Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia

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Abstract: Two Cordilleran and three Laurentide glacial advances are recorded in Quaternary sediments and landforms in the Peace River valley, northeast British Columbia. The advances are inferred from fluvial gravels, glaciolacustrine sediments, and tills within nested paleovalleys excavated during three interglaciations and from the distribution of granitoid clasts derived from the Canadian Shield. Till of the last (Late Wisconsinan) Laurentide glaciation occurs at the surface, except where it is overlain by postglacial sediments. The advance that deposited this till was the most extensive in the study area, and the only advance definitively recognized in western Alberta south of the study area. Late Wisconsinan Cordilleran till has not been found in the study area, but Cordilleran and Laurentide ice may have coalesced briefly during the last glaciation. Support for this supposition is provided by the inferred deflection of Laurentide flutings to the southeast by Cordilleran ice. The earliest Laurentide advance may have been the least extensive of the three Laurentide events recognized in the study area. Erratics attributed to this advance occur only east of the Halfway River – Beatton River drainage divide.

Résumé : Deux avancées glaciaires de la Cordillère et trois de l’Inlandsis laurentien sont évidentes dans les sédiments et la topographie du Quaternaire de la vallée de la rivière Paix, dans le nord-est de la Colombie-Britannique. Les avancées sont déduites à partir des graviers fluviatiles, des sédiments glacio-lacustres et des tills dans des paléovallées emboîtées excavées durant trois périodes interglaciaires et à partir de la distribution des clastes granitoïdes provenant du Bouclier canadien. Un till de la dernière glaciation laurentienne (Wisconsinien tardif) se retrouve à la surface, sauf là où il est recouvert de sédiments post-glaciaires. L’avancée qui a déposé ce till a été la plus extensive dans le secteur à l’étude et c’est la seule avancée définitivement reconnue dans l’ouest de l’Alberta, au sud du secteur à l’étude. Aucun till de la Cordillère datant du Wisconsinien n’a été trouvé dans le secteur à l’étude. Cependant, la glace de la Cordillère et celle de l’Inlandsis laurentien pourraient s’être unis durant une brève période au cours de la dernière glaciation. Cette hypothèse est soutenue par la déflexion inférée de rainures glaciaires laurentiennes vers le sud-est par la glace de la Cordillère. L’avancée glaciaire laurentienne la plus précoce pourrait être la moins étendue des trois événements laurentiens reconnus dans le secteur à l’étude. Les blocs erratiques attribués à cette avancée ne se retrouvent qu’à l’est de la ligne de partage des eaux entre les rivières Halfway et Beatton.

[Traduit par la Rédaction]

Introduction

The Quaternary stratigraphy of Peace Valley was documented 30 years ago by Mathews (1978) but, since then, some researchers working in northeast British Columbia and northwest Alberta have come to conclusions incompatible with Mathews’ interpretation of the history of Cordilleran and Laurentide glaciations of the area. Moreover, the Quaternary history along the entire Canadian Rocky Mountain front has, in recent years, been revised. Early researchers inferred up to four Laurentide glaciations of the Alberta Plateau, but recent work has reduced this number, and some workers have suggested that only one advance reached Edmonton, Simonette, and Watino (Fig. 1). The number of Cordilleran advances has also been reduced from that proposed by early workers.

These revisions have been driven, in part, by improvements in describing and interpreting sediments, especially diamictons (Eyles et al. 1983). Equally important, MacDonald et al. (1987) demonstrated that radiocarbon ages on gyttja and some freshwater aquatic plants suffer an “old carbon effect.” These and other developments led to the re-evaluation of interpretations based on incorrectly described deposits or spurious radiocarbon ages. The work of early researchers however, cannot be completely discounted. Henderson (1959), Tokarsky (1967), St-Onge (1972), and Mathews (1978) present evidence for multiple glaciations that is not dependent on lithofacies interpretations and radiocarbon ages.

Even recent researchers, however, do not agree on the extent and times of Cordilleran advances and whether or not...
Cordilleran glaciers ever coalesced with the Laurentide ice sheet. Jackson et al. (1997), Bednarski (1999, 2001), Dyke et al. (2002), and Bednarski and Smith (2007) have argued for extensive Late Wisconsinan Cordilleran glaciation, involving coalescence of Cordilleran and Laurentide ice over a considerable distance of the Rocky Mountain front. Bobrowsky (1989), Bobrowsky et al. (1991, 1992), Bobrowsky and Rutter (1992), and Catto et al. (1996), on the other hand, concluded that the Late Wisconsinan Cordilleran advance was restricted, and they attributed the most extensive Cordilleran advance to an earlier glaciation.

The Peace River valley in northeast British Columbia is ideally located for a study of interactions of Cordilleran and Laurentide glaciers. It was affected by both the Cordilleran and Laurentide ice sheets, and Quaternary sediments are well exposed along Peace River and its tributaries. In addition, interstadial and interglacial paleovalleys have been partially preserved, allowing an assessment of the stratigraphic relations between valley-fill sediments of different age.

**Study area**

This study was conducted in the Charlie Lake map area (National Topographic System (NTS) 94A), which is located within the Alberta Plateau subprovince of the northern Interior Plains (Fig. 1). The area is a flat to gently rolling
Methods

Exposures of Quaternary sediments were visited and described during the summers of 2002 and 2003 (Fig. 3). This task entailed locating intact exposures, defining and describing sedimentary units, measuring elevations of unit contacts, and collecting samples.

