Mapping the Susceptibility to Amplification of Seismic Ground Motions in the Montney Play Area of Northeast British Columbia

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ABSTRACT

Seismicity has increased significantly in northeast British Columbia in recent years due to fluid injection by the petroleum industry for hydraulic fracturing and wastewater disposal. The objective of this study is to map the susceptibility to amplification of seismic ground motions due to local soil conditions within the Montney play trend of northeast British Columbia. Results of this study include: compilation of a surficial geological map from several published sources; compilation of a subsurface geological borehole database to characterize the geological units of the shallow subsurface; acquisition of new shear-wave velocity (V_s) data and development of a V_s model for the shallow geological units. These data were used to assign NEHRP Site Classes and amplification susceptibility ratings to the surficial geological map units. This analysis demonstrates that areas underlain by Holocene and recessional phase deposits of the last glaciation, where sufficiently thick, are in NEHRP Site Class D, and so susceptible to amplification of seismic ground motions. Where these deposits are thinner, along their margins, amplification of ground motions may also occur due to resonance. Ground motions recorded in recent induced seismic events are generally consistent with these conclusions, although there is considerable variability.

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INTRODUCTION

The recent increase in seismicity in northeast British Columbia (BC) has been attributed mainly to the increase in hydraulic fracturing and to a lesser extent to subsurface fluid injection for wastewater disposal by the petroleum industry (Horner *et al*., 1994; Atkinson *et al*., 2015, 2016; Babaie Mahani, 2017b). Although the increase in seismicity is well documented, the associated ground motions have not been studied until recently (*e.g*. Babaie Mahani *et al*., 2017a; Babaie Mahani and Kao, 2018a, b; Babaie Mahani, 2018). Also, ground motions can be amplified significantly due to local soil[1] conditions (Idriss, 1990; Finn, 1994; Kramer, 1996; Finn and Wightman, 2003; Finn *et al*., 2004), but susceptible areas have not been identified previously in this region.

The variability of seismic ground motions due to local soil conditions can be mapped using surficial and shallow subsurface geological and geophysical data. Such maps are useful for planning purposes: for identifying areas where infrastructure could be at greater risk, prioritizing seismic retrofit programs, calculating damage estimates, and identifying areas where the public could be more significantly affected or at greater risk.

The objectives of this project are:

- to prepare a map showing the susceptibility to amplification of seismic ground motions due to shallow geological conditions in the Montney Play area. This is currently the most active gas play in BC and is being extensively exploited by hydraulic fracturing in horizontal wells, and
- to develop a shear-wave velocity (V_s) database and model of the shallow geological units, which will serve as tools for ongoing studies.

Ground-motion amplification due to soil conditions can be estimated by the average shear-wave velocity of the upper 30 m (V_{s30}; Finn and Wightman, 2003; Finn *et al*., 2004). The National Earthquake Hazards Reduction Program (NEHRP) in the United States has defined five site classes based on V_{s30} and these have been adopted by the National Building Code of Canada (NBCC; Table1; Building Seismic Safety Council, 2003, NRC, 2015).

V_{s30} is the time-averaged V_s in the upper 30 m (i.e., harmonic mean), and is calculated using the following formula (it is a common error to calculate the arithmetic rather than the harmonic mean):

$V_{s30} = \sum h / \sum t$, where

h = each measured interval thickness, where $\sum h = 30$ m, and

t = the measured interval travel time; $t = h/V_s$ for each interval.

[1] In this report, the term soil is used in the engineering sense and applies to all unconsolidated sediments.

Site Class	General description	Definition by V_{s30} (m/s)	Susceptibility Rating
A	Hard rock	V_{s30}>1500	Nil
B	Rock	760<V_{s30}<1500	Very Low
C	Very dense soils and soft rock	360<V_{s30}<760	Low
D	Stiff soils	180<V_{s30}<360	Moderate
E	Soft soils, or soil profile with >3 m soft silt or clay	V_{s30}<180, or >3m silt and clay with plasticity index >20, moisture content >40%, and undrained shear strength <25kPa	High

Table 1. National Earthquake Hazards Reduction Program (NEHRP) Site Classes (Building Seismic Safety Council, 2003). Susceptibility ratings from Hollingshead and Watts, 1994.

Moderate to high amplification of seismic ground motions can occur in Site Classes D and E. Table 2 shows the NBCC Site Class amplification factors at various levels of peak ground acceleration (PGA) on firm ground for PGA, peak ground velocity (PGV), and spectral periods of 0.2 and 0.5 seconds (NRC, 2015). These amplification factors have been derived from large datasets with a large degree of variation and represent average values. As shown on the table, amplification is nonlinear, and decreases as PGA increases (Idriss, 1990; Finn, 1994; Kramer, 1996; Finn and Wightman, 2003; Seyhan and Stewart, 2014). This effect is more pronounced at lower V_{s30} and for shorter period ground motions. For example, amplification can be significant for Site Classes D and E for firm ground PGA=0.1 g, but amplification of short period ground motions is near zero at firm ground PGA=0.3 g. However, the threshold of damage is approximately 0.1 g (Wald *et al*., 1999; Worden, 2012), so that significant amplification can occur within the range of damaging ground motions. Note that the NBCC amplification factors are relative to Site Class C, which represents firm ground.

Amplification of ground motions can also be caused by topography and the geometry of sedimentary basins at horizontal scales of ten of metres to tens of kilometers (Finn, 1994; Kramer, 1996). These effects are not considered directly in this report.

Peak Ground Acceleration (PGA)					
Site Class	PGA on firm ground, g				
	≤0.1	**0.2**	**0.3**	0.4	≥0.5
A	**0.9**	**0.9**	**0.9**	0.9	0.9
B	**0.87**	**0.87**	**0.87**	0.87	0.87
C	**1.00**	**1.00**	**1.00**	1.00	1.00
D	**1.29**	**1.10**	**0.99**	0.93	0.88
E	**1.82**	**1.23**	**0.98**	0.83	0.74

Peak Ground Velocity (PGV)					
Site Class	PGA on firm ground, g				
	≤0.1	**0.2**	**0.3**	0.4	≥0.5
A	**0.62**	**0.62**	**0.62**	0.62	0.62
B	**0.67**	**0.67**	**0.67**	0.67	0.67
C	**1.00**	**1.00**	**1.00**	1.00	1.00
D	**1.47**	**1.3**	**1.2**	1.14	1.1
E	**2.47**	**1.8**	**1.48**	1.3	1.17

0.2 sec					
Site Class	PGA on firm ground, g				
	≤0.1	**0.2**	**0.3**	0.4	≥0.5
A	**0.69**	**0.69**	**0.69**	0.69	0.69
B	**0.77**	**0.77**	**0.77**	0.77	0.77
C	**1.00**	**1.00**	**1.00**	1.00	1.00
D	**1.24**	**1.09**	**1.00**	0.64	0.9
E	**1.64**	**1.24**	**1.05**	0.93	0.85

0.5 sec					
Site Class	PGA on firm ground, g				
	≤0.1	**0.2**	**0.3**	0.4	≥0.5
A	**0.57**	**0.57**	**0.57**	0.57	0.57
B	**0.65**	**0.65**	**0.65**	0.65	0.65
C	**1.00**	**1.00**	**1.00**	1.00	1.00
D	**1.47**	**1.30**	**1.20**	1.14	1.10
E	**2.47**	**1.8**	**1.48**	1.3	1.17

Table 2. NBCC Site Class amplification factors at various levels of peak aground acceleration (PGA) on firm ground for PGA, peak ground velocity (PGV) and spectral periods of 0.2 and 0.5 seconds (NRC, 2015). Note that NBCC amplification factors are relative to Site Class C, which represents firm ground.

Geologically based maps showing the variability of seismic ground motions due to local soil conditions can be prepared at different levels of complexity. The simplest uses existing surficial geological maps, and assigns a susceptibility to amplification (or Site Class) to each map unit based on V_{s30} data from that or similar units. An example is the Site Class Map of California (Wills *et al*., 2000). A higher level also employs existing surficial geological mapping but adds the acquisition of sufficient V_s and geotechnical borehole data to better define the Site Class and geological characteristics of each map unit. This level was used for the map prepared for the Seismic Retrofit Guidelines for BC Schools (Taylor, *et al*., 2006; Association of Professional Engineers and Geoscientists of British Columbia, 2016). The most complex involves collection of sufficient geotechnical borehole data to generate new geological mapping that better reflects the *subsurface* geological conditions relevant to amplification susceptibility, and assigning Site Classes to the map units so defined. Examples are the Quaternary geology and relative earthquake hazard maps prepared by the BC Geological Survey for Chilliwack and Victoria, BC (Levson *et al*., 1996; Monahan and Levson, 2000; Monahan *et al*., 2000), and the Site Class map prepared for the Oakland, California area (Holzer et al., 2005) [2]. More recently, topographic slope has been introduced as an indicator of amplification susceptibility to complement geologically-based maps (Wald and Allen, 2007; Wald *et al*., 2011).

[2] Similar approaches can be used for mapping other site specific earthquake hazards, such as liquefaction susceptibility. An example of the most detailed level are the Quaternary geology and liquefaction maps of Richmond, BC (Monahan *et al*., 2010a, b).

This study, follows the intermediate approach, using existing surficial geological mapping combined with collection of sufficient geotechnical and other borehole data to characterize the geological conditions relevant to amplification within each map unit. The limitations of this level are the scale and level of detail of the source maps and that the map units reflect the surface than subsurface conditions. However, this is a necessary first step to address the regional variation in amplification susceptibility in such a large area. Topographic slope was not considered as a predictor because of the diverse geology represented in the steep slopes of the Peace River and other major valleys.

The project area was defined to include areas where significant induced seismicity has been observed within the Montney play area, and where the BC Oil and Gas Commission requires seismic monitoring for hydraulic fracturing operations (Figure 1, Map 1). This area includes parts of National Topographic System (NTS) Grids (1:250,000 map sheets) 93P, 94A, 94B, 94G, and 94H. A small area around Groundbirch, immediately southwest of the main project outline, was included because a suite of well described boreholes was available for V_s logging. The project area includes Petrel-Robertson Consulting Ltd.'s (2016; Hayes *et al*., 2016) depth-to-bedrock study of the north Peace region, and incorporates data and interpretations from that work.

The following steps have been followed to achieve the objectives described above:

- Compilation of a surficial geological map from published sources at a scale of 1:250,000 (Figure 1, Map 1).
- Compilation and interpretation of a database of shallow borehole data to determine the properties and thicknesses of unconsolidated deposits.
- Acquisition of new V_s data to develop a V_s model for the shallow geological units.
- Assigning V_{s30} ranges to the mapped surficial geological units to create a NEHRP Site Class map, which reflects the susceptibility to ground motion amplification (Map 2).
- Comparison of recently recorded induced seismic ground motions with published attenuation models to assess the validity of the Site Class Map in predicting amplified ground motions.

