ERCB/AGS Open File Report 2010-11

Surficial Geology and Quaternary History of the Cleardale Area, Northwestern Alberta (NTS 84D/SW)

Energy Resources Conservation Board

Alberta Geological Survey

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N. Atkinson[1] and R.C. Paulen[2]

[1]Energy Resources Conservation Board/Alberta Geological Survey
[2]Geological Survey of Canada

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Author address:
R.C. Paulen
Geological Survey of Canada
601 rue Booth Street
Ottawa, ON K1A 0E8
Canada

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Alberta Geological Survey
4th Floor, Twin Atria Building
4999 – 98th Avenue
Edmonton, AB T6B 2X3
Canada

Tel: 780-422-1927
Fax: 780-422-1918
E-mail: AGS-Info@ercb.ca
Website: www.ags.gov.ab.ca

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Abstract

In this report, we describe the distribution, character and origin of surficial sediments in the Cleardale area (NTS 84D/SW) and discuss the Quaternary history of the region. The Cleardale area is located south of the Clear Hills, along the Alberta-British Columbia border, and comprises a broad lowland (450–750 m asl) that is incised by the Peace River.

Three gravel sheets identified in the Cleardale area, each grading to different base levels, are attributed to three major cycles of fluvial aggradation and incision. These cycles are attributed to the evolution of regional braided river systems draining eastward from the Rocky Mountains since the Middle Tertiary.

Widely dispersed till documents the advance of the Laurentide Ice Sheet across the Cleardale area during Late Wisconsinan glaciation. This advance covered the Cleardale area, including local uplands, and deposited one major till facies across much of the map area. These sediments provide insight into regional stratigraphy and landscape evolution in northwestern Alberta.

During regional deglaciation, the Laurentide Ice Sheet retreated from the Cleardale area at ca.11 ka BP, exposing a broad lowland basin flanking the ancestral Peace River. Due to the down-drainage retreat of the Laurentide Ice Sheet, this basin became infilled by subaerial and glacial meltwater discharge that converged toward the ice margin, forming the western part of a regional proglacial lake termed Glacial Lake Peace. The extent of this former lake is demarcated by widespread glaciolacustrine sediments that cover the Cleardale area, up to approximately 780 m asl. Glacial Lake Peace progressively drained from the Cleardale area as the retreating Laurentide Ice Sheet exposed lower basins and outlets along the ancestral Peace River valley and surrounding lowlands to the east of the map area.

Following lake drainage, Holocene fluvial processes incised through approximately 120 m of Quaternary sediments and 30 m into the underlying bedrock, forming the modern Peace River valley. Concomitant mass movement along the river valley and its tributaries is responsible for the widespread distribution of colluvium, which is a regionally significant surficial material that is a cause for infrastructure problems in the area.

1 Introduction

As part of an ongoing, multi-year initiative, Alberta Geological Survey (AGS) continued its surficial mapping program, focusing on the Cleardale area, in the southwest quadrant of the Clear Hills map sheet (NTS 84D/SW; Figure 1). Alberta Geological Survey released this work in 2009 as AGS surficial geology Map 422 (Atkinson and Paulen, 2009).

The mapping objectives were to describe the distribution, character and origin of surficial sediments in the Cleardale area. This report accompanies Map 422, and provides a more detailed description of these sediments and discusses the Quaternary history of the Cleardale area and the surrounding region of northwestern Alberta.

The surficial geology map of the Cleardale area was based on the interpretation of 1:60 000 scale airphotos, augmented by GIS mapping techniques. Field mapping in the summer of 2008 provided 230 site descriptions to constrain the airphoto interpretation. A widespread network of gravel roads provided vehicle access across most of the map area, and a boat and helicopter provided access to remote areas. The interpreted airphotos were scanned and georeferenced, and the boundaries of the interpreted surficial units were vectorized using ArcInfo. The final map products were prepared following internal review and editing.

2 Physiography

The Cleardale area occupies approximately 3400 km^2 within the Northern Alberta Lowlands of the Interior Plains of Canada, south of the town of Worsley (Figures 1 and 2; Pettapiece, 1986). It is bounded by latitudes 56º00'N and 56º30'N, and longitudes 119ºW and 120ºW. The region is characterized by flat to gently undulating terrain that was incised by Late Tertiary fluvial activity and subsequently modified by Quaternary glacial processes. The major physiographic feature is the Peace River Lowland (600–700 m asl). This lowland is incised by the Peace River, which flows east along a 150 m deep, 3.5 km wide valley. The Clear Hills Upland (up to 1050 m asl) extends north of the Cleardale area, and the Wapiti Plains, which contain local uplands, including Blueberry Hill, occur to the south (Figure 2). These uplands are drained by rectilinear stream networks that are captured by the tributaries of the Clear, Eureka and Pouce Coupé rivers, which in turn drain into the Peace River.

3 Bedrock Lithology

The Cleardale area is located in the northwestern part of the Western Canada Sedimentary Basin (Mossop and Shetsen, 1994). This area is underlain by rocks of the middle Cretaceous Colorado Group, which consists of a succession of mudstone with thin sandstone and conglomerate beds. These sediments were deposited within a shallow epicontinental seaway during a 25–30 million year interval of marine transgression, when Tethyan water from the Gulf of Mexico mixed with water extending south from the Arctic (Kauffman, 1977; Haq et al., 1987; Leckie et al., 1994). Deposition coincided with regional downflexing of the North American craton, which formed a north-south trending foreland basin that separated the eastern flanks of the ancestral Rocky Mountains from the stable interior platform (Lambeck et al., 1987; Leckie and Smith, 1992).

The Colorado Group comprises economically important formations that contain significant hydrocarbon reserves. In northwestern Alberta, the base of the Colorado Group is defined by a major erosional unconformity, which formed during a marine transgression at 97.5 Ma (Leckie et al., 1994). The Shaftesbury Formation, which outcrops along the Peace River valley overlies this unconformity (Figure 3) and comprises dark grey, fish-scale–bearing marine shale that contains silty and sandy interbeds, as well as occasional ironstone concretions.

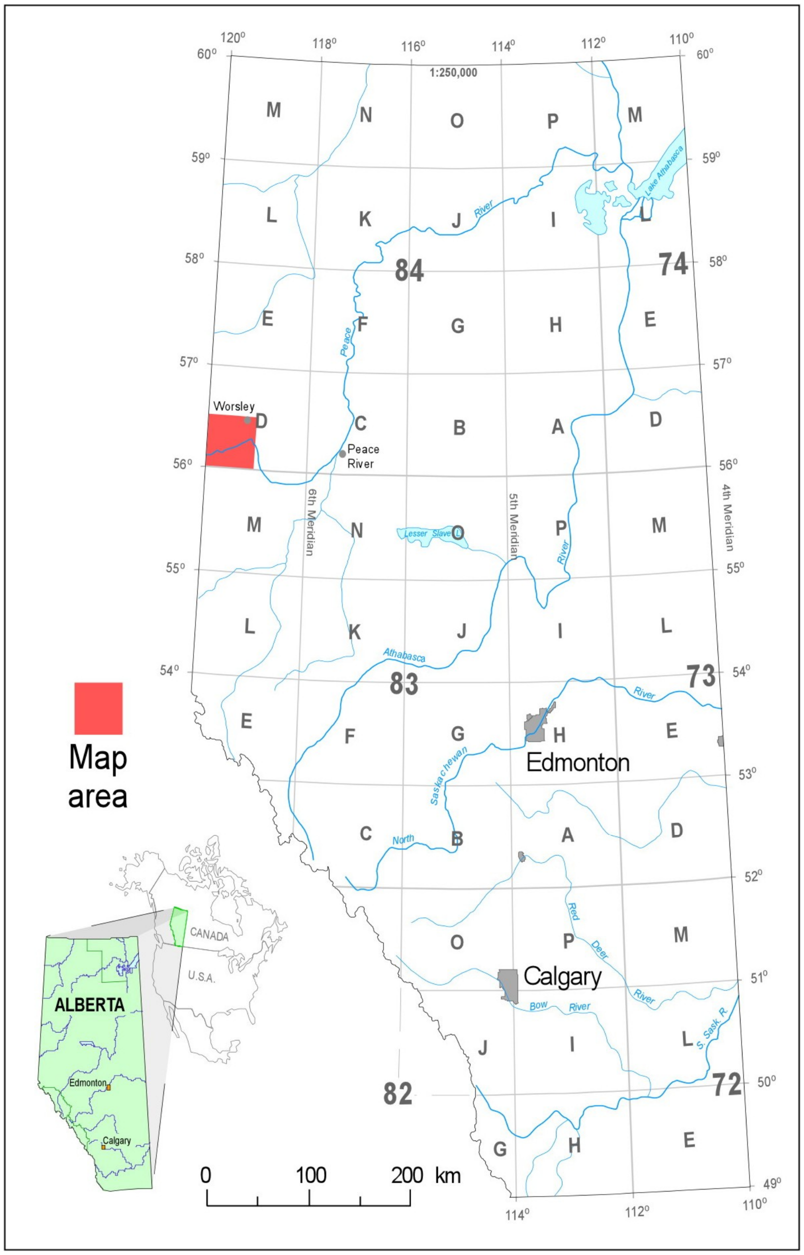

Figure 1. Location of the Cleardale map area, northwestern Alberta.

Marine transgression was punctuated by a major regressive cycle and resulted in the deposition of the Dunvegan Formation in an actively subsiding foreland basin. The Dunvegan Formation is exposed along the Peace, Eureka and Pouce Coupé rivers, and comprises a southward-thinning fluviodeltaic wedge of interbedded marine and nonmarine sandstone and shale (Figure 3). In northwestern Alberta, sand-rich progradational cycles are separated by regional transgressive surfaces that document the southward progradation of the Dunvegan Formation associated with global sea level lowering at 94 Ma BP (Bhattacharya, 1988; Bhattacharya and Walker, 1991).