Sediments were described and grouped using the lithofacies analysis method (Eyles et al. 1983). Characteristics and features that were noted include grain size, sorting, sedimentary structures, colour, clast lithology, compaction, jointing, weathering, sliding planes, rupture surfaces, and the angle of the exposure face. Basal and upper contacts of units were also described, and fossils, erratics, striated surfaces, fabric, and deformation features, if present, were noted.

The colours of moist sediment samples were determined using the Geological Society of America Rock Color Chart (Goddard et al. 1963). Pebble fabrics were determined by measuring the trends and plunges of 50 (Woodcock 1977) rod-shaped clasts \((a:b \geq 2)\) from a small area of exposure. Elevations of unit contacts were determined using a barometric altimeter and a laser range finder (Hartman 2005). Pink orthoclase-rich granite and granitoid gneiss pebbles, which are exotic lithologies in western Canada, were collected for examination in the laboratory.

Additional stratigraphic information was acquired from water well drill logs, and geotechnical drill logs. The drill logs were obtained from a database maintained by the BC Ministry of Sustainable Resource Management. Geotechnical drilling and water well logs also provided data on the elevation of the bedrock surface in drift-covered areas.

Stratigraphic data were entered in a geographic information system (GIS) to examine lithostratigraphic units in three dimensions. The GIS was also used to interpolate a bedrock surface and discern the form of buried paleovalleys. The surface was interpolated over known and estimated bedrock surface points using inverse distance weighting.

Paleovalleys, planation surfaces, and deep bedrock basins

Three relict fluvial drainage systems are graded to different base levels, providing a framework for understanding the Quaternary stratigraphy and history of the study area. Post-glacial Peace River has incised almost 50 m deeper into bedrock than any of its precursors; the river today flows over bedrock through most of the study area. Two incised bedrock straths at different elevations, and thus different ages, are exposed in the valley walls of Peace River and its tributaries (Fig. 4). The straths and overlying fluvial sediments have been identified in water well drill logs away from valley wall exposures. A broad gravel-covered fluvial planation surface, which is not incised, occurs locally on the uplands at a higher elevation than the higher of the two incised straths.

The two incised straths are the floors of paleovalleys that are buried beneath up to 180 m of Pleistocene sediments. As Mathews (1978) suggested, the paleovalleys define drainage systems that pre-date the glaciations responsible for their burial. The straths are best delineated where they are near and intersect the modern Peace River. Limited exposure along tributaries of Peace River precludes detailed assessment of the tributary paleovalleys beyond their lower reaches.

The lower incised strath is locally well exposed about 50 m above Peace River and has been encountered in water wells elsewhere. It slopes 0.0006 down to the east, a gradient similar to that of modern Peace River. The higher in-
The higher paleovalley system is more difficult to delineate than the lower one. It was only definitively identified on the north side of Peace River between Moberly River and the British Columbia – Alberta boundary. Although only a portion of the upper paleovalley is preserved, what remains indicates that it was almost four times as wide as the modern Peace River valley and wider than the lower paleovalley. The lower paleovalleys of Peace and Beatton rivers are incised into the higher paleovalley, as are the modern valleys of Peace, Beatton, and Alces rivers and many smaller tributaries.

Deep bedrock basins occur below the Portage Mountain end moraine and near Lynx Creek (Fig. 5; Rutter 1977; Matthews 1978; Hartman 2005). The basins are close to the Rocky Mountain front, where a former lobe of the Cordilleran ice sheet flowed onto the Alberta Plateau. The location and depth of the basins suggest that they were carved by a Cordilleran outlet glacier. This interpretation is supported by the presence of diamicton near the base of a drill hole through the Portage Mountain end moraine (Rutter 1977). The basins are localized and do not appear to be structurally controlled.

**Quaternary stratigraphy**

**Fluvial deposits of the high planation surface**

Fluvial gravel overlies a bedrock strath that stands slightly higher than the adjacent plateau (Fig. 6; Table 1). Erosion has removed most of this unit and lowered the surface of the uplands around its remnants.
The unit is, on average, 6 m thick; its upper surface is about 330 m above present-day Peace River. It is composed mainly of well-sorted, cross-bedded, pebble–cobble gravel with minor lenses of silt and sand. Cross-beds at section M-3 (Imperial gravel pit) record northward flow. All clasts are of Cordilleran or local provenance.

**Fluvial deposits of the upper paleovalley**

A younger fluvial gravel unit overlies the higher of two incised bedrock straths, within the upper paleovalley of Peace River (Fig. 6; Table 1). The strath is located on the north side of Peace River valley between the confluence of Peace and Moberly rivers and the British Columbia – Alberta boundary.
The unit has an average thickness of about 8 m, and its top is about 225 m above present-day Peace River. The dominance of lithofacies interpreted to be channel deposits suggests that the sediments were deposited by a braided river (Miall 1977). The gravel consists mainly of Cordilleran lithologies, notably quartzite, chert, sandstone, granitic and volcanic rocks, and carbonates. Eastern exposures near Alices River also contain rare granite gneiss clasts derived from the Canadian Shield. No gneiss clasts were found in western exposures of the unit near Old Fort.

**Advance-phase glaciolacustrine deposits of the upper paleovalley**

Up to 66 m of glaciolacustrine silt and sand conformably overlie fluvial gravel of the upper paleovalley (Fig. 6; Table 1). They occur up to 613 m above sea level (a.s.l.) within the upper paleovalley.

This lithostratigraphic unit is dominated by lithofacies indicative of deposition from suspension and underflows in a lake, including laminated mud and sand, massive sand, rippled sand, and trough cross-bedded sand. Dropstones and diamicton pods, some containing Canadian Shield clasts, increase in abundance toward the top of the unit. The transition upwards from ice-distal to ice-proximal lithofacies indicates the approach of Laurentide ice.

