplying diamict to the western edge of the glacial Lake Peace basin.

If it is accepted that the LIS reached its maximum extent during the late Wisconsinan and only reached the study area during this time, then landforms that record flow to the east must have formed after the LIS vacated the area. The fact that the landforms record deflection, but are comprised of eastern-provenance till with no distinct boundary, means that till emplacement from the LIS and its subsequent reworking from western ice probably occurred within a short timeframe, i.e., essentially contemporaneous. This supports the notion that both the LIS and the CIS/montane ice occupied the area in the late Wisconsinan, first dominated by LIS and later by the CIS/montane ice, and coalesced as described by Mathews (1980). This sequence of events is evident at Section 11. The diamict shows geochemical, lithological and grain-size trends that imply that the base of the section has LIS affinity but transitions to a CIS affinity at top of the section (Figs. 8 and 11). The evidence from Section 11 must be considered exploratory, however, and invites further study of other local sections.

Although truncation of CIS/montane ice flow features by the LIS is disputed in this study, discordant ice flow features do occur where the northeast trending Redwillow streamlined field overprints the main deflected ice flow trajectory (Fig. 3E). We argue that the Redwillow features record a younger CIS/montane ice-flow readjustment that occurred as ice-flow became unobstructed. This is consistent with Catto et al. (1996) although they conclude that the glacial system that generated these features pre-dates the LIS. They suggest the LIS overrode these landforms, draping them in Laurentide till, but did not have the erosive power to modify the landscape (p. 28, Catto et al., 1996). We submit that it is unlikely

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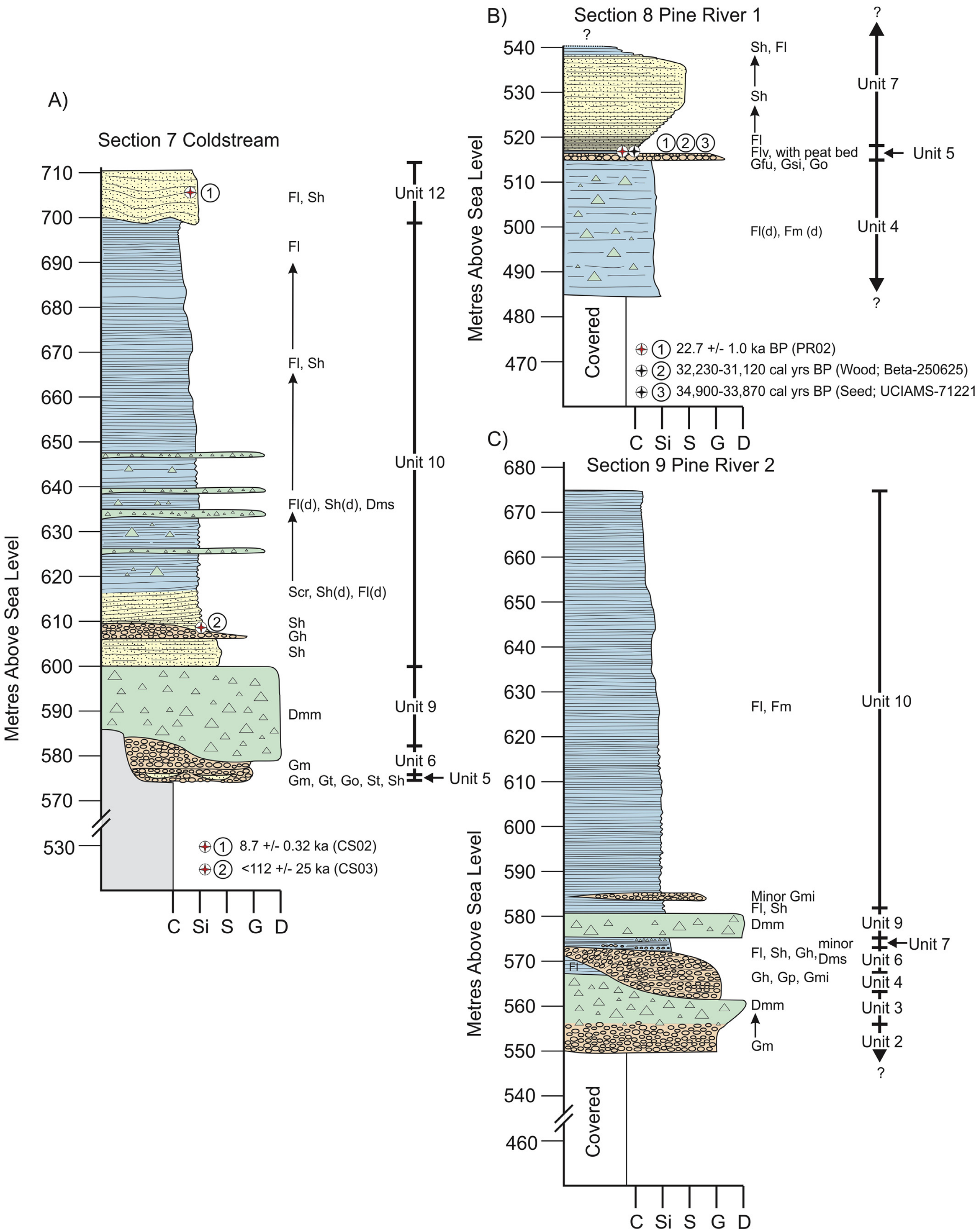

Figure 6. Stratigraphy of A) Section 7: Coldstream; B) Section 8: Pine River 1; C) Section 9: Pine River 2 (see Fig. 2 for section locations; legend is the same as for Fig. 4).

