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Alberta Energy Regulator

Architecture and Geometry of Basal Sand and Gravel Deposits, Including the 'Grimshaw Gravels', Northwestern Alberta (NTS 84C and 84D)

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Abstract

The ‘Grimshaw gravels’ deposit in northwestern Alberta hosts an important producing aquifer (the Grimshaw gravels aquifer) and aggregate resource for the surrounding communities. This report presents a revised and expanded subsurface stratigraphy of the Grimshaw gravels and other basal sand and gravel units in the Peace River Lowland, based on field investigation of outcrops and regional correlation of sand and gravel units between wells. Three basal sand and gravel units are identified: the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel. The three basal sand and gravel units are mapped on a regional scale, which allows correlation with previously described units in the adjacent NTS 94A map area in British Columbia. This report also provides an updated assessment of the Grimshaw gravels deposit as both an aquifer and an aggregate resource.

Geological data on the basal sand and gravel units identified in this report are available in the form of figures, cross-sections, and tabular data. The intended primary users of these data include municipalities, gravel pit operators, hydrogeologists, landowners, and other government groups with an interest in aquifer management and protection in the Grimshaw area.

1 Introduction

The 'Grimshaw gravels' (coined by Tokarsky, 1967) deposit in northwestern Alberta (Figure 1) serves as an important producing aquifer, which the Prairie Farm Rehabilitation Administration (PFRA, 1998) termed the 'Grimshaw gravels aquifer', and aggregate resource for the surrounding communities (Figure 2; PFRA, 1998). In places, the aquifer is protected by a relatively thin (up to ~7 m thick) cover of fine-grained glaciogenic sediments (e.g., till); however, the aquifer is commonly unconfined, making it susceptible to contamination (Tokarsky, 1971; PFRA, 1998). Nearly two decades ago, the PFRA conducted a hydrogeological assessment of the Grimshaw gravels aquifer. One outcome of the assessment was identification of the need for detailed geological information in order to develop well-informed and effective aquifer protection and management plans. In particular, the assessment identified the need for better understanding of the geometric and stratigraphic relationships between the Grimshaw gravels and 1) adjacent buried valley and terrace gravels, and 2) bedrock strata. However, publicly available geological information on the Grimshaw gravels has been previously presented in the form of conceptual geological cross-sections and 2D surficial geological maps (e.g., Tokarsky, 1971; PFRA, 1998), which makes assessment of the geometric and stratigraphic relationships challenging.

This report provides an updated geological framework of the Grimshaw gravels and adjacent sand and gravel units, including their geometric distribution and stratigraphic history. It also provides an updated hydrogeological assessment based on recent data from the Alberta Water Well Information Database

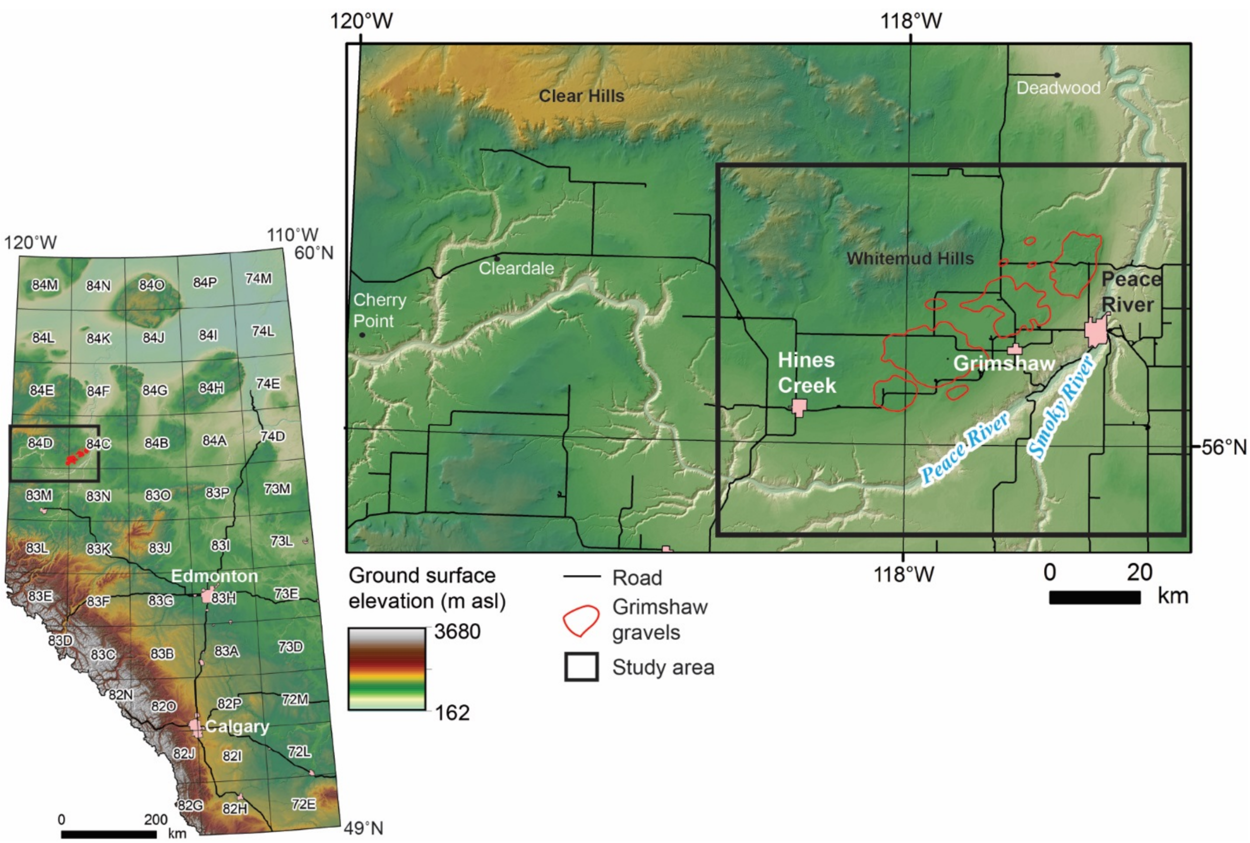


Figure 1. Regional study area, including the Grimshaw gravels (red polygons; PFRA, 1998) and Peace River valley (the inset map shows the study area location in northwestern Alberta), overlain on a hill-shaded provincial digital elevation model (DEM; data in metres above sea level [m asl]; data from Alberta Environment and Parks [AEP], 2015). The grid system and labels in the inset refer to the National Topographic System (NTS) sheet numbers.

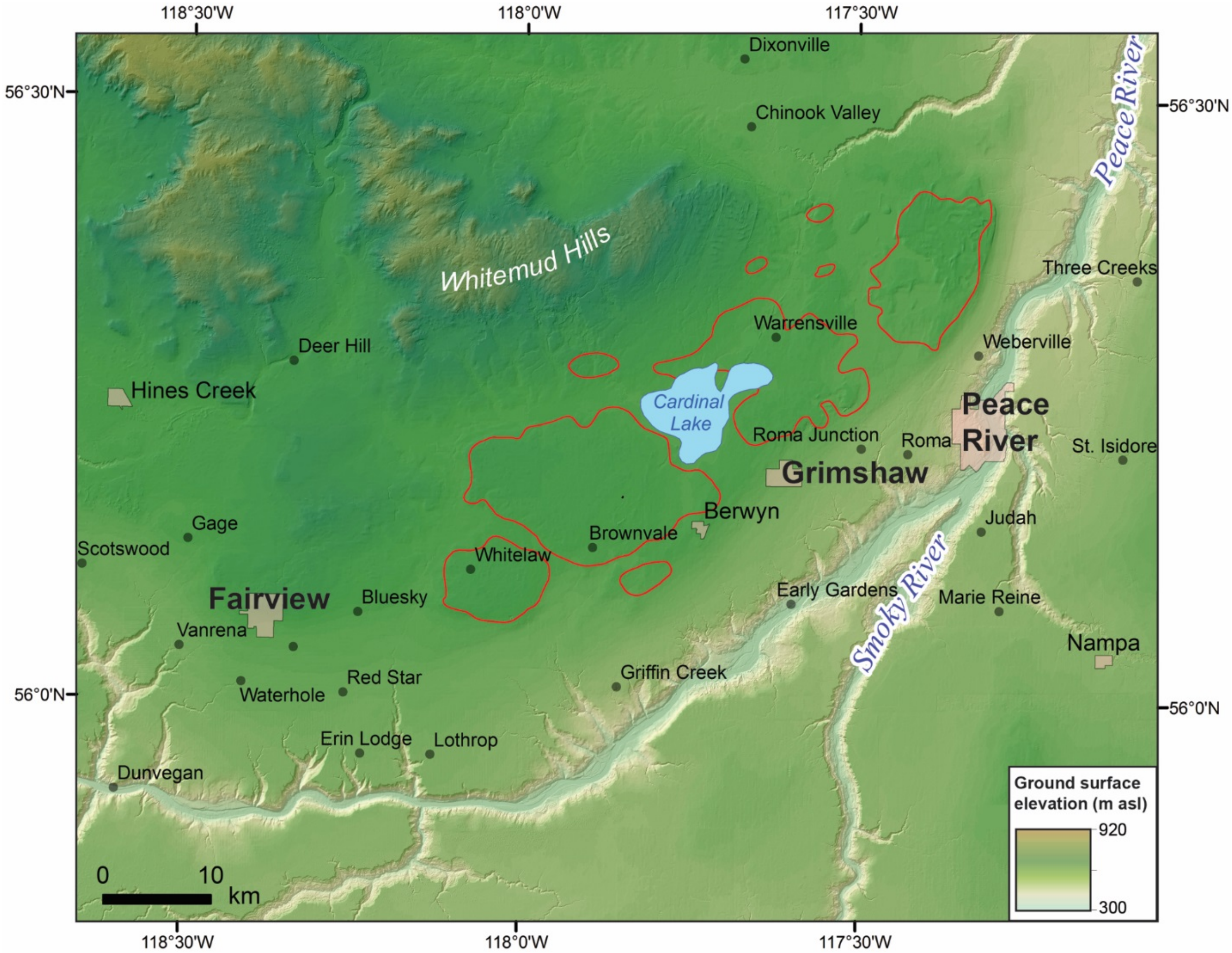


Figure 2. Grimshaw gravels (red outline; PFRA, 1998) and topographic features in the local study area, including towns (pink polygons), villages (black circles), and Cardinal Lake overlain on a hill-shaded DEM (data from AEP, 2015).

(AWWID), and a summary of the aggregate resource potential within the study area based on the updated geological framework. Additionally, it includes background information on bedrock geology and topography, Cenozoic stratigraphy and physiography, and a literature review of the state of knowledge on the hydrogeology and on aggregate resources of the Grimshaw gravels area prior to the work completed and presented in this report. The geological framework is constructed by examination of subsurface geological data collected in the field and interpreted from AWWID lithology logs, oil and gas well logs, and previously recorded outcrop and borehole logs (Leslie and Fenton, 2001; Botterill, 2007; Morgan et al., 2008). The data and interpretations provided in this report are intended to be used primarily by municipalities, gravel pit operators, hydrogeologists, and other government groups with an interest in aquifer management and protection in the Grimshaw area.

2 Study Area Physiography and Surficial Geology

2.1 Study Area

The Grimshaw gravels are located between the Whitemud Hills (a southeastern extension of the Clear Hills upland; Pettapiece, 1986) and the Peace River valley, within the Peace River Lowland of northwestern Alberta. The largest communities on or adjacent to the Grimshaw gravels are Whitelaw, Brownvale (including Duncan's First Nation), Berwyn, Grimshaw, Warrensville, and Weberville (Figure 2). The Town of Peace River is located approximately 10 km east of the Grimshaw gravels, within the Peace River valley. Cardinal Lake is the largest waterbody in the study area (approximately 50 km² and 3 m deep). It topographically separates the Grimshaw gravels into western and eastern deposits (Figure 2).

2.2 Physiography and Surficial Geology

The physiographic classification of Alberta (Pettapiece, 1986) provides an efficient means by which to describe the physiography of the Grimshaw gravels study area. The classification system is hierarchical and includes the following three-fold hierarchy of physiographic subdivisions (from largest to smallest): regions, sections, and districts. The Grimshaw gravels are situated on the northwestern edge of the Peace River Lowland section (450–750 m asl; Figure 3), approximately between the Clear Hills (400–1050 m asl) and Utikuma Uplands (600–1000 m asl) sections. At the district level of classification, the Grimshaw gravels occupy the Cardinal Lake Plain (Figure 3), which is slightly elevated relative to the Worsley and Manning plains that bound it to the south and east, respectively. In turn, these lower plains are bounded by the Peace River valley, which is 200–250 m deep.

Tokarsky (1967) and PFRA (1998) mapped the Grimshaw gravels as four major, and five minor, areas of positive relief on the Cardinal Lake plain; the areas of positive relief are termed 'lobes' (Figure 4). The

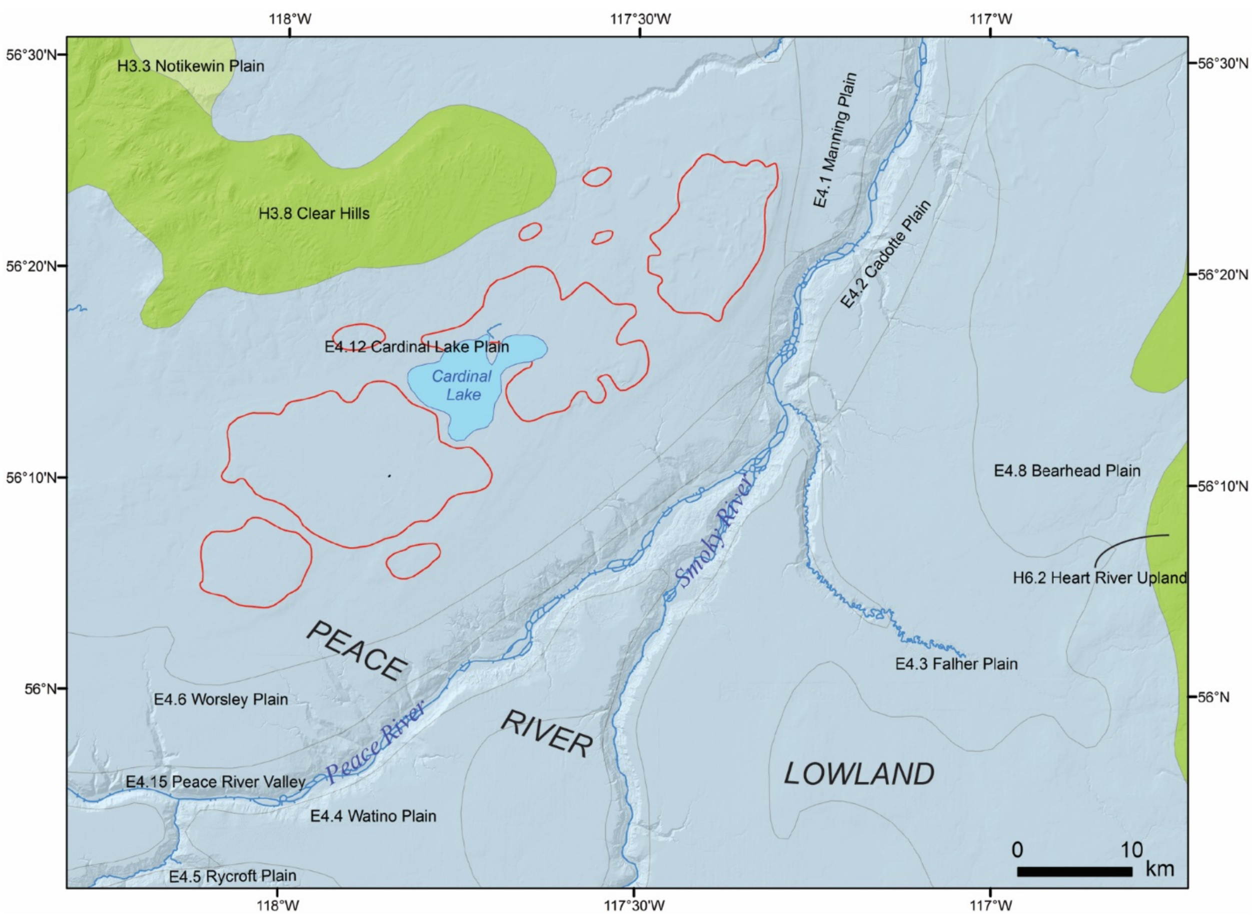


Figure 3. Physiographic districts in the local study area (from Pettapiece, 1986), draped on a hill-shaded DEM (data from AEP, 2015). The Grimshaw gravels (red outline) are located within the Cardinal Lake Plain district in the Peace River Lowland physiographic section.

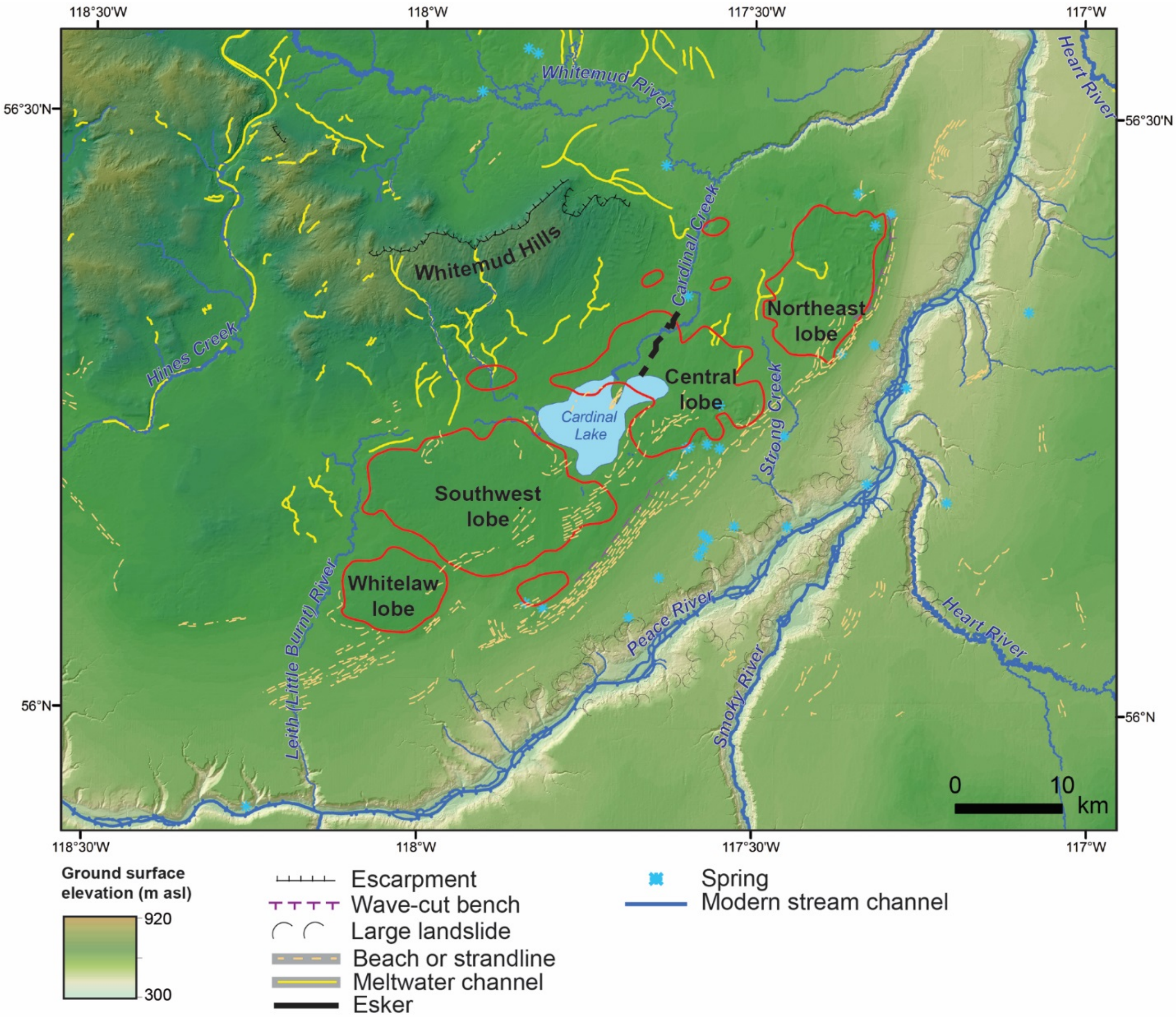


Figure 4. Modern stream and glacial outwash channels, former shorelines, eskers (Paulen, 2005; Atkinson and Paulen, 2010b), and springs in the local study area, overlain on a hill-shaded DEM (data from AEP, 2015). Lobes of the Grimshaw gravels (red) are labelled (southwest, central, and northeast lobes named by PFRA, 1998; Whitelaw lobe named in this report).

lobes are generally flat topped with steep margins. The major lobes extend from northeast to southwest, roughly parallel to the Peace River: the northeastern lobe (near Weberville; Figure 2); the central lobe (near Grimshaw); the southwestern lobe (at Brownvale; PFRA, 1998); and, named herein, the Whitelaw lobe (at Whitelaw; Figures 2 and 4). The total area of all major lobes of the Grimshaw gravels is approximately 500 km², each accounting for 50–200 km². The total area of the minor lobes is approximately 20 km² (Figure 4). The lobes are composed predominantly of gravel and capped by finer grained glacial sediment, including till and glaciolacustrine deposits (Figure 5; Tokarsky, 1967, 1971; PFRA, 1998; Paulen, 2005; Atkinson and Paulen, 2010b).

The Grimshaw gravels lobes are separated, and dissected in places, by glacial meltwater channels (PFRA, 1998; Paulen 2005; Atkinson and Paulen, 2010b) that are commonly overlain by small lakes and tributary streams to the Peace River (e.g., Leith River; Figures 4 and 5). In addition to detailed mapping of the surficial geological materials of the Grimshaw gravels area (Figure 5), Paulen (2005) and Atkinson and Paulen (2010b) mapped a number of glacial landforms on and adjacent to the Grimshaw gravels,

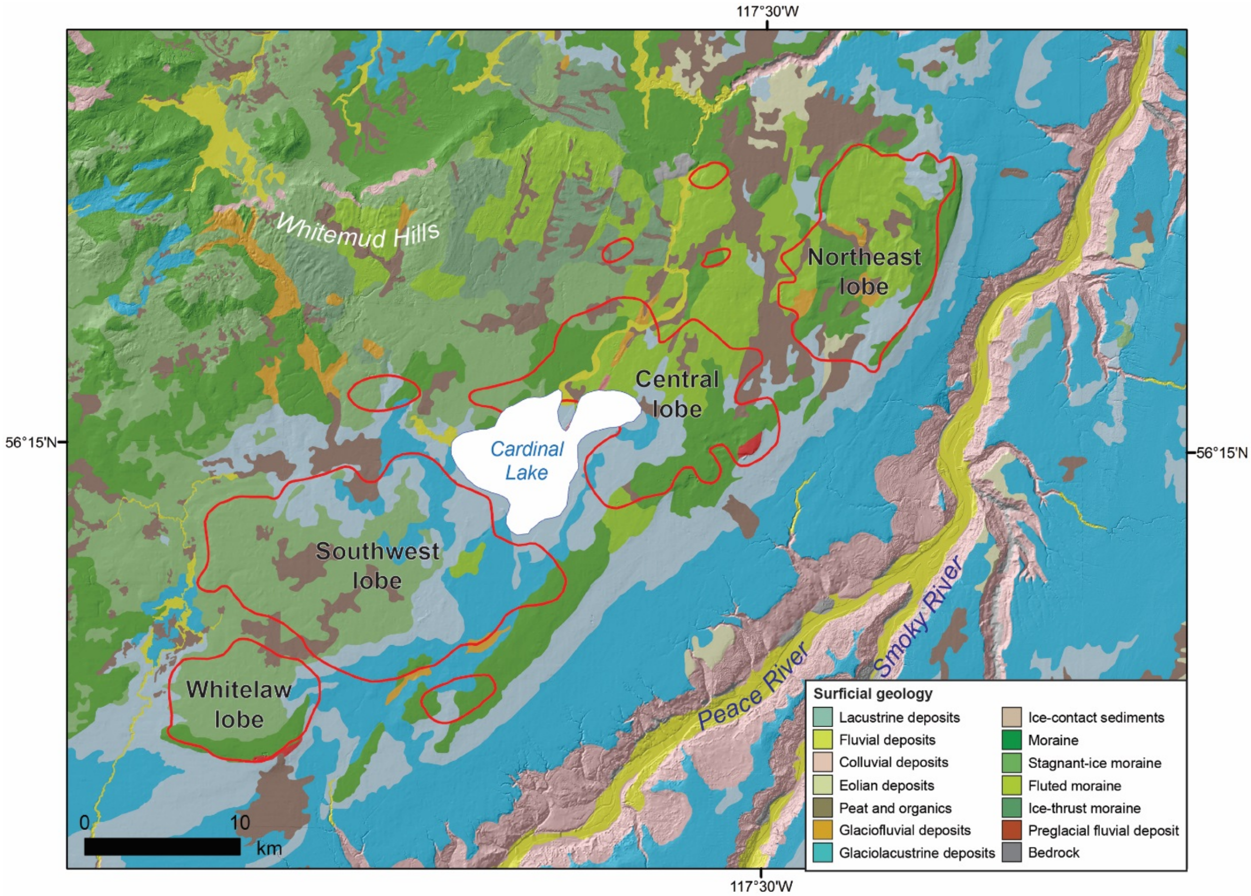


Figure 5. Surficial geology of the Grimshaw area from Paulen (2005) and Atkinson and Paulen (2010b), draped on a hill-shaded DEM (data from AEP, 2015). Lobes of the Grimshaw gravels (red) are labelled.

including glacial flow lineations, an esker that extends from the central lobe to Cardinal Lake (Figure 4), and a small area of sand dunes on the southern portion of the northeastern lobe. Paulen (2005) and Atkinson and Paulen (2010b) also mapped a series of beaches and strandlines mainly along the southeast margin of the Grimshaw gravels lobes (Figure 4). The beaches and strandlines are associated with decreasing water levels during the paleogeographic evolution of Glacial Lake Peace (Deadwood stage; cf. Slomka and Utting, 2017).