**Pre-Late Wisconsinan Laurentide till?**

Mathews (1978) hypothesized that tills of two Laurentide glaciations are present in exposures on the north side of Peace River valley near Old Fort (Fig. 6). He assigned the
lower of the two tills to a pre-Late Wisconsinan glaciation. An attempt was made to test this hypothesis by measuring the clast fabric of the lower till. A clast fabric from the base of section SS-26 has a polymodal to girdle distribution with a dominant mode oriented 120°, perpendicular to the regional ice flow direction during the last glaciation (Mathews 1978). Striations on a boulder pavement at the base of this unit trend 112°, similar to the direction of the dominant fabric mode. However, at section SS-24, a clast fabric from the base of a similar diamicton has a spread unimodal distribution with a dominant mode of 218°, parallel to surface ice-flow indicators.

Two Laurentide tills directly overlie one another at section SS-50 near Old Fort. They can be distinguished by their clast content, colour, and the presence of a recessive band at the sharp undulating contact between the two units. The lower till has a strong bimodal fabric with clusters oriented 248° and 68°. A large anvil-shaped boulder at the base of the lower till appears to have been lodged and has a flat upper surface with two sets of striations, an older set oriented 240° and a younger set oriented 220°. The fabric and striations are roughly parallel to the surface ice-flow indicators. The upper till corresponds stratigraphically with the Late Wisconsinan Laurentide till.

**Western-provenance till**

Up to 60 m of till of western provenance is exposed in lower Halfway River valley (Fig. 6; Table 1). The high clast content (about 30%), silty sand matrix, and greyish-orange (10YR 7/4) colour distinguish the unit from Laurentide till (clast content typically 10%, clay-rich matrix, and olive grey (5Y 3/2) colour). Clasts are almost entirely of Cordilleran or local provenance; only two possible Laurentide pebbles were found at section SS-75. A clast fabric taken near the middle of the unit at section SS-75 has a strong unimodal distribution with a primary eigenvector of 221°, parallel to the orientation of a nearby gap in the mountains through which Peace River once flowed (Beach and Spivak 1943). The western-provenance till is overlain across an unconformable contact by Late Wisconsinan outwash, glaciolacustrine sediments, and till, and thus is older than the last glaciation.

**Fluvial deposits of the lower paleovalleys**

Fluvial gravel lies on the floors of the lower paleovalleys (Fig. 6; Table 1). It is well exposed in the walls of the modern Peace River valley and its larger tributaries (Fig. 7).

The unit is 13 m thick on average; its top is about 50 m above modern river level. It is interpreted to be channel deposits of a braided river (Miall 1977). Gravel transported by the paleo-river is about the same size as that carried by the modern river. Eastward flow is indicated by paleoflow measurements. The gravel is dominated by Cordilleran and local lithologies, but it contains rare clasts derived from the Canadian Shield in exposures between Lynx Creek and the eastern boundary of the study area.

**Advance-phase glaciolacustrine deposits of the lower paleovalleys**

Up to 100 m of glaciolacustrine sediments conformably overlie fluvial gravel of the lower paleovalleys (Figs. 6, 7, 8; Table 1). They record damming of the paleo-Peace valley and its tributaries early during the last glaciation. The unit is dominated by laminated mud and horizontal and drape-laminated sands deposited from suspension and underflows in ice-distal, deep-water environments (Gustavson et al. 1975; May 1977; Ashley 1988; Wolfe and Teller 1995).

Coarser sediments are present in the glaciolacustrine unit near paleovalley walls. They include clast-supported massive diamicton deposited by subaqueous debris flows (May 1977) and cross-bedded, horizontally bedded, and rippled sands deposited by energetic density underflows (Wolfe and Teller 1995). Similar sediments have been interpreted to be basin-marginal glaciolacustrine deposits (Ashley 1988; Wolfe and Teller 1995).

The dominant, laminated mud facies generally contains no dropstones. However, at sections where the unit has not been extensively eroded by Laurentide ice, dropstones and diamicitic pods increase in abundance upward through the unit.

Advance-phase glaciolacustrine sediments may extend into the Rocky Mountain Foothills between Portage and Bullhead mountains. The log of the drill hole through the Portage Mountain end moraine records silt, silty sand, and clayey sand overlying interbedded gravel, sand, and silt (Campbell 1959). Based on its thickness and elevation range, the gravel is assigned to fluvial deposits of the lower paleovalley. The overlying finer sediments likely record deposition in a lake dammed by advancing Laurentide ice.

The highest known elevation of the lower paleovalley glaciolacustrine unit is 632 m a.s.l. The lake thus extended to at least this elevation at its maximum stage.

**Till of the last glaciation**

Laurentide till is a widespread surface or near-surface unit in the study area. It is a massive matrix-supported diamicton with <15% clasts and a silt and clay matrix. Many of the clasts are granite and granitoid gneiss derived from the Canadian Shield.

Drumlins and flutings mapped by Mathews (1978) suggest that the Laurentide ice sheet flowed to the south-southwest during the Late Wisconsinan. The flow indicators shift to the south-southeast in the southeast part of the study area, indicating an interaction between Cordilleran and Laurentide ice. Previously mentioned pebble fabric orientations and striated pavements measured at the base of the till at two sections (SS-24 and SS-50) match the direction of regional ice flow. However, at sections SS-26 and SS-91, the fabrics are parallel to the local paleovalley axis and transverse to the regional flow direction. These data may be interpreted in two ways—either till from two separate glaciations are superposed at sections SS-26 and SS-91 (Mathews 1978), or initial Laurentide ice flow into these areas was topographically controlled (Catto et al. 1996).

