ERCB/AGS Open File Report 2012-04

Geological Setting for Large Landslides at the Town of Peace River, Alberta (NTS 84C)

Energy Resources Conservation Board

Alberta Geological Survey

ERCB/AGS Open File Report 2012-04

Geological Setting for Large Landslides at the Town of Peace River, Alberta (NTS 84C)

A.J. Morgan,[1] R.C. Paulen,[2] S.R. Slattery[3] and C.R. Froese[1]

[1] Energy Resources Conservation Board
Alberta Geological Survey
[2] Geological Survey of Canada
[3] Syncrude Canada Ltd.

April 2012

ISBN 978-0-7785-8658-6

If you use information from this publication in other publications or presentations, please acknowledge the ERCB/AGS. We recommend the following reference format:

Morgan, A.J., Paulen, R.C., Slattery, S.R. and Froese, C.R. (2012): Geological setting for large landslides at the Town of Peace River, Alberta (NTS 84C); Energy Resources Conservation Board, ERCB/AGS OFR 2012-04, 33 p.

Author addresses:

R.C. Paulen
Geological Survey of Canada
601 rue Booth Street
Ottawa, ON K1A 0E8
Canada
Tel: 613.947.8963
E-mail: Roger.Paulen@NRCan-RNCan.gc.ca

S.R. Slattery
Syncrude Canada Ltd.
P.O. Bag 4009, M.D. A250
Fort McMurray, AB T9H 3L1
Canada
Tel: 780.715.9579
E-mail: slattery.shawn@syncrude.com

Published April 2012 by:
Energy Resources Conservation Board
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

Contents

Figures

Acknowledgments

This work was funded by the Alberta Geological Survey (AGS) Peace River Project and by contributions from the town of Peace River, Alberta Transportation, the University of Alberta, ATCO Pipelines, ATCO Electric and Canadian National (CN). S. Botterill (summer student), K. Mckay (AGS), J.E. Warren (AGS), D. Borthwick and A. Weber (summer students) provided field assistance. A. Beaudoin (Royal Alberta Museum) prepared the organic material submitted for radiocarbon dating. The evolution of our models greatly benefited from contributions and constructive discussions with L.D. Andriashek (AGS), S. Chowdhury, D. Cruden (University of Alberta), B. Hathway (AGS), G. Jean (AGS) and J.G. Pawlowicz (Energy Resources Conservation Board [ERCB]). N. Atkinson (AGS), T.G. Lemay (AGS), M. Grobe (AGS) and F.J. Hein (ERCB) critically read this paper and the authors wish to thank them for their comments and suggestions.

Abstract

The Peace River lowlands of Alberta and British Columbia are one of the most historically active mass-movement areas in Western Canada. At the town of Peace River, near the confluence of the Peace and Smoky rivers, Holocene fluvial and colluvial processes have incised approximately 180 m of Quaternary sediments and 30 m into the underlying bedrock. Landslide movements of varying types have occurred in both the Quaternary sediments and the underlying bedrock.

This open file report provides a geological framework for large landslides within the Peace River valley at the town of Peace River and provides details of the development of a bedrock topography model and the corresponding surficial terrain model. Field-based mapping of the Quaternary stratigraphy overlying the bedrock surface is outlined, as well as an interpretation of the results of a drilling program conducted in December 2008. Based on sediment-core analysis and examination of sediment-outcrop sections adjacent to the Peace River valley along the Heart River, the geological history of the examined portion of the Peace River valley can be characterized by a four-stage event sequence model. The distribution of deep-seated landslides at the town of Peace River is spatially correlated with the location of buried valleys, including the ancestral Peace River and its tributaries. This may be, in part, due to groundwater in the basal sediments of these buried valleys penetrating and weakening the bedrock. Glaciolacustrine sediments deposited in advance of and subsequently overridden and overconsolidated by the Laurentide Ice Sheet are also suspected for a number of failures along weak, presheared zones. The report results provide stakeholders with information on the landslide hazard risk posed to the population and infrastructure within the bounds of the study area and can be used to aid municipal planning decisions.

1 Introduction

The Peace River lowlands of Alberta and British Columbia are one of the most historically active mass-movement areas of Western Canada. Urban areas, such as the town of Peace River, and their associated infrastructure, have been, and continue to be, affected by these movements. The Alberta Geological Survey (AGS), with the support of various stakeholders, initiated a multidisciplinary geohazard study of the town of Peace River, Alberta, to develop a better understanding of the type and extent of landsliding within the Peace River valley (Froese, 2007). A bedrock surface model generated from multiple data sources shows that the ancestral Peace River formed a large valley, eroding the bedrock surface almost to the same base level as the modern Peace River. During Quaternary glaciation, the advancing Laurentide Ice Sheet inundated the Peace River valley and its tributaries, depositing a thick and complex sequence of glaciogenic sediments. Fieldwork and a rotosonic drilling program (Morgan et al., 2009) indicate that the Quaternary stratigraphy consists of fluvial sediments derived from the Cordillera, aggrading fluvial and glaciofluvial sediments overlain by glaciolacustrine deposits, till and finally deglacial sediments deposited within Glacial Lake Peace. Collectively, this information provides the geological framework within the Peace River valley at the town of Peace River and can be applied to understanding landsliding in this area.

2 Setting

2.1 Study Area and Physiography

The study area (NTS 84C; Figure 1) is in the Interior Plains of Canada (Bostock, 1981), within the Peace River lowlands physiographic zone (Pettapiece, 1986). Much of the surface morphology in this area is the result of Paleogene and Neogene (Tertiary) fluvial erosion and deposition, and subsequent erosion and deposition by the Late Wisconsin Laurentide Ice Sheet (LIS), and finally by ongoing Holocene fluvial erosion. The Peace River valley is the dominant geomorphological feature of the region, which evolved as the Peace River incised the Quaternary and Paleogene sediments and, in places, the Cretaceous bedrock. The river valley is an important transportation corridor and includes highways and a railway line. The Peace River lowlands separate the Buffalo Head Hills to the east and the Whitemud and Clear hills to the west. The Peace River district is mainly fertile farmland characterized by flat topography and stone-free fields developed on fine-grained sediments deposited within the former basin of Glacial Lake Peace, which inundated most of the region up to approximately 610 m above sea level (asl) during the retreat of the LIS (Mathews, 1980; Leslie and Fenton, 2001; Paulen, 2004; Paulen et al., 2004). Elevation within the study area ranges from 320 m asl at the floodplain in the town of Peace River to 625 m asl in the northwestern part of the study area.

2.2 Bedrock Geology

The stratigraphic units relevant to landslide processes in the Peace River area occur within the Cretaceous Fort St. John Group of the Western Canada Sedimentary Basin (Hayes et al., 1994). Within the study area, the Fort St. John Group consists of the Spirit River and Peace River formations overlain by the marine shale of the Shaftesbury Formation. The sandstone of the Dunvegan Formation overlies the units in the Fort St. John Group. The Smoky Group, which occurs west of the Peace River, consists of the Kaskapau and Puskwaskau formations and stratigraphically overlies the Dunvegan Formation sandstone. The Shaftesbury Formation is an upper Lower Cretaceous unit that outcrops along the Peace River south of the town of Peace River (Hamilton et al., 1999). This formation consists of dark grey marine shale with bentonite partings and occasional sand and silt interbeds. The upper contact grades into the regionally extensive Dunvegan Formation (Leckie et al., 1994). Slope failures by translational and compound slides are very common in the thinly bedded shales of the Kaskapau and Shaftesbury formations (Cruden et al., 1990) because of the lithology of these bedrock formations.

Figure 1. Location of Peace River study area (in red), west-central Alberta.

2.3 Quaternary Geology

The Quaternary stratigraphy of the Peace River region is generally considered to be the product of a single advance of the LIS during the Late Wisconsin (Bayrock, 1969; Fenton, 1984; Liverman et al., 1989). However, some researchers have described Canadian Shield erratics within gravels that predate the Late Wisconsin along the Peace River, suggesting that an earlier advance of the LIS may have at least extended into the catchment of the ancestral Peace River (Leslie and Fenton, 2001; Hartman, 2005). Leslie and Fenton (2001) described the stratigraphy and distribution of Quaternary sediments in the Peace River area of Alberta. Stratigraphic correlations of these sediments with those documented in the Peace River District of British Columbia (Bobrowsky et al., 1991) have been provided by Miller and Cruden (2002) and Atkinson and Paulen (2010).

Pre-Laurentide gravels preserved in preglacial valleys and on the upland west of Peace River near the town of Grimshaw are the oldest Quaternary sediments in the Peace River valley of Alberta. These sediments are interpreted to have been reworked from Paleogene (Tertiary) quartzite in the Clear Hills to the northwest and deposited in a nonglacial Peace River drainage system during the Sangamon interglacial stage (125 000 to 75 000 years ago) or perhaps earlier (Davies et al., 2005).

The LIS advanced into the region approximately 22 000 BP (Dyke et al., 2002). During this advance, the LIS blocked regional drainage, forming a series of short-lived proglacial lakes, including Glacial Lake Mathews, which occupied the Peace River region and into which glaciolacustrine sediments and glaciofluvial outwash were deposited (Bobrowsky et al., 1991; Catto et al., 1996; Leslie and Fenton, 2001; Hartman and Clague, 2008). These advance-phase proglacial sediments were subsequently overridden and overconsolidated by the LIS, which deposited till across much of the region, forming a thick (2 to >25 m) continuous blanket over large parts of western Alberta. Regional deglaciation is estimated to have occurred approximately 11 000 BP (Dyke, 2004), during which time the LIS retreated northward and down-drainage, blocking subaerial and glacial meltwater drainage systems, thereby ponding water at the ice margin. Glacial Lake Peace (Mathews, 1980; Hartman and Clague, 2008) was one of the larger deglacial lakes that developed and occupied successive proglacial positions extending from British Columbia in the west (Mathews, 1980) to High Level in the north (Plouffe et al., 2007). In the Peace River region, till is overlain by Glacial Lake Peace sediments, which comprise silt, clay and minor sand of varying thickness. These sediments blanket the landscape up to approximately 610 m asl (Paulen, 2004; Paulen et al., 2004).

Glacial Lake Peace drained in the early Holocene and the Peace River immediately began incising through the glacial sediments. Several terrace levels record the rapid rate of incision. Local Holocene deposits also include organic sediments, cliff-top loess and anthropogenic materials from infrastructure development. Landslides have occurred throughout the Holocene affecting the region to this day. Along the Peace River and its tributaries, slope failure and mass movement have resulted in thick accumulations of colluvium.

2.4 Hydrogeology

Aquifers in the area include near-surface gravel within the glacial drift and sandstone lenses within the Upper Cretaceous Dunvegan Formation (Tokarsky, 1971). However, the majority of water used by the municipality is treated water taken from the Peace River. In uplands adjacent to the contemporary Peace River valley, shallow deposits of sand and gravel provide an accessible source of good quality water. In the town of Grimshaw, located on the plateau west of the town of Peace River, drinking water is obtained from an approximately 10 m thick, regional-scale, preglacial gravel deposit informally named the Grimshaw gravels (Tokarsky, 1971; Cowen, 1994).

The Grimshaw gravels predominately occur to the west and north of the Peace River, extending north to the eastern edge of the Clear Hills. These gravels extend to the edge of the ancestral Peace River valley, which formed prior to glaciation, and are often flanked on the valley sides by Holocene alluvial terrace gravel formed during the downcutting of the contemporary Peace River. These deposits are also of interest to the landslide investigation as a potential source of groundwater seepage, which over time could contribute to the retrogressive movement observed in the slide masses on the western side of the Peace River.

3 Previous Work

3.1 Geology

A number of regional-scale projects investigating the bedrock geology, surficial geology and Quaternary stratigraphy of the Peace River area provide a good understanding of the general geology within the study area (Pawlowicz et al., 1996; Leslie and Fenton, 2001; Paulen, 2004; Paulen et al., 2004). Previous investigations into bedrock topography of the Peace River area were conducted and updated by various authors, culminating in the 1:1 000 000-scale bedrock geology compilation map by Hamilton et al. (1999). Tokarsky (1971) and Borneuf (1981, 1983) expanded on work of Jones (1966) and reported on the hydrogeology of the Peace River area. Additional data and stratigraphic information exist in unpublished geotechnical and consulting reports.