3 Geological Background

3.1 Bedrock Geology

The western half of the Grimshaw gravels (west of Cardinal Lake) overlies primarily the Kaskapau Formation, which is composed of marine shale and siltstone. The eastern half of the Grimshaw gravels overlies the Dunvegan Formation, which is coarser grained than the Kaskapau Formation and composed of deltaic sandstone, siltstone, and shale (Figure 6; Hathaway et al., 2013; Prior et al., 2013). The bedrock that underlies the Grimshaw gravels is Upper Cretaceous in age.

3.1.1 Bedrock Topography

At a regional scale, the land-surface topography largely resembles the bedrock topography. Within the Peace River Lowland (Figure 3), however, the coherence between bedrock topography and the land-

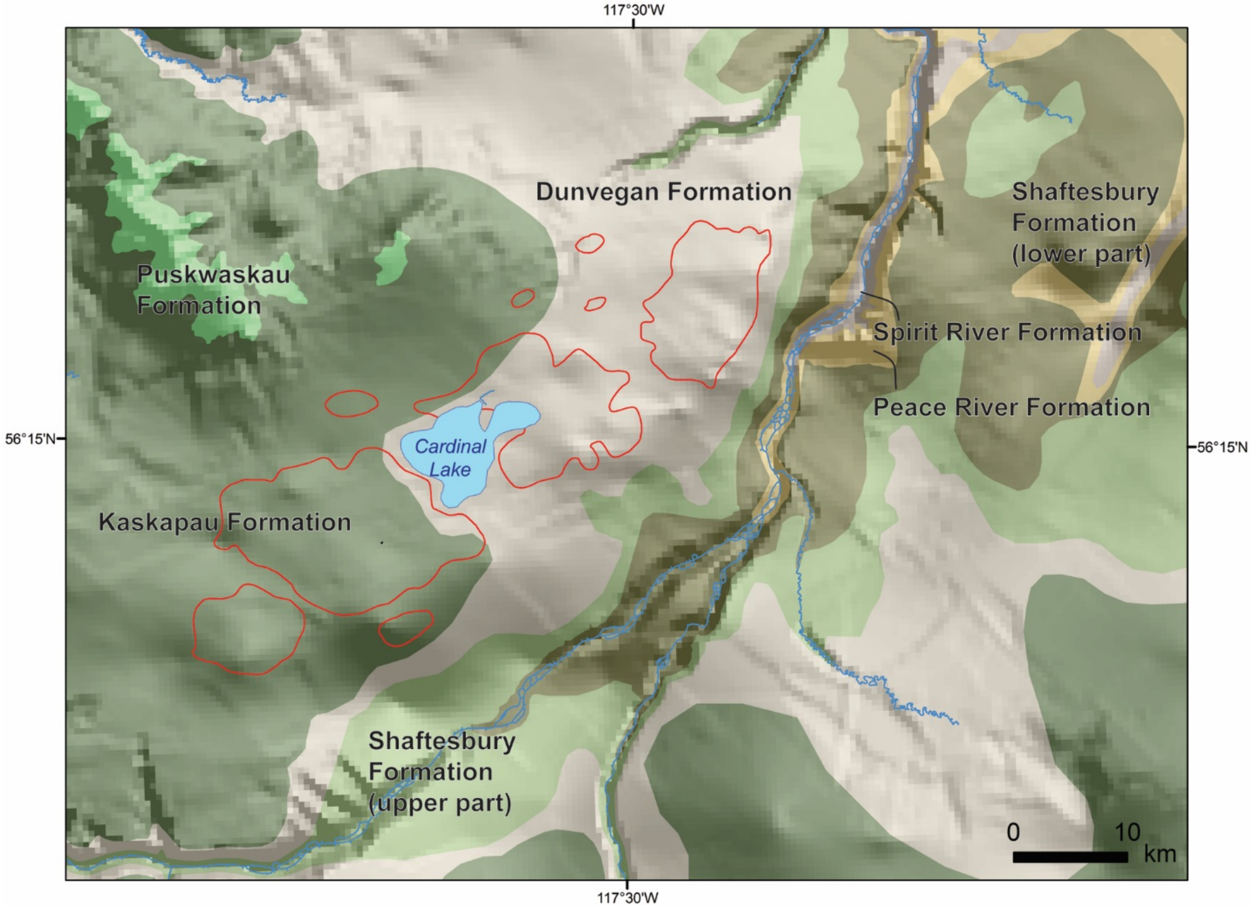


Figure 6. Bedrock geology of the local study area (and east of the Peace River), draped over a hill-shaded DEM of bedrock topography (MacCormack et al., 2015a). The Grimshaw lobes (red outline) are underlain by the Kaskapau and Dunvegan formations (Prior et al., 2013).

surface topography is less apparent due to the presence of thick accumulations of sediment within buried bedrock valleys (Figure 7). Tokarsky (1967) identified the Shaftesbury bedrock valley (300–400 m asl), which is superposed by, but much broader than, the modern Peace River valley adjacent to the Grimshaw gravels.

A strath is a type of fluvial terrace formed by fluvial erosion of bedrock surfaces, which are commonly overlain by fluvial gravels and result from a balance between sediment-transport capacity and sediment supply in channels (Mackin, 1948), and may record a transition from a single-thread to braided channel (Finnegan and Balco, 2013). The Grimshaw gravels are located on a bedrock strath (600–700 m asl) positioned between the Whitemud Hills bedrock upland and the Shaftesbury bedrock valley (PFRA, 1998). A second strath (400–600 m asl) occurs between the Grimshaw gravels strath and the Shaftesbury bedrock valley. Tokarsky (1967) identified gravel upon the intervening strath that he termed 'intermediate terrace gravels'. Following the above definition of a 'strath', the bedrock floor of the Shaftesbury bedrock valley is also a strath where it is incised by the modern Peace River.

At a local scale, the Grimshaw gravels lobes are underlain by positive-relief bedrock topography, which is apparent in a southwest to northeast topographic profile of the bedrock topography (Figure 7). Areas between the Grimshaw gravels lobes have negative-relief bedrock topography as a result of bedrock valleys formed by meltwater channel incision (Section 2.2). One such bedrock valley, the 'Berwyn channel' (Tokarsky, 1967), underlies Cardinal Lake and separates the southwestern and central lobes; however, the geometry and continuity of the Berwyn channel are poorly defined (A–A' in Figure 7; Tokarsky, 1967; PFRA, 1998).

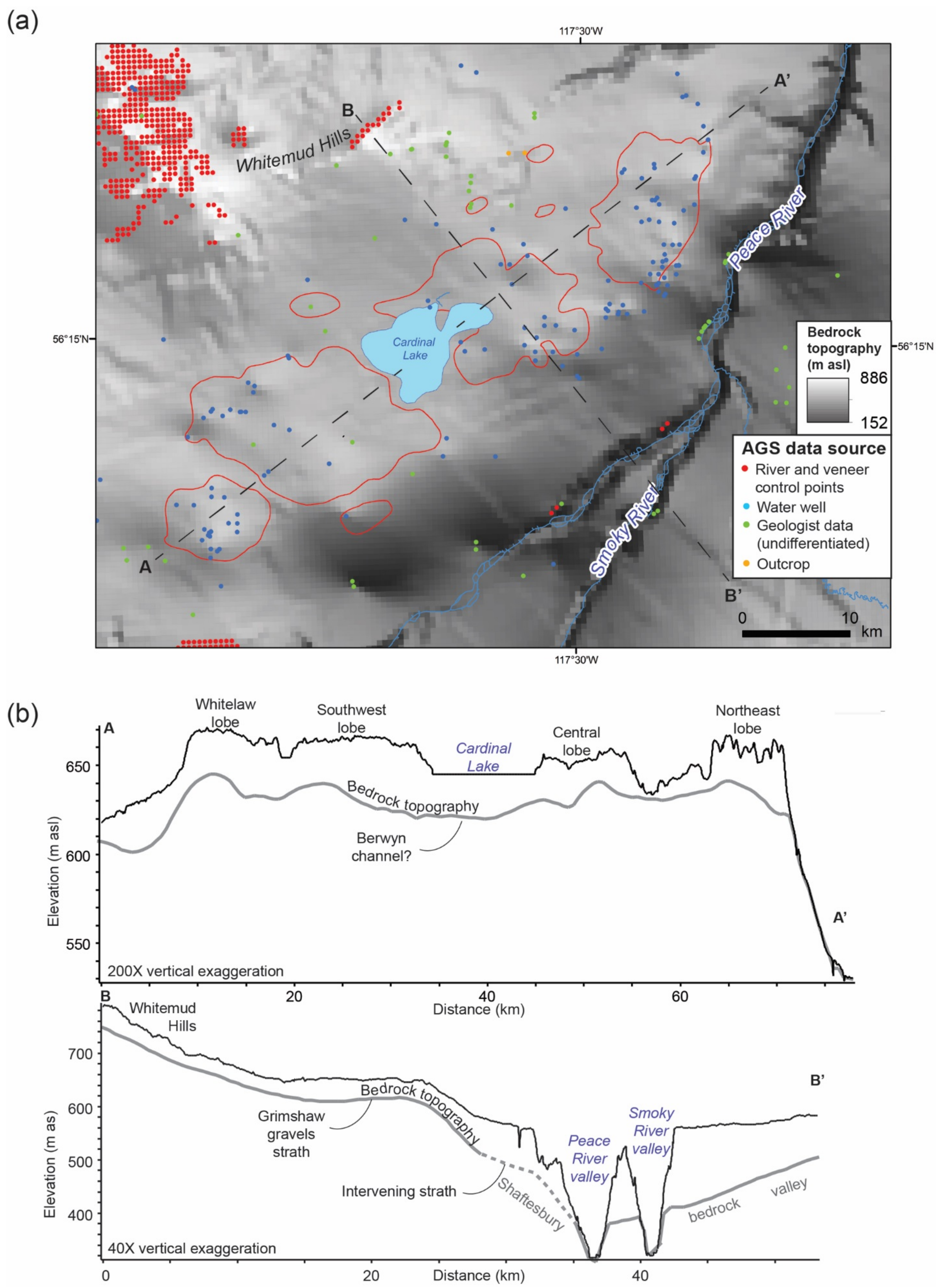


Figure 7. Bedrock and ground-surface topography in the local study area (Grimshaw gravels lobes are outlined in red): a) hill-shaded DEM of bedrock topography (500 m cell size; MacCormack et al., 2015a); coloured points indicate data sources used to construct bedrock topography (from Lyster et al., 2016); topographic profile transects (dashed lines) are labelled A-A' and B–B'; b) topographic profiles A-A' and B–B' of bedrock topography (grey line) and ground surface (black line); positive-relief bedrock topography underlies Grimshaw gravels lobes (A–A'); strath underlying Grimshaw gravels and Shaftesbury bedrock valley shown in B–B'; intervening strath between Grimshaw gravels strath and Shaftesbury bedrock valley indicated by dashed line (B–B'); note that bedrock topography is poorly defined in area of intervening strath as a result, in part, of poor data control (in part a).

3.2 Basal Sand and Gravel Deposits

3.2.1 History and Stratigraphy

At a provincial scale, uplift, fluvial incision, and erosion have removed an approximately 900–1900 m thickness of sediment from the western Interior Plains (Nurkowski, 1984). Evidence of these processes is provided, in part, by relict fluvial-gravel deposits that cap plateaus and uplands distributed across the plains (e.g., the Cypress Hills in southeastern Alberta and adjacent Saskatchewan; Leckie, 2006). The rivers that deposited these gravels were likely the main drainage elements of the region, based on the thickness of the deposits and large calibre of the gravel clasts (commonly up to boulder size; Vonhof, 1969; Edwards and Scafe, 1996). The gravel, being more erosion resistant than the surrounding soft Mesozoic sedimentary bedrock, protected valley floors during cycles of uplift and erosion such that they are now topographically elevated. Howard (1960) termed this process 'topographic inversion'. Successive cycles of uplift, incision, and erosion have resulted in the emplacement of younger gravel deposits at lower topographic elevations by each successive fluvial system.

The cycles of uplift, fluvial incision, and erosion, and subsequent deposition of gravel have been investigated in southern Alberta, southern Saskatchewan, and northeastern Montana where a broad fluvial stratigraphy, resulting from four episodes of uplift, incision, erosion, and deposition, was resolved (recently reviewed by Hartman, 2015; see references therein). The four episodes are recorded by gravel deposits on the highest uplands (mid- to late Tertiary), on lesser uplands (late Tertiary), on plateaus at approximately the level of the modern plains (late Tertiary to early Pleistocene), and within valleys incised below the plains (mid- to Late Pleistocene). Within glacial limits, gravel deposits are typically buried beneath glaciogenic sediments.

Edwards and Scafe (1996) extended the four-fold stratigraphy to previously recorded gravel deposits scattered across the Alberta portion of the Interior Plains, assigning each deposit to one of four units (units 1–4; Figures 8, 9, and 10) defined primarily by elevation of the deposit relative to the general plains surface, and secondly by gravel petrology (Figure 9). Unit 4 is composed of the oldest gravel deposits that are located on the highest uplands, while unit 1 includes gravel deposits within valleys incised below the plains. Edwards and Scafe (1996) also analyzed the lithology of gravel deposits and potential source areas to identify seven stratigraphically independent lithological groups (Figure 8). Lithological group boundaries approximate divides between major paleo–river systems that are broadly superposed by modern divides at the western edge of the Interior Plains.

In northwestern Alberta, the highest (and thus oldest) gravel deposits cap the Clear Hills and Halverson Ridge (Figures 1 and 11; mapped by Green and Mellon [1962] and Scafe et al. [1989]) and have been assigned to unit 3 (Figure 9) by Edwards and Scafe (1996). In the study area, Edwards and Scafe (1996) assigned the Grimshaw gravels to unit 2 (Figure 9, Table 1). Other gravel deposits that may stratigraphically correlate with the Grimshaw gravels have been previously mapped north of Hines Creek (Edwards and Budney, 2009), at Fairview (Edwards and Budney, 2009), and west of Berwyn (Figure 2; Edwards et al., 2004). Furthermore, Tokarsky (1967) noted that a gravel deposit near Cherry Point may correlate with the Grimshaw gravels, and Atkinson and Paulen (2010a) suggested that gravel deposits underlying till in the Cleardale area (Figure 1) may also be equivalent to the Grimshaw gravels (Table 1). A bedrock strath that occurs between the Grimshaw lobes and Shaftesbury bedrock valley (Figures 7 and 12) is overlain by gravel (Tokarsky, 1967; PFRA, 1998) and has been called the 'intermediate terrace level' (Table 1) by Tokarsky (1967, 1971). The gravel that overlies the 'intermediate terrace' bedrock strath is presumed to be younger than the Grimshaw gravels, based on topographic elevation (Figures 7 and 12; Edwards and Scafe, 1996). Gravel deposits at the base of the Shaftesbury bedrock valley (Botterill, 2007) and other buried valleys in the study area (Rutherford, 1930; Henderson, 1959; Jones, 1966; Tokarsky 1967; Borneuf, 1981; Leslie and Fenton, 2001; Slomka, in press) are correlated with unit 1 (Table 1) of Edwards and Scafe (1996).

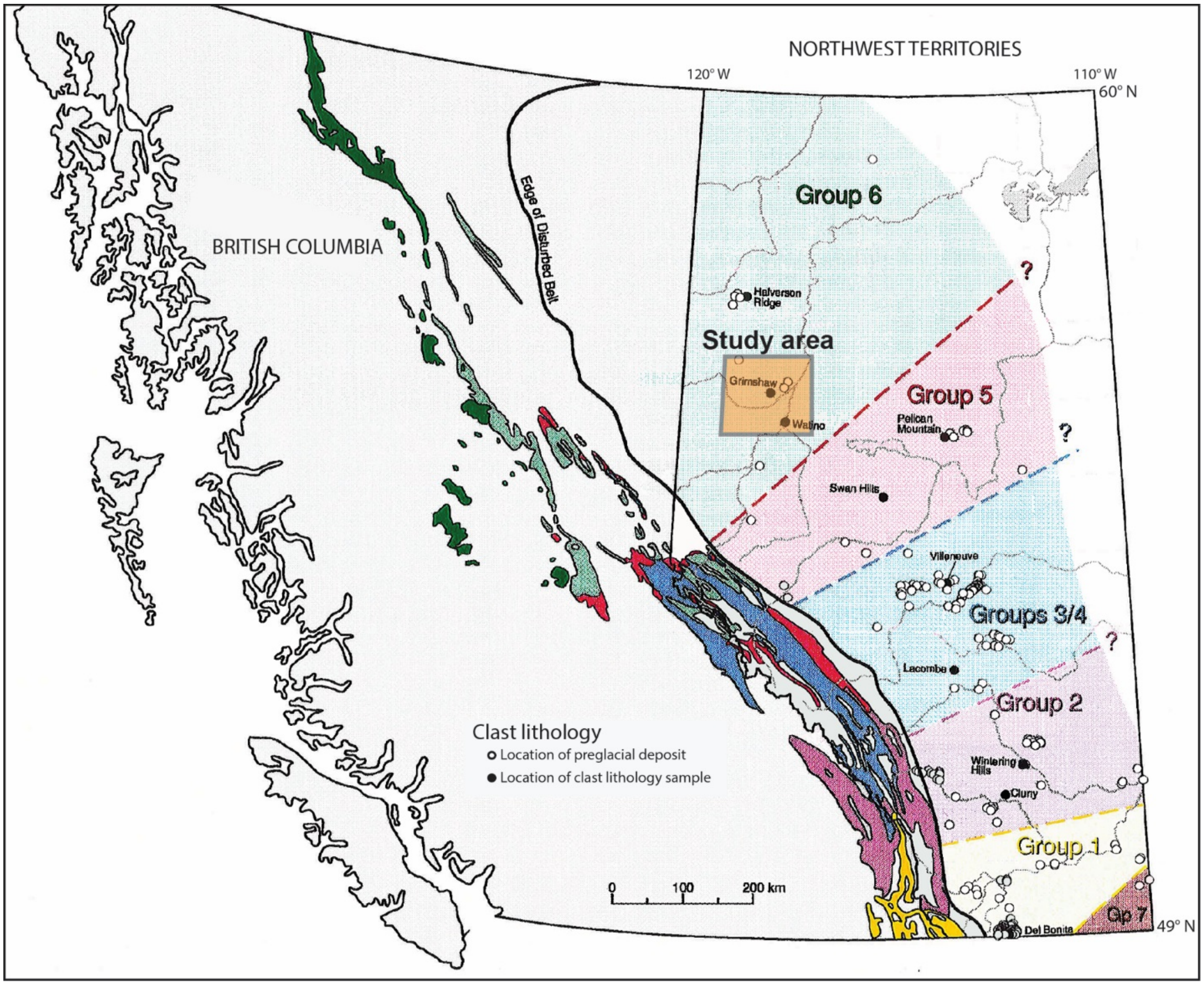


Figure 8. Sediment source area of preglacial gravel deposits classified into groups based on clast lithology (from Edwards and Scafe, 1996). Preglacial gravels of Group 6 (green-coloured source areas) are located in the study area (orange box).

3.2.2 Previous Terminology

Gravel deposits overlying bedrock and resulting from cyclic uplift, fluvial incision, and erosion of the Interior Plains have proven to be stratigraphically important because they are widely distributed, can be regionally correlated, are easily identified in borehole logs, and are informative in provenance studies. As such, a number of deposits have been mapped and named, either formally or informally (see recent review by Hartman, 2015). In particular, the lithological composition of the youngest gravels (unit 1; Edwards and Scafe, 1996) provides insight into the history of Laurentide glaciation of the Interior Plains. Gravels that were deposited prior to the first Laurentide glaciation of their watersheds do not contain material derived from the Canadian Shield (typically recognized as pink-red granite and granite gneiss), whereas those that were emplaced subsequent to Laurentide glaciation do contain this material because Laurentide glaciation is the only mechanism by which large quantities of Canadian Shield clasts could be excavated and transported up the regional slope of the plains. Once deposited on the plains, Canadian Shield clasts may be eroded from the uplands and recycled in fluvial (or glaciofluvial) deposits by rivers that generally flow down the regional slope to the northeast.

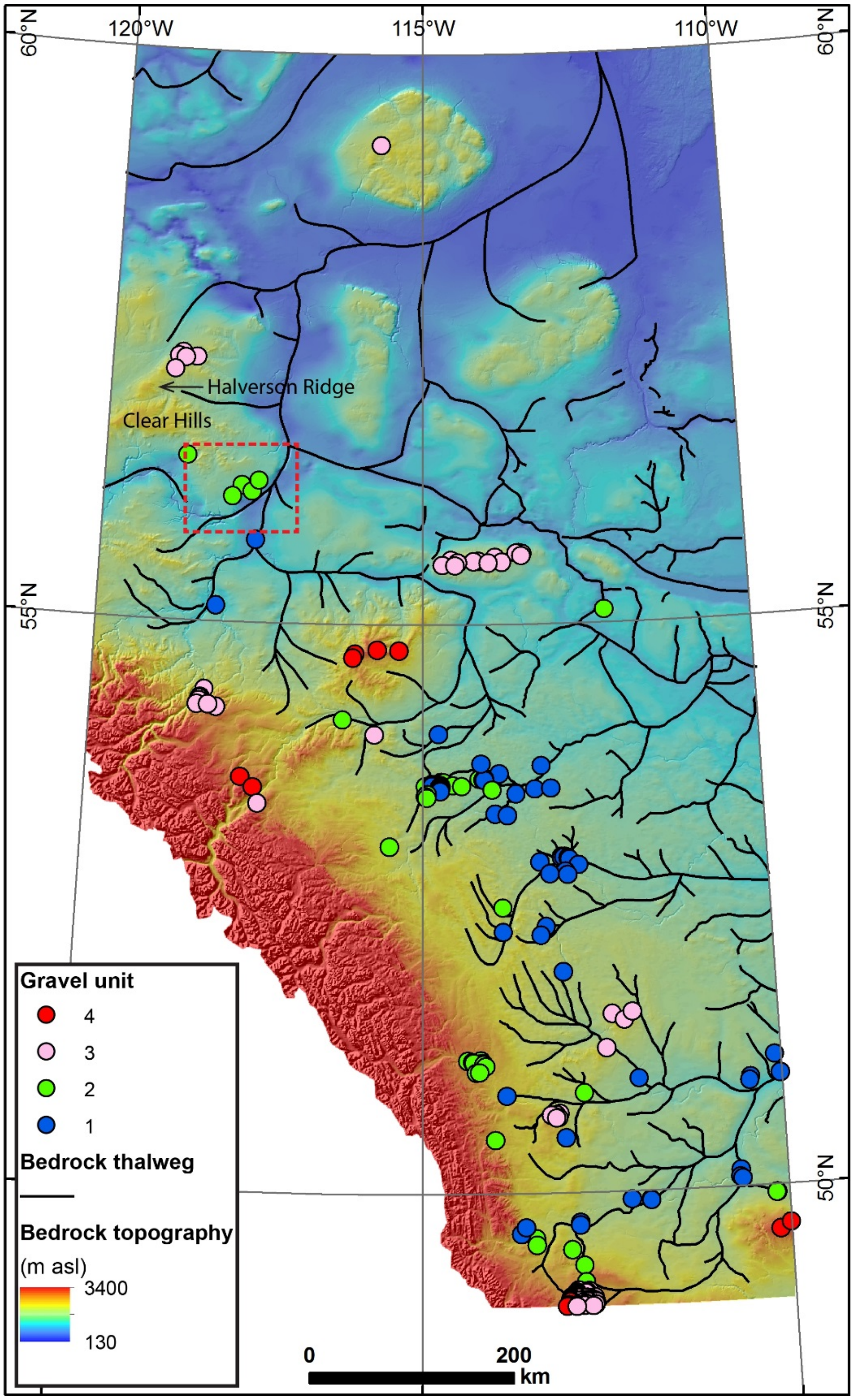


Figure 9. Preglacial deposits (units 1–4 of Edwards and Scafe, 1996), differentiated based on clast lithology and elevation (from Edwards and Scafe, 1996), overlain on a hill-shaded provincial bedrock topography DEM (MacCormack et al., 2015a). Preglacial gravels of units 1 and 2 are located in the Grimshaw study area (red dashed box). Gravel of unit 3 is located on bedrock uplands (Clear Hills and Halverson Ridge) beyond the margins of the study area. Bedrock thalwegs from Pawlowicz and Fenton (1995).