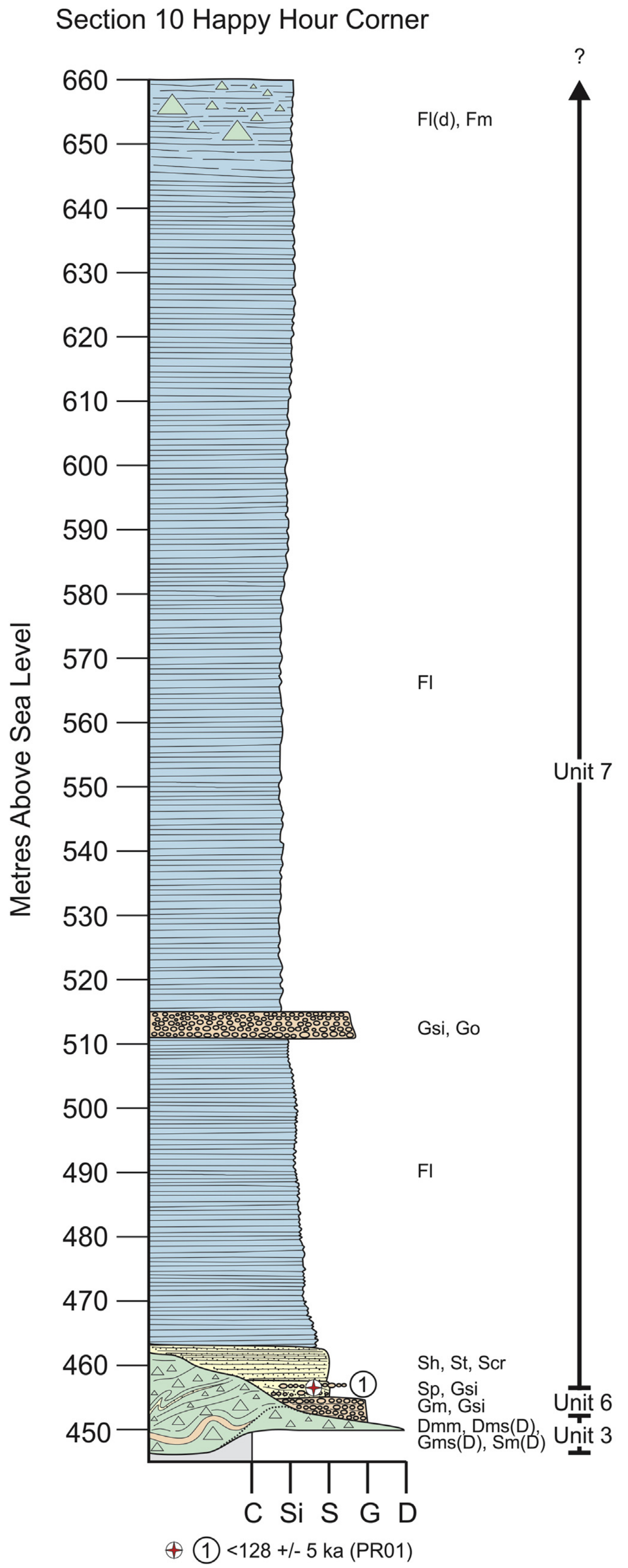

Figure 7. Stratigraphy of Section 10: Happy Hour Corner (see Fig. 2 for section locations; legend is the same as for Fig. 4).

that the very well preserved flutes (visible in LiDAR DEMs) that demarcate the Redwillow streamlined field (Fig. 3C and D) were overridden by the LIS. In fact, we imply that these features are indicative of the CIS overriding the LIS till.

We suggest the flow path of the ice lobe responsible for the Redwillow streamlined landforms was established after recession of the LIS, allowing western-sourced ice to flow unimpeded into glacial Lake Peace (Mathews, 1980; Hickin et al., 2015). The narrow flutes associated with this field (Fig. 3C and D) probably formed from a streaming ice lobe (Patterson, 1994; Evans and Rea, 2005) that terminated in glacial Lake Peace. Rapid ice flow and increased calving, facilitated by saturated and easily deformed glaciolacustrine substrate and reduced friction from ice made buoyant by deep proglacial lake water, would have depleted the source region, draining the ice reservoir (cf. Stokes and Clark, 2003). If the ice reservoir (Cordilleran or montane) was exhausted, it would be unable to support continued ice flow, resulting in stagnation. In many parts of the east side of the study area, well-developed streamlined features are overlain by hummocky terrain that is interpreted to be stagnant ice moraine (e.g. Fig. 3D). Therefore, the hummocky terrain represents the switch from an active ice phase to a stagnant ice phase.

The stratigraphy recorded in the Murray–Pine river valleys also supports the notion of an extensive late Wisconsinan Cordilleran/montane glacial event. The stratigraphy spans at least two glacial cycles (Fig. 11) and correlates well with that of the Peace River valley suggested by Mathews (1980), Hartman and Clague (2008) and Morgan et al. (2012). The valley-fill succession is complex and represents many depositional environments. We discuss the units in terms of temporal context and climatostratigraphy and provide only general comment on their depositional settings but there is opportunity for additional detailed study of the precise genesis of these deposits.

There is no chronological control on Unit 1, and because the base of the unit is obscured and the top is unconformably bound, its relative stratigraphic position remains unclear. Unit 1 is highly deformed, but is interpreted to have been deposited in a non-glacial fluvial setting. The sediment comprising the unit is over-consolidated and lithologically distinct from other fluvial units represented in this stratigraphy. The unit is tentatively assigned to the Sangamonian (MIS 5e) interglacial. Since this unit is stratigraphically isolated it is conceivable that it may be younger and correlative to Unit 5 (middle Wisconsinan; MIS 3). Without an age constraint its assignment to MIS 5e is speculative.

Units 2, 3, and 4 represent a CIS/montane glacial sequence and are interpreted as having been deposited during, or before, the penultimate glacial event of the early Wisconsinan (MIS 4). Unit 2 is interpreted to be a glaciofluvial deposit that conformably grades upwards into diamict interpreted to be a glaciogenic sediment flow and till. This unit is overlain by glaciolacustrine sediment. The succession represents, first, the deposition of glacial outwash, followed by the arrival of a glacier, resulting in the deformation, comminution and incorporation of existing substrate and deposition of subglacial till (cf. Dreimanis, 1988; Elson, 1988). The glaciolacustrine sediments that cap the penultimate glacial succession likely represent a retreat-phase glaciolacustrine environment and demonstrate that water was impounded by a local valley obstruction such as a glacier or landslide in a downstream tributary valley, or by a regional barrier such as a penultimate LIS.