The ice sheet that deposited the till extended west beyond the study area into the Rocky Mountain Foothills, but no terminal moraine related to this advance has been identified. Canadian Shield erratics occur above the maximum limit of Glacial Lake Peace in east-draining valleys of the foothills (Bobrowsky et al. 1991; Catto et al. 1996).
Late-glacial glaciolacustrine deposits

Glacial Lake Peace was impounded behind retreating Laurentide ice at the end of the last glaciation (Fig. 6; Mathews 1978, 1980). Sediments deposited in this lake consist mainly of laminated mud with <5% dropstones. Several stages of Glacial Lake Peace have been identified from relict shorelines, deltas, and spillways (Rutter 1977, Mathews 1980, Woolf 1993).

Postglacial deposits

Fluvial gravel underlies terraces cut during postglacial incision of the modern Peace River valley (Fig. 6). The most prominent terrace is 45 m above present-day Peace River; its capping gravel is about 17 m thick. Postglacial gravel is similar to older gravel units, except for its much greater proportion of eastern-provenance clasts. Landslide deposits are ubiquitous in Peace River valley and its major tributaries. Most of the deposits are massive matrix-supported diamicton that is less compact than typical Laurentide till and generally has a lower clast content. Recognition of postglacial landslide deposits, however, is based less on lithofacies than on geomorphology. Landslide deposits typically have hummocky surfaces with gentle to moderately inclined slopes. The surfaces of active landslides are marked by tension cracks, tilted trees, and sag ponds, and are located down-slope from scalloped head scarp.

Geologic history

Four drainage systems of different age, including the modern drainage system, are recognized in the study area (Fig. 9). A fifth, older system is recorded by fluvial gravel overlying an eastward-sloping peneplain east of the study area (Mathews 1978; Liverman 1989). East-draining rivers in the study area established themselves at successively lower elevations during middle and late Cenozoic time following the Laramide Orogeny. Mathews (1989) noted local dissected gravel-capped peneplains of early Oligocene to late Tertiary age in the Rocky Mountain Foothills and western Interior Plains from Montana north to the Richardson Mountains in Yukon Territory. Remnants of lower drainage systems are probably Pleistocene in age. Successive drainage systems cross-cut and nest within one another, producing a palimpsest of valley in-fills that provide a framework on which a relative chronology of geologic events can be placed.

Incision of the drainage systems is probably due to a combination of epeirogenic uplift (Pazzaglia et al. 2001; McMillan and Heller 2002), increased erosion due to climatic forcing in the late Cenozoic (Dethier 2001), and base-level lowering resulting from drainage integration and glaciation (Pederson and Pazzaglia 2002).

Pre-Laurentide river system

Fluvial gravel of the high planation surface is the oldest post-Cretaceous lithostratigraphic unit in the study area. It lacks eastern-provenance clasts and thus was deposited prior to the first Laurentide glaciation of the study area. The gravel records a period of deposition following planation of bedrock surfaces by an east- to north-flowing river system. Its wide distribution on low-relief upland bedrock surfaces suggests deposition on a broad peneplain.

The gravel is younger than higher gravels of middle to late Tertiary that cap peneplains at the west edge of the Interior Plains, including the Clear Hills, Saddle Hills, and Chinchaga Hills (Mathews 1978; Liverman 1989; Stott and Aitken 1993). It is tentatively assigned a late Tertiary or

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**Table 1. Characteristics of lithostratigraphic units recognized in the study area.**

<table>
<thead>
<tr>
<th>Lithostratigraphic unit</th>
<th>Avg. elev. above Peace River (m)</th>
<th>Thickness (m)</th>
<th>Areal extent</th>
<th>Dominant lithofacies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postglacial deposits</td>
<td>Variable</td>
<td>17 (mean)</td>
<td>valley slopes and floors</td>
<td>gravel, matrix-supported diamicton, massive silt laminated mud</td>
</tr>
<tr>
<td>Late-glacial glaciolastrine deposits</td>
<td>Variable</td>
<td>10 (mean)</td>
<td>various stages of Glacial Lake Peace</td>
<td></td>
</tr>
<tr>
<td>Till of the last glaciation</td>
<td>Variable</td>
<td>12 (mean)</td>
<td>Regional</td>
<td>Matrix-supported diamicton</td>
</tr>
<tr>
<td>Advance-phase glaciolastrine deposits of the lower paleovalley</td>
<td>Variable</td>
<td>18 (mean), 100 (max)</td>
<td>Lower paleovalley</td>
<td>Laminated mud, massive, rolled, and trough cross-bedded silt and sand</td>
</tr>
<tr>
<td>Fluvial deposits of the lower paleovalley</td>
<td>50</td>
<td>13 (mean), 67 (max)</td>
<td>Lower paleovalley</td>
<td>Horizontally bedded gravel</td>
</tr>
<tr>
<td>Western-provenance till</td>
<td>Variable</td>
<td>40 (mean), 60 (max)</td>
<td>Lower Halfway valley</td>
<td>Matrix-supported diamicton</td>
</tr>
<tr>
<td>Pre-middle Wisconsinan eastern-provenance till?</td>
<td>Variable</td>
<td>32 m (one locality only)</td>
<td>Local</td>
<td>Matrix-supported diamicton</td>
</tr>
<tr>
<td>Advance-phase glaciolastrine deposits of the upper paleovalley</td>
<td>Variable</td>
<td>33 (mean), 66 (max)</td>
<td>Upper paleovalley</td>
<td>Laminated mud, massive, rolled, and trough cross-bedded silt and sand</td>
</tr>
<tr>
<td>Fluvial deposits of the upper paleovalley</td>
<td>225</td>
<td>8 (mean)</td>
<td>Upper paleovalley</td>
<td>Horizontally bedded gravel</td>
</tr>
<tr>
<td>Fluvial deposits of the high planation surface</td>
<td>330</td>
<td>6 (mean)</td>
<td>Regional</td>
<td>Horizontally bedded gravel</td>
</tr>
</tbody>
</table>
early Pleistocene age because it pre-dates the oldest Laurentide glaciation of the study area and because it lies on highly dissected, fluvially eroded bedrock. Drainage subsequently became incised into this broad planation surface.