Details of the methodology are presented below to serve as a guide for future investigations. The surficial geological map and non-proprietary data acquired for this study are included in this report because they provide basic data for future studies, regardless of how methodologies for estimating amplification evolve. Monahan *et al.* (2018) present a preliminary report of this study.

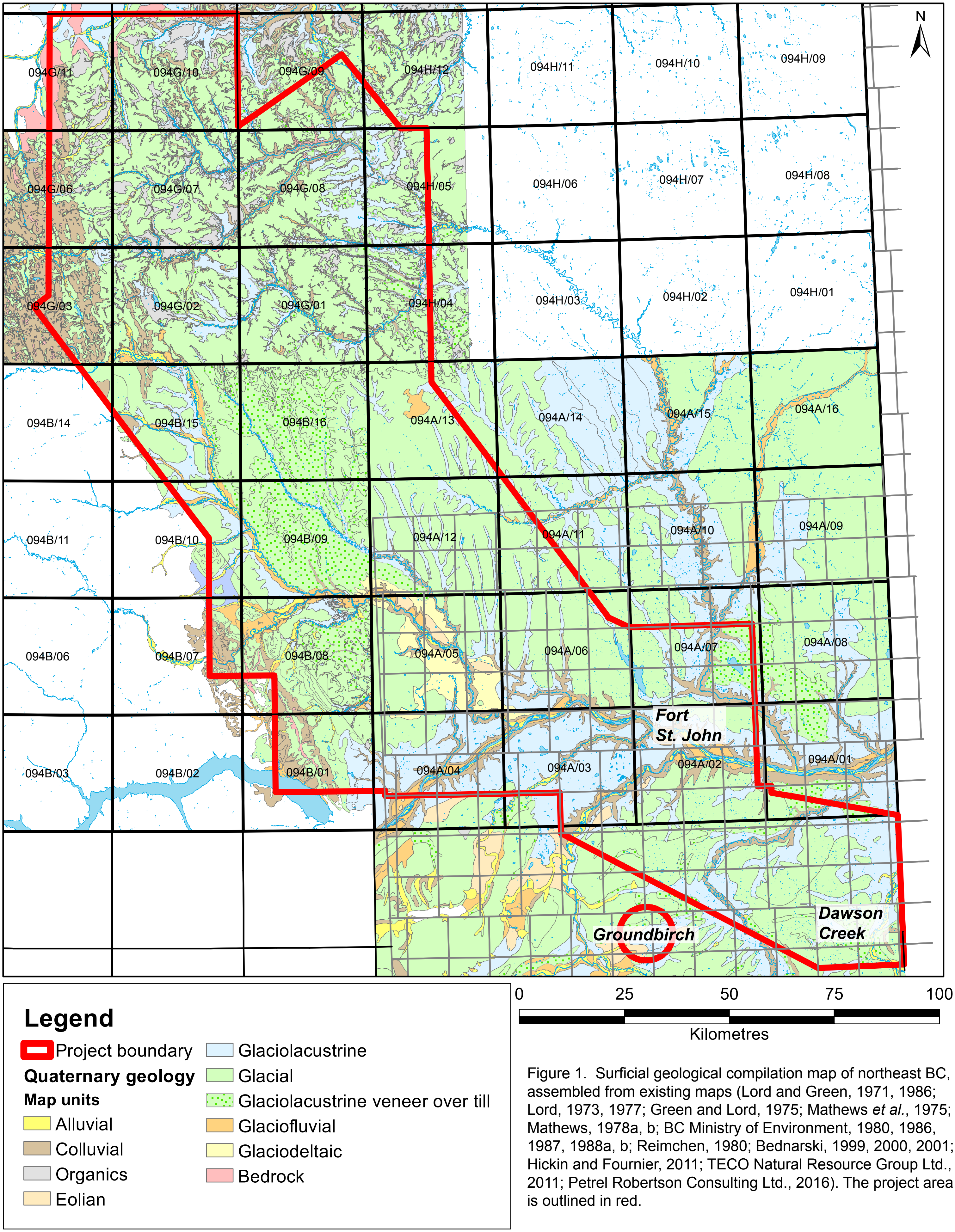


Figure 1. Surficial geological compilation map of northeast BC, assembled from existing maps (Lord and Green, 1971, 1986; Lord, 1973, 1977; Green and Lord, 1975; Mathews *et al.*, 1975; Mathews, 1978a, b; BC Ministry of Environment, 1980, 1986, 1987, 1988a, b; Reimchen, 1980; Bednarski, 1999, 2000, 2001; Hickin and Fournier, 2011; TECO Natural Resource Group Ltd., 2011; Petrel Robertson Consulting Ltd., 2016). The project area is outlined in red.

GEOLOGICAL SUMMARY

The project area lies mainly in the southern part of the Alberta Plateau of northeast BC, east of the Rocky Mountain Foothills (Holland, 1976). A small area of the Foothills is present in the north-westernmost part of the area. This part of the Alberta Plateau is a rolling upland, much of which stands at 800 to 1200 m in elevation. The valleys of the Peace River and other major rivers are incised up to 250 m below plateau level. Most of the area is in the drainage of the Peace River, which flows eastward across the plateau. Its major tributaries in the project area are the Halfway, Cameron, Beatton and Blueberry Rivers on the north, and the Moberly, Pine and Kiskatinaw Rivers on the south. In the northernmost part of the study area the principal rivers are the Sikanni Chief and its tributary, the Buckinghorse, which are in the drainage of the Liard River.

Bedrock Geology

Bedrock consists mainly of gently easterly dipping Cretaceous shale and sandstone, except in the north-westernmost corner of the project area, where Lower Cretaceous and older strata have been brought to the surface on Foothills structures (Stott, 1975, 1982). The principal geological units exposed from west to east across the study area are, in ascending order: the Fort St. John Group which includes primarily marine shale with some interbedded marine sandstone units; the Dunvegan Formation, which consists of marine, deltaic and non-marine sandstone, conglomerate and shale; the Kaskapau Formation, composed of marine shale; and in the south-easternmost part of the study area, the Cardium Formation, which consists of marine to non-marine sandstone, conglomerate and shale (Table 3).

<table>
<tr><th>Epoch</th><th colspan="2">South of the Peace River</th><th>North of the Peace River</th></tr>
<tr><td rowspan="4">Upper Cretaceous</td><td colspan="3">Cardium Formation (marine to non-marine sandstone, conglomerate and shale)</td></tr>
<tr><td colspan="3">Kaskapau Formation(marine shale)</td></tr>
<tr><td colspan="3">Dunvegan Formation (marine to non-marine sandstone, conglomerate and shale)</td></tr>
<tr><td rowspan="4">Fort St. John Group</td><td rowspan="2">Shaftesbury Formation (marine shales)</td><td>Sully Formation (marine shale)</td></tr>
<tr><td rowspan="4">Lower Cretaceous</td><td>Sikanni Formation (marine sandstone and shale)</td></tr>
<tr><td>Peace River Formation (marine sandstone and shale)</td><td rowspan="2">Buckinghorse Formation (marine shale)</td></tr>
<tr><td>Spirit River Formation (marine and non-marine sandstone, conglomerate and shale)</td></tr>
<tr><td colspan="3">Gething Formation (non-marine and marine sandstone, conglomerate, shale and coal)</td></tr>
</table>

Table 3. Principal Cretaceous units in the project area.

Topography is largely controlled by bedrock, with higher elevations being preferentially underlain by sandstone and conglomerate. Shale near the surface is locally deeply weathered. The uppermost bedrock itself is commonly disrupted by glaciotectonic processes and marked by a zone of mixed bedrock and till.

Bedrock geological maps and reports for the project area at a scale of 1:250,000 have been prepared by McMechan (1994, 93-P), Irish (1958, 94A), Thompson (1986, 1989, 94B), Pelletier and Stott (1963, 94G), Stott *et al*. (1963, 94G), and Thompson (1976, 1977, 94H).

Unconsolidated Sediments

Knowledge of the unconsolidated deposits preceding the last glaciation is fragmentary. The earliest consist of pre-glacial gravels deposited on a planation surface that sloped away from the Rocky Mountains and Foothills, and may be Later Tertiary or Pleistocene in age (Table 4; Mathews, 1978a; Hartman and Clague, 2008).

During the Quaternary, at least three glaciations occurred in the area (Mathews, 1978a; Hartman and Clague, 2008; Hickin *et al*., 2016a). The Quaternary succession indicates a repetitive pattern of fluvial incision and deposition during non-glacial periods, followed by deposition of glaciolacustrine silt as the drainages were blocked by advancing Laurentian ice, and finally, till during a glacial maximum. During ice retreat, drainage was again blocked forming retreat-phase glacial lakes and, after retreat of the ice, fluvial incision and deposition recommenced. Fluvial incision cut deeper following each glaciation, and now the modern valleys of the Peace River and its major tributaries are incised through the earlier Quaternary deposits into bedrock. In most cases, each river re-established itself along its earlier course, although in some cases it cut an entirely new channel though bedrock (Figure 2).

The earliest glaciation is inferred from the presence of Canadian shield-derived clasts in the succeeding unit of non-glacial fluvial gravels (Mathews, 1978a, Hartman and Clague, 2008). The latter unit occurs within the Peace River valley, ~225 m above the current river level, and represents deposits of an early precursor of the Peace River that was incised into the plateau surface. These gravels are overlain by the advance phase glaciolacustrine deposits and then till of the penultimate glaciation. This glaciation is undated but interpreted to be early Wisconsin.

Fluvial gravels that were deposited during the non-glacial period between the penultimate and the last glaciations are the oldest firmly dated Quaternary sediments (Mathews, 1978a; Hartmann, 2005; Hartmann and Clague, 2008). These are commonly heavily oxidized, and have provided radiocarbon dates of 27,400$\pm$580 and 26,450$\pm$310 ^{14}C years, making them mid-Wisconsin in age (Mathews, 1978a; Hartmann and Clague 2008). They occur deeper in the Peace River valley fill than the earlier non-glacial gravel unit, about 50 m above current river level.