Unit 5, a critical unit in the stratigraphy, was dated using radiocarbon (32,230–31,120 cal yr BP and 34,900–33,870 cal yr BP) and optical (22.7 ± 1.0 ka BP) methods. The unit consists of non-glacial fluvial gravel that fines upward to overbank sediments that were subsequently flooded resulting in the deposition of what is interpreted to be advance-phase glaciolacustrine sediments (Unit

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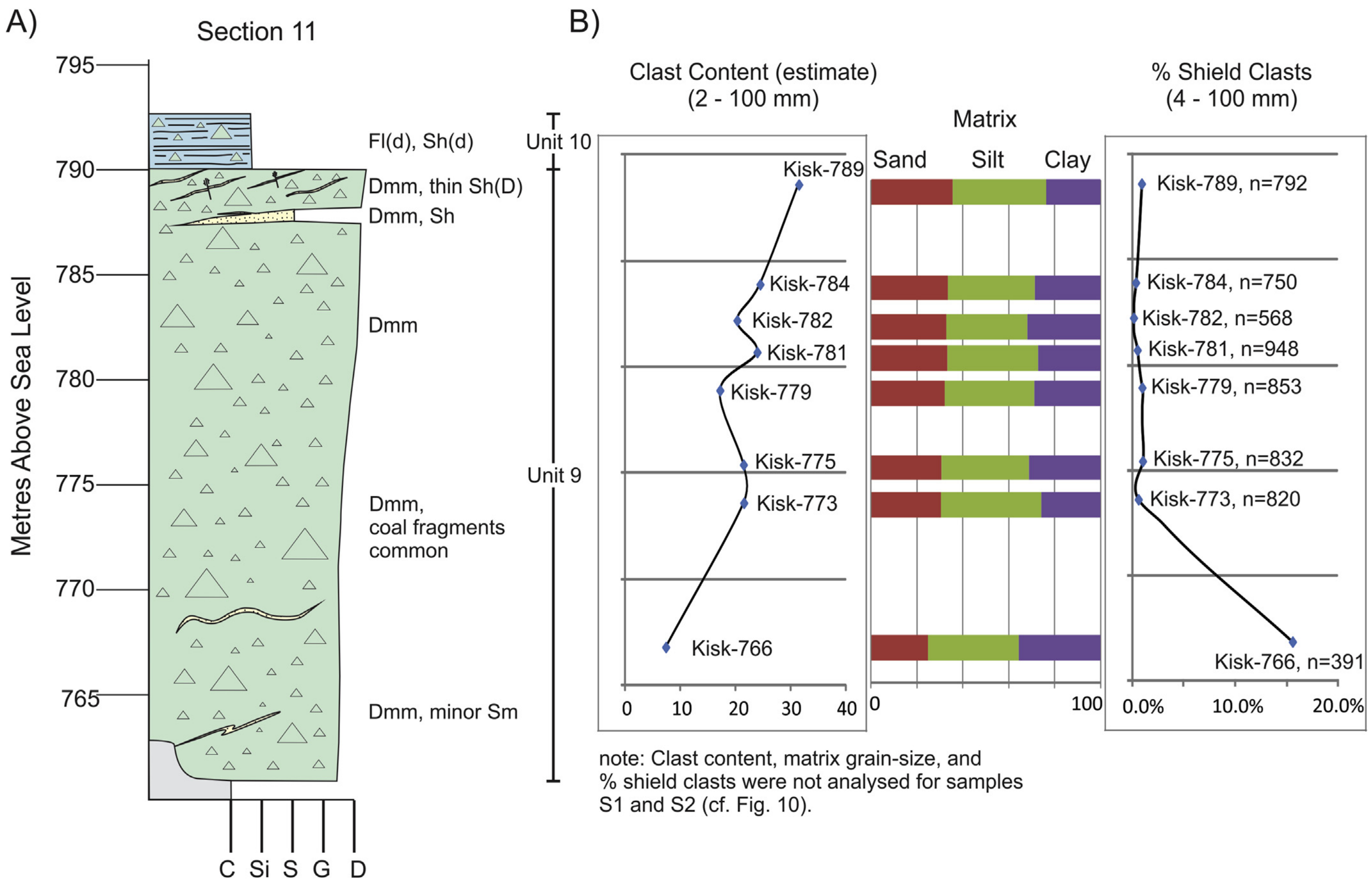

Figure 8. A) Stratigraphy of the Section 11, Kiskatinaw River (see Fig. 2 for section location; legend is the same as for Fig. 4); B) Clast content (proxy), matrix grain-size composition, and proportion of shield clasts (elevations axis same as 8a).

Table 2
Radiocarbon ages.

Sample	Lab number	Material dated	Section/Unit	Method	^{14}C age BP	cal yrs BP[a]
080929-03a	Beta-250625	wood	8/5	AMS^{14}C	27,760 ± 230	32,230–31,120
080929-03b	UCIAMS-71221	*Potentillo anserine* achenes	8/5	AMS^{14}C	30,380 ± 300	34,900–33,870

[a] Calibration based on OxCal 4.2 (Bronk Ramsey, 2009) and the IntCal 13 data set (Reimer et al., 2013).