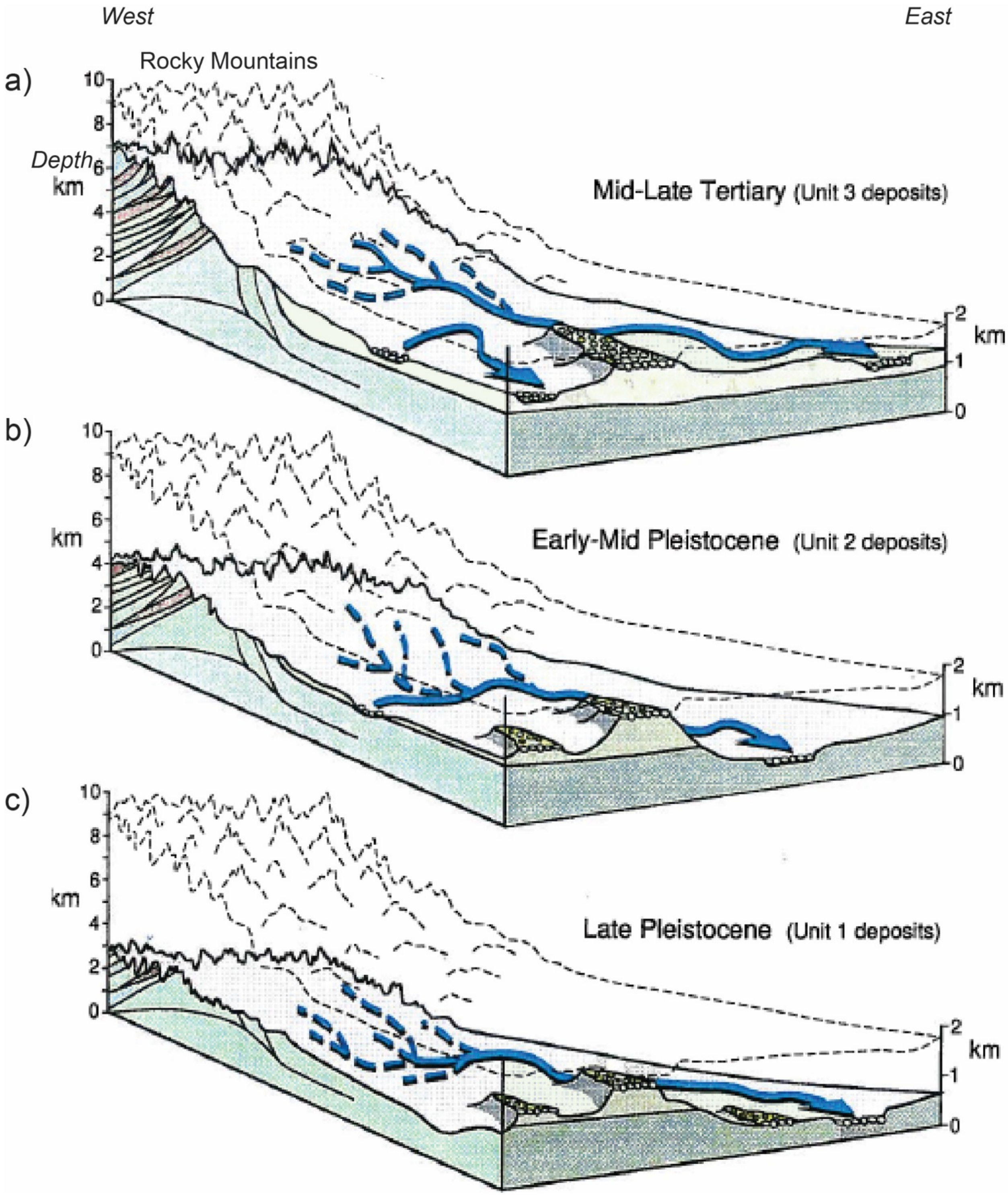


Figure 10. Conceptual block diagrams showing the deposition of preglacial gravel units 1–4 (from Edwards and Scafe, 1996) in large fluvial braidplains, which transported sediment eastwards from the Rocky Mountains. Subsequent erosion resulted in the development of gravel-capped uplands and terraces.

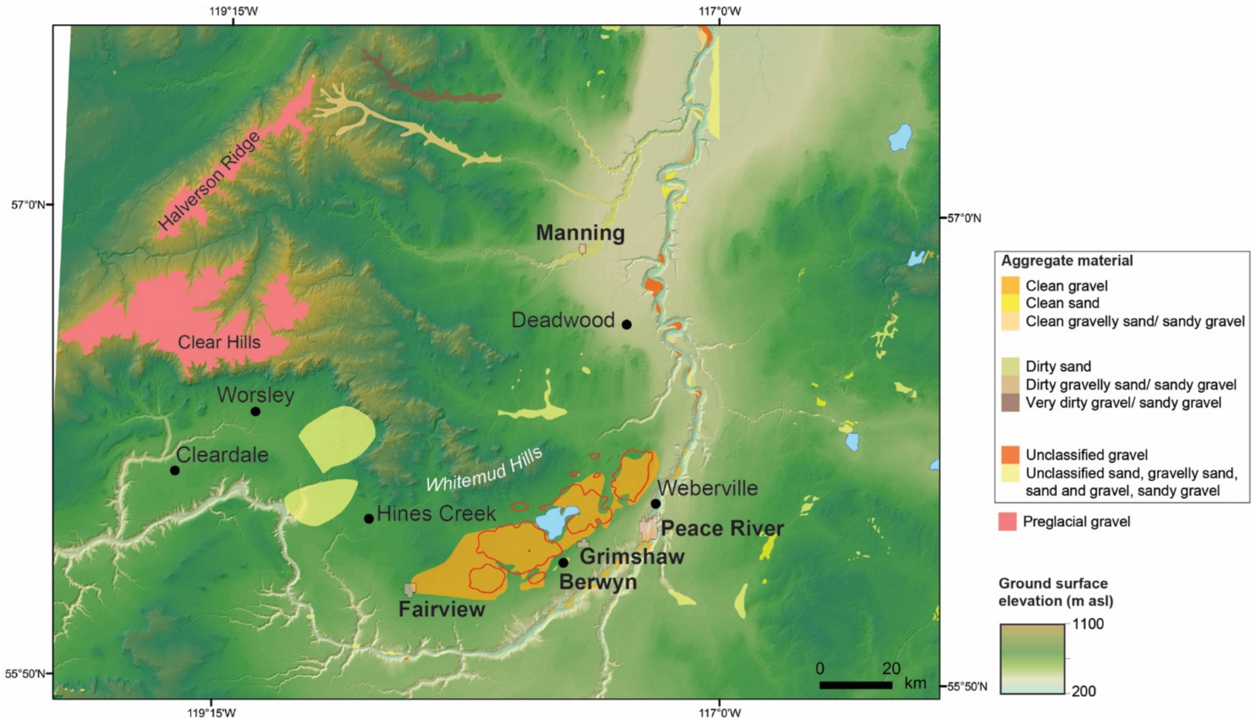


Figure 11. Sand and gravel deposits, including Paleogene preglacial fluvial deposits (dark pink; Green and Mellon, 1962; Prior et al., 2013) and aggregate materials (Edwards et al., 2004; Edwards and Budney, 2009), overlain on a hill-shaded DEM (data from AEP, 2015). Lakes are coloured in blue.

The stratigraphic significance of the presence/absence of Canadian Shield material was first recognized by McConnell (1885), who gave the name 'South Saskatchewan gravels' to exclusively Cordilleran or local provenance gravel deposits that overlay bedrock and were in turn conformably overlain by glaciogenic sediment that contained Canadian Shield material. Later, Dawson and McConnell (1895) changed the name to 'Saskatchewan gravels' to reflect their distribution beyond the watershed of the South Saskatchewan River. Rutherford (1937) applied the name 'Saskatchewan gravels and sands' to numerous deposits at various topographic elevations across Alberta and relaxed the requirement that Saskatchewan gravel be conformably overlain by glaciogenic sediment. As such, the term became synonymous with 'preglacial gravel' and could be applied to gravel deposits of varying ages that had been emplaced at varying topographic elevations. Horberg (1954) concluded that the term 'Saskatchewan gravels', being applicable to deposits of varying genesis and age, served no stratigraphic purpose and should be dismissed. However, Stalker (1968) provided criteria by which to differentiate Saskatchewan gravels from other gravel deposits and incorporated it as the basal unit in his stratigraphy of the southwestern Interior Plains. Whitaker and Christiansen (1972) formalized the 'Saskatchewan Gravel' as the lowest formation in the 'Empress Group', which is conformably overlain by stratified fine-grained sediment capped by diamicton bearing Canadian Shield lithologies.

Re-establishment of the requirement for a conformable contact between 'Saskatchewan Gravel' and overlying fine-grained glaciolacustrine sediment (Whitaker and Christiansen, 1972) indicates that gravel deposition was active immediately prior the first advance of Laurentide ice within the watershed from which the gravel was derived (McConnell, 1885; Stalker, 1968; Hartman, 2005; Slomka and Utting, 2017). As such, identification of Saskatchewan gravel persists as an important baseline in stratigraphic studies. However, due to episodic and increasingly extensive Laurentide glaciations of the Interior Plains, Saskatchewan gravel is likely time transgressive (Cummings et al., 2012). Importantly, the Saskatchewan gravel or other 'preglacial' gravels are preglacial with respect only to Laurentide glaciation. Relative to

Table 1. Regional correlation of units in the Peace River Lowland (Alberta and British Columbia), including absolute dates (if available) and source publications.

	British Columbia (west Peace River Lowland)	Alberta (east Peace River Lowland)	Radiocarbon dates (^{14}C ka BP)	Source
Shaftesbury gravel (youngest)	Lower paleovalley gravel		27.4 ±0.58 (tooth); 26.45 ±0.31 (bone)	Mathews (1978), Hartman (2005), Hartman and Clague (2008)
		Deeply buried channel deposits		Tokarsky (1967)
		Unit 1: Saskatchewan Sands and Gravels		Edwards and Scafe (1996)
		Unit B: Early and Late Glacial Advance deposits		Leslie and Fenton (2001)
		Middle Wisconsinan fluvial sediments	25.12 ±0.14 (antler)	Botterill (2007), Morgan et al. (2009)
		Unit 1, subunit c (U1c)		Slomka (in press)
Old Fort gravel	Upper paleovalley gravel			Mathews (1978), Hartman (2005), Hartman and Clague (2008)
		Intermediate-level terrace deposits		Tokarsky (1967)
		Buried terrace gravels		PFRA (1998)
		Grimshaw sediments		Morgan et al. (2009)
Grimshaw gravels (oldest)	High planation surface gravel			Hartman (2005), Hartman and Clague (2008)
		High-level deposits; 'Grimshaw gravels'		Tokarsky (1967, 1971); PFRA (1998)
		Unit 1: Grimshaw gravels		Chlachula and Leslie (1998)
		Unit 2: Upland Gravels; Grimshaw		Edwards and Scafe (1996)
		Unit A: preglacial deposits		Leslie and Fenton (2001)
		LTA 4: Interbedded gravel and fine- to medium-grained sand		Atkinson and Paulen (2010a)
		Grimshaw sediments		Morgan et al. (2009)
		Unit 1, subunit b (U1b)		Slomka (in press)

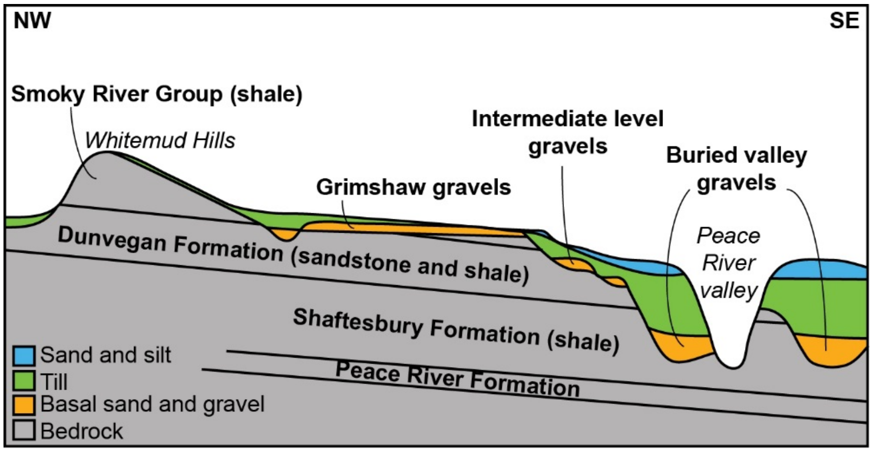


Figure 12. Conceptual geological cross-section of basal sand and gravel and overlying glaciogenic sediment, from the Whitemud Hills to the Peace River valley. The basal sand and gravel deposits are named following Tokarsky (1967, 1971).

glaciation by the Cordilleran Ice Sheet (CIS) from the west, a preglacial age of gravels is more difficult to determine because the preglacial sediments and outwash deposits of the CIS have similar source areas and can seldom be differentiated by the presence of an exotic lithology (cf. Jackson et al., 2011).

Due to the long history of use and intermittent dismissal and redefinition, the terms ‘preglacial’ and ‘Saskatchewan gravels’ (or variation) unduly result in confusion in the literature and are not used further in this report. Alternatively, we apply the term ‘basal sand and gravel’ (after Henderson, 1959; who used the term ‘basal gravels’) to gravel deposits overlying bedrock and underlying glaciogenic sediment. This term implies no stratigraphic information and better reflects the majority of data upon which this report is based (i.e., water well logs, in which the lithological composition of gravel units is typically not recorded). In addition, some descriptions of basal sand and gravel deposits in the Peace River Lowland have included the identification of pink granite gravel clasts potentially derived from the Canadian Shield, and thus the deposit may not strictly predate Laurentide glaciation (Jones, 1966; Tokarsky, 1967; Mathews, 1978; Hartman, 2005; Botterill, 2007; Hartman and Clague, 2008).

3.2.2.1 Grimshaw Gravels

Tokarsky (1967) conducted an extensive hydrogeological investigation of the Cardinal Lake area, which also included surficial geological mapping and analysis of borehole geological data (AWWID lithology logs, seismic shot-hole driller’s logs, and test drilling). Tokarsky (1967) described the Grimshaw gravels as at least 30 m thick and composed of well-sorted, well-rounded, and slightly flattened and elongated pebbles with sandy interbeds. Interbeds of micaceous sand are well to poorly sorted. The gravels are horizontally bedded and cross-bedded, and commonly channelized. Pebble lithologies include quartzite, quartz, and black chert, and minor amounts of low-grade metamorphic rocks (micaceous schist and banded argillite), muscovite-rich granite, ironstone, and volcanic rocks (Tokarsky, 1967; Edwards and Scafe, 1996; Chlachula and Leslie, 1998). Lithologies typical of a Canadian Shield provenance (e.g., pink-red granite and granitic gneiss) have not been previously recorded in the Grimshaw gravels (Tokarsky, 1967, 1971; Edwards and Scafe, 1996). Alkali feldspathic (pink) granites were noted by Edwards and Scafe (1996); however, these pebbles were previously attributed to a Cordilleran source (the Cassiar Suite). Paleocurrent measurements of gravel cross-bedding do not show a strong preferred orientation; however, average paleoflow is toward the northeast. Tokarsky (1967) reported paleocurrent directions in the Grimshaw gravels toward the northeast, north, and south, and less so toward the southwest and east; Edwards and Scafe (1996) reported paleocurrent toward the northeast, east-southeast, and south and west. The Grimshaw gravels are overlain primarily by Laurentide till (Tokarsky, 1967; Paulen, 2005; Atkinson and Paulen, 2010b; Figures 5 and 12).

The genetic origin of the Grimshaw gravels has been variously interpreted. Rutherford (1930) described a 'ridge' extending from Grimshaw to Fairview (Table 2) composed of Pleistocene gravels in the east (at Grimshaw) to boulder clay in the west (at Fairview), and interpreted this ridge as a potential terminal moraine. Jones (1966) interpreted the Grimshaw gravels as the deposits of a fluvial system, most likely equivalent to the Saskatchewan gravels and sands of Rutherford (1937), that predates Laurentide glaciation. Conversely, Scheelar and Odynsky (1968) classified the Grimshaw gravels as 'glaciofluvial' in an early soil survey. Based on interpretations of Scheelar and Odynsky (1968), Fox et al. (1987) mapped the Grimshaw gravels area as primarily glaciofluvial deposits and channels bounded by a tract of till on the outer margins of the Grimshaw lobes, and glaciolacustrine sediments in the area of Cardinal Lake (Figure 5). Rutherford (1937), Henderson (1959), Tokarsky (1967, 1971), Edwards and Scafe (1996), and Chlachula and Leslie (1998) previously interpreted the Grimshaw gravels as the deposits of a fluvial system that predated Quaternary glaciation. However, as a result of limited sedimentological investigation and an absence of absolute dates, the depositional history and relative age of the Grimshaw gravels, and their stratigraphic relationship to other coarse-grained deposits in the area, are not well understood.

4 Aggregate Resources Background

The Grimshaw gravels have long been recognized as an important source of aggregate in the Peace River district (Rutherford, 1930). Systematic aggregate resource mapping by the Alberta Research Council in the 1980s (summarized in Fox et al., 1987) consistently assessed the deposit as high-quality aggregate, based on the high proportion of gravel and low proportion of fines (i.e., 'clean' gravel; Figure 11), consistent thickness (estimated at >4 m), and continuity through the subsurface. Fox et al. (1987) estimated that the total volume of the Grimshaw gravels aggregate resource was more than 2 billion cubic metres.

Edwards and Scafe (1996) provided lithological analyses of the Grimshaw gravels, which consist of predominantly coarse-grained (pebble–cobble size), clean gravel that is composed of erosion-resistant ('hard') lithologies. Edwards and Scafe (1996) classified the deposit as 'above-average' in aggregate quality and noted that, when crushed, it is suitable for use in concrete. Edwards and Scafe (1996) outlined other aspects of the deposit that enhance its utility as an economic aggregate resource, including relatively thin overburden, consistent thickness and distribution over an area of more than 1000 ha, good access to transportation routes, and rural setting of the deposit. In addition to aggregate, Edwards and Scafe (1996) measured an average of 13.97 ounces of gold per 100 000 tons of gravel for the group of gravels of which the Grimshaw deposit is a part (group 6; Figure 8). Furthermore, they noted that, in large-scale operations, gold (and platinum) have proven to be a viable by-product of gravel extraction from deposits with a similar grade in the Onoway region northwest of Edmonton.

The major constraints on extraction of aggregate from the Grimshaw gravels involve measures taken to protect and preserve the Grimshaw gravels aquifer, which is simply the portion of the gravel deposit below the seasonally high water table (PFRA, 1998; Mackenzie Municipal Services Agency, 2011). The most significant of these, from a resource point of view, is the maintenance of a 3 m thick buffer between the bottom of an aggregate pit and the high water table.

Other aggregate resources (or potential aggregate resources) that have been identified in the study area include large areas on the upper surfaces of the Clear Hills and Halverson Ridge (Green and Mellon, 1962; Prior et al., 2013), two large areas between Worsley and Hines Creek, and isolated smaller deposits (Figure 11). However, the two areas of aggregate identified between Worsley and Hines Creek ('unclassified' in Figure 11), and the preglacial gravel deposits on the Clear Hills and Halverson Ridge, have not been assessed for aggregate quality; the smaller, isolated aggregate deposits in the Peace River Lowland are generally of lower quality and smaller in lateral extent than the Grimshaw gravels (Figure 11).

5 Hydrogeological Background

The Grimshaw gravels form one of the most important aquifers in the Peace River region because of their high yields and excellent water quality (Tokarsky, 1971; PFRA, 1998). Tokarsky (1967, 1971) and PFRA (1998) identified separate aquifers delineated as separate gravel bodies (lobes; Figure 4) within the Grimshaw gravels, which are together locally referred to as the 'Grimshaw gravels aquifer' (termed by PFRA, 1998). The Grimshaw gravels 'lobes', sediments within adjacent buried terraces and valleys (Figures 7 and 12), overlying glaciogenic sediment, and the local surface water bodies, springs (Figure 4), and wetlands all make up the aquifer system in the study area (PFRA, 1998).

The main aquifers within the aquifer system are the near-surface Grimshaw gravels, which receive recharge primarily from rain or snowmelt, although local recharge can occur from surface water bodies such as Cardinal Lake (Tokarsky 1971; PFRA, 1998). The groundwater flow direction within the Grimshaw gravels is typically from northwest to southeast (PFRA, 1998). Areas of high groundwater levels that are unrelated to ground surface topography are commonly indicative of a perched aquifer (Tokarsky 1971; PFRA, 1998). Artesian flow conditions have been recorded at the base of the Whitemud Hills (mainly wells completed in the Dunvegan Formation) and on the southeast margin of the Grimshaw lobes (which includes wells that are screened in Dunvegan bedrock or the Grimshaw gravels; cf. Rutherford, 1930; Tokarsky, 1971).

Overlying glaciogenic deposits (primarily fine-grained till and glaciolacustrine sediments; Figure 5) act as natural protection for the Grimshaw gravels aquifer, as they can inhibit or prevent downward movement of contaminants. These deposits vary in both thickness and sedimentological heterogeneity (cf. Slomka and Utting, 2017) and are not present in all areas (Figure 5), making the Grimshaw gravels susceptible to groundwater contamination from surface in places (PFRA, 1998). Tokarsky (1971) found that recharge areas within the Grimshaw gravels are characterized by fresh calcium bicarbonate waters, whereas discharge areas show an increase in total dissolved solids (TDS), iron, sodium, and sulphate (which may also be present in recharge areas); Tokarsky (1971) also noted that groundwater with moderate levels of calcium sulphate ($CaSO_4$) is common throughout the study area.

6 Methods

6.1 Fieldwork (Grimshaw Gravels)

Fieldwork was conducted in July 2016 and involved recording 13 sedimentary logs from outcrop exposures in active gravel pits in the Grimshaw gravels. Sedimentary logs include grain size, sedimentary structure, rounding, size, and lithology of gravel clasts; facies types and the nature of facies contacts (e.g., erosional, conformable); and paleocurrent measurements (Figure 13). Sedimentary logs were superimposed on photomosaics of outcrop faces, and major facies contacts were delineated between logs, aided by field sketches, to record the geometry and spatial relationship of beds.

Facies types were interpreted based on facies models (e.g., Postma, 1990; Eyles and Eyles, 2010; Miall, 2010) and comprise matrix-supported massive gravel (Gmm; may contain clayey sand, Gmm(c)); weakly matrix-supported, massive imbricated gravel (Gmi); clast- and matrix-supported graded gravel (Gcg, Gmg; normal grading); clast-supported, massive and crudely horizontally bedded gravel (Gcm(h)); clast-supported stratified gravel (Gms); and matrix- and clast-supported, planar (Gp) and deformed gravel (Gd). Sand facies comprise planar cross-bedded, medium- to coarse-grained sand (Sp); low-angle cross-bedded, medium- to pebbly coarse-grained sand (Sl); trough cross-bedded, medium- to pebbly coarse-grained sand (St); and deformed very fine to pebbly coarse-grained sand (Sd(g)). Fine-grained facies are rare and grouped into massive clay, silt, and mud (Fm). Diamict facies are recorded above the Grimshaw gravels, and include matrix-supported, massive clayey diamict (Dmm); and matrix-supported, stratified diamict and sorted sediment (Dms). Facies types are recorded in logs in Figure 13, and summarized in Table 2.