**Early nonglacial river system**

The next younger deposit in the study area is fluvial gravel of the upper paleovalley. It contains the same lithologies as the older, pre-glacial gravel unit, with one important exception. Rare clasts of granite and granitoid gneiss derived from the Canadian Shield occur in exposures near Alces River and Golata Creek and at section SS-109, but not farther west. The Canadian Shield clasts must have been transported westward up the regional slope of the Interior Plains during an early Laurentide glaciation. Matthews (1978) concluded that the clasts were transported as far west as Golata Creek by Laurentide ice. Alternatively, they could have been rafted on icebergs in a lake dammed by the Laurentide ice sheet somewhere to the east, or they could have been transported into paleo-Peace River valley by a northern tributary or by meltwater diverted along the Laurentide ice margin. At the very least, the presence of these clasts indicates that an early Laurentide advance approached the study area.

This early glaciation may be younger than the Matuyama Reversed Polarity Chron (0.78 Ma). Barendregt and Irving (1998) found that all glacial sediments on the central Interior Plains are normally magnetized and concluded that the Laurentide ice sheet first reached the western Interior Plains after 0.78 Ma ago.

Glaciation may have been partly responsible for entrenchedment of the high bedrock planation surface. Pederson and Pazzaglia (2002) concluded that glacial repositioning and integration of drainage were important causes of base-level lowering.

**Penultimate glaciation**

**Laurentide advance**

Advance-phase glaciolacustrine sediments of the upper paleovalley conformably overlie nonglacial fluvial gravel. They were deposited when Laurentide ice advanced up the regional slope of the western Interior Plains and blocked east-flowing paleo-Peace River. The glaciolacustrine sediments occur in outcrop west to Old Fort, but the lake reached to at least 613 m a.s.l. and thus extended farther west.

Advance-phase glaciolacustrine sediments have not been dated, but they are older than the lower paleovalley system into which they are cut. The lower paleovalley is no younger than Middle Wisconsinan (see later in the text), consequently the glaciolacustrine sediments filling the upper paleovalleys, as well as the Laurentide ice sheet that impounded the lake in which these sediments accumulated, are Early Wisconsinan or older.

Older advance-phase glaciolacustrine sediments and Canadian Shield clasts within the lower paleovalley fluvial gravel provide definitive evidence for the penultimate Laurentide advance. Although uncommon, shield clasts were recovered from lower paleovalley gravel as far west as Lynx Creek, corroborating Mathew’s assertion that the penultimate Laurentide glaciation transported eastern-provenance clasts farther west than an earlier Laurentide advance.

The western limit of the penultimate Laurentide advance is unknown. No definitive landforms or till of the pen-
ultimate glaciation have been found, thus the possibility that Canadian Shield clasts were transported into the study area by an agent other than a glacier must be considered. Perhaps the clasts were rafted on icebergs or carried by streams to the positions they are found today.

The penultimate and last glaciations were separated by an interglaciation during which the lower paleovalley system developed. Based on this evidence, the penultimate event is Early Wisconsinan or older.

Cordilleran advance

A till in lower Halfway River valley is the only western-provenance glacial unit found in the study area. It may have been deposited by the glacier that eroded the bedrock basins beneath the Portage Mountain end moraine and Lynx Creek. The basins contain thick glaciolacustrine sediments that are truncated by fluvial deposits of the lower paleovalley. These stratigraphic relations suggest that the early Cordilleran advance is older than the lower paleovalley. Furthermore, Cordilleran till is not present in any of the exposures between the Rocky Mountain front and Halfway River, making it unlikely that the Cordilleran till at Halfway River is Late Wisconsinan in age. This inference is in agreement with Bobrowsky (1989), Bobrowsky and Rutter (1992), and Catto et al. (1996), who assigned the early Cordilleran till to an Early Wisconsinan or older glaciation.

The last interstade

The lower paleovalley fluvial deposits record an east-
flowing river system. They are the oldest sediments in the study area that have been securely dated. Mathews (1978) recovered a mammoth tooth that yielded a radiocarbon age of 27,400 ± 580 14C years BP (GSC-2034) from paleovalley gravel beneath postglacial terrace gravel at Taylor. A bison vertebra from the same unit at section SS-29 gave an age of 26,450 ± 310 14C years BP (Beta-188305). The two ages indicate that Peace River was aggrading its channel within the lower paleovalley late during the Middle Wisconsinan.

Ancestral Peace River flowed north of Portage Mountain before the last glaciation. Fluvial gravel encountered between 527 and 547 m a.s.l. during drilling through the Portage Mountain end moraine (Campbell 1959) is the same height above modern Peace River as gravel of the last interstade elsewhere in the study area and probably was deposited by ancestral Peace River during the Middle Wisconsinan. Drainage north of Portage Mountain was blocked when Cordilleran ice built the end moraine there. During deglaciation, Peace River was forced through a saddle south of Portage Mountain, where it excavated Peace River Canyon (Beach and Spivak 1943).

