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Cenozoic Stratigraphy of Northwestern Alberta (parts of NTS 83M-O and 84B-G)

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Abstract

The Cenozoic stratigraphy of northwestern Alberta has been previously characterized for the purpose of landslide analysis, aggregate resources inventory, natural gas migration, kimberlite indicator mineral assessment, and understanding the glacial history of the area. However, the lateral extent of Cenozoic stratigraphic units that host significant aquifers, aggregate resources, semi-impermeable units, and hydrocarbon reservoirs, and their interconnectivity are poorly understood. Delineation of the geometry and interconnectivity of fine- and coarse-grained Cenozoic stratigraphic units is important for predicting potential contaminant migration pathways, estimating the volume of coarse-grained units for groundwater and aggregate investigations, and evaluating the reservoir architecture in places of natural gas accumulations.

This report outlines the methodology of 1) facies analysis to characterize six stratigraphic units and 2) data collation and analysis to correlate stratigraphic units on a regional scale. Relogging of cored boreholes allowed reinterpretation and confirmation of previously delineated stratigraphic units. Stratigraphic correlations of Cenozoic units were made on cross-sections using lithology data from water-well records, previously recorded data from outcrops and boreholes, and re-examined core. These stratigraphic correlations were used to construct a regional Cenozoic stratigraphic framework in the Peace River area, which was subsequently used to inform modelling of the Cenozoic geological column that overlies the Peace River bedrock model previously completed by the Alberta Geological Survey.

1 Introduction

The Cenozoic stratigraphy in the Peace River area (northwestern Alberta) has received much attention in the last nearly 100 years (e.g., Rutherford, 1930) as a result of its significance to potable water supply (e.g., Tokarsky, 1971), landslide hazards (e.g., Kim et al., 2010), natural gas accumulations (e.g., Kellett, 2007; Ahmad et al., 2009), and the glacial history of northern Alberta (e.g., Mathews, 1980; Liverman et al., 1989). Historical and modern stratigraphic data is publicly available in a piecemeal collection of soil survey reports (e.g., Wyatt, 1935; Reeder and Odynsky, 1965; Scheelar and Odynsky, 1968), geological reports and papers (e.g., Rutherford, 1930; Henderson, 1959; Green and Mellon, 1962; Jones, 1966; Balzer, 2000; Leslie and Fenton, 2001; Paulen and McClenaghan, 2015), core drilling reports (e.g., Pawlowicz and Fenton, 1998; Pawlowicz et al., 2005; Morgan et al., 2009), surficial geology maps (e.g., Fox et al., 1987; Fenton et al., 2013), glacial lake reconstructions (e.g., St-Onge, 1972; Mathews, 1980), aggregate maps and reports (e.g., Scafe et al., 1989; Edwards and Scafe, 1996; Edwards et al., 2004; Edwards and Budney, 2009), hydrogeological assessments (e.g., Tokarsky, 1967, 1971; Borneuf, 1981; PFRA, 1998), and landslide papers and reports (e.g., Nasmith, 1964; Thomson and Hayley, 1975; Cruden et al., 1997; Miller and Cruden, 2002; Kim et al., 2010; Morgan et al., 2012). The abundance of local-scale geological data in the Peace River area, together with limited data in a digital GIS-based format, makes assessment of the geology and rendering of a three-dimensional (3D) model of subsurface Cenozoic stratigraphy at a regional scale in the Peace River area (Figure 1; cf. Anderson et al., 2015) challenging.

This study expanded on the geological framework developed by Leslie and Fenton (2001). To assess the possible regional extent of Cenozoic stratigraphic units in the study area, a compilation of previous stratigraphic work in the Peace River area (e.g., Henderson, 1959; Leslie and Fenton, 2001), together with facies analysis of core and regional correlation of stratigraphic units, was undertaken. The primary intended end-users of this report include, but are not limited to, hydrogeologists, aggregate pit operators, geologists, landowners, and other government employees, including those involved in land-use planning and natural resource management. The following report includes a brief overview of the bedrock geology and topography, previously described Cenozoic stratigraphic units, and physiography of the Peace River area, followed by an outline of the conceptual stratigraphic framework developed for this report, data sources and methods, paleoenvironmental reconstruction, and depositional history. The revised Cenozoic stratigraphy presented here is constrained to the domain of the Peace River 3D bedrock model constructed by Anderson et al. (2015), and informs 3D modelling of the Cenozoic stratigraphy, which is the uppermost component of the Peace River (Anderson et al., 2015) and provincial-scale Geological Framework 3D models (Alberta Geological Survey, 2017).

1.1 Study Area

The study area (~64 000 km^2; Figure 1) is located in northwestern Alberta and encompasses parts of the municipal districts of Peace No. 135, Fairview No. 136, Birch Hills No. 19, Smoky River No. 130, Clear Hills No. 21, Northern Lights No. 22, and Northern Sunrise County. Towns with the largest population include the Town of Peace River, Grimshaw, and Manning (2016 populations: ~6800, ~2700, ~1200, respectively; Statistics Canada, 2017). The Peace River bisects the study area and flows northwards into the Slave River in northeastern Alberta. Historically, the Peace River valley and other tributary valleys in and around the study area have been subject to several landslides, including some of the largest landslides recorded in Alberta (Nasmith, 1964; Thomson and Hayley, 1975; Cruden et al., 1993, 1997; Fletcher and Hungr, 2000; Fletcher et al., 2002; Miller and Cruden, 2002; Kim et al., 2010; Morgan et al., 2012). The major industries in the study area include oil and gas operations, agriculture, and forestry, and locally significant aggregate, metals, and kimberlite mining activities.

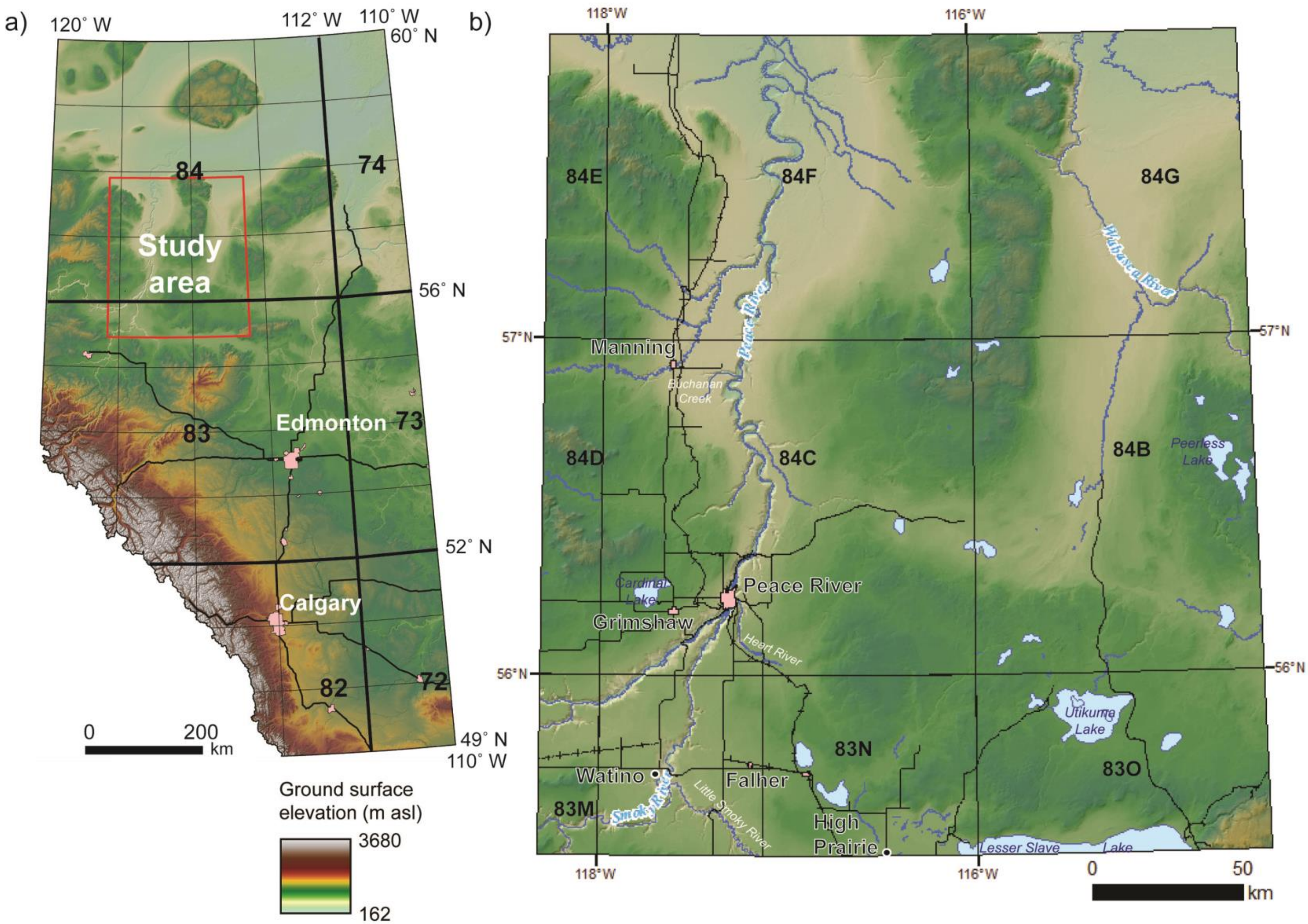

Figure 1. Study area (red box) in a) Alberta and b) at a regional scale, overlain on the provincial ground surface digital elevation model (DEM; in metres above sea level) and draped on a hill-shaded image (Alberta Environment and Parks, 2015). National Topographic System (NTS) grid and sheet numbers are included.

2 Geological Background

2.1 Bedrock Physiography

The bedrock physiography is characterized by a series of bedrock uplands in the west (e.g., Birch, Whitemud, Clear, Hawk, and Naylor hills), a prominent bedrock upland in the central part of the study area (Buffalo Head Hills), and more subdued bedrock uplands to the south and east (Figure 2). The Shaftesbury (Tokarsky, 1967, 1971) and Notikewin bedrock valleys are incised by the modern Peace River (Figure 2). Tokarsky (1967) reported a bedrock valley underlying Cardinal Lake, called the Berwyn channel, and interpreted it as a south-trending tributary to the Shaftesbury bedrock valley; however, the Berwyn channel is not recognizable in the bedrock topography gridded surface at a cell size of 500 by 500 m (Figure 2).

Borneuf (1981) reported a bedrock valley, the l'Hirondelle valley (Figure 2), trending from the Peace River eastwards to the Lubicon Lake area, and suggested the valley continued eastwards to the Peerless Lake area. Pawlowicz and Fenton (2005) mapped bedrock valley thalwegs in the Peerless Lake area and renamed the eastward continuation of Borneuf's (1981) l'Hirondelle bedrock valley the Muskwa bedrock valley, and its northward extension the Red Earth bedrock valley (Figure 2). A southeast-trending bedrock valley that parallels the l'Hirondelle is tentatively identified in this report (Gift bedrock valley; Figure 2). The High Prairie bedrock valley (southwestern part of the study area) extends eastwards beneath Lesser Slave Lake (Figure 2). Other smaller bedrock valley thalwegs have been previously mapped by Pawlowicz et al. (2007), including Gods valley in the northeastern part of the study area and the Manning bedrock valley (after Marciniuk and Kerr, 1971) north of Clear Hills (Figure 2).

2.2 Bedrock Geology

The bedrock geology, which underlies the Cenozoic stratigraphy, consists primarily of Cretaceous marine and fluvial sandstone, siltstone, shale, and mudstone (Hathway et al., 2013; Prior et al., 2013). The southernmost part of the study area (NTS 83M–O; Figure 3) consists primarily of siltstone and shale of the Puskwaskau and Kaskapau formations. In the remaining parts of the study area (NTS 84B–G; Figure 3), the bedrock uplands are commonly composed of siltstone, shale, sandstone, and mudstone of the Wapiti, Puskwaskau, and Kaskapau formations and Smoky Group (Figure 3); however, in the easternmost part of the study area (NTS 84B; Figure 3), the bedrock upland in the Peerless Lake area (Figure 2) is capped by mudstone, shale, and siltstone of the Lea Park, Fish Scales, Belle Fourche, and Second White Specks (including Carlile and Niobrara) formations (Figure 3).

The bedrock formations that compose the bedrock upland areas have been incised by rivers (Figure 2), resulting in the exposure of older (i.e., deeper) bedrock units. The Spirit River and Peace River formations (mudstone, siltstone, and sandstone) are the oldest (lowermost) units exposed in the bedrock valleys (Figure 3). The bedrock valleys are commonly floored by the Shaftesbury Formation (Figure 3), which is primarily weakly lithified (soft) mudstone although siltstone and bioclastic sandstone are present in the upper Shaftesbury Formation (Hathway et al., 2013; Prior et al., 2013). Bedrock valleys in the northern part of the study area (northern half of NTS 84F and G; Figure 2) are floored almost entirely by mudstone of the Loon River Formation (Figure 3).

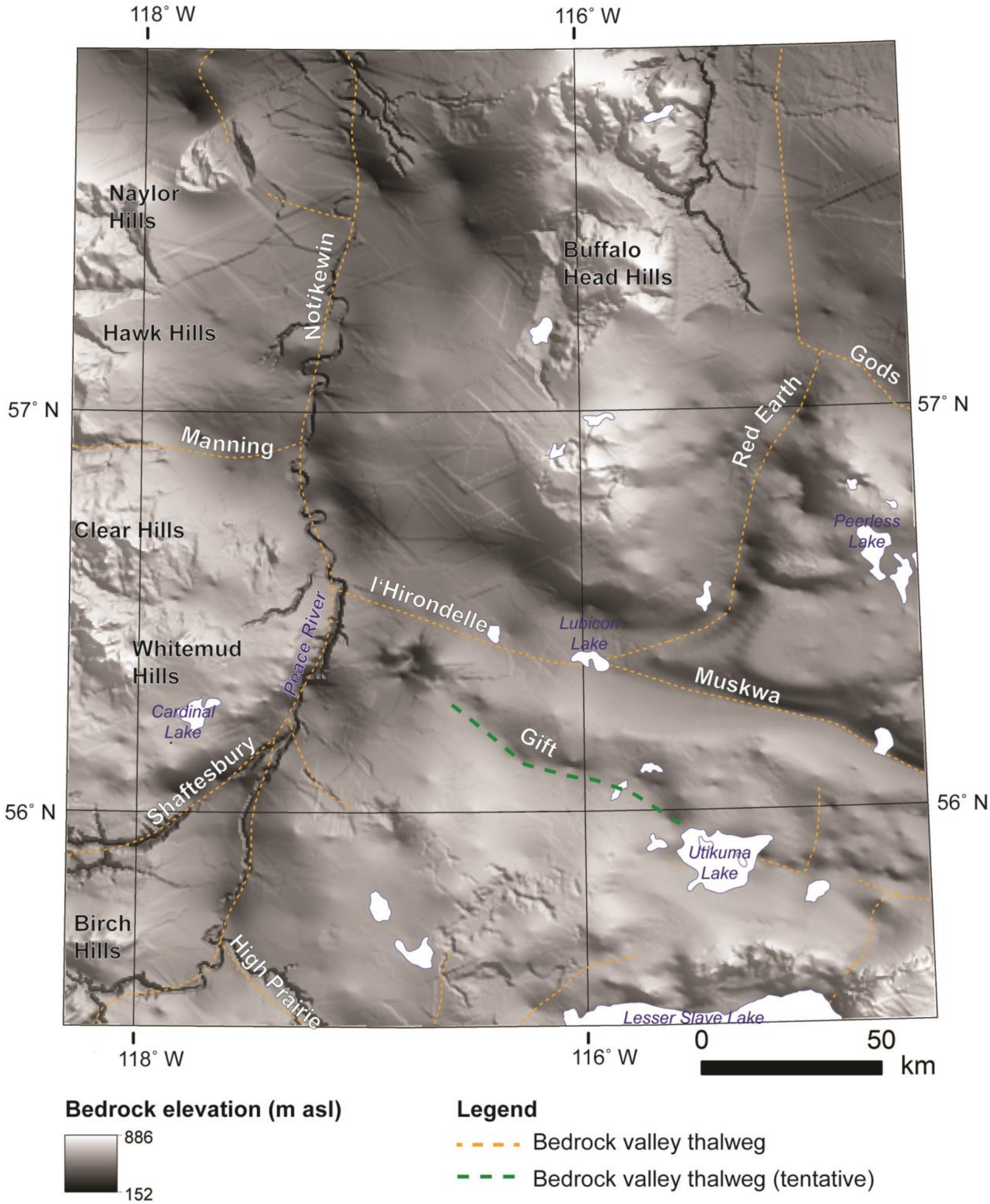

Figure 2. Bedrock topography in the study area (hill-shaded image, illuminated from the northeast at an azimuth of 45°, 60 times vertical exaggeration; data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), including thalwegs of major bedrock valleys (white labels; after Jones, 1966; Tokarsky, 1967, 1971; Borneuf, 1981; Pawlowicz and Fenton, 2005; data from Pawlowicz et al., 2007) and bedrock uplands (black labels), northwestern Alberta.

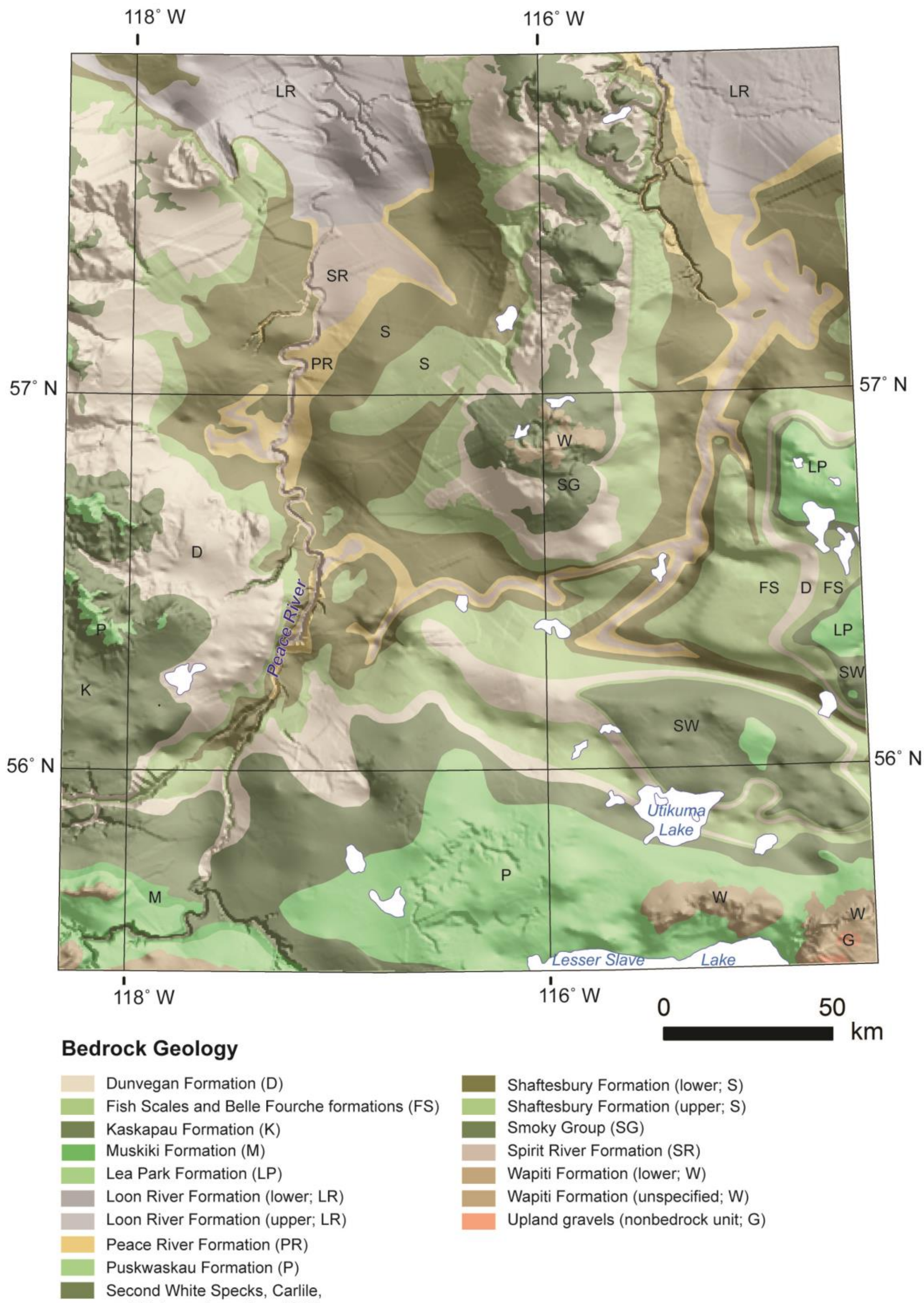

Figure 3. Bedrock geology of the study area, northwestern Alberta (modified from Prior et al., 2013). Bedrock geology is draped over a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m, MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

2.3 Physiography

The study area is located in the Northern Alberta Lowlands and Uplands physiographic regions (Figure 4; Pettapiece, 1986). It is characterized by physiographic uplands in the western, central, and eastern parts, which are separated by physiographic lowland areas. The western margin of the study area contains the Clear Hills Uplands, which is bounded on its northern margin by the Vermilion Lowland and eastern and southern margins by the Peace River Lowland (Figure 4). The central part of the study area contains the Buffalo Head Hills and Utikuma uplands, which are separated by a relatively narrow tract of land of the Wabasca Lowland in the area of Lubicon Lake (Figures 2 and 4). The eastern part of the study area contains the Birch Mountains Upland, which is bounded by the Wabasca Lowland on its southern and western margins in the study area. The extreme southwestern corner of the study area contains small parts of the Saddle Hills Upland and Wapiti Plains (Puskwaskau Hills) of the Southern Alberta Uplands region (Figure 4).

2.4 Cenozoic Geology

The Cenozoic geology of the Peace River area (Figure 1) has been compiled by several authors over nearly the last century (e.g., Rutherford, 1930). This section provides an overview of the major Cenozoic geological units described and mapped in the study area, and the events responsible for their deposition. Subsurface Cenozoic geological units commonly do not directly correspond to morphogenetic units mapped at the surface (Figure 5) as a result, in part, of different criteria used to characterize the units and the purpose of geological investigations (e.g., soil survey versus hydrogeological assessment). Hence, this section is subdivided into a description of the surficial geology and landforms mapped in the study area (Figures 5 and 6; Section 2.4.1) and a summary of subsurface geological units previously described by various workers (Section 2.4.2). An attempt is made to identify surficial units that may be equivalent (whole or in part) to subsurface units, where possible, in the subsurface geology section (Section 2.4.2) below.

2.4.1 Surficial Geology and Landforms

The most recent compilations of the surficial geology and glacial landforms in the study area are presented in Figures 5 and 6. The surficial geology and landforms are briefly summarized below with reference to the physiographic regions, sections, and districts of Pettapiece (1986; Figure 4).

2.4.1.1 Peace River Lowland

The Peace River Lowland section (Figure 4) is underlain primarily by glaciolacustrine and lacustrine sediments (Figure 5). Glacial landforms are rare in the Peace River Lowland and are predominantly drumlinoid or streamlined (Figure 6). Fluvial and colluvial sediments and organic deposits are common along the valley margins of the Peace River and its tributary streams (Figure 5). Organic deposits commonly overlie glaciolacustrine sediments in the eastern part of the Peace River Lowland (Figure 5). A large tract of eolian sediments and dune forms is mapped in the Watino Plain (Smoky River area; cf. Henderson, 1959), and a similarly large tract of fluvial sediments is recorded in the High Prairie Plain (west of Lesser Slave Lake; Figures 4 and 5). Moraine is rarely mapped in the Peace River Lowland; however, it covers most of the Cardinal Lake Plain (which contains streamlined landforms orientated northeast; Figure 6) and is mapped in isolated patches on the Falher, Sturgeon, Manning, Bearhead, and Cadotte plains (Figures 4 and 5). The northern margin of the Fish Creek moraine (Mathews, 1980) was previously delineated in the southwestern corner of the study area (Sturgeon Plain, Figure 4) and was mapped as primarily ‘moraine’ at surface (Figure 5).

The Cardinal Lake Plain (Figure 4) was historically mapped as containing primarily surficial sand and gravel and buried terrace gravel (Tokarsky, 1967, 1971; Scheelar and Odynsky, 1968; Borneuf, 1981); however, Jones (1966) and Fox et al. (1987) mapped primarily stony till at surface in the Cardinal Lake Plain and Pettapiece (1986) indicated undulating till moraine in the area.

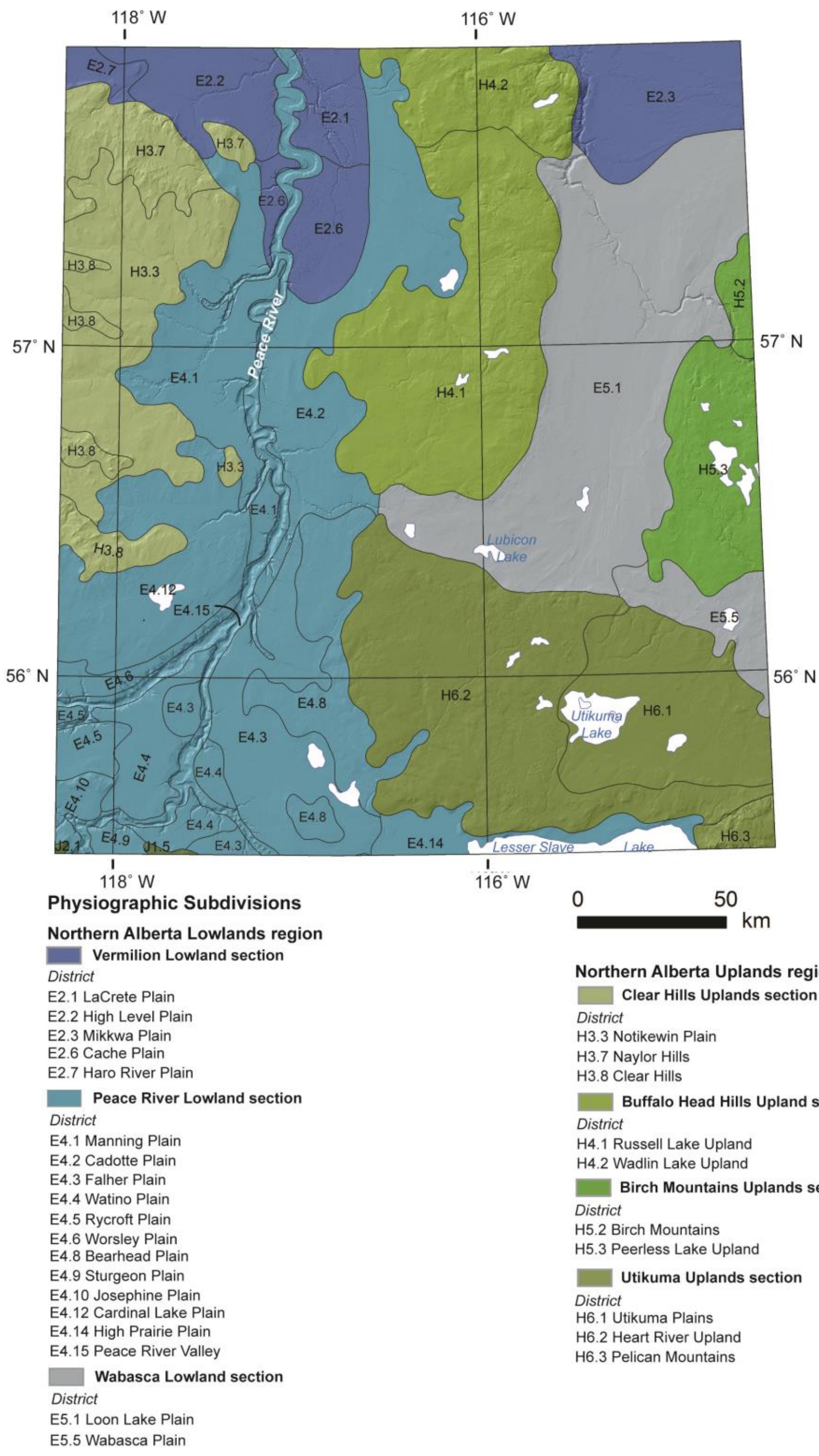

Figure 4. Physiography of the study area subdivided into regions, sections, and districts (Pettapiece, 1986) draped over a hill-shaded image of the ground surface topography (Alberta Environment and Parks, 2015), northwestern Alberta. Uplands are in shades of green and lowlands are in shades of blue. Small parts of the Saddle Hills Upland (J2.1) and Wapiti Plains (Puskwaskau Hills, J1.5) sections of the Southern Alberta Uplands region are located in the extreme southwestern corner of the study area.

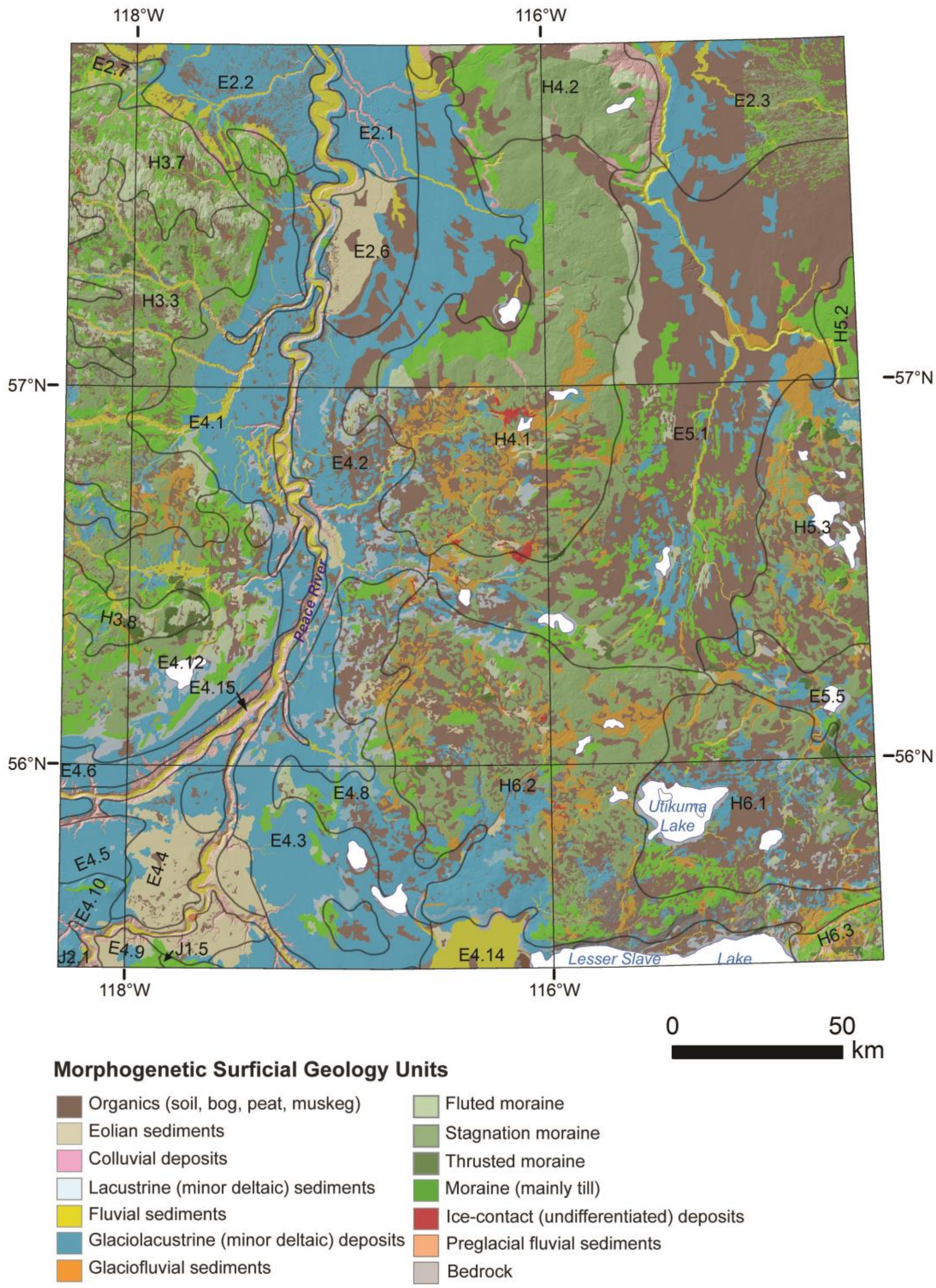

Figure 5. Surficial geology in the study area compiled from digital polygon data at 1:100 000 and 1:250 000 map scales, northwestern Alberta (data from Fenton et al., 2006a, b, 2013; Paulen, 2006a, b; Paulen et al., 2006a–f; Atkinson, 2008, 2011; Fenton, 2008; Atkinson and Paulen, 2010; Pawley, 2011, 2015; Shipman et al., 2011; Utting et al., 2016a, b). Surficial geology is draped over a hill-shaded image of the ground surface topography (Alberta Environment and Parks, 2015). Physiographic districts (black outlines) of Pettapiece (1986) are included (refer to Figure 4 for the physiographic district legend).