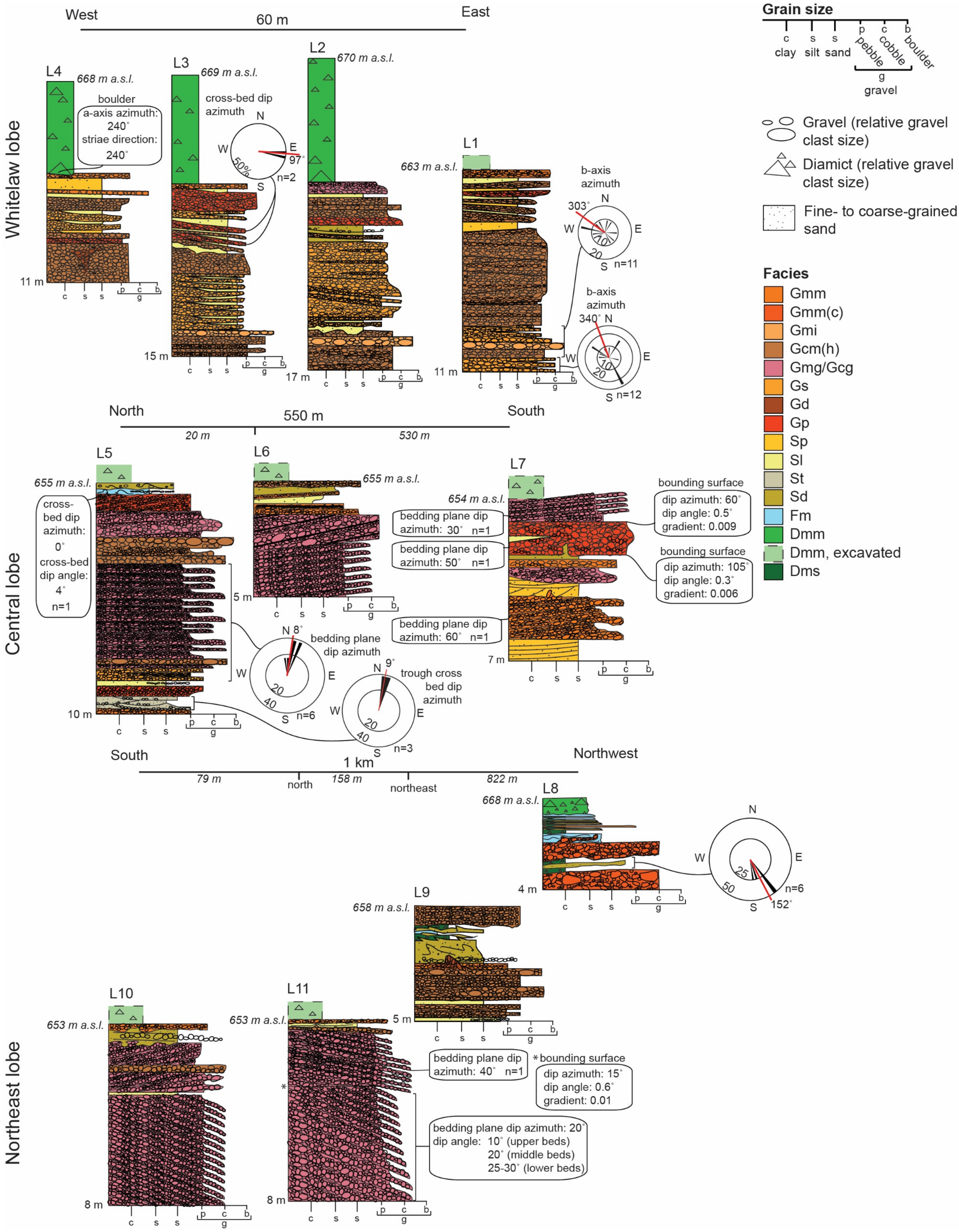


Figure 13. Sedimentological logs (L1–L11) recorded from outcrop in the Grimshaw gravels area. Facies codes are included to the right of each log. See Table 2 for facies codes.

Table 2. Facies codes, description, and interpretation (facies codes modified from Eyles et al., 1983; Miall, 2010).

Facies	Grain size	Sedimentary Structure and Bedding	Thickness and Lateral Extent	Interpretation
Gmm: matrix-supported, massive gravel	Granule to pebble in a silty, medium- to coarse-grained sand matrix	Massive tabular bed (pockets in Gs facies)	Pockets are 0.1 m thick, bed is ~1 m thick and tens of metres in lateral extent	Cohesive, viscous debris-flow deposit (Miall, 2010)
Gmm(c): matrix-supported, massive, very poorly sorted, clayey sandy gravel	Granule to boulder in a silty sand matrix (rare coal and ironstone nodules)	Apparently massive (structureless) dipping beds	1–2 m thick, ≥15 m in lateral extent.	Slumping and backwasting of sand and gravel, likely as a result of downwasting of buried ice (Kjær and Krüger, 2001)
Gmi: weakly matrix-supported, imbricated gravel	Granule to cobble in a silty, medium- to coarse-grained sand matrix	Imbrication; wedge- to lens-shaped beds and isolated pockets	0.1–2 m thick, beds are tens of metres in lateral extent, pockets commonly extend laterally up to 1 m	High-concentration frictional debris-flow deposit, likely generated by flood flows (Postma, 1984; Sohn et al., 1999)
Gmg: matrix-supported, graded gravel	Cobble and pebble in a silty, coarse- to very coarse grained sand matrix	Normal grading; trough-like beds in cross-section and dipping beds in longitudinal section	0.15–0.2 m thick, 5–10 m wide	High-concentration debris-flow deposit, likely generated by flood flows (Postma, 1984; Sohn et al., 1999)
Gcm(h): clast-supported, massive gravel with crude horizontal beds (modified from Gh of Miall, 2010)	Granule to boulder with medium- to very coarse grained sand matrix	Massive, crudely imbricate, commonly open-work; tabular to lens- and wedge-shaped beds	0.3–2 m thick, commonly tens of metres in lateral extent	Bedload deposition as a longitudinal bar or gravel sheet (Hein and Walker, 1977; Miall, 2010) or deposition from a noncohesive debris flow where internal bedding is not apparent (Kostic et al., 2005)
Gcg: clast-supported, graded gravel	Cobble, pebble, and granule (rare boulder); rare, very coarse grained sand matrix in gravel interstices	Normal grading; open-work gravel; trough-shaped and planar cross-beds (1 m to ≥5 m tall)	0.1–2 m thick, 3–15 m in lateral extent	Deposition from high-density turbidity currents (avalanching of oversteepened clasts resulting in debris flows; Lowe, 1982; Postma, 1984); large-scale trough and planar cross-beds record gravel dunes (Miall, 2010)
Gs: stratified matrix- and clast-supported gravel	Granule to cobble and rare medium to very coarse grained sand	Massive (rare inverse graded), crudely imbricated a-axis, texturally sorted, horizontal to subhorizontal beds and pockets	1–20 cm thick, tens of metres in lateral extent	Traction current bedload deposits (minor channel fills; Miall, 2010); rare inverse grading indicates deposition from freezing of nonturbulent debris flows (Kostic et al., 2005); crude imbrication resulted from laminar shear and grain-to-grain collision and rotation during or following deposition (Nemec, 1990; Kostic et al., 2005)
Gd: deformed gravel	Granule to cobble, clast and matrix supported	Massive gravel containing soft-sediment deformation structure (pillars and loaded contacts)	Isolated structures (pillar is 10–30 cm wide and 2 m tall)	Soft-sediment deformation as a result of water escape and liquefaction (Mills, 1983)
Gp: planar cross-bedded gravel	Clast-supported granule to pebble; massive to crude normal grading (see facies Gcg)	Cross-bedded gravel	0.5–2 m thick, <10 m in lateral extent	Avalanching of gravel clasts down foresets on the lee side of a gravel bedform (Miall, 2010)
Sp: planar cross-bedded sand	Medium- to coarse-grained sand (rare pebble)	Planar cross-bedded sand	0.5 m thick, tens of metres in lateral extent	Traction-current deposits (minor channel fill with sandy bedforms; Miall, 2010)
Sl: low-angle cross-bedded sand	Medium- to pebbly coarse- grained sand	Low-angle cross-beds and planar lamination, forming trough-shaped and tabular beds and lenses	3–10 cm thick, 1–15 m in lateral extent	Traction-current sediments deposited from the concurrent transport of sandy bedload and rolling pebbly bedload (Miall, 2010) or a turbulent high-density turbidity current (Lowe, 1982)
St: trough cross-bedded sand	Medium to pebbly, very coarse grained sand	Trough cross-beds, commonly fine upwards	0.5 m thick, at least 5 m in lateral extent (poorly exposed)	Traction-current deposits (sandy sinuous-crested dunes; Miall, 2010)
Sd: deformed sand	Very fine to pebbly coarse-grained sand (rare coal)	Folds, flames (apparently sheared in places), contorted bedding and laminae apparent by textural sorting and arrangement of dark-coloured minerals and coal	0.1–1 m thick, tens of centimetres to ≥30 m in lateral extent	Plastic deformation as a result of slumping, water escape (Mills, 1983), and frictional forces (glaciotectonism)
Fm: massive fine-grained sediment	Clay, silt, and mud	Massive, rare contorted laminae and beds, lenses, and U-shaped pockets (apparent by textural sorting)	0.01–2 m thick, 0.1–1.5 m in lateral extent	Settling of suspended load (Miall, 2010), soft-sediment deformation by water escape (Mills, 1983) or cryoturbation (Van Vliet-Lanoë et al., 2004)
Dmm: matrix-supported, massive clayey diamict	Granule to boulder in a silty clay matrix	Apparently massive (structureless), increase in average grain size along a dipping bedding plane in places, contains pink granite and gneissic gravel clasts	0.5–7 m thick, 50 to ≥100 m in lateral extent	Subglacial amalgamation of mud, sand, and gravel without subsequent textural sorting or reworking by alluvial and eolian processes (Boulton and Paul, 1976); increase in grain size on a dipping bedding plane suggests subsequent fall-sorting on a paleoslope in places (Kjær and Krüger, 2001)
Dms: matrix-supported, stratified diamict and sorted sediments	Interstratified Dmm, Fm, Sd, Gmm, and Gms	Dipping beds (downlap on Gmm(c)), folds, faults, lenses, gravel pockets contorted and convolute laminae parallel to bedding, gravel clasts are imbricated parallel to bedding in places	0.5–2 m thick, ≥15 m in lateral extent	Deposition of fine-grained suspended sediment from meltwater flows, resedimentation of diamicts by debris flows (Lawson, 1979), and deposition of gravels by backwasting (Eyles, 1979); dipping beds record postdepositional tilting of strata; faults and folds indicate postdepositional deformation, likely as a result of downwasting of buried ice (Kjær and Krüger, 2001)

Genetically and spatially related facies types were grouped into six facies associations (FAs; Dalrymple, 2010): a gravel sheet (FA1), channelized interbedded gravel and sand (FA2), gravelly macro-scale troughs (FA3), gravelly large-scale foresets (FA4), cross-stratified gravel and sand sheet (FA5a) and cryoturbated gravel and sand (FA5b), and a massive and stratified diamict sheet (FA6). Knowledge of depositional environments gained from established facies models (e.g., Postma, 1990), outcrop analogues elsewhere (e.g., Kostic et al., 2005), and modern analogues (e.g., Smith and Jol, 1997) served as the basis for interpreting the depositional environment of the facies associations.

6.2 Database

A database, constructed in RockWorks17™ (RockWare®) and VIEWLOG (EarthFX), contains previously logged core data (Slomka and Utting, 2017), previously recorded outcrop and borehole logs (Leslie and Fenton, 2001; Hartman, 2005; Botterill, 2007; Atkinson and Paulen, 2010a), AWWID lithology logs, geological test holes (Waters and Andriashek, 2014), remote sensing of gravel deposits in gravel pits, and oil and gas gamma-ray logs (current as of 2007; Figure 14). Data in the eastern part of the study area (east of Bluesky; Figure 2) were derived from an existing dataset in the Peace River area (Slomka, in press). Data in the western part of the study area were amended to the existing dataset following the stratigraphic framework outlined by Slomka (in press). The distribution and types of data are represented in Figure 14. Refer to Slomka (in press) and Slomka and Utting (2017) for a detailed description of the methodology used in core analysis.

6.2.1 Stratigraphic Assignment

Stratigraphic assignment of data presented in logs involved grouping lithological intervals in logs following the notion that similar grain sizes and sedimentary structures are deposited under similar environmental conditions, which may indicate a common depositional environment. Slomka (in press) delineated basal sand and gravel, collectively grouped as ‘Unit 1’ (herein referred to as ‘U1’), in logs in the Peace River area. However, the architecture and stratigraphy of basal sand and gravel deposits, correlated with U1 of Slomka (in press), are refined in this report (see Hartman and Slomka, 2017) and discussed in more detailed in Section 7.

6.2.1.1 Basal Sand and Gravel

The upper surfaces of U1 identified in logs were plotted on a Cartesian plane (Figure 15). The vertical axis of the Cartesian plane represents the height of the upper surface of U1 relative to the modern Peace River as represented in a 25 m DEM, which is the elevation datum used in this study (Alberta Environment and Parks (AEP), 2015; Figure 15a). The horizontal axis of the Cartesian plane represents the down-valley distance (along the general trend of the Peace River Lowland) of the log from the western edge of the Interior Plains (Figure 15b). Three distinct groups of U1 tops were identified that correlate both in relative height (Figure 16a) and plan distribution (Figure 16b) with the three bedrock straths outlined in Section 3: the Grimshaw strath, the intermediate terrace strath, and the Shaftesbury bedrock valley (refer to Section 3.1.1). Hence, U1 located on the Grimshaw strath is called the ‘Grimshaw gravels’, U1 on the intermediate terrace strath is called the ‘intermediate terrace gravel’, and U1 on the floor of the Shaftesbury bedrock valley is called the ‘Shaftesbury gravel’, following the naming convention previously used by Tokarsky (1967), PFRA (1998), and Botterill (2007). Note that the ‘intermediate terrace gravel’ is renamed the ‘Old Fort gravel’ in Section 7 of this report (see Hartman and Slomka, 2017). Detailed descriptions of each U1 subunit are included in Section 7 of this report. The U1 sediments positioned on bedrock uplands (e.g., Clear Hills, approximately 600–700 m above the Peace River; cf. Edwards and Scafe 1996) are not described in this report.

Relative to the modern Peace River, the average heights of the top of the Grimshaw, intermediate terrace (Old Fort gravel), and Shaftesbury gravel units are 320, 220, and 25 m, respectively (Figure 16a). While

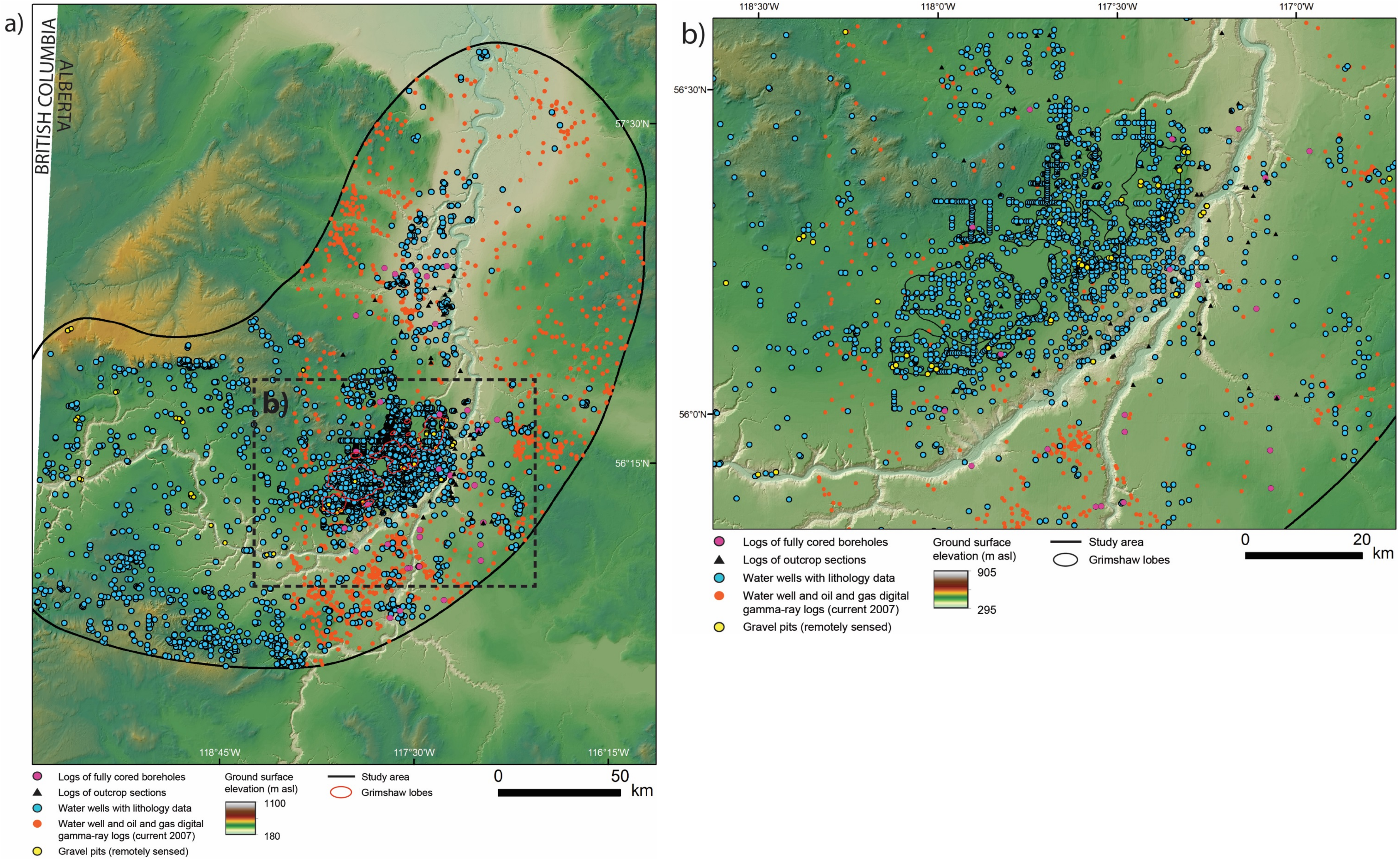


Figure 14. Data in the study area categorized by data source and overlain on a hill-shaded DEM (data from AEP, 2015): a) regional view (solid line shows extent of data assessed in regional analysis; b) local study area surrounding the Grimshaw lobes (as mapped by PFRA, 1998).

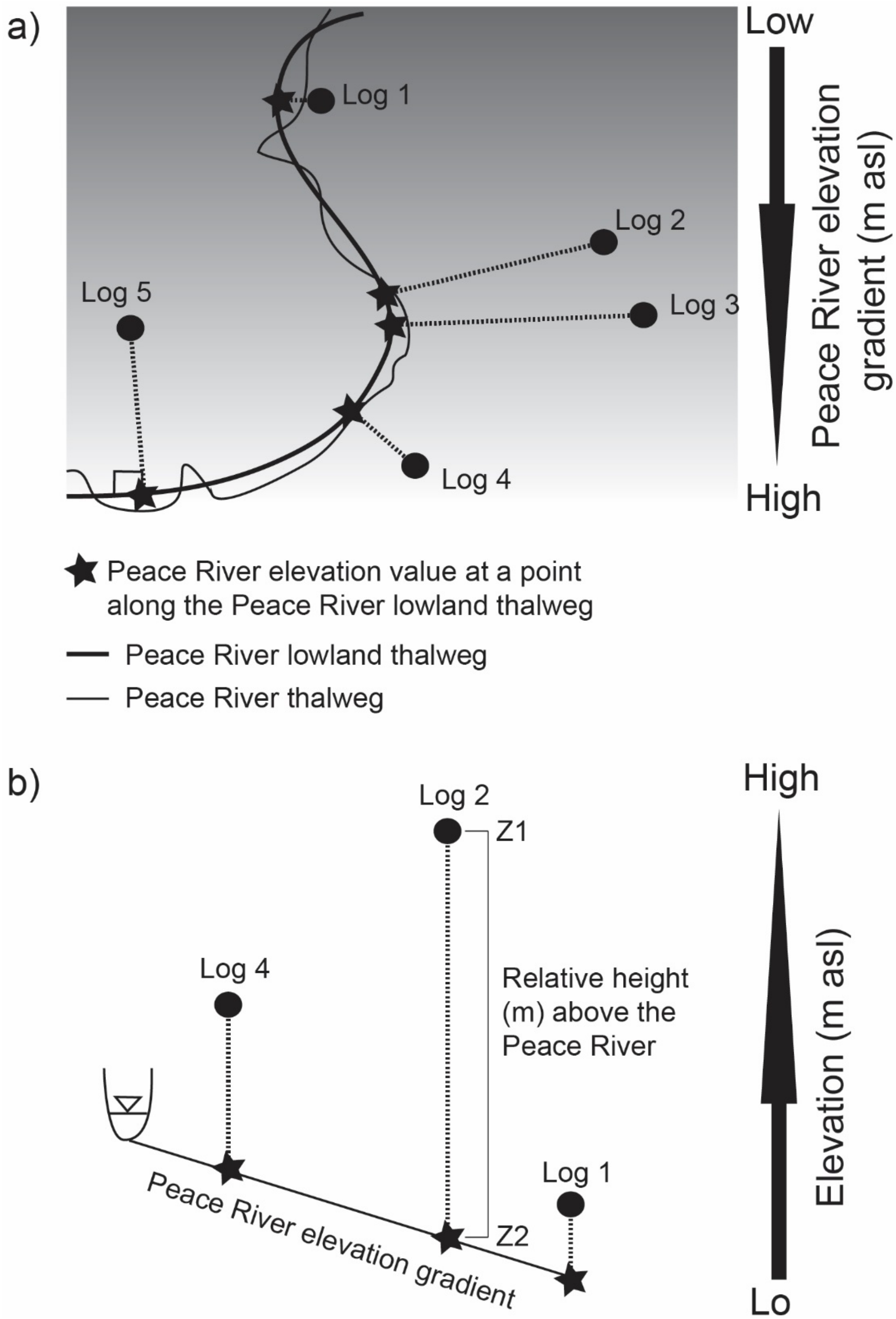
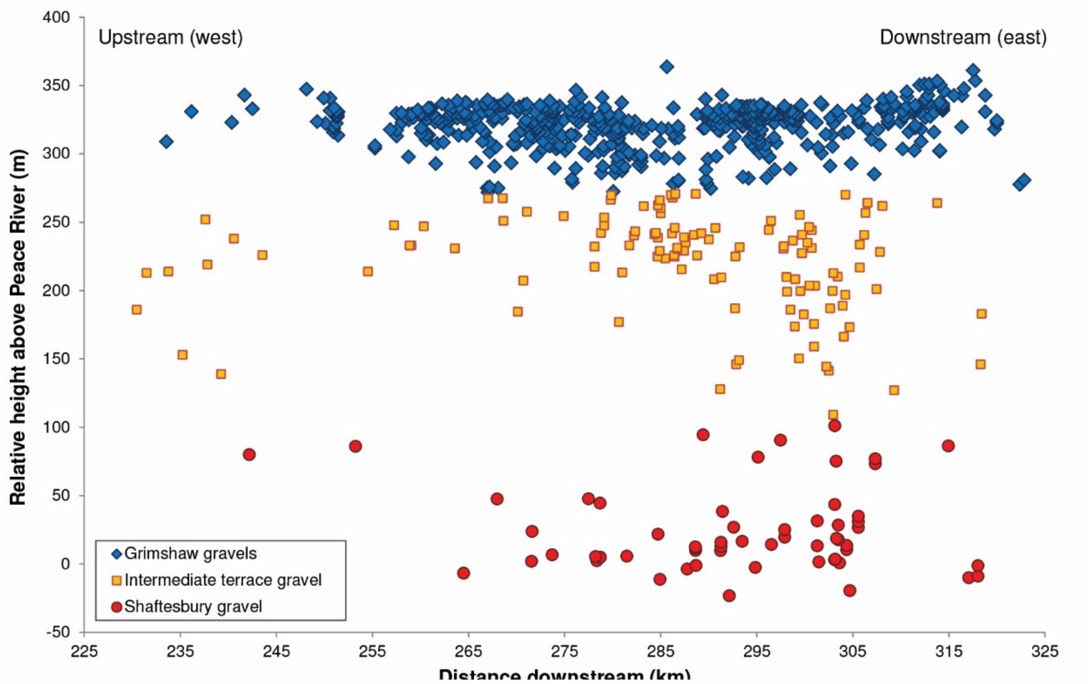


Figure 15. Conceptual schematic of the method used to calculate the relative height of the upper surface of basal sand and gravel in logs relative to the modern Peace River: a) elevation (in metres above sea level; m asl) of the Peace River is laterally extrapolated as a three-dimensional surface (shaded area), from which the height of the upper surface of U1 is measured (Z1–Z2 in b). Down-valley distance is measured along a generalized trend of the Peace River Lowland (thick line) where the log is perpendicular to the trend; b) cross-sectional view of the heights (Z1–Z2) of the upper surface of basal sand and gravel in logs relative to the gradient of the modern Peace River

a)



b)