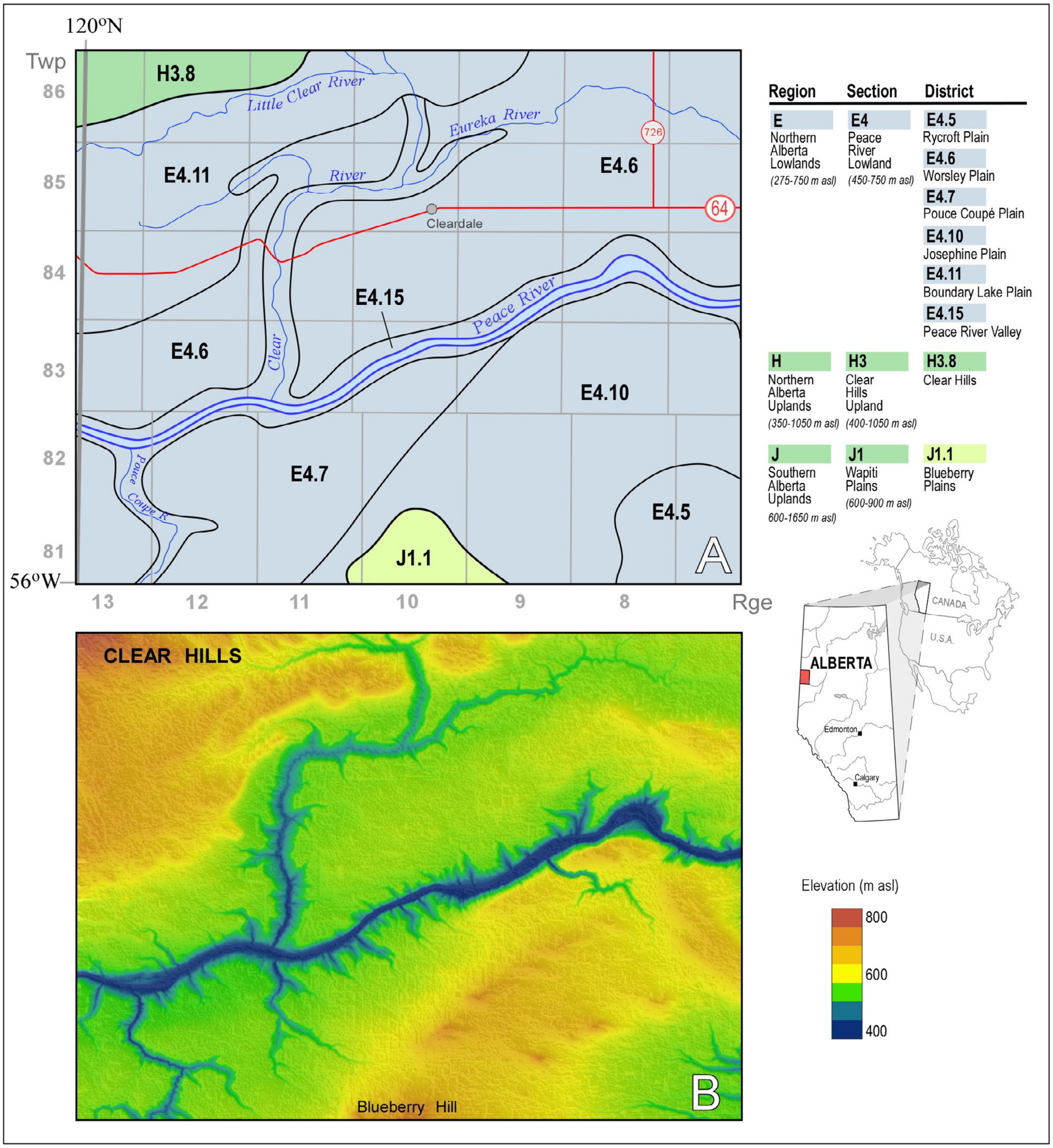

Figure 2. A) Physiographic regions of the Cleardale area, northwestern Alberta (modified from Pettapiece, 1986). B) Hillshaded digital elevation model of the Cleardale area.

The Kaskapau Formation subcrops throughout much of the Cleardale area (Figure 3) and comprises a retrogradational succession of shallow marine sandstone and shale, which was deposited after the Dunvegan Formation (Leckie et al., 1994).

For additional information concerning the lithology, thickness and sedimentary environment of the Shaftesbury and associated mid-Cretaceous formations refer to Leckie et al. (1994) and Reinson et al. (1994).

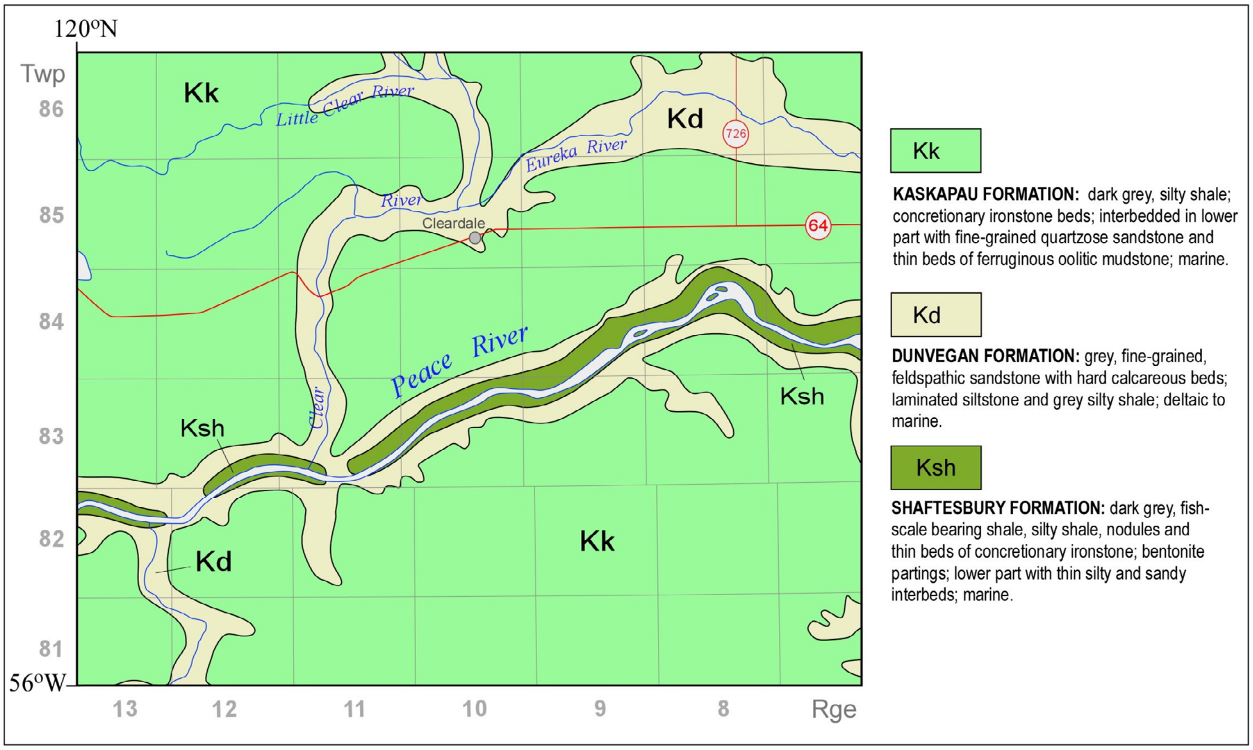

Figure 3. Bedrock geology of the Cleardale area, northwestern Alberta (modified from Hamilton et al., 1999).

4 Vegetation

The Cleardale area encompasses two natural regions: the Boreal Forest in the north and the Foothills in the south (Downing and Pettapiece, 2006). These regions comprise three natural subregions: Dry Mixedwood, Northern Mixedwood and Lower Foothills. The Dry Mixedwood Natural Subregion occurs across the broad, flat terrain of the Peace River Lowland. Cultivated land and occasional mixed tree stands, together with bogs and fens in poorly drained or low-lying areas, characterize this subregion. The Northern Mixedwood Natural Subregion occupies the upland terrain of the Clear Hills and comprises a mosaic of mixed conifer and deciduous stands. The Lower Foothills Natural Subregion occurs across the Wapiti Plains and comprises cultivated land with pine, spruce and occasional birch stands. Widespread energy development exists throughout these subregions.

5 Surficial Geology

The surficial geology map of the Cleardale area shows the distribution of six genetic types of surficial material (Atkinson and Paulen, 2009). These six units and their associated landforms are described below in the order in which they appear in the legend of AGS Map 422 (Atkinson and Paulen, 2009). Section 7 describes the Quaternary history of the Cleardale area based on the stratigraphic interpretation of these units and associated sediment-landform relationships.

5.1 Moraine (Units M, MF)

Moraine, subsequently described in this report as till, is a minor surficial unit, occurring locally in the northwestern and southeastern parts of the Cleardale area (Figure 4). However, due to extensive landsliding along the Peace, Clear, Eureka and Pouce Coupé rivers, till is exposed within numerous stratigraphic sections in the Cleardale area.