<table>
<tr><th colspan="2">Time Stratigraphic Unit</th><th>^{14}C dates</th><th colspan="3">Lithological Unit</th></tr>
<tr><td colspan="2">Holocene</td><td><10,000</td><td>modern alluvial sands, gravels and silts</td><td>peat, silt and clays</td><td>colluvium, slide deposits and alluvial fans</td></tr>
<tr><td rowspan="6">Late Wisconsin glaciation</td><td rowspan="4">recessional phase</td><td>10,240±160</td><td colspan="3">raised terrace gravels</td></tr>
<tr><td></td><td colspan="3">eolian, sand dunes and loess</td></tr>
<tr><td rowspan="2">10,770 ± 120
to
13,970±170</td><td>till of late stage re-advance of Cordilleran ice.</td><td colspan="2">glaciolacustrine and glaciodeltaic sands silts and clays; Glacial Lake Peace in Peace River region</td></tr>
<tr><td colspan="2">flow and melt-out tills</td><td rowspan="2">kames</td></tr>
<tr><td>glacial maximum</td><td></td><td colspan="2">lodgment tills, Cordilleran and Laurentide ice</td></tr>
<tr><td>advance phase</td><td></td><td colspan="3">glaciolacustrine fine sands silts and clays; Glacial Lake Mathews in Peace River region</td></tr>
<tr><td colspan="2">Mid Wisconsin non-glacial</td><td>27,400±580,
26,450±310</td><td colspan="3">cemented and oxidized fluvial gravels</td></tr>
<tr><td rowspan="2">penultimate glaciation (Early Wisconsin?)</td><td>glacial maximum</td><td></td><td colspan="3">tills, Cordilleran and Laurentide ice</td></tr>
<tr><td>advance phase</td><td></td><td colspan="3">glaciolacustrine fine sands silts and clays</td></tr>
<tr><td colspan="2">pre-early Wisconsin non-glacial</td><td></td><td colspan="3">fluvial gravels - some shield-derived clasts</td></tr>
<tr><td colspan="2">pre-early Wisconsin glacial</td><td></td><td colspan="3">not directly represented by sediments , inferred from some shield-derived clasts in later gravels</td></tr>
<tr><td colspan="2">pre-glacial (Tertiary?)</td><td></td><td colspan="3">fluvial gravels - no shield-derived clasts, deposited on planation surface extending from Rocky Mountains and Foothills</td></tr>
</table>

Table 4. Unconsolidated units in Peace River Area

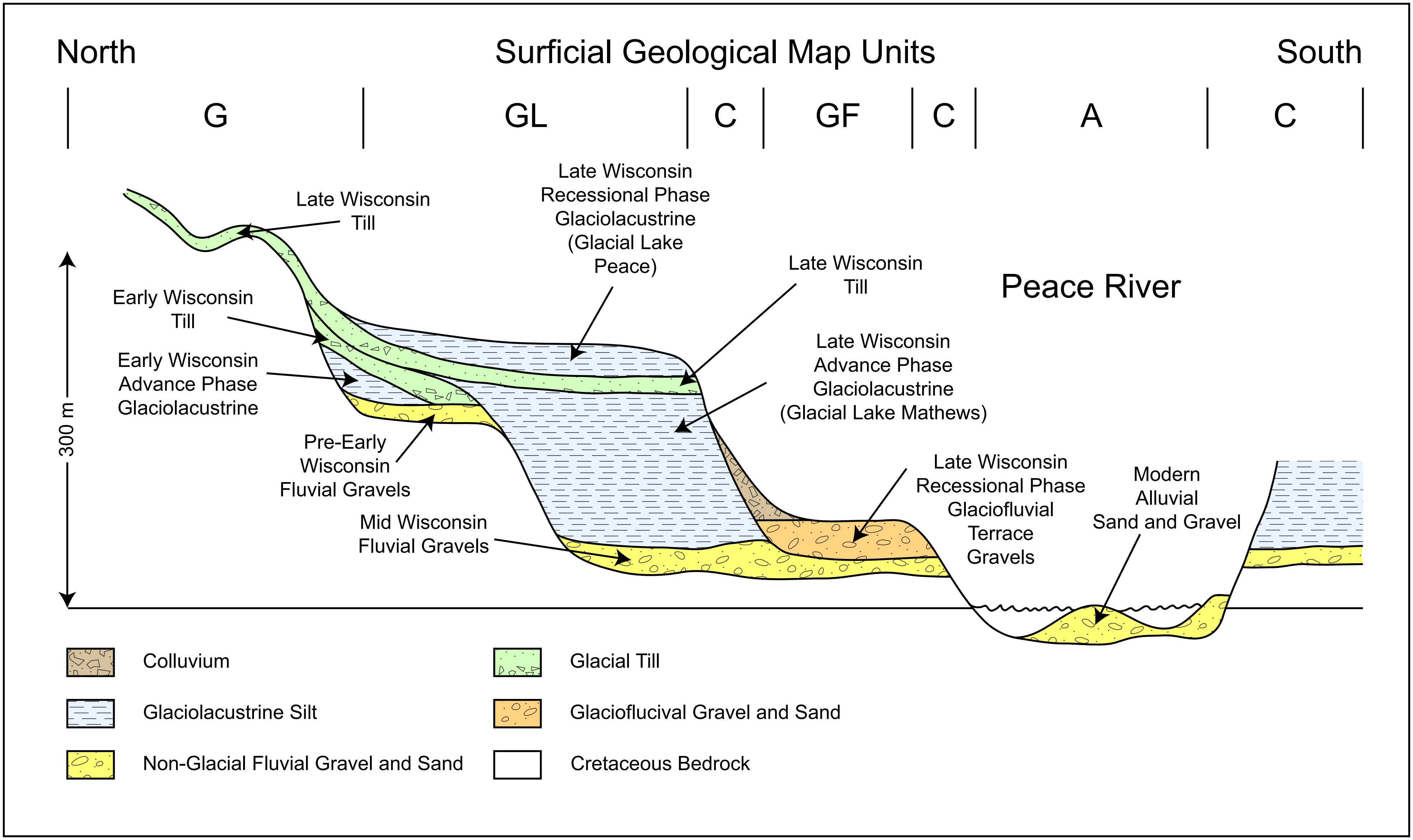


Figure 2. Schematic cross section across the Peace River valley in the vicinity of Fort St. John, showing stratigraphy of Quaternary fill of the Peace River valley, and the geomorphic expression of the principal surficial geological units. Abbreviations: G, glacial; GL, glaciolacustrine; GF, glaciofluvial; C colluvial (i.e. steep slopes and slope deposits); A, Alluvial. Based on data from Mathews (1978a) and Hartman and Clague (2008).

The conformably overlying advance phase glaciolacustrine silts, clays and very fine sands of the last glaciation are up to 120 m thick in the Peace River area, where Glacial Lake Mathews formed (Mathews, 1978a; Hartmann and Clague 2008). The overlying tills were derived from both eastern and western sources. Laurentide ice extended over most of the eastern part of the area. Cordilleran ice extended out from the Rocky Mountain front and coalesced with the Laurentide Ice Sheet (Hickin *et al*., 2016b). The maximum extents of each sheet do not appear to have occurred synchronously (Bednarski and Smith, 2007; Hickin *et al*., 2016b). The latest glaciation is late Wisconsin in age.

As the glaciers receded, an extensive system of glacial lakes formed where major drainages were blocked by retreating Laurentide ice (Mathews, 1978a, 1980; Hartman, 2005; Hartman and Clague, 2008; Hickin *et al*., 2015, 2016a). The best known is Glacial Lake Peace in the Peace River drainage area, which drained in several stages beginning around 13,970±170 ^{14}C years. Glaciolacustrine sediments are primarily silt, clay and very fine sand, commonly with scattered pebbles. Mathews (1978a) reports average thicknesses of 30 m and 17 m in the western and eastern parts, respectively, of Glacial Lake Peace. However, extensive deposits of glaciodeltaic sands are also present in the upstream reaches of Glacial Lake Peace in the Peace and Halfway River Valleys (Mathews, 1978a, b).

Mathews (1978a, b) inferred the occurrence of a late stage re-advance of Cordilleran ice over glaciolacustine deposits on the basis of flutings in the southwestern part of the project area, on the glaciolacustrine plains west of Farrell Creek and between Pine and Peace Rivers. Although no widespread till sheet has been identified, additional support for this suggestion is provided by a near surface till overlying recessional phase deposits west of Farrell Creek (Levson and Best, 2017, borehole 10x).

As the lakes drained, sand dunes were deposited, generally in the vicinity of the glaciodeltaic sand deposits which were their sources (Mathews, 1978a, b). Following complete drainage, the river systems began to incise the earlier Quaternary deposits, forming a succession of alluvial terraces that show the progression of Late Pleistocene and Early Holocene incision down to the current river levels. A bison bone in glaciofluvial terrace gravels at the Ostero gravel pit at Taylor has been dated to 10,240±160 ^{14}C years (Bobrowsky *et al*., 1991).

Holocene deposits include modern alluvial sands and gravels, silts and organic soils, colluvium, landslide deposits and alluvial fans (Hansen, 1950; Mathews, 1978a; Fletcher *et al*., 2002).

Most Pleistocene non-glacial fluvial sediments and advance-phase glaciolacustrine deposits are restricted to Quaternary river valleys (paleovalleys) and are exposed only in the valley walls of the Peace and other major rivers. Elsewhere, only till and recessional-phase deposits of the last glaciation and modern sediments can be mapped at the surface. Surficial units have characteristic geomorphic expressions (Figure 2; Mathews, 1978a). Upland areas, where topography is controlled by bedrock, are underlain mainly by till or colluvial deposits, commonly with a veneer of glaciolacustrine silt at lower elevations (Figure 3). Low relief areas bordering major valleys and extending up minor tributaries are underlain by recessional-phase glaciolacustrine, glaciodeltaic and related deposits. Terraces flanking major valleys are underlain by later glaciofluvial sand and gravel representing the earliest phases of postglacial fluvial incision (Figure 4). Modern fluvial sand and gravel occupy river valley bottoms (Figure 5).

Figure 3. View northward across glaciolacustrine plain toward till upland, which commences at break in slope in distance; west side of Fort St. John, adjacent to Margaret Murray Community School, where site SL-6 of the multichannel analysis of surface waves (MASW) program is located.

Figure 4. View northward across the Ostero gravel pit at Taylor. The gravels here are 39 m thick (T.Ostero, personal communication, June 28, 2017). The deepest levels are cemented and oxidized and represent the fluvial gravels preceding the last glaciation (Mathews, 1978a; Hartmann and Clague, 2008). A mammoth tooth from these gravels has been dated at 27,400±580 ^{14}C years (Mathews, 1978a). The overlying gravels comprising most of the succession here are terrace gravels of the recessional phase of the last (late Wisconsin) glaciation. These gravels yielded a bison bone dated at 10,240±160 ^{14}C years (Bobrowsky *et al*., 1991). Site SL2-5 of the multichannel analysis of surface waves (MASW) program is located to the right of the house in the right mid-distance on the terrace surface. The cliff in the distance is incised into Quaternary deposits, and the top is the glaciolacustrine plain surface.

Figure 5. View west along Sikanni Chief River from the Highway 97 bridge. Campground on the floodplain on the right is underlain by 10 m of alluvial silt, sand and gravel. The cliffs on the left are incised into Cretaceous sandstones and shales. Site SL2-2 of the multichannel analysis of surface waves (MASW) program is located in the campground.