Late Wisconsinan glaciation

Glacial Lake Mathews

Advance-phase glaciolacustrine sediments record damming of east-flowing rivers by advancing Laurentide ice. The lake in which the sediments accumulated is here termed “Glacial Lake Mathews” in recognition of the many contributions of the late Dr. W.H. Mathews to our understanding of the Quaternary geology of western Canada. The sediments have not been directly dated, but they are younger than 26,450 ± 310 14C years BP, which is the age of a bison vertebra recovered from underlying fluvial gravel.

The approach of the Laurentide ice sheet is indicated by an upward transition from ice-distal to ice-proximal glaciolacustrine sediments in sections in the western part of the study area. Diamictic pods containing Canadian Shield clasts are restricted to the upper part of the glaciolacustrine sequence.

The waters of Glacial Lake Mathews appear to have risen quickly, inundating paleo-Peace valley without significant interruption. The transition from fluvial channel sedimentation to lacustrine sedimentation spans <1 m in most sections (Fig. 8).

Fluvial gravel at some sections (SS-18, SS-19, SS-44, and possibly SS-47) records a minor lake regression followed by renewed glaciolacustrine sedimentation shortly after Glacial Lake Mathews inundated the sites. The gravel occurs about 3–4 m above the base of the glaciolacustrine sequence at these sites, and it sharply and unconformably overlies bedded and laminated mud. Possible explanations for a lake regression include (1) minor retreat of Laurentide ice, exposing lower lake outlets that previously had been blocked by ice, (2) erosion of the lake outlet or development of new and lower spillways when the lake overtopped drainage divides across which channels were subsequently eroded by out-flow, and (3) draining of the lake during an outburst flood (jökulhlaup). No other lake-lowering event is recognized in Glacial Lake Mathews deposits.

To our surprise, we found no exposures of deltaic sediments deposited by paleo-Peace River in Glacial Lake Mathews. However, a buried delta may be present beneath the...
end moraine in ancestral Peace River valley north of Portage Mountain (Beach and Spivak 1943). Well sorted gravel occurs from 481 to 527 m a.s.l. in the borehole through the end moraine (Campbell 1959). We correlate this unit with the lower paleovalley gravel. It is overlain by 66 m of interstratified silt, sand, and gravel, which are likely Glacial Lake Mathews deposits.

**Late Wisconsinan Laurentide glaciation**

Bobrowsky et al. (1992) and Catto et al. (1996) found Canadian Shield clasts up to about 950 m a.s.l. in the Rocky Mountain foothills west of the study area and argued that the Laurentide ice sheet could not have ascended valleys in the foothills if it had been opposed by east-flowing Cordilleran ice. This observation is consistent with the conclusions of Bobrowsky (1989) and Bobrowsky and Rutter (1992) that the Cordilleran advance was restricted and that its limit in Peace River valley was at Portage Mountain. Radiocarbon ages from Finlay River valley, a major tributary of Peace valley, bracket the time of Late Wisconsinan Cordilleran glaciation there to between 15 180 ± 100 14C years BP (TO-708) and 10 100 ± 90 14C years BP (GSC-2036) (Bobrowsky 1989). A series of Middle Wisconsinan radiocarbon ages on sediments underlying till indicate that only one advance occurred in Finlay River valley during the Late Wisconsinan.

These data are inconsistent, however, with the interpretation that flutings east of Fort St. John and adjacent to the mountain front formed beneath coalescent Laurentide and Cordilleran ice during the last glaciation (Mathews 1978). If the flutings are indeed Late Wisconsinan, Cordilleran ice probably reached east of Portage Mountain, albeit perhaps only for a short time. Restricted Cordilleran glaciation in Peace valley also appears to be inconsistent with the evidence presented by Bednarski (1999, 2001) and Bednarski and Smith (2007) for overtopping of high ridges in the Rocky Mountains northwest of the study area by the Cordilleran ice sheet (see below).

Glacial Lake Peace formed behind the retreating Laurentide ice sheet. Wood recovered from the contact between Late Wisconsinan Laurentide till and overlying Lake Peace sediments near Fort St. John yielded a radiocarbon age of 13 970 ± 170 14C years BP (TO-2742) (Catto et al. 1996), which is a minimum for local Laurentide deglaciation.

Glacial Lake Peace drained in stages, perhaps with rapid lowering of the lake between stages. The lake was east of Fort St. John before 10 770 ± 120 14C years BP (SFU-454), which is the age of the lowest cultural layer at the Charlie Lake cave archaeological site (Fladmark et al. 1988). Geertsema and Jull (2002) and Jull and Geertsema (2006) report a series of radiocarbon ages on charcoal layers in a debrisflow fan on a prominent river terrace at Bear Flat. The charcoal layers increase in age consistently with depth to about 10 500 14C years BP, indicating that Glacial Lake Peace had drained and Peace River had incised its modern valley to the level of the terrace before 10 500 14C years BP.

**Postglacial Peace River valley**

Peace River may have excavated its modern valley rapidly, soon after deglaciation. Entrenchment did not commence until Glacial Lake Peace drained from the study area, sometime after 13 970 ± 170 14C years BP (TO-2742) (Catto et al. 1996) and was well advanced or complete before 10 500 14C years BP (Geertsema and Jull 2002). The rock-walled, incised canyons of Beatton, Halfway, and Kiskatinaw rivers have a meandering planform. Meandering rivers typically are alluvial; lateral channel migration produces the meanders (Miall 1992). The walls of the Beatton, Halfway, and Kiskatinaw canyons are bedrock, and the meandering planform could not have developed after the rivers incised to their present levels. Rather, it developed when the rivers flowed over the floor of Glacial Lake Peace soon after the lake drained. Incision was so rapid that the rivers did not migrate laterally, preventing the canyons from being widened and preserving the meandering form.