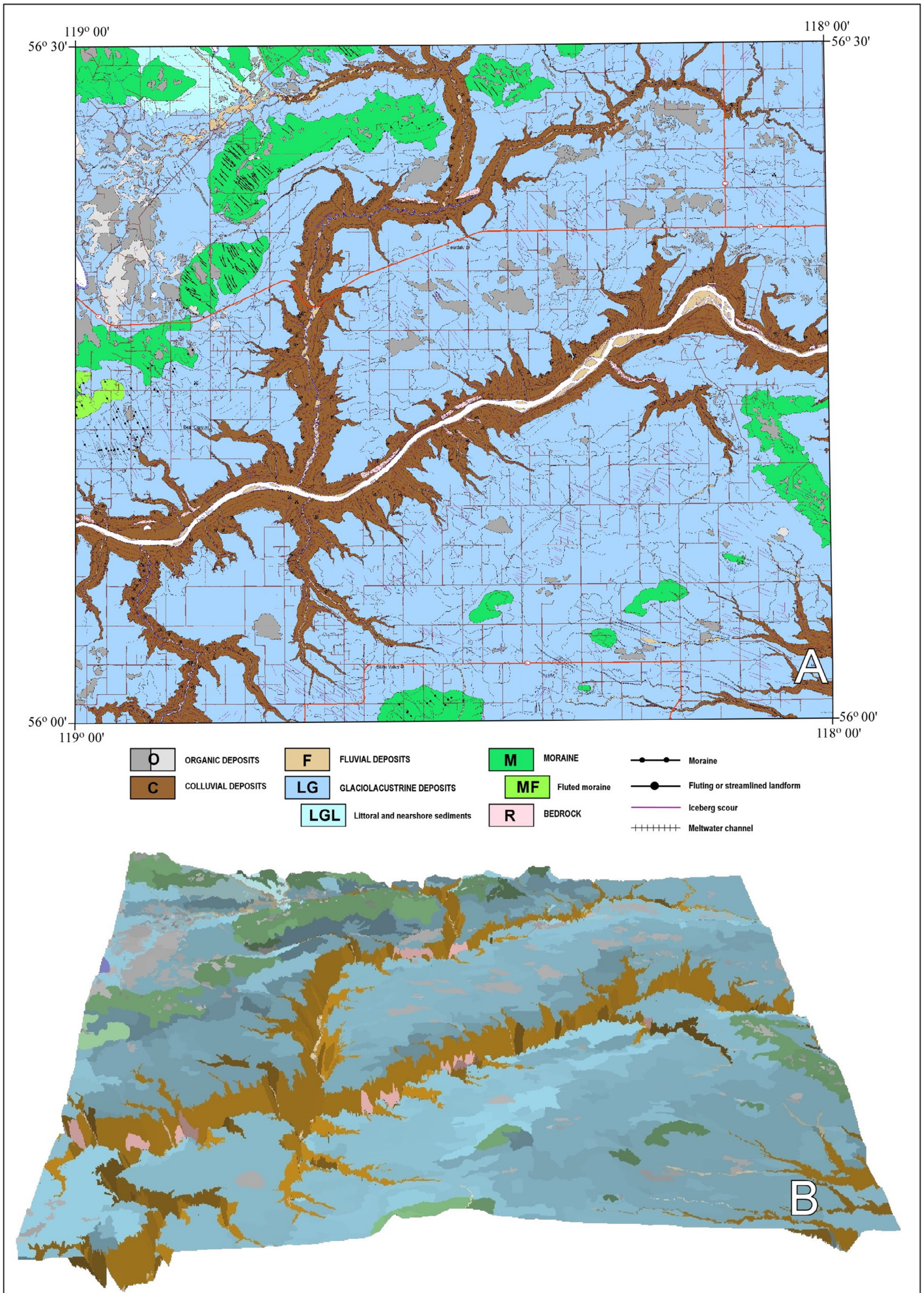

Figure 4. A) Simplified surficial geology map of the Cleardale area, northwestern Alberta (Atkinson and Paulen, 2009). B) Simplified surficial geology map draped on an oblique hill-shaded digital elevation model with a 15x vertical exaggeration.

Moraine veneer (unit Mv) is mapped wherever till is insufficient to obscure the relief of the underlying units (<2 m thick). Isolated patches of till veneer occur above approximately 720 m asl on low uplands of the Josephine Plain, south of the Peace River (Figures 2 and 4). Elsewhere in the map area, till veneer occurs above approximately 700 m asl on the northeast-trending ridge that separates the Worsley Plain from the Boundary Lake Plain, and at a similar elevation on the Clear Hills Upland, approximately 20 km to the north. A 5 km wide tract of till veneer on the Worsley Plain is streamlined and fluted. Individual flutes range from 0.5–2 km long, and exhibit a southeasterly orientation of 155°. Moraine plain (unit Mp) is mapped wherever till obscures the underlying materials (≥2 m thick) and occurs above approximately 710 m asl on Blueberry Hill, in the southern part of the map area. In places, this till plain is fluted and streamlined. Individual flutes are up to 1 km long and exhibit a southeasterly orientation, ranging from 120°–155°, with local divergence occurring around physiographic highs (Figure 4).

Till plain on the western slope of the northeast-trending ridge separating the Worsley and Boundary Lake plains contains a series of approximately 35 subparallel, northwest-southeast trending moraines. These moraines are up to 10 m high, 1.5 km long, 200–500 m apart and consist of till, mantled by a lag of subrounded cobbles and boulders. They also exhibit an asymmetrical profile, with a steeper western (ice-distal) than eastern (ice-proximal) slope. Till extends upslope of these moraines, forming a northeast-trending plain, mantled by occasional veneers of cobbly diamict. Till plain also overlies the low, north-trending ridge on the Josephine Plain, along the eastern boundary of the map area. A veneer of cobbly diamict mantles this plain, which in places exhibits a pitted topography.

5.1.1 Till Composition

A qualitative assessment of till characteristics based on field examination demonstrates that one major till facies occurs across the map area. This comprises a greyish brown, matrix-supported, clayey silt diamict. Clast content, which includes both local and Shield lithologies, is typically 2%–5%, predominantly comprising subrounded granule- to cobble-sized clasts. Based on the subcrop exposure of this till, as well as its distribution across local uplands, it likely forms a widespread blanket over much of the region, and correlates to till identified in the George Lake and Grimshaw map areas to the east (NTS 84D/SE and 84C/SW, respectively; Atkinson and Paulen, 2010; Paulen, 2004).

5.2 Glaciolacustrine Deposits (Units LG, LGL)

Glaciolacustrine sediment is the major surficial unit in the Cleardale area, covering the Peace River Lowland, where it onlaps till up to approximately 780 m asl on the Clear Hills Upland in the north, and approximately 730 m asl on the Blueberry Plains in the south (Figure 4). Glaciolacustrine deposits comprise a number of facies, ranging from massive clay to horizontally laminated, rhythmically bedded, fine sandy silt and clay with occasional dropstones (Figure 5).

Although these glaciolacustrine deposits typically blanket underlying units, they exhibit variable relief across the map area, ranging from nearly flat to gently undulating plains (0–2 m relief) to areas of local undulations (2–5 m) comprising reticulate, orbicular, hummocky, doughnut-like and brain-like patterns (Figure 6; c.f., Mollard, 1996). Areas mapped as glaciolacustrine plain occur mainly in the central and eastern parts of the map area, to the north and south of the Peace River valley. The most extensive areas of undulating glaciolacustrine sediments occur in the northeastern and southwestern parts of the map area. Here, orbicular, doughnut-like and brain-like patterns are common, in places increasing local relief by up to 5 m. These areas are commonly associated with discontinuous bogs and fens due to the formation of wetlands between undulations.

Glaciolacustrine sediments covering the western margin of the Worsley Plain are fluted and streamlined, and exhibit evidence of glaciotectonic deformation (Figures 4 and 7). Individual flutes range from 0.75–2 km in length and mainly occur within an approximately 5 km wide tract of southeasterly (approximately 155°) oriented lineaments.

Figure 5. Horizontally laminated, rhythmically bedded glaciolacustrine sediments covering the Worsley Plain, northwestern Alberta. Inset illustrates dropstone within this glaciolacustrine facies. One-cent coin for scale.

5.2.1 Iceberg Scours

Iceberg scours are widespread lineaments on glaciolacustrine sediment on the Pouce Coupé, Josephine and Worsley plains (Figure 4). These scars are 1–3 km long, <1 m deep, and extend as generally southeast-trending (120°–160°), straight to slightly curved lineaments, although some exhibit crosscutting orientations (approximately 245°). They stand out clearly on air photographs, and are discernible from flutings as they are more heavily vegetated, due to the accumulation of moisture within the scour. However, iceberg scours are generally unnoticeable at ground level due to sediment compaction following glacial lake drainage and recent agricultural activities (Figure 8).

Figure 6. Hummocky relief in an area of glaciolacustrine sediment in the southwestern part of the Cleardale area, northwestern Alberta. Internally, these hummocks are composed of massive silty clay.

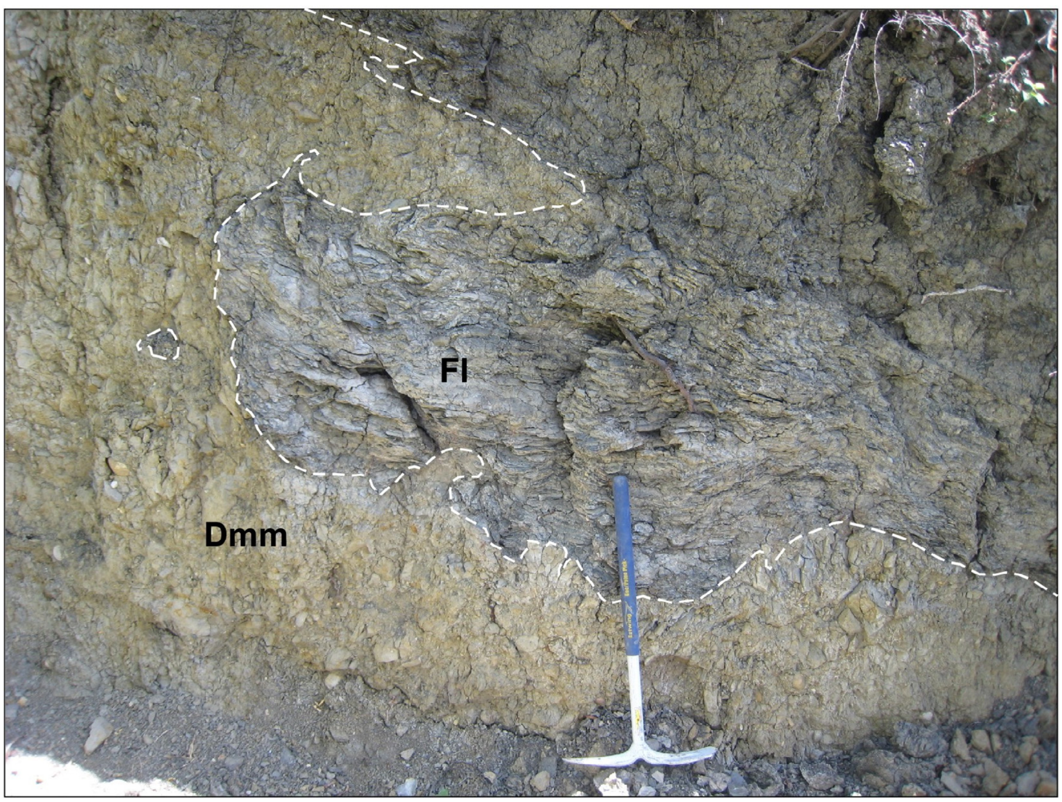

Figure 7. Glaciotectonic deformation of laminated glaciolacustrine sediments (Fl) into the underlying matrix-supported, clayey silt diamict (Dmm) on the southern Worsley Plain, along the Peace River valley, northwestern Alberta.