7). The discrepancy between the radiocarbon ages and the optical age remains an avenue for more research. Regardless, the ages support a middle Wisconsinan (late MIS 3) time interval for the deposition of this unit (Fig. 12). This is consistent with a correlative fluvial unit near Town of Peace River, Alberta (Fig. 1C) where Morgan et al. (2012) reports and age of 25,120 ± 140 ^{14}C yr BP (29,530–28,800 cal yr BP). The age of Unit 5 is also consistent with ages accepted in Hartman (2005) summary for a correlative unit in the region, i.e., beyond the limits of radiocarbon dating to 22,020 ± 450 ^{14}C yr BP (27,330–25,550 cal yr BP; Fig. 12). This unit

Table 3
Radioisotope concentrations, sample depths beneath the ground surface (d), equivalent dose (D_e), cosmic-ray ($\dot{D}_c$) and total ($\dot{D}_T$) dose rates, overdispersion (OD) values, and optical ages.

Sample	Section/Unit	K (%)	U (μg/g)	Th (μg/g)	d (cm)	D_e (Gy)	$\dot{D}_c$ (Gy/ka)[a]	$\dot{D}_T$ (Gy/ka)[b]	OD (%)	Age (ka)
PR01	10/6	0.94 ± 0.06	1.93 ± 0.12	4.10 ± 0.14	20000	254 ± 12	Neg.	1.62 ± 0.10	26.1 ± 3.8	157 ± 9 [c]
						207 ± 3				128 ± 5 [d]
PR02	8/5	1.61 ± 0.08	2.93 ± 0.16	7.2 ± 0.23	1500	61.2 ± 1.7	0.0310	2.69 ± 1.70	12.0 ± 2.3	22.7 ± 1.0 [c]
CS02	7/12	1.26 ± 0.06	2.74 ± 0.16	9.40 ± 0.29	130	22.4 ± 0.5	0.168	2.57 ± 0.15	12.5 ± 1.8	8.7 ± 0.32 [c]
CS03	7/10	0.65 ± 0.04	1.57 ± 0.10	3.20 ± 0.11	8700	132 ± 29	Neg.	1.18 ± 0.07	30.5 ± 4.3	112 ± 25 [d]

Notes: uncertainties are analytical only, and are reported as ±1 standard deviation. An uncertainty was added to the "as-collected" water content values (±10%) for the dose rate calculation and is intended to account for any reasonable variation of the water content over the burial time. Radioisotope concentrations found by neutron activation analysis (NAA).

[a] Found using present burial depths and the formula of Prescott and Hutton (1994).

[b] Total dose rate, that due to α, β, particles and γ rays, and cosmic rays. The external contribution to the α dose rate was removed by etching. Calculated using standard formulae (e.g. Aitken, 1985; Berger, 1988; Lian et al., 1995) and dose-rate conversion factors of Guérin et al. (2011) and the β attenuation factors reported by Brennan (2003).

[c] Using the D_e found using the central age model (CAM).

[d] Using the D_e found using the minimum age model (MAM).

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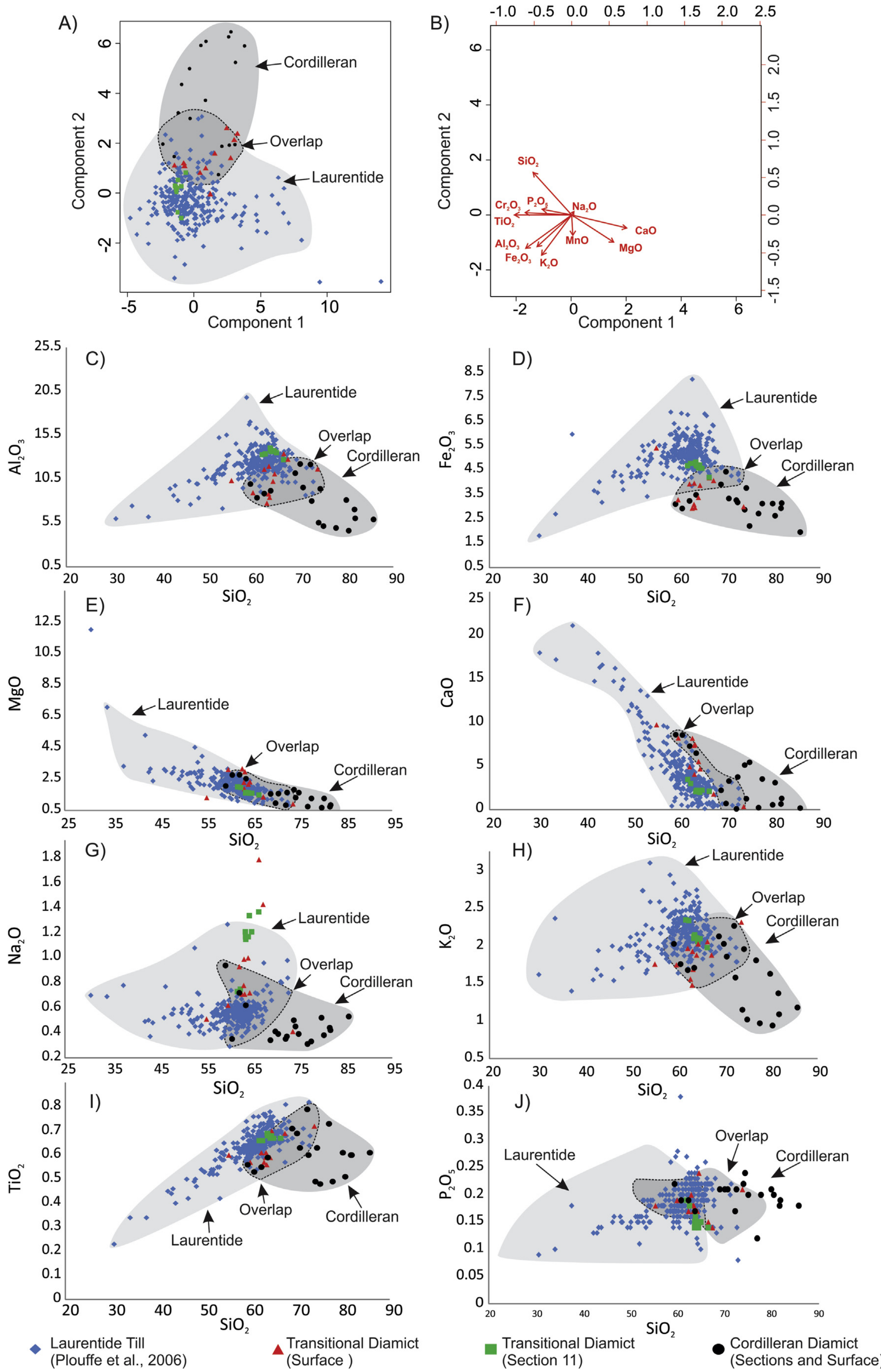