3.2 Landslide Documentation

Landslides occurring along the Peace River and its tributaries have been well documented. Mass-movement processes remain active and recent events have been documented in northeastern British

Columbia (Bobrowsky and Smith, 1992), near the town of Peace River (Hardy, 1957; Alberta Transportation, 1985; Cruden et al., 1990) and in the western Peace River lowlands of Alberta (Cruden et al., 1993; Miller and Cruden, 2001, 2002). Typical landslides within the Peace River valley fail along weak layers of overconsolidated ice-advance–phase glaciolacustrine sediments deposited in Glacial Lake Mathews. Elsewhere in west-central Alberta, many other documented large landslides are similarly seated within subtill glaciolacustrine deposits. Examples include the Rycroft (Saddle River) landslide (Cruden et al., 1993), the Montagneuse River slide (Cruden et al., 1997), the Eureka River slide (Miller and Cruden, 2002) and the Attachie landslide (Fletcher et al., 2002). However, not all rupture surfaces in the Peace River region are limited to the subtill glaciolacustrine sediments. Earth movements with failure surfaces located in weak Shaftesbury Formation marine shale occur on the Smoky River a few kilometres to the south of the study area and have been documented farther south along the Little Smoky River (Thomson and Hayley, 1975).

Davies et al. (2005) created a digital inventory of Holocene landslides for the Peace River map area (NTS 84C) from surficial geology maps and airphoto analysis. This inventory summarized the geology of the study area and photos of landslides, as well as scarp locations and classifications of slope movement, as outlined by Cruden and Varnes (1996).

4 Geological Model

Analysis of landslides and modes of failure within the Peace River valley relied on the preparation of a bedrock surface model, the incorporation of two digital terrain models of varying resolution and a detailed examination of the valley-fill Quaternary stratigraphy and sediments.

4.1 Bedrock and Terrain Surface Models

The bedrock surface model was created from multiple lithological and stratigraphic data sources. Approximately 1400 water well logs, oil and gas geophysical logs and geotechnical logs were examined. These data were supplemented by 62 outcrop surveys, where geological features such as bedrock contacts were described and their elevations recorded. Integration of all of these data into the modelling geodatabase provided the basis for the creation of the bedrock surface using ViewLog® downhole modelling software.

A high-resolution (1 m), bare-earth, Light Detection and Ranging (LiDAR) survey was conducted over a 100 km^2 region centred on the town of Peace River (Figure 2). LiDAR data show the ground surface stripped of vegetation and buildings. A second ground surface model, extending beyond the 100 km^2 landslide study area, was produced using a 60 m Shuttle Radar Topography Mission (SRTM) terrain model (United States Geological Survey, 2000). This approximately 2400 km^2 area was chosen to include the trend of the buried preglacial valley at the boundaries of the 100 km^2 landslide study area. These digital elevation models (DEM) were supplemented with satellite imagery, including a QuickBird high-resolution satellite colour image of the town.

The bedrock surface model was generated using available borehole data from the study area, or picks of the bedrock surface based on the description of lithological units, or characteristic log responses for bedrock on geophysical borehole logs. Picks were checked against the stratigraphy of surrounding boreholes and the interpreted trend of the bedrock surface. The confidence of the bedrock picks in holes with little or no lithological descriptions and poorly defined stratigraphy often relied on the density and quality of the surrounding borehole data. The bedrock surface was modelled in ViewLog as a gridded raster using bedrock picks, field observations and an interpreted user-defined bedrock surface in areas of low borehole density.

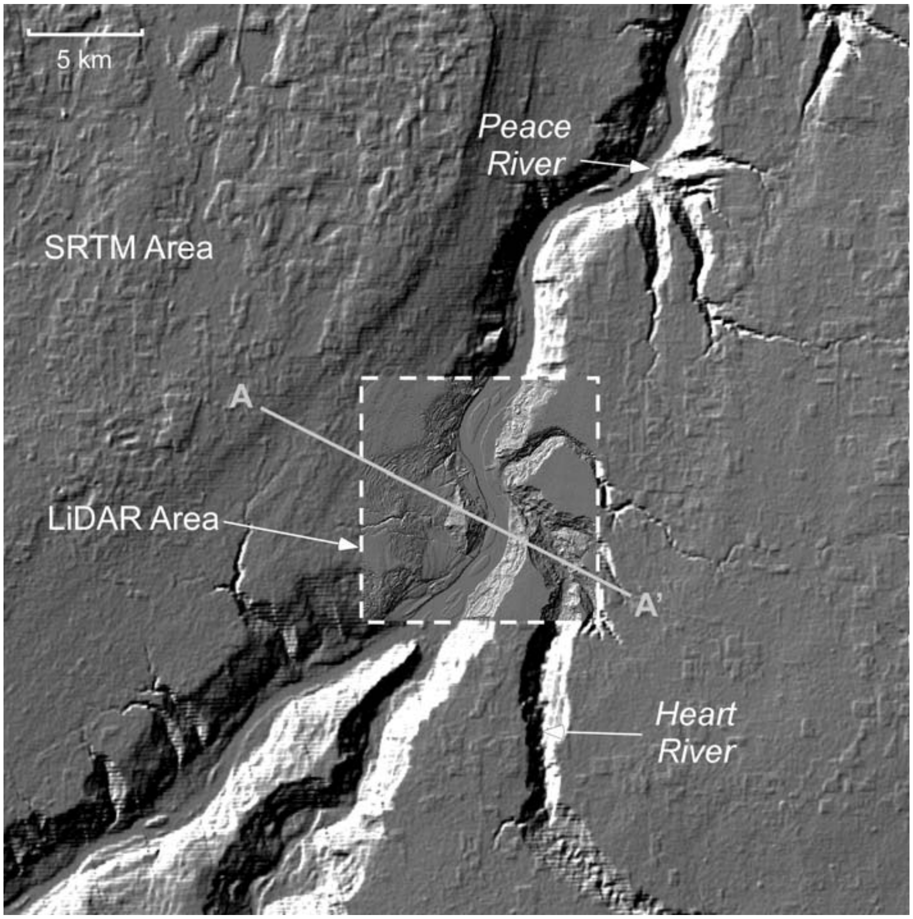


Figure 2. Shaded Light Detection and Ranging (LiDAR) digital elevation model (DEM) of the landslide study area (dashed line) and surrounding Shuttle Radar Topography Mission (SRTM) DEM, west-central Alberta. UTM boundaries of the LiDAR area are 476028E (left), 486198E (right), 6236843N (top) and 6226338N (bottom), Zone 11, NAD83. The shaded images were created using a sun inclination of 40° and an azimuth of 315°. Line A –A' refers to the cross-section depicted in Figure 20 (Section 5.4).

4.2 Composite Quaternary Stratigraphy

Key exposures from the Heart River, Peace River and roadcuts within the study area provided detailed sedimentological information on the Quaternary stratigraphy on the flanks and within the base of the valley. The Quaternary stratigraphy was compiled from field mapping and from unpublished geotechnical core log data provided by Alberta Transportation, Canadian National (CN) and the Town of Peace River. We augmented this information with shallow borehole data (Pawlowicz et al., 1996; Leslie and Fenton, 2001), geotechnical logs and overburden drilling (Morgan et al., 2009), which provided the first detailed, complete Quaternary record of the unconsolidated sediments in the Peace River valley at the town of Peace River.

5 Results

5.1 Bedrock Topography

The modern-day Peace River has incised through Quaternary sediments and into the bedrock at the base of the river valley and meanders within the talweg of the ancestral Peace River valley.

The bedrock surface was modelled using a combination of borehole-derived bedrock picks and user-defined surfaces. The user-defined surfaces added resolution for areas where borehole density was low and an interpretation for the bedrock surface was required. Figure 3 shows the distribution of the picks used to generate the gridded bedrock surface. A total of 304 bedrock picks (271 borehole and 33 field outcrop locations) were used within the SRTM area (Figure 3a), and 142 of the picks reside within the 100 km^2 LiDAR landslide study area. The focus for bedrock surface generation was to obtain the elevation of bedrock beneath the landslides being studied. The bedrock surface was also generated over an extended area (SRTM area) to gain insight about the geometry of the preglacial Peace River valley as it continues outside of the study area.

A first-order, nearest-neighbour interpolation method generated the bedrock grid surface. The resulting surface was checked for any outlier elevation picks relative to the trend of the generated surface. The source data for these outlier borehole picks were rechecked for errors and either corrected or removed if they were deemed unreliable. The bedrock surface is best defined within the study area covered by the LiDAR information due to the higher density of available data. The portion of the study area covered by the SRTM contains a lower density of boreholes, with the exception of the western uplands; hence confidence in the modelled bedrock surface in the area covered by the SRTM DEM is lower.

5.2 Quaternary Stratigraphy

In Alberta, the Quaternary stratigraphy is best preserved in settings such as the ancestral buried valleys of the Peace River and its tributaries. Figure 4 summarizes the general stratigraphy of the study area.

The lowermost Quaternary sediments are dominated by heavily oxidized, clast-supported, sandy, planar-bedded pebble gravels that are entirely composed of Cordilleran lithologies. Rounded to well-rounded clasts show low sphericity, and abundant chatter marks are visible on many quartzite pebbles. This unit is up to 8 m thick in places. The absence of Canadian Shield lithologies indicates that these sediments predate continental glaciation in central Alberta (Figure 5).

A pebbly sand unit, approximately 5 m thick, with clast content ranging from 5% to 15%, overlies the oxidized gravels. This unit is tabular and trough crossbedded with coarser gravels defining channel beds. This unit contains rare (<0.5%) Canadian Shield lithologies (Figure 6).

A 10 to 12 m thick unit of massive clast-supported coarse gravel overlies the pebbly sand. This unit contains a higher concentration of Canadian Shield pebbles, particularly towards the top of the unit. Discontinuous and scoured interbeds of planar-bedded to cross-bedded sand up to 0.8 m thick occur within these gravels. The sand beds are dominantly coarse grained and contain a low pebble fraction. Bedding ranges from planar to low-angle cross-stratification. In general, modal clast size and content increase from bottom to top in this coarse gravel unit (Figure 7). Approximately 20 km to the southwest of the study area, a sedimentary package thought to be the same stratigraphic unit yielded a fragment of barren-ground caribou antler; subsequently, this antler produced a Middle Wisconsin accelerator mass spectrometry (AMS) radiocarbon date of 25 120 ±140 ^{14}C BP (Beta –226811; test conducted by Beta Analytic Inc., Miami, Florida; sample location: 468945E, N6217800, UTM Zone 11, NAD83).

An approximately 20 m thick unit of stratified sand overlies the gravels. The sands are medium to fine grained but exhibit a slight fining-upwards sequence. Trough cross-bedding, climbing ripples and high-angle planar cross-bedding are seen in the lower portion of the unit (Figure 8).

a)

b)