5.2.2 Raised Beaches

Raised beaches occur as parallel suites of low amplitude, northeast-oriented ridges on the gently sloping Worsley and Josephine plains, between 655 and 625 m asl and 700 and 660 m asl, respectively (Figure 9). These beaches, developed by wave erosion of glaciolacustrine sediment, are composed of fine-grained sediments. Well-developed beaches did not form across the nearly level expanses of the Josephine Plain, although the occurrence of stone lags indicates that glaciolacustrine sediments in this part of the map area were influenced by wave erosion. In agricultural areas, these winnowed lags have been cleared and left in piles along field margins.

5.2.3 Meltwater Channels

Suites of subparallel, southeast-trending valleys that extend orthogonally to slope or exhibit overdeepening and/or overwidening are inferred to have been eroded by glacial meltwater during regional deglaciation. These include minor meltwater channels, which commonly occur as nested, subparallel incisions comprising relatively short (1–3 km), narrow (<100 m), shallow (<20 m) and discontinuous segments.

5.3 Lacustrine Deposits (Unit L)

Lacustrine sediment is a minor unit in the Cleardale area, and comprises sand along the margins of Boundary Lake, along the western margin of AGS Map 422 (Atkinson and Paulen, 2009).

Figure 8. Southeast-oriented iceberg scour (marked by arrows) along the Worsley Plain, northwestern Alberta.

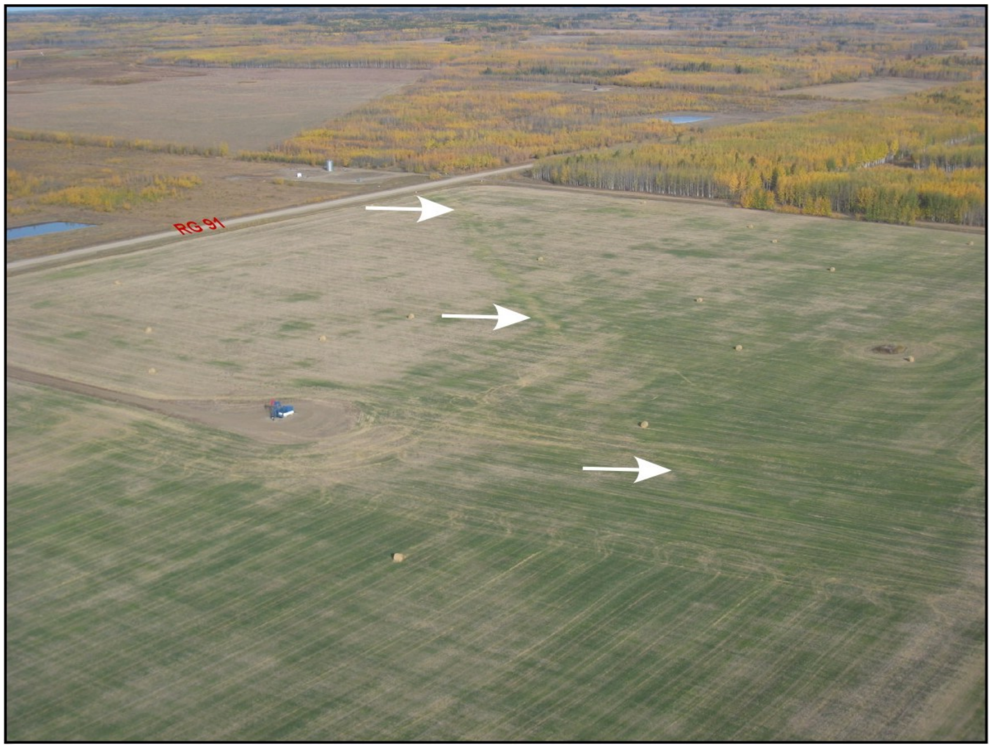

Figure 9. Raised beaches (marked by arrows) formed on glaciolacustrine sediment covering the Worsley Plain, northwestern Alberta.

5.4 Fluvial Deposits (Unit F)

Alluvium is a minor surficial material in the Cleardale area, and is divided into two types, depending on whether the sediment is being modified by modern fluvial processes or if it is presently inactive. Active alluvium is restricted to the valley floors of the Peace, Clear, Little Clear, Eureka and Pouce Coupé rivers, and consists of sand and cobbles within the modern flood plain. The remaining sand and gravel in the Cleardale area is categorized as inactive alluvium. This occurs in paired and unpaired terraces, mainly along the margins of the Clear, Little Clear, Eureka rivers, and within large vegetated bars along the Peace River (Figure 10).

5.5 Colluvial Deposits (Unit C)

The Peace River Lowlands are one of the most historically active mass-movement areas of Western Canada, thus, colluvium, resulting from the downslope movement of till, glaciolacustrine sediment and bedrock, is a regionally significant surficial material. These movements are frequently retrogressive and include deep-seated rotational and translational slides that comprise multiple arcuate blocks, as well as local slumps and earth flows. Recent rotational landslides along parts of the Eureka River comprise back-tilted stacked blocks. The depressions between the heads of adjacent stack blocks are frequently infilled by narrow, crescentic sag ponds (Figure 11).

5.6 Organic Deposits (Unit O)

Most wetlands, including peatlands, overlie fine-grained glaciolacustrine sediments. These organic sediments are more heavily vegetated than the surrounding terrain, and include small, isolated patches occupying poorly drained basins across the irregular, till-covered terrain of the Southern Alberta Uplands, to large tracts (up to approximately 40 km^2) overlying till on the Sturgeon Plain, along the East Prairie River.

Figure 10. Active and inactive alluvial terraces along the flanks of the Peace River, northwestern Alberta.

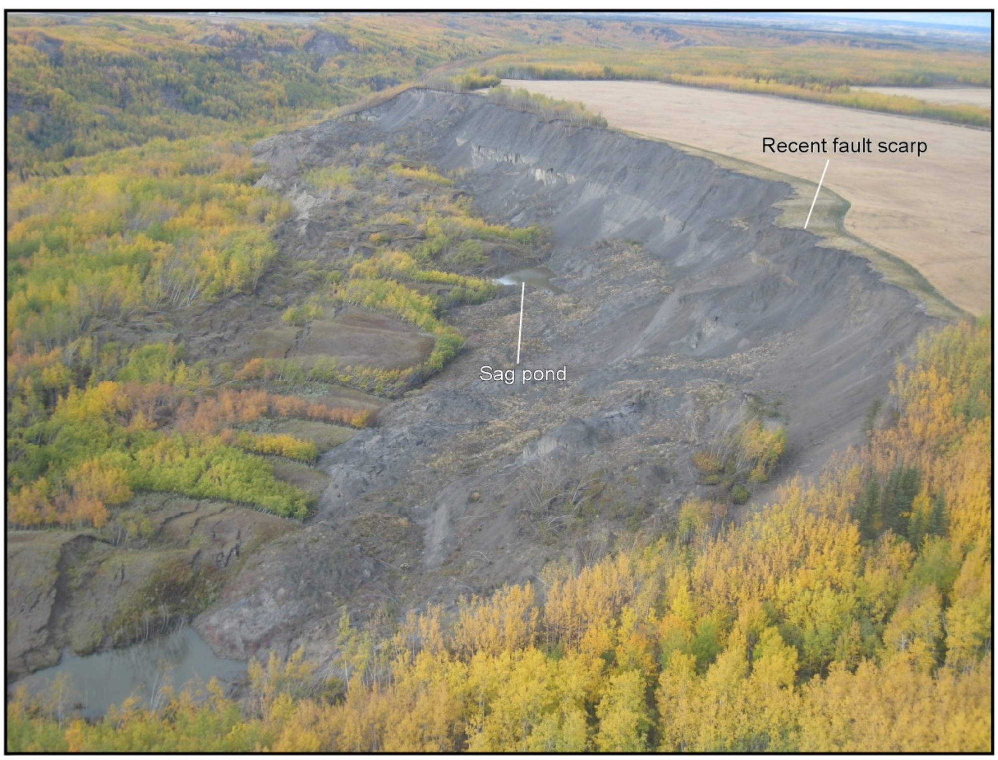

Figure 11. Sag pond located along the head of a stack block resulting from a recent landslide on the Pouce Coupé Plain, northwestern Alberta.

6 Stratigraphy

The Quaternary stratigraphy of the Cleardale area is not preserved at a single section because of extensive landsliding along the Peace River valley. However, we present a composite stratigraphy that encompasses the entire sedimentary succession using seven sections exposed in the Worsley and Boundary Lake plains (Figure 12). Analyses of these sections indicate that six major lithotype assemblages characterize the Quaternary stratigraphy of the Cleardale area. The term lithotype provides a nongenetic description of the physical characteristics of the deposit, with no reference to its depositional environment, whereas the genetic term facies implies or states a specific mode of deposition. Lithotype assemblage refers to an assemblage of lithotypes that are interpreted to be genetically related and separated from adjoining lithotypes by major erosional surfaces or bounding discontinuities (c.f., Miall, 1978; Allen, 1983). The facies code used in this report is from Benn and Evans (1998; Table 1), which was modified from Eyles et al. (1983).

6.1 Lithotype Assemblage 1: Interbedded Gravel and Sand

Lithotype assemblage (LTA) 1 (Gsi/Gh/Gt/Sh) was logged between approximately 535 and 554 m asl at section NA08-077, which forms a cliffed outcrop along the Peace River valley (Figures 12 and 13). Lithotype assemblage 1 forms the basal unit of the sedimentary succession in the Cleardale area and is defined by laterally extensive, tabular sheetlike bodies. Internally, LTA 1 is composed of approximately 20 m of interbedded, structureless to imbricated, horizontal and trough cross-stratified pebble to cobble gravels (lithotypes Gsi, Gh and Gt) and fine- to medium-grained horizontally bedded sands (lithotype Sh).

Table 1. Facies coding scheme of Benn and Evans (1998), modified from Eyles et al. (1983).