SURFICIAL GEOLOGICAL MAP COMPILATION

A surficial geology map of the study region (Figure 1, Map 1) was compiled by Quaternary Geosciences Inc. from a variety of sources, and builds on a previous compilation map completed for Petrel-Robertson Consulting Ltd.'s (2016; Hayes *et al*., 2016) depth-to-bedrock study. Data and map sources used in the compilation included 1:250,000 scale surficial geology maps and reports produced by the Geological Surveys of Canada and British Columbia (Mathews, 1978a, b; Reimchen, 1980; Bednarski, 1999, 2000, 2001; Hickin and Fournier, 2011) and soils, landforms and surficial geology maps and reports produced by Green and Lord (1975), Lord (1973, 1977), Lord and Green (1971, 1986) and the BC Ministry of Environment (1980, 1986, 1987, 1988a, b) at a variety of scales ranging from 1:20,000 to 1:125,000. A regional (1:1,000,000 scale) glacial features map was also used (Mathews *et al*., 1975). In addition, some predictive ecosystem mapping at a scale of 1:20,000 (TECO Natural Resource Group Ltd., 2011) was used in the compilation to provide additional detail in areas originally mapped at 1:250,000, such as the Trutch map sheet (NTS 94G; Bednarski, 2000, 2001). The map units defined are shown in Table 5.

Generalized map unit	Dominant composition	Description and example subunits
Alluvial	Sand, gravel and floodplain silt	Modern river and stream deposits including floodplains (Ap) and alluvial fans (Af)
Colluvial	Poorly sorted, stratified diamicts and slump deposits	Slope deposits mainly along steep valley walls incised into both bedrock and unconsolidated sediments (Cb, Cv); also includes minor alluvial and glaciofluvial deposits along valley bottoms
Organics	Organic-rich mud and minor peat	Mainly poorly drained fen deposits (Ov) and minor bogs (Ob)
Eolian	Well sorted sand (dunes) and silt and very fine sand (loess)	Windblown sediments; mainly eolian dunes (Er) and thin silt veneers (Ev)
Glaciofluvial	Sands and gravel; minor silt and diamict	Glacial outwash sand and gravel forming terraces (At, FGt, Gt), thick blankets (GFb), outwash plains (GFp), fans (GFf), hummocky or kettled outwash (GFh), kames (Agh), esker ridges (GFr), spillway floor deposits (AGp) and thin veneers (GFv)
Glaciolacustrine veneer over till	Sands and silt; minor clay	Thin and discontinuous cover of glacial lake sediments (LGv), usually overlying till and other glacigenic deposits
Glaciolacustrine	Mainly silt, clay and fine sand; minor coarse sand and gravel	Glacial lake sediments that blanket topography (GLb) or form glacial lake plains (GLp, AGp)
Glaciodeltaic	Mainly fine to very fine sand	Prograding delta deposits built into glacial Lake Peace in the form of an apron (AGp, GD) in valleys such as the Halfway River and Farrell Creek valleys
Glacial	Poorly sorted, massive diamict; usually over-consolidated sediments	Glacial deposits including thick till blankets (Tb), hummocky moraine (Th), till plains (Tp, Mp), fluted terrain (Tr) and thin till veneers (Tv, Mv); commonly includes glaciolacustrine veneer, particularly at lower elevations.
Bedrock	Sandstones, conglomerates and shales	Exposed or thinly covered bedrock outcrops (R), usually sandstone or conglomerate

Table 5. Surficial geology units defined in the study area, northeast BC. The abbreviations in brackets refer to the unit designations in the source documents.

Reinterpretation of some map unit designations, grouping of map units and minor adjustments to map unit boundaries were required for overall consistency of the final compilation map and to eliminate artificial changes across map borders. Some map unit designations were changed as a result of field investigations conducted in June 2017. In addition, the mapping was revised in the vicinity of Fort St. John, where sufficient borehole data collected for this study were available to better represent the surface and subsurface conditions.

SUBSURFACE GEOLOGICAL DATA COMPILATION AND INTERPRETATION

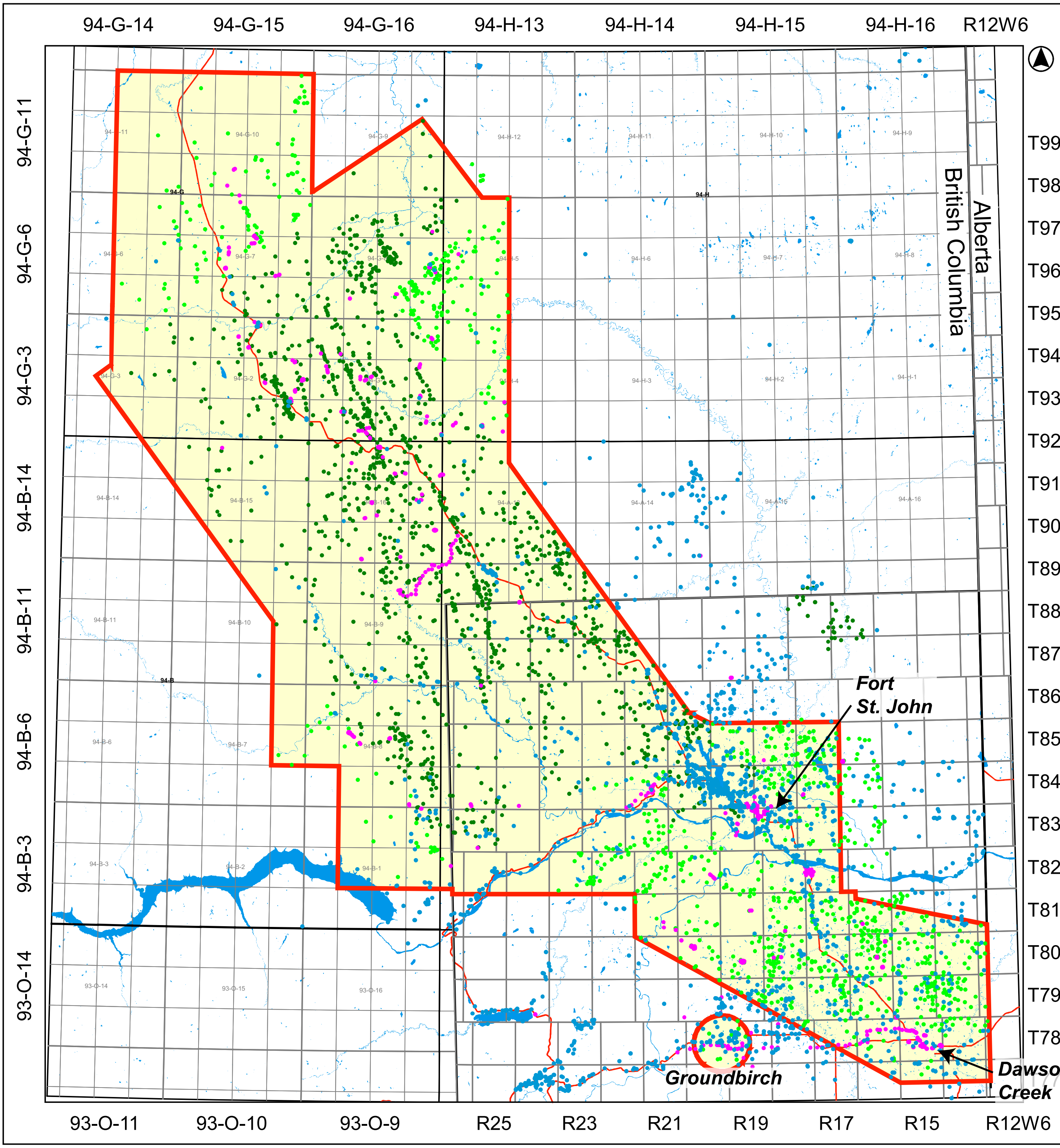
Three sources of subsurface geological data have been used: cased-hole gamma-ray logs from petroleum wells, water well logs, and geotechnical borehole logs. The distribution of these data sources is shown on Figure 6.

Normalized Gamma Ray Logs

Gamma-ray logs run through surface casing to surface are now required for most petroleum well sites in British Columbia, and can be an important source of subsurface geological data for Quaternary studies. Normalization for surface casing effects (documented by Quartero *et al*., 2014) and interpretation of depth to bedrock were conducted on gamma-ray logs from 1351 petroleum wells in the north Peace Region by Petrel Robertson Consulting Ltd. (2016; Hayes *et al*., 2016), and these have been used in the present study. An additional 1076 gamma-ray logs were similarly normalized and interpreted for the current project (Figure 6). The principal advantages of this dataset are the repeatability of the data and the fact that they are in the public domain. The principal disadvantage is that each data point is a single log curve that provides only incomplete information on the Quaternary section, and identification of specific Quaternary lithological units is often not possible.

Top of bedrock generally can be picked with reasonable confidence where highly correlative units in Cretaceous marine shales are truncated and overlain by Quaternary sediments (Figure 7). However, where bedrock consists of sandstones, particularly discontinuous non-marine sandstones of the Dunvegan Formation, picking the bedrock contact is much more interpretive. In such areas, surficial geological and topographical maps (including those of Dyke *et al.,* 2011) provide useful checks on depth to bedrock interpretations. For example, wells on the crests of bedrock ridges will not have thick Quaternary sections. In addition, nearby gamma ray, water well or geotechnical borehole logs, can aid the interpretation. To assist the depth to bedrock correlations, a suite of cross sections was constructed across the study area, and these are included in Appendix 2.

In many wells, attenuation of the gamma-ray signal by the conductor pipe obscures the lithological signature in the upper 10-30 m. In such cases, the base of conductor pipe can be mistaken for the top of bedrock. A repetitive signature of 10 m of low gamma ray material apparently truncating bedrock in multiple wells in an area is usually better interpreted as conductor pipe rather than the Quaternary, the thickness of which usually varies by several metres. Conductor pipe depth has not normally been reported in well history reports, but can sometimes be inferred from the tour sheets.



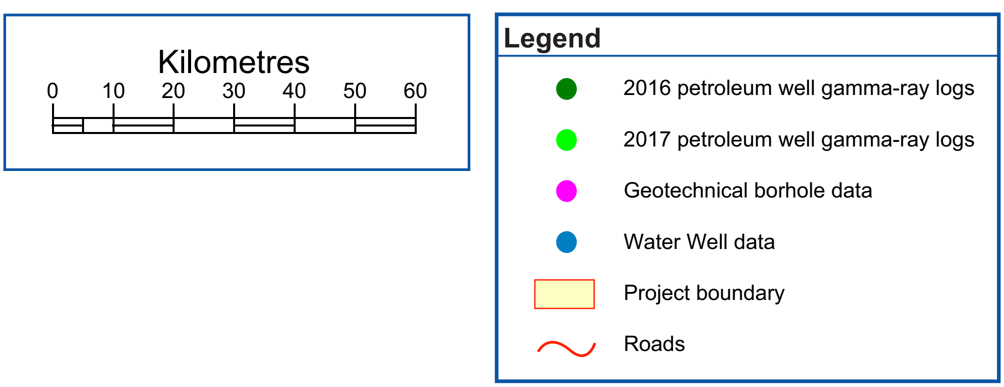


Figure 6. Map showing petroleum well, water well and geotechnical borehole data distribution in the study area, northeast British Columbia.