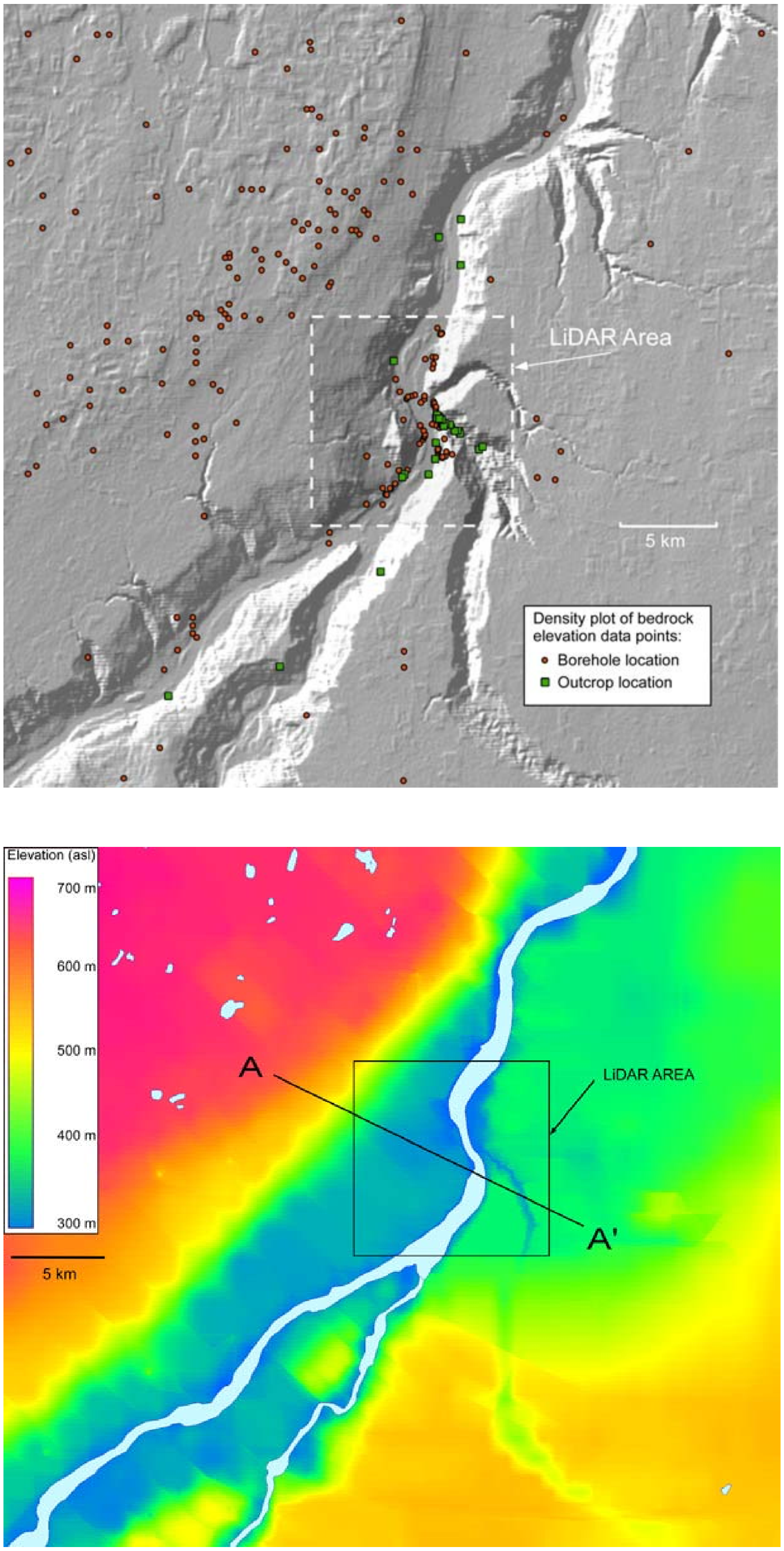


Figure 3. a) Borehole density plot showing the location of bedrock picks (red dots) used to generate the bedrock surface. b) Generated bedrock topography for the study area (Light Detection and Ranging [LiDAR] area) and surrounding area, west-central Alberta. UTM boundaries of the LiDAR area are 476028E (left), 486198E (right), 6236843N (top) and 6226338N (bottom), Zone 11, NAD83.

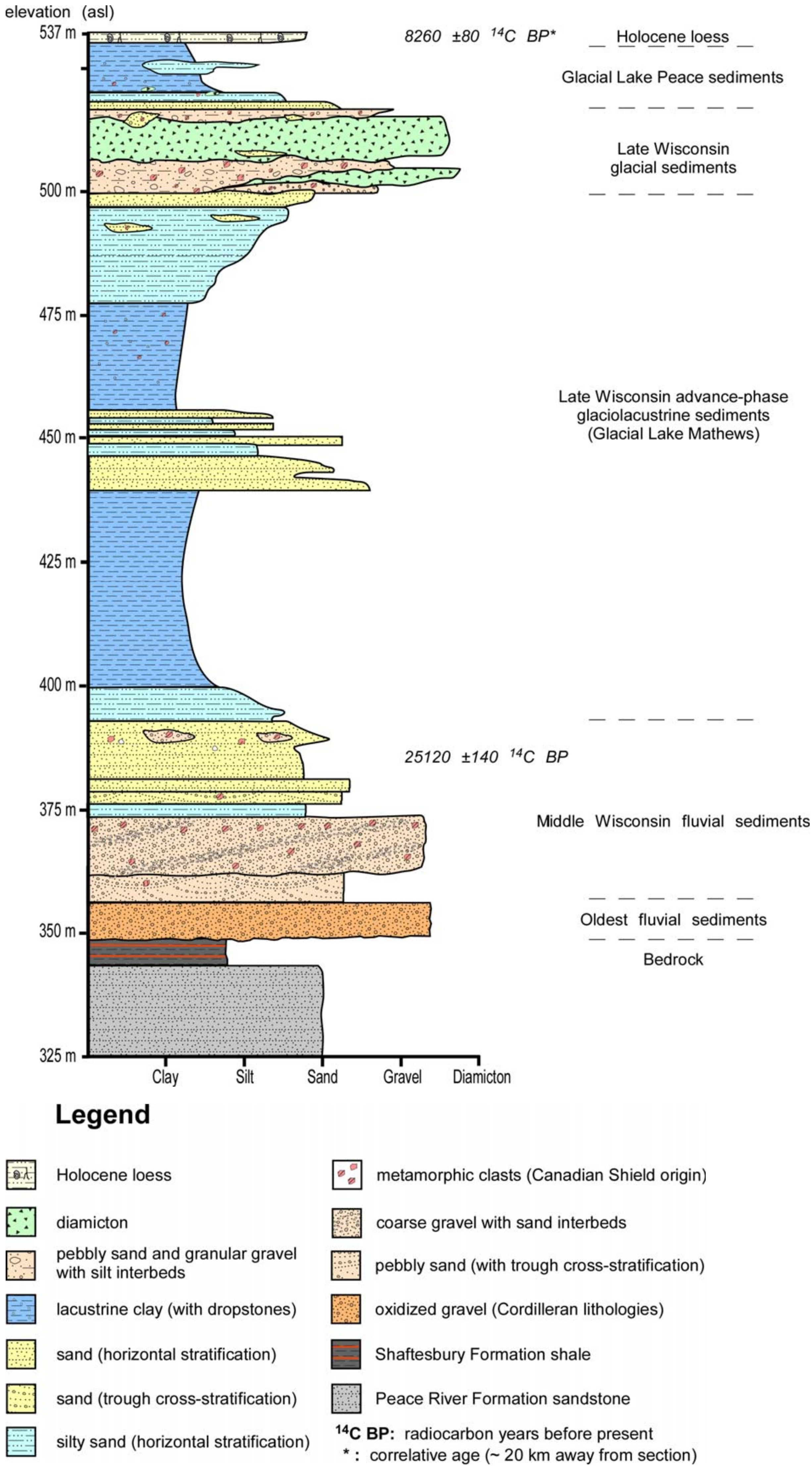


Figure 4. Composite Quaternary geology section as mapped at the confluence of the Heart and Peace rivers, west-central Alberta.

Figure 5. Lowermost, Cordilleran-derived, fluvial, clast-supported gravels overlying Shaftesbury Formation shale. The Shaftsbury shale is located below the pencil. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

Figure 6. Pebbly to cobbly basal sand unit containing rare clasts of Canadian Shield origin. A metamorphosed granitic cobble can be seen to the left of the trowel handle. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

Figure 7. Thick beds of coarse, cross-bedded, clast-supported gravels with planar sandy interbeds. The relatively large boulder in the upper gravel bed is a metamorphic rock from the Canadian Shield. The holes in the sand interbeds are abandoned nest tunnels made by bank swallows. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

Figure 8. Fine-grained beds with climbing ripples and trough cross-bedding occur within coarse granular sandy beds with high-angle planar cross-bedding. Note the pencil for scale. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

In the upper part of the unit, planar-bedded to massive sandy beds are the dominant structures (Figure 9), but thin horizons of low-angle crossbeds are present.

As the Late Wisconsin LIS advanced into the region, regional drainage outlets became progressively blocked resulting in the formation of Glacial Lake Mathews within the ancestral Peace River valley (Hartman and Clague, 2008). This lake is proposed to have been regionally extensive and deep (Mathews, 1980), accumulating tens of metres of fine sand, silt and clay (Figures 10 and 11). This thick unit coarsens upwards into well sorted, rhythmically bedded sands (Figure 12), with dropstones becoming more common in the upper part of the unit. Collectively, these data reflect increasingly ice-proximal sedimentation as the LIS advanced farther into the Glacial Lake Mathews basin. This overconsolidated sequence of glaciolacustrine sediments is likely a rupture surface for large, upper valley–wall, translational earth slides, and therefore could be responsible for the majority of the deep-seated failures in the Peace River valley. It was therefore the focus of field mapping.

Glacial Lake Mathews sediments are overlain by poorly sorted glaciogenic sediments, which, in places where they have not been eroded, include chaotic stratified and weakly deformed pebble sand and granule gravel with interbeds of diamicton and silt (Figure 13). This unit is interpreted as subaqueous outwash and debris flows that were subsequently overridden by the Late Wisconsin LIS.

As the LIS advanced across the area, it deposited a dense, fissile, massive dark grey till of variable thickness above the Glacial Lake Mathews deposits. The till contains a sandy silt matrix with approximately 5% clast content (Figure 14). Less common interbeds and discontinuous stringers (<10 cm thick) of silt and/or sand occur throughout this unit, likely the result of subglacial shearing of Glacial Lake Mathews sediments and their incorporation into the overriding till matrix.

Figure 9. Thick sequences of massive medium-grained sand and planar-bedded medium to fine-grained sand. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

Figure 10. Rhythmically bedded, fining-upwards, glaciolacustrine fine sand and silt occurs near the base of the Glacial Lake Mathews sediment sequence. Pick handle is approximately 75 cm long. Location: gully on east side of the Heart River valley, Peace River, Alberta (base of gully at 483520E, 6231090N, UTM Zone 11, NAD83).

Figure 11. Fine-grained Glacial Lake Mathews sediments. Photo of rotosonic core obtained from borehole PR08-5, Peace River, Alberta (483199E, 6229419N, UTM Zone 11, NAD83). Note the dime for scale.

Figure 12. Ice-proximal glaciolacustrine sand beds near the top of the Glacial Lake Mathews sequence. Location: west side of the Heart River valley, Peace River, Alberta (484530E, 6227355N, UTM Zone 11, NAD83).

Figure 13. Chaotic to rhythmically bedded sequences of diamicton, poorly sorted stratified sands and gravels and moderately sorted pebbly silty sand. Location: Highway 744, Peace River, Alberta (483055E, 6230375N, UTM Zone 11, NAD83). Taken in 2002 during road repair.

Figure 14. Dense, fissile diamicton interpreted as lodgement till. Location: Highway 744, Peace River, Alberta (483185E, 6230000N, UTM Zone 11, NAD83). Taken in 2002 during road/slope repair.

The LIS retreated from the Peace River region approximately 11 000 BP (Dyke, 2004), exposing the broad basin of the Peace River lowlands. This basin was subsequently filled by a proglacial lake that is now documented by widespread glaciolacustrine sediments that drape the landscape up to approximately 610 m asl. These sediments form part of a larger area of proglacial lake sediments deposited in Glacial Lake Peace at the end of the last glaciation (Mathews, 1980). Glacial Lake Peace sediments consist of a fining-upwards sequence of bedded and laminated silt and sand, in places up to 30 m thick (Leslie and Fenton, 2001; Figure 15). These ice-distal sediments are the product of suspension settling, although as the LIS retreated to the north, exposing progressively lower outlets, lake levels would have lowered periodically, exposing these sediments to periods of wave action, resulting in the winnowing and redeposition of fine-grained material (cf., Ashley, 1996). Horizontally stratified glaciolacustrine sands were deposited as the LIS continued to retreat to the north, further lowering Glacial Lake Peace within the study area.

The cliff-top loess is massive to finely laminated, medium brown with a sandy silt matrix and varies in thickness from <0.5 to 2.5 m. The colour is partly due to its rich organic content. Abundant terrestrial molluscs, seeds and charcoal are present throughout the unit. A basal date from wood fragments yielded an AMS radiocarbon date of 8260 ±80 BP (TO-11927; test conducted by IsoTrace Laboratory, University of Toronto, Toronto, Ontario; sample location 483195E, 6229515N, UTM Zone 11, NAD83), providing a minimum age for drainage of Glacial Lake Peace.

Figure 15. Rhythmically bedded Glacial Lake Peace silt and clay. Location: Highway 744, Peace River, Alberta (483195E, 6229515N, UTM Zone 11, NAD83). Taken in 2002 during road repair.