Diamict		Gravels		Sands		Silts and Clays	
Dmm	Matrix-supported, massive	Gms	Matrix-supported, massive	Sh	Horizontally bedded or low-angle crosslamination	Fl	Fine lamination with minor fine sand
		Gmh	Matrix-supported, horizontally bedded	Sm	Massive	Flv	Fine lamination with rhythmites
		Gsi	Matrix-supported, imbricated	Sr	Ripple crosslaminated		
		Gh	Horizontally bedded	f_ _	Fine-grained		
		Gt	Trough crossbedded	_ _(w)	With dewatering structures		
		Gp	Planar crossbedded	Su	Fine to coarse with shallow scours and cross-stratification		
		Gcu	Upward-coarsening	St	Trough crossbedded		
				Sh	Horizontally bedded		

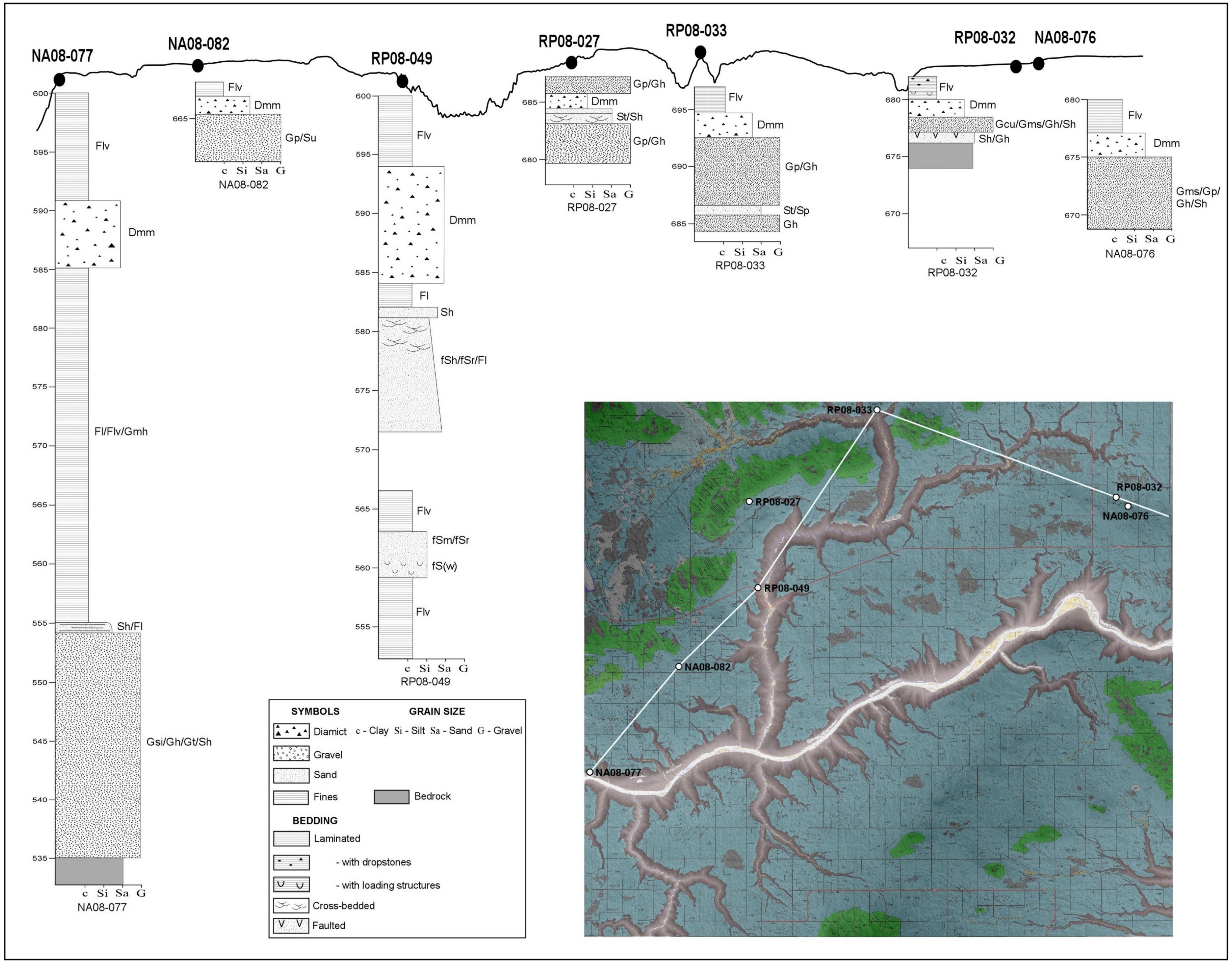

Figure 12. Stratigraphic logs from the Cleardale area, northwestern Alberta. Facies coding scheme from Benn and Evans (1998), modified from Eyles et al. (1983).

Figure 13. Cliffed outcrop along the Peace River showing the stratigraphic relationship between lithotype assemblages (LTA) 1 and 2, northwestern Alberta.

Framework clasts within Gsi typically comprise 50% of the lithotype, whereas coarse-grained sands define the remaining matrix (approximately 50%). Lithotype Gt is predominantly composed of small to medium, pebble-sized framework clasts that comprise approximately 70% of the lithotype. A medium-grained sand matrix defines the remaining 30% of the lithotype. Erosional and gradational bounding surfaces define the basal contacts that separate these two lithotypes. The a-axes of imbricated clasts generally show an east to southeast trajectory. Framework clasts are oxidized and are entirely composed of Cordilleran lithologies, which are well rounded but display low sphericity. Lithotype Sh is entirely composed of laterally discontinuous, 0.4–0.8 m thick, tabular sheets of horizontal to ripple-drift crosslaminated, fine- to medium-grained sands. Planar, erosional contacts define the bounding discontinuities that separate lithotypes within LTA 1.

6.1.1 Interpretation

Lithotype assemblage 1 is interpreted as having been deposited in a network of gently dipping, shallow, high-energy, unstable, low-sinuosity distributary channels. The deposition of structureless and imbricated gravels collectively indicates that sediment was transported as bedload under high-energy conditions (Harms et al., 1982). Gravel trough–cross-stratification in this assemblage represents slugs of gravel that formed minor channel-fill deposits and acted as nuclei for barform generation (Leddy et al., 1993). Events such as rainfall and lobe switching most likely had a catastrophic effect on the channel network, promoting bank collapse and the release of gravel slugs into the system (Hein and Walker, 1977). The abundance of lithotype Gt within the assemblage is likely the result of low bank stability due to the lack of rooted-vegetation within the system (Bluck, 1974; Rust, 1975).

Horizontally bedded deposits of sand and ripple-drift sequences within the assemblage support an environment dominated by suspension settling under low-energy conditions (Lowe, 1988). These sediments likely reflect periodic channel abandonment within the complex.

The limited lateral extent and absence of Shield lithologies within LTA 1 indicate deposition was restricted to the floor of a regionally integrated preglacial drainage system incised into middle Cretaceous bedrock. It is inferred that this drainage system formed part of the ancestral Peace River valley, which has evidently been reoccupied and further incised by the contemporary river.

6.2 Lithotype Assemblage 2: Interbedded Gravel, Sand and Rhythmically to Crudely Laminated Fines

The top of LTA 1 was logged at approximately 554 m asl in section NA08-077 and is marked by a gradational contact into LTA 2, which comprises a 1–2 m thick sequence of interbedded, upward-fining pebble gravel, planar-bedded sand, fine-grained rhythmites, and crudely laminated clay, silt and fine-grained sands (lithotype Sh/Fl; Figure 12). Lithotype assemblage 2 is poorly exposed in the map area due to the widespread effects of mass movement along the Peace River valley, therefore the nature of its contact with LTA 3 is uncertain.

6.2.1 Interpretation

Sediments that constitute LTA 2 reflect deposition under lower flow regimes during a period of waning flow within the channel-fill complex. The gradational contact with LTA 1 suggests that both lithotypes form a temporally related, upward-fining succession deposited in a progressively lower energy environment. This may have resulted from channel switching and subsequent abandonment in the system, or a progressive reduction of base level in response to the damming of the lower reaches of the ancestral Peace River by the advancing Laurentide Ice Sheet, and the consequent inundation by proglacial lake water.

6.3 Lithotype Assemblage 3: Rhythmically Bedded Fine Sand and Silt

Lithotype assemblage 3 was logged between approximately 550 and 585 m asl in sections NA08-077 and RP08-049 (Figure 12). The assemblage is composed of rhythmically bedded, fine-grained sands and silts with minor sequences of matrix-supported pebble to cobble interbeds (Fl/Flv/Gmh), upward-fining planar to ripple-bedded sand (fSh/fSm/fSr), and fine-grained rhythmites and laminated clay and silt (Fl/Flv; Figure 12). The lower part of LTA 3 is defined by poorly consolidated, disaggregated rafts of ripple-drift, fine-grained sands and silts within a massive clay matrix and laminated fine-grained sands and silts with dewatering structures, including dislocated and convolute laminae (fS(w)), swirled lamination, penetrative clay diapirs and dish structures (Figure 14).

6.3.1 Interpretation

Lithotype assemblage 3 is interpreted as a glaciolacustrine unit, deposited by suspension settling under low-flow regimes in a restricted environment. Consequently, LTAs 1, 2 and 3 record a depositional continuum from shallow, high-energy, unstable, low-sinuosity distributary channels to a proglacial lacustrine system, associated with the progressive advance of the Laurentide Ice Sheet into the lower reaches of the ancestral Peace River valley.