Figure 9. Comparison of major oxide geochemistry of diamict matrix from this study and Plouffe et al. (2006); A) results from principal component analysis (PCA) of major oxide geochemistry plotted in component 1 and 2 space; B) major oxide geochemical vectors from PCA plotted in component 1 and 2 space; C) Al_2O_3 verses SiO_2; D) Fe_2O_3 verses SiO_2 E) MgO versus SiO_2; F) CaO versus SiO_2; G) Na_2O versus SiO_2; H) K_2O versus SiO_2; I) TiO_2 versus SiO_2; J) P_2O_5 versus SiO_2.

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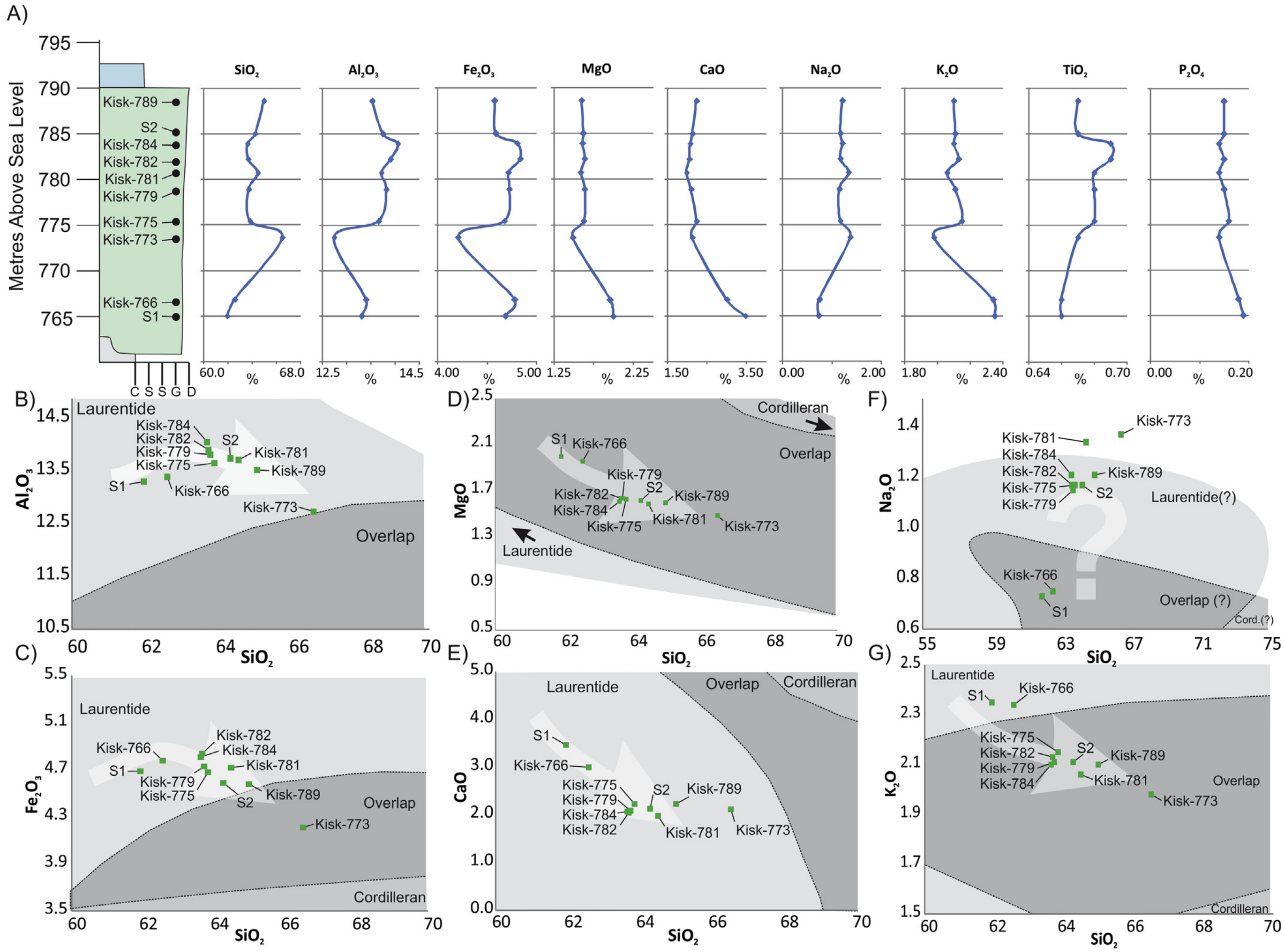

Figure 10. Major oxides geochemical trends from diamict matrix samples from Section 11. A) Major oxides in profile; B) Al_2O_3 verses SiO_2; C) Fe_2O_3 verses SiO_2 D) MgO versus SiO_2; E) CaO versus SiO_2; F) Na_2O versus SiO_2; g) K_2O versus SiO_2. Empirical discrimination fields are the same as those determined in Fig. 9.

represents the middle Wisconsinan interstadial (MIS 3) equivalent to the Olympia nonglacial interval recognized elsewhere in British Columbia (Clague, 1989).