5.3 Event Sequence of the Peace River Study Area

Based on the analysis of sediments retrieved from continuous coring (Morgan et al., 2009) and the examination of sediment-outcrop sections adjacent to the Peace River valley along the Heart River, the geological history of the examined portion of the Peace River valley can be characterized by a four-stage event sequence model. The depositional setting of each stage of the model is outlined below and accompanied by illustrative figures. These simplified and generalized figures are designed to assist the reader visualize the scenarios being described. The figures are not intended to be exact models of the Peace River valley study area and should not be treated as such since the illustrations show stylized slope failures that may not precisely reflect the mechanisms of sliding observed and described in Section 6. In addition, stratigraphic thicknesses and slope angles are not to scale.

5.3.1 Event Sequence: Stage I

Stage I depicts a preglacial river valley formed through the incision of Cretaceous bedrock by the ancestral Peace River (Figure 16). This active process of river downcutting is analogous to present systems whereby a river undermines the toe of a valley slope creating instability and mass wasting.

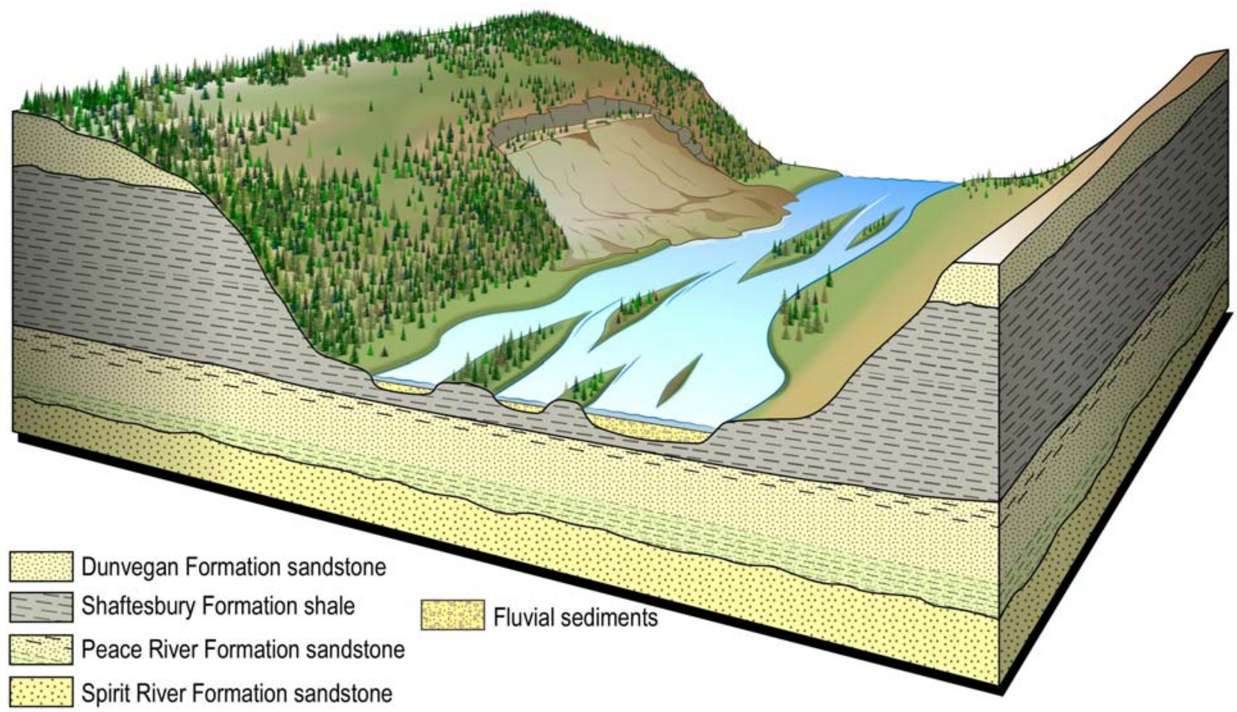


Figure 16. Simplified illustration depicting the ancestral Peace River valley within the study area (not to scale). Fluctuating water levels and lobe switching facilitated by bank erosion within the fluvial system likely acted as a mechanism for bank collapse. Yellow-coloured fill depicts sediment deposited within this preglacial fluvial system.

Evidence of the preglacial fluvial system likely responsible for creation of this preglacial valley is found in sediments intersected in boreholes PR08-02, PR08-03 and PR08-05 (Morgan et al., 2009), which are characterized by 6.3 to 9.1 m thick intervals of medium- to very coarse-grained pebbly sands. Framework clasts are predominately of large pebble grade and are characterized by quartzite and sandstone lithologies originating from the Rocky Mountains. Clast lithologies from the Precambrian Shield were not observed within the lithotype assemblage. The absence of these lithologies suggests a western sediment source (Rocky Mountains) and sediment deposition prior to glaciation in the Peace River valley.

Gravel lithotypes are interpreted as slugs of gravel that formed minor channel-fill deposits and acted as nuclei for barform generation within the fluvial system. Events such as rainfall, lobe switching and fluctuating flow regimes likely had a catastrophic effect, promoting bank collapse through undercutting and the release of gravel slugs into the fluvial system. The abundance of gravel observed within the sediments filling the present day preglacial valley may suggest low bank stability due to the lack of rooted vegetation within the system.

5.3.2 Event Sequence: Stage II

During the Quaternary period, northward drainage of the Peace River was dammed by the southwest advance of the LIS (Figure 17a). This event, in addition to an influx of glacial meltwater into the examined portion of the Peace River valley, formed Glacial Lake Mathews. Sediments deposited within this lake are defined by 0.25 to 14 m thick sequences of rhythmically bedded to flat-laminated deposits of silts and clays and interbeds of slightly silty, fine- to medium-grained sands.

Continued ice-marginal advance of the LIS into the Peace River valley deposited a dark grey to brown, dense, slightly sandy (very fine to fine-grained sands), clayey, silty, stone-poor till (Figure 17b). This lithotype unconformably overlies fine-grained sediments deposited in Glacial Lake Mathews and was intersected in all boreholes. This assemblage is similar to an unnamed silt-rich till documented by Leslie and Fenton (2001) and Paulen et al. (2004) in the Peace River area. Clasts of Precambrian Shield provenance within the till indicate transport from the northeast, which is consistent with ice-marginal advances in the area (Bayrock, 1969). The significant thickness of the LIS overconsolidated and pre-sheared the underlying sediments. Evidence of this reduction in shear strength was observed in the form of slickensides or shear planes in both lacustrine and till sediment-core samples collected in the study area.

5.3.3 Event Sequence: Stage III

During ice-marginal retreat from the Peace River valley, the LIS was fronted by a proglacial lake named Glacial Lake Peace (Figure 18a). Sediments deposited within this lake are defined by fine-grained sediments, intersected in the uppermost portions of boreholes PR08-02 through PR08-05 (Morgan et al., 2009). These sediments are characterized by 0.25 to 14 m thick rhythmically bedded deposits of very fine to fine-grained sandy silts and clays and interbeds of slightly silty, fine to medium-grained sands.

Soft sediment deformation features and deformed to convoluted bedding within these sediments are attributed to a fluctuating ice-margin, more specifically, an overriding ice-margin within the Peace River valley. Based on the limited aerial distribution of these features, a localized ice-marginal advance likely occurred within the confinements of the Peace River valley.

As ice-marginal retreat continued from the Peace River valley, meltwater outlets located north of the study area became ice free causing drainage of Glacial Lake Peace towards the north and east. During this time, water levels in the Peace River valley were lowered (Figure 18b). Soft sediment deformation and the formation of shear surfaces (slickensides), identified in the borehole investigation (Morgan et al., 2009), may be related to meltwater drainage from the Peace River valley followed by bank erosion, subsequent bank collapse and the onset of mass-flow deposits. This sequence of events would cause stress release and a gravitationally unstable profile conducive to shearing and soft sediment deformation.

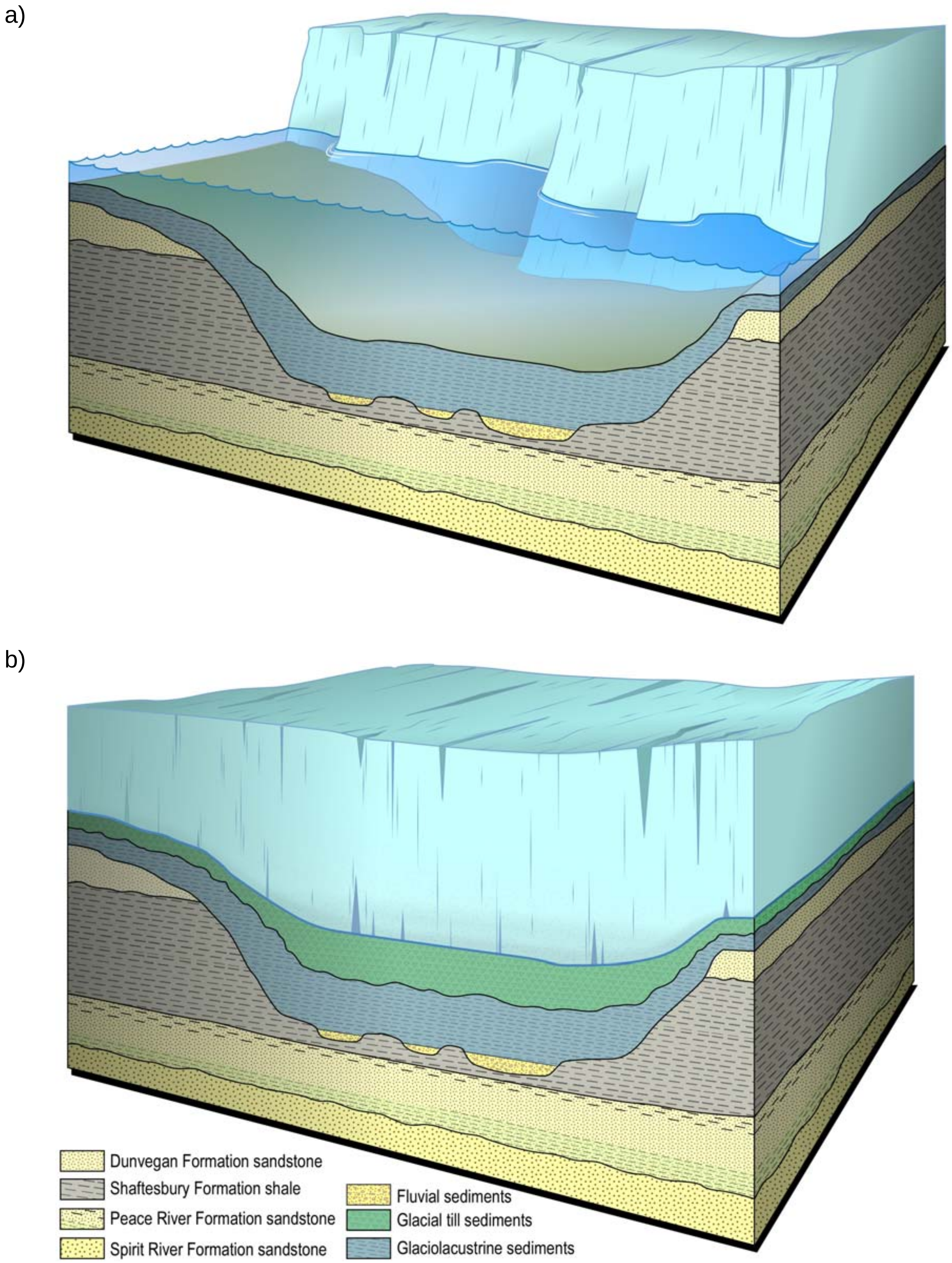


Figure 17. a) The Laurentide Ice Sheet advanced from the northeast, blocking river drainage and impounding water, creating ice-marginal lakes (Glacial Lake Mathews). Fine-grained sediments suspended in lakewater settled to the bottom forming thick sequences of glaciolacustrine deposits (blue-coloured fill). b) Inundation of the study area by the LIS and ice-marginal advance deposited a silt-rich till (green-coloured fill) while overconsolidating and preshearing the previously deposited glaciolacustrine sediments (not to scale).