The occurrence of disaggregated sand rafts and deformed and diapirized laminated sediments in the lower part of LTA 3 suggests that suspension settling was punctuated by the emplacement of subaqueous mass-flow deposits. Sporadic gravitational failures of unstable banks within the ancestral valley likely triggered the mass flows. These failures may be attributed to an increase in porewater pressure within sediments following inundation by rising proglacial lake levels, comparable to the effects of “first-filling” reported around reservoirs (c.f., Eyles, 1987), or undermining of the channel banks by helical flow within the

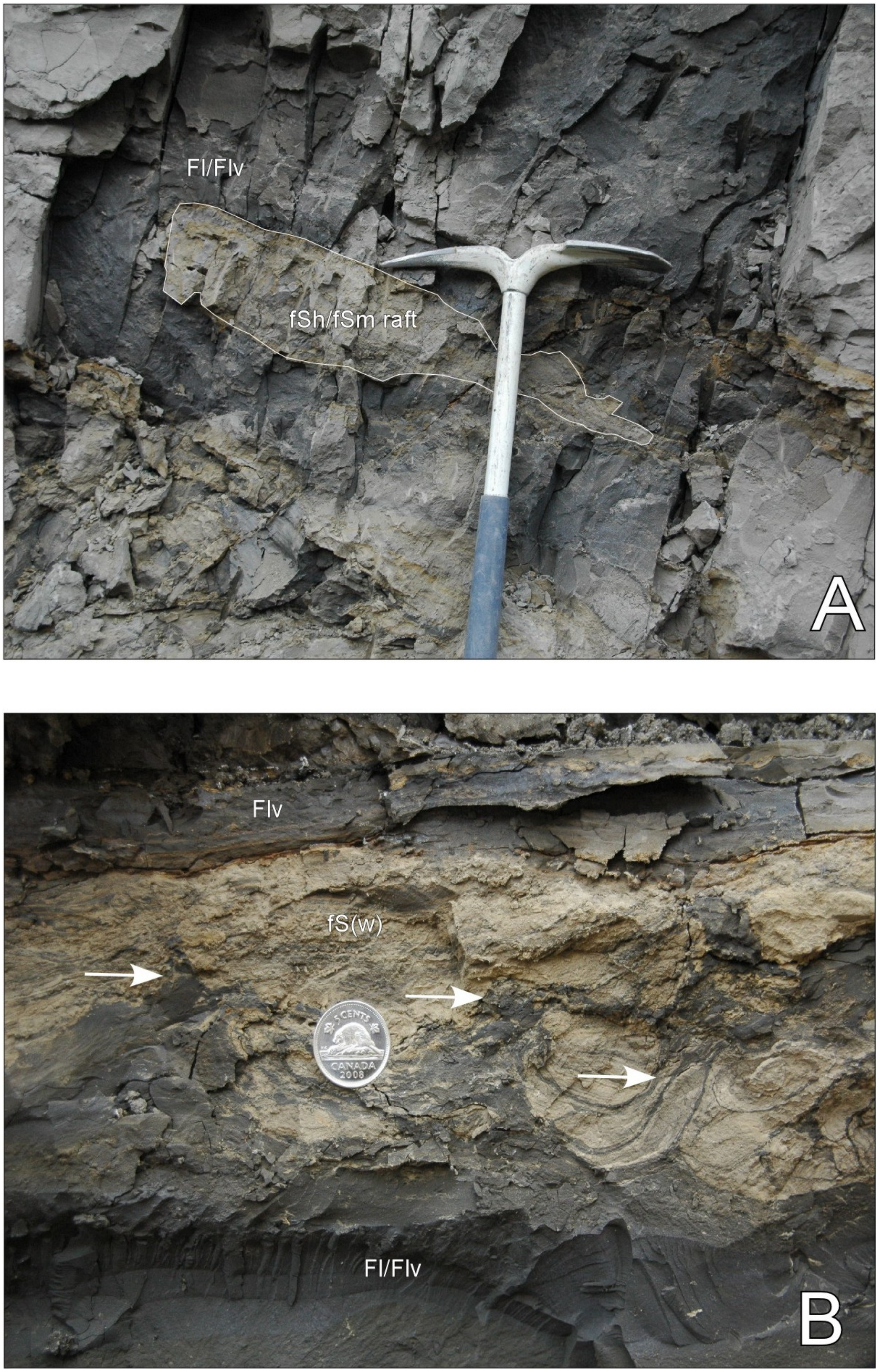

Figure 14. A) Disaggregated raft of fine sand and silt (fSh/fSm) within a massive clay matrix (Fl/Flv) at section RP08-049. B) Dewatering structures (denoted by the white arrows) along a contact between massive clay (Fl/Flv) and laminated fine sand (fS(w)) at section RP08-049, northwestern Alberta. Five-cent coin for scale.

channel(s). Laminated and rippled, cross-stratified, fine-grained sands were likely deposited as density underflows. Dislocated and convoluted ripple-drift and flat-laminated strata within the assemblage reflects soft-sediment deformation processes triggered by the onset of mass-flow deposits (c.f., Ankertell and Dzulynski, 1968).

6.4 Lithotype Assemblage 4: Interbedded Gravel and Fine- to Medium-Grained Sand

Lithotype assemblage 4 was logged between approximately 665 and 693 m asl in gravel pits excavated on the lowlands of the Worsley Plain (section NA08-082) and at the crests of low uplands on the Boundary Lake (sections RP08-027 and RP08-033) and Worsley plains (sections RP08-032 and NA08-076). The base of LTA 4 was only observed in one section (RP08-032), therefore its total thickness and the nature of the underlying unit are uncertain. Nevertheless, based on an examination of these gravel pits, LTA 4 comprises a 2 to ≥8 m thick sequence of interbedded pebble to cobble gravels and fine- to medium-grained sands.

In section RP08-032, the base of LTA 4 is defined by an approximately 1 m thick sand unit overlying a bedrock unconformity at approximately 676 m asl. This unit comprises horizontally bedded, coarse- to medium-grained sands with fine gravel interbeds, often only several clasts thick (Sh/Gh). The sand unit is overlain by a laterally discontinuous interbedded gravelly diamict, comprising an upward-coarsening sequence of horizontally bedded pebbles and cobbles with a sand matrix, rhythmically interbedded with well-sorted medium sand (Gcu/Gms/Gh/Sh; Figure 15). The contact between the sand and diamict units is sharp and horizontal and exhibits mesoscale evidence of both brittle fracture and ductile deformation. This includes injection structures, demarcated by a vertically displaced bed of oxidized gravel (Figure 16), as well as detached synforms, including rafts of matrix-supported gravel (Figure 17).

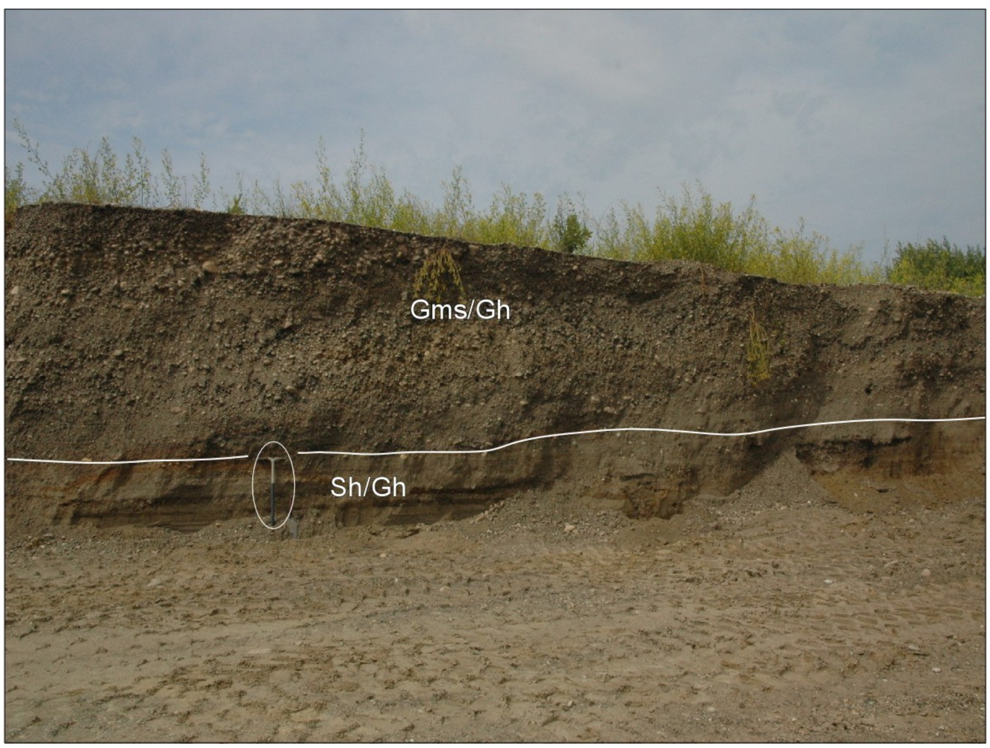

Figure 15. Horizontally bedded sheetlike deposits of coarse- to medium-grained sands interbedded with boulder gravels (Sh/Gh) overlain by upward-coarsening sheets of pebbles and cobbles with a sand matrix (Gms/Gh) at section RP08-032, northwestern Alberta. Pick circled for scale.

Figure 16. Injection structure at the top of a sand unit (Sh/Gh) containing vertically displaced sediments from the overlying gravel (Gms/Gh) at section RP08-032, northwestern Alberta.

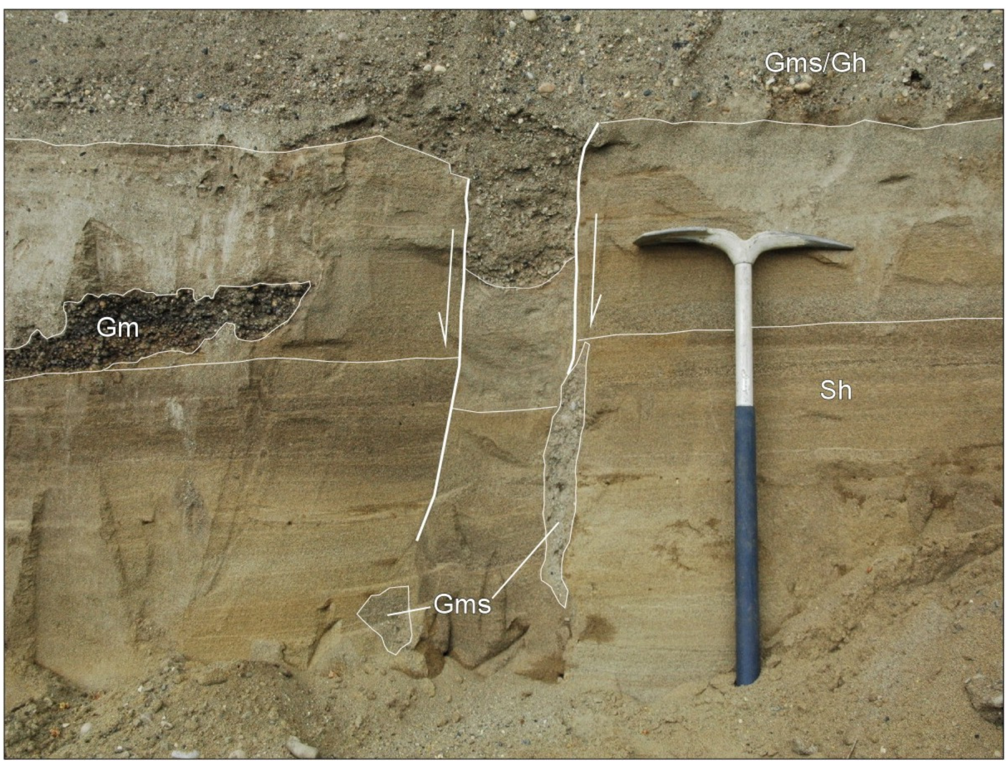

Figure 17. Detached synforms, including rafts of matrix-supported gravels (Gm/Gms), within horizontally bedded sand (Sh) at section RP08-032, northwestern Alberta.