Units 6–11 represent a second CIS/montane succession assigned to the Late Wisconsinan (MIS 2) substage equivalent to the Fraser glaciation in British Columbia. Unit 6 represents an advance-phase glaciofluvial setting and it commonly precedes the advance-phase glaciolacustrine deposits associated with what is interpreted to be glacial Lake Mathews (Hartman and Clague, 2008). The transition from Unit 5 to Unit 6 represents the switch from non-glacial fluvial deposition to glaciofluvial deposition reflecting the increased influence of advancing glaciers in the valley. Although Unit 6 (glaciofluvial) is stratigraphically lower than Unit 7 (sediments of glacial Lake Mathews) these units are probably, in part, time equivalent units and reflect transgression of glacial Lake Mathews and the contemporaneous advance of valley glaciers. The optical age (sample PR01) from sand at the contact between the glaciofluvial unit (Unit 6) and glacial Lake Mathews sediments (Unit 7) does not resolve the age of this succession. The MAM optical age suggests the deposit is no older than 128 ± 5 ka indicating it was deposited in a glacial interval during or after MIS 6. The age for this sample is surprisingly old, so two possible conclusions may be drawn: 1) the sand was deposited during MIS 6; or 2) the grains were not exposed to sufficient light to reset the luminescence 'clock' and the unit was deposited during one of MIS 6, 4 or 2. Overdispersion is relatively high, so it is likely that at least some of the grains were not exposed to enough light to reset the luminescence clock. Stratigraphic position, a conformable upper contact, and correlation of this section with the other in the study favours formation during MIS 2 (late Wisconsinan) age.

Unit 7 represents an advance-phase glaciolacustrine deposit stratigraphically equivalent to deposits assigned to glacial Lake Mathews (Hartman and Clague, 2008). This is a regionally extensive unit that is recognized throughout the Peace River district. The unit marks the arrival of the LIS east of the study area where it blocked regional drainage. The transition from fluvial to glaciolacustrine environments occurs over <1 m suggesting a very rapid rise in lake level (Hartman and Clague, 2008). Since this unit conformably overlies Unit 5 at Section 8, it must be younger than ~22.7 ± 1.0 ka (based on the optical age). Because Unit 7 is interpreted to have a glacial origin it must be of late Wisconsinan (MIS 2) age and deposited during the Fraser glaciation. This unit was observed an elevation of 760 m asl which raises the maximum elevation of glacial Lake Mathews (previously 632 m asl; Hartman and Clague, 2008) by more than 130 m. In many of the sections this unit is deformed, likely reflecting glacial tectonism and loading associated with the arrival of the MIS 2 CIS/montane glaciers.

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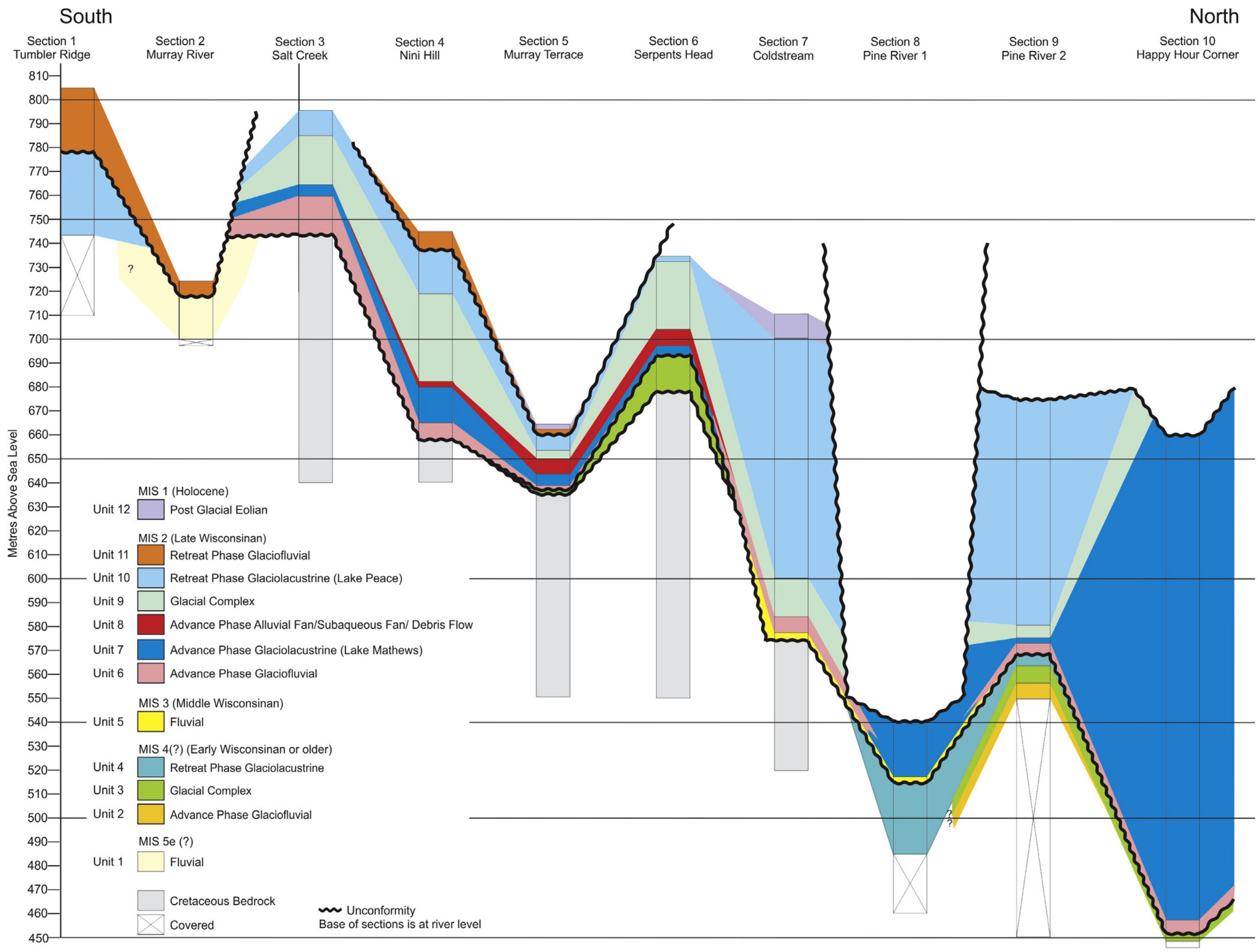

Figure 11. South to North correlated cross-section of the stratigraphy of the Murray and Pine river valleys.