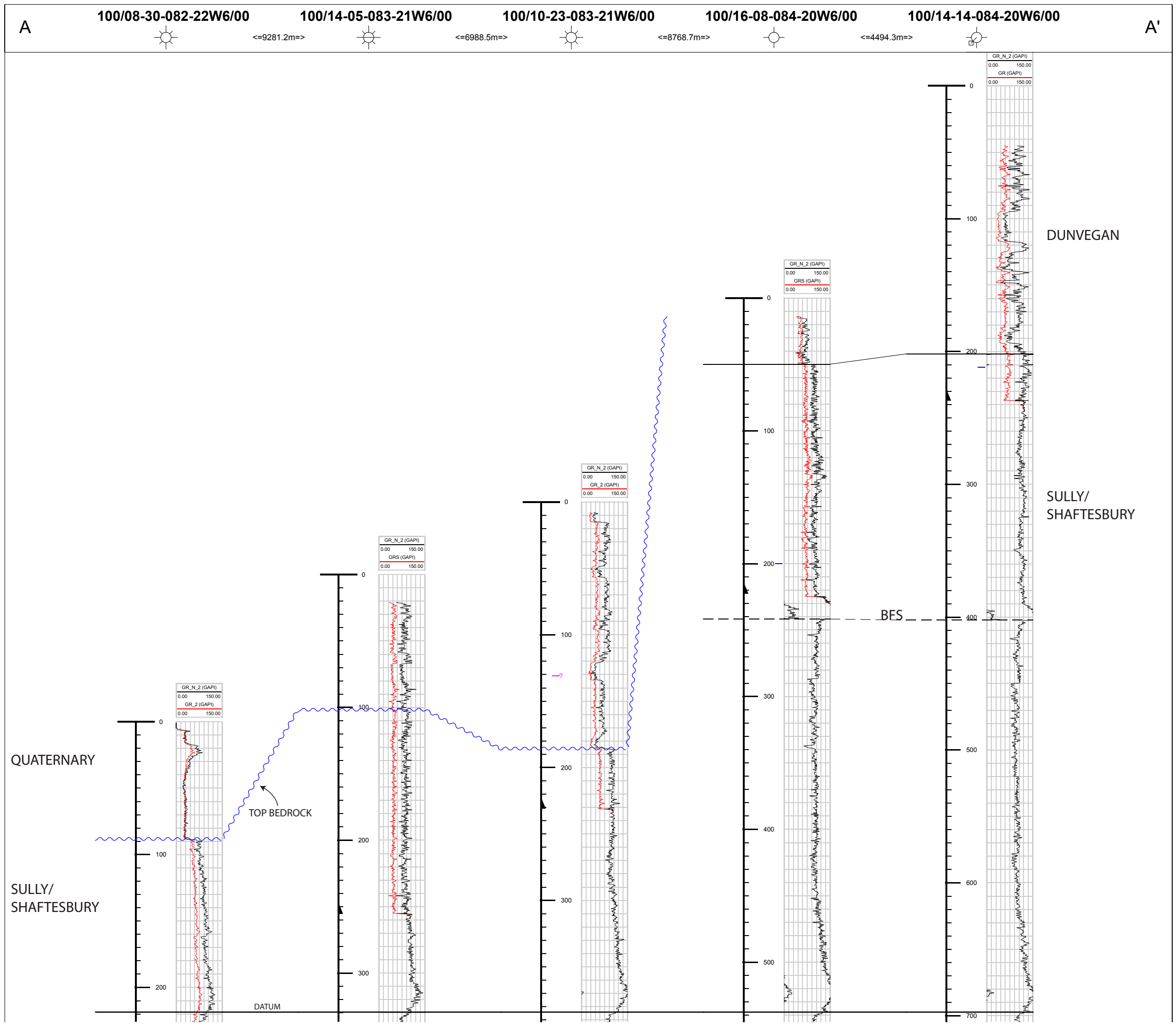


Figure 7a. Gamma ray log cross section, showing the high correlatability of the Cretaceous shales and the identification of thick Quaternary sediments in the southwest part of the cross section. Note in two wells on the right the log does not go to surface, so only a maximum depth to bedrock could be determined. Note the red curve is the originally recorded gamma ray signal behind surface casing, and the adjacent black curve is the corrected curve.

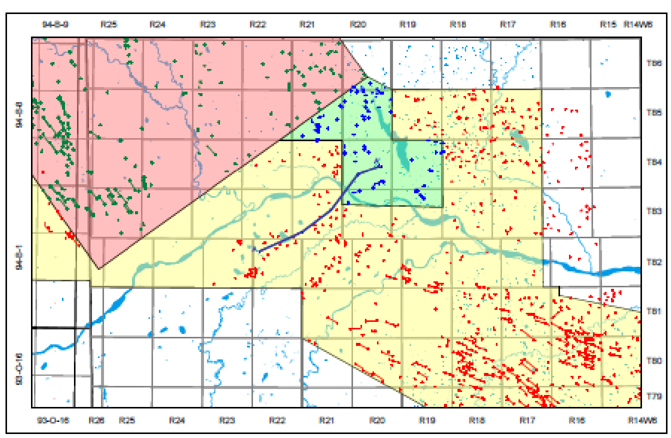


Figure 7b. Location map for cross section in Figure 7a.

Furthermore, not all logs have been run continuously to surface. Where the bedrock top lies above the top of the logged section or the bottom of conductor pipe, all that can be reported is a maximum depth to bedrock. Nonetheless, cased-hole gamma-ray logs provide important constraints on the Quaternary thickness and lithology, particularly when combined with other subsurface geological data. The digital files of the normalized logs are included in Appendix 3, and the depth to bedrock interpretations for normalized gamma ray log data interpreted for this study are included in Appendix 4. The latter also includes some revisions to the picks made for the Petrel Robertson Consulting Ltd. 2016 study.

Water Well Logs

An edited database of depth to bedrock values in northeast BC water wells was prepared by Hickin (2013), primarily from the BC Ministry of Environment WELLS database[3], and was included in the Petrel Robertson Consulting Ltd. (2016) study of the north Peace region. This database has been used in the present project and updated from the WELLS database, except in the vicinity of Fort St. John, where there is already abundant well control.

While the WELLS database includes an enormous amount of useful information, it has been generated from water well records prepared with a large variation in care and accuracy. Some well logs were prepared by professionals, but most have been prepared by drillers, who use geological and non-geological terms with varying degrees of consistency. Lithological uncertainty can be minimized by comparing descriptions from several wells – if the descriptions in several nearby wells logs are similar, then at least one can have confidence that similar lithologies are being described.

The depth to bedrock is usually reliably reported, and this is the parameter of most importance for this study. However, in the Fort St. John area, many wells logs report interbedded clay and sandstone, a sequence that most likely represents bedrock comprised of sandstone and weathered shale. This suggests that in nearby wells clay at shallow depths may include weathered bedrock and that the well logs may overstate the Quaternary thickness.

Well location is another source of uncertainty. The locations in the WELLS database have been digitized from maps of different scales, or estimated from written descriptions. Although location errors of a few ten of metres is not an issue in a regional study such as this, some wells have been assigned to incorrect NTS blocks or grids, resulting in errors of hundreds of kilometres. The street address and area reported in the WELLS database are useful tests for location accuracy.

Eighteen hundred and thirty-one water well logs from this database have been used in this project (Figure 6), and these are tabulated in Appendix 5.

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[3] WELLS database accessed at https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp.

Geotechnical Borehole Logs

Geotechnical borehole logs provide the best data for Quaternary geological studies, because they are professionally and consistently described, reliably located, and include repeatable quantitative measurements that can be correlated to physical properties. The latter include standard penetration test (SPT) blowcount (N) values and moisture content, which are important stratigraphic indices. The SPT N value is the number of hammer blows required to drive a sample tube 305 mm (1 ft.) under standardized conditions. In the project area, N values in recessional-phase glaciolacustrine silt and clay of the last glaciation are between 2 and 15. However, N values for Quaternary sediments that have been glacially overridden are between 40 and >50 (if after 50 blows, penetration has not reached 305 mm, the test is usually terminated; this upper limit is termed refusal, and indicates a material very resistant to penetration). Till of the last glaciation is a possible exception, as N values in this till range from 15 to >50. The low N values (<40) in some till may be due to being melt-out or flow till (ablation) rather than lodgment till, although being clay-rich is also likely a factor.

The main disadvantages of this data source are that the boreholes tend to be shallow, rarely exceeding a few tens of metres in depth, and data are proprietary, so they are laborious to collect and details cannot be routinely published without the owners' approval.

For this project we obtained 885 borehole logs from 200 sites, of which 158 sites include borehole data deeper than 10 m (Figure 6). The data were acquired directly from 4 engineering consultancies, 13 public agencies, and 9 energy companies. These include 17 boreholes drilled for scientific research by the BC Geological Survey and Geoscience BC, of which 13 have wireline logs (Hickin and Best, 2013; Hickin *et al.*, 2016a, Levson and Best, 2017). The total includes twelve water well logs that were acquired directly from industry sources and were not included in the WELLS database.

Geotechnical borehole data are unevenly distributed across the study area. Data from public agencies are associated with public infrastructure projects, whereas data from energy companies are associated with gas processing facilities and pipeline stream crossings.

SHEAR-WAVE VELOCITY DATA ACQUISITION

New V_s data acquisition was required to determine shear-wave velocities in the shallow geological materials, as insufficient V_s data were obtained during the geotechnical data collection phase of the project. Although several correlations of SPT N values with V_s have been proposed (*e.g.*, Hutchinson and Beird, 2016), these have large uncertainties. Monahan and Levson (2001) showed that topset sand and foreset silt at the same depth in the Fraser River delta have similar V_s but greatly different N values (Monahan and Levson, 2001, Figures 5, 6; note that these figures show cone penetration test tip resistance rather than SPT N, but these correlate well). Consequently, acquisition of new V_s data specific to the present study area provides more reliable data than correlations.

V_{s30} calculations were made at each of the V_s data sites, and from these, the NEHRP Site Classes were determined.

The new V_s data were obtained by three methods: V_s borehole logging by the vertical seismic profile (VSP) method, multichannel analysis of surface waves (MASW), and dipole sonic logging. The VSP logging and MASW were conducted by Frontier Geosciences Inc. as part of this project, and the dipole sonic logs were run by Weatherford in boreholes drilled by Geoscience BC in 2017. The distribution of V_s sites is shown on Figure 8.