Interbedded, matrix-supported pebble to cobble gravels are unconformably overlain by a southeastward steeply dipping sequence of planar tabular crossbedded gravels that are interbedded with sheetlike deposits of massive, poorly sorted gravels within a sand-rich matrix (Gp/Gms). Crossbedded gravels within the sequence comprise up to 4 m of alternating, southeast-dipping beds of openwork pebbles with clay skins and clast-supported pebbles and cobbles with a sand matrix (Figure 18). The upper contact of the crossbedded gravel sequence is defined by a horizontal erosional surface. The overlying facies comprises tabular sheets of sand interbedded with massive, poorly sorted gravels within a sand-rich matrix (Sh/Gms). Cut-and-fill structures with thin, laterally discontinuous sheets or concave lenses of stratified sand (Gp/Su) occur in the upper part of LTA 4. Gravel examined in LTA 4 is entirely composed of Cordilleran lithologies and is weakly oxidized, particularly along the contacts of beds with differing permeabilities.

6.4.1 Interpretation

Lithotype assemblage 4 is interpreted as a composite-compound bar complex deposited during upper flow regime conditions within the proximal reaches of a braided river system. The internal architecture of this bar complex documents the superimposition of morphologically and texturally distinct internal elements due to the downstream migration of a succession of accretionary bedforms across former bar positions.

The horizontally bedded sand and gravel identified in LTA 4 resembles diffuse sheets described by Miall (1985). Consequently, these sand and gravel sequences are interpreted to reflect the progradation of a downstream accretionary element (longitudinal bar) within the composite-compound bar complex. During peak-flow events within the channel, the addition of clasts to the leading edges of the gravel sheets would have accelerated progradation. Steeply dipping, planar tabular crossbedded, openwork gravels that overlie the downstream accretionary element are interpreted as a lateral accretionary element (lateral bar)

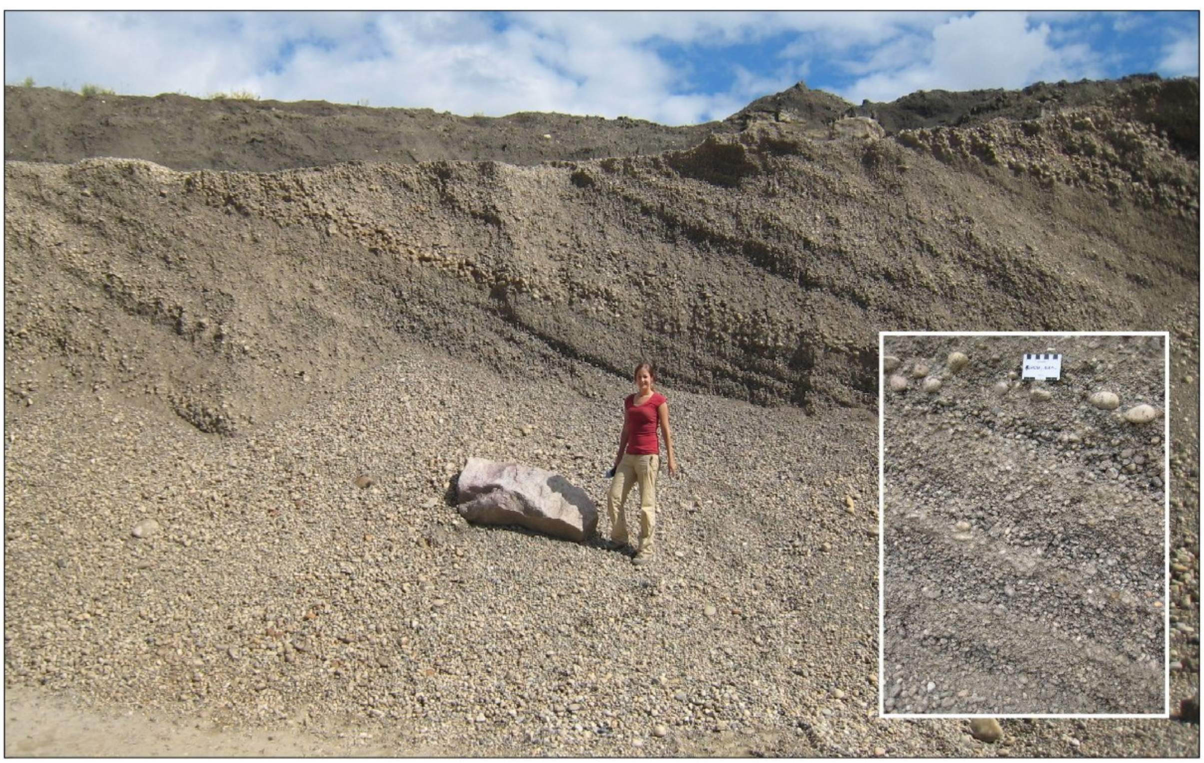

Figure 18. A southeast-dipping macroform composed of crossbedded gravel at a pit adjacent to section NA08-076, northwestern Alberta. Inset illustrates beds of openwork pebbles with clay skins and clast-supported pebbles and cobbles with a sand matrix. Note the coarsening-upwards sequence below the scale card.

deposited during shifts in the direction of current flow. Such shifts would have reduced shear stress along the bar flank, resulting in lateral accretion or slipface migration of the element at an oblique angle to the main flow direction (c.f., Allen, 1983; Miall, 1985). The clay that coats pebbles within the crossbedded gravels likely filtered into the openwork gravel framework during lowstands or waning-flow events within the channel.

The truncation of these crossbedded gravels by a horizontal erosion surface was likely the result of the headward erosion of the top of the gravel slipface, as the bar continued to accrete downstream. A tabular sheet of interbedded sands and gravels subsequently overrode the planar contact due to the progradation of a new longitudinal bar. The interbeds of infilled channel scours indicate that during stage fluctuations, the bar complex became emergent and was dissected by minor channels or chutes. During waning-flow events, these channels were infilled by silt and sand drapes forming concave lenses of variable lateral extent, with the thickest sediments occurring in the middle of the relict channel. The occurrence of composite successions of longitudinal and lateral barforms within LTA 4 suggests that the loci of sedimentation within the channel was spatially and temporally variable, largely due to shifting flow directions, variations in channel morphology and fluctuating rates of sedimentation as the complex evolved (c.f., Allen, 1983; Miall, 1985).

The detached synforms and small-scale grabens at the top of the basal sand unit, which contains downthrown rafts from the overlying horizontally bedded sandy gravel, are interpreted as synsedimentary structures formed along a sedimentary discontinuity between the two units. Consequently, these structures are not considered to be ice-wedge features resulting from periglacial exposure during a depositional hiatus that predates the emplacement of the overlying sandy gravel. Instead, they are considered to be the result of rheological variations in the basal sands, which we infer to have been saturated at the time of gravel deposition. This interpretation assumes that the basal sands behaved like a non-Newtonian fluid, within which strain rate responded nonlinearly to an increase in shear stress imposed by the overriding gravel. At low strain rates, the increased shear stress imposed by the gravel would have been accommodated by deformation, but as strain rates increased toward yield strength, the basal sands would have dilated, increasing their viscosity and promoting brittle deformation and the formation of high-angle extensional faults.

6.5 Lithotype Assemblage 5: Matrix-Supported Clayey Silt Diamict

All seven sections logged in the Cleardale area exposed LTA 5 (Figure 12). In sections NA08-077 and RP08-049, LTA 5 overlies LTA 3 along a sharp, horizontal contact. Similarly, in sections NA08-082, RP08-027, RP08-033, RP08-032 and NA08-076, LTA 5 overlies LTA 4 along a sharp, horizontal contact. LTA 5 comprises a 2–10 m thick sequence of massive greyish brown, matrix-supported clayey silt diamict (Dmm) deposited between 585 and 695 m asl (Figures 7 and 12). Clast content, which includes both local and Shield lithologies, is typically 2%–5%, predominantly comprising subrounded granule to cobble-sized clasts. This diamict has a high bulk density, and exhibits a fissile structure, characterized by well-developed subvertical dilation joints.

6.5.1 Interpretation

Lithotype assemblage 5 is interpreted as the product of the vertical accretion of deforming till, which commenced during the advance of the Laurentide Ice Sheet across the region. This till likely originated, in part, as proglacial lake sediment, which would have been overridden and advected down-flow by subglacial deformation, forming the clayey silt till facies that occurs across the Cleardale area. The sharp, horizontal base of this till facies documents subglacial shear, which is demonstrated by erosion of LTA 3 in sections NA08-077 and RP08-049, and the presence of a shear amalgamation zone in sections NA08-082, RP08-027, RP08-033, RP08-032 and NA08-076, in which the overriding deforming layer ingested clasts from LTA 4.

6.6 Lithotype Assemblage 6: Rhythmically Bedded Silt and Clay

Lithotype assemblage 6 forms the uppermost sequence in all but one of the logged sections (RP08-027), and forms the most common surficial map unit across the Cleardale area. LTA 6 comprises up to 8 m of inversely graded, rhythmically bedded silt and clay with dropstones, which overlies LTA 5 along a sharp, horizontal boundary (Flv; Figure 12). The base of this unit consists of an approximately 20 cm thick sequence of finely laminated clay. Glaciolacustrine rhythmites overlie this clay along a sharp, horizontal contact. Individual sandy silt/clay couplets vary in thickness from 1–10 cm. Clay laminae range from 0.5–1 cm thick, whereas the thickness of the sandy silt component of the couplet is more variable, ranging from <2 cm immediately above the contact with the basal clay, to approximately 10 cm farther up the section (Figure 5). Within some sections in the Cleardale area, the laminated sediments in the upper part of LTA 6 exhibit evidence of ductile deformation and liquefaction, including boudinage, nonpenetrative deformation and homogenization of the sediments.