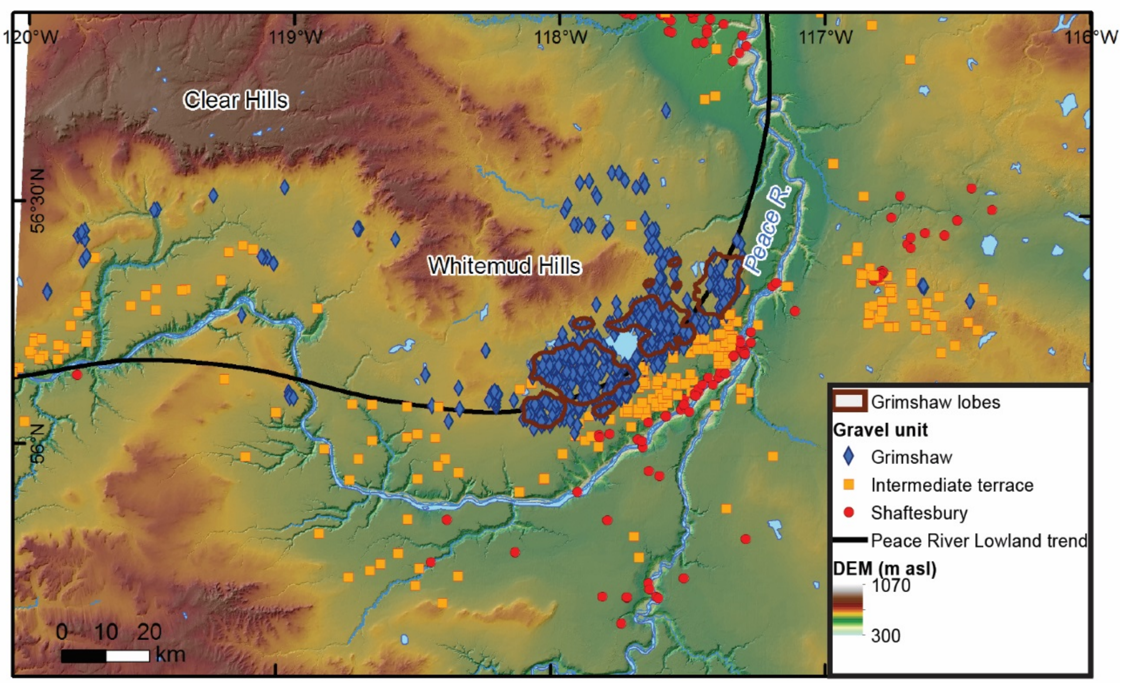


Figure 16. Relative height and plan distribution of basal sand and gravel subunits (Grimshaw gravels, intermediate terrace gravel, and Shaftesbury gravel) identified in logs (Hartman and Slomka, 2017): a) height of the upper surface of U1 above the modern Peace River plotted against distance downstream from the western edge of the Interior Plains (refer to part b for the Peace River Lowland trend used to calculate relative height and distance); b) distribution of U1 subunits grouped by relative height above the modern Peace River, overlain on hill-shaded DEM (data from AEP, 2015).

the range of heights within each U1 subunit is broad, the height ranges of each subunit do not overlap. In places within a subunit, the highest value of the upper surface of U1 may be similar to the lowest value within the overlying subunit (Figure 16a); this is likely due, in part, to variability in the paleotopography (e.g., terraces) and postdepositional processes such as erosion or translocation as a result of deep-seated landslides (Morgan et al., 2008; Pawley et al., 2016). The relative height of the upper surface of U1 (Figure 16a) identified in logs also includes such systematic errors as 1) inherent error in the DEM elevation (see MacCormack et al., 2015b), from which unit elevations are calculated; 2) inexact well or borehole location and thus inexact elevations calculated from the DEM; and 3) inexact unit depths recorded in driller's logs. Systematic sources of error in evaluating U1 subunit heights above the Peace River comprise inherent error in the DEM elevation (as above) and error associated with measuring the downstream distance of each U1 subunit using an interpreted thalweg (Figure 15 and 16b).

6.2.2 Hydrogeological Data

Hydrogeological data were queried and extracted from the Alberta Water Well Information Database (AWWID), maintained by Alberta Environment and Parks (AEP, 2016), in order to evaluate groundwater flow and groundwater chemistry within the study area. Hydrogeological data included static water level from 1996 to 2015 and groundwater chemistry (common ions , such as Ca, Mg, K, Cl, HCO_3, and SO_4), resulting in two separate datasets. The query produced 278 wells with static water level data and 355 wells with full chemistry; however, only 110 (water level) and 20 (chemistry) of these had lithology data recorded at the well screen interval. Lithological data at the well screen interval are important for assigning stratigraphic units to the well screen interval, which in turn helps to assess the relationship between stratigraphic units and groundwater chemistry data. The remaining wells were assigned the stratigraphic unit at the bottom of the well unless the lowest unit was bedrock, in which case the unit above bedrock was assigned.

7 Results

7.1 Bedrock Strath Mapping

Strath mapping is important for defining the geometry of the fluvial systems in which the gravel units were deposited, which in turn provides insight into the pattern of physiographic evolution of the Peace River Lowland. Mapping of bedrock straths is based on a combination of the expression of straths in the bedrock topography grid, elevation of bedrock recorded in logs, distribution of gravel deposits, projection of fluvial gradients between remnant portions of straths, and review of previous bedrock topography interpretations (Jones, 1966; Tokarsky, 1967, 1971; Carlson and Hackbarth, 1974; Borneuf, 1981; PFRA, 1998; MacCormack et al., 2015a).

Strath mapping is interpretive, and the confidence by which straths can be delineated is largely a function of data density (Figure 17). The degree of confidence in the accuracy of mapped straths is qualitatively conveyed as polygon boundaries that are either 'defined' (high confidence), 'approximate' (medium confidence) or 'assumed' (low confidence; Figure 17). Mappable remnants of bedrock straths are preserved throughout the Peace River Lowland between the Alberta–British Columbia border and Deadwood (Figures 1 and 17). The combined area of all mapped straths accounts for much of the total area of the Peace River Lowland.

7.1.1 Grimshaw Strath

The Grimshaw strath includes bedrock underlying 1) the Grimshaw gravels lobes (PFRA, 1998) and surrounding area; 2) an area north of Fairview extending to the Whitelaw and southwest lobes; 3) three areas near to the confluence of the Peace and Montagneuse rivers, and 4) the Peace River Lowland east of Boundary Lake (Figure 17).

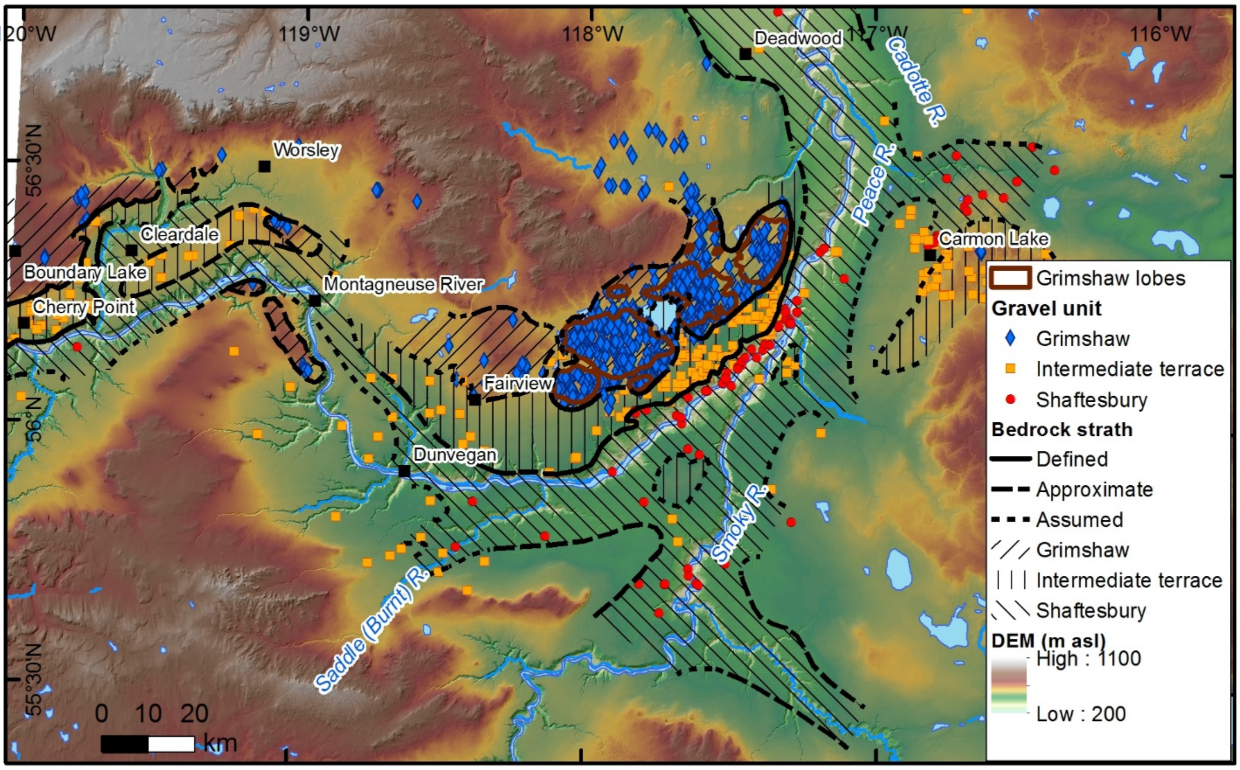


Figure 17. Mapped bedrock straths underlying SU1 subunits (Grimshaw gravels, intermediate terrace gravel, and Shaftesbury gravel) between the British Columbia border (120°W) and the downstream extent of the study area at Deadwood, overlain on a hill-shaded DEM (data from AEP, 2015).

7.1.2 Intermediate Terrace Strath

Portions of the intermediate terrace strath include bedrock underlying 1) an area adjacent to the Grimshaw lobes that includes a large area between Fairview and the Peace River valley; 2) an area east of Carmon Lake; 3) an area east of Cleardale; and 4) the north side of Peace River valley surrounding Cherry Point (Figure 17). Interestingly, Tokarsky (1967) tentatively correlated the Cherry Point gravel with the Grimshaw gravels. Based on strath mapping and analysis of the plan distribution and relative height of the Cherry Point gravel above the Peace River, the Cherry Point gravel correlates with the intermediate terrace gravel (Figure 17).

7.1.3 Shaftesbury Bedrock Valley Strath

The floor of the Shaftesbury bedrock valley is relatively well preserved because it has been incised only by the modern drainage system. The modern Peace River is superimposed upon the Shaftesbury bedrock valley throughout the study area with the exception of one reach of the modern valley between the Montagneuse River and Dunvegan (Figure 17). Possible tributaries of the Shaftesbury bedrock valley include the High Prairie bedrock valley (Jones, 1966) that is superposed by the Smoky River, the L'Hirondelle bedrock valley (Pawlowicz and Fenton, 1995) that is superposed by the Cadotte River, and an unnamed bedrock valley (Carlson and Hackbarth, 1974) that is superposed by the Saddle (Burnt) River (Figure 17).

7.2 Regional Subunit Correlation

Interpretation of the relative age of the U1 subunits follows the notion that fluvial deposits located at higher elevations have been incised by younger fluvial systems and are therefore older than gravels deposited at lower elevations (cf. Edwards and Scafe, 1996; Leckie, 2006). The oldest gravel unit recognized in this study is the 'Grimshaw gravels' (after Tokarsky, 1967; 320 m average height above the Peace River). The Grimshaw gravels are exposed in aggregate pits within the Grimshaw lobes and in places west of the Grimshaw area (Figure 17).

The intermediate terrace gravel (Tokarsky, 1967, 1971) is an average height of 220 m above the Peace River and therefore younger than the Grimshaw gravels. The intermediate terrace gravel is positioned on a bedrock strath that is lower in elevation than the strath underlying the Grimshaw gravels. Portions of this strath and overlying gravel are found well beyond the Grimshaw lobes area to the west and south (Figure 17).

The Shaftesbury bedrock valley is positioned at the lowest elevations and therefore contains the youngest basal sand and gravel deposits in the study area, excluding modern alluvium within the Peace River valley (25 m average height above the Peace River). Radiocarbon dates recorded from basal sand and gravel within the Shaftesbury bedrock valley (25.12 ±0.14 ka ^{14}C BP; Botterill, 2007; Morgan et al., 2009; Table 1) and overlying lacustrine-glaciolacustrine sediments (30.24 ±0.16 ka ^{14}C BP; Slomka and Utting, 2017) indicate that sediments within the Shaftesbury bedrock valley were deposited during or following the Middle Wisconsinan, prior to impoundment of the Shaftesbury bedrock valley by the Laurentide Ice Sheet in the Late Wisconsinan (Slomka and Utting, 2017).

Adjacent to the west side of the study area in the NTS 94A map area (British Columbia), Hartman (2005) and Hartman and Clague (2008) reported a (glacio)fluvial stratigraphy consisting of three units (from oldest and highest to youngest and lowest), the 'high planation surface gravel', the 'upper paleovalley gravel', and the 'lower paleovalley gravel' (Table 1), which record deposition in three separate fluvial systems (after Mathews 1978). The upper surfaces of these three fluvial units in the NTS 94A map area are at average heights of 330, 225, and 50 m above the modern Peace River. These heights are comparable to the Grimshaw gravels, intermediate terrace gravel, and Shaftesbury gravel identified in this report. Furthermore, Middle Wisconsinan radiocarbon dates (~27–22 ka ^{14}C BP) on gravel deposits of the lowest paleovalley in the NTS 94A map area (Mathews, 1978; Hartman, 2005; Hartman and Clague, 2008) suggest chronostratigraphic correlation with the Shaftesbury gravel. Correlation of the stratigraphy outlined by Mathews (1978), Hartman (2005), and Hartman and Clague (2008) in British Columbia and gravel units in Alberta is discussed in Section 7.3 (and presented in Table 1) of this report.

7.2.1 Informal Naming Convention

Correlation and mapping of the straths and associated gravel subunits, extending for up to 400 km within the Peace River Lowland between the western edge of the Interior Plains and the Deadwood area, indicate that these are regional gravel subunits. As such, we propose that the following common informal naming convention be applied to the basal sand and gravel (U1 subunits). The 'high planation surface gravel' of Hartman (2005) and Hartman and Clague (2008) is included with the 'Grimshaw gravels' (in keeping with Tokarsky, 1967, 1971; Table 1). The 'upper paleovalley gravel' of Mathews (1978), Hartman (2005), and Hartman and Clague (2008) and the 'intermediate terrace gravel' of Tokarsky (1967, 1971) are named 'Old Fort gravel' (Table 1) in recognition of the very good exposures of this unit near Old Fort, B.C., on the north bank of Peace River adjacent to Fort St. John (Hartman, 2005). Lastly, the 'lower paleovalley gravel' of Mathews (1978), Hartman (2005), and Hartman and Clague (2008) is included with the 'Shaftesbury gravel' (Table 1). The Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel are henceforth used as informal names of the U1 subunits described in this report.

7.3 Subunit Description and Interpretation

7.3.1 Grimshaw Gravels

7.3.1.1 Sediments

The Grimshaw gravels directly overlie bedrock and are overlain by structureless (massive) to stratified diamict (till containing Canadian Shield lithologies) deposited by the Laurentide Ice Sheet. In the area of the four major Grimshaw lobes (Figures 4 and 5), the deposit contains a transition from predominantly horizontally bedded and massive gravel in the west (Whitelaw lobe), through planar and trough cross-bedded gravel in the central part (central lobe), to large-scale gravel foresets in the east (northeastern lobe; Slomka and Hartman, 2017).

Sediments within the Grimshaw lobes area (Figures 4 and 5) are composed of clast-supported, massive and crudely horizontally bedded gravel; clast-supported stratified gravel; clast- and matrix-supported, graded gravel; matrix-supported, massive and imbricated gravel; and matrix- and clast-supported, planar and deformed gravel facies. Gravel clasts are granule to boulder size, subangular to well rounded, and somewhat spherical to elongate and faceted. Rarely, gravels contain an orange-rust–coloured staining in places, particularly along bedding planes and on the surface of gravel clasts; the staining is most apparent in the coarsest grained beds and commonly traverses bedding planes that separate coarse- and fine-grained gravel.

Sands are rare within the Grimshaw lobes area and commonly form lenses within horizontally bedded gravel, and laterally continuous beds truncated by cross-bedded gravel facies in the upper part of the Grimshaw deposit. Sand facies include planar cross-bedded, medium- to coarse-grained sand; low-angle cross-bedded, medium- to pebbly coarse-grained sand; trough cross-bedded, medium- to pebbly coarse-grained sand; and deformed, very fine- to pebbly coarse-grained sand. Sands are heterolithic and micaceous. Fine-grained facies are very rare and are recorded in the upper part of the Grimshaw gravels succession. Fine-grained facies include massive and deformed clay, silt, and mud (Slomka and Hartman, 2017).

Sediments equivalent to the Grimshaw gravels, located south of Worsley (Figures 1, 18 and 19), include planar and trough cross-bedded and crudely horizontally bedded gravel that form tabular bed sets (1–1.5 m thick) and large-scale (~2 m thick and ~15–30 m wide) bed sets. In cross-section, the large-scale bed sets are trough shaped and contain smaller scale trough-shaped beds within bed sets; in longitudinal-section, the large-scale bed sets are wedge to tabular shaped and contain smaller scale dipping cross-beds (Slomka and Hartman, 2017).

7.3.1.2 Paleoflow

Paleoflow measurements were recorded from sediments within the Grimshaw lobes area. In the western part of the Grimshaw lobes (Figure 17), paleocurrent data indicate a paleoflow direction toward the east. Measurements of the dip direction of major bedding planes record a paleoflow gradient toward the east and northeast. The b-axis azimuths and dip angles recorded from 23 gravel clasts indicate a variable paleocurrent direction that is predominantly to the southeast. Paleocurrent measurements from gravel cross-beds (average dip azimuth of 097°) and a single bedding plane of massive gravel (dip azimuth of 060°) indicate a paleoflow direction toward the east (Slomka and Hartman, 2017).

In the central and western parts of the Grimshaw lobes area (Figure 17), paleocurrent data indicate paleoflow toward the north. Paleocurrent measurements recorded from three trough cross-beds (average dip azimuth of 009°), a single planar cross-bed of gravel (dip azimuth of 0°), and six bedding planes (average dip azimuth of 008°) indicate a paleoflow direction toward the north. However, measurements of bedding plane dip azimuths of 030°, 040°, and 050° suggest lateral mobility of the paleoflow gradient toward the north-northeast.

In the eastern part of the Grimshaw lobes area (Figure 16), large-scale gravel foresets have a dip azimuth of ~020°, indicating a paleoflow direction toward the north-northeast. The angle of dip of the large-scale

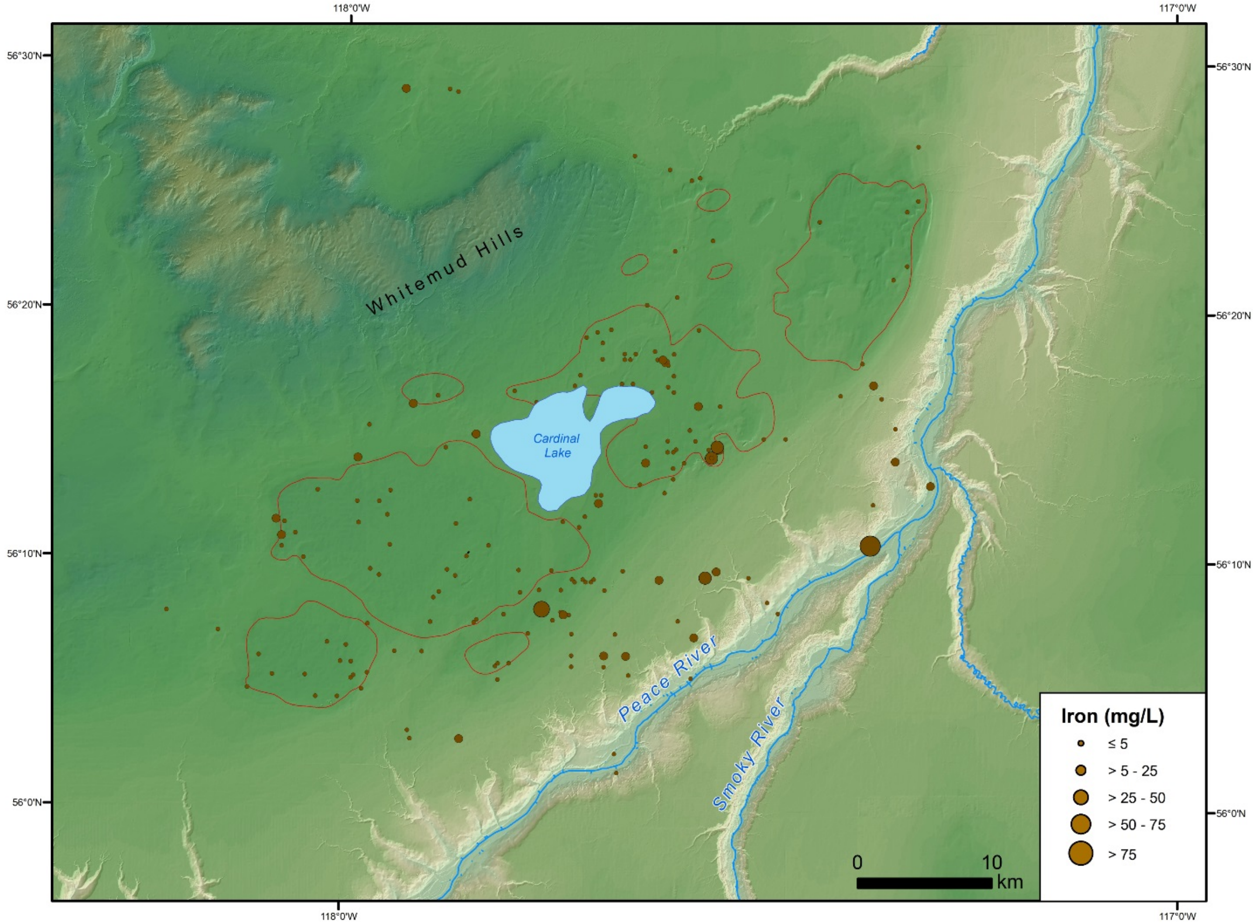


Figure 18. Groundwater iron (Fe) concentrations recorded from wells screened in basal sand and gravel, and other sediments (data from AEP, 2016) overlain on a hill-shaded DEM (data from AEP, 2015).

foresets decreases upwards in the section from ~030° at the base to ~010° at the top (Slomka and Hartman, 2017).

7.3.1.3 Gravel Lithology

The lithology types of gravel clasts in the study area include quartzite, quartz, chert, ironstone, sandstone, siltstone, conglomerate, chalcedony, argillite, white and pink granite, diorite, grey gneiss, green and white porphyry, green fine-grained volcanic rocks, basalt, amphibolite, schist, and undifferentiated metasedimentary rocks (Edwards and Scafe, 1996). Limestone is noticeably absent from the Grimshaw gravels. Major spatial variation in relative abundances of gravel lithologies is not apparent; however, the relative abundance of ironstone increases and local fine-grained lithologies decrease towards the east in the Grimshaw gravels lobes (Figure 17). Additionally, the coarsest textured pink granites were collected in the western part of the Grimshaw gravels lobes (Figure 17).