Downhole V_s logging by the VSP method was conducted in six cased boreholes in the Groundbirch area (Figure 8). This method is described by Arsenault *et al*. (2012). The stratigraphy of these boreholes is well described by Hickin and Best (2013) and Hickin *et al*. (2016a)[4], so that the V_s of each geological unit can be readily determined. High quality V_s data were obtained throughout the logged intervals. In five of these boreholes, recessional-phase deposits of the last glaciation extend from surface to depths of 26 to 49 m, the lower contact being marked by an abrupt increase in V_s from <350 m/s to >400 m/s. The recessional phase deposits overlie earlier glacigenic sediments, which in turn overlie bedrock in three of the boreholes. In the other two, bedrock was not encountered, being deeper than 147 and 118 m. The sixth borehole penetrated 3 m of till over bedrock. The results of this program are summarized in Table 6, and an example is shown in Figure 9. The field report by Frontier is included in Appendix 6, and interpreted logs of these boreholes are included in Appendix 7.

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[4] The stratigraphic interpretation of Boreholes 15-1 and 15-2 was revised on the basis of the Vs logging in intervals of significant lost core.

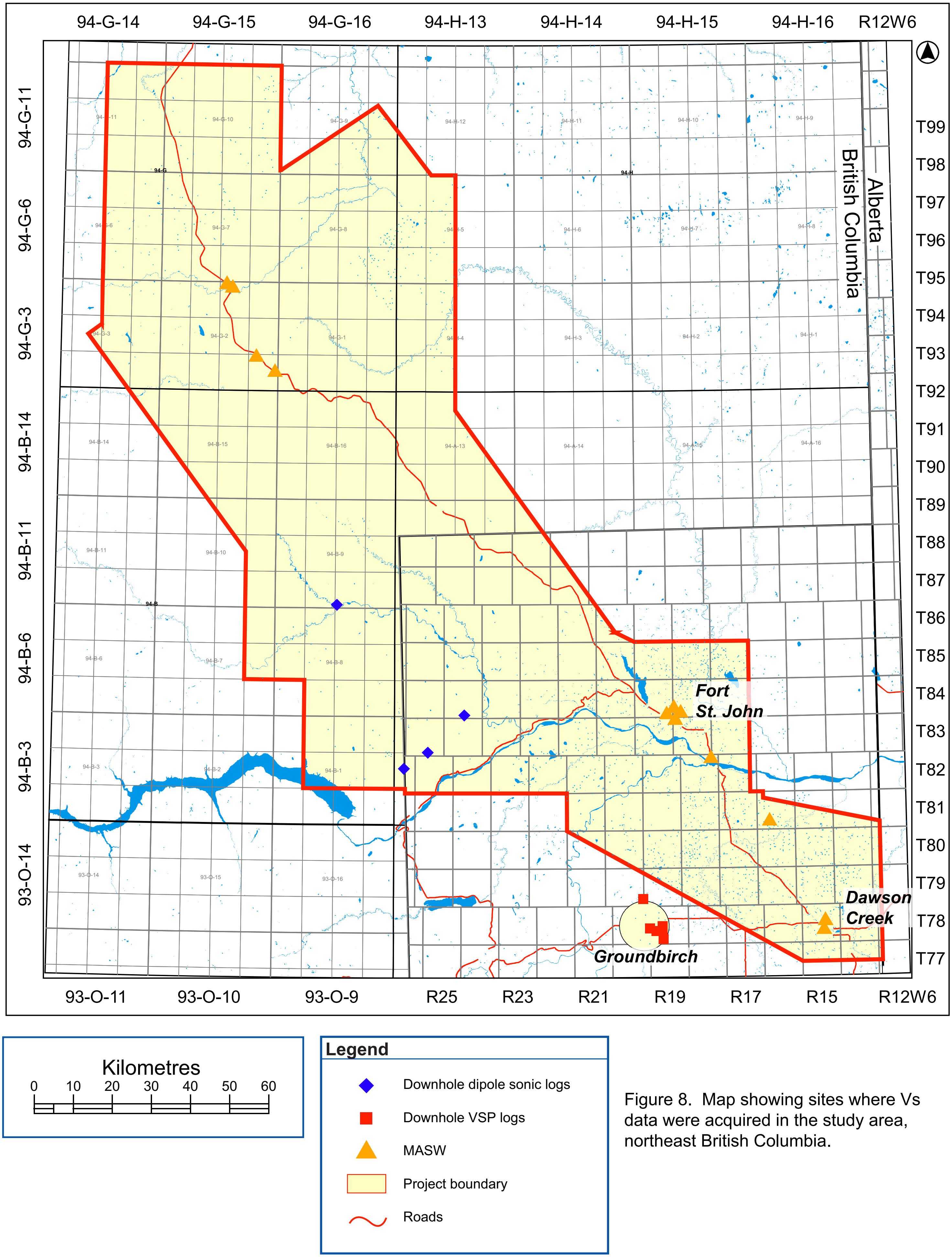

Figure 8. Map showing sites where Vs data were acquired in the study area, northeast British Columbia.

Borehole	easting	northing	DLS location	depth logged m	Recessional phase deposits m	bedrock depth m	map unit	V_{s30} m/s	Site Class
GB12-2	626794	6188497	1-13-79-20	31	0	3	G	806	B
GB15-1	631920	6181633	9-17-78-19	112	26	82	GL	290	D
GB15-2	631941	6180936	8-17-78-19	149	49	>147	GL	207	D
GB15-3	628700	6180968	8-13-78-20	70	36	54	GL	263	D
GB15-4	632257	6178342	12-4-78-19	67	26	71	GL	272	D
GB15-5	630317	6180352	16-7-78-19	100	44	>118	GL	231	D

Table 6. Summary of shear-wave velocity (V_s) data acquisition by VSP in boreholes at Groundbirch, northeast BC. Abbreviations: DLS, Dominion Land Survey; G, glacial; GL, glaciolacustrine. UTM coordinates NAD83 Zone 10N.

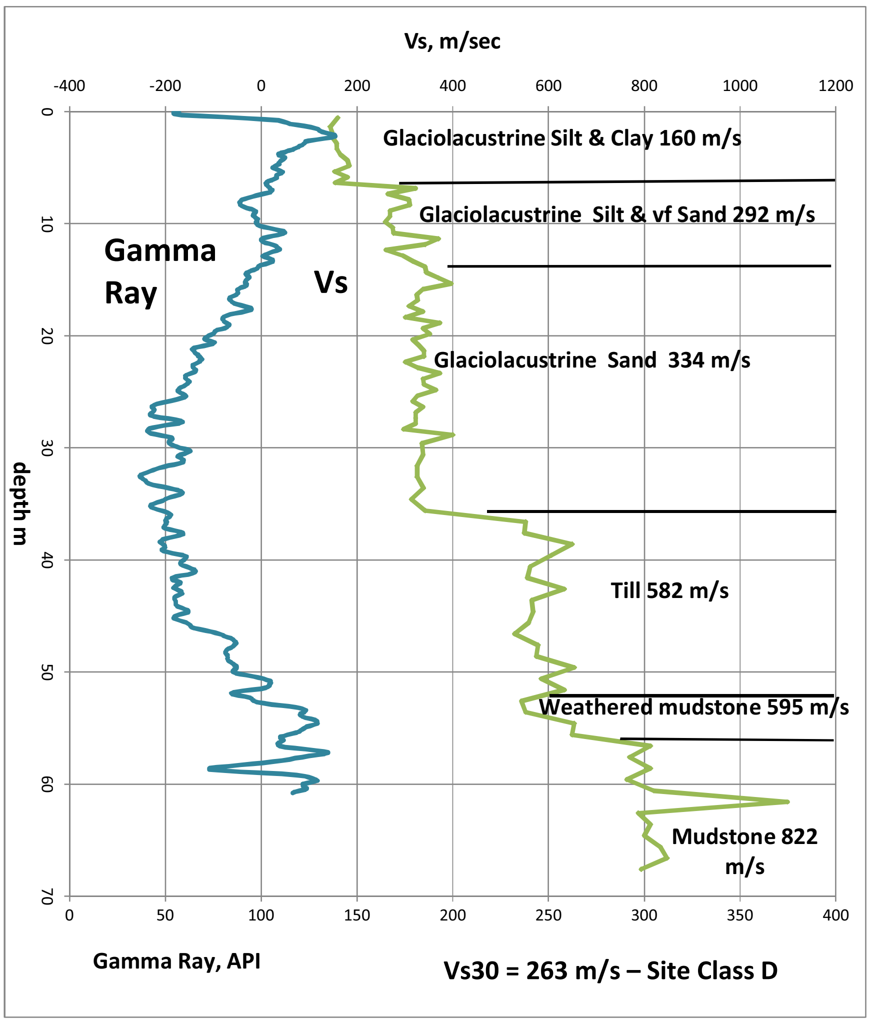

Figure 9. Shear-wave velocity (V_s) and gamma-ray logs from borehole GB15-3 at Groundbirch, northeast British Columbia. Gamma-ray data from Weatherford, in Hickin *et al.* (2016a). Abbreviation: vf, very fine; V_{s30}, average shear-wave velocity in the upper 30 m.

Two MASW programs were conducted, in April and September 2017. MASW is a surface geophysical technique in which the velocities of Rayleigh waves, measured along a ~100 m spread of geophones, are used to calculate a V_s profile (Phillips and Sol, 2012). These programs were conducted using two 24 channel, signal enhancement seismographs and two 24 channel geophone cables set in a straight line. Geophone spacing was 2.5 metres in order to ensure high resolution data in the subsurface. A sledgehammer striking a steel plate provided the seismic signal energy. Details of the field and interpretive procedures are described in Frontier's survey reports. These and the interpreted data files for each site are included in Appendices 8 and 9.

The first program consisted of six sites in Fort St. John and Dawson Creek, and the second consisted of six sites distributed from south of the Peace River to the Sikanni Chief River. The sites were selected adjacent to boreholes in order to determine the V_s of the geological units penetrated. The stratigraphy represented at these sites includes 5 to >18 m of till over bedrock, 11 to ~30 m glaciolacustrine silt over till, 11m of Holocene alluvium and ~30 m of glaciofluvial terrace deposits. Depth of penetration by this method ranged from 30 m to 54 m. The results of the MASW programs are summarized in Table 7, and representative examples are shown in Figure 10.

The V_s calculations are made at 2 m depth intervals at every geophone on the spread (except at the ends of the spread), so that multiple V_{s30} calculations can be made at each site. The averages and standard deviations of the calculated V_{s30} are shown in Table 7.