**Comparison with previous work**

Two models have been developed to explain the Quaternary stratigraphy and landforms of the westernmost Alberta Plateau (Bobrowsky et al. 1991). One model is based on the work of Rutter (1976, 1977) and Mathews (1978, 1980). It features two or three Laurentide advances, three or four Cordilleran advances, and coalescence of the Cordilleran and Laurentide ice sheets during one glaciation. The second model is based on Bobrowsky (1989) and includes one Laurentide advance and two Cordilleran advances without coalescence of the Laurentide and Cordilleran ice sheets.

The stratigraphy presented in this study (Fig. 10) supports, with some modification, the interpretation of Mathews (1978, 1980), specifically that there were three Laurentide and two Cordilleran advances in the region. This stratigraphy is discussed in the following two sections in the context of previous stratigraphic work.

**Laurentide stratigraphy**

Several researchers have argued that the Laurentide ice sheet reached Edmonton, Watino, and areas to the south and west only once in the Pleistocene, during the Late Wisconsinan (Westgate et al. 1971, 1972; Catto 1984; Liverman 1989; Liverman et al. 1989; Young et al. 1994). The stratigraphy reported in this study requires three Laurentide glacial events separated by interglaciations or long interstades. Only the last of the three glacial events is Late Wisconsinan.

Laurentide glaciations were centred in northern Quebec and Labrador, Keewatin, and the Foxe Basin (Dyke et al. 2002; Kleman et al. 2002; Dyke 2004). To reach the study area, ice had to flow southwest to south-southwest from the Keewatin ice dome. Flutings in the study area that match this flow direction were noted by Mathews (1978, 1980). Ice flowing into the study area from the northeast or north-northeast during pre-Late Wisconsinan glaciations may have terminated short of Edmonton, 500 km to the southeast, and Watino, 160 km to the east-southeast.

Two, pre-Late Wisconsinan Laurentide advances are inferred in the study area from the presence of Canadian Shield erratics in gravels of the upper and lower paleovalley systems and from glaciolacustrine sediments. The penultimate Laurentide advance is interpreted to have been the more extensive of the two based on the distribution of shield erratics in the paleovalley gravels.
The limits of these pre-Late Wisconsinan advances must be north and east of Edmonton and Watino, yet close enough to the study area to introduce shield clasts into the paleo-Peace River drainage and to impound lakes in its valleys. No Laurentide glacier extended beyond the most distal shield clasts that it transported, but the locations of the clasts do not necessarily delineate the ice margin. The presence of eastern-provenance clasts in paleovalley fluvial gravels merely indicates that Laurentide ice entered the watershed of the paleo-drainage system.

The interpretation presented in this study can be reconciled with those of Catto (1984), Liverman (1989), Liverman et al. (1989), and Young et al. (1994) by considering the paleogeography of the rivers that deposited the sediments on which these researchers have based their stratigraphies and within which Canadian Shield clasts are absent. All stratigraphies from which only a single Laurentide advance has been postulated come from north- and east-draining watersheds south and west of Watino and Edmonton. Pre-Late Wisconsinan advances that terminated north and east of these watersheds would not have introduced shield clasts into the sediments on which the stratigraphies are based.

The distribution of the Canadian Shield clasts on the westernmost Interior Plains and the paleogeography of the watersheds in which they occur constrain pre-Late Wisconsinan Laurentide ice limits. An early Laurentide glacial advance was extensive enough to deposit shield clasts in the watersheds of northern tributaries of ancestral Peace River, including ancestral Beatton River. This early Laurentide advance did not cross the drainage divide that separates ancestral Beatton and Halfway rivers, nor did it extend south and west of Watino. The penultimate Laurentide glacial advance extended west at least as far as the British Columbia – Alberta boundary because ancestral Peace River in the study area was dammed by this advance. In addition, Canadian Shield clasts are present in the lower paleovalley gravel as far west as Lynx Creek.

The pre-Late Wisconsinan, Laurentide glacial history proposed here is similar to that of Mathews (1978). It is also consistent with the finding of Liverman et al. (1989) that
the early Laurentide advances recognized by Mathews (1978) did not reach Edmonton and Watino.

Cordilleran stratigraphy

The stratigraphy presented in this paper argues for two Cordilleran glacial advances—an earlier advance sometime prior to the Middle Wisconsinan, and a Late Wisconsinan advance that reached at least as far east as Portage Mountain. Cordilleran till has not been found east of Portage Mountain, but Mathews (1978) argued that the Cordilleran glacier in Peace valley during the Late Wisconsinan was extensive and that it merged with the Laurentide ice sheet, depositing a single till consisting of mixed eastern and western lithologies. He was unable to distinguish Cordilleran and Laurentide tills, which he attributed to the absence of a distinct boundary between the two till sheets and to a shifting zone of interaction between the two glaciers. He noted that the eastern-provenance clasts decrease significantly in a narrow zone in the western third of the study area, coincident with an increase in the abundance of western-provenance clasts. This area coincides with the zone of coalescence of Cordilleran and Laurentide ice delineated by flutings (Mathews 1978). The flutings suggest that Cordilleran ice emanating from ancestral Peace valley was deflected to the southwest by Laurentide ice.