7.3.1.4 Geometry

The Grimshaw gravels underpin slightly elevated portions of the Peace River Lowland, and the boundary of the Grimshaw gravels can be recognized in many places as a hillslope up to 40 m high, which partially reflects the thickness of the Grimshaw deposit. Both the Grimshaw gravels and the bedrock strath are mapped along the north side of the Peace River lowland for more than 200 km in Alberta (Figure 17). Mapping by Hartman (2005) suggests that the length of the Peace River Lowland over which the Grimshaw gravels

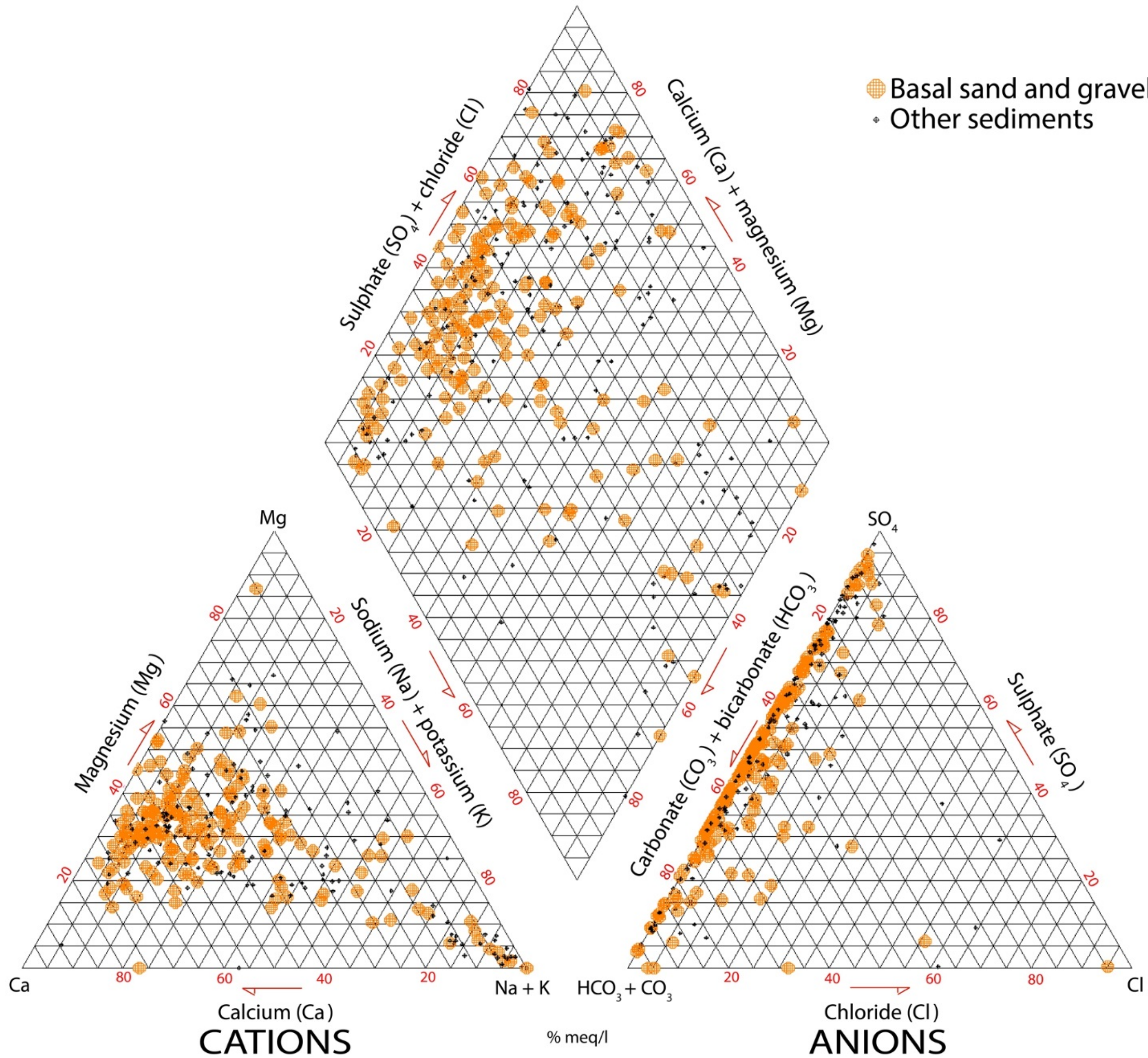


Figure 19. Relative concentrations of major cations and anions within the basal sand and gravel (permeable material) and other less permeable sediments (glaciolacustrine, lacustrine, outwash, and subglacial deposits) within the Grimshaw gravels lobes displayed on a piper diagram (data from AEP, 2016). Ion concentrations were converted from mg/L to meq/L to account for charge differences so that anions and cations can be compared to one another and plotted on the piper diagram.

and underlying strath can be traced across British Columbia and Alberta is greater than 250 km. The maximum width of the Grimshaw gravels is approximately 20 km in the Grimshaw lobes area. The Grimshaw gravels and the underlying bedrock strath have been incised and partially removed by younger fluvial systems; thus, the current distribution of the deposit is fragmented. The Grimshaw gravels and underlying bedrock strath have not been identified north of Deadwood (Figure 17).

7.3.1.5 Interpretation

The Grimshaw gravels record a braid-delta system (Postma, 1984) composed of a braided river channel belt system in the west that transitions to a Gilbert-type delta in the east (Slomka and Hartman, 2017). The large-scale troughs composed of gravel in the Worsley area record infill of broad channels with gravelly bedload (Atkinson and Paulen, 2010a). The tabular gravel beds in the western part of the Grimshaw gravels record aggradation of gravel bars and rare debris-flow deposits. Rare lenses of laminated sand record infilling of bar-top channels with sandy bedload. Trough-shaped gravel beds in the middle part of the Grimshaw gravels lobes record the migration and superposition of sinuous-crested gravel dunes and infilling of minor channels with gravelly bedload. The large-scale gravel foresets in the eastern part of the Grimshaw lobes record a Gilbert-type delta that prograded towards the northeast (Slomka and Hartman, 2017).

The upper part of the Grimshaw gravels deposit is composed of sand and gravel within well-defined channel margins, which record an increase in the supply of sandy bedload and the development of channelized flow. Paleoflow measurements indicate that sediment was transported toward the north and northeast, and gravel lithologies of the Grimshaw gravels indicate a predominant western sediment source (Canadian Cordillera). However, rare pink granite pebbles are recorded in the Grimshaw gravels within the Grimshaw lobes area and, as outlined in Section 3.2.2, may indicate fluvial erosion and reworking of previously deposited sediment containing Canadian Shield lithologies. Conversely, Edwards and Scafe (1996) noted these lithologies in the Grimshaw gravels but suggested they were derived from the Cassiar Suite in northeastern British Columbia.

In order to assess the provenance of the pink granites, a subpopulation of zircon-bearing pink granitic pebbles (monzogranite) collected from the Grimshaw gravels was dated by U-Pb geochronology on extracted zircons. The results indicate a early Jurassic crystallization age, suggesting that monzogranite pebbles in the Grimshaw gravels were derived from western sources, albeit not the Cassiar Suite (which is early Cretaceous; Mihalynuk et al., 1996). The early Jurassic age of the subpopulation of monzogranite (pink granitic) pebbles in the Grimshaw gravels has significant implications for the use of ‘pink granites’ as a proxy for direct evidence of glaciation in the Peace River Lowland.

7.3.2 Old Fort Gravel

7.3.2.1 Sediments

Old Fort gravel is not exposed in outcrop in the study area, nor, to our knowledge, has it been sampled in core. However, Old Fort gravel is recorded in AWWID lithology logs in the study area. As a result of limited sedimentological descriptions in AWWID records, the sedimentological composition of the Old Fort gravel is based on the observations of equivalent sediments in the Fort St. John area (NTS 94A) by Hartman (2005). Hartman (2005) described the unit as being dominated by massive and horizontally bedded, coarse-grained gravel with occasional silt lenses. No paleoflow measurements were reported, but the paleovalley in which the Old Fort gravel was deposited dips gently to the east and follows the trend of the modern Peace River.

7.3.2.2 Gravel Lithology

Mathews (1978) described the Old Fort gravel (‘upper paleovalley’ of Mathews, 1978) as being composed dominantly of Cordilleran lithologies, including quartzite, chert, and igneous rocks from western sources. Mathews (1978) and Hartman (2005) noted the presence of pink granitoid Canadian Shield erratics near Alces River (10 km west of the Alberta–British Columbia border) but not near Fort St. John (50 km west of the border).

7.3.2.3 Geometry

The deposits of Old Fort gravel underlie subdued plains within the Peace River Lowland and, unlike the Grimshaw gravels, their presence is not indicated by topographic expression. The Old Fort gravel deposit is laterally fragmented due to subsequent incision and, as a result, it is recorded intermittently along the Peace River Lowland from approximately Fort St. John (British Columbia) to the Town of Peace River (Alberta; approximately 250 km along the Peace River Lowland; Figure 17). The maximum width of the Old Fort gravel mapped in the study area is approximately 16 km (in the area adjacent to the Whitelaw lobe; Figures 4 and 17); however, the low density of data in this region makes mapping the lateral extent of the deposit uncertain. In other areas with greater data density (e.g., adjacent to the central lobe), the mapped width of the Old Fort gravel is approximately 10 km (Figures 4 and 17).

7.3.2.4 Interpretation

Hartman (2005) and Hartman and Clague (2008) interpreted the Old Fort gravel to have been deposited in a braided fluvial system. Based on the lateral extent of the preserved portion of the Old Fort gravel (Figure 16 and 17), the paleovalley in which the unit was deposited is estimated to have been between two and five times wider than the modern Peace River valley.

7.3.3 Shaftesbury Gravel

7.3.3.1 Sediments

The Shaftesbury gravel subunit forms a fining-upwards succession ranging from interbedded sand and gravel at the base to predominantly sand at the top (Leslie and Fenton, 2001; Botterill, 2007). Botterill (2007) observed sediments exposed in outcrop at sections located ~20 km southwest of the Town of Peace River. Leslie and Fenton (2001) described similar sand and gravel at the confluence of the Peace River and Buchanan Creek (north of Deadwood). The Shaftesbury gravel is tentatively subdivided into four facies associations based on the observations of Botterill (2007).

The lowermost (oldest) gravel overlies bedrock in the Shaftesbury bedrock valley (Botterill, 2007). North of the Grimshaw area, Leslie and Fenton (2001) reported a gravel bed between 1.5 and 8 m thick directly overlying bedrock that contains poorly sorted, well-rounded to subrounded, clast-supported pebble gravel; Leslie and Fenton (2001) interpreted this basal bed as preglacial gravel. Elsewhere, the lowermost Shaftesbury gravel is ~8 m thick and composed of a coarsening-upwards succession of pebbly sand (~50% gravel clasts) at the base to clast-supported sandy pebble gravel at the top (~75% gravel clasts; Botterill, 2007). The clast-supported gravel contains a thin (20 cm) bed of massive sand near the top of the unit (Botterill, 2007). The upper ~2 m contains trough cross-bedded, medium-grained sand overlain by low-angle cross-bedded gravel that is highly oxidized. The gravel clasts are rounded to well rounded, have low sphericity, and are not well imbricated. Gravels contain pods or lenses (10–20 cm thick) of clast-supported granules or pebbles that are highly oxidized (Botterill, 2007).

The lowermost sediments of the Shaftesbury gravel are overlain by a thick (~10 m) succession of interbedded clast- and matrix-supported gravel and gravelly sand (Leslie and Fenton, 2001; Botterill, 2007). The lower part (lower 2 m) is composed of horizontally bedded pebble to granule gravel (3–10 cm thick beds) overlain by a thin (~10–50 cm) bed of horizontally bedded medium-grained sand (Leslie and Fenton, 2001; Botterill, 2007). The middle part (~3 m thick) is composed of clast-supported gravel with a fine-grained sand matrix texture. The gravels in the middle part are crudely stratified, contain Canadian Shield lithologies, and are overlain by a thin (25 cm) bed of horizontally bedded, medium-grained sand (Botterill, 2007). The upper part (~3 m thick) is composed of a fining-upwards succession of sandy gravel (with a fine-grained sand matrix) at the base to gravelly sand at the top, with interbeds (~50 cm thick) composed of ripple cross-laminated, trough cross-bedded, and horizontally bedded, very fine grained sand to medium-grained pebbly sand (Botterill, 2007). Rarely, sands contain interbeds of clayey silt and load structures (Leslie and Fenton, 2001). Gravel clasts are imbricated, subangular to well-rounded pebbles to boulders, which increase in sphericity upwards in the unit (Botterill, 2007).

The upper part of the Shaftesbury gravel is overlain by 7 m of interbedded gravel and pebbly medium-grained sand (Botterill, 2007). The gravel consists of well-rounded, spherical pebbles to boulders that are increasingly oxidized from the base to top of the unit. Gravel beds are <0.5–1.5 m thick and contain sand lenses (15 cm thick) composed of horizontally bedded and cross-bedded, medium-grained sand. Sand beds (<0.1–0.5 m thick) are composed of horizontally bedded and low-angle cross-stratified sand at the base and high-angle cross-stratified, trough cross-bedded, and horizontally bedded sand (with silt and clay rip-up clasts containing wood fragments) at the top (Botterill, 2007). The uppermost part of the Shaftesbury gravel is composed of a fining-upwards succession (~7–8 m thick) of interbedded trough cross-bedded and high-angle cross-stratified, fine-grained sand and cross-bedded sandy gravel at the base to horizontally bedded and low-angle cross-stratified, fine-grained sand at the top (Botterill, 2007).

7.3.3.2 Paleoflow

The paleoflow indicator that was measured by Botterill (2007) is not explicitly indicated and, in places where gravel clast imbrication measurements were recorded, it is unclear which gravel clast axis was measured (a- or b-axis). As a result, the direction of paleoflow recorded in the data is uncertain. Nevertheless, paleoflow measurements reported here follow the presentation of Botterill (2007; in Figure 15 of the thesis). Paleoflow direction is predominantly toward the south (southeast and southwest) in the lower and upper part, and the north and northeast in the middle part, of the Shaftesbury gravel (Botterill, 2007). Paleovalley mapping (Figure 17) suggests that paleoflow generally followed the trend of the Shaftesbury bedrock valley.

7.3.3.3 Gravel Lithology

The most common gravel lithologies include quartzite (commonly containing chatter marks), quartz, Cordilleran-sourced sandstone, and black and white chert. Canadian Shield lithologies (red-pink granites and gneisses) are present from the base to the top of the unit; the relative abundance of Canadian Shield lithologies increases from the base (<5%) to the top (~10–15%) of the unit (Botterill, 2007). In the Fort St. John area (British Columbia; NTS 94A), Shield erratics have not been recorded in western exposures of basal sand and gravel (Mathews, 1978; Hartman, 2005; Hartman and Clague, 2008). Minor gravel lithologies include locally derived sandstone, Athabasca sandstone (eastern provenance), green chert, mudstone, ironstone, and very rare white granite, diorite gneiss, limestone, and jasper (Leslie and Fenton, 2001; Botterill, 2007).

7.3.3.4 Geometry

The Shaftesbury bedrock valley predominantly underlies the Peace River Lowland in areas south of the remnants of the Grimshaw gravels and Old Fort gravel straths (Figure 17), and is superposed by the modern Peace River valley throughout its mapped extent with only two exceptions: near Old Fort and between the Montagneuse River and Dunvegan (as discussed in Section 7.1; Figure 17). However, paleovalley mapping between the Montagneuse River and Dunvegan is not well constrained and the actual position of the Shaftesbury bedrock valley relative to the modern Peace River valley is uncertain.

The Shaftesbury bedrock valley is two to six times wider than the modern Peace River valley and, although it has been incised by the modern river, the bedrock valley has been preserved well enough to allow near-continuous mapping of the Shaftesbury bedrock valley and its infill sediments throughout the study area and into British Columbia (NTS 94A; Mathews, 1978; Hartman, 2005; Hartman and Clague, 2008). The maximum width of the Shaftesbury bedrock valley near Deadwood (Figure 17) is approximately 30 km, but mapping of bedrock valley margins in that area is uncertain as a result of poor data control. Where bedrock valley delineation is more certain (e.g., south of Whitelaw), the Shaftesbury bedrock valley reaches a maximum width of approximately 15 km.

7.3.3.5 Interpretation

The fining-upwards succession of sand and gravel at the base of the Shaftesbury bedrock valley has been interpreted by Botterill (2007) to record a glaciofluvial-deltaic succession. The presence of Canadian Shield lithologies has been previously interpreted to record advance and subsequent retreat of the Laurentide Ice Sheet prior to the Middle Wisconsinan (Leslie and Fenton, 2001; Botterill, 2007). The Shaftesbury bedrock valley, and the coarse-grained sediments that infill the base of the bedrock valley, record a period of incision followed by an aggradation stage. The aggradation stage, resulting in the deposition of basal sand and gravel in the Shaftesbury bedrock valley, may have been controlled by a rise in the regional or local base level (adjustment of the river equilibrium profile; Mackin, 1948), increased sediment supply, or decreased transport capacity of the fluvial system.

The Shaftesbury gravel is overlain by fine-grained lacustrine and glaciolacustrine sediments that were previously interpreted to record glaciolacustrine sediment of Glacial Lake Mathews (Tokarsky, 1967, 1971; Leslie and Fenton, 2001; Botterill 2007; Morgan et al., 2008; Atkinson and Paulen, 2010a; Slomka and Utting, 2017). As such, the interbedded sand and gravel, interpreted as deltaic sediments by Botterill (2007), likely record deposition of coarse-grained sediment during early stages of Glacial Lake Mathews in the study area. Radiocarbon dates recorded from basal sand and gravel within the Shaftesbury bedrock valley (25.12 ±0.14 ka ^{14}C BP; Table 1; Botterill, 2007; Morgan et al., 2009) and overlying lacustrine-glaciolacustrine sediments (30.24 ±0.16 ka ^{14}C BP; Slomka and Utting, 2017) indicate that sediments within the Shaftesbury bedrock valley were deposited during or following the Middle Wisconsinan, prior to impoundment of the Shaftesbury bedrock valley by the Laurentide Ice Sheet during the Late Wisconsinan (Slomka and Utting, 2017).

7.4 Hydrogeology

A potentiometric surface was generated (Figure 20) for wells screened in the basal sand and gravel (Figure 21), using water level data from 1996–2015 sourced from the August 2016 version of the AWWID. The general direction of groundwater flow is topographically controlled, and flows from areas of high elevation in the northwest to areas of low elevation in the southeast on the north side of the Peace River.

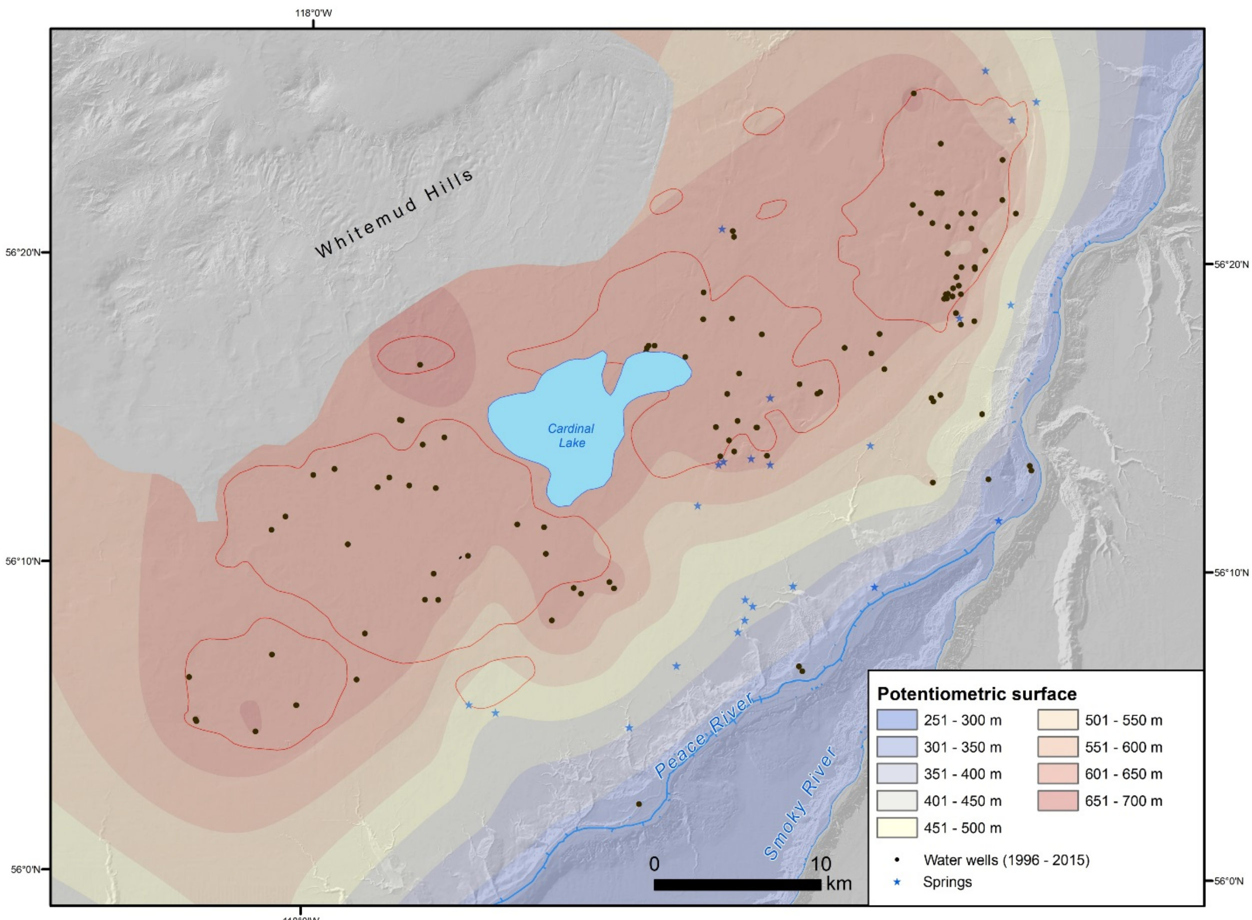


Figure 20. Generalized potentiometric surface from water level data for wells screened in basal sand and gravel, measured during 1996–2015 (data from AEP, 2016), overlain on a hill-shaded DEM (data from AEP, 2015).

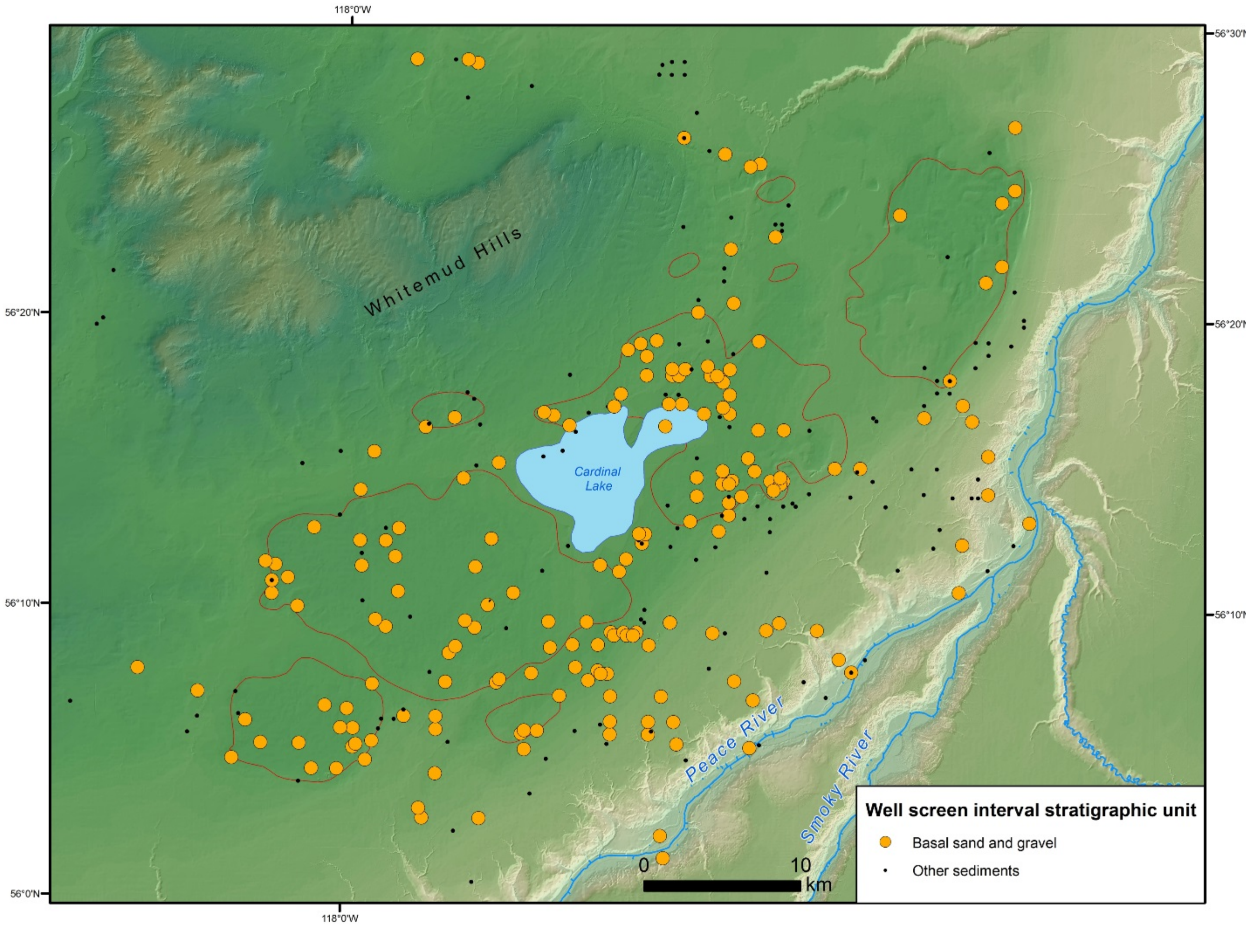


Figure 21. Groundwater wells screened in basal sand and gravel, and other sediments (data from AEP, 2016), overlain on a hill-shaded DEM (data from AEP, 2015).