6.6.1 Interpretation

Lithotype assemblage 6 was deposited by suspension settling in a low-energy, glaciolacustrine environment. The sandy silt/clay couplets record ice-distal sedimentation within the deeper parts of a former lake basin, although the reverse grading and incremental thickening of sandy silt laminae toward the top of LTA 6 suggests that sedimentation occurred within a progressively shallowing basin.

The occurrence of ductile deformation and liquefaction in the upper part of LTA 6 suggests that glaciolacustrine sedimentation was succeeded by an interval of pro- or subglacial deformation. This deformation may have been initiated by loading of saturated sediments, either due to the emplacement of subaqueous mass-flow deposits or the readvance of Laurentide ice lobes across the former lake basin.

7 Discussion

Three gravel sheets, each occupying a distinct stratigraphic and topographic position and grading to different base levels, document the evolution of relict fluvial drainage systems across the Cleardale region. The oldest gravel sheet caps monadnocks to the north and south of the map area, including to the Clear Hills and the Saddle Hills. These fluvial sediments form part of a broad peneplain that was deposited by an eastward-flowing braided river system across a basin-wide unconformity during the Oligocene to Miocene (Middle to Late Tertiary), following regional uplift associated with the Laramide Orogeny (Leckie, 1989, 2006; Leckie and Cheel, 1989; Leckie et al., 2004). During ongoing uplift and associated changes in base level, eastward-flowing rivers eroded this peneplain, leaving the gravel-capped monadnocks within a broad, regional planation surface. Lithotype assemblage 4 is inferred to have been deposited following this interval of planation, due to its sedimentary architecture and position on the Peace River Lowlands, between the gravel-capped Clear and Saddle hills. Although the age of LTA 4 is uncertain, it is tentatively assigned a Late Tertiary to Early Quaternary age since it was deposited prior to the incision of the Peace River Lowlands and the establishment of the ancestral Peace River valley. Lithotype assemblage 4 lies within the same stratigraphic and topographic position as a regionally extensive gravel sheet mapped along the northern flank of the Peace River, up to 100 km to the east and west of the Cleardale area. Consequently, we suggest that LTA 4 correlates with this regional sheet, known locally in Alberta as the Grimshaw gravels (Edwards and Scafe, 1996; Chlachula and Leslie, 1998), and in British Columbia as the “high planation surface” (Hartman and Clague, 2008).

The remaining lithotype assemblages described in the Cleardale area relate to the infilling of a regionally integrated preglacial drainage system, which formed part of the ancestral Peace River valley. The base of this infill sequence occurs at least 120 m below the Peace River Lowlands planation surface, demonstrating that considerable valley incision and filling occurred in the region after the deposition of LTA 4.

The sedimentary succession of the Cleardale area is broadly correlative to other valley fill sequences in the region (Bayrock, 1969; Fenton, 1984; Liverman et al., 1989; Catto et al., 1996; Geological setting for large landslides at the town of Peace River, Alberta, Morgan et al., work in progress, 2010). Collectively, this succession has been interpreted as the product of a single Laurentide glaciation during the Late Wisconsinan. Lithotype assemblage 1 is inferred to be the oldest Quaternary sediment in the Cleardale area. The sedimentary architecture of this fluvial sequence, together with the absence of Shield lithologies, records the infilling of the ancestral Peace River valley by a regional, eastward-flowing braided river prior to the onset of Laurentide glaciation. Although the age of LTA 1 is unknown, its sedimentary architecture and stratigraphic position suggests that it correlates with the basal sand and gravel unit of valley fill sequences described in exposures close to the town of Peace River (Geological setting for large landslides at the town of Peace River, Alberta, Morgan et al., work in progress, 2010) and at the Watino and Simonette River outcrops (Liverman et al., 1989; Catto et al., 1996). Wood samples recovered from this correlative unit at the Watino and Simonette River outcrops have yielded radiocarbon ages between 43.5 and 27.4 ka BP (Reimchen, 1968; Westgate et al., 1971, 1972; Liverman et al., 1989). Close to the town of Peace River, approximately 100 km to the east of the Cleardale area, a piece of caribou antler recovered from the upper portion this basal sand and gravel produced a radiocarbon age 25.1 ka BP (Morgan et al., 2008). Collectively, these data indicate that the basal sand and gravel unit exposed along the Peace River and its tributaries comprises a conformable fluvial sequence deposited during the Middle Wisconsinan.

The gradational contact with LTA 2, which fines upwards into LTA 3, records the progressive damming of regional drainage by the advancing Laurentide Ice Sheet and the consequent increase in base level associated with inundation by proglacial lake water (c.f., Bobrowsky et al., 1991; Catto et al., 1996; Leslie and Fenton, 2001; Hartman and Clague, 2008). Lithotype assemblage 3 is interpreted as ice-advance–phase glaciolacustrine sediments that have been mapped throughout the Peace River region, and are considered to have been deposited in a proglacial lake informally termed Glacial Lake Mathews (Hartman and Clague, 2008). This lake is proposed to have been regionally extensive and deep (Mathews, 1980) and likely filled rapidly, which destabilized the flanks of the ancestral Peace River valley, triggering the subaqueous debris flows that are observed at the base of LTA 3. Although these sediments have not been dated, they are younger than 25.1 ka BP, which is the minimum age of the underlying fluvial sand and gravel units (LTAs 1 and 2).

These advance-phase glaciolacustrine sediments were overridden by the Laurentide Ice Sheet, which advanced into the region approximately 22 ka BP (Dyke et al., 2002) and deposited till across large parts of the Cleardale area and the surrounding region of western Alberta.

The Laurentide Ice Sheet retreated northeastward, and down-drainage from the Cleardale area after 11 ka BP (Dyke, 2004), exposing the Worsley, Pouce Coupé, Josephine and Boundary Lake plains. Subaerial and glacial meltwater discharge subsequently filled this basin, forming a proglacial lake, which is documented by the glaciolacustrine sediments that cover much of the Cleardale area. These glaciolacustrine sediments form part of a larger expanse of proglacial lake sediments, which were deposited within Glacial Lake Peace (Mathews, 1980).

Glacial Lake Peace was a large, time-transgressive proglacial lake that extended from British Columbia in the west (Mathews, 1980) to High Level in the north (Plouffe et al., 2007) when the Laurentide Ice Sheet exposed the Peace River valley and surrounding lowlands during its retreat at the end of the last glaciation. This lake occupied successive proglacial positions, as the retreating Laurentide Ice Sheet exposed progressively lower outlets to the north and east. Previous paleoshoreline studies have suggested that Glacial Lake Peace inundated the Cleardale area from the early Clayhurst to the Indian Creek stages (Mathews, 1980). During these stages, Glacial Lake Peace extended along the Peace River valley for 300 km north and 175 km west of the Cleardale area.

The highest glaciolacustrine sediments (780–750 m asl) described in this report onlap the southern flank of the Clear Hills, in the northwest portion of the Cleardale area. These are interpreted to have been deposited as a Laurentide ice lobe retreated from a small basin east of Boundary Lake, impounding local drainage and forming a short-lived proglacial lake. The suite of subparallel, northwest-trending moraines on the low upland separating the Worsley and Boundary Lake plains are interpreted as De Geer moraines (Benn and Evans, 1998). These record the successive retreat positions of a Laurentide ice lobe that terminated within this proglacial lake and deposited subaqueous sediments at its margin. The asymmetrical profile of these moraines documents either brief standstills or minor readvances of the subaqueous margin (Boulton, 1986) or seasonal calving of the floating snout (Aartolahti, 1972; Holdsworth, 1973).

Continued ice retreat, primarily eastward along the ancestral Peace River valley, opened a lower basin along the axis of the Worsley and Pouce Coupé plains. This basin was subsequently inundated by Glacial Lake Peace, which onlapped the northern flank of Blueberry Mountain to approximately 730 m asl. However, the occurrence of lower elevation till plains on the southern flank of the Clear Hills and on the low ridges and uplands on Josephine Plain indicate that these areas lay inside the ice margin during this lake stage. As the Laurentide Ice Sheet continued to retreat eastward along the ancestral Peace River valley, and northward into the Clear Hills, these till plains were exposed to glaciolacustrine onlap, although by this time, the lake level had dropped to approximately 700 m asl. By the time the Laurentide Ice Sheet had evacuated the ancestral Peace River valley in the Cleardale area, Glacial Lake Peace had receded to at least 680 m asl. Paleoshorelines deposited between 660 and 625 m asl document the further lowering of Glacial Lake Peace across the Cleardale area, in response to the opening of lower basins as the Laurentide Ice Sheet continued to retreat down-drainage along the Peace River Lowlands.

Previous research has indicated that during lake drainage, the regional retreat of the Laurentide Ice Sheet was punctuated by readvances of localized ice lobes (Henderson, 1959; Fenton, 2008; Atkinson, 2009). The fluted and deformed glaciolacustrine sediments described in this report document the incursion of Laurentide ice lobes into a former basin of Glacial Lake Peace. The streamlining and deformation of these sediments either relate to readvance of ice lobes from the Clear and Saddle hills across the former lakebed, and/or the loading of saturated sediments associated with the recoupling of ice shelves following Glacial Lake Peace drainage.

Following final lake drainage in the early Holocene, postglacial rivers reoccupied the ancestral Peace River valley and its tributaries, since drainage systems are less likely to incise new channels through bedrock when deep valleys infilled by unlithified sediment already exist (Evans and Campbell, 1992). Holocene fluvial processes have incised through approximately 120 m of Quaternary sediments and up to 30 m into the underlying bedrock. Consequently, postglacial fluvial erosion has removed much of the Quaternary depositional record of the Peace River valley. Recent fluvial processes are responsible for the ongoing aggradation and incision of sand and gravel along the Peace River, leaving active alluvium along and within the modern channel and terraces perched above the modern floodplain. The postglacial evolution of the Peace River valley and its tributaries has been further influenced by slope failures and mass movements that have occurred throughout the Holocene and continue to affect the region. The distribution of deep-seated landslides correlates with the location of buried valleys, including the ancestral Peace River and its tributaries (Cruden et al., 1990, 1997). This may in part be related to elevated groundwater pressures within the basal sand and gravel unit of the valley infills (Morgan et al., 2008). However, the ice advance phase glaciolacustrine sediments at the base of the Late Wisconsinan and Early Holocene sequences in the Peace River region have been recognized as a prominent décollement plane for a number of failures (Morgan et al., 2008; Geological setting for large landslides at the town of Peace River, Alberta, Morgan et al., work in progress, 2010).

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