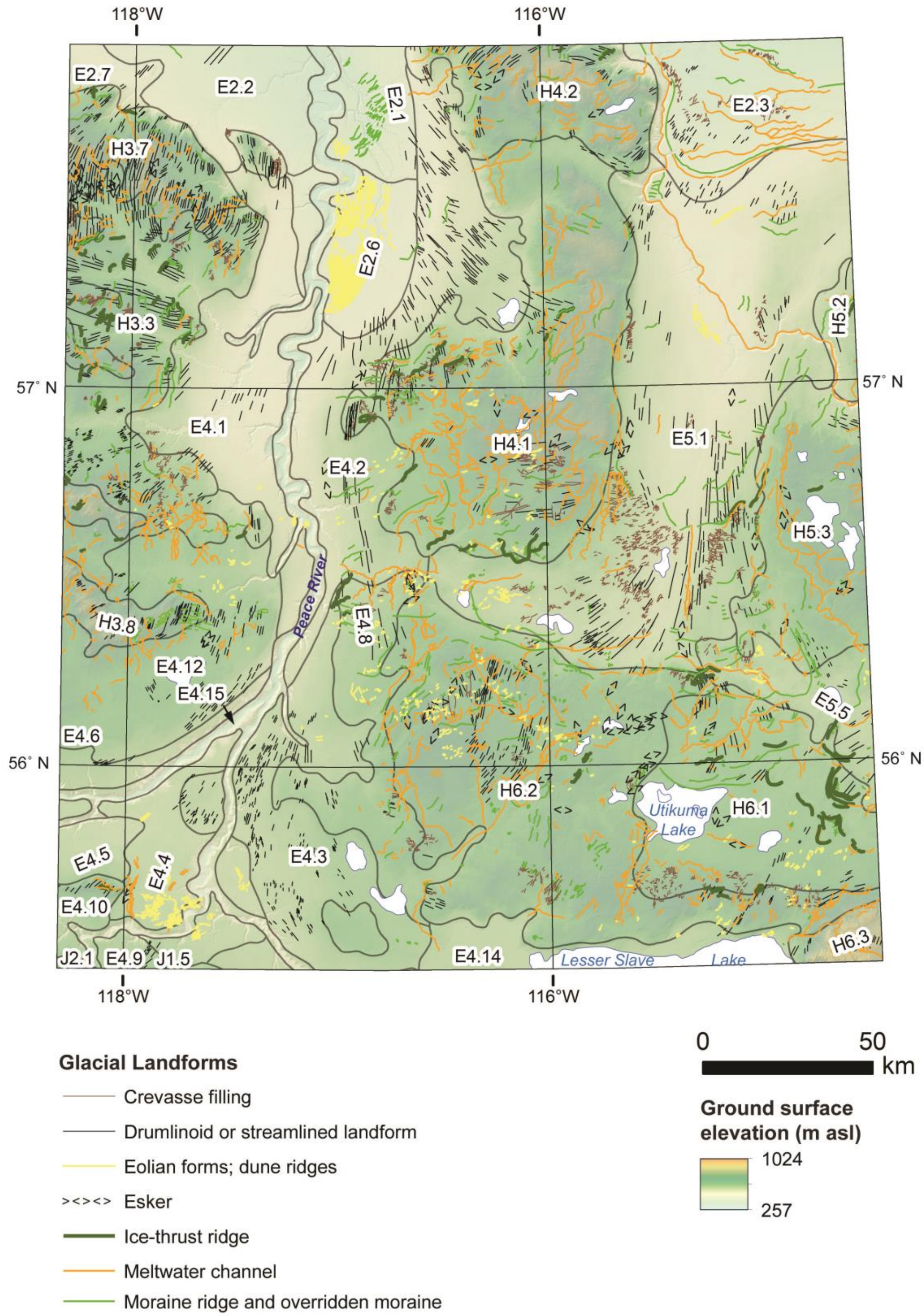

Figure 6. Glacial landforms mapped in the study area, northwestern Alberta (data from Atkinson et al., 2014), draped over a hill-shaded image of the ground surface topography (Alberta Environment and Parks, 2015). Physiographic districts (black outlines) of Pettapiece (1986) are included (refer to Figure 4 for the physiographic district legend).

2.4.1.2 Vermilion Lowland

In the area of the Peace River, the Vermilion Lowland contains primarily glaciolacustrine sediments and organics (Figures 4 and 5), which are crosscut by minor tributary streams infilled with fluvial and colluvial deposits (Figure 5). A large tract of land in the Cache Plain (Figure 4), east of the Peace River, is composed of eolian deposits and dune forms (Figures 5 and 6). Glacial landforms in the northwestern Vermilion Lowland are rare. In the northeastern part of the study area (Mikkwa Plain; Figures 4 and 5), large swaths of organic material are overlain by isolated patches of till moraine and rare glaciolacustrine and fluvial sediments (Figure 5).

2.4.1.3 Wabasca Lowland

The surficial geology of the Wabasca Lowland (Figure 4) is predominantly organics (Figure 5) interspersed with isolated patches of glaciolacustrine sediments, till moraine, stagnation moraine, glaciofluvial sediments, and very rare thrusted moraine, fluvial deposits, and eolian sediments. The largest accumulation of glaciofluvial sediments mapped at surface is located on the northern and eastern margin of the Wabasca Lowland section (Figures 4 and 5). Stagnation and thrusted moraine are located primarily in the southernmost part of the Wabasca Lowland section (Figure 5).

2.4.1.4 Clear Hills Uplands

The Clear Hills Uplands (Figure 4) are primarily covered by stagnation and till moraine, with minor areas of fluted and thrusted moraine, and very rare undifferentiated ice-contact deposits (Figure 5). The moraine deposits are interspersed with isolated patches of organic material and rare glaciolacustrine sediments. Fluvial sediments are confined primarily to stream valleys and colluvium is rarely found in, or proximal to, stream valleys and on the northern margin of the Clear Hills Uplands (Figures 4 and 5). Glaciofluvial sediments form isolated tracts in the southern half of the Clear Hills Uplands (Figures 4 and 5).

2.4.1.5 Buffalo Head Hills Upland

The Buffalo Head Hills Upland (Figure 4) is underlain primarily by stagnation moraine with minor till moraine and organics primarily on the western and southern margins, and colluvium and fluted moraine on the eastern margin (Figures 4 and 5); however, the southern margin of the Buffalo Head Hills Upland contains glaciofluvial, glaciolacustrine, and ice-contact sediments in addition to the surficial sediment types mapped in the northern part of the physiographic section (Figures 4 and 5). The predominant glacial landforms in the Buffalo Head Hills Upland are glaciofluvial (meltwater) channels (Figure 6). The southern part of the Buffalo Head Hills Upland contains streamlined landforms orientated east, whereas streamlined landforms in the northern part of Buffalo Head Hills Upland have variable azimuthal orientations (Figure 6).

2.4.1.6 Birch Mountains and Utikuma Uplands

The Birch Mountains and Utikuma uplands sections (Figure 4) are each characterized by stagnation moraine interspersed with organic material and glaciofluvial sediments (Figures 4 and 5). Glaciolacustrine and till moraine are rare (mapped primarily on the margins of the physiographic sections; Figures 4 and 5). Fluvial, eolian, and colluvial sediments and thrusted moraine are very rare in each of the Birch Mountains and Utikuma uplands sections (Figure 5).

2.4.2 Subsurface Stratigraphy

This section provides a brief summary of the subsurface stratigraphy reported in the literature. Oldest to youngest deposits are described with reference to the advance and retreat of the Laurentide Ice Sheet in the study area, including pre-Laurentide deposits (referring to sediments that antedate the advance of the Laurentide Ice Sheet, and are commonly called preglacial in the literature; e.g., Edwards and Scafe, 1996), glacial deposits during ice advance and retreat, and postglacial deposits. The informal names given to deposits and paleogeomorphological features (e.g., glacial lakes; e.g., Mathews, 1980; Slomka and Utting, 2018) reported in the literature are retained where possible.

2.4.2.1 Pre-Laurentide (Preglacial) Deposits

Pre-Laurentide, or preglacial, deposits are commonly identified based on the absence of Precambrian-aged igneous and metamorphic lithologies, which are characteristic of the Canadian Shield (e.g., Tokarsky, 1967; Edwards and Scafe, 1996). In the Canadian Prairies, Stalker (1968) classified preglacial sand and gravel (named 'Saskatchewan Gravels and Sands'), which rest on bedrock and underlie Laurentide till, into three groups based on physiographic position. Stalker's (1968) groups included high level deposits (oldest preglacial deposits) found as remnants on uplands, intermediate level deposits found on benches and terraces of preglacial river valleys, and low level deposits (youngest preglacial deposits) located in preglacial valleys. Stalker (1968) proposed that a cyclic sequence of gradual uplift of the plains, fluvial incision, and fluvial deposition resulted in the development of the physiographic levels of preglacial deposits, which were formed prior to the first Quaternary glaciation (Stalker, 1968). A review of the preglacial fluvial depositional history of Alberta is found in Edwards and Scafe (1996). Leckie (2006) provided a detailed overview of the preglacial depositional history of southern Alberta and Saskatchewan and the northern part of Montana, and Hartman (2015) focused on the preglacial history of west-central Alberta.

In the study area, pre-Laurentide fluvial sand and gravel was classified into two informal quasi-lithostratigraphic units (units 1 and 2; Figure 7) by Edwards and Scafe (1996) based on Stalker's (1968) physiographic levels, as well as gravel clast lithology (source area) and elevation. The oldest pre-Laurentide deposits in the study area (unit 2 of Edwards and Scafe, 1996; Figure 8) are located on bedrock straths (e.g., Grimshaw gravels; Tokarsky, 1967, 1971) and the youngest pre-Laurentide deposits (unit 1 of Edwards and Scafe, 1996; Figure 8) are recorded at the base of bedrock valleys (Figures 2 and 7). Leslie and Fenton (2001) grouped sands and gravels of units 1 and 2 (Figure 7) into a single unit of preglacial deposits (called Unit A in Leslie and Fenton, 2001). Edwards and Scafe (1996) proposed six preglacial gravel groups (groups 1–6; Figure 9) within Alberta based on similar sediment source areas, derived from analysis of gravel clast lithologies in units 1–4 (Figure 7).

Unit 3 of Edwards and Scafe (1996) was recorded just beyond the western and southeastern margins of the study area (Figure 7) on Pelican Mountain (group 5 in Figure 9) and Halverson Ridge (group 6 in Figure 9; Green and Mellon, 1962). These gravel deposits were previously interpreted by Edwards and Scafe (1996) to have been deposited in large braided river systems flowing eastwards from the Rocky Mountains across the Alberta plains during the Middle–Late Tertiary[1] (Figure 8).

[1] The International Commission on Stratigraphy recommends using the terms 'Paleogene' (Paleocene to Oligocene epochs) and 'Neogene' (Miocene and Pliocene epochs) instead of Tertiary. The term 'Tertiary' is used here to be consistent with the source material used for this report.

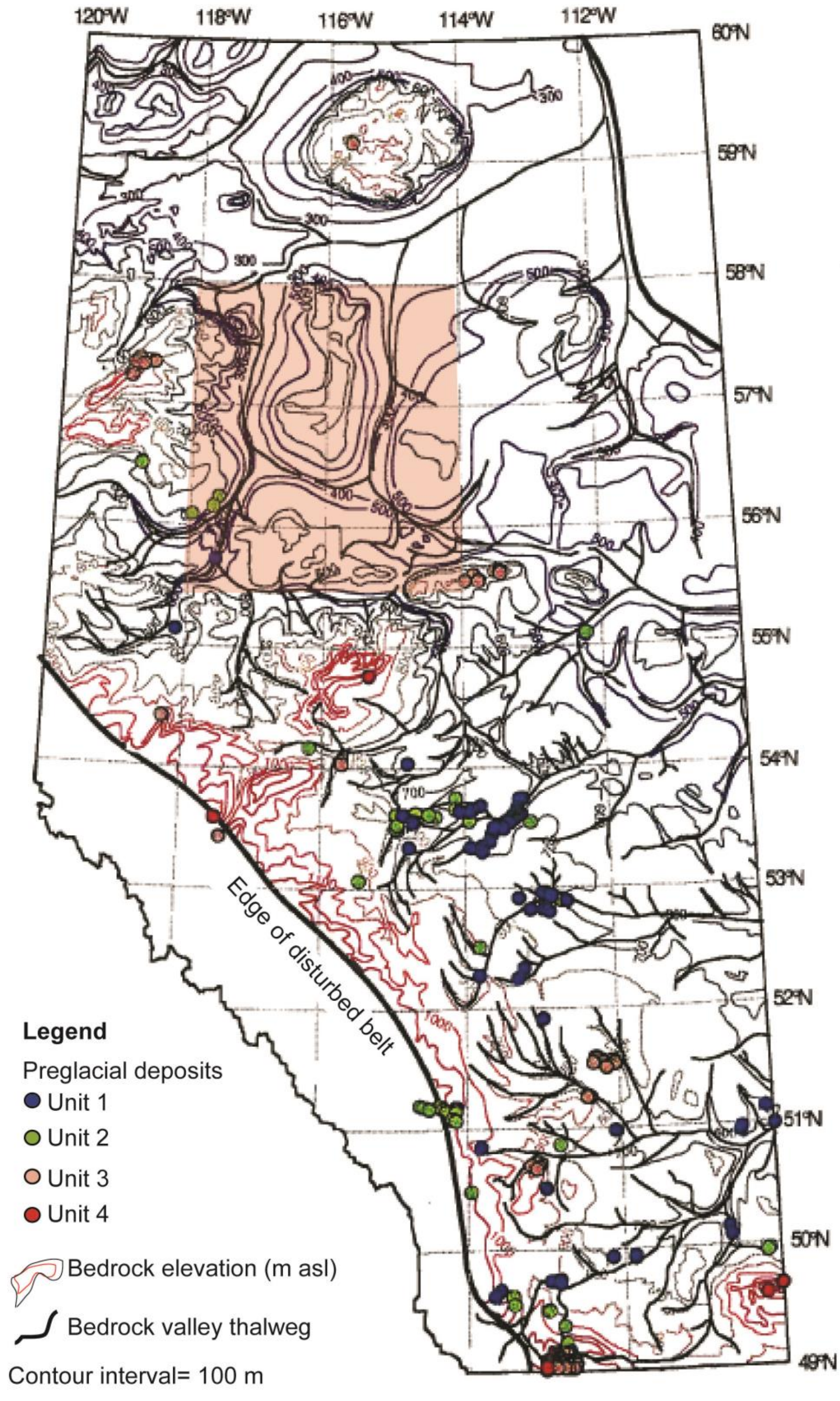

Figure 7. Preglacial deposits organized into four units (units 1–4) based on clast lithology and elevation (from Edwards and Scafe, 1996). Preglacial sands and gravels of units 1 and 2 are located in the study area (pink box), and sands and gravels mapped as units 3 and 4 are located on bedrock uplands beyond the margins of the study area (e.g., Clear Hills and Pelican Mountain).

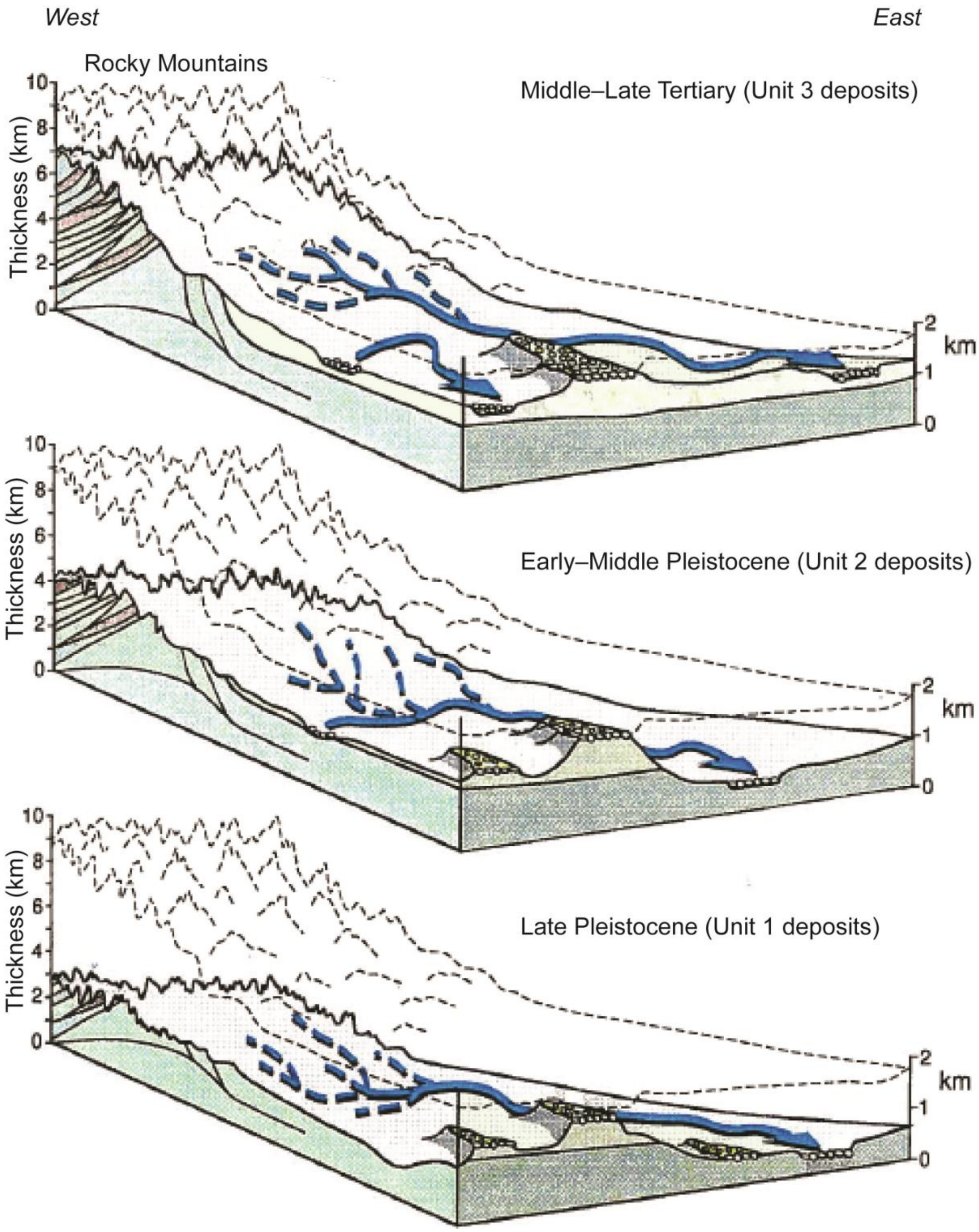

Figure 8. Block diagrams showing the conceptual paleoenvironmental reconstruction of preglacial deposits of units 1–3 (from Edwards and Scafe, 1996). Large fluvial braided river systems transported sediment eastwards from the Rocky Mountains. Fluvial incision of previously deposited preglacial gravel resulted in the development of terraces and uplands capped by remnants of preglacial fluvial deposits. Note: the International Commission on Stratigraphy recommends using the terms 'Paleogene' (Paleocene to Oligocene epochs) and 'Neogene' (Miocene and Pliocene epochs) instead of Tertiary. The term 'Tertiary' is used here to be consistent with the source material used for this report.

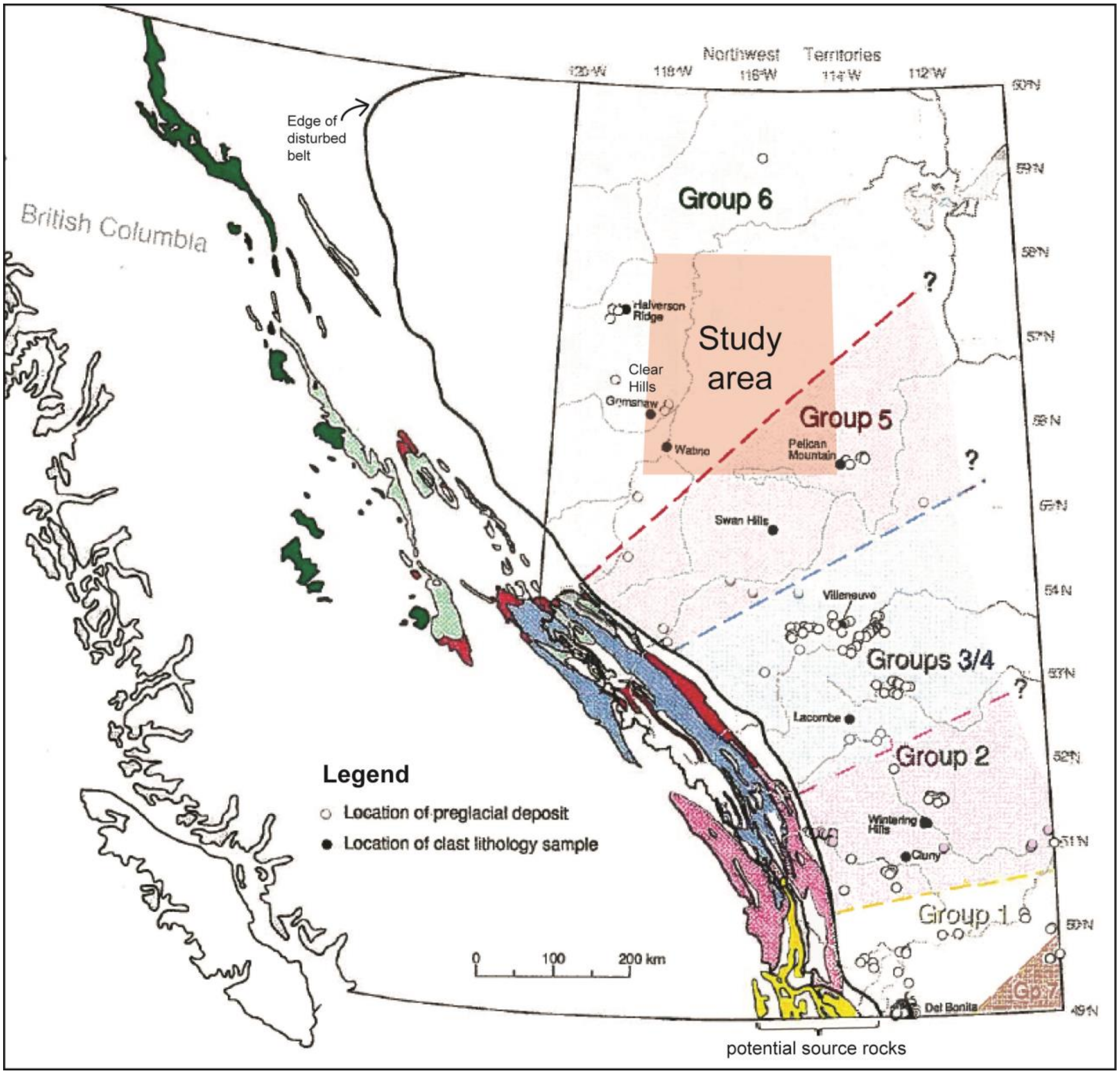

Figure 9. Preglacial gravel deposits classified into groups based on sediment source area derived from clast lithology (from Edwards and Scafe, 1996). Preglacial gravels of groups 5 (red) and 6 (green) are located in the study area (pink box).

Unit 2 of Edwards and Scafe (1996) included sand and gravel located on bedrock straths above bedrock valleys (Figure 7). Pre-Laurentide sand and gravel deposits are recorded in the Cardinal Lake Plain district (positioned at ~600–700 m asl; Figure 4) on a bedrock strath above the Shaftesbury bedrock valley (Tokarsky, 1967; Leslie and Fenton, 2001; Figures 2 and 7). Tokarsky (1967) referred to the coarse-grained preglacial deposits in the Cardinal Lake Plain as the Grimshaw gravels, which has retained its name in the literature (e.g., Edwards and Scafe, 1996; Chlachula and Leslie, 1998; PFRA, 1998; Atkinson and Paulen, 2010). The Grimshaw gravels overlie bedrock and are overlain by Laurentide till (Rutherford, 1930; Jones, 1966; Tokarsky 1967, 1971). Tokarsky (1967) noted that lithologies from the Canadian Shield were not found in the Grimshaw gravels. Tokarsky (1967) stated that muscovite-rich granite clasts in the Grimshaw gravels showed the greatest degree of weathering and were the most likely source of micaceous sands within the Grimshaw gravels. Paleocurrent measurements from cross-bedding in the Grimshaw gravels indicated a north to northeast paleocurrent direction (Tokarsky, 1967; Chlachula and Leslie, 1998). Scafe et al. (1989) observed that the Grimshaw gravels were likely not present on the east side of the Peace River valley. The Grimshaw gravels were interpreted to have been deposited in an ice-marginal (Rutherford, 1930), glaciofluvial (Scheelar and Odynsky, 1968), and pre-Laurentide fluvial (Tokarsky, 1967; Edwards and Scafe, 1996) depositional environment, and may be equivalent to the Saskatchewan Gravels and Sands (Tokarsky, 1967; Stalker, 1968). The Grimshaw gravels were interpreted as Tertiary (Tokarsky, 1967), Early–Middle Pleistocene (Edwards and Scafe, 1996), and Middle Wisconsinan (Chlachula and Leslie, 1998) age. Tokarsky (1967) also recorded ‘intermediate terrace gravels’ positioned between the Grimshaw gravels and Shaftesbury bedrock valley sand and gravel.

Unit 1 of Edwards and Scafe (1996; Figure 7) included gravel located at the base of bedrock valleys and were commonly referred to as ‘basal gravels’ because the deposits overlie bedrock and underlie Laurentide till (Rutherford, 1930; Henderson, 1959). Rutherford (1930) and Henderson (1959) mapped basal gravels (positioned at ~500 m asl) in the Watino area, along the Smoky and Heart rivers, and in preglacial valleys in the vicinity of the confluence zone of the Peace and Smoky rivers (Figure 1). Leslie and Fenton (2001) recorded gravel deposits of unit 1 from outcrop sections in the floodplain of the Peace River (confluence zone of the Peace and Smoky rivers) and along Buchanan Creek (east of Manning; Figure 1). Lithologies found in the basal gravels were predominantly chert and quartzite; lithologies typical of the Canadian Shield (e.g., gneiss and granite) were reportedly absent from the basal gravels (Henderson, 1959), however, Botterill (2007) and Morgan et al. (2008) recorded Canadian Shield clasts in the gravel deposits in the Shaftesbury bedrock valley (Figure 10). Henderson (1959) interpreted the basal gravels to have been transported by glaciofluvial meltwater streams draining the Cordilleran Ice Sheet in the early to late Pleistocene, prior to the advance of the Laurentide Ice Sheet into the study area. Liverman et al. (1989) also studied the basal gravels at Watino and interpreted these to be pre-Laurentide fluvial sediments of Middle Wisconsinan age (based on radiocarbon dates and conformable unit contacts). Basal gravels containing very rare Canadian Shield lithologies were recorded at the base of the Shaftesbury bedrock valley in the area of the Town of Peace River (Balzer, 2000; Leslie and Fenton, 2001; Botterill, 2007) and preglacial gravels were recorded in the Manning area (at ~330 m asl; Marciniuk and Kerr, 1971).

2.4.2.2 Ice-Advance Deposits

The earliest ice-advance deposits include sand and gravel that contains Canadian Shield lithologies and overlies pre-Laurentide gravel deposits in bedrock valleys (Leslie and Fenton, 2001; Botterill, 2007; Figure 10). Ice-advance sand and gravel has been recorded in the Watino area, at the Town of Peace River, at the confluence of Buchanan Creek and Peace River, in the Heart River valley, and in the High Prairie area (Figure 1; Jones, 1966; Tokarsky, 1967; Liverman et al., 1989; Balzer, 2000; Leslie and Fenton, 2001; Botterill, 2007; Morgan et al., 2008). The frequency and grain size of Canadian Shield–derived gravel commonly increase upwards in the stratigraphic column (Balzer, 2000; Botterill, 2007; Morgan et al., 2008). Accelerator mass spectrometry (AMS) radiocarbon dating (Beta Analytic, Miami, Florida) of a caribou antler recovered from an ice-advance gravel unit in the Shaftesbury bedrock valley (Figure 10) resulted in a Middle Wisconsinan age (25 120 ±140 ^{14}C BP; lab number Beta-226811; Botterill, 2007; Morgan et al., 2008). The ice advance gravel deposits described here are equivalent to ‘Sub-unit B1’ of Leslie and Fenton (2001).

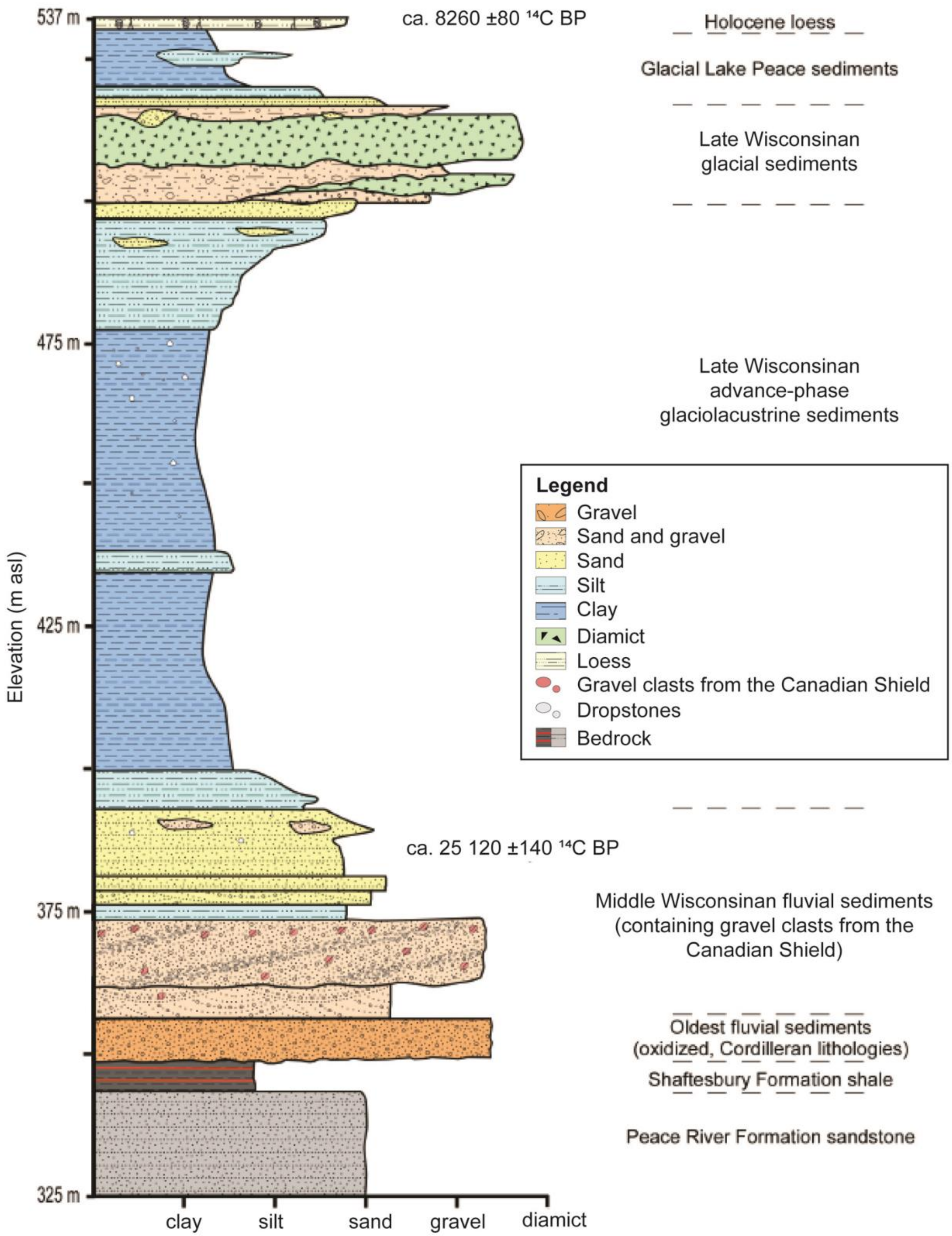

Figure 10. Idealized log of the stratigraphy in the Shaftesbury bedrock valley near the Town of Peace River, northwestern Alberta (from Morgan et al., 2008). The vertical axis is elevation in metres above sea level, and the horizontal axis records grain size. Radiocarbon dates from a caribou antler (lower date; from Botterill, 2007) and organic material (upper date; from Morgan et al., 2008) are provided to the right of the log.