7.4.1 Groundwater Chemistry

This section contains an updated and expanded hydrogeochemical overview of the Grimshaw gravels, based on recent and historical hydrogeological and geological data contained within the AWWID.

In general, water quality within the Grimshaw gravels is good. The average TDS content of groundwater sampled from wells screened in basal gravel units (Figure 21) within and beyond the Grimshaw lobes is 630 mg/L (n = 137) and 1365 mg/L (n = 218), respectively (in Alberta, groundwater is considered saline when the TDS is >4000 mg/L). The average iron (Fe) content of groundwater shows a similar spatial distribution: within the Grimshaw lobes, Fe is 2 mg/L on average and, in areas beyond the Grimshaw lobes, average Fe content is 5 mg/L (Figure 18). The spatial distribution of Fe content reported herein is similar to that noted by PFRA (1998; <3 mg/L within the Grimshaw lobes compared to >10 mg/L in areas beyond the margins of the lobes). Interestingly, high Fe concentrations were recorded in a few wells within the Grimshaw gravels lobes (Figure 18). Within the Grimshaw lobes, there is little difference in the major ion chemistry of groundwater found in the basal sand and gravel unit, and the other, less permeable units (Figure 19).

As groundwater flows through an aquifer system, its chemistry evolves as a result of interaction with geological materials. Fresh water near recharge zones is typically characterized by high Ca/MgHCO_3, whereas groundwater near discharge zones is higher in TDS and potentially SO_4 and Na. Therefore, the spatial distribution of fresh and evolved groundwater may be used to identify recharge and discharge zones, respectively. For the purpose of this report, groundwater chemistry samples that had TDS

>1500 mg/L and SO_4 and Na content >65% of the anions and cations, respectively, were used to identify discharge areas within the study area (Figure 22). Figure 23, which shows the spatial distribution of TDS, SO_4, and Na content in the study area, indicates that groundwater is recharged within the Grimshaw gravels and discharged to nearby streams and rivers. The distribution of recharge and discharge zones complements the potentiometric surface presented in Figure 20.

8 Discussion

8.1 Stratigraphy and Sedimentary Architecture

The geological framework of the basal sand and gravel (U1) presented in this report consists of (from oldest to youngest) the Grimshaw gravels (~320 m above the Peace River), Old Fort gravel (~220 m above the Peace River), and Shaftesbury gravel (~25 m above the Peace River). The straths upon which the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel were deposited, together with the modern

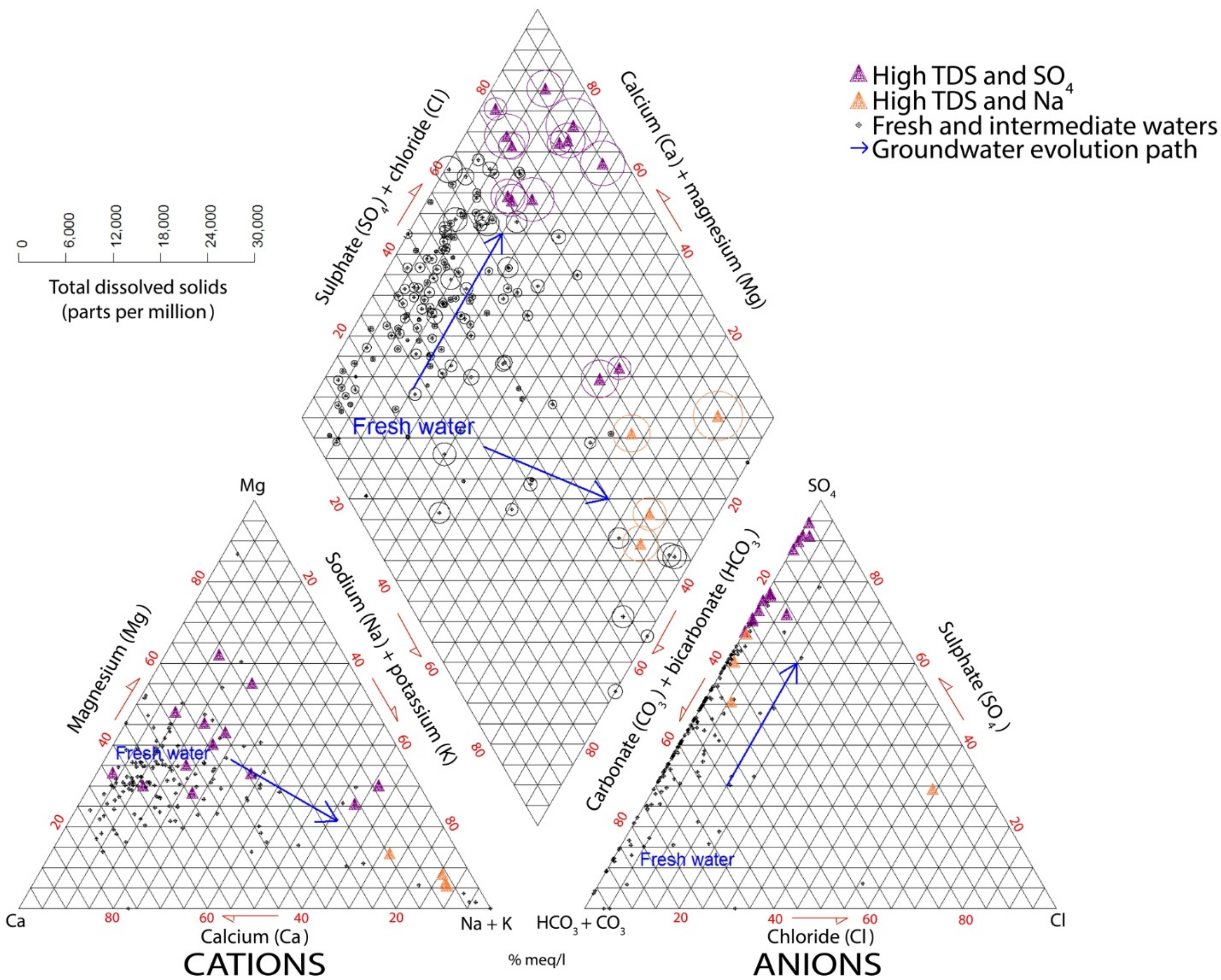


Figure 22. Groundwater chemistry and evolution within the study area displayed on a piper diagram (data from AEP, 2016). Areas of groundwater recharge are characterized by waters containing primarily $CaMgHCO_3$, and areas of discharge are characterized by an increase in total dissolved solids (TDS) and waters containing high $CaMgSO_4$ or $NaSO_4$. TDS is plotted as rings around each point and the radius represents the total of all cations and anions in parts per million (refer to the TDS scale bar).

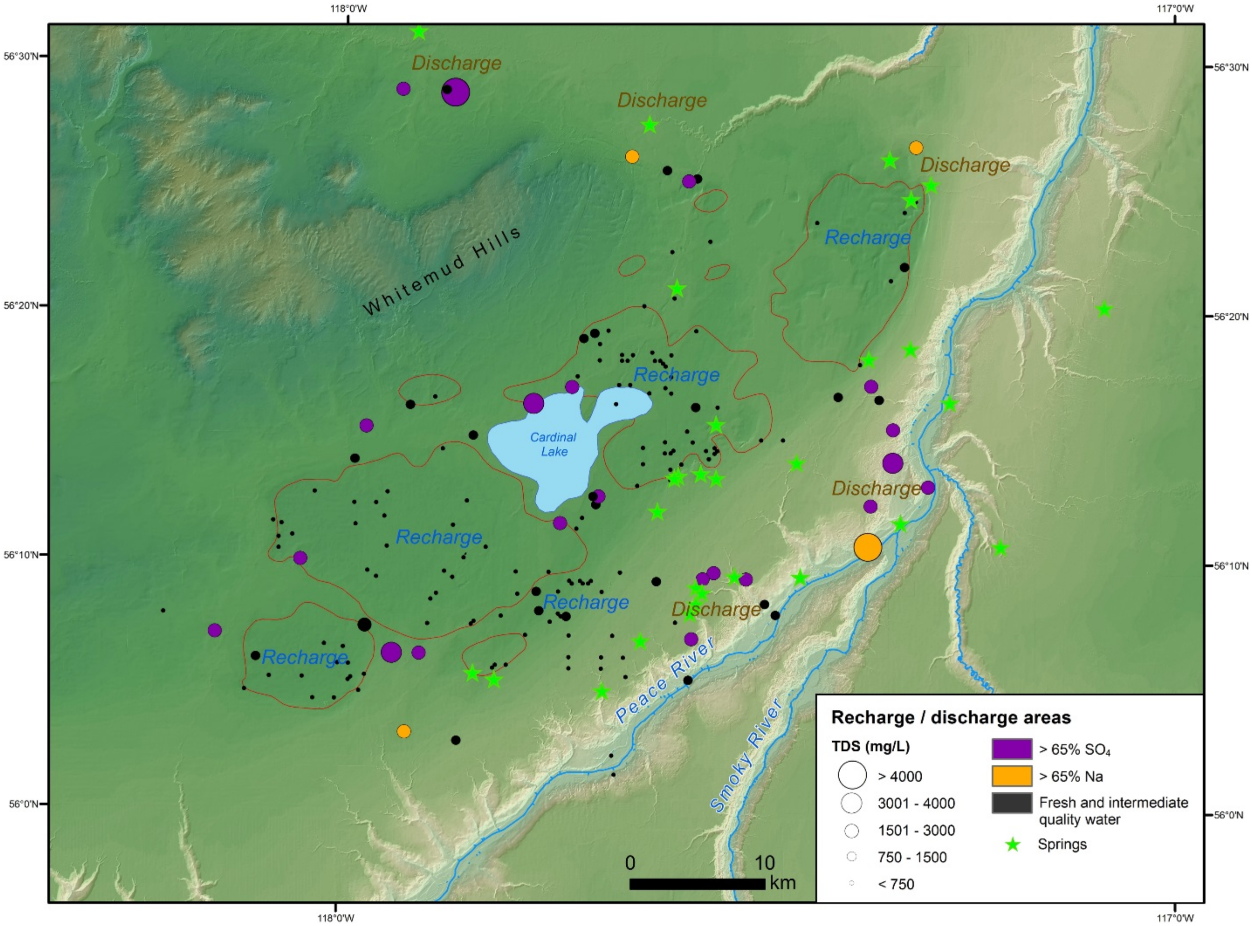


Figure 23. Groundwater chemistry, including total dissolved solids (TDS), SO_4, and Na for wells screened in the basal sand and gravel (data from AEP, 2016), overlain on a hill-shaded DEM (data from AEP, 2015). Recharge areas are indicated by black wells with low TDS, and discharge areas are shown by purple and orange wells with high TDS. TDS >4000 mg/L is considered saline in Alberta.

Peace River bedrock valley, record four major periods of glaciofluvial and fluvial incision (termed ‘incision events’ or IEs; Figure 24). Subsequent aggradation of basal sand and gravel on each of the straths likely records a period of fluvial stability (i.e., an equilibrium profile; Mackin, 1948), an increase in sediment supply, or a decrease in sediment transport capacity of the system. Aggradation and subsequent incision of the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel, and deposition of modern alluvium in the Peace River valley, form a sedimentary architecture composed of nested glaciofluvial/fluvial paleovalleys and the modern valley (Figure 24).

Tokarsky (1967, 1971) previously interpreted that the Grimshaw gravels, ‘intermediate terrace’ (Old Fort gravel), and Shaftesbury bedrock valley gravel to have been deposited by the same fluvial system that downcut to lower elevations (Figure 12); however, we interpret the Grimshaw gravel, Old Fort gravel, and Shaftesbury gravel as the deposits of three distinct fluvial or glaciofluvial systems (Figure 24), based on the elevation difference between the deposits (Figure 16), scale of the mapped straths (Figure 17), and stratigraphy in the upper reaches of the Peace River Lowland (Hartman, 2005; Hartman and Clague, 2008). The modern Peace River valley records a fourth, distinct fluvial system, separated in time from the Shaftesbury gravel (previously interpreted by Leslie and Fenton [2001] and Botterill [2007] as a glaciofluvial-deltaic deposit) by a full glacial cycle of advance and retreat during the Middle to Late Wisconsinan (Slomka and Utting, 2017). Hence, it is possible that each incision event (IEs1-4; Figure 24)

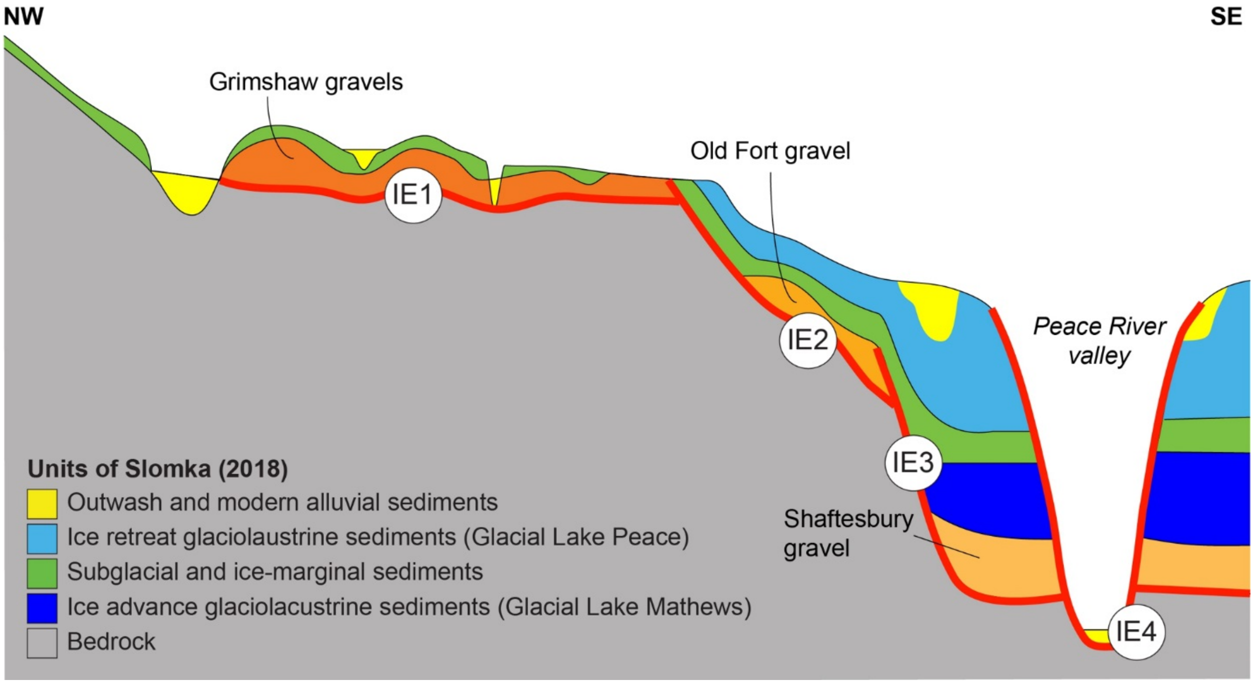


Figure 24. Conceptual sedimentary architecture of the Peace River Lowland, including the Grimshaw gravels, Old Fort gravel, Shaftesbury gravel, and modern Peace River alluvium, within a framework of glaciofluvial and fluvial incision events (IEs 1–4).

records a climatic transition from glacial to interglacial, based on modern (Peace River; IE4) and Middle Wisconsinan (Shaftesbury gravel; IE3) analogues; however, because absolute dates have not been established on the Grimshaw gravels (IE1) or the Old Fort gravel (IE2), their ages remain uncertain.

8.1.1 Regional Correlation

Geological mapping and hydrogeological analysis presented in this report confirm that the Grimshaw gravels, as a geological unit, are not confined to the topographic 'lobes' (Figures 17, 18, 19, 20, 21, 22, and 23) presented in PFRA (1998). Regionally, the Grimshaw gravels form a laterally extensive unit that is mapped from the Fort St. John (B.C.) area in the west to the Grimshaw area (and potentially Deadwood) in the east (Figures 17 and 25). The Grimshaw gravels form a narrow deposit in the west, confined by a relatively narrow bedrock valley that broadens towards the east (potentially up to 40 km wide; Figures 17, 25, and 26). Sedimentological analysis of the Grimshaw gravels indicates that they were deposited in a braid-delta system that prograded towards the northeast, and a lobe-shaped northward extension of the Grimshaw gravels on the northern margin of the Whitemud Hills (Figure 16) suggests deposition of a delta lobe in the Whitemud River valley area; however, further work is required to confirm the depositional environment, and correlation, of the gravel in that area. The presence of Grimshaw gravels in the Fairview area, together with the ground surface topography, suggests the presence of a western Grimshaw gravels 'lobe' (cf. PFRA, 1998) that had not been previously delineated (demarcated in this report by an 'assumed' and 'approximate' mapped strath; Figure 17), although gravel located east of Fairview had been previously mapped by Edwards et al. (2004) and Edwards and Budney (2009) as part of an aggregate resources investigation (Figure 11). Sediments correlated with the Grimshaw gravels in the Deadwood and Carmon Lake areas (Figures 2 and 17) are considered outliers because they are relatively isolated (~15–40 km) from other Grimshaw gravels deposits and, hence, may have been deposited by a different depositional system; further work is required to confirm their correlation with the Grimshaw gravels mapped elsewhere (Figure 17).

Similarly, the Old Fort gravel forms a relatively narrow deposit in the Fort St. John (B.C.) area and broadens towards the east (up to ~30 km wide) in the Peace River Lowland (Figure 25); the Old Fort gravel is not mapped beyond Deadwood, and the cluster of data correlated with the Old Fort gravel in the Carmon Lake area (Figure 17) may have been deposited in a different depositional system, potentially derived from the Heart River Upland (Figure 3). The Shaftesbury gravel also forms a relatively narrow deposit in the Fort St. John area (Figure 25), and the Shaftsbury bedrock valley is difficult to delineate between Cherry Point and Dunvegan (Figure 17) due to data sparsity. However, the Shaftesbury gravel occupies a well-defined bedrock valley in the Saddle (Burnt) River and Smoky River areas, and adjacent to the Grimshaw lobes area north of the Town of Peace River (Figures 17 and 25). The cluster of Shaftesbury gravel identified north of Carmon Lake (in the l'Hirondelle bedrock valley) requires further investigation to understand the stratigraphic relationship of those deposits with the Shaftesbury gravel mapped elsewhere in the Peace River Lowland.

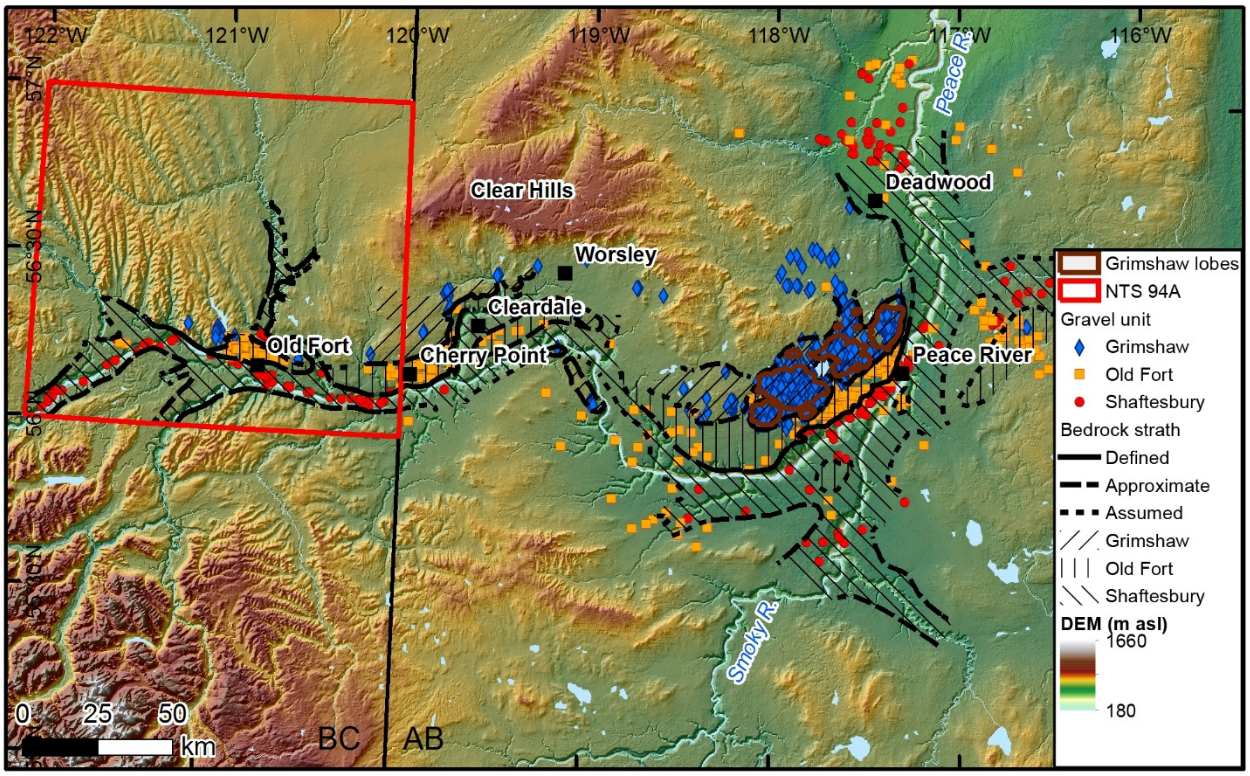


Figure 25. Regional correlation of the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel in the Peace River Lowland, overlain on a hill-shaded DEM (NASA Jet Propulsion Laboratory, 2013). Mapping within NTS 94A study area (red box) from Hartman (2005).

8.2 Aggregate Resources Potential

8.2.1 Grimshaw Gravels

The Grimshaw gravels within the Grimshaw lobes area (Figure 6) are heavily exploited as an aggregate resource, notwithstanding constraints imposed on aggregate extraction that are required to protect the Grimshaw gravels aquifer (e.g., restrictions on the depth of excavation). The deposit is a valuable aggregate resource due in part to its significant thickness, thin overburden, laterally continuous distribution, high aggregate quality, and proximity to good transportation routes. In this report, we have identified remnant portions of the fluvial system in which the Grimshaw gravels were deposited and which provide insight to the potential lateral extent of the Grimshaw gravels aggregate resource. With the exception of the Worsley area (Atkinson and Paulen, 2010a), gravel deposits correlated with the Grimshaw gravels in this report have not been previously assessed from an aggregate resources perspective. However, from a geological perspective, these unassessed areas may contain aggregate deposits with characteristics similar to those of the Grimshaw lobes.

8.2.2 Old Fort Gravel

The aggregate quality of the Old Fort gravel in the study area is not known due to an absence of outcrop sections and cored holes; however, the interpreted depositional environment (glaciofluvial) offers the potential that its aggregate quality is similar to that of the Grimshaw gravels. The relatively thick overburden covering the Old Fort gravel reduces its economic viability and may explain its apparent underexploitation in the study area; conversely, the Old Fort gravel is heavily exploited in the Fort St. John (B.C.) area, where it is less deeply buried.

8.2.3 Shaftesbury Gravel

Basal sand and gravel at the base of the of the Shaftesbury bedrock valley is likely too deeply buried within the study area to provide a viable aggregate resource. However, Shaftesbury gravel is exploited as an aggregate resource in British Columbia (NTS 94A map area) where it overlies terraces in the modern Peace River valley and in places where the overburden has been removed (e.g., aggregate pits at Taylor, B.C.; Hartman, 2005). Shaftesbury gravel may be exposed in terraces in the modern Peace River valley (Figure 6) in the study area; in that case, it might provide an economically viable aggregate resource.

8.3 Hydrogeological Significance

The architecture of the basal sand and gravel deposits, including their lateral extent (Figures 16 and 17), and the interconnectivity and lateral extent of overlying sediments (Figure 24) form the geological framework of aquifer systems in the study area. Assessment of the groundwater chemistry data from the AWWID both supports and provides insight to the plan-view mapping and log correlation of the Grimshaw gravels, Old Fort gravel, and Shaftesbury gravel (Figure 26).

Groundwater chemistry is influenced by the geological materials with which the water is in contact, and by the residence time within an aquifer system. Residence time is influenced by the flow system, the composition of the geological materials, and the length of time and distance it takes for water to move through those materials. Pore space and connectivity are expressed as permeability, which is an important control on groundwater movement and residence time within an aquifer (Tokarsky, 1971). Coarse-grained materials such as gravel are generally far more permeable than fine-grained glaciogenic deposits (e.g., till and glaciolacustrine silt and clay). Consequently, water moves through gravel units more quickly (low residence time) and water quality tends to be higher.

Water quality within the area of the main Grimshaw gravels deposit (Grimshaw lobes area) is relatively high (low TDS; Figure 26). Tokarsky (1971) attributed the high quality to a short residence time within the gravel and, hence, limited opportunity for dissolution of clay minerals. However, within the Grimshaw gravels deposit, a correlation between sediment type at the well screen interval and groundwater chemistry composition could not be established Figure 19). Alternatively, groundwater chemistry appears to be correlated with areas of recharge and discharge (Figure 23).