Several researchers have presented evidence for an extensive Cordilleran advance onto the plains and foothills adjacent to the Rocky Mountains during the Late Wisconsinan (Jackson et al. 1997; Bednarski 1999, 2001; Dyke et al. 2002; Dyke 2004; Bednarski and Smith 2007). Jackson et al. (1997) showed that the Foothills Erratics Train was deposited during the Late Wisconsinan by coalescence of Laurentide and Cordilleran ice on the westernmost Interior Plains. The erratics extend more than 1000 km from Athabasca valley in the north to Lethbridge in the south. Dyke et al. (2002) suggested that coalescence of the ice sheets over such a distance would not be possible without the ice sheets also coalescing in the vicinity of Peace River. This assertion is, however, debatable. Significant coalescence of the Cordilleran and Laurentide ice sheets south of Athabasca valley does not require coalescence more than 400 km north of the head of the Foothills Erratics Train.

Bednarski (1999, 2001) and Bednarski and Smith (2007) have argued for an extensive Late Wisconsinan Cordilleran ice sheet in the Rocky Mountains northwest of the study area. They found striaie on mountain ridges that trend perpendicular to the ridge crests. The implication is that the striaie were produced by ice flowing unhindered by topography. 36Cl exposure dating of the striated surfaces suggests that they were deglaciated between 14 020 ± 760 and 13 100 ± 1560 cal years ago. The presence of limestone and schist erratics of western provenance on the plains east of the Rocky Mountains supports extensive Late Wisconsinan Cordilleran glaciation. Bednarski (1999, 2001) and Bednarski and Smith (2007) also noted eastern-provenance erratics and Laurentide till in east-draining valleys of the Rocky Mountain Foothills, and suggested that Laurentide ice advanced into these valleys shortly after Cordilleran ice retreated from them.

Bobrowsky (1989) presented arguments against extensive Late Wisconsinan Cordilleran glaciation in the Finlay River valley northwest of the study area. The upper part of Finlay valley remained ice-free until at least 15 180 ± 100 14C years BP (TO-708). Cordilleran ice thus advanced to its eastern limit and retreated significantly in <5000 years.

Bobrowsky (1989) also argued that the western-provenance clasts noted by Mathews (1978) probably were transported and deposited by a pre-Late Wisconsinan Cordilleran glacier and were subsequently entrained by Late Wisconsinan Laurentide ice and deposited as part of its till. Catto et al. (1996) suggested that the marked decrease in eastern-provenance lithologies in Mathews’ mixing zone is due more to entrainment of a greater amount of surficial sediment by the Laurentide ice sheet in this area than to coalescence of Laurentide and Cordilleran ice.

Canadian Shield erratics occur in east-draining valleys in the Rocky Mountain Foothills to 950 m a.s.l. (Bobrowsky et al. 1991, 1992; Catto 1991; Catto et al. 1996). This elevation is higher than the upper limit of Glacial Lake Peace, therefore the erratics must have been deposited by the Laurentide ice sheet. In addition, Laurentide ice could not have ascended the valleys in contact with Cordilleran ice.

If Bobrowsky (1989), Bobrowsky and Rutter (1992), and Catto et al. (1996) are correct, the flutings noted by Mathews (1978) can only be a product of coalescence of the Laurentide and Cordilleran ice sheets prior to the Late Wisconsinan. This scenario, however, requires that the flutings survive overriding by the Laurentide ice sheet during the Late Wisconsinan. An argument to this effect was made by Catto et al. (1996) to explain the Redwillow Fluting fan south of the study area. They argued that the Redwillow Fluting fan formed at the base of a tongue of pre-Late Wisconsinan Cordilleran ice that extended from the Rocky Mountains through Redwillow valley and onto the Alberta Plateau. The flutings are overlain locally by Late Wisconsinan Laurentide till.

Any coalescence of the Cordilleran and Laurentide ice in the study area during the Late Wisconsinan must have been brief and would have ended with rapid retreat of Cordilleran ice to Portage Mountain. At the same time, the Laurentide ice sheet may have spread westward into the Rocky Mountain Foothills (Bednarski and Smith 2007).

In summary, the pattern of restricted Late Wisconsinan Cordilleran glaciation envisioned by Bobrowsky (1989), Bobrowsky and Rutter (1992), and Catto et al. (1996) is incompatible with the more extensive glacial model of Bednarski (1999, 2001) and Bednarski and Smith (2007). The area where Bednarski and Smith worked and the Rocky Mountain Trench, studied by Bobrowsky and Rutter, are separated by the Rocky Mountains, but such a fundamental difference in extent of Late Wisconsinan Cordilleran ice cannot be explained by the different locations of the two study areas. Our study fails to resolve this issue. Late Wisconsinan Cordilleran ice may have reached only as far east as Portage Mountain, or it may have advanced about 50 km farther east, where it coalesced briefly with Laurentide ice.

Conclusion

Four relict drainage systems have been identified in the Peace River area in northeast British Columbia. The two youngest relict drainages are buried valleys. Each of the
The valley-fill sediments of the study area provide evidence for three Laurentide and two Cordilleran glaciations. The glaciations are separated by interglaciations or lengthy interstades, during which the east-flowing drainage was re-established and rivers achieved maturity. The earliest Laurentide advance was less extensive than the penultimate advance, and the penultimate advance, in turn, was less extensive than the Late Wisconsinan advance. An advance of the Cordilleran ice sheet reached beyond the Rocky Mountain front, but the extent of the Cordilleran glacier in Peace River valley during the Late Wisconsinan remains uncertain.

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