Lacustrine and glaciolacustrine sediments (including debris flow deposits) commonly overlie the ice-advance gravel in bedrock valleys (Tokarsky, 1967) and are classified as ‘Sub-unit B2’ by Leslie and Fenton (2001), which includes massive, cross-bedded, and rippled sand, gravel, diamict, and massive and laminated silt and clay. In the Heart River area, Tokarsky (1967) recorded at least 16 m of silt and clay overlying Canadian Shield–derived gravel clasts. At the Town of Peace River, Tokarsky (1967) recorded a unit (40 m thick) of clay and silt overlying gravel containing Canadian Shield lithologies, rare gravel interbeds, and crushed shells of snails and ostracodes. At the Town of Peace River, Morgan et al. (2008) recorded at least 100 m of fine-grained lacustrine sediments overlying a unit of sand and gravel of Canadian Shield provenance. The ice-advance lacustrine sediments in the Peace River area are likely equivalent to sediments of Glacial Lake Mathews (Hartman, 2015) identified upstream in the Peace River valley in the Cleardale (west of the study area; Atkinson and Paulen, 2010) and Fort St. John (west of the study area in British Columbia; Hartman and Clague, 2008) areas. Leslie and Fenton (2001) interpreted sediments of their ‘Sub-unit B2’ as ice-marginal debris flow and glaciofluvial deposits.

A single unit composed of Laurentide till (Late Wisconsinan) was identified in the study area (Tokarsky, 1967; Chlachula and Leslie, 1998; Leslie and Fenton, 2001; Botterill, 2007; Morgan et al., 2008); however, Henderson (1959) and Scheelar and Odynsky (1968) mapped multiple tills interpreted to record pre-Late Wisconsinan glaciation in the study area. An ‘ancient till’ at the confluence of the Smoky and Little Smoky rivers was identified by Henderson (1959); the till was described as a sandy till containing lenses of laminated clay and Henderson (1959) presumed it to have been deposited during the Nebraskan or Kansan glaciation. Henderson (1959) also identified ‘lower’, ‘middle’, and ‘upper’ tills in the Sturgeon Lake area (south of the study area) based on correlation with the glacial stratigraphy in the Mississippi River drainage basin; although, Henderson (1959) cautioned that the till stratigraphy was tentative and required further consideration (Henderson, 1959, p. 68).

Henderson (1959) identified the lower till in deep gullies on the flanks of uplands in the Peavine Metis Settlement area (south of the study area) and described it as a discontinuous sheet of till containing predominantly granite, gneiss, and schist clasts. The middle till directly overlies the ancient and lower tills; although, the nature of the bedding contacts (e.g., erosional, conformable) was not described by Henderson (1959). Henderson (1959) described the middle till as a laterally continuous unit with a light brown to brownish-grey clayey matrix, blocky fracture pattern, and predominantly Canadian Shield–derived gravel lithologies, which Henderson (1959) interpreted to have been deposited during the last glacial maximum in the Late Wisconsinan. The upper till of Henderson (1959) had a clayey matrix with rare gravel and was restricted to the Little Smoky River valley and northern and eastern margins of the Fish Creek moraine (Mathews, 1980). The Fish Creek moraine is located on the southwesternmost corner of the study area and extends to the southeast beyond the study area boundary (Mathews, 1980). The upper till was interpreted to record either a minor readvance, or major phase of retreat and subsequent advance, of the ice margin into a glacial lake (Glacial Lake Fahler) ponded in the Little Smoky River paleovalley (Henderson, 1959).

Scheelar and Odynsky (1968) identified a fine-grained brown to grey-brown till on Whitemud Hills, a medium-grained, yellow- to grey-brown, weakly calcareous till east of the Peace River (on Buffalo Head Hills and Heart River Upland; Figure 2), and a dark brown to grey-brown noncalcareous till in the Peace River valley; however, the correlation of tills identified by each of Henderson (1959) and Scheelar and Odynsky (1968) is not known. Paulen and McClenaghan (2015) identified two Late Wisconsinan tills on Buffalo Head Hills based primarily on colour and clast orientation, and interpreted these to record ice advance during the last glacial maximum and localized flow during overall ice retreat in the Late Wisconsinan. Recently, Andriashek and Barendregt (2016, 2017) used paleomagnetic analysis of diamicts and lake sediments recovered in cored boreholes to provide a relative till chronology on Buffalo Head Hills; the oldest relative age interpreted from a reversed paleomagnetic signature in diamict was assigned to the Matuyama Chron (~0.780 Ma; Andriashek and Barendregt, 2016, 2017).

In the southwestern part of the study area, Balzer (2000) and Leslie and Fenton (2001) identified a single till unit composed of a grey massive silty clay till overlain by a brown massive to stratified silty clay till, which was sandy in the rare locations where the till overlay sandstone and Grimshaw gravels. The grey till contained laminae and lenses of clay, silt, and sand, and rarely pebbles, in places, and the brown till contained relatively thicker laminae and lenses of sand and silt. Leslie and Fenton (2001) interpreted the tills, together with the interlaminae and lenses, as englacial and ablation till deposits.

2.4.2.3 Ice-Retreat Deposits

Ice retreat is recorded primarily by glaciolacustrine and coarse-grained outwash sediments (Henderson, 1959; Balzer, 2000; Leslie and Fenton, 2001), which overlie most of the study area (Figure 5). The Laurentide Ice Sheet retreated in the form of ice lobes, which were restricted primarily to lowland areas of the paleotopography (Mathews, 1980). The Peace River paleovalley was occupied by the Peace River lobe, which retreated northwards with a series of glacial lakes in front of the ice margin. Glacial lakes occupied the Peace River paleovalley from the Fort St. John area (to the west in British Columbia) to the town of High Level (just north of the study area). Shoreline features and evidence of meltwater outlets at several elevations record different lake level stages of Glacial Lake Peace (Mathews, 1980; Hartman and Clague, 2008; Atkinson and Paulen, 2010; Hartman, 2015; Slomka and Utting, 2018). Henderson (1959) and St-Onge (1972) reconstructed smaller glacial lakes that occupied tributaries to the Peace River paleovalley and the Lesser Slave Lake basin. Henderson (1959) identified proglacial lacustrine sediments in the Smoky and Little Smoky river valleys, and interpreted these to record ice retreat during the Early Wisconsinan (Glacial lakes Rycroft and Puskwaskau I) and Late Wisconsinan (Glacial lakes Fahler and Puskwaskau II).

2.4.2.4 Deglacial Deposits

Deglaciation of the study area is recorded by alluvial, eolian, and lacustrine sediments and accumulations of organic materials (Henderson, 1959; Balzer, 2000; Leslie and Fenton, 2001). Morgan et al. (2008) recorded Holocene loess dated at ca. 8260 ±80 ^{14}C BP in the Town of Peace River area (Figure 10). The spatial distribution of the deglacial deposits is shown in Figure 5. As a result of deglaciation and a lowered local base level, which was the result of ice retreat and draining of ice-marginal lakes, the Peace River has incised at least 250 m of previously deposited sediment (Leslie and Fenton, 2001) and continued into the Shaftesbury, Peace River, and Spirit River formations (Figure 3).

3 Methods

3.1 Conceptual Geological Framework

Development of a conceptual geological framework (Figure 11) was the first stage of this investigation and formed the basis of unit correlation in the study area. A conceptual Cenozoic geological framework in the Peace River area is based on the stratigraphy collectively devised primarily by Balzer (2000), Leslie and Fenton (2001), Botterill (2007), and Slomka and Utting (2018), and informed by stratigraphies described by Henderson (1959), Tokarsky (1967), Mathews (1980), Edwards and Scafe (1996), Morgan et al. (2008), and Paulen and McClenaghan (2015).

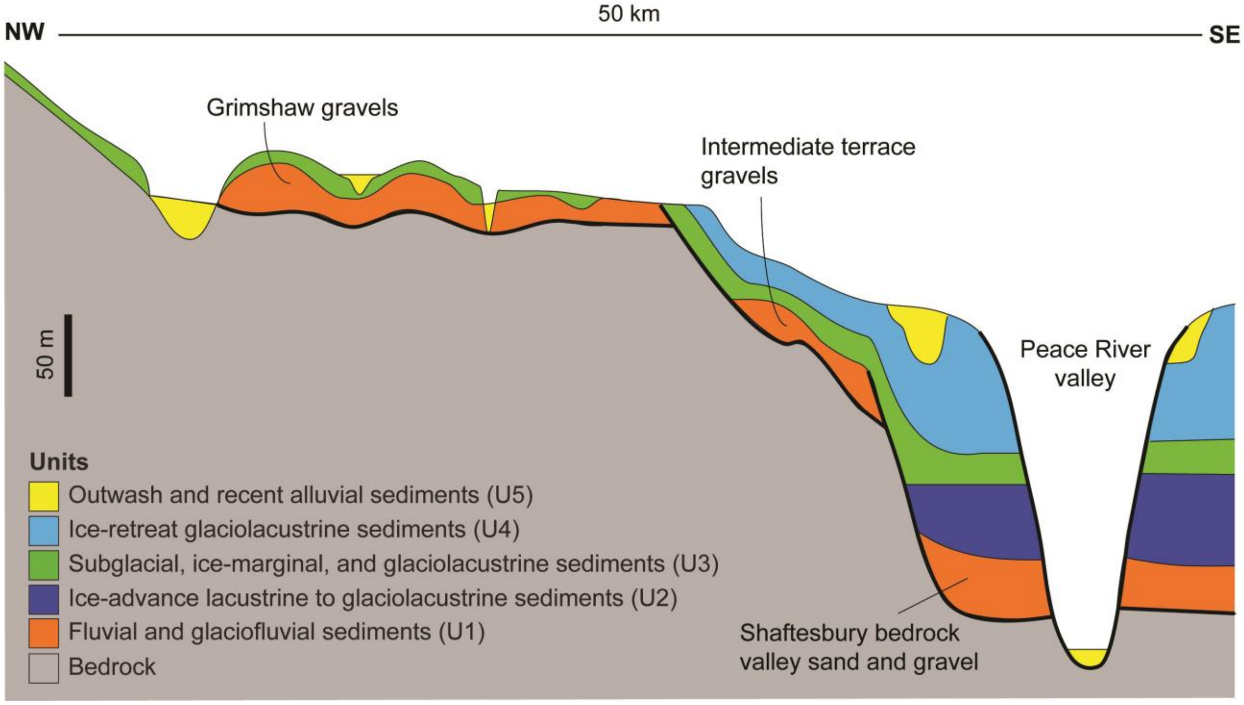

Figure 11. Conceptual geological cross-section from Whitemud Hills to the area southeast of the Peace River valley (northwestern Alberta) showing gravels on the Cardinal Lake Plain (Grimshaw gravels), intermediate terrace level, and base of the Shaftesbury bedrock valley (revised from Tokarsky, 1967; from Slomka et al., 2018). Units (U) are based on Tokarsky (1967), Leslie and Fenton (2001), and Botterill (2007). Unit 6 (organics and anthropogenic materials) is not shown because it is too thin to resolve at this scale. Thick black lines represent erosional surfaces from Slomka et al. (2018). Abbreviations: NW, northwest; SE, southeast. Scale is approximate.

The conceptual geological framework consists of six informal units (U1–6) based on facies associations, defined by analyzing sediments in cored boreholes (n=16; drilled by Pawlowicz and Fenton, 1998; Leslie and Fenton, 2001; Pawlowicz et al., 2005; Morgan et al., 2009), and correlated regionally by reviewing previously recorded outcrop and borehole descriptions (Tokarsky, 1967; Balzer, 2000; Leslie and Fenton, 2001; Pawlowicz et al., 2005; Botterill, 2007). Units in this report include (from oldest to youngest) fluvial and glaciofluvial sediments (U1), ice-advance lacustrine to glaciolacustrine sediments (U2), subglacial, ice-marginal, and glaciolacustrine sediments (U3), ice-retreat glaciolacustrine sediments (U4), outwash and recent alluvial sediments (U5; Figure 11), and organic and anthropogenic materials (U6).

Three basal sand and gravel units identified by Edwards and Scafe (1996; their units 1–3; Figures 7 and 8), primarily based on topographic position and lithology, served as the foundation to tentatively define three subunits of U1: upland gravel (U1a; e.g., Clear Hills gravel), bedrock strath gravel (U1b; e.g., Grimshaw gravels and intermediate terrace gravels of Tokarsky, 1967), and bedrock valley sand and gravel (U1c; e.g., Shaftesbury bedrock valley sand and gravel; Figure 11). Further refinement of U1 subunits is presented in Slomka et al. (2018). Units 1–6 were correlated between cored boreholes, and on a regional scale, using previously recorded logs from boreholes (n=30) and outcrop sections (n=121; Balzer, 2000; Leslie and Fenton, 2001; Botterill, 2007), and water well lithologs (n=3473; Alberta Environment and Sustainable Resource Development, 2014). The methodology of data collection, collation, processing, and analyses, including stratigraphic correlation of U1–6, is discussed below. Detailed unit descriptions and interpretations are discussed in Section 4.

3.2 Data

3.2.1 Cored Boreholes

Cores from 16 previously cored boreholes (Pawlowicz and Fenton, 1998; Leslie and Fenton, 2001; Morgan et al., 2009; Figure 12) were relogged using a facies analysis approach (Dalrymple, 2010) to understand the depositional processes involved in the emplacement of the sediments, interpret depositional environments, and gain insight into the depositional history of the study area. Sedimentary logs contain grain size (clay, silt, sand, and gravel) on the x-axis and depth (from below ground surface) on the y-axis (Appendix 1, Figure 36). The primary grain size of diamict is based on the matrix texture (Eyles et al., 1983). Logs include a visual and written record of grain size, sedimentary structure, sorting and fabric, colour, gravel clast shape, size, and lithology, reaction to hydrochloric acid, organic materials, sample locations, facies types, and the nature of facies contacts (e.g., gradational, sharp, erosional, conformable; Boggs, 2005).

Facies analysis was conducted by characterizing facies types (Appendix 1, Table 1) based on observation of grain size and sedimentary structure (e.g., laminated diamict facies; Dalrymple, 2010) and interpreting the processes responsible for the deposition of each facies based on published literature on sedimentary structures (e.g., Boggs, 2005). Core intervals that contained a range of grain sizes from clay to gravel (i.e., diamict) were first described in the log, and interpretation of the diamict was conducted during facies analysis (Eyles et al., 1983). Grouping of genetically related facies recorded in vertical succession in the logs allowed the characterization of facies associations, and depositional environments of facies associations were based on previously published facies models (e.g., James and Dalrymple, 2010). Genetically related facies associations, in turn, were grouped into units (1–6; discussed above), which were correlated between logs.

3.2.2 Outcrop Sections and Borehole Lithologs

Lithologs previously recorded from 121 outcrop sections and 30 cored and augered boreholes (Balzer, 2000; Leslie and Fenton, 2001; Pawlowicz et al., 2005; Botterill, 2007; Figure 13) were re-examined and re-interpreted based on the stratigraphic framework delineated in the relogged cores (described above). The re-interpreted units are consistent with the unit interpretations by Balzer (2000), Leslie and Fenton (2001), and Botterill (2007); however, the positions of unit boundaries were modified to reflect the new information derived from facies analysis of primarily subglacial and glaciolacustrine sediments in the cores (Slomka and Utting, 2018), and from the grouping of outwash and recent alluvial sediments as a result of regional data quality.

3.2.3 Water Well Lithology Data

Water well data for the study area was obtained from Alberta Environment and Sustainable Resource Development (now Alberta Environment and Parks [AEP]) in 2014 (Alberta Environment and Sustainable Resource Development, 2014). Water well records (n=3473) containing lithology data (Figure 14) were queried using Microsoft Access. The queried water well lithologs contained 1035 unique lithology descriptors (composed of a combination of descriptions and comments). Lithology descriptors were manually grouped into eight different ‘lithology groups’ (Appendix 2, Table 2) using a colour-coding scheme in order to streamline stratigraphic correlation of units and simplify visualization of lithology information. Lithology groups include bedrock, gravel, sand, silt, clay, till, diamict, and organics. The diamict lithology group includes lithology descriptors with a range of grain sizes such as ‘boulders and clay’ (Appendix 2, Table 2). Despite the uncertainty in the genetic interpretation of diamicts (e.g., Eyles et al., 1983), till was classified as a group separate from diamict in this report (Appendix 2, Table 2) because it was not possible to re-examine, and subsequently re-interpret, the sediments contained in the intervals labeled with the genetic term till; however, during the correlation of units between holes, water well intervals containing till descriptors were subsequently re-interpreted, in places, based on the suite of lithology descriptors above and below the till intervals and the conceptual geological framework (Figure 11).

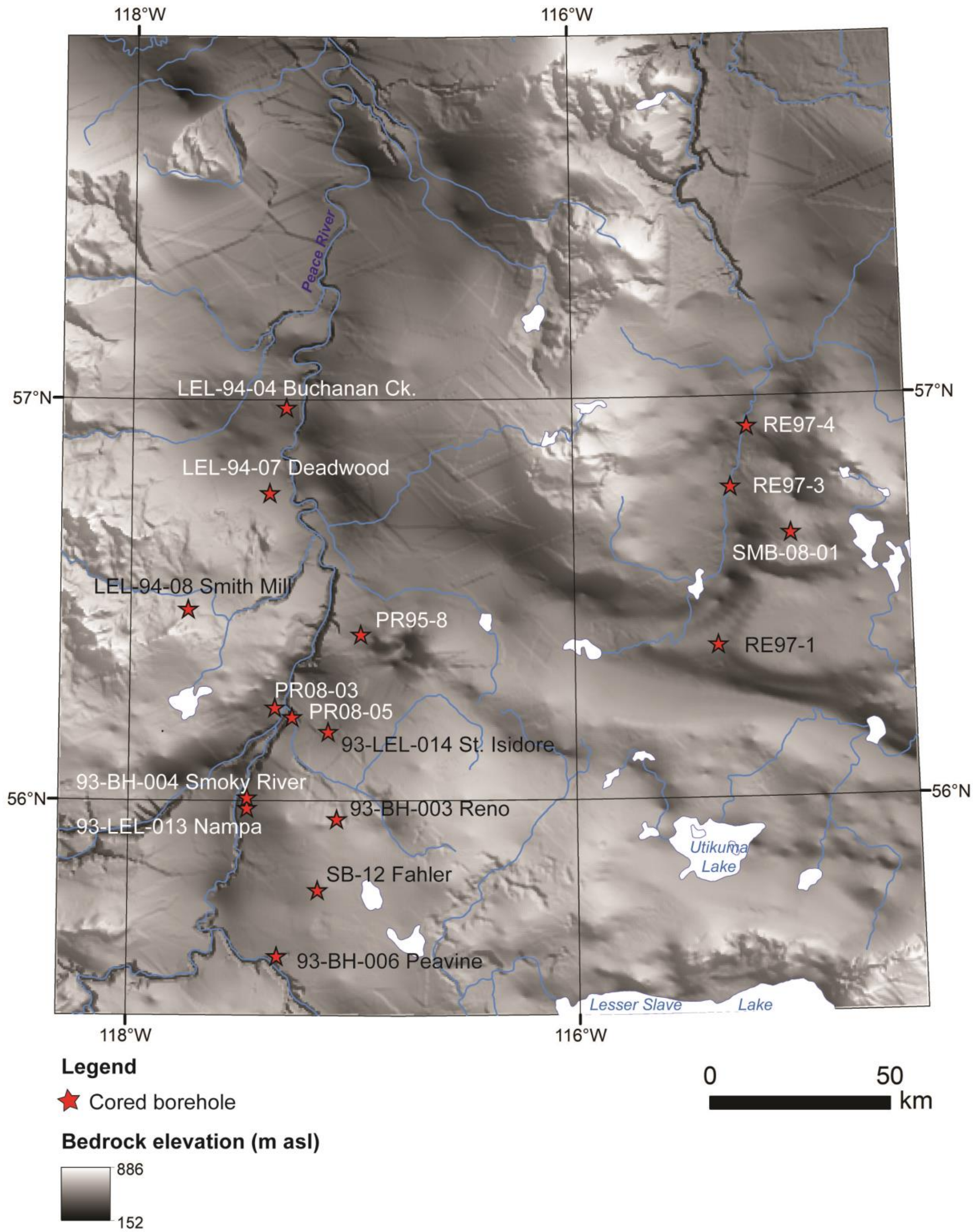

Figure 12. Cored borehole locations (from Pawlowicz and Fenton, 1998; Leslie and Fenton, 2001; Morgan et al., 2009) in the study area (northwestern Alberta) overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

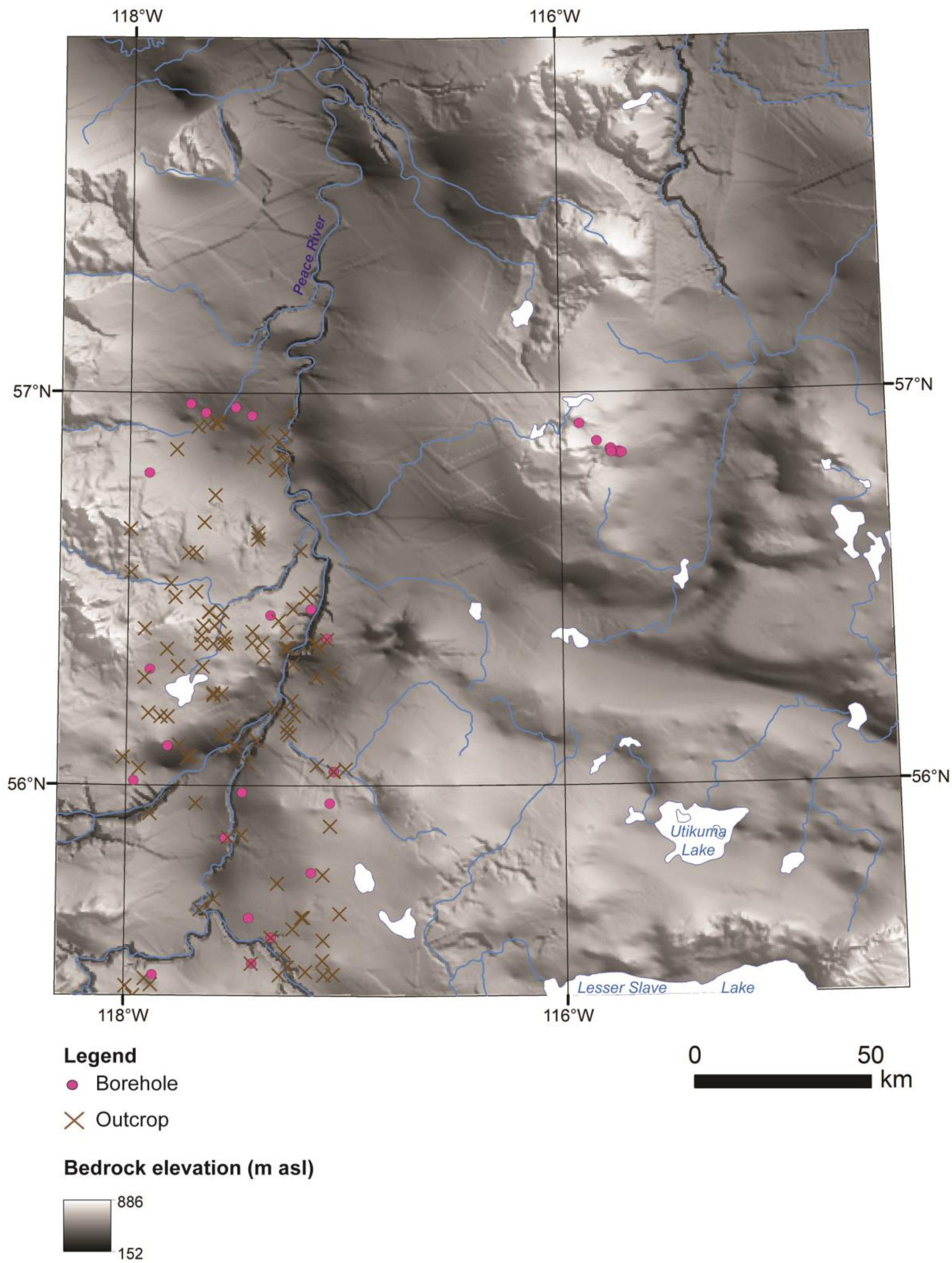

Figure 13. Locations of outcrop sections and boreholes with lithologs (from Balzer, 2000; Leslie and Fenton, 2001; Pawlowicz et al., 2005; Botterill, 2007) in the study area (northwestern Alberta), overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

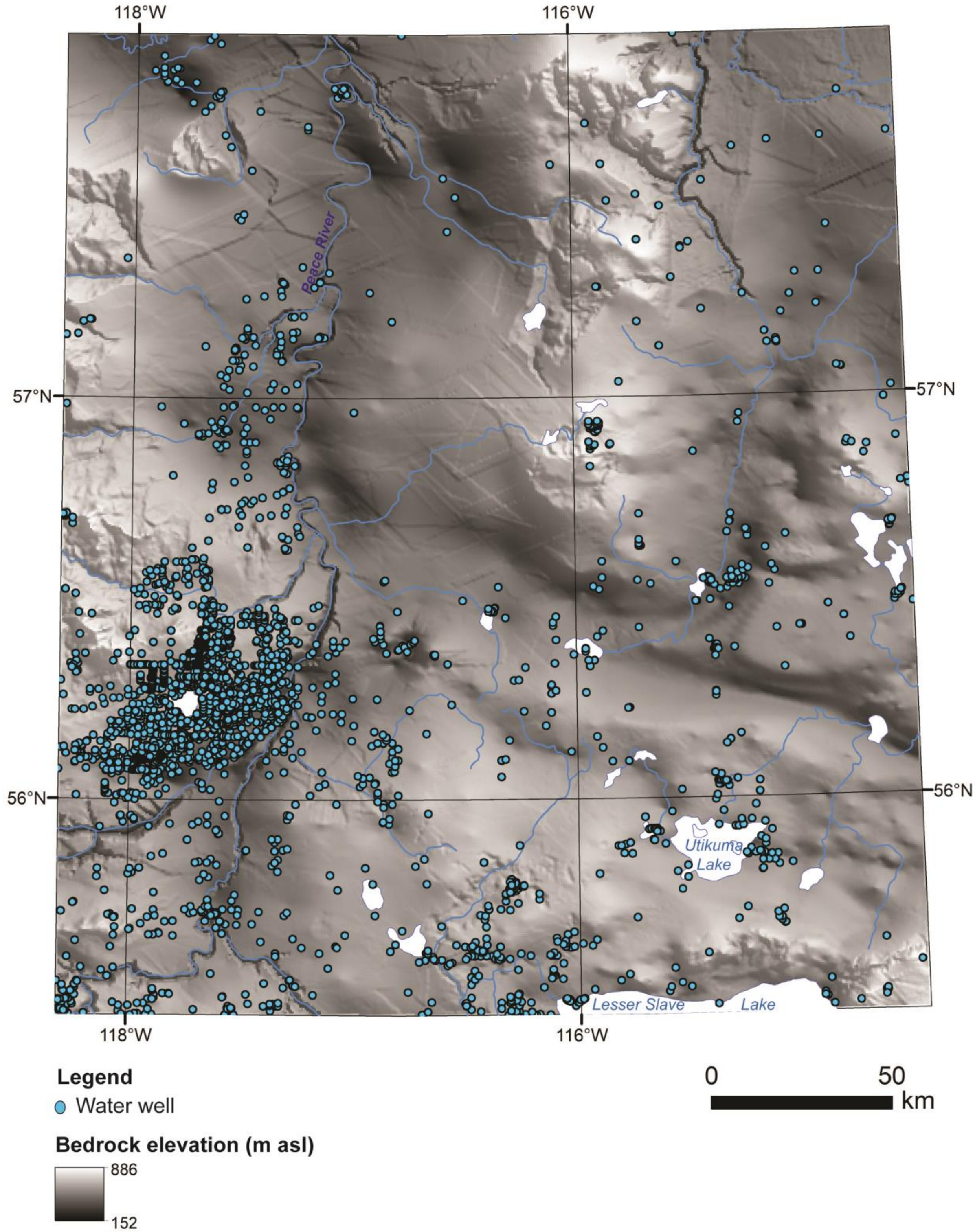

Figure 14. Locations of water wells with lithology data in the study area, northwestern Alberta (Alberta Environment and Sustainable Resource Development, 2014), overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

Water well data were filtered for duplicate well records, including well identification numbers and locations; however, water well records with unique well IDs and non-unique location coordinates were manually compared to the driller's report (Alberta Environment and Parks, 2016) and satellite imagery in order to provide insight to the cause of the duplicate location coordinates. Well records that represent virtually the same point on Earth may have been recorded from deepened wells and boreholes drilled a small distance apart (<10 m), possibly as a result of collapse of the hole, plugging of the hole by malfunctioning drill parts, unanticipated and unfavourable drilling conditions (e.g., a boulder), multilevel monitoring well installations (e.g., upper, middle, and lower wells), and redrilling of an old or abandoned well (G. Jean, pers. comm., 2014). In some cases, well records contain spatial coordinates based on the Alberta Township Survey system, which is a grid system approx. 400 by 400 m at the smallest scale (Legal Subdivisions, LSD; Alberta Environment and Parks, 2016). As a result, multiple wells within a LSD are commonly assigned spatial coordinates of the LSD centre point in the absence of accurate spatial reference data (Alberta Environment and Parks, 2016). Well records with duplicate spatial coordinates as a result of any of the reasons described above remained in the database and lithology data were treated as a single record containing a suite of lithological information for a single location.

Elevation data for the top of the well were provided in a small number of well records; therefore, elevation data were assigned to the top of each well (at zero depth) by extracting Z-values from a digital elevation model (DEM; resampled to 12 m cell size; Alberta Environment and Parks, 2015). An assumption was made that depths recorded under the column 'depth from ground level' in water well driller reports (Alberta Environment and Parks, 2016) indicate the base of the lithology interval. Depths recorded in feet in the water well database were converted to metres.

3.3 Unit Correlation

Units 1–6 (Figure 11) were first characterized in core logs, which were then used to inform identification of units in previously recorded outcrop section and borehole logs (Balzer, 2000; Leslie and Fenton, 2001; Botterill, 2007), followed by correlation of units in water well lithologs. Unit correlation was manually conducted in RockWorks17™ (RockWare®). Data from cored boreholes, outcrop and borehole logs, and water well records were plotted on cross-section in RockWorks17™ and units 1–6 (Figure 11) were correlated between subsurface data points. In an iterative process, unit correlations were revisited in places of apparent inconsistency or outliers, and revised where necessary.

3.3.1 Water Well Lithology Data

Units 1–6 were correlated in water well lithology logs by analyzing the complete succession of lithology descriptors and comments (predominantly grain size) and colour-coded lithology groups (Appendix 2, Table 2). Analysis of the vertical succession of water well descriptors, comments, and lithology groups allowed the grouping of similar descriptors into units based on the assumption that similar grain sizes (e.g., clay, silt, fine-grained sand) are deposited in a similar depositional environment and, hence, compose a stratigraphic unit (Appendix 2, Table 3).

Water well descriptors and comments were honoured where possible in order to minimize the degree of interpretation during unit correlation; however, intervals containing genetic interpretations such as 'till' were re-interpreted in places based on expert geological knowledge of facies associations and analysis of surrounding boreholes.

The first (i.e., uppermost) record of a lithified rock descriptor (e.g., shale, sandstone) was assigned as the top of bedrock; however, in places where the bedrock descriptor interval was relatively thin (approx. <1 m) and bounded above and below by similar unlithified lithology descriptors (e.g., gravel), the bedrock descriptor interval was interpreted as a bedrock raft or boulder and lumped into the surrounding material.

In places, units were correlated on cross-section only if the log contained a distinct succession of sediments. For example, U1and U2 were identified in wells where U3 was delineated; rarely, U1 and U2 were assigned to lithology intervals adjacent to a well containing U3 at a higher elevation. In wells where U3 was absent, fine- and coarse-grained lithology intervals were commonly delineated as U4 and U5, respectively (Figure 11).

4 Cenozoic Stratigraphy

The Cenozoic stratigraphy in the Peace River study area consists of six informal units (U1–6; Figure 11), based primarily on facies associations characterized from core. Units in this report include (from oldest to youngest) fluvial and glaciofluvial sediments (U1), ice-advance lacustrine to glaciolacustrine sediments (U2), subglacial, ice-marginal, and glaciolacustrine sediments (U3), ice-retreat glaciolacustrine sediments (U4), outwash and recent alluvial sediments (U5), and organic and anthropogenic materials (U6), and are described below.