9 Conclusions

This report presents a revised stratigraphic framework and sedimentary architecture of the basal sand and gravel unit (U1; after Slomka, in press) in the Peace River Lowland, including an updated assessment of the hydrogeology and summary of the aggregate resources potential of the Grimshaw gravels. Sediments of U1 are subdivided into three subunits in this report (from oldest to youngest): the Grimshaw gravels, the Old Fort gravel, and the Shaftesbury gravel. The three subunits are identified, characterized,

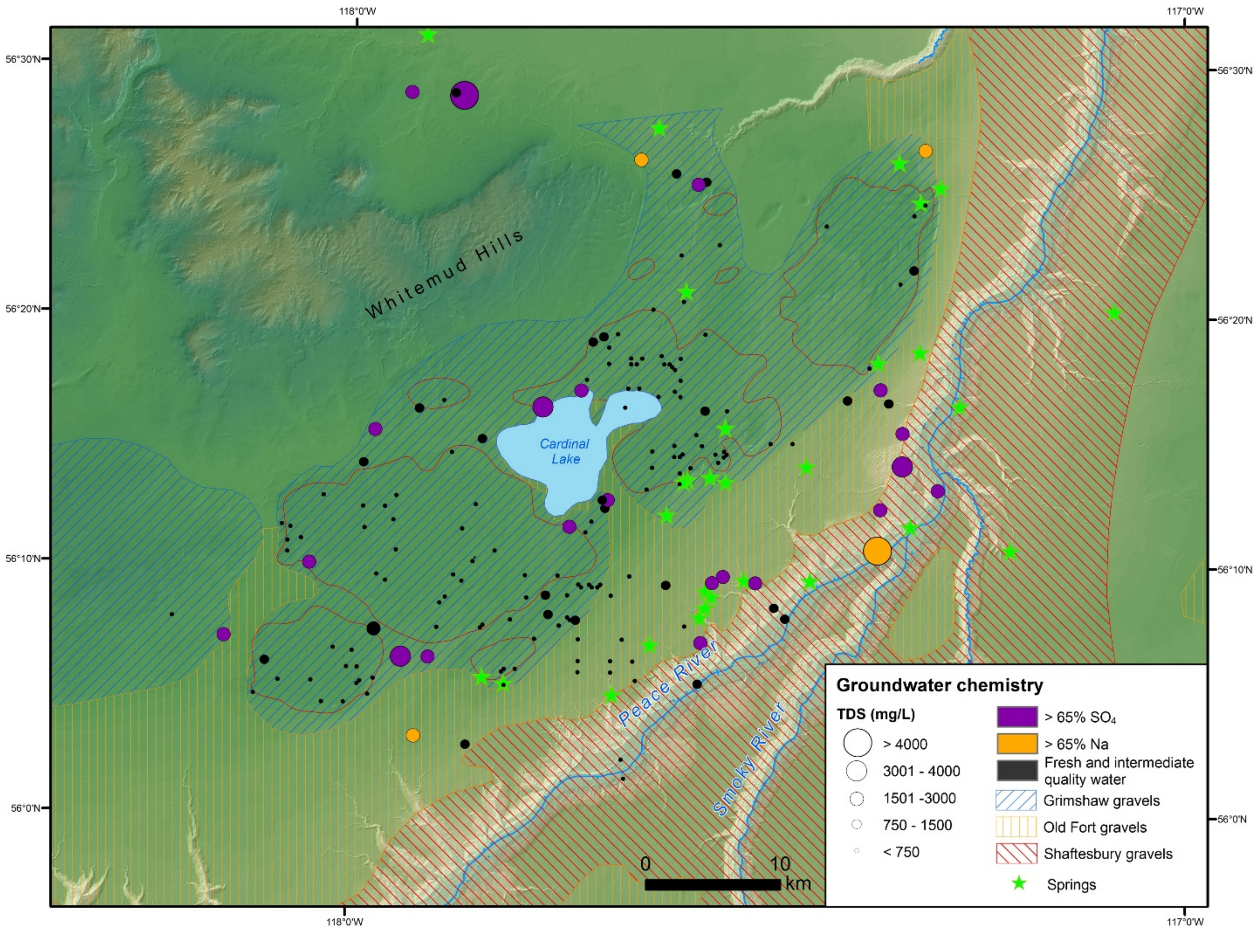


Figure 26. Distribution of groundwater chemistry from wells screened in the Grimshaw gravels, Old Fort gravel, and Shaftesbury bedrock valley sand and gravel (data from AEP, 2016), overlain on a hill-shaded DEM (data from AEP, 2015).

correlated, and mapped on a regional scale, based primarily on 1) analysis of outcrops, 2) interpretation and correlation of AWWID lithology logs, 3) calculating the relative height of basal sand and gravel above the modern Peace River, and 4) examining the surface expression of bedrock straths using a 25 m DEM (AEP, 2015). Radiocarbon dates reported in the literature from material within the Shaftesbury gravel and overlying glaciolacustrine sediment indicate a Middle Wisconsinan age, making the Grimshaw gravels and Old Fort gravel pre–Middle Wisconsinan deposits.

Analysis of water chemistry data from the AWWID indicates that the groundwater within the Grimshaw gravels is of good quality. The majority of the Grimshaw gravels are areas of recharge and are characterized by $CaMgHCO_3$ waters with low TDS. However, lower water quality is found near areas of discharge (near streams, rivers, and springs). Groundwater near discharge areas may contain higher concentrations of Na and SO_4, along with an increased TDS content.

Assessment of the lateral distribution and thickness (geometry) of the subunits and their stratigraphic relationships (architecture) provides insight to potential unmapped aggregate resources and aquifers in the study area to the west of the Grimshaw lobes area, where resource extraction is currently most heavily concentrated.

10 References

AEP (Alberta Environment and Parks; 2015): Provincial DEM, digital topographic data; AltaLIS, URL <http://www.altalis.com/products/terrain/dem.html>, 25 m cell, Esri® Grid format [December 2016].

AEP (Alberta Environment and Parks; 2016): Alberta Water Well Information Database, URL <http://aep.alberta.ca/water/reports-data/alberta-water-well-information-database/default.aspx> [August 2016].

Atkinson, N. and Paulen, R.C. (2010a): Surficial geology and Quaternary history of the Cleardale area, northwestern Alberta (NTS 84D/SW); Energy Resources Conservation Board, ERCB/AGS Open File Report 2010-11, 27 p., URL <http://ags.aer.ca/publications/OFR_2010_11.html> [June 2017].

Atkinson, N. and Paulen, R.C. (2010b): Surficial geology of the George Lake area (NTS 84D/SE; GIS data, polygon features); Energy Resources Conservation Board, ERCB/AGS Digital Dataset 2010-0010, URL <http://ags.aer.ca/publications/DIG_2010_0010.html> [June 2017].

Borneuf, D. (1981): Hydrogeology of the Peace River area, Alberta; Alberta Research Council, Alberta Geological Survey, Earth Sciences Report 81-2, URL <http://ags.aer.ca/publications/ESR_1981_02.html> [June 2017].

Botterill, S. (2007): Sedimentology, stratigraphy and depositional environment of the basal Peace River valley; undergraduate thesis, University of Alberta.

Boulton, G.S. and Paul, M.A. (1976): The influence of genetic processes on some geotechnical properties of glacial tills; Quaternary Journal of Engineering Geology, v. 9, p. 159–194.

Carlson, V.A. and Hackbarth, D.A. (1974): Bedrock topography of the Grande Prairie area, NTS 83M, Alberta; Alberta Research Council, Alberta Geological Survey, Map 61, scale 1:250 000, URL http://ags.aer.ca/publications/MAP_061.html [June 2017].

Chlachula, J. and Leslie, L. (1998): Preglacial archaeological evidence at Grimshaw, the Peace River area, Alberta; Canadian Journal of Earth Sciences, v. 35, p. 871–884.

Cummings, D.I., Russell, H.A.J. and Sharpe, D.R. (2012): Buried-valley aquifers in the Canadian Prairies: geology, hydrogeology, and origin; Canadian Journal of Earth Sciences, v. 49, no. 9, p. 987–1004.

Dalrymple, R.W. (2010): Interpreting sedimentary successions: facies, facies analysis and facies models; Chapter 2 *in* Facies Models 4, N.P. James and R.W. Dalrymple (ed.), Geological Association of Canada, St. John’s, Newfoundland and Labrador, GEOtext 6, p. 3–18.

Dawson, G.M. and McConnell, R.G. (1895): Glacial deposits of southwestern Alberta in the vicinity of the Rocky Mountains; Bulletin of the Geological Society of America; v. 7, p. 31–66.

Edwards, W.A.D. and Budney, H.D. (2009): Alberta sand and gravel deposits with aggregate potential (GIS data, polygon features); Alberta Energy and Utilities Board, EUB/AGS Digital Dataset 2004-0034, URL <http://ags.aer.ca/publications/DIG_2004_0034.html> [October 2016].

Edwards, W.A.D. and Scafe, D. (1996): Mapping and resource evaluation of the Tertiary and pre-glacial sand and gravel formations of Alberta; Alberta Energy and Utilities Board, EUB/AGS Open File Report 1994-06, 247 p., URL <http://ags.aer.ca/publications/OFR_1994_06.html> [January 2016].

Edwards, W.A.D., Budney, H.D., Berezniuk, T. and Butkovic, L. (2004): Sand and gravel deposits with aggregate potential, Peace River, Alberta (NTS 84C); Alberta Energy and Utilities Board, EUB/AGS Map 303, scale 1:250 000, URL <http://ags.aer.ca/publications/MAP_303.html> [June 2017].

Eyles, N. (1979): Facies of supraglacial sedimentation on Icelandic and Alpine temperate glaciers; Canadian Journal of Earth Sciences, v. 16, p. 1341–1361.

Eyles, C.H. and Eyles, N. (2010): Glacial deposits; Chapter 5 *in* Facies Models 4, N.P. James and R.W. Dalrymple (ed.), Geological Association of Canada, St. John's, Newfoundland and Labrador, GEOtext 6, p. 73–105.

Eyles, N., Eyles, C.H. and Miall, A.D. (1983): Lithofacies types and vertical profile models: an alternative approach to the description and environmental interpretation of glacial diamict and diamictite sequences; Sedimentology, v. 30, p. 393–410.

Finnegan, N.J. and Balco, G. (2013): Sediment supply, base level, braiding, and bedrock river terrace formation: Arroyo Seco, California, USA; GSA Bulletin, v. 125, p. 1114–1124.

Fox, J.C., Richardson, R.J.H., Gowan, R. and Sham, P.C. (1987): Surficial geology of the Peace River–High Level area, Alberta; Alberta Research Council, Alberta Geological Survey Map 205, scale 1:500 000, URL <http://ags.aer.ca/publications/MAP_205.html> [June 2017].

Green, R. and Mellon, G.B. (1962): Geology of the Chinchaga River and Clear Hills (north half) map-areas, Alberta; Research Council of Alberta, Alberta Geological Survey, Preliminary Report 62-8, URL <http://ags.aer.ca/publications/ESR_1962_08.html> [June 2017].

Hartman, G.M.D. (2005): Quaternary stratigraphy and geologic history of the Charlie Lake (NTS 94A) map-area, British Columbia; M.Sc. thesis, Simon Fraser University, URL <http://summit.sfu.ca/item/10223> [June 2017].

Hartman, G.M.D. (2015): Synthesis of a post-Laramide stratigraphic framework of the South Saskatchewan River basin, Alberta, in support of hydrostratigraphic modelling; Alberta Energy Regulator, AER/AGS Open File Report 2015-01, URL <http://ags.aer.ca/publications/OFR_2015_01.html> [June 2017].

Hartman, G.M.D. and Clague, J.J. (2008): Quaternary stratigraphy and glacial history of the Peace River valley, northeast British Columbia; Canadian Journal of Earth Sciences, v. 45, p. 549–564.

Hartman, G.M.D. and Slomka, J. (2017): Regional Neogene-Quaternary stratigraphy of the Peace River Lowland, northwestern Alberta; Geological Society of America, Rocky Mountain Section Meeting, June 9–10, 2017, Calgary, Alberta, Paper 20-4, URL<https://gsa.confex.com/gsa/2017RM/webprogram/Paper293187.html> [July 2017].

Hathway, B., Dolby, G., McNeil, D.H., Kamo, S.L., Heizler, M.T., and Joyce, N. (2013): Revised stratigraphy, regional correlations and new bentonite radiometric ages for the Albian Loon River Formation, Fort St. John Group, northwestern Alberta; Bulletin of Canadian Petroleum Geology, v. 61, no. 4, p. 331–358.

Hein, F.J. and Walker, R.G. (1977): Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia; Canadian Journal of Earth Sciences, v. 14, p. 562–570.

Henderson, E.P. (1959): Surficial geology of Sturgeon Lake map-area, Alberta; Geological Survey of Canada, Memoir 303, 108 p.

Horberg, C.L. (1954): Rocky Mountain and continental Pleistocene deposits in the Waterton region, Alberta, Canada; Geological Society of America Bulletin, v. 65, no. 11, p. 1093–1150.

Howard, A.D. (1960): Cenozoic history of northeastern Montana and northwestern North Dakota with emphasis on the Pleistocene; United States Geological Survey, Professional Paper 326, 110 p.

Jackson, L.E., Andriashek, L.D. and Phillips, F.M. (2011): Limits of successive Middle and Late Pleistocene continental ice sheets, Interior Plains of southern and central Alberta and adjacent areas; Developments in Quaternary Science, v. 15, p. 575–589.

Jones, J.F. (1966): Geology and groundwater resources of the Peace River district, northwestern Alberta; Research Council of Alberta, Alberta Geological Survey, Bulletin 016, URL <http://ags.aer.ca/publications/BUL_016.html> [June 2017].

Kjær, K.H. and Krüger, J. (2001): The final phase of dead-ice moraine development: processes and sediment architecture, Kotlujokull, Iceland; Sedimentology, v. 48, p. 935–952.

Kostic, B., Becht, A. and Aigner, T. (2005): 3-D sedimentary architecture of a Quaternary gravel delta (SW-Germany): implications for hydrostratigraphy; Sedimentary Geology, v. 181, p. 143–171.

Lawson, D.E. (1979): Distinguishing characteristics of diamictons at the margin of the Matanuska Glacier, Alaska; Annals of Glaciology, v. 2, p. 78–84.

Leckie, D.A. (2006): Tertiary fluvial gravels and evolution of the Western Canadian Prairie landscape; Sedimentary Geology, v. 190, p. 139–158.

Leslie, L.E. and Fenton, M.M. (2001): Quaternary stratigraphy and surficial geology, Peace River – final report; Alberta Energy and Utilities Board, EUB/AGS Special Report 10, 34 p., URL <http://ags.aer.ca/publications/SPE_010.html> [September 2014].

Lowe, D.R. (1982): Sediment gravity flows: II Depositional models with spatial reference to the deposits of high-density turbidity currents; Journal of Sedimentary Petrology, v. 52, p. 279–297.

Lyster, S., MacCormack, K.E., and Atkinson, N. (2016): Pick elevations for the bedrock topography of the Alberta Plains; Alberta Energy Regulator, AER/AGS Digital Dataset 2016-0038, URL<http://ags.aer.ca/publications/DIG-2016-0038.html> [April 2017].

MacCormack, K.E., Atkinson, N. and Lyster, S. (2015a): Bedrock topography of Alberta, Canada; Alberta Energy Regulator, AER/AGS Map 602, scale 1:1 000 000; URL <http://ags.aer.ca/publications/MAP_602.html> [September 2014].

MacCormack, K.E., Atkinson, N. and Lyster, S. (2015b): Sediment thickness of Alberta; Alberta Energy Regulator, AER/AGS Map 603, scale 1:1 000 000; URL <http://ags.aer.ca/publications/MAP_603.html> [June 2017].

Mackenzie Municipal Services Agency (2011): Gravel pit study, Municipal District of Peace No. 135; Mackenzie Municipal Services Agency, 47 p.

Mackin, J.H. (1948): Concept of the graded river; Bulletin of the Geological Society of America, v. 59, p. 463–512.

Mathews (1978): Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map-area, British Columbia; Geological Survey of Canada, Paper 78-20, 25 p.

McConnell, R.G. (1885): Report on the Cypress Hills, Wood Mountain, and adjacent country, embracing that portion of the District of Assiniboia, lying between the International Boundary and the 51st parallel and extending from long. 106° to long. 110° 50'; Geological Survey of Canada, Annual Report, v. 1 (1885), pt. C, 92 p. and 2 maps.

Miall, A.D. (2010): Alluvial deposits; Chapter 6 *in* Facies Models 4, N.P. James and R.W. Dalrymple (ed.), Geological Association of Canada, St. John’s, Newfoundland and Labrador, GEOtext 6, p. 105–138.

Mihalynuk, M.G., Bellefontaine, K.A., Brown, D.A., Logan, J.M., Nelson, J.L., Legun, A. and Diakow, L. (1996): Digital geology data, NW British Columbia (NTS 94/E, L, M; 104/F, G, H, I, J, K, L, M, N, O, P; 114/I, O, P); British Columbia Geological Survey, Open File 1996-11; URL <http://www.empr.gov.bc.ca/Mining/Geoscience/PublicationsCatalogue/OpenFiles/1996/Pages/1996-11.aspx> [August 2017].

Mills, P.C. (1983): Genesis and diagnostic value of soft-sediment deformation structures: a review; Sedimentary Geology, v. 35, p. 83–104.

Morgan, A.J., Paulen, R.C. and Froese, C.R. (2008): Ancestral buried valleys of the Peace River: effects on the Town of Peace River; GeoEdmonton08 – 61st Canadian Geotechnical Conference and 9th Joint CGS/IAH-CNC Groundwater Conference, Edmonton, Alberta, Abstracts, p. 1219–1226.

Morgan, A.J., Slattery, S.R. and Froese, C.R. (2009): Results of sediment coring at the town of Peace River, northwestern Alberta (NTS 84C); Energy Resources Conservation Board, ERCB/AGS Open File Report 2009-18, 94 p., URL<http://ags.aer.ca/publications/OFR_2009_18.html> [September 2014].

NASA Jet Propulsion Laboratory (2013): NASA Shuttle Radar Topography Mission 1 arc second, Version 3. NASA EOSDIS Land Processes DAAC, USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaac.usgs.gov), accessed at <https://earthexplorer.usgs.gov> [April 2017].

Nemec, W. (1990): Aspects of sediment movement on steep delta slopes; *in* Coarse-Grained Deltas, A. Colella and D.B. Prior (ed.), International Association of Sedimentologists, Special Publication 10, p. 29–73.

Nurkowski, J.R. (1984): Coal quality, coal rank variation and its relation to reconstructed overburden, Upper Cretaceous and Tertiary plains coals, Alberta, Canada; American Association of Petroleum Geologists Bulletin, v. 68, p. 285–295.

Paulen, R.C. (2005): Surficial geology of the Grimshaw area, Map 291 (NTS 84C/SW) – polygon features; Alberta Energy and Utilities Board, EUB/AGS Digital Dataset 2004-0044, URL<http://ags.aer.ca/publications/DIG_2004_0044.html> [June 2017].

Pawley, S.M., Hartman, G.M.D. and Chao, D.K. (2016): Relative landslide susceptibility model of the Alberta Plains and Shield regions; Alberta Energy Regulator, AER/AGS Map 605, 1:1 000 000 scale, URL <http://ags.aer.ca/publications/MAP_605.html> [January 2018].

Pawlowicz, J.G. and Fenton, M.M. (1995): Bedrock topography of Alberta; Alberta Energy and Utilities Board, EUB/AGS Map 226, 1:2 000 000 scale.

Pettapiece, W.W. (1986): Physiographic subdivisions of Alberta; Land Resources Research Centre, Agriculture Canada, Research Branch, scale 1:1 500 000, URL <http://sis.agr.gc.ca/cansis/publications/surveys/ab/abp/index.html> [June 2017].

PFRA (Prairie Farm Rehabilitation Administration; 1998): Proposed community-focused management strategy for the Grimshaw Gravels Aquifer; Agriculture and Agri-Food Canada, technical report, 44 p.

Postma, G. (1984): Mass-flow conglomerates in a submarine canyon: Abrioja fan-delta, Pliocene, southeast Spain; *in* Sedimentology of Gravels and Conglomerates, E.H. Koster and R.J. Steel (ed.), Canadian Society of Petroleum Geologists, Memoir 10, p. 237–258.

Postma, G. (1990): An analysis of the variation in delta architecture; Terra Nova, v. 2, p. 124–130.

Prior, G.J., Hathway, B., Glombick, P.M., Pană, D.I., Banks, C.J., Hay, D.C., Schneider, C.L., Grobe, M., Elgr, R. and Weiss, J.A. (2013): Bedrock geology of Alberta; Alberta Energy Regulator, AGS Map 600, 1:1 000 000, URL <http://ags.aer.ca/publications/MAP_600.html> [August 2016].

Rutherford, R.L. (1930): Geology and water resources in parts of the Peace River and Grande Prairie districts, Alberta; Research Council of Alberta, Report 21, URL <http://ags.aer.ca/publications/REP_21.html> [June 2017].

Rutherford, R.L. (1937): Saskatchewan gravels and sands in central Alberta; Transaction of the Royal Society of Canada, ser. 3, v. 31, sec. 4, p. 81–95.

Scafe, D.W., Edwards, W.A.D., and Boisvert, D.R. (1989): Sand and gravel resources of the Peace River area; Alberta Research Council, ARC/AGS Open File Report 1991-21, 58 p., URL <http://ags.aer.ca/publications/OFR_1991_21.html> [June 2017].

Scheelar, M.D. and Odynsky, W. (1968): Reconnaissance soil survey of the Grimshaw and Notikewin area; Research Council of Alberta, RCA/AGS Report 88, 83 p., URL <http://ags.aer.ca/publications/REP_88.html> [June 2017].

Slomka, J.M. (in press): Cenozoic stratigraphy of northwestern Alberta (parts of NTS 83M–O and 84B–G); Alberta Energy Regulator, AER/AGS Open File Report 2018-05.

Slomka, J.M. and Hartman, G.M.D. (2017): The stratigraphy, depositional environment, and geologic history of the Grimshaw gravel deposit, Peace River Lowlands, Alberta; Canadian Society of Petroleum Geologists, Geoconvention2017, May 15–19, 2017, Calgary, Alberta, Abstract 140-GC2017, URL <https://www.geoconvention.com/archives/2017/140_GC2017_The%20stratigraphy_depositional_environ_geologic_history_Grimshaw_gravel.pdf> [March 2018].

Slomka, J.M. and Utting, D.J. (2017): Glacial advance, occupation, and retreat sediments associated with multi-stage ice-dammed lakes: north-central Alberta, Canada; Boreas, v. 47, no. 1, p. 150–174, doi:10.1111/bor.12257.

Smith, D.G. and Jol, H.M. (1997): Radar structure of a Gilbert-type delta, Peyto Lake, Banff National Park, Canada; Sedimentary Geology, v. 113, p. 195–209.

Sohn, Y.K., Rhee, C.W. and Kim, B.C. (1999): Debris flow and hyperconcentrated flood-flow deposits in an alluvial fan, northwestern part of the Cretaceous Yongdong Basin, central Korea; Journal of Geology, v. 107, p. 111–132.

Stalker, A.MacS. (1968): Identification of Saskatchewan gravels and sands; Canadian Journal of Earth Sciences, v. 5, p. 155–163, URL <https://doi.org/10.1139/e68-014> [January 2018].

Tokarsky, O. (1967): Groundwater and groundwater resources of the Grimshaw–Cardinal Lake area, Alberta; M.Sc. thesis, University of Alberta, 179 p.

Tokarsky, O. (1971): Hydrogeology of the Grimshaw–Chinook Valley area, Alberta; Research Council of Alberta, RCA/AGS Earth Sciences Report 1971-02, 22 p., URL <http://ags.aer.ca/publications/ESR_1971_02.html> [June 2017].

Van Vliet-Lanoë, B., Fox, C.A. and Gubin, S.V. (2004): Micromorphology of cryosols; Chapter 2 *in* Cryosols: Permafrost-Affected Soils, J.M. Kimble (ed.), Springer, Berlin, Heidelberg, p. 365–390.

Vonhof, J.A. (1969): Tertiary gravels and sand in the Canadian Great Plains; Ph.D. thesis, University of Saskatchewan, 381 p.

Waters, E.J. and Andriashek, L.D. (2014): Compilation of boreholes drilled or logged by the Alberta Geological Survey; Alberta Energy Regulator, AER/AGS Open File Report 2014-06, 10 p.

Whitaker, S.H. and Christiansen, E.A. (1972): The Empress Group in southern Saskatchewan; Canadian Journal of Earth Sciences, v. 9, p. 353–360.