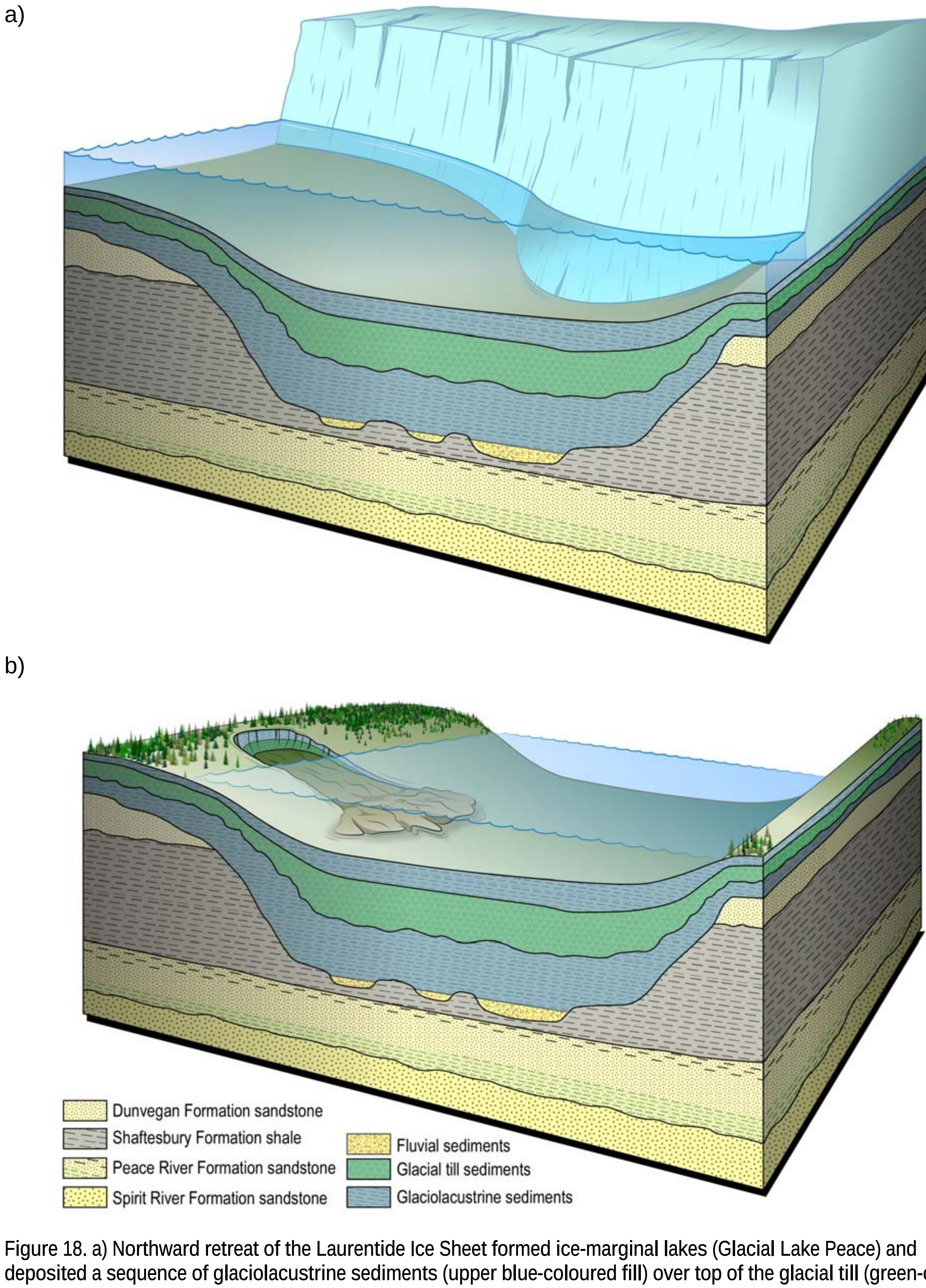


Figure 18. a) Northward retreat of the Laurentide Ice Sheet formed ice-marginal lakes (Glacial Lake Peace) and deposited a sequence of glaciolacustrine sediments (upper blue-coloured fill) over top of the glacial till (green-coloured fill). b) As meltwater outlets located north of the study area became ice free, northern drainage was established. Rapid meltwater discharge may have led to bank erosion, subsequent collapse and the onset of mass-flow deposits in the valley (not to scale).

5.3.4 Event Sequence: Stage IV

Following the drainage of Glacial Lake Peace from the study area and the continued northward ice-marginal retreat of the LIS, proglacial meltwater entered the Peace River valley. Sediment outcrops adjacent to the present-day Peace River reveal the sediments deposited within this system. They are characterized by 0.6 to 2.2 m thick and 4 to 40 m wide sheetlike bodies that are predominantly composed of sand and gravel. Sediments related to this system are interpreted to represent the deposits of a network of gently dipping, shallow, high-energy, unstable, low-sinuosity distributary channels.

An increase in sediment and flow velocities within the system during highstands (flood events) likely contributed to bank collapse in the valley. Bank incision or bank undercutting during highstands would cause bank instability and subsequent bank collapse during the later stages of the highstands within the system (Figure 19). It is anticipated that in areas of helical flow within the system, such as river bends, where flow velocity is typically greater, bank incision and collapse events would occur more frequently. The morphology of the present-day Peace River valley is attributed to these events and the events described in the stages above.

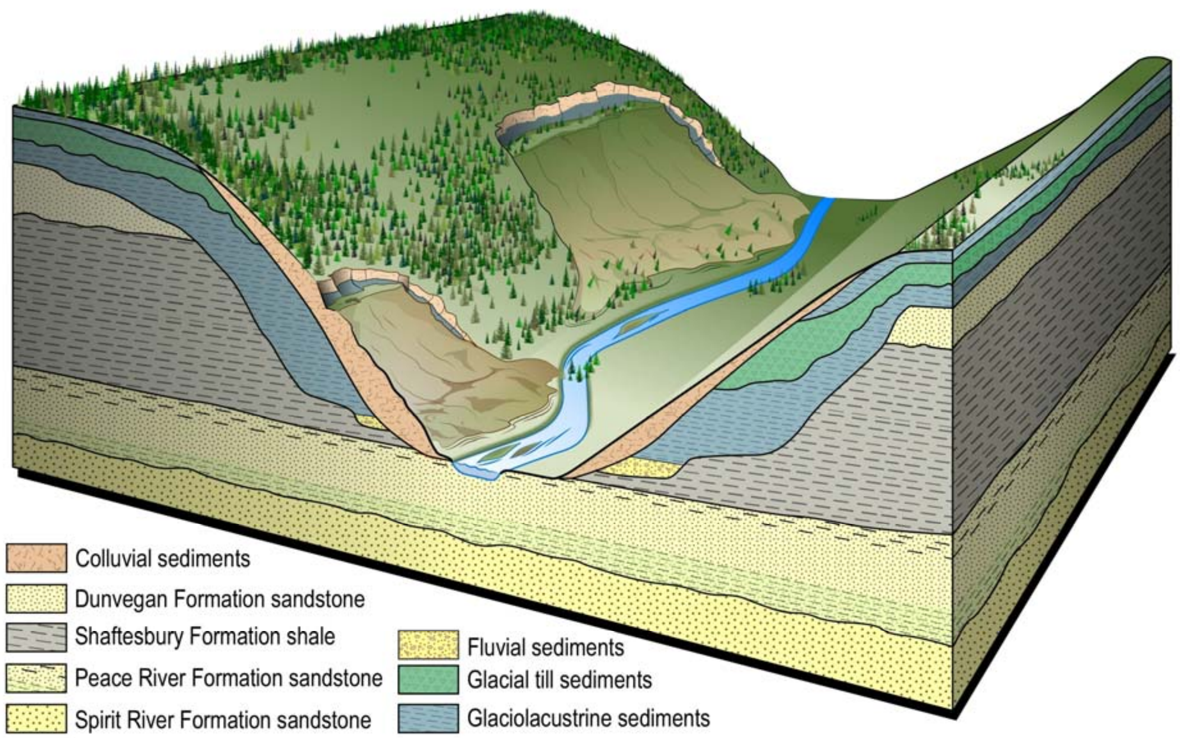


Figure 19. Present-day, simplified representation of the Peace River valley (not to scale). Areas of slope failure are primarily caused by downcutting of the present-day river system through the glacial sediments.

5.4 Cross-Section

A northwest-southeast trending vertical cross-section was generated (Figure 20). The cross-section shows the erosional bedrock surface, which defines the buried ancestral Peace River valley, the contacts between the bedrock units and the inferred Quaternary stratigraphy. Borehole geophysical logs and geotechnical borehole logs aided in the interpretation of the Quaternary sediments, yet the Quaternary stratigraphy lacks detailed resolution throughout the entire study area. The cross-section line A–A’ can be seen in Figures 2 and 3b.

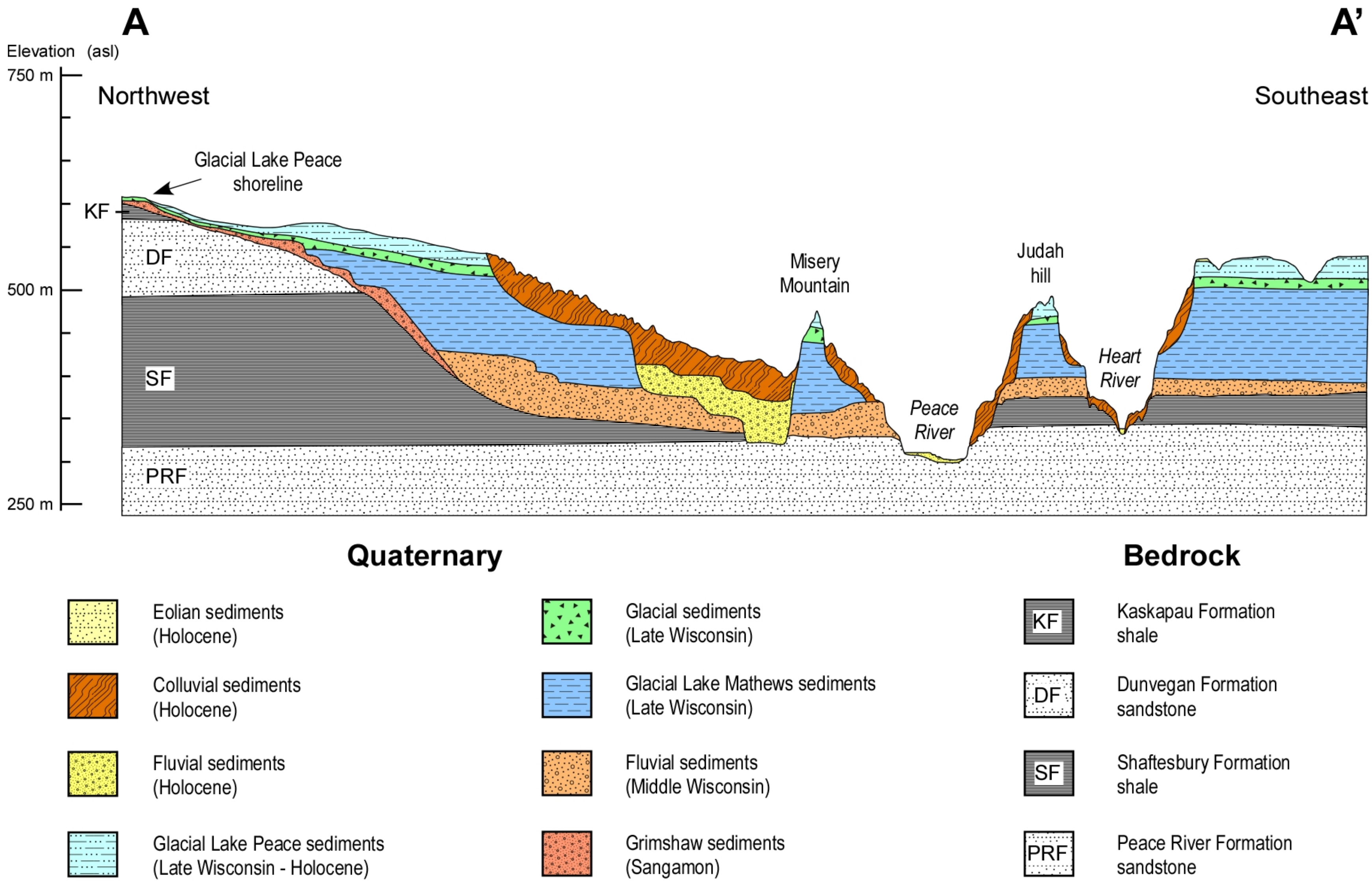


Figure 20. Vertical cross-section through the study area showing bedrock surface and overlying sediments infilling the preglacial valley, west-central Alberta. The location of the cross-section line is shown in Figures 2 and 3b.