Geoscience BC drilled and cased 10 boreholes in 2017 in the project area (Levson and Best, 2017). Wireline logs were run in six of these, and dipole sonic logs were successfully run in four. Three of these are located in a small area west of Farrell Creek, and the fourth is located on a terrace above the confluence of the Halfway and Graham Rivers. However, V_s data were not collected in the upper 5.4 to 22.3 m. Consequently, V_{s30} in three of the boreholes was estimated by projecting the average V_s of the recessional phase sediments to surface, and in the fourth, there was insufficient V_s data to make an estimate. The boreholes were continuously cored and the stratigraphy is well described by Levson and Best (2017), so that the V_s of each geological unit can be readily determined. The thickness of recessional-phase deposits of the last glaciation interpreted from the V_s profile varies from 7 to 33 m. The results of the dipole sonic logging program are summarized in Table 8, and interpreted logs are included in Appendix 11.

site	location	easting	northing	map unit	V_{s30} m/s	Site Class	geological setting
SL-1	112th Ave, by hospital, Fort St. John	635403	6236789	G	607±50	C	5-6 m till over sandstone bedrock
SL-2	94th Ave, east of arena, Fort St. John	634065	6234926	GL	344±14	D	>7 m glaciolacustrine silt
SL-3	10th St Bridge, Dawson Creek	673426	6181918	GL	322+24	D	4? m glaciolacustrine silt over 20 m till, N=14-35
SL-4	Frank Ross School, Dawson Creek	673697	6184224	GLv	469±23	C	6 m clay (glaciolacustrine?) over shale bedrock
SL-5	Northern Lights College, Fort St John	633642	6237942	GL	394±17	C	6 m glaciolacustrine silt over till, NRCan seismograph location NBC 7
SL-6	Margaret Murray School, Fort St. John	631899	6236305	GL	355±11	C-D	11 m glaciolacustine silt over till
SL2-1	Bench north of Sikanni Chief River, by b-87-J/94-G-02 pad	516797	6344598	O	294±9	D	glaciolacustrine terrace, ~30 m glaciolacustrine clay; bedrock at 134 m
SL2-2	Sikanni Chief Campground	518302	6343691	A	218±11	D	11 m alluvial gravels, sand and silt
SL2-3	Beatton River Crossing; by a-98-A/94-G-2 well	524717	6326079	GL	269±12	D	11 m glaciolacustrine clay, 9 m till & gravel over shale bedrock
SL2-4	Buffalo Inn, Pink Mountain	529597	6322267	G	519±25	C	5 m clay (glaciolacustrine?) over sandstone and shale bedrock
SL2-5	Ostero Gravel Pit, Taylor	643476	6225244	GF	339±12	D	recessional phase glaciofluvial terrace, ~30 m glaciofluvial
SL2-6	Parkland Tower	658823	6209470	G	401±56	C-D	6 m silty clay N=22-28 over 12+m clay N>50

Table 7. Summary of multichannel analysis of surface waves (MASW) programs. Abbreviations: G, glacial; GL, glaciolacustrine; GLv, glaciolacustrine veneer; GF, glaciofluvial; A, alluvial; O, organic; N, standard penetration test N value is the number of hammer blows to advance a sampler 305 mm at the base of the hole), NRCan, Natural Resources Canada; V_{s30}, average shear-wave velocity in the upper 30 m. UTM coordinates NAD83 Zone 10N.

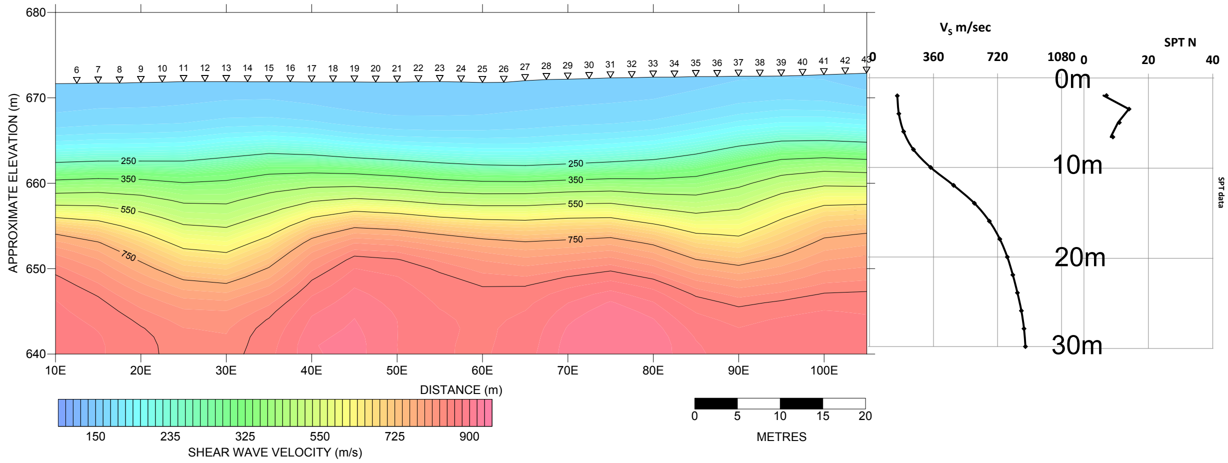

Figure 10a. Multichannel analysis of surface waves (MASW) profile for site SL-2, 94th Avenue, Fort St. John. V_{s30} is 344±14, Site Class-D (Table 5). The borehole near east end (right) of line penetrated 7 m of glaciolacustrine silt with SPT N<15.. V_s panel right of profile is the trace at a single geophone. Note low velocities in the upper ~10 m. Note that V_s levels off at high value at base of profile, indicating unweathered bedrock.

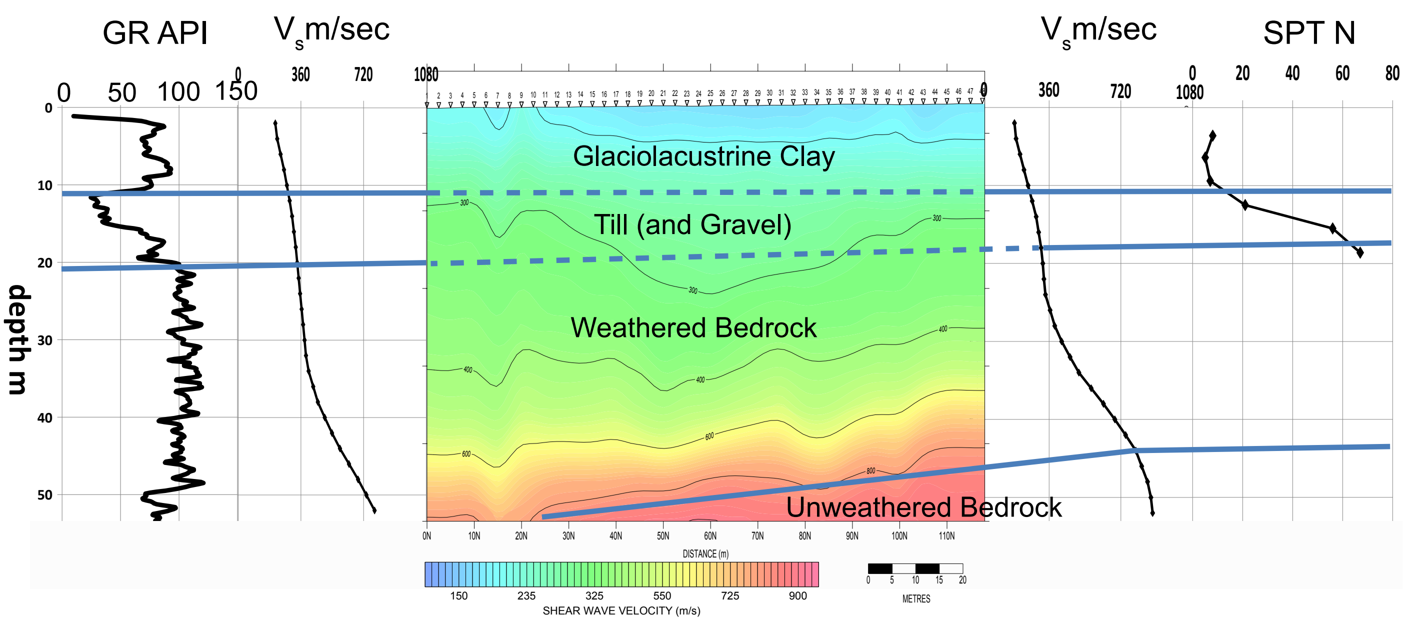

Figure 10b. Multichannel analysis of surface waves (MASW) profile for site SL2-3, Beatton River Crossing. V_{s30} is 269±12, Site Class-D (Table 5). At left is gamma ray log from a-98-A/94-G-2 well, and at right is SPT profile from nearby geotechnical borehole. V_s panels on either side of profile are traces from geophones near the ends of the line. Note low V_s and SPT N <10 in glaciolacustrine clay, increased N through the till, and low V_s in weathered bedrock. Unweathered bedrock interpreted at base of profile on right.

Bore-hole	easting	northing	location	depth driller (m)	V_s log interval (m)	reces-sional phase sediments (m)	map unit	V_{s30} m/s*	Site Class
GBC 6a	546650	6262600	Terrace above confluence of Halfway & Graham Rivers	14.02	6.9-9	6.7	GF	**	**
GBC 10b	564660	6220787	northeast of Beryl Prairie	59.74	5.7-54.5	12.1	GL	479*	C
GBC 10X	570720	6225047	~3.5 km west of Farrell Creek Road	71.93	22.3-66.7	32.5	GL	329*	D
GBC 13	579923	6234812	Farrell Creek, end of Swanson Road	50.6	5.4-46.1	9.3	GL	475*	C

* V_s of recessional phase deposits projected to surface to estimate V_{s30} .
** insufficient V_s data to determine V_{s30}.

Table 8. Summary of dipole sonic logging program in Geoscience BC boreholes. Abbreviations: GL, glaciolacustrine, GF, glaciofluvial, UTM coordinates NAD83 Zone 10N.

V_s MODEL OF THE SHALLOW STRATIGRAPHIC UNITS

The V_s data have been correlated with specific stratigraphic units to develop a V_s model of the Quaternary and shallow bedrock units. In computing the average V_s (V_{sav}) for each unit, the harmonic mean was used, to be consistent with the calculation of V_{s30}.

For the borehole V_s data, published core descriptions and wireline log data are sufficient to confidently assign V_s data points to specific stratigraphic units. However, in the MASW data stratigraphic boundaries are not well resolved because of the effects of averaging across adjacent units. Consequently, layered interpretations were made at each site at the geophone closest to a nearby borehole (Figure 11). In these, the average V_s for each layer is the time-averaged V_s of all points included in that layer.These interpretations are included in Appendix 10. Data from the layered interpretations were then used in the V_s model, excluding layers deeper than those encountered in the adjacent borehole. In spite of the poor bed resolution, the V_{sav} values for the geological units identified at the MASW sites compare well with V_{sav} of the same units observed in boreholes. Bedrock V_s data from MASW sites are included in the model only where bedrock is confirmed in the adjacent borehole. The V_s model is summarized in Table 9. The ranges shown on the table are the lowest and highest interval values rather than individual data points.