Unit 8 consists of sediments interpreted as being deposited in alluvial fans or sediments dominantly transported by gravitational processes from the unstable slopes of the valley and debris-flows from advancing glaciers. These deposits may, in part, represent glacial debris shed from the advancing ice front into glacial Lake Mathews.

The succession at Section 6 provides a nearly complete summary of the late Wisconsinan sequence for the Murray River valley. At Section 6, Unit 8 forms a 1 km-long wedge-shaped deposit and is likely a debris-flow fan deposited into glacial Lake Mathews in front of an advancing glacier. Unit 9 is complex and represents a number of glaciogenic depositional settings. The lower part of Unit 9 (Unit 9a) is interpreted to be glacially tectonized waterlain diamict. Unit 9a is in turn overlain by basal till of Unit 9b.

Retreat-phase glaciolacustrine sediments (Unit 10) were deposited in glacial Lake Peace. These sediments are ubiquitous across the Peace Region of northeast British Columbia and northwest Alberta. Glacial Lake Peace formed as a proglacial lake when regional (eastward) drainage was blocked by the LIS. Glacial Lake Peace followed the LIS margin as it retreated to the northeast (Mathews, 1980; Hickin et al., 2015). An optically dated sample (CS03) collected from sand over subaqueous outwash gravel above diamict at the base of Unit 10 (Section 7) returned a MAM optical age of no older than 112 ± 25 ka years BP, but as noted earlier the luminescence signal measured from many of the aliquots was near saturation. This indicates that many of the grains were not exposed to sufficient sunlight prior to burial. Although the time of formation of this unit is inconclusive (i.e. younger than 112 ka) the optical age value does support the notion that these sediments probably accumulated in an environment with limited sunlight exposure. This supports the interpretation that the unit was deposited in a subaqueous environment, probably from a glacier in contact with glacial Lake Peace. Optical ages determined by Hickin et al. (2015) from shorelines associated with glacial Lake Peace range from ~16 to 14 ka. Organic material from the base of Unit 10 in the Ft St John area provides an age of 13,970 ± 170 ^{14}C yr BP (17,470–16,410 cal yr BP; Catto et al., 1996) which is the oldest age for a unit over till from Hartman (2005) summary (Fig. 12).

The youngest glacial unit in the succession, Unit 11, is a retreat-phase glaciofluvial unit. It is common in terraces along the major river valleys and also occurs as relic deltas from stable phases of glacial Lake Peace (Fig. S6a). Numerous radiocarbon ages have been published for the glaciofluvial gravels in the Peace Region between Fort St John and Tumbler Ridge. Those in Hartman (2005) summary range from 10,380 ± 100 to 9880 ± 130 ^{14}C yr BP (12,570–10,820 cal yr BP).

The final unit in the stratigraphic sequence is an aeolian unit that is represented by sand dunes and loess. Following glaciation, but before widespread forests became established, aeolian activity occurred in northeast British Columbia, i.e., in a paraglacial setting