6 Landslide Setting

6.1 Landslide Morphology

Over two summers, fieldwork was carried out to observe landslide types and morphologies and document the geological units within the study area. Access to the majority of landslide sites was by four-by-four vehicle and by foot, but some of the more inaccessible sites were visited using a jet boat, and a helicopter was used to provide and record an aerial reconnaissance of the project area. The valley slopes within the 100 km^2 LiDAR study area are composed of a thick sequence of Quaternary sediments that overlie the eroded bedrock surface of the preglacial valley (described in Section 5). Deep-seated earth movements with failure surfaces located in these Quaternary sediments occur on both sides of the river valley. The largest failures occur on the western slope and are characterized by large semicircular headscarps with failure blocks that display an undulating, eroded surface morphology. These block features can be observed as large bumps along the roadway when driving east on Highway 2 into the valley towards the river. Large western slope failures typically have low-angle slopes, approximately 3° to 5°, and their surfaces have well-developed drainage patterns and support mature vegetation, which is indicative of failure that occurred perhaps thousands of years ago, and a low level of current landslide activity.

Slopes on the eastern side of the Peace River, including the tributary slopes of the Heart and Smoky rivers, have steep, short slopes with slope angles in the order of 8° to 15°, and in a few cases greater than 15°. These landslides also have semicircular headscarps, but the surface morphology of the slide mass appears rough, and scarps free of vegetation are observed. The slopes appear to be more active than the western slopes. It should be noted that the landslides occurring on Misery Mountain, located on the western side of Peace River and immediately south of Highway 2, are similar in morphology to the eastern landslides.

The ongoing nature of valley instability resulting from the downcutting of the Peace River has draped the valley slopes with a varying thickness of displaced material, or colluvium. This colluvium is observed both as a veneer of broken Quaternary sediments with no discernible layering or structure and as large displaced blocks up to tens of metres in thickness, which retain the general stratigraphic order recorded in undisturbed Quaternary sections in the study area. The colluvial veneer offers a unique challenge for landslide study as it typically obscures the surface of failure and can confuse attempts to match stratigraphic elevations between sites. Sometimes large, seemingly intact blocks are in fact failed material that is displaced down slope (the banks along Pats Creek, located on the east side of the Peace River, are good examples of these large displaced blocks). To compound the issue, there are many reactivated landslides within the study area that occur within colluvial material (Figure 21). Typically, these reactivated slides are located on the lower portions of the valley slopes and their movements display different kinematics than the older, larger, deep-seated failures that occur within the intact Quaternary sediments and in some cases the underlying Cretaceous bedrock. After some excavation, a rupture surface was noted for the slide shown in Figure 21 where disturbed colluvial material was observed overlying intact Quaternary sediments; Figure 22 shows the smeared rupture surface. Exposed failure surfaces can be difficult to find since colluvial materials tend to obscure the underlying intact material.

Landslides with failure surfaces within Cretaceous bedrock certainly occur in the Peace River region and are observed within the Shaftsbury Formation shale underlying Quaternary sediments. Kim et al. (2010) outlined movement characteristics of well-documented colluvial landslides at the project site with detailed instrumentation data indicating rupture surfaces within the colluvium and underlying shale bedrock. An excellent example of a large failure within the Shaftsbury Formation shale occurs on the east side of the Smoky River, approximately 3 km south of the study area boundary (Figure 23). Failures almost entirely within shale are not observed in the study area since the ancestral Peace River eroded much of the Shaftsbury Formation.

Figure 21. Oblique aerial photo of a landslide seated in colluvium along the east side of the Heart River. Debris can be seen spilling over the Peace River Formation sandstone into the river. Location: Peace River, Alberta (483520E, 6231090N, UTM Zone 11, NAD83).

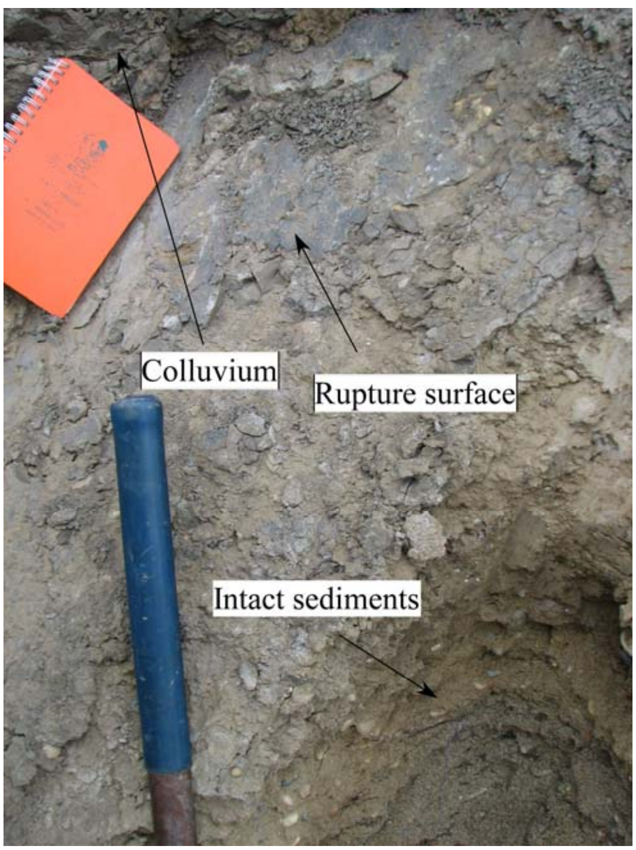


Figure 22. Rupture surface of landslide shown in Figure 21 showing colluvial material on top of intact Quaternary sediments. Location: east side of the Heart River, Peace River Alberta, left flank of landslide (483425E, 6231130N, UTM Zone 11, NAD83).

Figure 23. Oblique aerial photo of a large landslide seated in Shaftsbury Formation shale along the east side of the Smoky River. Location: Peace River, Alberta (479590E, 6224040N, UTM Zone 11, NAD83).

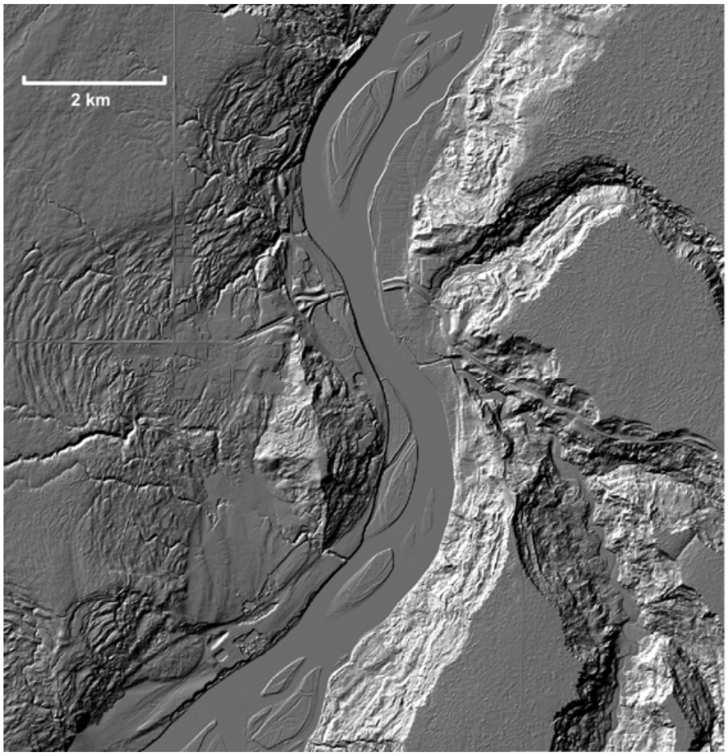
Unpublished consultant reports document a landslide with a failure surface located in the Peace River Formation sandstone at the town of Peace River wastewater treatment plant, which is on the east floodplain of the Peace River, just north of the town. Borehole logs and instrumentation installed at the plant site during construction indicate movement in weak bentonitic mudstones close to river level and beneath the wastewater treatment plant. The Cadotte Member of the Peace River Formation sandstone contains thin shale beds and overlies the Harmon Member, which is described as marine shale containing thin beds of bentonite and silt (Leslie and Fenton, 2001). Based on the geotechnical description of movement at the wastewater treatment plant and the corresponding borehole logs, it is suspected that the failure is located in either the Cadotte or Harmon Member.

The majority of deep-seated landslides in the study area are classified as retrogressive, translational earth slides according to the naming convention outlined by Cruden and Varnes (1996). However, reactivated landslide movements in colluvial material can display rotational movements and shallow earthflows have also been documented in the Peace River region.

6.2 LiDAR Analysis and Proposed Model

A unique review of the morphology and extent of the Holocene landslides was conducted within the study area using high-resolution, bare-earth LiDAR data and QuickBird satellite imagery. The bare-earth LiDAR DEM is derived from raw aerial laser scanning data using filtering software that effectively removes buildings and vegetation from the DEM, leaving an elevation model that represents the bare-ground surface. Three-dimensional software packages, including ArcGIS, Global Mapper and ViewLog®, enable detailed analysis of the DEM. Digital techniques allow for a unique desktop study of the slide

a)



b)

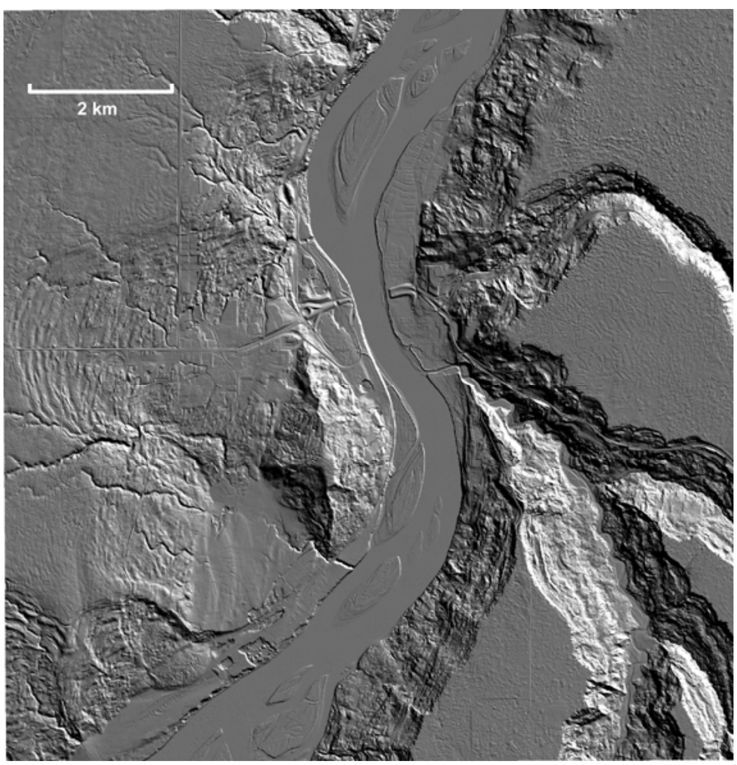


Figure 24. View of bare-earth, Light Detection and Ranging (LiDAR) digital elevation model highlighting the morphology of a) the western-facing landslides (40° sun inclination, 315° azimuth) and b) the eastern-facing landslides (40° sun inclination, 40° azimuth). UTM (Zone 11, NAD83) boundaries of the area are 476028E (left), 486198E (right), 6236843N (top), and 6226338N (bottom).

masses along the Peace River and its tributaries. The user is able to vary the sun angle and azimuth to highlight different morphological features (Figure 24). Viewing the slides from multiple perspectives and at user-defined vertical exaggerations enables the identification of subtle features that may not be obvious in the field. This is especially powerful in cases where the slopes are heavily vegetated, access to the site is difficult or safety is a concern. Available borehole information can be accurately superimposed onto vertical cross-sections cut through the LiDAR DEM.

Collectively, these techniques and data provided a powerful means with which to assess the extent of different slide masses and to interpret the intact versus failed material (colluvium). Incorporating the composite geological section (Section 5.2) with digital analysis techniques is a powerful way to classify landslides and interpret within which geological unit the failure appears to be seated.