4.1 Unit 1 (U1): Fluvial and Glaciofluvial Sediments

Unit 1 (U1) is present on uplands (e.g., Clear Hills and Buffalo Head Hills), on bedrock straths above bedrock valleys (e.g., Grimshaw gravels on the Cardinal Lake Plain), and at the base of bedrock valleys (e.g., Shaftesbury bedrock valley; Figures 2, 4, 11, and 15). Unit 1 is subdivided into three subunits (U1a–c) based on Edwards and Scafe (1996; Figure 7).

4.1.1 Unit 1 Subunit a (U1a): Upland Sand and Gravel

4.1.1.1 Description

The oldest sediments of U1, subunit a (U1a; Figures 11 and 16), are located on uplands, including the Whitemud, Clear, Hawk, and Buffalo Head hills (Figure 2), and Pelican Mountain. Sediments of U1a are <1 to 15 m thick and composed of sand and interbedded sand and gravel that rest on bedrock. Sand of U1a was described as sand (water well Groundwater Information Centre [GIC] ID 421743) and fine-grained sand and gravel (water well GIC ID 425747) in places. Green and Mellon (1962) described gravel exposed on the southern part of the Clear Hills as well-rounded quartzite, chert, and chert conglomerate pebbles to boulders (up to 15 cm in diameter). On Buffalo Head Hills (Figures 2 and 17), U1a is correlated in a cluster of water wells, all of which contain U1a sand and gravel deposits that are ~5–15 m thick. On Whitemud, Clear, and Hawk hills, U1a consists primarily of fine-grained sand and gravel. Unit 1a appears to thin on topographically high points on the bedrock surface (e.g., water wells GIC IDs 490836, and 493795; Figure 17) and thicken on the flanks of bedrock highs (e.g., water well GIC IDs 493805, and 493812; Figure 17); however, the geometry of U1a is poorly constrained as a result of low data density (Figure 16).

4.1.1.2 Interpretation

Sediments of U1a were likely deposited in a fluvial depositional environment based on the coarse-grained texture of the lithology descriptors in wells (Figure 17). Based on the model proposed by Edwards and Scafe (1996), sediments of U1a may have been deposited in a large braided river system flowing eastwards from the Rocky Mountains in the Middle–Late Tertiary (unit 3 of Edwards and Scafe, 1996; Figure 8); however, it is possible that sediments of U1a were deposited in localized glaciofluvial systems, which transported water and sediment in relatively low relief or channelized areas on the bedrock topography during ice advance over bedrock uplands. Alternatively, sediments of U1a may record localized fluvial deposition of locally eroded bedrock material that was transported by meteoric runoff, similar to deposition by present-day streams that drain bedrock uplands.

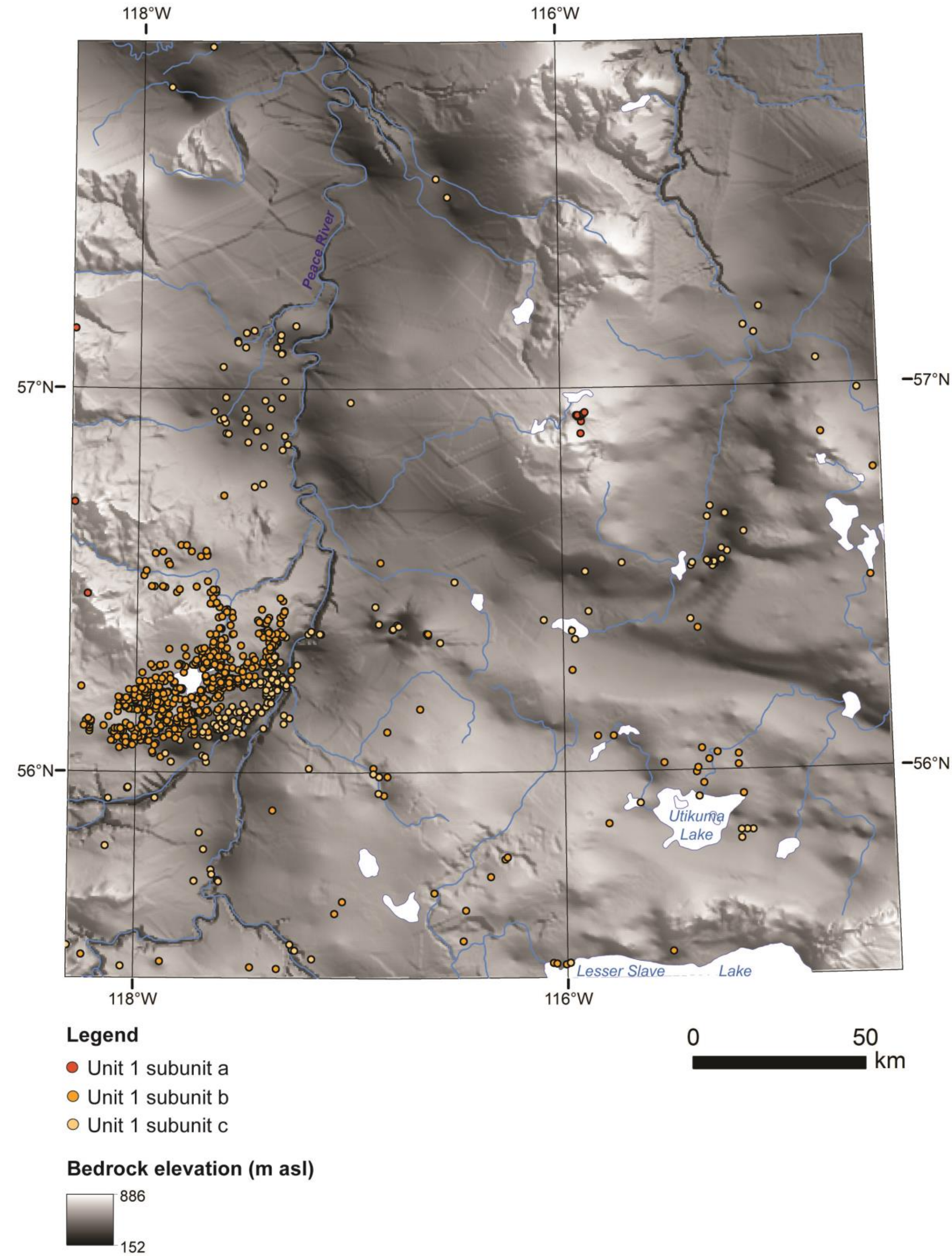

Figure 15. Locations where stratigraphic unit 1 subunits (U1a, b, and c) were identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

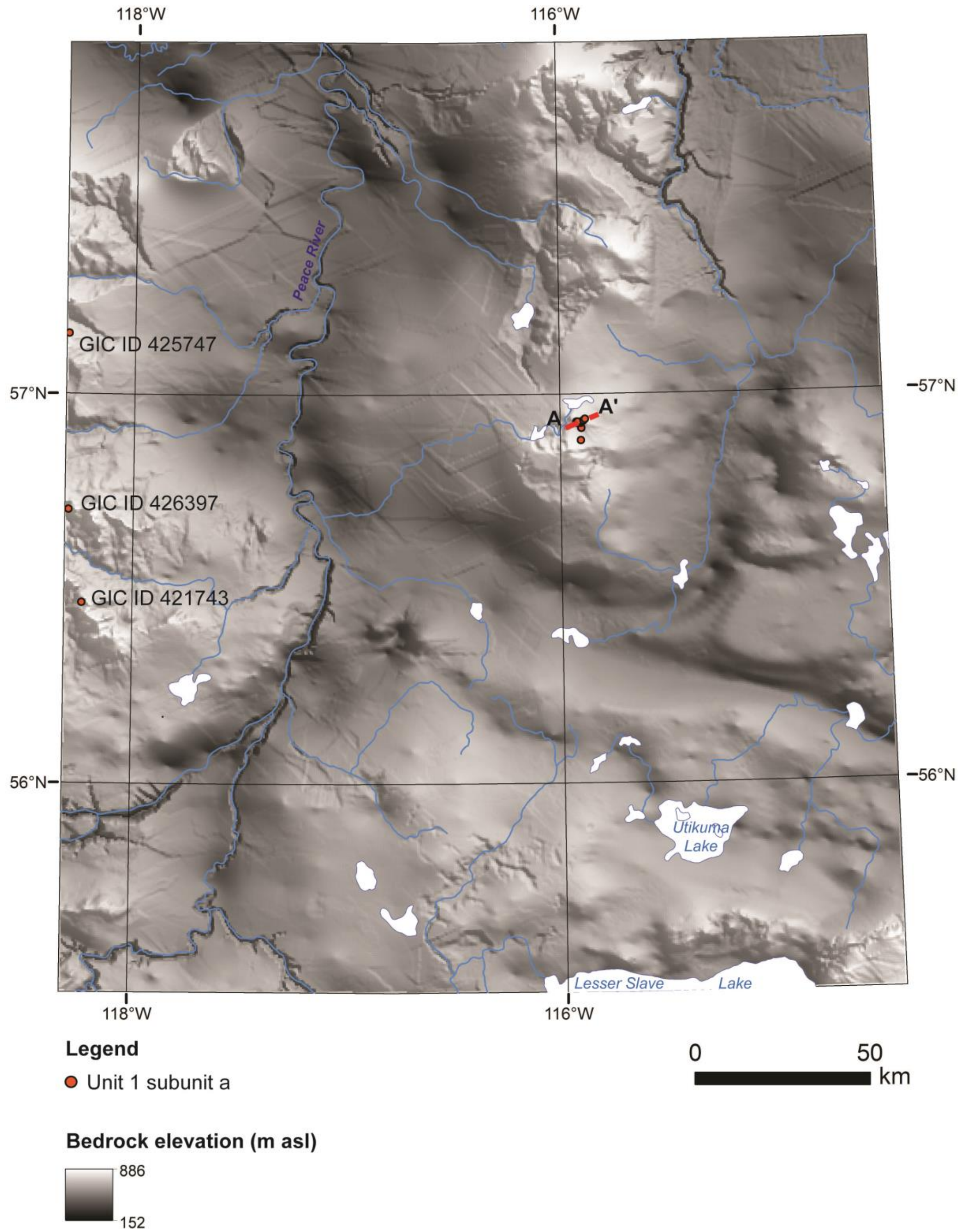

Figure 16. Locations where stratigraphic unit 1 subunit a (U1a) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times). The red line indicates the location of cross-section transect A–A'. Abbreviation: GIC, Groundwater Information Centre.

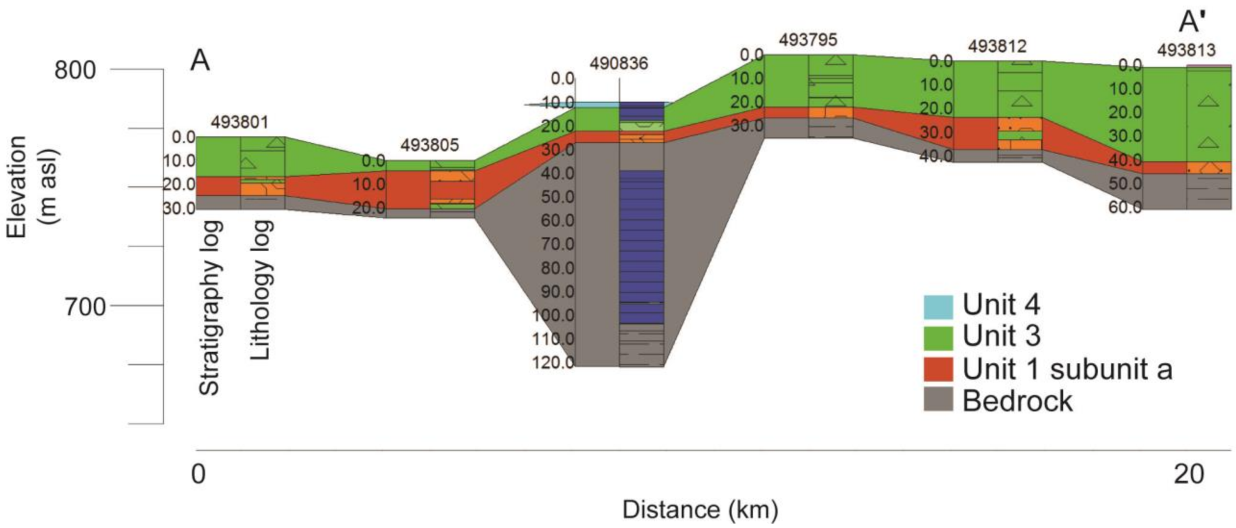

Figure 17. Straight-line correlation of units in water wells on Buffalo Head Hills (A–A'; refer to Figure 16 for the transect location), northwestern Alberta. Depth (in metres) is indicated on the log vertical axis and water well Groundwater Information Centre (GIC) IDs are included above each log (vertical exaggeration is 50 times and logs are equally spaced along the transect). Refer to Appendix 2, Figure 37 for water well log lithology descriptions.

4.1.2 Unit 1 Subunit b (U1b): Terrace Sand and Gravel

4.1.2.1 Description

Unit 1 subunit b (U1b; Figure 18) is present on terraces of bedrock valleys, including the Cardinal Lake Plain district (B–B' and C–C'; Figures 4, 18, 19, and 20), Utikuma Uplands section (D–D'; Figures 4, 18, and 21), and very rarely on the Peerless Lake Upland district (Figures 4 and 18). Sediments of U1b are recorded in 17 outcrop sections and two borehole logs (Leslie and Fenton, 2001). Unit 1 subunit b is <1 to ~60 m thick and composed of massive fine- to medium-grained sand, horizontally stratified medium- to coarse-grained sand, and trough and planar cross-bedded, fine- to medium-grained sand and gravel. Gravel deposits in U1b are clast-supported with subrounded to well-rounded granules to boulders (with a medium- to coarse-grained sand matrix in place). Gravel clasts are composed primarily of quartzite, quartz, chert (commonly black), sandstone (commonly red), conglomerate, chalcedony, argillite, white and pink granite, schist, and metasedimentary and mafic lithologies (including basalt). Lithologies typical of the Canadian Shield were not observed (Tokarsky, 1967; Edwards and Scafe, 1996; Chlachula and Leslie, 1998; Leslie and Fenton, 2001). In outcrop section, gravel deposits of U1b commonly contain an orange discolouration along bedding planes as a result of iron and manganese oxidation, and sand deposits commonly contain gypsum mineral crystals, and muscovite and potassium feldspar mineral flakes (Leslie and Fenton, 2001). Average paleoflow direction measured from crossbeds and gravel clast fabrics in the Grimshaw gravels deposit is towards the northeast, and rarely east-southeast, south, and west (Tokarsky, 1967; Edwards and Scafe, 1996).

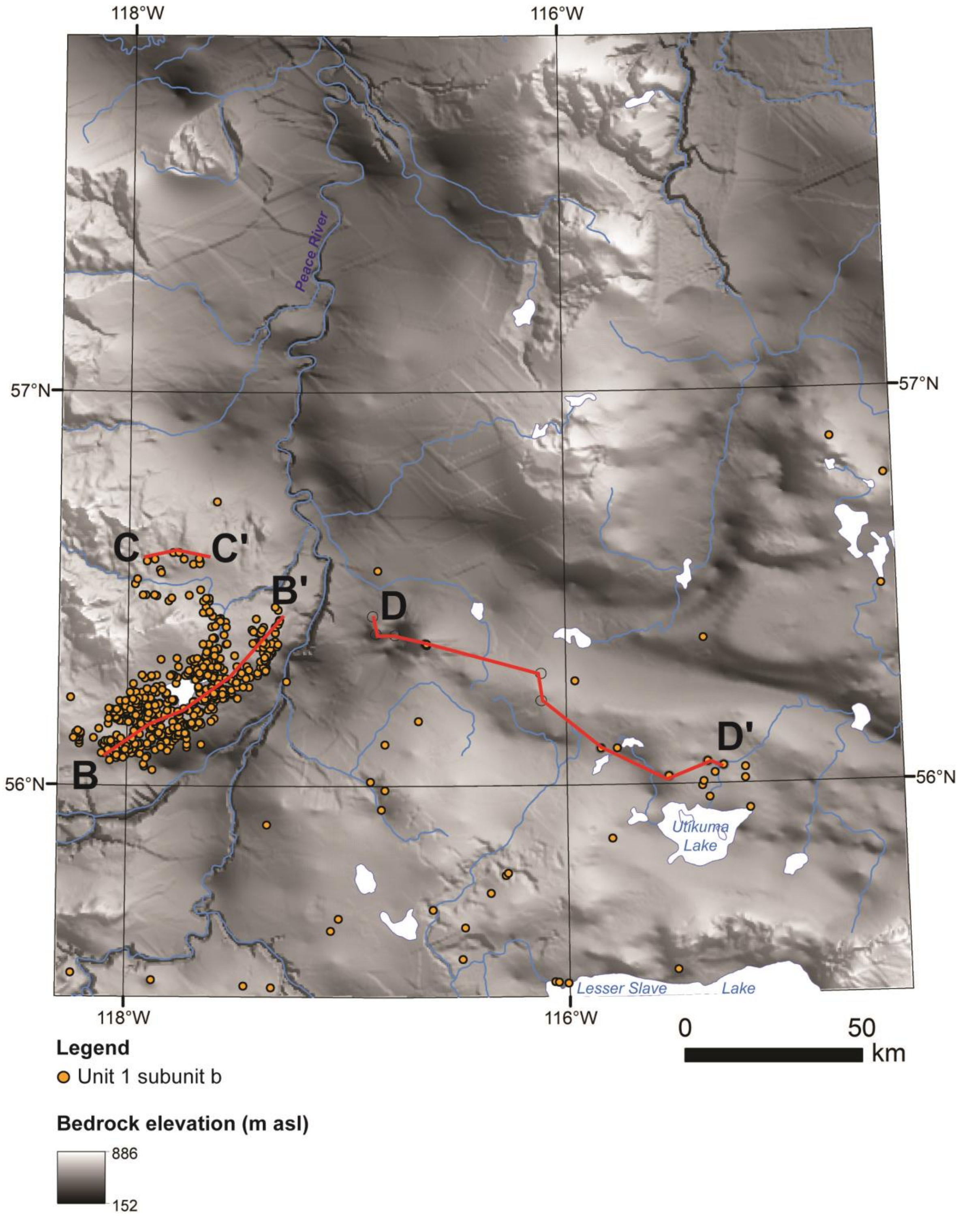

Figure 18. Locations where stratigraphic unit 1 subunit b (U1b) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times). Red lines indicate the locations of cross-section transects B–B', C–C', and D–D' (open circles on D–D' indicate wells on the transect that do not contain U1b).

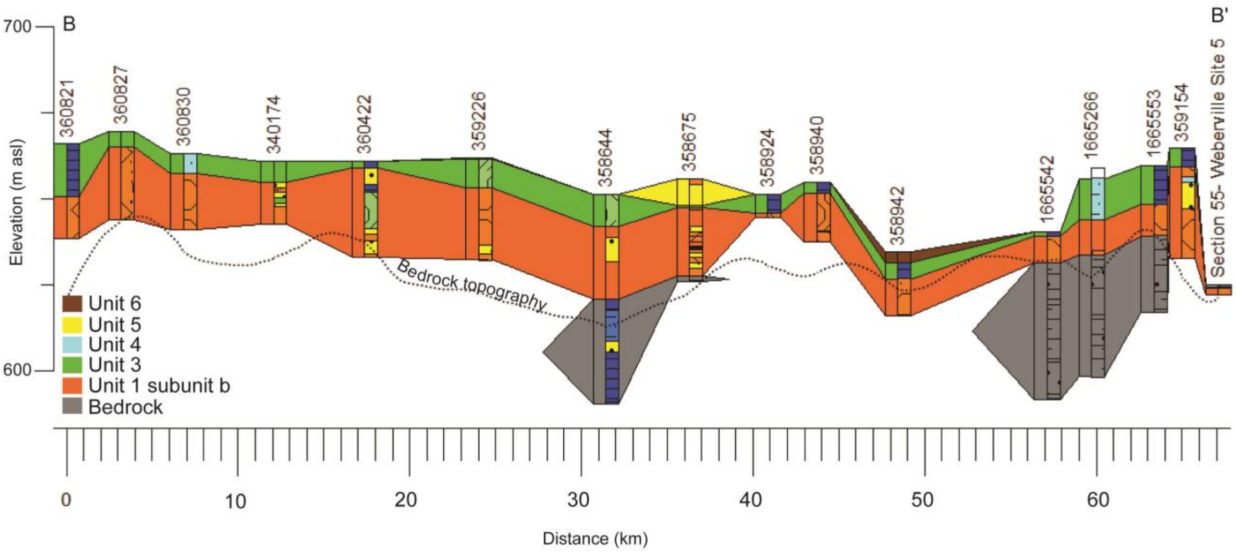

Figure 19. Straight-line correlation of units in the Cardinal Lake Plain (B–B'; refer to Figure 18 for the transect location; northwestern Alberta) delineated in water well and outcrop section logs (vertical exaggeration is 200 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs and outcrop labels are included above each log). Refer to Appendix 2, Figure 39 for water well log/outcrop section lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

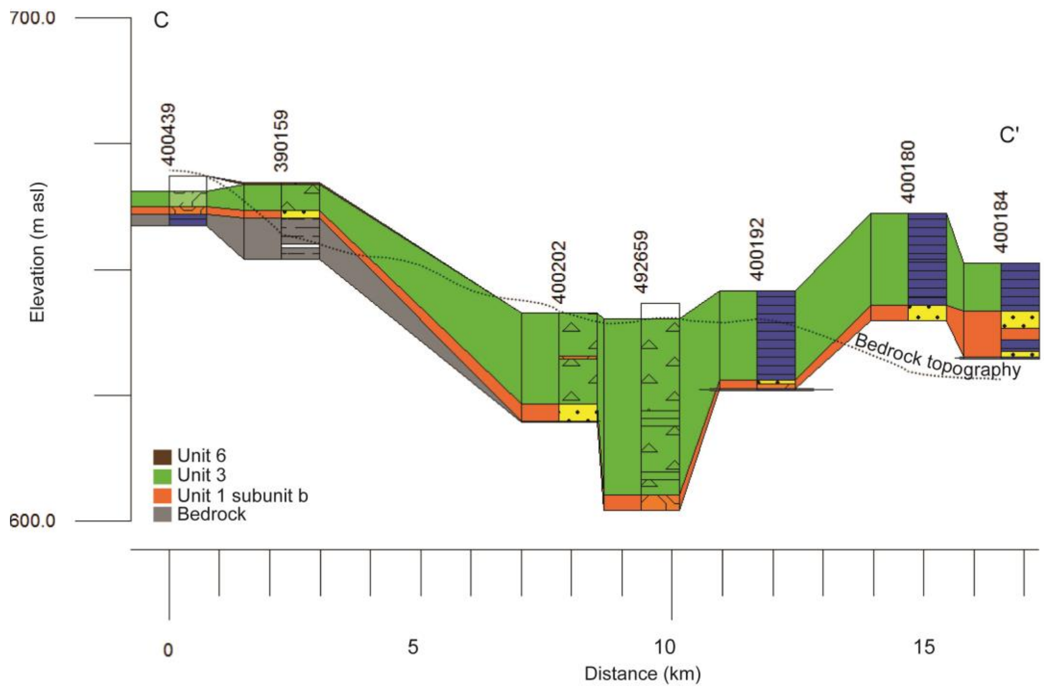

Figure 20. Straight-line correlation of units on the margin of the Whitemud Hills (C–C'; refer to Figure 18 for the transect location; northwestern Alberta) delineated in water well logs (vertical exaggeration is 100 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs are included above each log). Refer to Appendix 2, Figure 40 for water well log lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

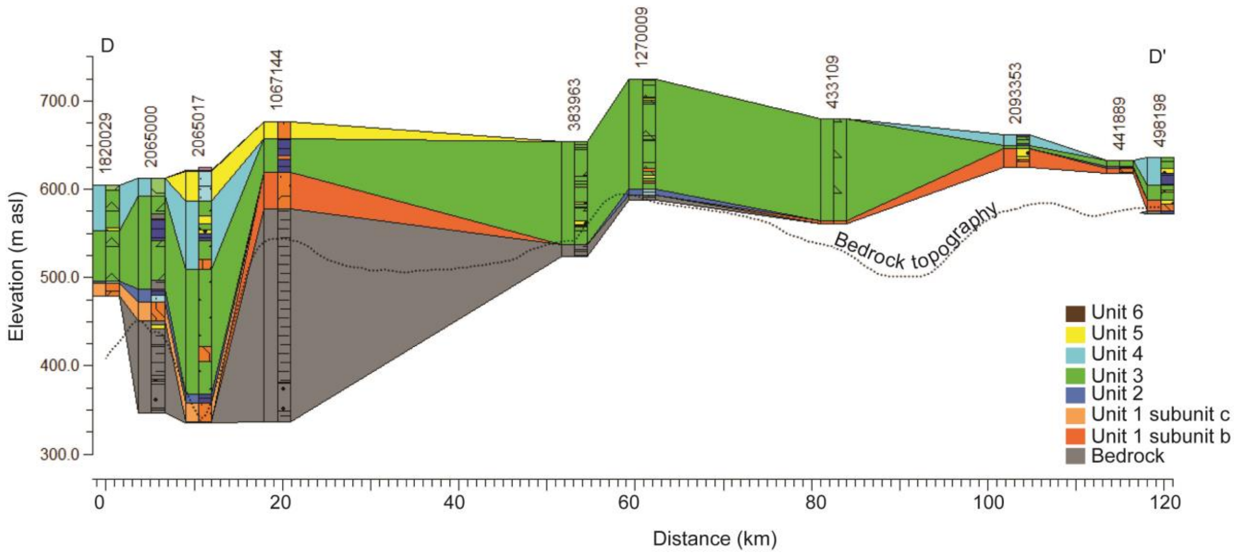

Figure 21. Straight-line correlation section of units on the Utikuma Uplands (D–D', refer to Figure 18 for the transect location; northwestern Alberta) delineated in water well logs (vertical exaggeration is 100 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs are included above each log). Refer to Appendix 2, Figure 41 for water well log lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

The highest data density of U1b picks is located on the Cardinal Lake Plain district (B–B'; Figure 18), where sand and gravel of U1b are locally referred to as the Grimshaw gravels (Tokarsky, 1967, 1971). The Grimshaw gravels host a significant aquifer (the Grimshaw gravels aquifer), which supplies potable water to surrounding communities (PFRA, 1998). The Grimshaw gravels are also an important source of aggregate (Mackenzie Municipal Services Agency, 2010). In the Cardinal Lake Plain (B–B'; Figure 18), U1b forms a tabular unit that appears to thin towards the northeast (Figure 19). Edwards and Scafe (1996) recorded 64–80% gravel (maximum gravel clast size of 30 cm) and 20–36% sand in the Grimshaw gravels deposit on the Cardinal Lake Plain. North of the Grimshaw gravels deposit (B–B'), also in the Cardinal Lake Plain (C–C'; Figure 18), sediments of U1b are relatively thin and consist of primarily sand, and rare gravel and clay (Figure 20). On the Utikuma Uplands (D–D'; Figure 18), sediments of U1b form a sheet with irregular thickness (from 0 to 50 m; Figure 21). Sediments of U1b, on the Utikuma Uplands, consist of fine- to coarse-grained sand and gravel, including boulders in places (Appendix 2, Figure 41).

4.1.2.2 Interpretation

Sediments of U1b record fluvial deposition of sand, gravel, and rare fine-grained sediment (Tokarsky, 1967; Edwards and Scafe, 1996). In the Cardinal Lake Plain area, Tokarsky (1967, 1971) interpreted the sand and gravel to have been deposited in a fluvial system that transported sediment towards the northeast. Edwards and Scafe (1996) suggested that sand and gravel (their unit 2; Figure 8) was deposited in a large braidplain with a river system that incised older fluvial sediments (U1a), and transported sediment eastwards from the Rocky Mountains during the Early to Middle Pleistocene (Figure 8). A glacial origin of sediments of U1b (i.e., glaciofluvial) is uncertain based on the data in this study; however, Scheelar and Odynsky (1968) mapped the parent material of the soil in the Cardinal Lake Plain area as glaciofluvial sediments.

4.1.3 Unit 1 Subunit c (U1c): Bedrock Valley Sand and Gravel

4.1.3.1 Description

Unit 1 subunit c (U1c; Figure 22) is <1 to 92 m thick (Figures 23, 24, 25, and 26) and present at the base of bedrock valleys, including the High Prairie, Shaftesbury, Manning, Notikewin, l'Hirondelle, Muskwa, Red Earth, and Gods bedrock valleys (Figures 2 and 22). Unit 1 subunit c is also rarely identified in the Utikuma and Lesser Slave lakes areas (Figure 22). Sediments of U1c are composed of a crude fining-upwards succession of poorly sorted, massive and planar cross-bedded gravel at the base to ripple crosslaminated, horizontally bedded and laminated, planar and trough cross-bedded, fine- to coarse-grained sand (with rare silt and clay interbeds and angular intraclasts) at the top (Leslie and Fenton, 2001; Botterill, 2007).

Gravel deposits are primarily matrix-supported, with matrix material composed of sand to pebbles (Leslie and Fenton, 2001; Botterill, 2007); however, gravel deposits are clast-supported in places where gravel clast content increases upwards in the unit (Botterill, 2007). Gravel clasts are subangular to well-rounded (granule to boulder up to ~30 cm in diameter) and composed of Canadian Shield–derived and local lithologies, including quartzite (purple with chattermarks in places; Botterill, 2007), quartz, chert (black and white), ironstone, mudstone, sandstone, siltstone, shale, coal, pink and red granite, gneiss (granitic and dioritic), and fine-grained mafic rocks (Leslie and Fenton, 2001). The frequency of Canadian Shield–derived lithologies (granite and gneiss) increases upwards in U1c in places (Leslie and Fenton, 2001; Botterill, 2007). Individual planar crossbeds of gravel contain crude normal grading, from medium-grained pebble at the base to fine-grained pebble at the top of the bed (Leslie and Fenton, 2001). Gravel deposits contain rare interbeds (2 to ~50 cm thick) of horizontally laminated and ripple crosslaminated clayey silt and very fine to medium-grained sand, which are commonly oxidized (Leslie and Fenton, 2001). Rarely, medium- to coarse-grained sand forms dipping beds (~0.5–2 m thick), which contain interbeds of diamict, gravel, and silty clay (e.g., Buchanan Creek area; Leslie and Fenton, 2001).

Sediments of U1c are incised by modern drainage systems such as the Peace River (e.g., in the Shaftesbury bedrock valley; E–E'; Figures 2, 22, and 23). In the southern part of the study area, within the High Prairie bedrock valley (F–F'; Figures 2, 22, and 24), U1c forms a tabular unit composed of gravel at the base and sand and gravel at the top of the unit. Conversely, in the northern part of the study area, within the Notikewin and Red Earth bedrock valleys (G–G' and H–H'; Figures 2, 25, and 26), U1c appears finer grained, composed predominantly of sand, with more variability in its texture based on water well data (Appendix 2, Figures 43 and 44). Unit 1 subunit c is also present in the l'Hirondelle and Manning bedrock valleys (I–I' and J–J'; Figures 27, 28, and 29).