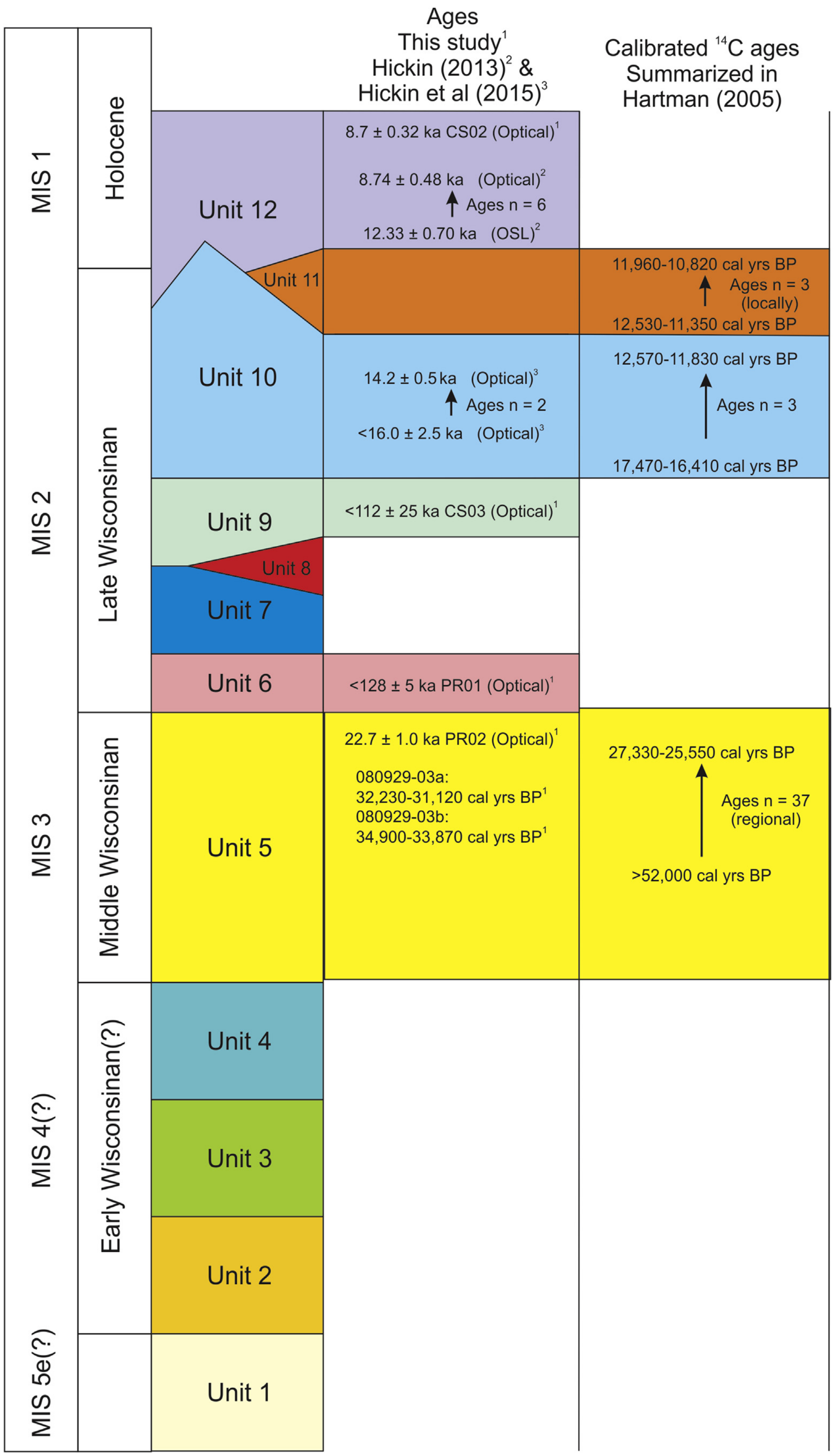

Figure 12. Summary of the stratigraphy and chronology from the study area (same legend as Fig. 11). Optical ages for units 6 and 9 are likely maximum ages, consequently, the depositional age for these units is younger. Correlation suggests they were deposited during the late Wisconsinan (MIS 2).

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(Wolfe et al., 2004, 2007; Hickin, 2013). An optical dated sample collected in the Coldstream area returned an age of 8.7 ± 0.3 ka from what is interpreted to be loess. This age is consistent with the radiocarbon age 8260 ± 80 ^{14}C yr BP (9440-9020 cal yr BP) from wood in the aeolian surface sediment at the town of Peace River (Morgan et al., 2012) and optical ages that range from 12.3 ± 0.7 to 8.7 ± 0.5 ka for sand dunes (stabilization ages) within the study area (Hickin, 2013).

Our stratigraphy is generally consistent with the conclusions of several studies in the region (e.g. Mathews, 1980; Liverman, 1989; Wolfe et al., 2004, 2007; Bednarski and Smith, 2007; Hartman and Clague, 2008; Morgan et al., 2012). The late Wisconsinan (MIS 2) glacial interval is well represented in the stratigraphy of the Murray-Pine river valleys. The chronology presented suggests that CIS/montane ice was present in the vicinity of the valleys between ~22 and 17 ka. Our interpretation of the stratigraphy implies that the surface landforms in the Dawson Creek map area are late Wisconsinan in age.

We are, however, unable to reconcile our stratigraphy with several other studies. Bobrowsky (1989) and Bobrowsky and Rutter (1992) present an age of 15,180 ± 100 ^{14}C yr BP (18,690–18,160 cal yr BP) from a sub-till wood from the Finlay River area, which restricts the time available for the CIS to expand and flow onto the interior plains. Our ages also cannot be reconciled with radiocarbon ages from bulk organics dated by Jull and Geertsema (2006) and Woolf (1993) that support limited ice coverage in the area during the late Wisconsinan. Jull and Geertsema (2006) have a series of radiocarbon ages from an incised alluvial fan on a fluvial terrace above the Peace River (known locally as Bear Flats) that implies no glaciation after ~ 36,000 ^{14}C yr BP (~40,000 cal yr BP). There are, however, many age inversions in the succession and they state that ages older than 19,500 cal yr BP should be treated with caution. The abundance of coal in these sediments casts some doubt on the validity of the older ages. Woolf (1993) presented radiocarbon ages ranging from 33,100 ± 1800 to 15,800 ± 1300 ^{14}C yr BP (42,020–34,190 to 23,000–16,200 cal yr BP) for a lacustrine deposit under the upper most till in the Cache Creek Road area west of Fort St John. Woolf (1993) recognizes the possibility of contamination; consequently we question the legitimacy of the youngest ages.

Conclusion

This study seeks to determine if the Laurentide and Cordilleran ice sheets coalesce or remain separate during the late Wisconsinan in northeastern BC. We conclude that, indeed, there was ice-sheet coalescence in this region at this time and we base our conclusion on three main lines of evidence:

(1) There exists in the Dawson Creek area a continuous field of streamlined landforms indicating that a major lobe of east flowing ice, sourced in, or west of the Rocky Mountains, was deflected from east-northeast to a north-northwest trajectory. There are no topographic features that could have caused this deviation to flow so it is inferred that it was caused by the presence of the LIS.

(2) The east to north-northeast flowing ice lobe post-dates the late Wisconsinan (MIS 2) maximum advance of the LIS. The streamlined landforms that record the flow of western-sourced ice are constructed of till with clasts of eastern provenance (Proterozoic Canadian Shield clasts). This implies that the LIS must have reached its maximum extent before the western-sourced ice flowed across the area. This sequence is recorded in the till (major oxide geochemistry, grain-size, and proportion of shield clasts) in this zone of overlap. Since it has been established by Liverman et al. (1989) that the LIS reached its maximum extent in this area during the late Wisconsinan, the CIS/montane ice responsible for the streamlined landforms must also have occupied the area in the late Wisconsinan (MIS 2).

(3) Stratigraphy from the Murray and Pine river valleys supports a late Wisconsinan age for the surface landforms. The stratigraphy represents at least two CIS/montane glacial advances separated by a non-glacial interval. Two calibrated radiocarbon ages of 32,230–31,120 and 34,900–33870 cal yr BP, and an optical age of 22.7 ± 1.0 ka indicate a middle Wisconsinan (MIS 3) age for the non-glacial interval. This confirms that the regionally extensive glacial sediments that occur stratigraphically above this unit are late Wisconsinan (MIS 2) in age.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.yqres.2016.02.005

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