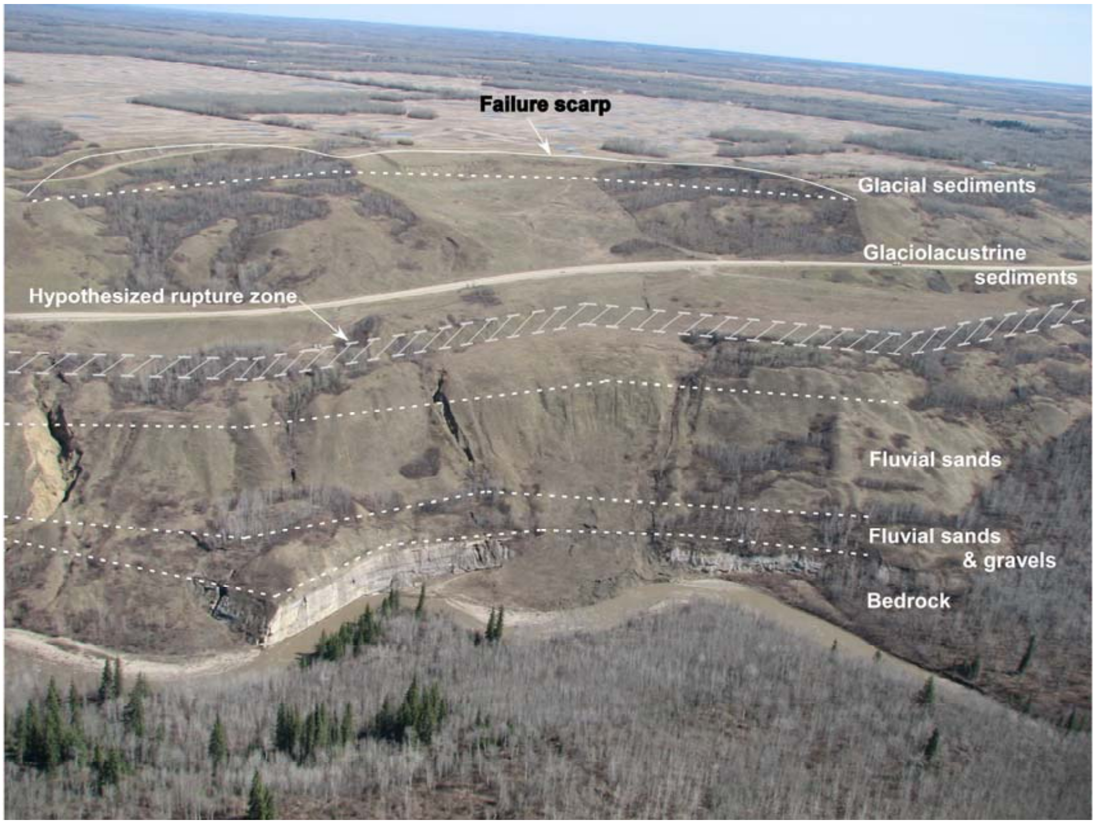
Figure 25 shows an oblique aerial view of the eastern slope (southwest facing) of the Heart River. The roadway running across this slope is Highway 2, the main access route to the town from the east. The boundaries of the Quaternary stratigraphic units are indicated on the photo as determined by the composite section and borehole results. By observing both the oblique aerial photo (Figure 25a) and the three-dimensional LiDAR DEM (Figure 25b) at similar orientations, the morphology of the various Quaternary units can be identified. This technique provides a means to examine other slopes in the study area using morphology, as well as supporting borehole data.

Examination of the high-resolution DEM across the study area indicates a sometimes small but fairly consistent change in overall slope angle, predominantly between 420 and 460 m asl. Figure 26 shows topographic profiles taken perpendicular to the slope at a few locations around the study area to demonstrate this observed change in slope angle. Based on the composite section, this slope break appears to occur within the overconsolidated glaciolacustrine unit deposited by Glacial Lake Mathews. Overall, slope angles below this apparent inflection point are typically greater than those above, indicating the retrogressive nature of the failed material in the glaciolacustrine unit. The morphology of the slopes suggest that the failure surface for many of the deep-seated movements is located within this glaciolacustrine unit of rhythmically bedded to flat-laminated fine sands, silts and clays.

Sediment core retrieved during an AGS drilling program lends further evidence to the theory of deep-seated translational movements occurring within advance-phase glaciolacustrine sediment. A number of slickensides are present in the core of borehole PR08-05, located at the Sagitawa lookout at the top of Judah hill on the east side of the Peace River. Slickensides are joints or fracture surfaces within the core that have polished surfaces indicating movement or shearing along the fracture. Horizontal slickensides are observed in the glaciolacustrine silts and clays in PR08-05 from 460 m asl to approximately 447 m asl (approximately 78 to 91 m depth). Horizontal and inclined (approximately 45° to 70°) slickenside surfaces continue from 442 m asl to the end of the core hole at 425 m asl (approximately 100 to 114 m depth). Inclined fracture surfaces (approximately 60°) also occur in core samples of glacial till (diamicton) at 523 and 511 m asl (approximately 22 and 28 m depth). Borehole PR08-03, located on the west side of the Peace River, also recorded horizontal slickenside surfaces from 355 m asl to the end of the core hole at 337 m asl (90 to 108 m depth) in glaciolacustrine sediments. Inclined slickensides (approximately 40° to 60°) are present nearer to surface in silts and clays above and near the bottom of the till deposits at 424 and 360 m asl, respectively (19 and 85 m depth). PR08-03 is located on the lower portion of the colluvial slope of a large western slide and encountered a stratigraphy analogous to PR08-05, but at a lower elevation. Further information regarding the core hole program conducted at Peace River, including core photos, is detailed in ERCB/AGS *Open File Report 2009-18* (Morgan et al., 2009).

The slickenside fractures in the sediment core also point to translational movements with failure surfaces in the glaciolacustrine unit deposited by Glacial Lake Mathews. Many of the large, deep-seated landslides in the study area display retrogressive behaviour. As the slide creeps downslope, the headscarp advances in the opposite direction into the slope. This retrogressive characteristic may be the cause of the high-

a)



b)

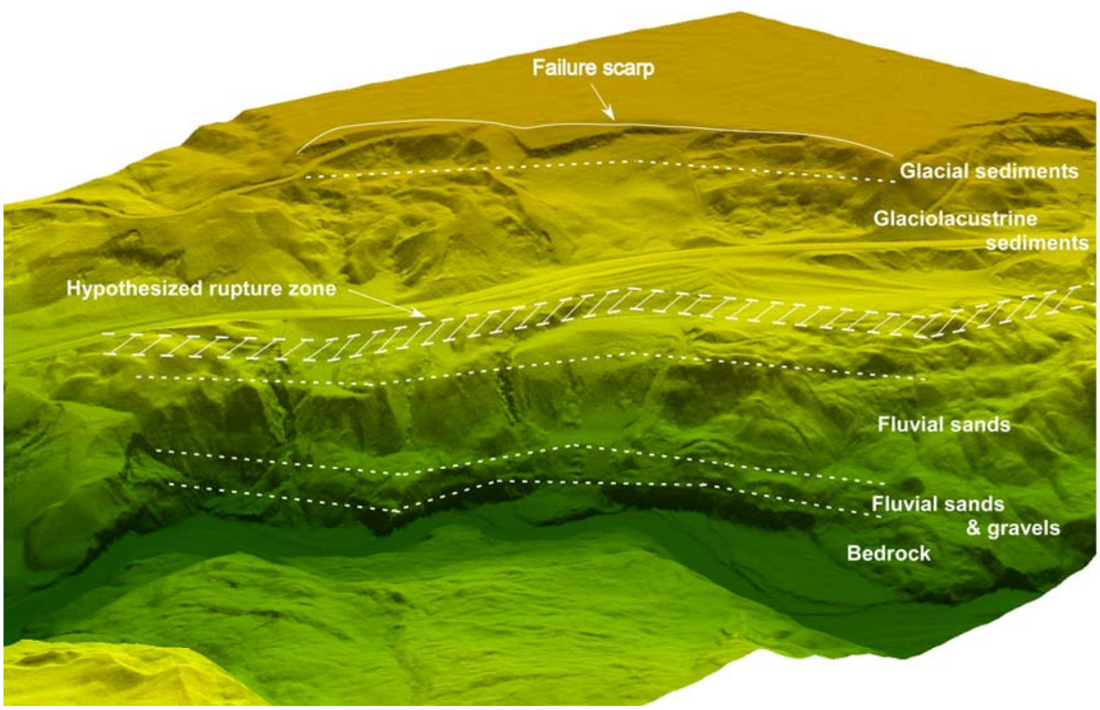
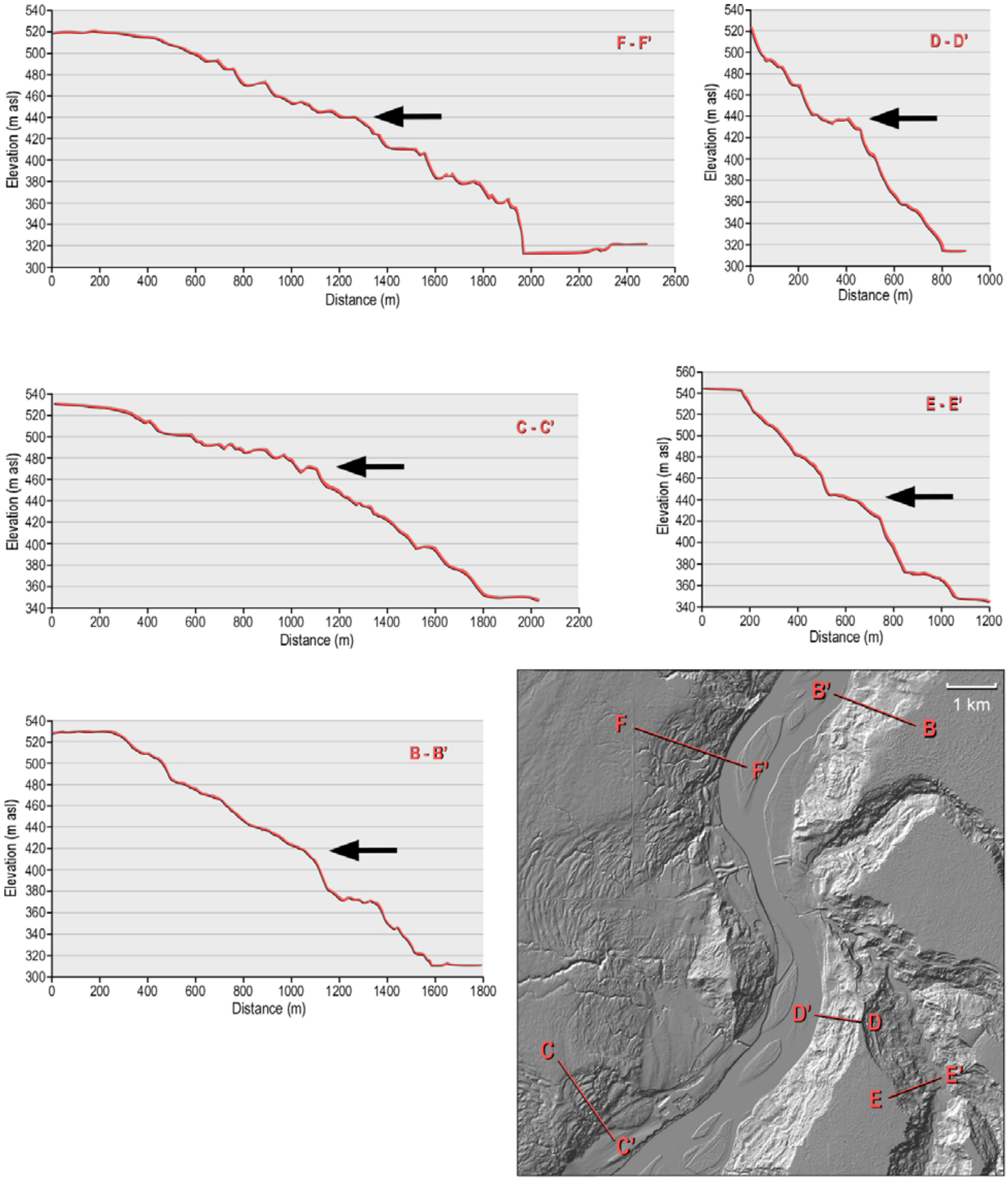


Figure 25. a) Oblique aerial photo of the eastern slope of the Heart River showing the approximate contacts between geological units. b) Same view of the slope using the LiDAR DEM. Location: Peace River, Alberta (479870E, 6229045N, UTM Zone 11, NAD83).



LiDAR UTM boundaries - left: 476028E, right: 486198E, top: 6236843N, bottom 6226338N, (Zone 11, NAD83).