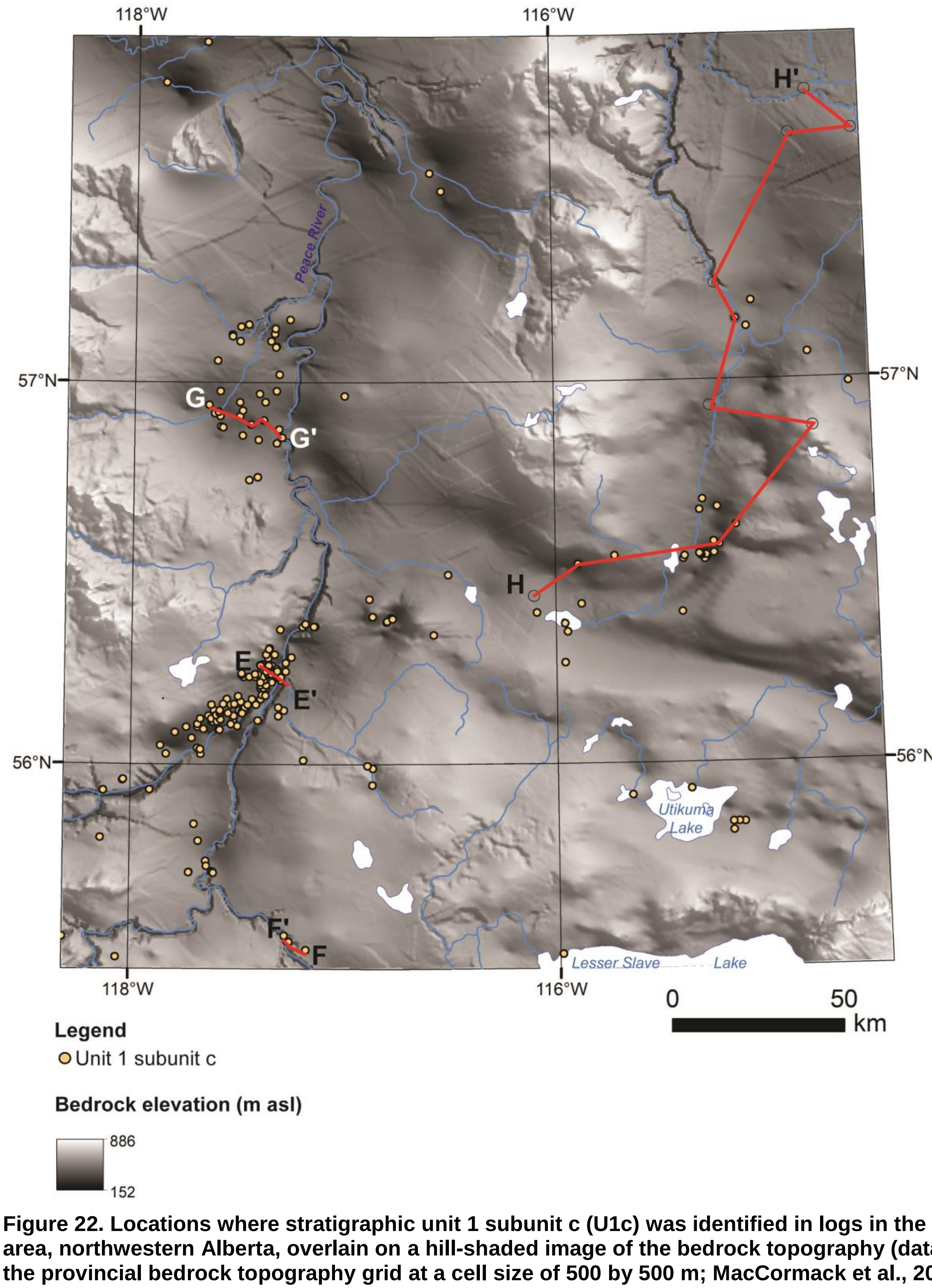

Figure 22. Locations where stratigraphic unit 1 subunit c (U1c) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times). Red lines indicate the locations of cross-section transects E–E', F–F', G–G', and H–H' (open circles on H–H' indicate wells on the transect that do not contain U1c).

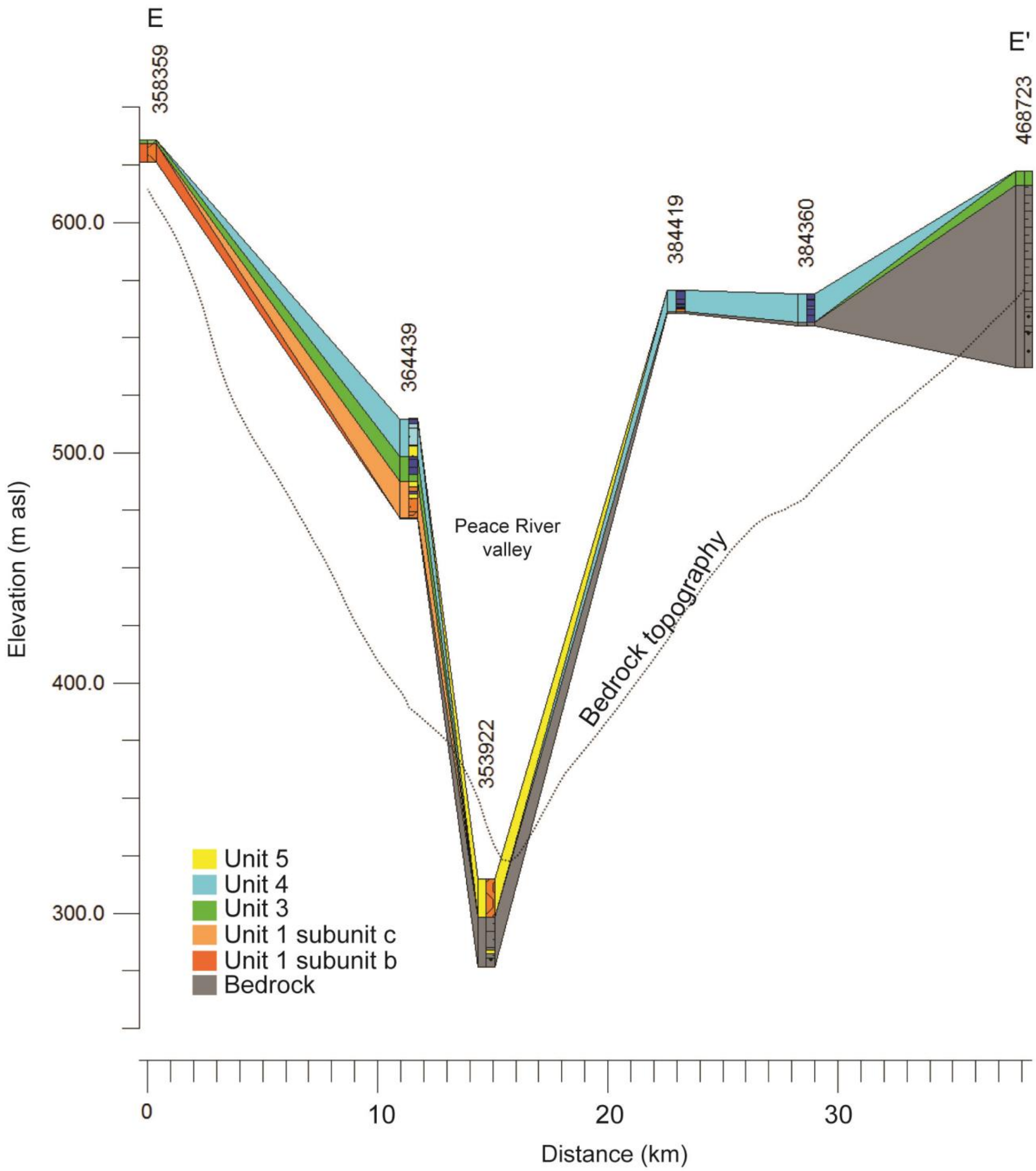

Figure 23. Straight-line correlation of units from the Cardinal Lake Plain across the Shaftesbury bedrock valley (E–E'; refer to Figure 22 for the transect location; northwestern Alberta) delineated in water well logs (vertical exaggeration is 100 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs are included above each log). Refer to Appendix 2, Figure 42 for water well log lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

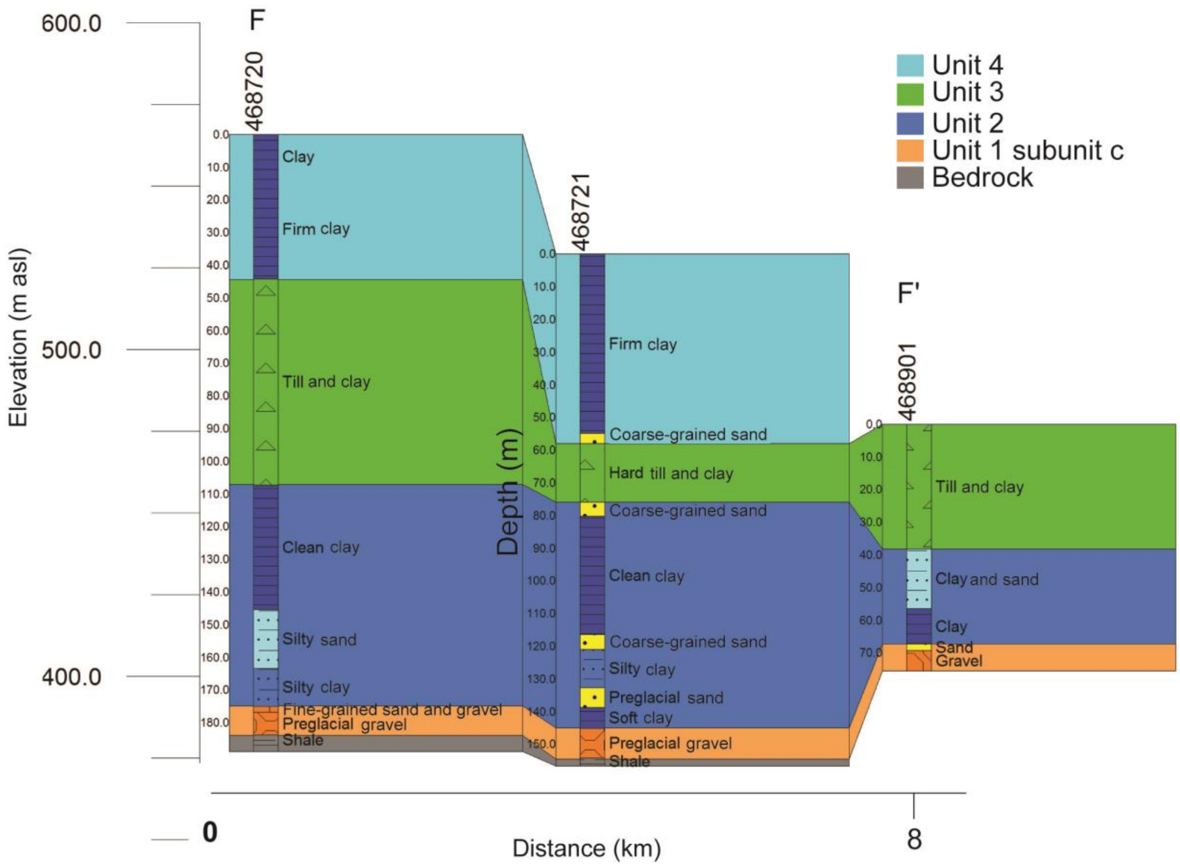

Figure 24. Straight-line correlation of units in the High Prairie area (F–F'; refer to Figure 22 for the transect location; northwestern Alberta) in water well logs (vertical exaggeration is 50 times; logs are equally spaced on the transect and water well Groundwater Information Centre [GIC] IDs are included above each log). Water well log lithology descriptions from driller reports are included to the right of each log. Depth (in metres) is included on the log vertical axis.

4.1.3.2 Interpretation

Sediments of U1c record fluvial and glaciofluvial deposition of sand, gravel, and rare fine-grained sediment. The presence of gravel composed of Canadian Shield lithologies positioned 15 m above the base of the Shaftesbury bedrock valley (Botterill, 2007) in the Town of Peace River area suggests that U1c records, at least in part, deposition of glaciofluvial sediments following retreat of the pre-Late Wisconsinan Laurentide Ice Sheet. An increase in the frequency of Canadian Shield clasts upwards in U1c (Botterill, 2007) may record the evolution in source material (eroded by the glaciofluvial system upstream) from the Cordilleran belt to the Canadian Shield. In the Shaftesbury bedrock valley, Leslie and Fenton (2001) and Botterill (2007) interpreted the sand and gravel to have been deposited in a pre-Laurentide glaciation fluvial system (base of unit) and glaciofluvial outwash system (post-Laurentide glaciation) and ice-marginal environment characterized by debris flows. Rutherford (1930) and Henderson (1959) interpreted sand and gravel at the base of bedrock valleys as glaciofluvial in origin. In the High Prairie area, Jones (1966) noted Precambrian gravel clasts in bedrock valley sand (~190 m deep) and interpreted the sand as ice-marginal outwash sediments. The Cordilleran ice margin would supply a sufficient amount of meltwater and sediment to form U1c; hence, it is likely that U1c records retreat of the Cordilleran Ice Sheet (CIS) towards an area west of the study area (Jones, 1966). The crude northwards fining of U1c (from the High Prairie to Notikewin and Red Earth bedrock valleys; Figures 2, 24, 25, and 26) suggests a decrease in discharge, likely as a result of increased transport distance from the CIS ice margin.

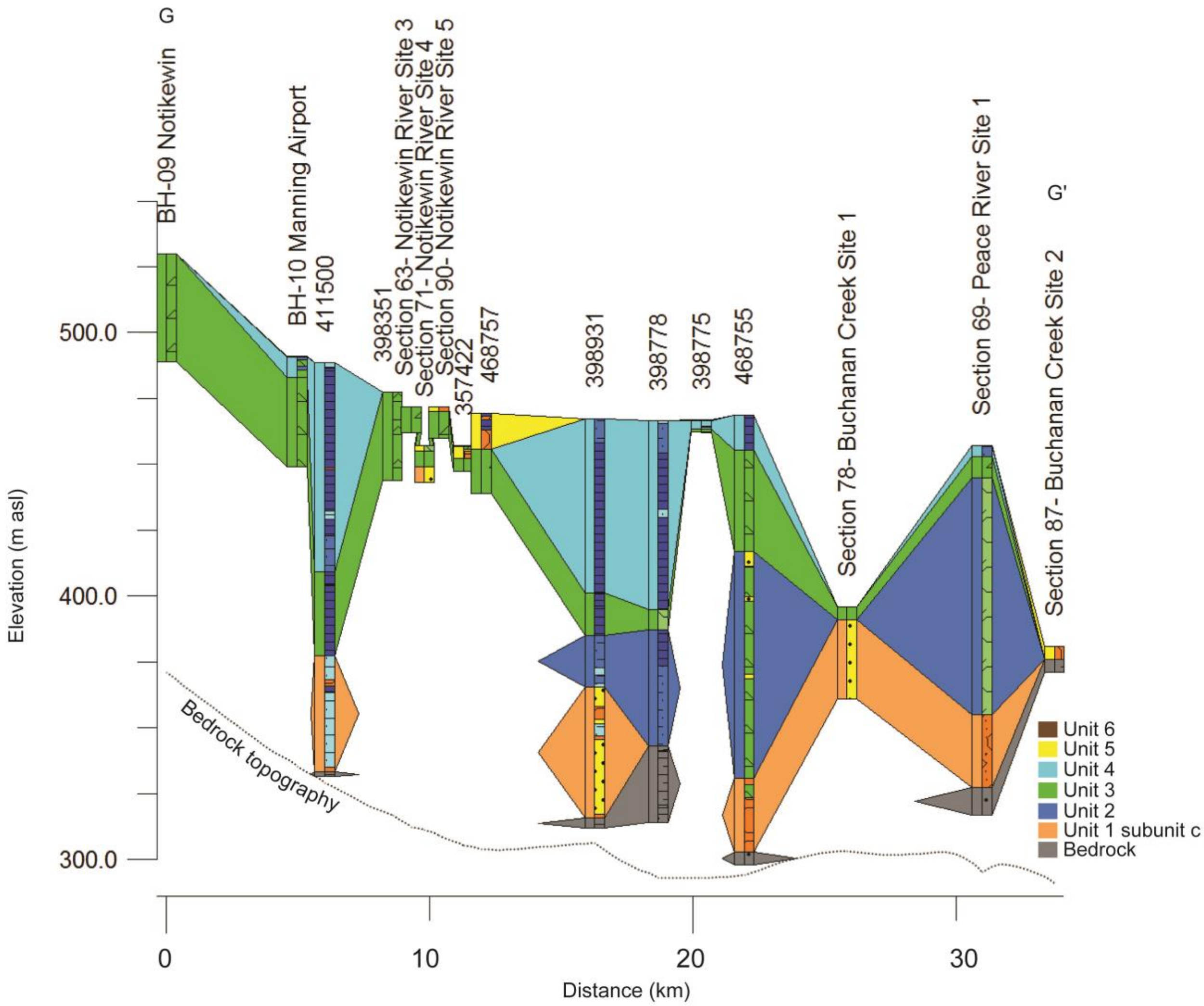

Figure 25. Straight-line correlation of units in the Notikewin bedrock valley (G–G'; refer to Figure 22 for the transect location; northwestern Alberta) delineated in water well logs, and outcrop section and borehole logs (vertical exaggeration is 100 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs or log names are indicated above each log). Refer to Appendix 2, Figure 43 for log/section lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

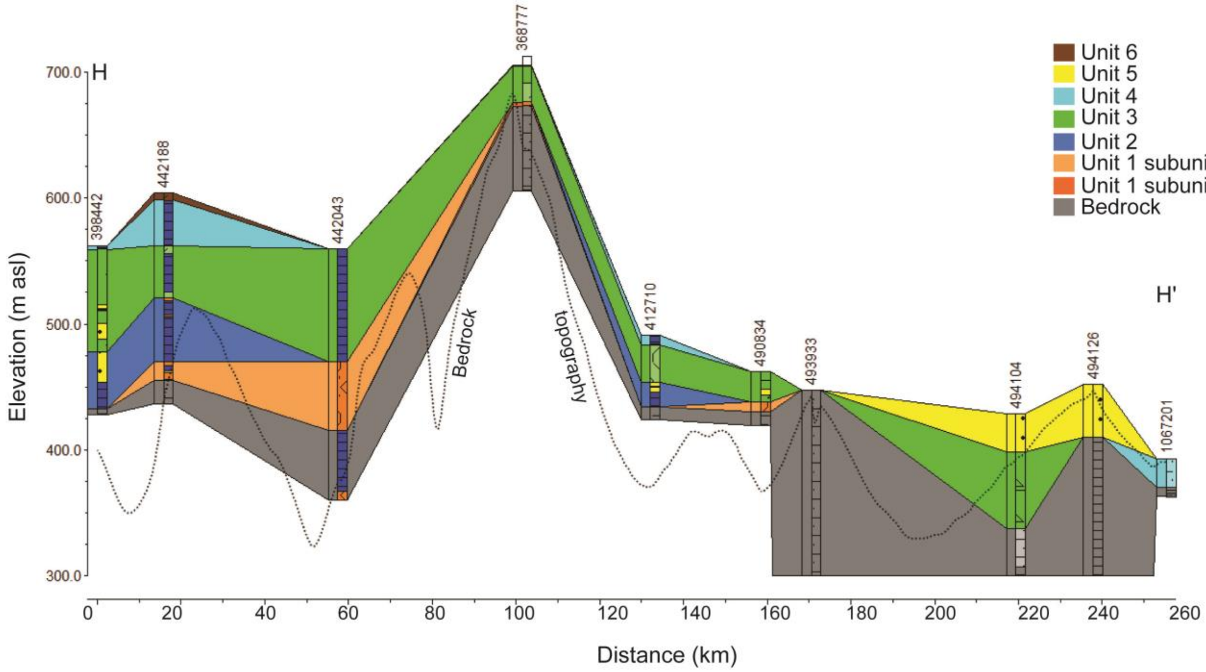

Figure 26. Straight-line correlation of units in the Red Earth bedrock valley (H–H'; refer to Figure 22 for the transect location; northwestern Alberta) in water well lithologs (vertical exaggeration is 300 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs are included above each log). Refer to Appendix 2, Figure 44 for water well log lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

4.2 Unit 2 (U2): Ice-Advance Lacustrine to Glaciolacustrine Sediments

4.2.1 Description

Unit 2 (U2; Figure 27) directly overlies U1, and bedrock in places where U1 is absent, and is present primarily in the Peace River and Wabasca lowlands sections, although it is also identified on the Utikuma Uplands section (Figures 4 and 27). Unit 2 is <1 to ~150 m thick (up to 90 m thick exposed in outcrop; Leslie and Fenton, 2001) and commonly pinches-out where truncated by overlying units or not deposited (Figures 21 and 26).

Unit 2 is composed of fine-grained sediments, including laminated, massive, deformed, and graded (normal and reverse) clay, silt, and sand (Leslie and Fenton, 2001; Slomka and Utting, 2018). Rarely, U2 contains matrix-supported massive, laminated, and stratified clayey silt diamict (and very rarely, clast-supported massive diamict). Diamict and sand in U2 contain granule to pebble clasts of local (shale, mudstone, sandstone, chert, coal) and far-travelled lithologies (K-feldspar–rich granite; Leslie and Fenton, 2001; Slomka and Utting, 2018). Normally graded rhythmites in the uppermost part of U2 contain very rare lithified clasts (≤2 mm in diameter) beneath which mud laminae appear to thin and sag (Slomka and Utting, 2018). Sand (~2–16.5 m thick), silt, and gravel interbeds and lenses are located in the lower and upper-middle section of U2 (Leslie and Fenton, 2001; Slomka and Utting, 2018). Sandy interbeds are composed of massive, deformed, crudely stratified (ripple crosslaminated), horizontally bedded, and graded fine- to very coarse grained sand. Woody material recovered from a sand interbed in U2 (~340 m asl in cored hole PR08-03; Appendix 1, Figure 36) produced a measured AMS radiocarbon date of 30 240 ±160 ^{14}C BP (34 267 ±282.5 cal BP; lab number Beta-412796, sample number PR8-3-S1; Slomka and Utting, 2018).

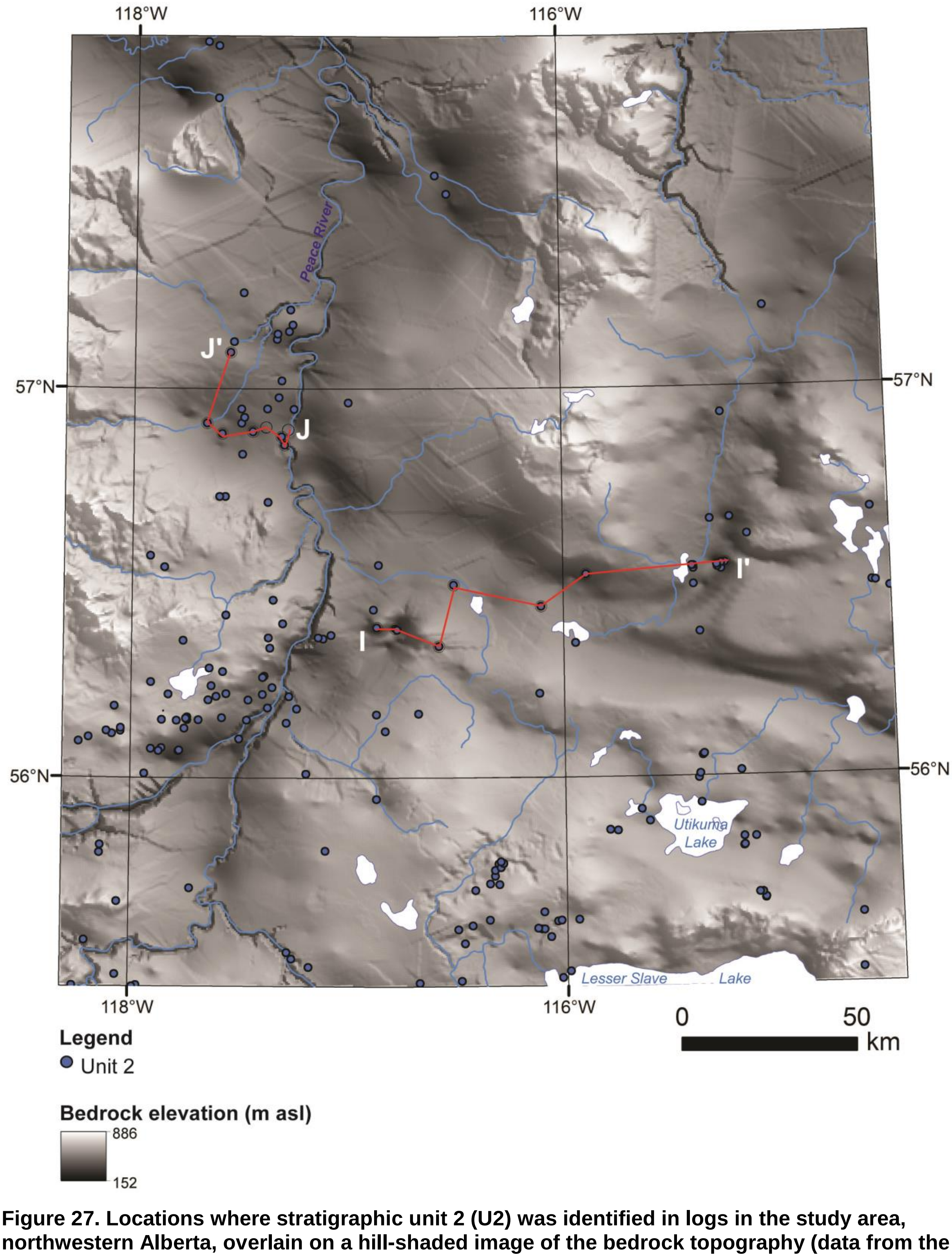

Figure 27. Locations where stratigraphic unit 2 (U2) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times). Red lines indicate the location of cross-section transects I–I' and J–J'.

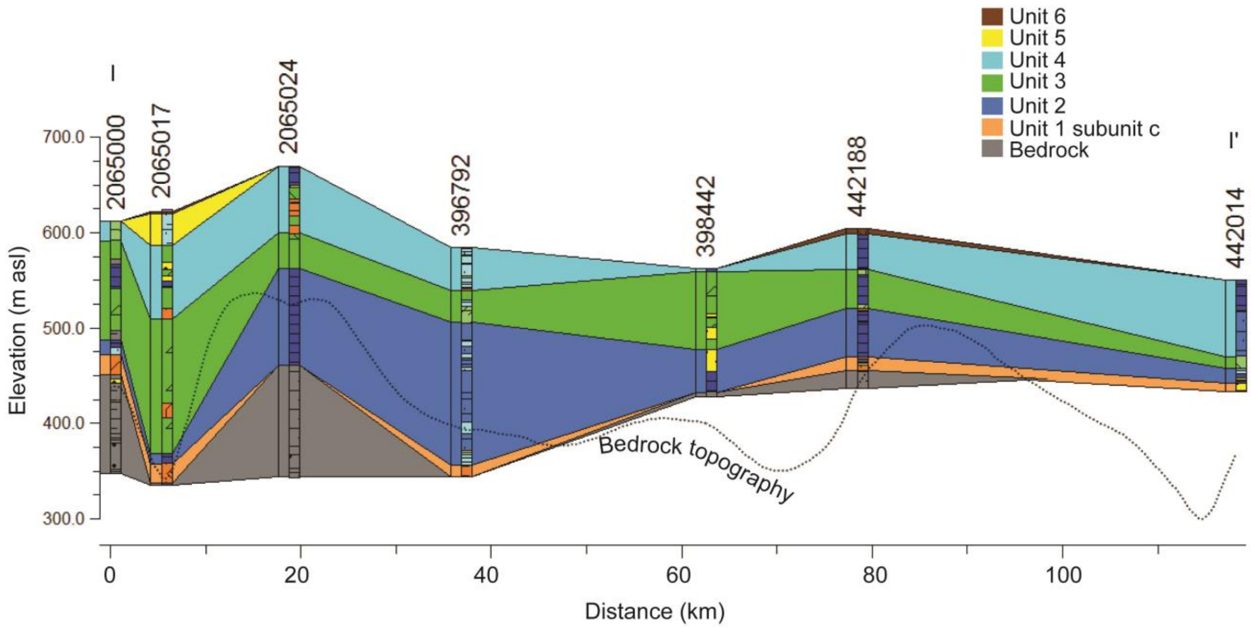

Figure 28. Straight-line correlation of units in the l'Hirondelle bedrock valley (I–I'; refer to Figure 22 for the transect location; northwestern Alberta) in water well lithologs (vertical exaggeration is 100 times; logs are spaced at collar distances and water well Groundwater Information Centre [GIC] IDs are indicated above each log). Refer to Appendix 2, Figure 45 for water well log lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

4.2.2 Interpretation

Sediments of U2 record deposition in a lacustrine to glaciolacustrine depositional environment. Small pebbles in U2 were transported into the lake basin by lake ice or far-travelled icebergs (e.g., Bennet et al., 1996) during ice margin advance into the study area (Slomka and Utting, 2018). Normally graded rhythmites with erosional bases are interpreted to record scour of lake-bottom sediment by bottom currents and subsequent deposition of massive and laminated silt and clay, likely as a result of turbidites generated from debris flows and density currents in the lake basin (e.g., Eyles, 1987; Liverman, 1991). Sandy, silty, and gravelly interbeds in the lower and upper-middle part of U2 are interpreted to record iceberg dump and sediment flows in the lake basin (e.g., Cheel and Rust, 1986; Hornung et al., 2007).

Fine-grained sediments of U2 within bedrock valleys are interpreted to record ponding of water by the advance of the Laurentide Ice Sheet during the Middle to Late Wisconsinan. A Middle Wisconsinan age is supported by a radiocarbon date of ca. 30 000 ^{14}C BP recorded from sediments in the mid-part of U2 in the Shaftesbury bedrock valley (Slomka and Utting, 2018). Hartman and Clague (2008) recorded glaciolacustrine sediments, in a similar stratigraphic position as U2, in the Peace River paleovalley in British Columbia and interpreted these sediments to record deposition in an ice-advance ice-marginal lake named Glacial Lake Mathews; hence, sediments of U2 within bedrock valleys are interpreted to have been deposited in early phases of Glacial Lake Mathews. Fine-grained sediments in the Cleardale area, ~70 km west of the study area, have been correlated to Glacial Lake Mathews (Atkinson and Paulen, 2010).

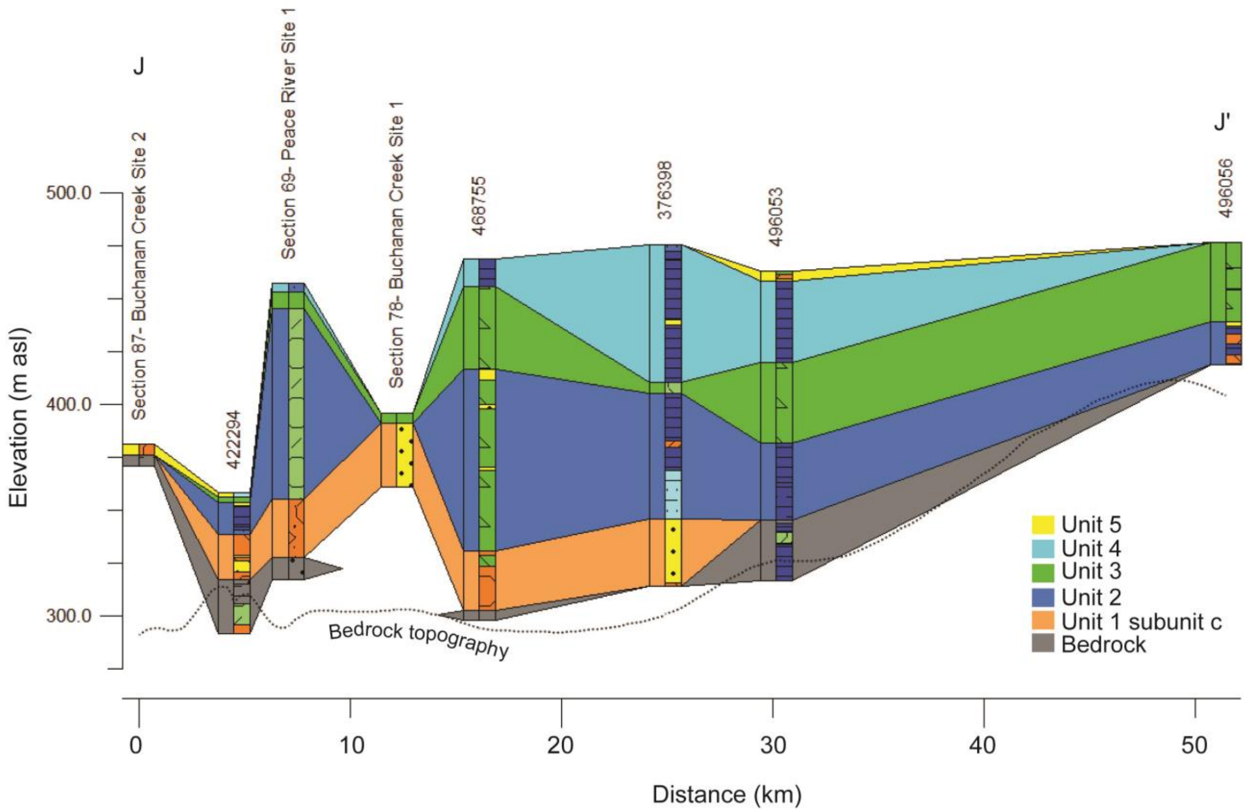

Figure 29. Straight-line correlation in the Manning bedrock valley (J–J'; refer to Figure 22 for the transect location; northwestern Alberta) in outcrop section and water well logs (logs are spaced at collar distances; vertical exaggeration is 100 times and water well Groundwater Information Centre [GIC] IDs and outcrop labels are included above each log). Refer to Appendix 2, Figure 46 for lithology descriptions and vertical depths for each log. The bedrock topography (limitations discussed in Section 4.8) is indicated by the dashed black line (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016).