Figure 26. Topographic profiles in the study area showing the apparent change in slope angle (indicated by arrow) observed throughout the study area (west-central Alberta), generally between 420 and 460 m asl.

angle slickensides recorded within the till, silt and clay deposits overlying the advance-phase glaciolacustrine material. The results of DEM morphological analysis and the sediment-core analysis support translational movement with horizontal movement along a failure surface within the glaciolacustrine sediments, with inclined failure surfaces accounting for movement along the main scarp and any minor scarps between failure blocks.

7 Summary

Over the past 50 years, there have been published and unpublished case histories documenting slope movements in and around the town of Peace River. Whereas each of these studies generated a site-specific interpretation of the geological setting to generate a model for interpreting and mitigating slope movements, the regional geological landslide model was not well understood. While numerous reports have focused on various components of the sedimentary succession at Peace River, our work combines the use of databases, new modelling tools and high-resolution, remote-sensing data with regional and site-specific mapping to develop a conceptual model for understanding the depositional history of Quaternary sediments in the ancestral Peace River valley system and their role in slope instability in the region. By coupling the bedrock topography model with the surface DEM, we observed that the distribution of large landslides is spatially correlated to the location of preglacial valleys infilled with thick Quaternary sediments. Coupling surface models with stratigraphy and sediment core obtained at key locations in the study area allowed us to estimate where the majority of the deep-seated failures are occurring. These data indicate that failure along Glacial Lake Mathews sediments initiates the large majority of the deep-seated movements that affect municipal development, residential development and infrastructure in and around the town. Many of the existing, slowly moving landslides in the town are seated in colluvium generated from earlier slides initiated along this unit.

The updated geological model for the landslide setting in the town of Peace River provides a basis for better informed planning for investigating and mitigating landslides. The knowledge that laminated deposits of overconsolidated, fine-grained glaciolacustrine sediments generally occur between 420 and 460 m asl and are the sediments most often associated with landslides in the region allows for a more realistic basis for modelling movements and planning mitigative measures to deal with these risks.

8 References

Alberta Transportation (1985): East Peace River hill slide; Alberta Transportation, File H2:62.

Ashley, G.M. (1996): Glaciolacustrine environments; *in* Modern glacial environments: processes, dynamics and sediments, J. Menzies (ed.), v. 1, Butterworth-Heinemann Ltd., Oxford, United Kingdom, p. 417–444.

Atkinson, N. and Paulen, R.C. (2010): Surficial geology and Quaternary history of the Cleardale area, northwestern Alberta (NTS 84D/SW); Energy Resources Conservation Board, ERCB/AGS Open File Report 2010-11, 27 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/OFR_2010_11.html> [May 2011].

Bayrock, L.A. (1969): Incomplete continental glacial record of Alberta, Canada; *in* Quaternary geology and climate, H.E. Wright, Jr. (ed.), v. 16 of the proceedings of the VII Congress of the International Association for Quaternary Research, National Academy of Sciences, Washington, District of Columbia, p. 99–103.

Bobrowsky, P.T. and Smith, C.P. (1992): Quaternary studies in the Peace River District, 1990: stratigraphy, mass movements and glaciation limits (94P); Geological Fieldwork 1991, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1992-1, p. 363–374.

Bobrowsky, P.T., Catto, N. and Levson, V. (1991): Reconnaissance Quaternary geological investigations in Peace River District, British Columbia (93P, 93A); Geological Fieldwork 1990, British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991-1, p. 345–358.

Borneuf, D.M. (1981): Hydrogeology of the Peace River area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 1981-02, 6 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/ESR_1981_02.html> [October 2011].

Borneuf, D.M. (1983): Hydrogeological map of the Peace River area, Alberta, NTS 84C; Alberta Research Council, Alberta Geological Survey, Map 162, scale 1:250 000, URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_162.html> [October 2011].

Bostock, H.S. (1981): Physiographic subdivisions of Canada; *in* Geology and economic minerals of Canada, part A, Geological Survey of Canada, Economic Report, no. 1, p. 10–42.

Catto, N.R., Liverman, D.G.E., Bobrowsky, P.T. and Rutter, N. (1996): Laurentide, Cordilleran and montane glaciation in the western Peace River – Grande Prairie, Alberta and British Columbia, Canada; Quaternary International, v. 32, p. 21–32.

Cowen, A. (1994): Hydrogeologic evaluation of the Grimshaw gravel aquifer, Grimshaw, Alberta; *in* Canada-Alberta Environmentally Sustainable Agriculture Agreement (CAESA) Interim Report, M. Zubel (ed.), Agriculture Canada, Prairie Farm Rehabilitation Administration, p. 12–16.

Cruden, D.M. and Varnes, D.J. (1996): Landslides types and processes; *in* Landslides: investigation and mitigation, Transportation Research Board, National Academy of Science, Special Report 247, Washington, District of Columbia, p. 36–75.

Cruden, D.M., Ruel, M. and Thomson, S. (1990): Landslides along the Peace River, Alberta; *in* Proceedings, 43rd Canadian Geotechnical Conference, v. 1, p. 151–158.

Cruden, D.M., Keegan, T.R. and Thomson, S. (1993): The landslide dam on the Saddle River near Rycroft, Alberta; Canadian Geotechnical Journal, v. 30, no. 6, p. 1003–1015.

Cruden, D.M., Lu, Z-Y. and Thomson, S. (1997): The 1939 Montagneuse River landslide, Alberta; Canadian Geotechnical Journal, v. 34, no. 5, p. 799–810.

Davies, M.R., Paulen, R.C. and Hicken, A.S. (2005): Inventory of Holocene landslides, Peace River area, Alberta (NTS84C); Alberta Energy and Utilities Board, EUB/AGS Geo-Note 2003-43, 23 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/GEO_2003_43.html> [May 2011].

Dyke, A.S. (2004): An outline of North American deglaciation with emphasis on central and northern Canada; *in* Quaternary glaciations - extent and chronology, part II: North America, J. Ehlers and P.L. Gibbard (ed.), Development in Quaternary Science Series, Elsevier B.V., p. 373–424.

Dyke, A.S., Andrews, J.T., Clark, P.U., England, J.H., Miller, G.H., Shaw, J. and Veillette, J.J. (2002): The Laurentide and Innuitian ice sheets during the Last Glacial Maximum; Quaternary Science Reviews, v. 21, no. 1, p. 9–31.

Fenton, M.M. (1984): Quaternary stratigraphy, Canadian Prairies; *in* Quaternary stratigraphy of Canada – a Canadian contribution to IGCP Project 24, R.J. Fulton (ed.), Geological Survey of Canada, Paper 84-10, p. 57–68.

Fletcher, L., Hungr, O. and Evans, S.G. (2002): Contrasting failure behaviour of two large landslides in clay and silt; Canadian Geotechnical Journal, v. 39, no. 1, p. 46–62.

Froese, C.R. (2007): Peace River Landslide Project: hazard and risk assessment for urban landsliding; *in* Proceedings of the 60th Canadian geotechnical conference, Ottawa, Ontario, p. 699–704.

Hamilton, W.H., Langenberg, C.W., Price, M.C. and Chao, D.K., comp. (1999): Geological map of Alberta; Alberta Energy and Utilities Board, EUB/AGS Map 236, scale 1:1 000 000, URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_236.html> [May 2011].

Hardy, R.M. (1957): Engineering problems involving pre-consolidated clay shales; Transactions, Engineering Institute of Canada, v. 1, p. 5–13.

Hartman, G. (2005): Quaternary stratigraphy and geologic history of the Charlie Lake (NTS 94A) map-area, British Columbia; M.Sc. thesis, Simon Fraser University, 279 p.

Hartman, G.M.D. and Clague, J.J. (2008): Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia; Canadian Journal of Earth Sciences, v. 45, no. 5, p. 549–564.

Hayes, B.J.R., Christopher, J.E., Rosenthal, L., Los, G., McKercher, B., Minken, D., Tremblay, Y.M. and Fennell, J. (1994): Cretaceous Mannville Group of the Western Canada Sedimentary Basin; *in* Geological atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, p. 317–334.

Jones, J.F. (1966): Geology and groundwater resources of the Peace River district, northwestern Alberta; Research Council of Alberta, Alberta Geological Survey, Bulletin 16, 143 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/BUL_016.html> [October 2011].

Kim, T., Cruden, D., Martin, C.D., Froese, C.R. and Morgan, A.J. (2010): Landslide movements and their characteristics, town of Peace River, Alberta; 63rd Canadian Geotechnical Conference and 6th Canadian Permafrost Conference, September 12–16, Calgary, Alberta.

Leckie, D.A., Bhattacharya, J.P., Bloch, J., Gilboy, C.F. and Norris, B. (1994): Cretaceous Colorado / Alberta Group of the Western Canada Sedimentary Basin; *in* Geological atlas of the Western Canada Sedimentary Basin, G.D. Mossop and I. Shetsen (comp.), Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, p. 335–352.

Leslie, L.E. and Fenton, M.M. (2001): Quaternary stratigraphy and surficial geology Peace River, final report; Alberta Energy and Utilities Board, EUB/AGS Special Report 10, 34 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/SPE_010.html> [May 2011].

Liverman, D.G.E., Catto, N.R. and Rutter, N.W. (1989): Laurentide glaciation in west-central Alberta: a single (Late Wisconsin) event; Canadian Journal of Earth Sciences, v. 26, no. 2, p. 266–274.

Mathews, W.H. (1980): Retreat of the last ice sheets in northeastern British Columbia and adjacent Alberta; Geological Survey of Canada, Bulletin 331, 22 p.

Miller, B.G.N. and Cruden, D.M. (2001): Landslides, landslide dams, and the geomorphology of tributaries in the Peace River lowland, Alberta; *in* Proceedings of the 54th Canadian geotechnical conference – 2001 an Earth odyssey, The International Society of Hydrogeologists/The Canadian Geotechnical Society, September 16–19, Calgary, Alberta, v. 1, p. 363–370.

Miller, B.G.N. and Cruden, D.M. (2002): The Eureka River landslide and dam, Peace River Lowlands, Alberta; Canadian Geotechnical Journal, v. 39, no. 4, p. 863–878.

Morgan, A.J., Slattery, S.R. and Froese, C.R. (2009): Results of sediment coring at the town of Peace River, northwestern Alberta (NTS 84C); Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-18, 94 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/OFR_2009_18.html> [May 2011].

Paulen, R.C. (2004): Surficial geology of the Grimshaw area (NTS 84C/SW); Alberta Energy and Utilities Board, EUB/AGS Map 291, scale 1:100 000, URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_291.html> [May 2011].

Paulen, R.C., Pawlowicz, J.G. and Fenton, M.M. (2004): Surficial geology of the Cadotte Lake area (NTS 84C/SE); Alberta Energy and Utilities Board, EUB/AGS Map 290, scale 1:100 000, URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_290.html> [May 2011].

Pawlowicz, J.G., Jean, G.M. and Fenton, M.M. (1996): Preliminary stratigraphic tests to support mineral exploration: northern Alberta; Alberta Energy and Utilities Board, EUB/AGS Open File Report 95-11, 34 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/OFR_1995_11.html> [May 2011].

Pettapiece, W.W. (1986): Physiographic subdivisions of Alberta; Agriculture Canada, Research Branch, Land Resource Research Centre, physiographic map, scale 1:1 500 000.

Plouffe, A., Kowalchuk, C.J. and Paulen, R.C. (2007): Surficial geology, Meander River, Alberta (NTS 84K/NW); Geological Survey of Canada, Open File 5461 and Alberta Energy and Utilities Board, EUB/AGS Map 414, scale 1:100 000, URL <http://www.ags.gov.ab.ca/publications/abstracts/MAP_414.html> [May 2011].

Thomson, S. and Hayley, D.W. (1975): The Little Smokey landslide; Canadian Geotechnical Journal, v. 12, p. 379–392.

Tokarsky, O. (1971): Hydrogeology of the Grimshaw-Chinook Valley area, Alberta; Research Council of Alberta, Alberta Geological Survey, Earth Sciences Report 1971-02, 17 p., URL <http://www.ags.gov.ab.ca/publications/abstracts/ESR_1971_02.html> [May 2011].

United States Geological Survey (2000): Shuttle Radar Topography Mission digital elevation model data (3-arc second resolution); Earth Resources Observation and Science (EROS) Center, URL <http://seamless.usgs.gov> [April 2004].