4.3 Unit 3 (U3): Subglacial, Ice-Marginal, and Glaciolacustrine Sediments

4.3.1 Description

Unit 3 (U3; Figure 30) contains primarily diamict, with rare interbeds of sand and fine-grained sediment. The water well descriptor ‘till’ was commonly correlated to U3 in places (e.g., Figure 24) where it occupied a similar stratigraphic position as that of U3 sediments in cores (see Appendix 1, Figure 36), regardless of the possible inaccuracy of the genetic interpretation in water well reports. Unit 3 is <1 to ~220 m thick and directly overlies U2 (where U2 is not present, it overlies bedrock or U1). Unit 3 is laterally extensive and found on uplands and lowlands in the study area (Figures 4 and 30). On the uplands, U3 is composed of apparently massive clayey and sandy diamict, which is oxidized in places, and contains rare gravelly and sandy interbeds (Figures 17 and 21). In the lowlands, U3 is composed of indurated massive clayey silt diamict, fissile massive sandy silty diamict, fine-grained sediments, and sand (Figures 23, 24, 25, 26, 28, and 29). In places, the lower bounding surface of U3 appears sheared or dewatered (Slomka and Utting, 2018). In other places, the lower bounding surface of U3 is sharp and apparently planar and erosional where it directly overlies deformed silt and clay of U2. Leslie and Fenton (2001) recorded local bedrock lithologies (coal, shale, siltstone, sandstone, and ironstone), gravel clasts from the Canadian Shield and northeastern Paleozoic strata (granite, volcanic rocks, fine-grained mafic rocks, pink-purple quartzite, carbonate, and schist), and Cordilleran lithologies (quartzite, chert, sodic granite, felsic volcanic rocks, and sandstone) in diamicts of U3 (Unit C of Leslie and Fenton, 2001).

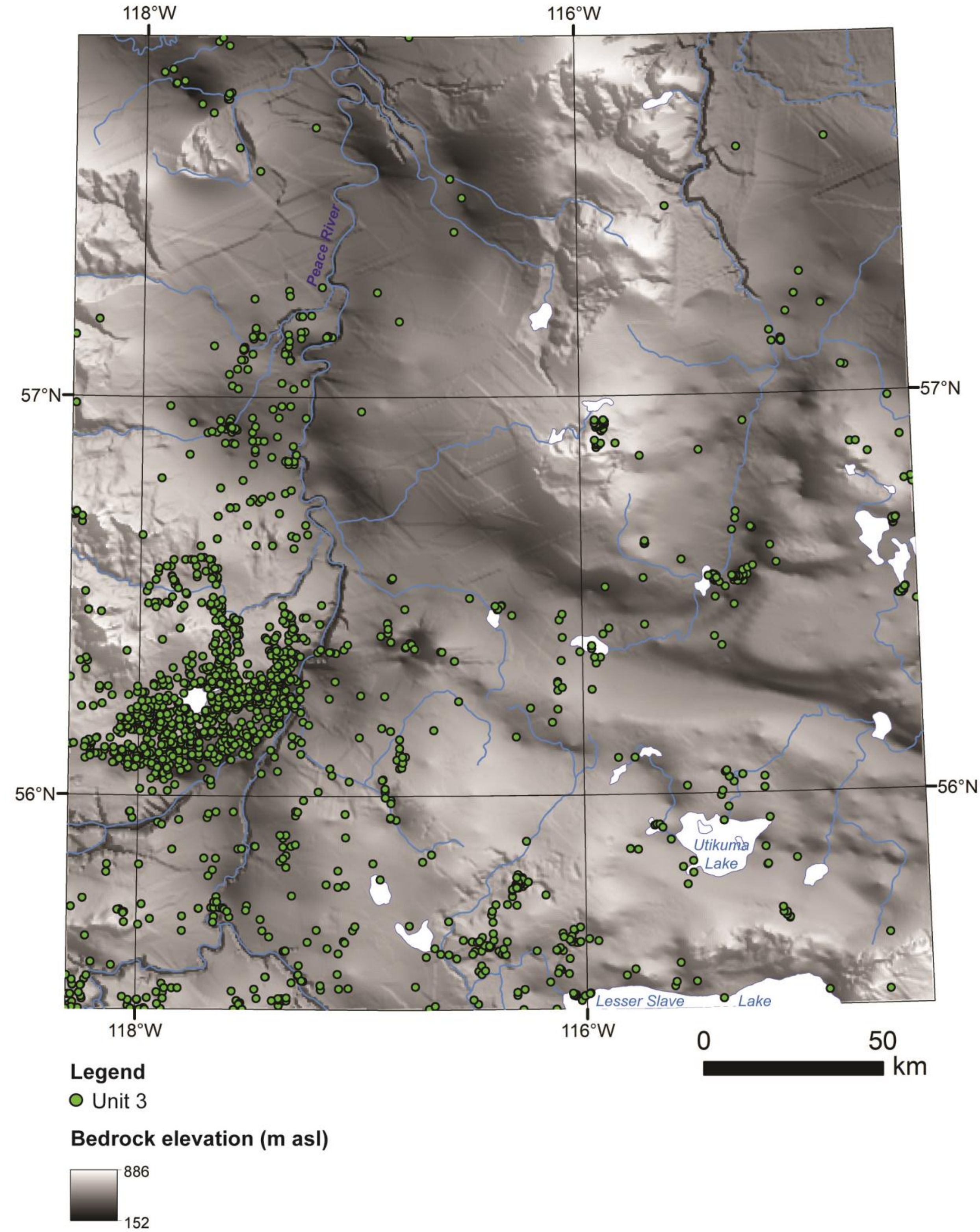

Figure 30. Locations where stratigraphic unit 3 (U3) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

On the Cardinal Lake Plain of the Peace River Lowland (Figure 18, B–B'; Figure 19), U3 forms a sheetlike deposit <1 to 15 m thick composed of massive clayey diamict (Leslie and Fenton, 2001). On the margin of the Cardinal Lake Plain, U3 appears to thicken towards the Shaftesbury bedrock valley (Figure 22, E–E'; Figure 23). In bedrock valleys, U3 forms a sedimentary complex of clayey silt diamict and sandy silt diamict with interbeds of massive silty clay and sand. The diamict contains angular to subangular unlithified clay and silt rip-up clasts, angular to subrounded lithified clasts (very coarse grained sand to granules) of local and far-travelled (i.e., Canadian Shield) lithologies, and rare contorted beds and convoluted laminae of silt and clay with flames and pillows (Appendix 1, Figure 36; Slomka and Utting, 2018). Clayey silt diamict beds contain rare irregularly shaped unlithified clasts (1–3 cm diameter made of sandy silt), rafts composed of granules, and angular to subrounded lithified clasts (0.1–5 cm diameter; average clast size commonly decreases upwards in U3). Conversely, sand-rich diamict beds are highly fissile, commonly dark grey-brown, and relatively more clast-rich, poorly sorted, and contain a larger average clast size than the clayey silt diamict (Slomka and Utting, 2018).

4.3.2 Interpretation

Sediments of U3 are interpreted to record ice advance (Laurentide Ice Sheet) into the study area (Leslie and Fenton, 2001). On Buffalo Head Hills (Figure 4), Paulen and McClenaghan (2015) identified two apparently massive diamict beds (>5 m thick) in outcrop section, which they interpreted as till recording regional paleoflow of the Laurentide Ice Sheet during the last glacial maximum (lower till) and local ice paleoflow (upper till) during deglaciation of the study area. Sediments correlated to U3 may record these Late Quaternary ice advances and possibly older ice-advance deposits (e.g., Andriashek and Barendregt, 2016).

4.4 Unit 4 (U4): Ice-Retreat Glaciolacustrine Sediments

4.4.1 Description

Unit 4 (Figure 31) overlies U3 and bedrock (where U1–3 are absent; Figures 21, 23, 24, 25, 26, 28, and 29). It is composed of silty diamict interbedded with sand, gravel, fine-grained sediment, and rare sand-rich diamict (Slomka and Utting, 2018). Unit 4 is <1 to 200 m thick (potentially up to 250 m thick), and is thickest in bedrock valleys (Figures 24, 25, and 29). Leslie and Fenton (2001) subdivided sediments of U4 into two subunits, including a lower diamict (up to 1 m thick) and an upper succession of massive to laminated silt and clay (2–30 m thick). Based on facies analysis of sediments in core (Appendix 1, Figure 36; Slomka and Utting, 2018), U4 is subdivided into three parts and described below.

The lower part of U4 contains thin (3–6 cm) beds of massive and deformed fine- to coarse-grained sand, silt, and sandy silt (including microfaults, pillows, and convolute bedding) with rare very coarse grained sand to granule clasts. The basal sediment assemblage is overlain by a succession of fining-upwards beds. Fining-upwards beds are composed of fine- to medium-grained sand to sandy silt (1–3 cm thick beds), deformed silt to very fine grained sand (including deformed sand rafts, vertically orientated laminae, convolute bedding, and flame structures; 1–30 cm thick beds), and clast-supported diamict to gravelly mud (0.6–1 m thick beds with erosional bases; Slomka and Utting, 2018).

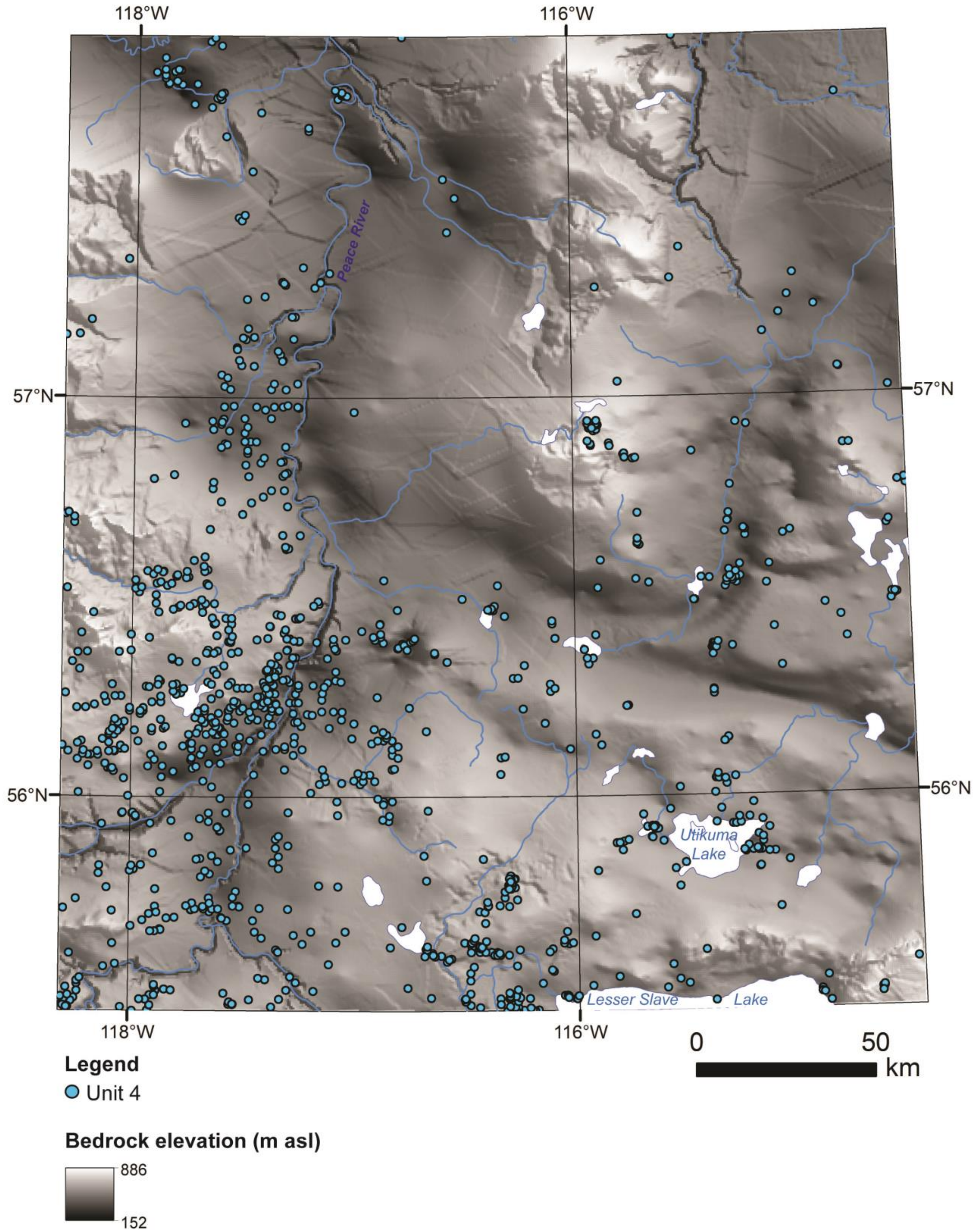

Figure 31. Locations where stratigraphic unit 4 (U4) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

The middle part of U4 is composed predominantly of friable sandy diamict, which appears to fine upwards to pebbly mud (clayey silt diamict). There are rare beds (1–30 cm thick) of deformed, massive, and stratified fine- to medium-grained and gravelly coarse-grained sand, silt, and mud (which have irregular facies contacts with diamict, commonly demarcated by flame structures, pillars, and pillows). Angular coal clasts (0.5–2 cm in diameter) and lithic pebble to boulder clast concentrations are common in the diamict of U4. Fragments of wood were collected from pebbly medium-grained sand in the upper to middle part of U4 in PR08-03 (~418 m asl; ~27 m below ground surface [bgs]; sample PR8-3-S2-S3, lab number Beta-412797; Appendix 1, Figure 36) and submitted to BetaAnalytic for AMS radiocarbon dating; however, the sample contained extremely low ^{14}C activity and, as a result, an infinite conventional radiocarbon date (>43 500 ^{14}C BP) was assigned to this sample. A wood fragment was collected from massive pebbly silt in the lower part of U4 from cored hole SMB-08-01 (~460 m asl; ~143 m bgs; sample SMB-08-01-S1, lab number UOC-2707; Appendix 1, Figure 36) and produced an infinite age (>50 000 ^{14}C BP; Slomka and Utting, 2018).

The upper part of U4 consists primarily of massive and stratified clayey silt diamict, massive gravelly silt, massive medium- to gravelly very coarse grained sand, and massive and deformed fine-grained sediment. Fine-grained facies in the upper part of U4 contain convoluted beds of silt and clay, interlaminated silt and clay (wavy and convoluted laminae), and massive and deformed silt (flames and vertically orientated laminae; Slomka and Utting, 2018). Fragments of wood were collected from sandy diamict (~498 m asl; ~40 m bgs; sample PR8-5-S1, lab number Beta-412798) and massive to stratified sandy diamict (~513 m asl; ~25 m bgs; sample PR8-5-S3, lab number Beta-412799) in the upper part of U4 in PR08-05 (Appendix 1, Figure 36). The samples were submitted to BetaAnalytic for AMS radiocarbon dating; however, the samples contained extremely low ^{14}C activity and, as a result, an infinite conventional radiocarbon date (>43 500 ^{14}C BP) was assigned to these samples. The upper bounding surface of U4 is the modern ground surface and, in places, is overlain by coarser grained sediment of U5 (Appendix 1, Figure 36).

4.4.2 Interpretation

Sediments of U4 are interpreted to record deposition of pebbly mud and stratified sediment in ice-marginal to ice-proximal (lower part of U4) and ice-distal (upper part of U4) positions in an ice-contact glacial lake (May, 1977; Fyfe, 1990; Balzer et al., 1996; Slomka and Utting, 2018). Clast-supported diamict that fines upwards to gravelly mud is interpreted to record hyperconcentrated debris flows in the lake basin, likely sourced from subglacial conduits at the ice margin (Slomka and Utting, 2018). Sandy interbeds in U4 are attributed to subaqueous deposition of coarse-grained sediment by underflows, which may have been supplied with sediment from subglacial conduits at the ice margin or deltas or subaqueous fans on the lake margin (Fyfe, 1990; Slomka and Utting, 2018). Laminated, deformed, and massive fine-grained facies in the upper part of U4 record deposition of suspended load in ice-distal areas of the lake basin and its subsequent fluidization as a result of sediment loading and a contrast in grain size (Slomka and Utting, 2018).

4.5 Unit 5 (U5): Outwash and Recent Alluvial Sediments

4.5.1 Description

Unit 5 is <1 to 90 m thick (potentially up to 160 m thick) and identified in boreholes primarily in lowlands and rarely on uplands (Figure 32). Unit 5 directly overlies U4 (and U3 in places where U4 is absent) and bedrock (Figures 19, 21, 23, 25, 26, 28, 29, and Appendix 1, Figure 36). Unit 5 is composed predominantly of a fining-upwards succession of sandy gravel, gravelly sand, and sand at the base to silt and clay at the top, and its lower bounding surface is apparently erosional in places (Appendix 1, Figure 36). The basal facies succession of U5 is commonly composed of a fining-upwards succession of interbedded stratified, massive, graded (coarsening-upwards) and deformed, fine- to coarse-grained sand at the base to massive, laminated, deformed, and graded (fining-upwards), silt, clay, and very fine to fine-grained sand at the top. The basal sand beds are commonly separated by facies contacts demarcated by pillars, flames, and pillows; the sand beds contain flame structures, vertically orientated laminae, and irregularly shaped to angular and apparently brecciated silt and clay rafts. The upper part of U5 is composed of massive and deformed silt, clay, and mud with rare pebble clasts (<1 cm in diameter) and, in places, very poorly sorted gravelly mud (Fm(g)) and massive clayey silt diamict (Dmm(f)) with deformed unlithified clasts. Convolute and vertical laminae, flame structures, contorted bedding, irregularly shaped silt and sand clasts, and diagenic iron-oxide staining and gypsum crystals are common in the upper part of U5 (Appendix 1, Figure 36). The upper contact of U5 is commonly demarcated by the modern ground surface and rarely overlain by U6.

A shell fragment (sample RE97-1-S1, lab number UOC-2708) was collected from cored hole RE97-1 (in sandy gravel at ~559 m asl, ~9 m bgs, in U5; Appendix 1, Figure 36) and submitted to The André E. Lalonde Accelerator Mass Spectrometry Laboratory (University of Ottawa, Ontario) for AMS radiocarbon dating. The shell fragment (RE97-1-S1) produced an age of 43 060 ±350 ^{14}C BP.

4.5.2 Interpretation

Sediments of U5 are interpreted to record deposition of sediment in both proglacial and modern alluvial depositional systems, including deposition of coarse-grained sediment in alluvial channel belts (coarse-grained sand and gravel) and deposition of fine-grained sediment from suspension in areas of ponded water (fining-upwards succession of sand and mud; Balzer et al., 1996; Morgan et al., 2008). Very fine grained sand and silt in U5 may record eolian deposition of loess (Figure 5). The precise depositional setting of the sand and gravel in U5 is uncertain; however, the coarse-grained sediments at the base of U5, and its association with lowlands (Figures 4 and 32), suggest relatively high-energy transport processes and deposition in channels or channel belts, which were incised into U4. The fining-upwards succession of interbedded massive, deformed, graded, and laminated sand and fine-grained sediments is interpreted to record a decrease in depositional energy or a decrease in the supply of sand and gravel, and may record channel belt or delta lobe abandonment with subsequent ponding of water and deposition of fine-grained sediment (e.g., Miall, 1977; Stouthamer, 2001) in a delta front to prodelta environment. Aggradation of interbedded gravelly mud, deformed and massive silt and very fine grained sand, and matrix-supported clayey silt diamict in the upper part of U5 record deposition by debris flow of previously deposited glaciogenic sediment (Boulton and Deynoux, 1981), likely as a result of backwasting during ice disintegration (Eyles, 1979; Kjær and Krüger, 2001), downslope movement of sediment on landforms of positive topographic relief, and unstable channel margins. The age of the shell fragment (43 060 ±350 ^{14}C BP) collected from sandy gravel in U5 should be used with caution because it nears the limit of radiocarbon dating; however, as a result of its interpreted stratigraphic position (U5; Figure 11), the shell fragment is likely detrital material transported by a glacial outwash system that eroded previously deposited Middle Wisconsinan sediment.

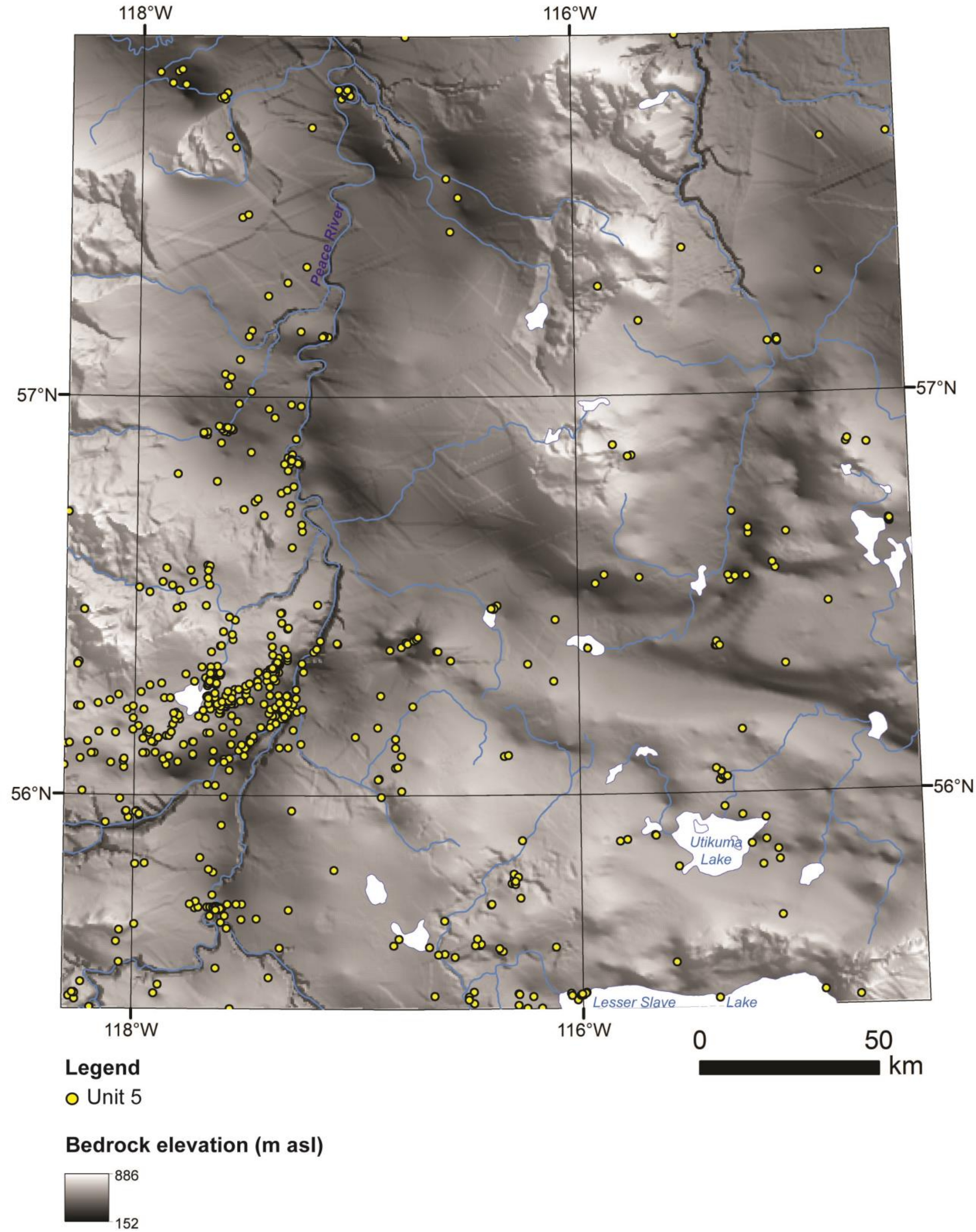

Figure 32. Locations where stratigraphic unit 5 (U5) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

4.6 Unit 6 (U6): Organics and Anthropogenic Materials

4.6.1 Description

Unit 6 (U6; Figure 33) is primarily identified in the Peace River Lowland and Utikuma Uplands sections (Figure 4). Unit 6 is composed of poorly to well-developed soil (~0.3–9 m thick; sedimentary structures are absent and parent material is difficult to identify), organic materials (fen, muskeg, and peat bog deposits; up to ~15 m thick), rare clay, loamy clay, and gravel beds (up to 1.52 m thick), and very poorly sorted dark-coloured aggregate fill (up to 3 m thick; PR08-05; Appendix 1, Figure 36). Leslie and Fenton (2001) grouped organic deposits with recent alluvial sediments (included in U5 in this report).

4.6.2 Interpretation

Unit 6 records the postglacial accumulation of biogenic materials (peat, muskeg, and fen materials), the development of soils by pedogenesis of previously deposited sediment and decomposition of organic materials, and rare accumulation of anthropogenic materials such as aggregate sand and gravel.

4.7 Summary of the Cenozoic Stratigraphy and Depositional History

The Cenozoic depositional history of the study area is documented by six units (U1–6) that record fluvial (or glaciofluvial) deposition (U1), the onset of glaciation (U2), glaciation (U3), deglaciation (U4, U5), and the accumulation of organic and anthropogenic materials (U6). Uplands (e.g., Buffalo Head Hills) contain remnants of the oldest deposits (U1a; Figure 34), which are composed of fluvial gravel. The gravelly U1 deposits (U1a–c) may record deposition during major events of deep fluvial incision to establish a new equilibrium profile (Mackin, 1948; Edwards and Scafe, 1996). The youngest of the fluvial deposits (U1c) is confined to bedrock valleys (Figure 34), whereas overlying glaciolacustrine and subglacial deposits (U2–U4) infill bedrock valleys, lowlands, and encroach on uplands (Figure 34). Fine- and coarse-grained outwash sediments (U5) and modern organic materials (U6) are locally deposited across the landscape.

The most complete stratigraphic record of Cenozoic geological events (U1c–U5) is contained within bedrock valleys (Figure 34). Facies analysis (Appendix 1, Figure 36) and regional correlation of U1–6 suggest that deposits of a complete glacial cycle (Late Wisconsinan) are preserved in northwestern Alberta (Slomka and Utting, 2018); however, the presence of possible Canadian Shield erratics in Middle Wisconsinan gravel deposits (U1c; Botterill, 2007; Morgan et al., 2008) suggests an earlier glacial advance of the LIS into (Leslie and Fenton, 2001), or proximal to, the study area (Early or potentially Middle Wisconsinan; Dredge and Thorleifson, 1987; Vincent and Prest, 1987; Stokes et al., 2012).

Downcutting of the U1c fluvial system through U1a and U1b (prior to deposition of U1c; Figure 34) may have resulted from glacio-isostatic uplift and establishment of an equilibrium river profile (Mackin, 1948) following a pre-Late Wisconsinan glaciation (Dredge and Thorleifson, 1987; Vincent and Prest, 1987; Catto et al., 1996; Hartman and Clague, 2008). A pre-Late Wisconsinan ice advance is consistent with previous interpretations of the presence of Canadian Shield erratics in areas to the west (e.g., Hartman and Clague, 2008) and east (e.g., Andriashek, 2003) of the study area and reconstructed ice margins during the Early and Middle Wisconsinan (Dredge and Thorleifson, 1987; Vincent and Prest, 1987; Stokes et al., 2012). Additional high-quality data (e.g., core and outcrop) and field investigation in the study area may provide further insight into the stratigraphic record of potential pre-Late Wisconsinan glaciations.

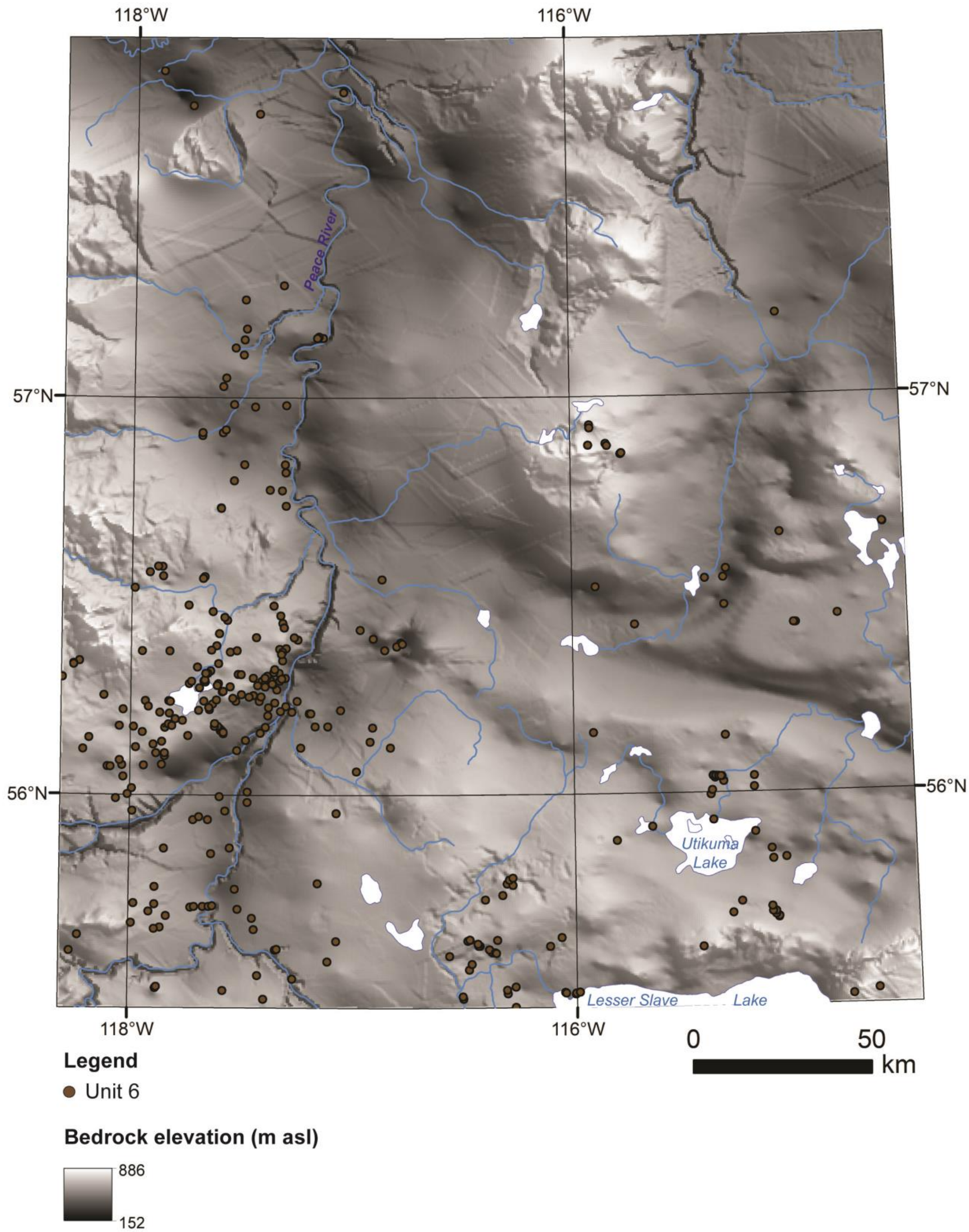

Figure 33. Locations where stratigraphic unit 6 (U6) was identified in logs in the study area, northwestern Alberta, overlain on a hill-shaded image of the bedrock topography (data from the provincial bedrock topography grid at a cell size of 500 by 500 m; MacCormack et al., 2016), illuminated from the northeast at an azimuth of 45° (vertical exaggeration is 60 times).

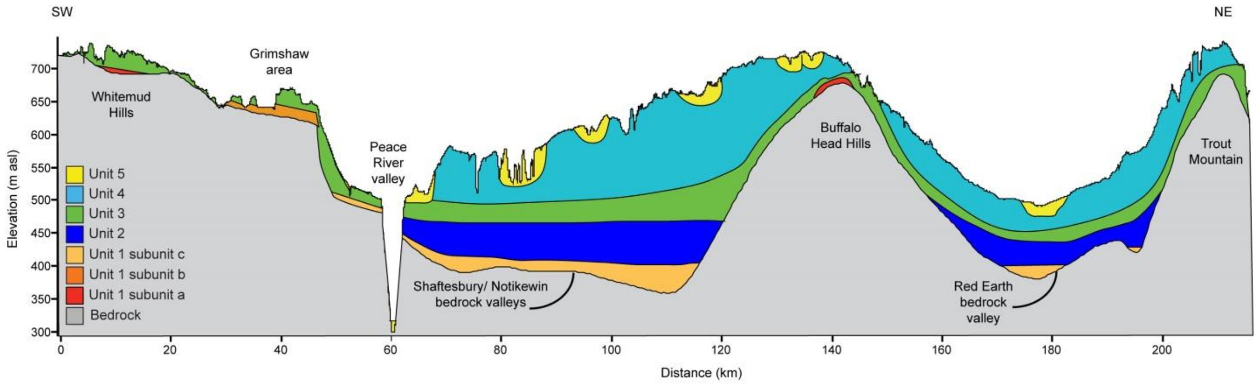

Figure 34. Conceptual cross-section (southwest [SW] to northeast [NE]) of the Cenozoic stratigraphy (units 1–5) from Whitemud Hills to Peerless Lake (Trout Mountain) areas, northwestern Alberta. Note that unit 6 is not shown because the unit is too thin to resolve at this scale.

Fine-grained lacustrine sediments of U2 in the Shaftesbury and Notikewin bedrock valleys (Figure 34) are interpreted to have been deposited in Glacial Lake Mathews (Hartman and Clague, 2008; Atkinson and Paulen, 2010; Hartman, 2015), which formed when the Peace River valley was blocked by the advancing LIS (Peace River lobe; Slomka and Utting, 2018). Similar advance-phase lakes formed in the Red Earth bedrock valley (Slomka and Utting, 2018). An AMS radiocarbon date of 30 240 ±160 ^{14}C BP measured from woody material collected from a sand bed in U2 (Town of Peace River) indicates a Middle Wisconsinan age (Slomka and Utting, 2018), which is supported by radiocarbon dates of bone, wood, and detritus previously collected from fine-grained sediments at Watino (correlated to U2) and Simonette River (south of the study area; ~27 400–43 5000 ^{14}C BP; Westgate et al., 1971, 1972; Liverman et al., 1989).

The LIS retreated from its maximum position west of the study area after ca. 15 000 BP (Woolf, 1988; Catto et al., 1996; Hickin et al., 2015). Retreat of the LIS, followed by ice-marginal proglacial lakes, is recorded by sediments of U4 (Figure 34; Slomka and Utting, 2018). Sediments of U4 were deposited in Glacial Lake Peace (Shaftesbury and Notikewin bedrock valleys) and other ice-dammed glacial lakes (Red Earth, l'Hirondelle, and Muskwa bedrock valleys; Slomka and Utting, 2018), and overlain by alluvial outwash sediments (U5) and modern organic materials (U6; Figure 34). Postglacial downcutting of rivers resulted in incision of the Middle to Late Wisconsinan sediments and bedrock, and entrenchment of modern river systems. The Peace River has incised at least 250 m of previously deposited sediment and into the underlying bedrock (Leslie and Fenton, 2001).

4.8 Uncertainty in Unit Correlation

Uncertainty in unit correlation results from ambiguous or erroneous water well information (Appendix 2). The 500 m cell size provincial bedrock topography grid (MacCormack et al., 2016) was used to inform unit correlation and identification of the bedrock. However, as a result of the cell size (500 m) and poor data control to constrain the bedrock topography (Figure 2; Lyster et al., 2016), several sections of sediments (high quality data) are truncated below the bedrock topography (Figure 35). For example, ≥30 m of sediments recorded in a core (PR08-03) drilled in the Shaftesbury bedrock valley is completely truncated below the regional-scale bedrock topography grid (Figure 35). Data generated from this study will be used to refine future versions of the regional-scale bedrock topography grid.

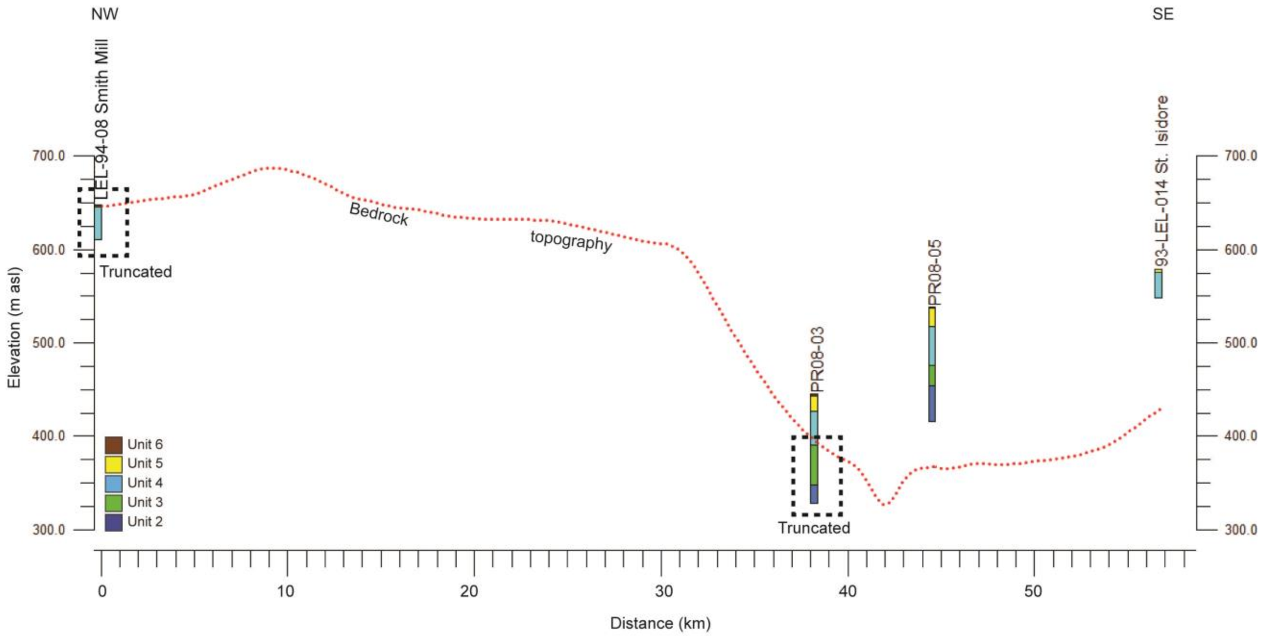

Figure 35. Section showing the logs of cored boreholes truncated (black boxes) by the bedrock topography grid (red dashed line), study area, northwestern Alberta. Vertical exaggeration is 50 times. Abbreviations: NW, northwest; SE, southeast.

5 Conclusions

The Cenozoic geological framework presented here is based on previous geological interpretations primarily by Rutherford (1930), Henderson (1959), Tokarsky (1967, 1971), Mathews (1980), Edwards and Scafe (1996), Balzer (2000), Leslie and Fenton (2001), Botterill (2007), and Morgan et al. (2008), and new data collected using facies analysis of previously drilled core (Slomka and Utting, 2018). Subsurface data from water well lithologs, previously recorded outcrop section and borehole lithologs, and relogged core were used to delineate six informal units (U1–6) in the Peace River area. Units include (from oldest to youngest) fluvial and glaciofluvial sediments (U1), ice-advance lacustrine to glaciolacustrine sediments (U2), subglacial, ice-marginal, and glaciolacustrine sediments (U3), ice-retreat glaciolacustrine sediments (U4), outwash and recent alluvial sediments (U5), and organic and anthropogenic materials (U6). The depositional history is constrained by radiocarbon dates measured from organic material collected from cores (Slomka and Utting, 2018) and outcrop sections (Botterill, 2007). Delineation of U1–6 on a regional scale helps to inform 3D modelling of the Cenozoic stratigraphy.

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Appendix 1 – Facies and Sedimentological Logs

Table 1. Facies codes, description, and interpretation (based on Eyles et al., 1983; Bhattacharya, 2010; Miall, 2010; modified from Slomka and Utting, 2018).

Facies	Grain Size	Sedimentary Structure	Interpretation
Gm	Poorly sorted granule to boulder with medium- to very coarse grained sand in gravel interstices.	Massive (apparently structureless), commonly graded (fining upwards). Other gravel facies are previously described as planar and trough crossbedded in places.	Massive gravels record the deposition of gravel sheets in an alluvial (probably fluvial) depositional environment. Graded gravels may record debris flows and decreasing current flow in a channel. Crossbedded gravels record the migration of bars and dunes and minor channel fill.
Sm (Sg)	Fine- to very coarse grained sand.	Massive (apparently structureless), may form fining-upwards graded beds (Sg).	Rapid deposition of sands by settling from suspension or high-energy sediment flows in a subaqueous depositional environment.
Sd	Very fine to coarse-grained sand.	Vertically orientated laminae, flames, pillows, convolute laminae, contorted bedding.	Secondary sedimentary structures formed by water escape as a result of sediment (and ice?) loading in a subaqueous depositional environment.
Ss	Fine- to coarse-grained sand.	Stratification, including planar lamination, ripple cross-lamination, planar bedding, may contain undulating (nonplanar) bedding.	Transport and deposition of sand by saltation under low- to high-energy traction currents.
Fm	Clay and silt.	Massive (apparently structureless).	Relatively constant settling of clay and silt from suspension in a subaqueous depositional environment, may form by rapid sedimentation as distal turbidity current flow deposits.
Fd (Fld)	Clay, silt, very fine grained sand.	Contorted beds, convolute laminae (Fld), brecciated beds, microfaults and microfolds, flow noses, irregularly shaped rafts, pillows, vertically orientated laminae.	Secondary sedimentary structures formed by water escape as a result of sediment (and ice?) loading and slope failure in a subaqueous depositional environment.
Fl	Clay, silt, very fine grained sand.	Laminated, planar to wavy lamination.	Settling of suspended clay, silt, and very fine grained sand in a subaqueous (lacustrine or glaciolacustrine) depositional environment.
Fg	Clay, silt, very fine grained sand.	Fining-upwards, and rare coarsening-upwards, massive, very fine grained sand, silt, and clay (rhythmites), may contain flow noses. Fining-upwards rhythmites commonly contain an erosional lower surface and flames and silt pillows along the upper surface.	Subaqueous debris flow and turbidity current deposits.
Dmm(f)	Diamict: clayey silt matrix (well sorted) with granule- to boulder-sized gravel clasts.	Matrix supported, massive (apparently structureless).	Subaqueous debris flow and ice-rafted debris deposited in a glaciolacustrine depositional environment.

Table 1 (*continued)*. Facies codes, description, and interpretation (based on Eyles et al., 1983; Bhattacharya, 2010; Miall, 2010; modified from Slomka and Utting, 2018).

Facies	Grain Size	Sedimentary Structure	Interpretation
Dmm(s)	Diamict: sandy silt matrix (poorly sorted) with medium-grained sand to boulder-sized gravel clasts.	Matrix supported, massive (apparently structureless).	Subglacial traction till and cohesive debris flow sediments deposited in a subglacial to subaerial depositional environment.
Dcm	Diamict: clayey silt matrix with granule- to cobble-sized gravel clasts (subangular to subrounded).	Clast supported, massive (apparently structureless), clast size decreases upwards.	Subaqueous hyperconcentrated debris flow in a glaciolacustrine depositional environment.
Dms	Diamict: silty diamict interstratified with silt and sand. Rare gravel clasts (granule- to pebble-sized, angular to subrounded).	Matrix supported, stratified.	Subaqueous turbidity flow deposits in a glaciolacustrine depositional environment.
Dml	Diamict: clayey silt diamict with laminae and beds of clayey silt.	Matrix supported, laminated.	Ice-rafted debris and massive to laminated clayey silt settling out of suspension in a glaciolacustrine depositional environment.

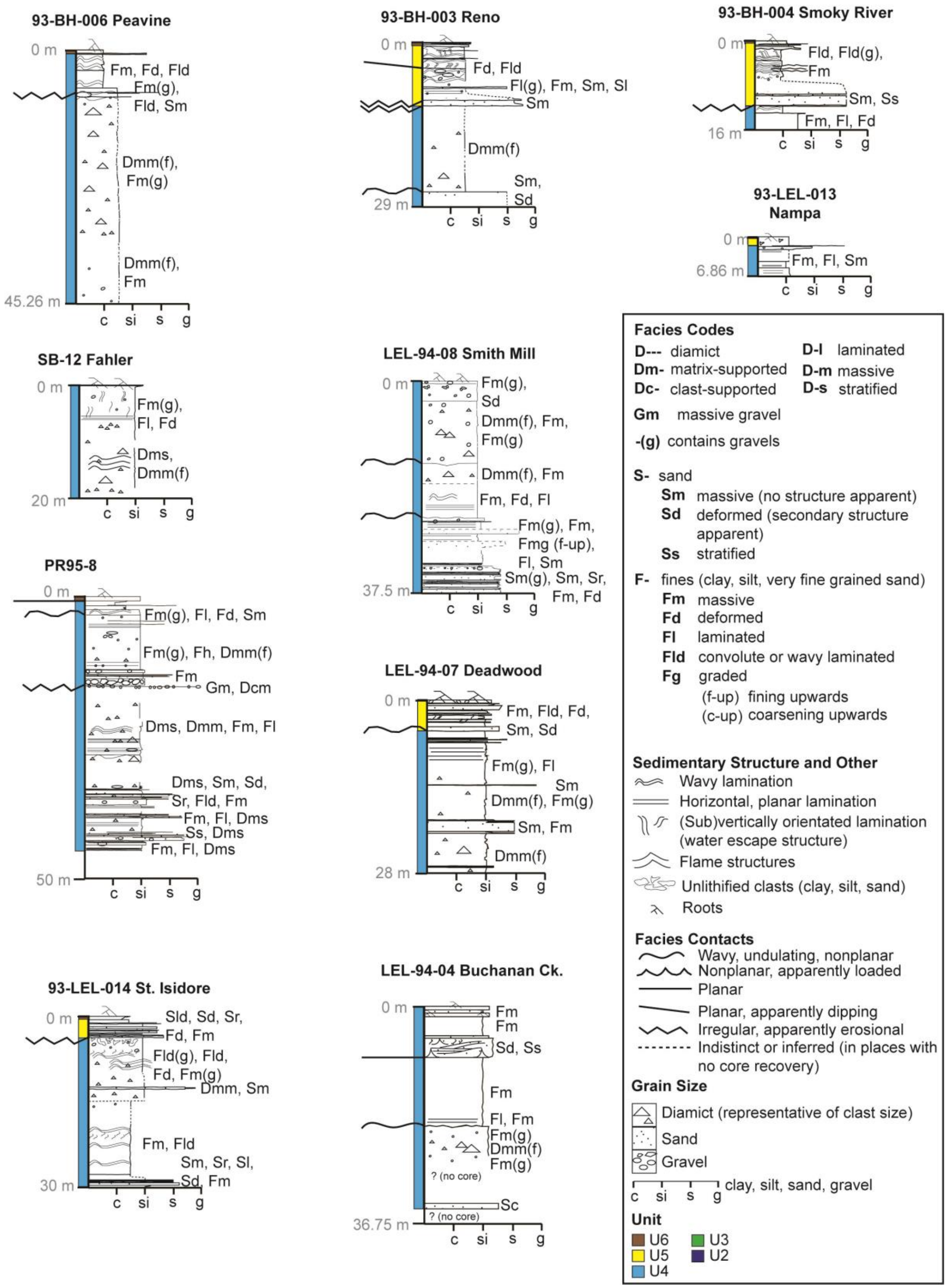

Figure 36. Sedimentological logs of cored boreholes in the study area, northwestern Alberta. Borehole number is included above each log and depth (in metres) is indicated on the vertical axis. Facies codes are included to the right of each log (modified from Slomka and Utting, 2018). Abbreviation: U, unit.

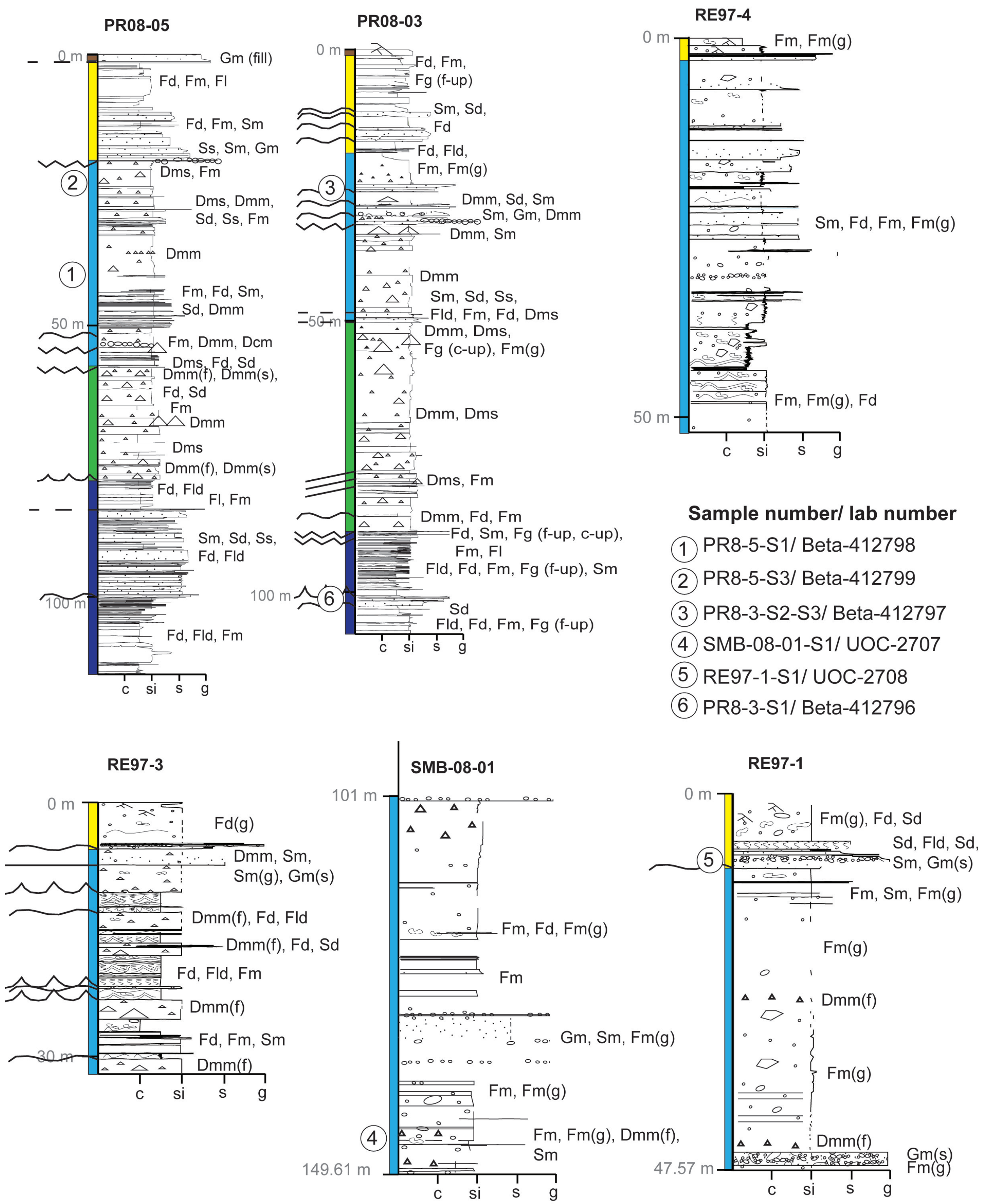

Figure 36 (*continued)*. Sedimentological logs of cored boreholes in the study area, northwestern Alberta. Borehole number is included above each log and depth (in metres) is indicated on the vertical axis. Facies codes are included to the right of each log (modified from Slomka and Utting, 2018). Abbreviation: U, unit.

Appendix 2 – Water Well Lithology Data

Table 2. Water well lithology descriptors classified as lithology groups (from Slomka and Utting, 2018).

Water Well Lithology Descriptors and Comments	Lithology Group
Alluvial, aquifer (water-bearing), blind (unknown), drift, fill, hard ledges, hard, lost circulation, old well, overburden, soft (blind, unknown), thin bentonite, unoxidized, water-bearing (unknown), predrilled, saturated	Unknown
Topsoil (clay, clayey, silty, dry, fill, fine-grained, loose, moist, stony, organic matter), organic matter, muskeg	Organics
Boulders and clay (coarse-grained sand, sandy clay), clay and gravel (carbonaceous, cemented, coarse-grained, dry, water-bearing), clay and rocks (gravel, sandstone, dry sand, fine-grained gravel, claystone, old well, sand and gravel, hard shale, lacustrine clay, water-bearing till, sand stringers) Clay and sand (clay and boulders, gravel, fine-grained gravel, silty sand), clay and shale (clayey till) Clay and silt (sandstone, till, silty gravel and boulders), silty clay (boulders, gravel, rocks, shale, pea gravel), clay (boulders, gravel, rocks, sand and gravel, sandstone, coarse-grained gravel, gravelly, medium-grained till, stony till, water-bearing gravel, sticky, stony), sandy clay (rocks, boulders, gravel) Gravel (coarse-grained, clay, dry clay, dry, sand, glacial till, gravelly clay, rocks, sand, shale), gravelly clay (rocks, sand, sandy clay, silt), hard clay (boulders, gravel, rocks), pebbly clay (sand, silt, coal) Sand and gravel (clay, clayey sand, clayey till, clay and rocks), silty gravel (coarse-grained sand, silty clay, sand)	Diamict
Till (calcareous, clay, clayey, caving, cemented, oxidized, rocks, sand stringers, boulders, hard shale, shale, clean, coarse-grained, gravel, gravelly, crumbly, moist, fine-grained, sand, firm, glacial sand, rocks, glacial, sticky clay, clayey sand, moist sand, gritty, hard, interbedded sand, interbedded gravel, interbedded clay, mixed sand, oxidized sand, pebbly, sandstone, sand, sandy, coarse-grained sand, sandy clay, silt, silty, silty sand, soft silt, soft, sticky, stony, organic matter, hard clay, topsoil, fine-grained sand, saturated sand, soft topsoil, unoxidized, unreadable, water-bearing, water-bearing sand, angular gravel, wet sand, wet)	Till
Clay (coal, calcareous, fill, hard pan, hard, lacustrine, sand, loose, alluvial, cemented, hard ledges, clean, coarse-grained, compacted, consolidated, dry, fine-grained, firm, glacial, interbedded, laminated, loamy, lost circulation, medium-grained, moist, mixed, old well, oxidized, soft, coal, sticky, tight, unknown, water-bearing, weathered, wet, bentonitic) Clay and sand (stringers, fine-grained, medium-grained, quicksand, silt, coarse-grained, dirty, dry)	Clay
Clay and silt (calcareous, fine-grained clayey, compacted, dry, glacial, gritty, interbedded, lacustrine, laminated, loamy, loose, moist, medium-grained, oxidized, stringers, coal, sand, silty sand, unreadable, very fine grained, carbonaceous, unconsolidated, water-bearing, wet) Silt (calcareous, coarse-grained, dry, sand, fine-grained, glacial, clay, hard, lacustrine, loamy, medium-grained, moist, laminated, oxidized, soft, water-bearing, wet, alluvial, coal, fill, quicksand, stringers) Sand and silt (alluvial, interbedded, very fine grained, loamy, medium-grained, quicksand, lacustrine, moist, calcareous, oxidized, hard, saturated, stringers)	Silt
Sand and clay (coarse-grained, water-bearing, stringers, lacustrine, wet) Silty sand (quicksand, clay stringers, clay, sandy clay, fine-grained, very fine grained) Sand (bentonitic, calcareous, carbonaceous, trace, wet, clay)	Sand
Sand and gravel (caving, cemented, coarse-grained, boulders, clean, fine-grained, medium-grained, dirty, dry, old well, rocks, fractured, silt, hard, lost circulation, mixed, moist, oxidized, rounded, sandstone and shale ledges, water-bearing, saturated, soft, very fine grained, wet, interbedded, glacial) Gravel (cemented, coarse-grained, boulders, dirty, dry, moist, fine-grained, firm, gassy, glacial, unknown, sandy boulders, hard pan, old well, rocks, water-bearing, fill, hard, hard rocks, laminated, loose, lost circulation, medium-grained, mixed, oxidized, pea, pebbly, preglacial, rocky, rounded, stones, stony, unreadable, caving, clean, consolidated, wet, angular, alluvial) Boulders	Gravel
Shale (weathered, fractured, sandstone, clay, clayey, soft clay, stringers, sand, sandy clay, calcareous, carbonaceous, siltstone, coarse-grained, compacted, consolidated, crumbly, dry, fine-grained, First White Speckled Formation, fractured, gravel, gravelly, gritty clay, gritty, hard, hard clay, moist, medium-grained, interbedded, loose, old well, oxidized, coal, sandstone ledges, silt, rocks, soft sand, saturated, sandy stringers, limestone, bentonite, tar sand, till, soft clay, sticky clay, stony clay, thin, unknown, water-bearing, wet) Sandstone (bentonitic, calcareous, cemented, clayey, clay stringers, fine-grained, soft siltstone, fractured, gritty, gravel, layers, hard clay, rocks, hard, interbedded, lost circulation, medium-grained, oxidized, mixed sand, rocky, sand, shale ledges, old well, soft sand and rocks, soft, water-bearing, sandy clay, clay and gravel, unconsolidated, very fine grained, Wapiti sandstone, medium-grained, weathered, wet) Ironstone, conglomerate, laminated sandrock, bedrock, coal (laminated, soft, thin, water-bearing, fine-grained sand) Siltstone (sandy clay, bentonitic, carbonaceous, cemented, sandstone, clayey, fine-grained, hard, fractured, lacustrine, moist, silty, soft, wet, moist) Granite (fine-grained) Dolomite (interbedded, sandy, silty) Limestone (interbedded, silty, sandy) Mudstone (calcareous, hard, soft) Claystone (bentonitic, soft, sandy, silty) Chert	Bedrock

Table 3. Water well lithology descriptors used to correlate units 1–6.

Unit (U)	Predominant Water Well Lithology Groups
U6	organics, fill
U5	sand, gravel, clay (minor silt, diamict, bedrock)
U4	clay, silt, sand, diamict, till (minor gravel, organics)
U3	till (minor sand, gravel, clay, silt, diamict, bedrock)
U2	sand, silt, clay (minor diamict, sand, gravel)
U1a,b,c	sand, gravel (minor silt, clay, diamict, till)
Bedrock	bedrock (minor unlithified material descriptors)

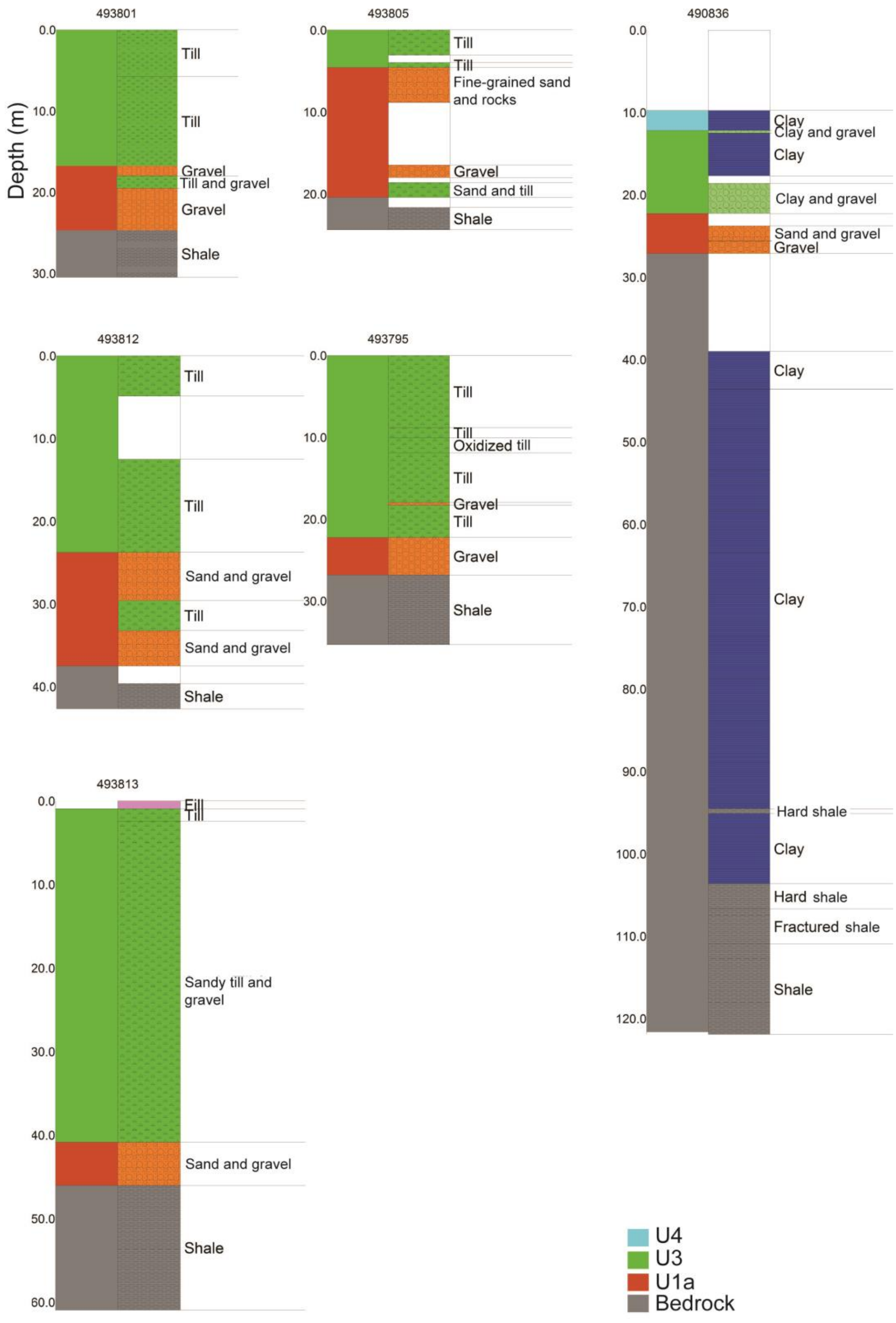

Figure 37. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section A–A', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1a, unit 1 subunit a.

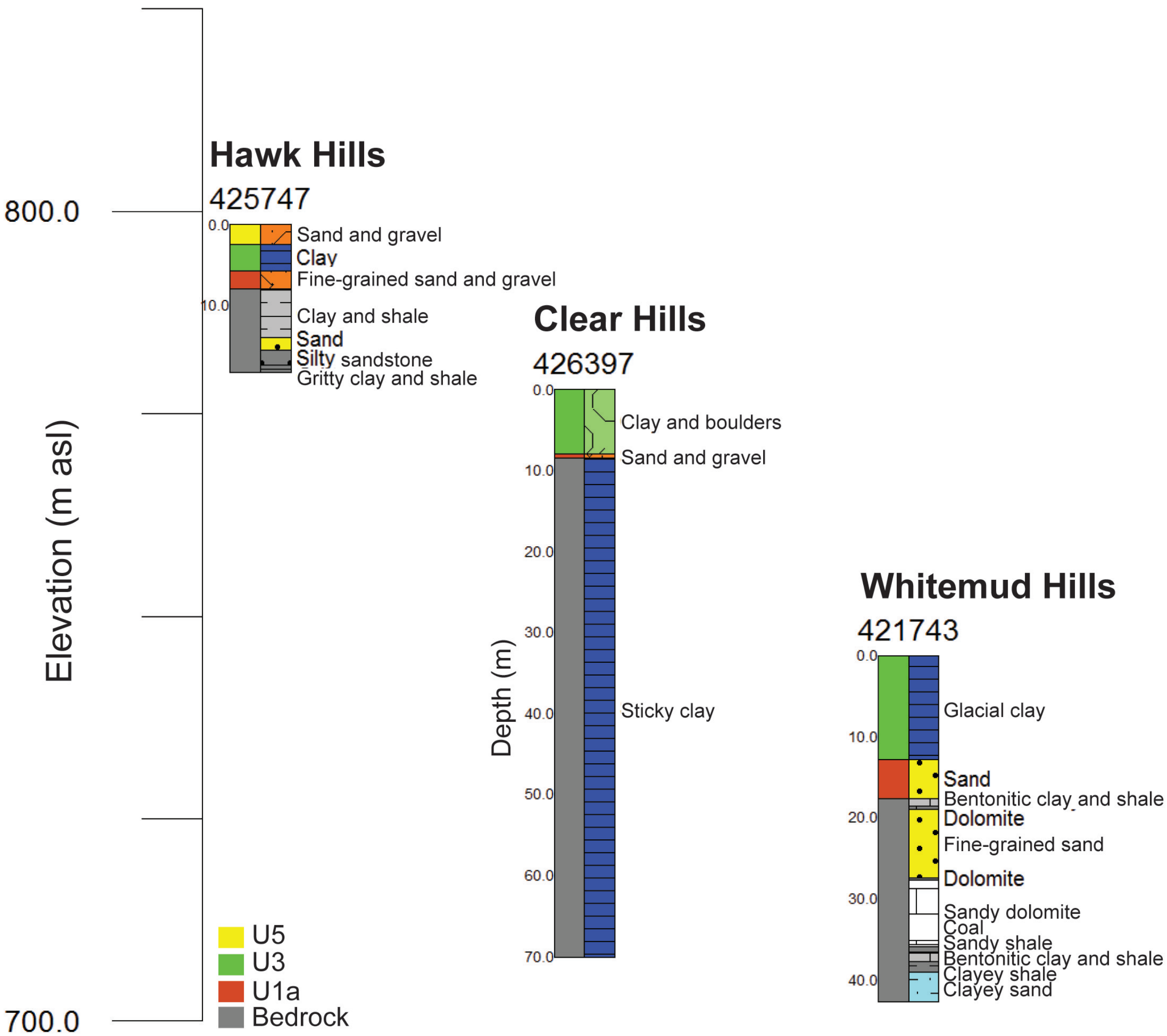

Figure 38. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) including lithology descriptions (to the right of each log) for wells located on Hawk Hills (Groundwater Information Centre [GIC] ID 425747), Clear Hills (GIC ID 426397), and Whitemud Hills (GIC ID 421743), northwestern Alberta (see Figure 16 for locations). Wells 425747 and 421743 are located ~80 km apart (no horizontal scale intended). See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1a, unit 1 subunit a.

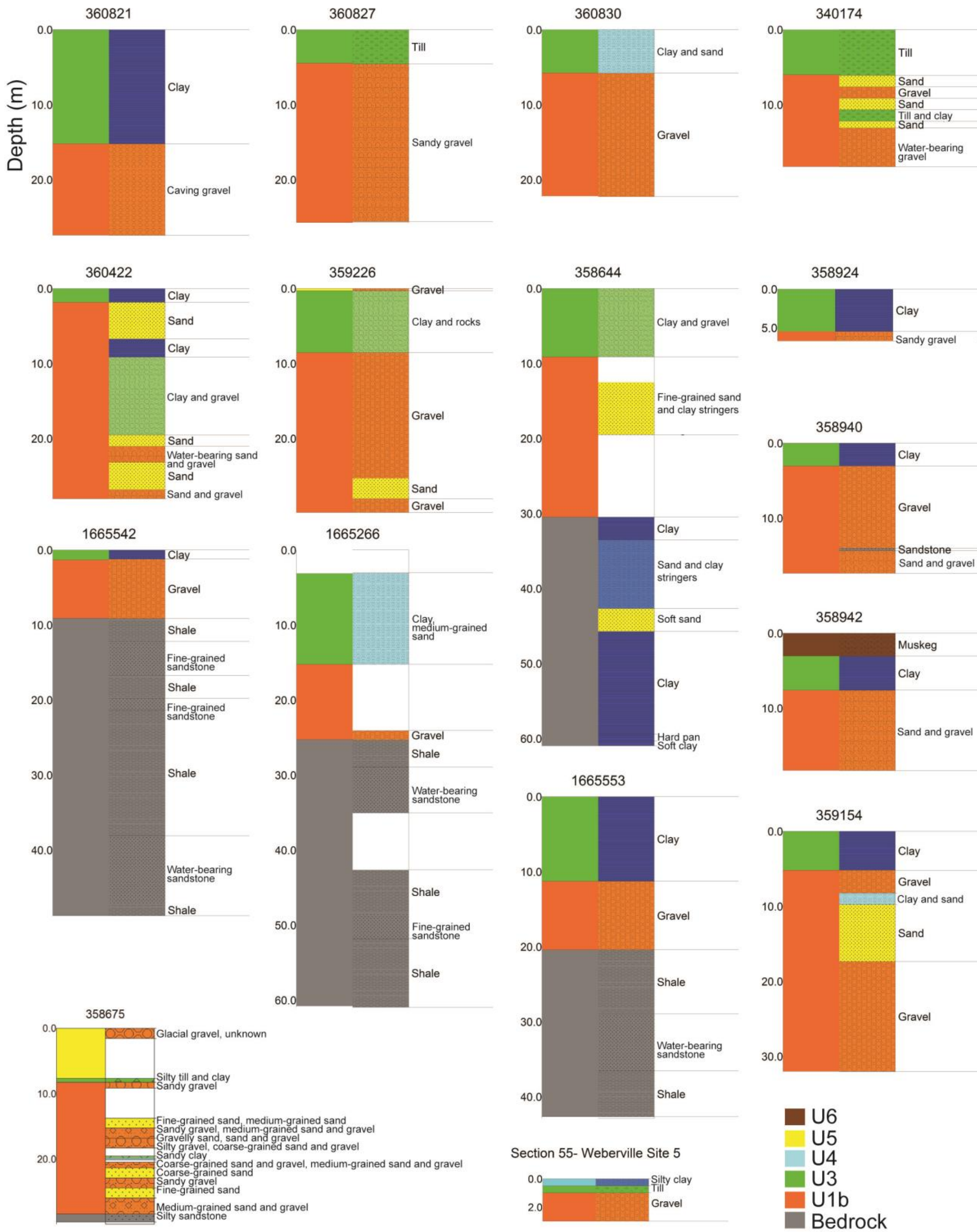

Figure 39. Water well lithologs/outcrop section logs (right-hand side log) and corresponding units (left-hand side log) from cross-section B–B', northwestern Alberta, including lithology descriptions to the right of each log. Section name or water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1b, unit 1 subunit b.

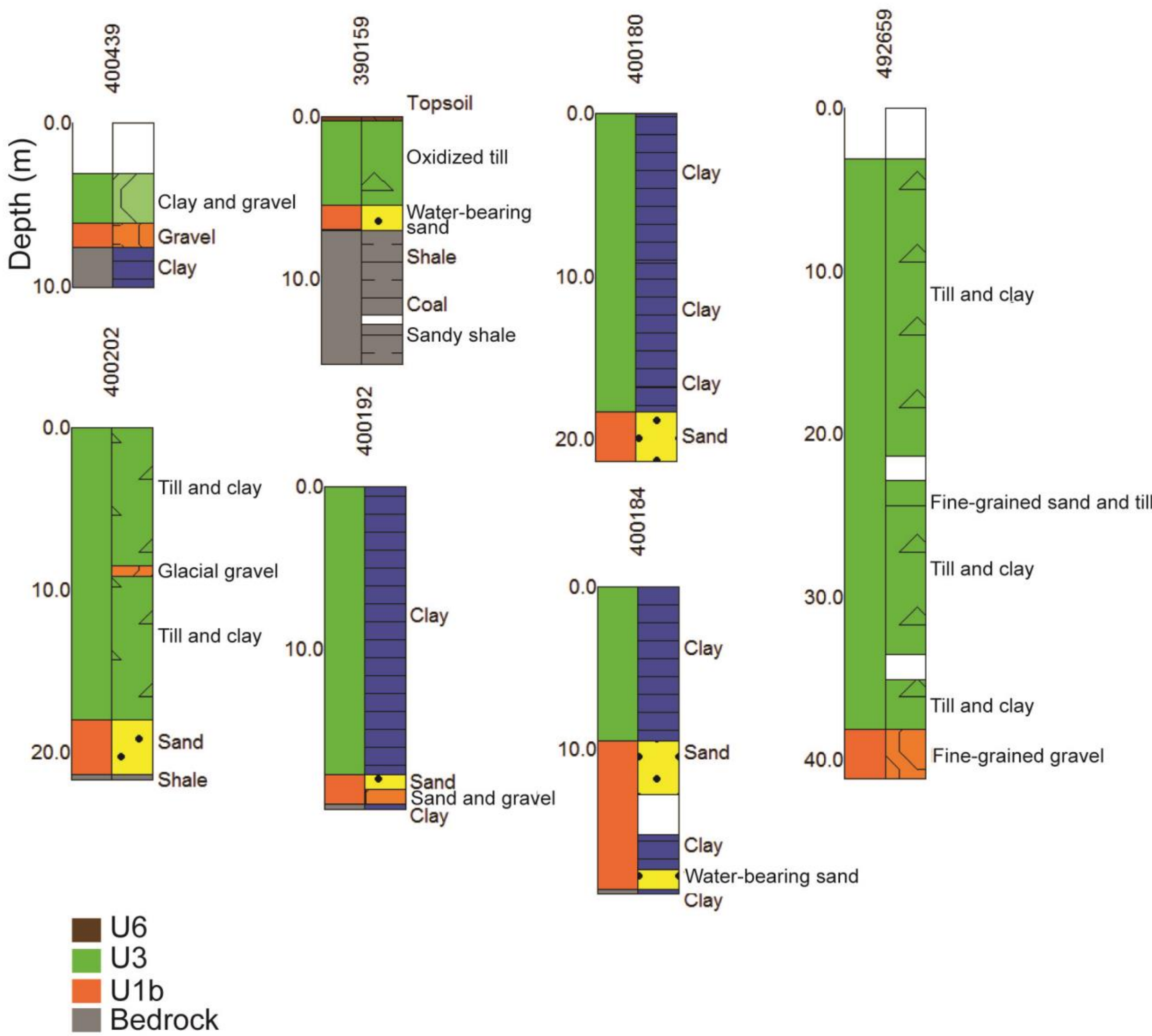

Figure 40. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section C–C', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1b, unit 1 subunit b.

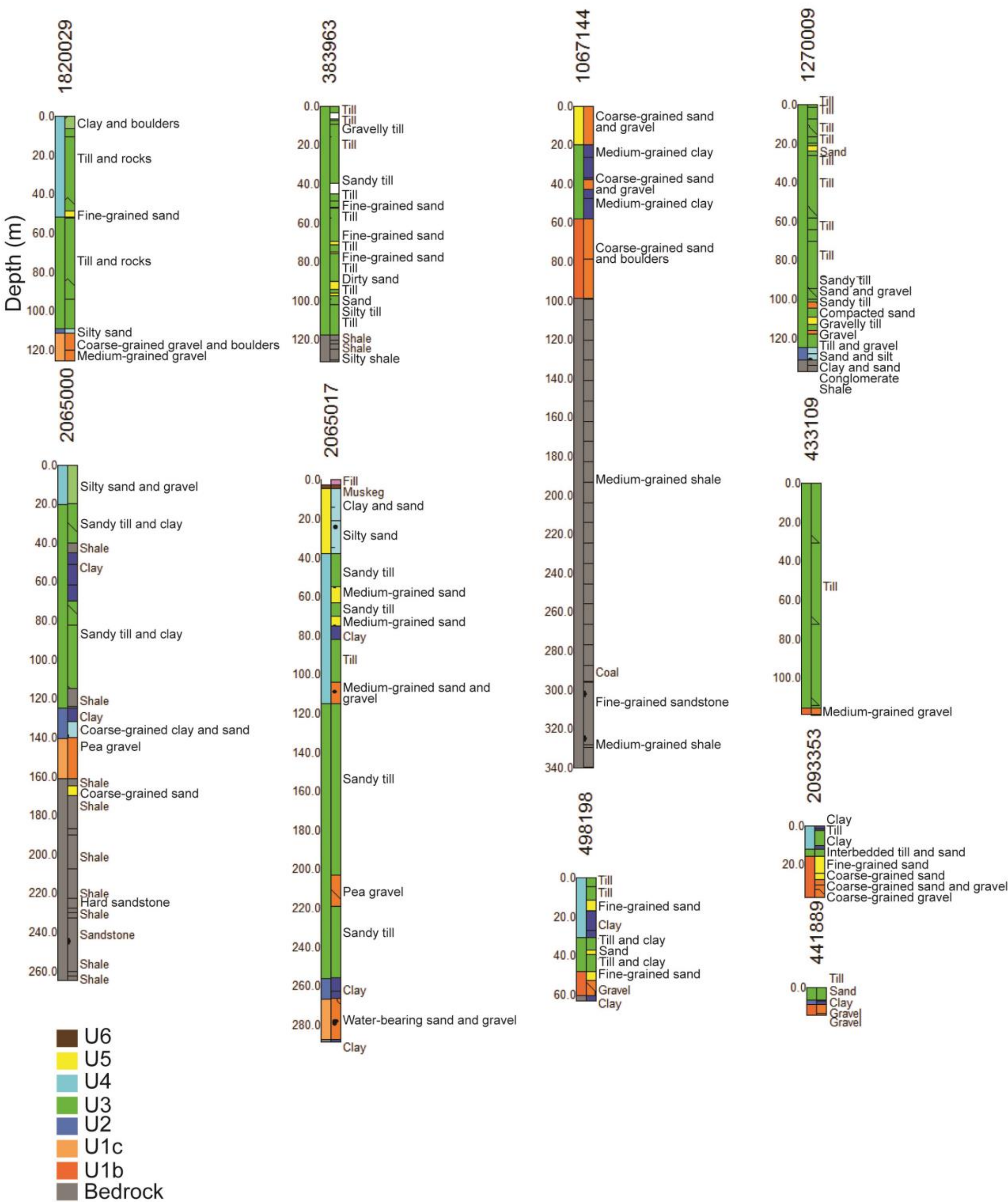

Figure 41. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section D–D', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1b, unit 1 subunit b; U1c, unit 1 subunit c.

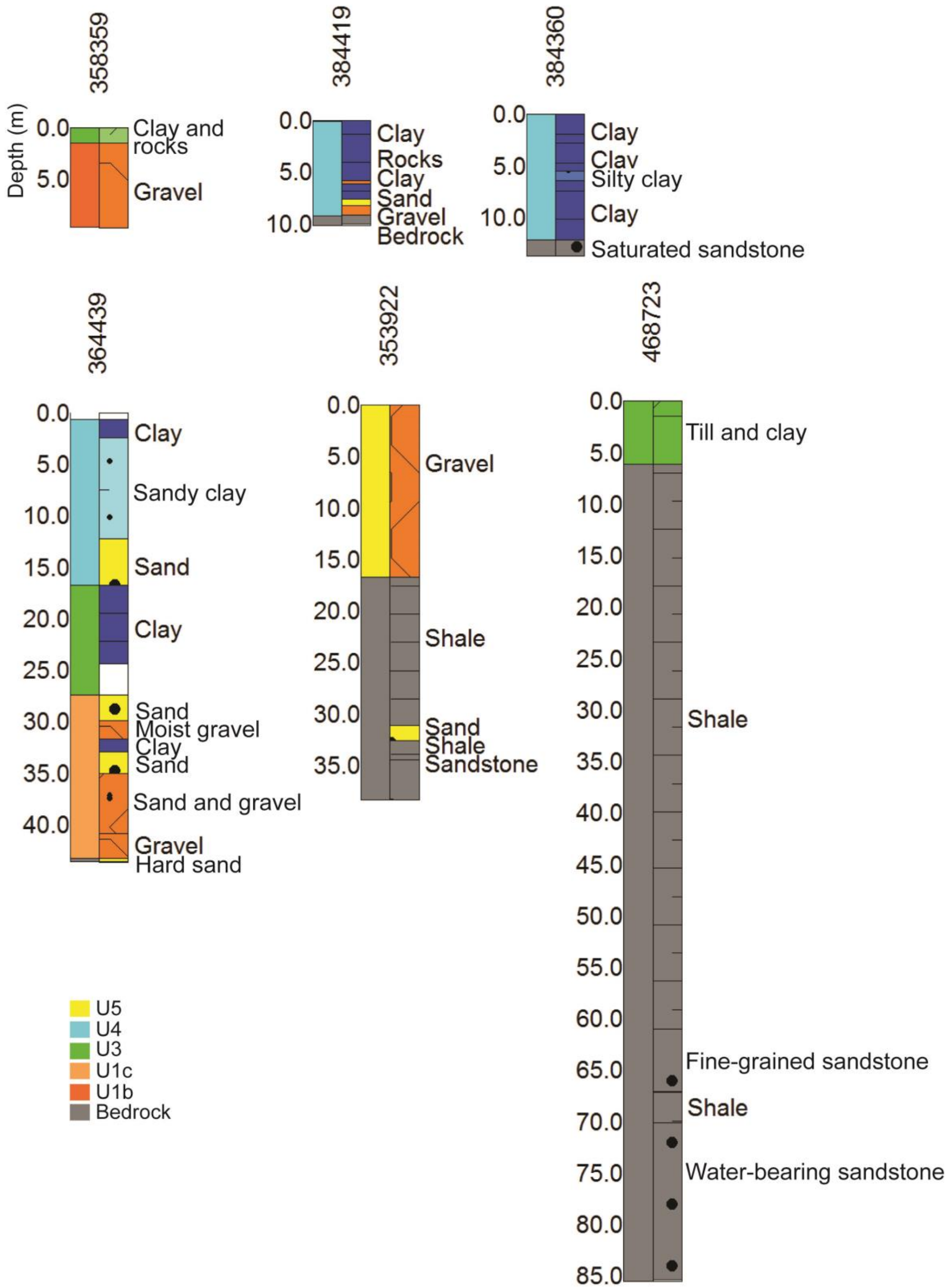

Figure 42. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section E–E', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1b, unit 1 subunit b; U1c, unit 1 subunit c.

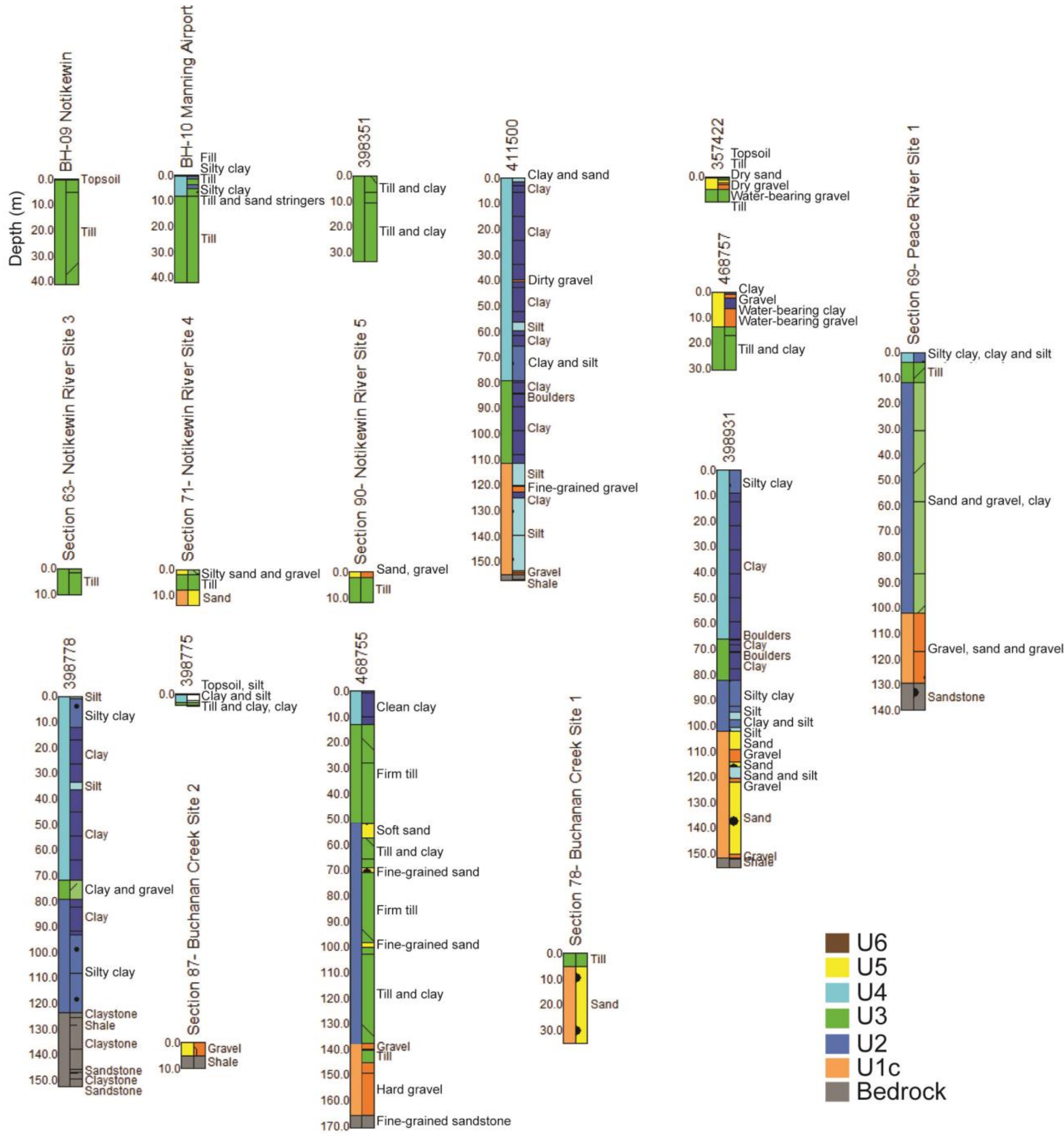

Figure 43. Water well lithologs/borehole logs/outcrop section logs (right-hand side log) and corresponding units (left-hand side log) from cross-section G–G', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1c, unit 1 subunit c.

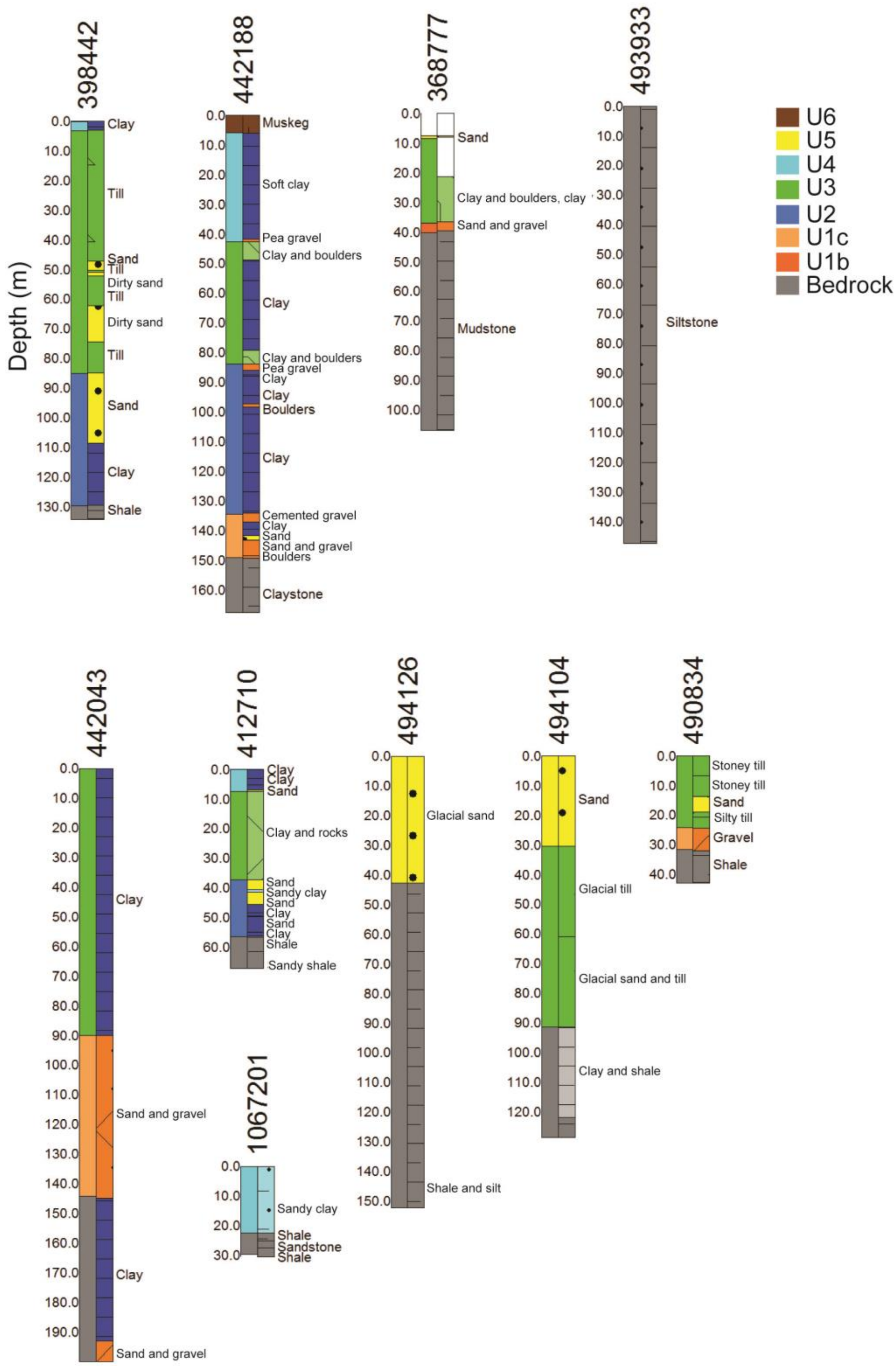

Figure 44. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section H–H', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1b, unit 1 subunit b; U1c, unit 1 subunit c.

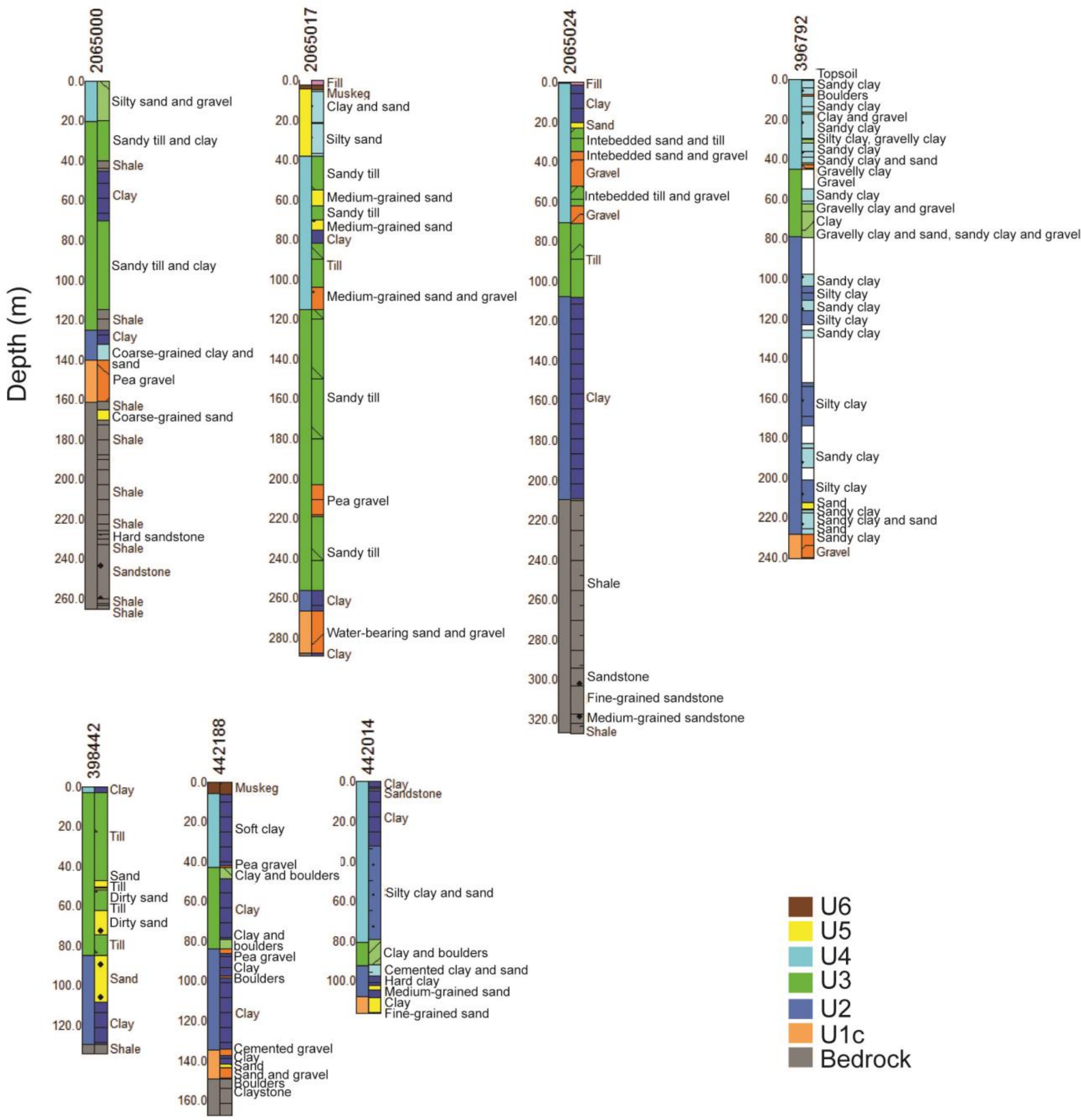

Figure 45. Water well lithologs (right-hand side log) and corresponding units (left-hand side log) from cross-section I–I', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1c, unit 1 subunit c.

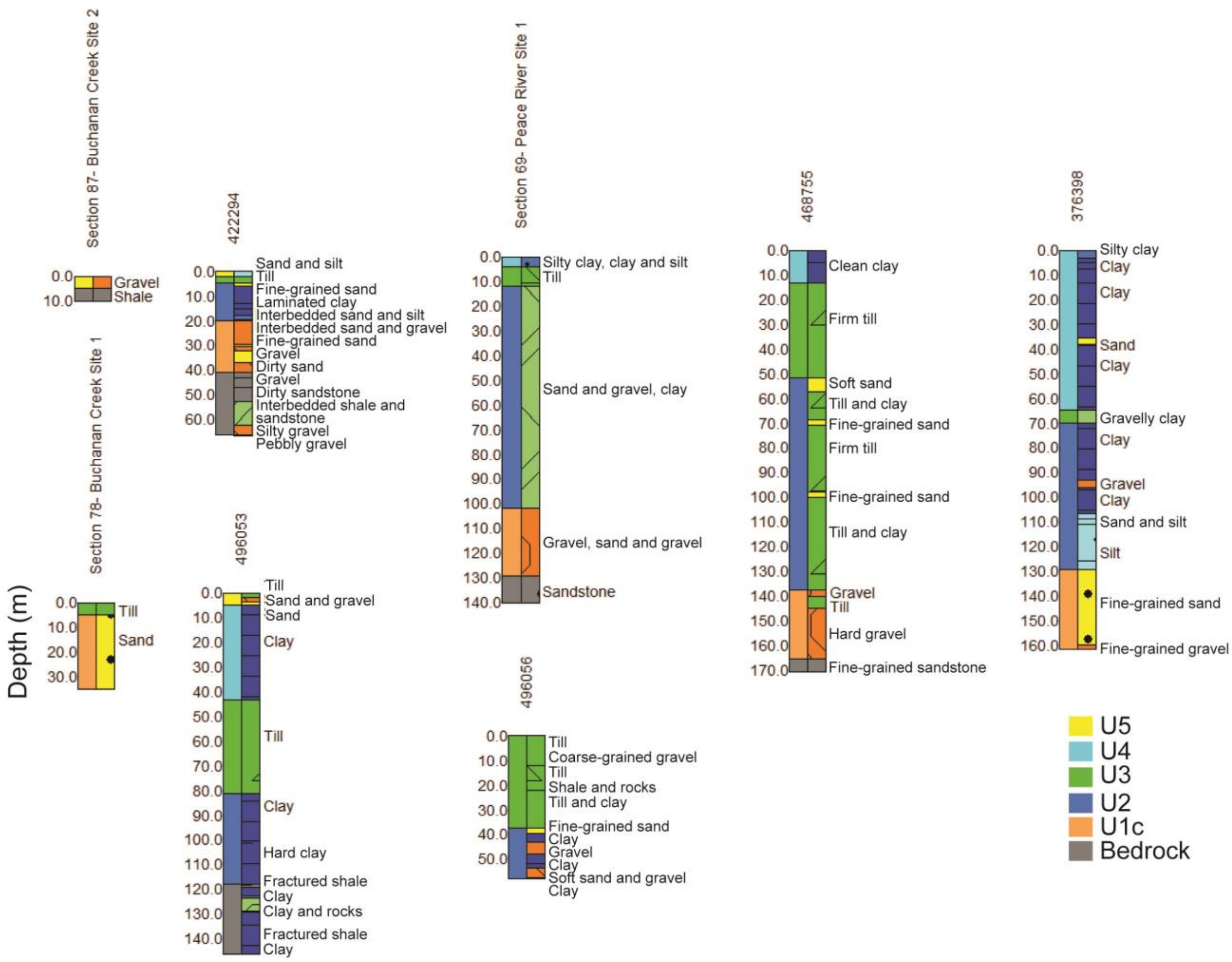

Figure 46. Water well lithologs/outcrop section logs (right-hand side log) and corresponding units (left-hand side log) from cross-section J–J', northwestern Alberta, including lithology descriptions to the right of each log. Water well Groundwater Information Centre (GIC) ID is included above each log and depth (in metres) is indicated on the vertical axis. See Appendix 2, Table 2 for litholog colour code. Abbreviations: U, unit; U1c, unit 1 subunit c.