The data demonstrate that V_s in the recessional-phase deposits of the last glaciation and Holocene deposits is generally less than 360 m/s, whereas V_s in sediments that have been overridden by glacial ice sheets is significantly higher. This observation is consistent with results of V_s studies elsewhere in BC (Monahan and Levson, 2001).

Holocene and Recessional Phase Deposits of the Last Glaciation

Holocene alluvium was tested at one MASW site (SL2-2; Figure 5), where the V_{sav} is 196 ± 14 m/s in 11 m of interbedded gravel, sand and silt. Little geotechnical data was obtained for this unit, but the available SPT N values range from 14 to 25. Where thick gravels are present, the N values are likely to be >50, and V_s is likely to be higher as well. Consequently, a range of 180 to 250 m/s should be considered.

Recessional phase deposits of the last glaciation show a pattern of increasing V_s with grain size: V_{sav} increases from 231 ± 48 m/s in silts, clays and very fine sands, to 298 ± 39 in sands with minor gravel, and to 364 ± 91 in gravels and sands. Details are provided below for each lithology.

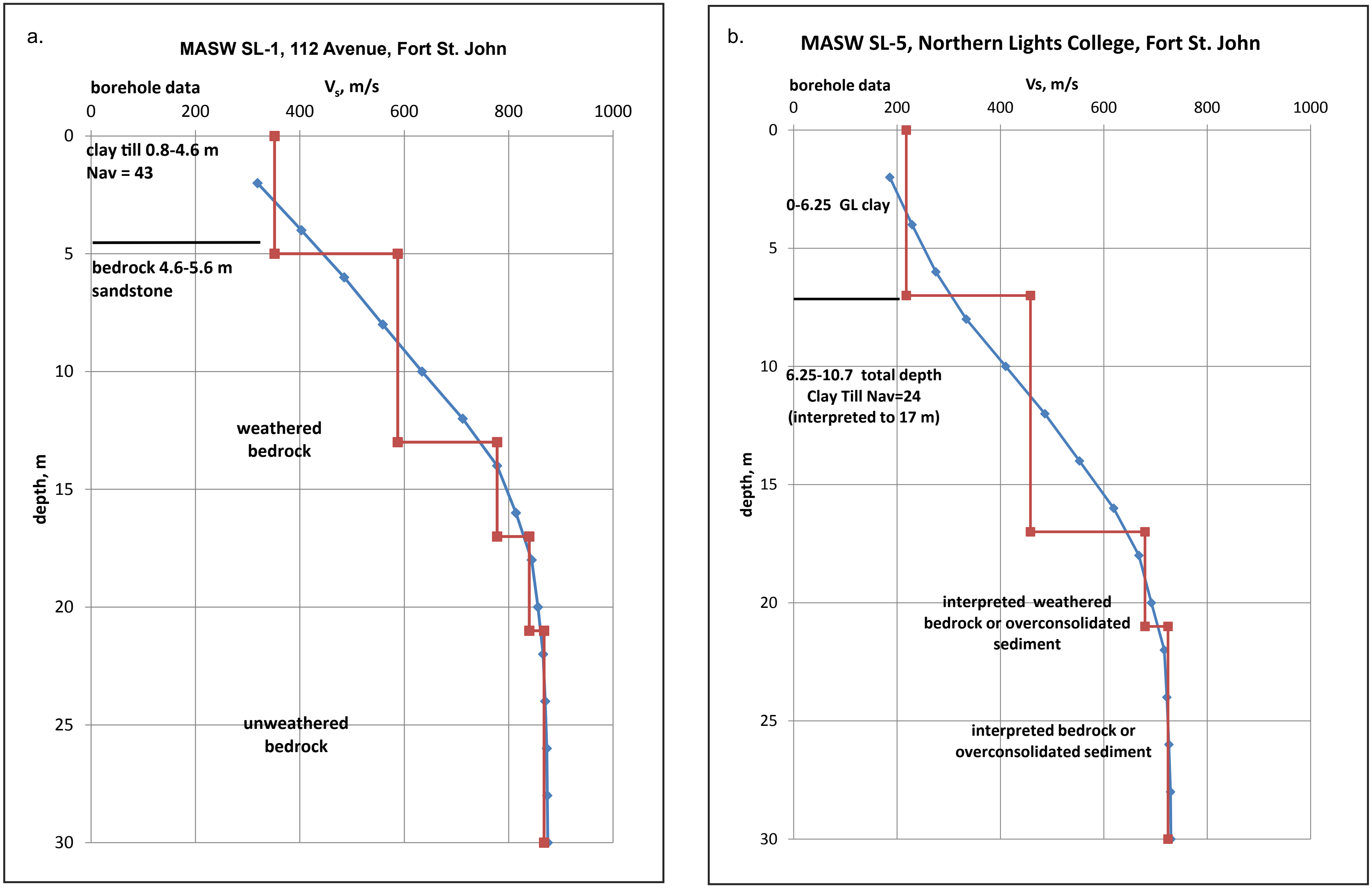

Figure 11. Layered interpretations for MASW sites; a, SL-1 (112th Avenue, Fort St. John) and b, SL-5 (Northern Lights College, Fort St. John). Blue Curve is the velocity depth fit, and the red line is the layered interpretation. Note that SL-5 (Northern Lights College) is the location of the NBC seismograph NBC 7. Note that Vs levels off in unweathered bedrock at site SL-1 (a) and is interpreted on the basis of a similar signature at base of SL-5 (b).

Period/Epoch	Time Stratigraphic Unit	Lithological Unit	Lithology	SPT N	V_{Sav} and range m/s
Holocene		Alluvium	silt, sand and gravel	14-25 (>50?)	196±14 (180-250?)
Pleistocene	Late Wisconsin Glaciation recessional phase	Glaciofluvial terrace	gravel, sand & silt		326±94 (250-400)
		Glaciolacustrine & glaciodeltaic	silt, clay & vf sand	2 to25	231±48 (135-330)
			Sand, silt & gravel	10 to 50	298±39 (250-350)
		Glacial tills	flow till	14 to 35	341±66 (270-460?)
			mixed till (ablation and lodgment	10 to >50	383±75 (320-460)
	Late Wisconsin Glaciation maximum		lodgment till	>50	502±94 (440-590)
	Late Wisconsin advance phase and earlier glacial and non-glacial deposits	Glaciolacustrine	clay, silt & vf sand	15 to >50	420±26 (360-490)
		Glaciolacustrine, glaciodeltaic	silty sand and sand	15 to >50	529±190 (400-860)
		glaciofluvial & fluvial	sand & gravel	>50*	519±117 (420-840)
		Glacial tills	till (flow, melt-out & lodgment)	>50*	660±158 (490-830)
Cretaceous	Kaskapau, Dunvegan & Sully	weathered shale, mudstone & sandstone		30 to >50	572±164 (350-850)
		shale and mudstone		>50	938±202 (770-1210)
		interbedded sandstone and shale		>50	996±124 (860-1100)
	Sikanni (one site)	sandstone		>50*	1549±287

*Assumed

Table 9. V_s model for shallow stratigraphic units.

Recessional phase glaciolacustrine silts, clays and very fine sands are represented at 15 sites: five of the Groundbirch boreholes (GB15-1 to 15-5), eight MASW sites (SL-2, SL-3, SL4, SL-5, SL-6, SL2-1, SL2-3, SL2-4[5]) and two Geoscience BC boreholes (GBC10b and 13). V_{sav} is 231±48 m/s, with a range of 135 to 330 m/s. At Groundbirch, the cores and logs permit a finer subdivision, further illustrating the grain size control over V_s: V_{sav} is 203±39 m/s in clays and silts at the top of the glaciolacustrine succession and 253±70 m/s in the underlying very fine sands and silts. In the two Geoscience BC boreholes V_{sav} is significantly higher at 319±8 m/s (315 and 327 m/s in boreholes GBC 10b and 13, respectively). These boreholes are located in the glaciolacustrine fluted terrain west of Farrell Creek noted by Mathews (1978a), and were probably overridden by a late stage re-advance of Cordilleran ice. Apparently, this re-advance was of insufficient extent or duration to compact the sediments to V_{sav} greater than 327 m/s.

SPT N values are generally between 2 and 15, and moisture content is usually greater than 20% in the recessional phase glaciolacustrine silts, clays and very fine sands. However, in one geotechnical borehole near Pine River in the eastern part of the area probably overridden by the late stage re-advance of Cordilleran ice, SPT values are between 13 and 25.

Recessional phase glaciolacustrine sands with minor gravel are represented at 6 sites: five of the Groundbirch boreholes (GB15-1 to 15-5) and one Geoscience BC borehole (10x). V_{sav} is 298±39 m/s.

Recessional phase Glaciofluvial terrace deposits were investigated at one MASW site (SL2-5; Figure 5). V_{sav} for these deposits is 326±94, with 251±4 for the surficial silts and sands and 364±91 for the gravels and sands.

Tills

Twenty-one intervals of till at fourteen sites are represented: five Groundbirch boreholes (GB12-2, 15-1, 15-3 to 15-5), six MASW sites (SL1, SL3, SL5, SL6, SL2-3 and SL2-6), and three Geoscience BC boreholes (GBC10b, 10x and 13). A wide range of V_s is represented: V_{sav} is 469±168 m/s, and the site averages range from 318 to 824 m/s. SPT N values in tills vary from 10 to >50. Tills with V_s values <400 m/s and N values <50 are interpreted to be melt-out or flow till (ablation tills), so not having been overridden by glacial ice, although being clay-rich may also be a factor. In thicker till sections observed in the geotechnical borehole logs, including at SL2-6, N values increase downward from ~20 to >50 without any compositional change being reported.

[5] Clay reported at elevation of ~1140m in the water well logs by SL2-4 is tentatively interpreted as an early glaciolacustrine clay, deposited in an ice-bounded lake. V_s in this section is consistent with other glaciolacustrine deposits.

At SL2-6, V_{sav} of the till units increases downward from 381 to 512 m/s[6]. These observations support the interpretation of a downward transition from ablation to lodgment tills. An alternative interpretation is that tills of two glaciations are represented, as observed locally by Mathews (1978a), but by either interpretation the high V_s and N values are due to glacial compaction.

The till intervals have been subdivided into those that are interpreted to be tills of the last glacial maximum, by occurring at surface or directly below the recessional phase succession, and those that are demonstrably older, occurring deeper in the section. By this reckoning, fourteen occurrences at twelve sites can be interpreted as till of the last glaciation. V_{sav} is 421$\pm$111 m/s, with still a large range in site averages from 318 to 582 m/s. These can be further subdivided into three groups.

Thin till packages occurring at the surface or immediately below glaciolacustrine sediments are likely a mixture of ablation and lodgment tills (mixed tills). These occur at seven sites (GB12-2, and 15-5; MASW Sl-1, SL-5, SL-6, SL2-3, and SL2-6). V_{sav} in these is 383$\pm$75 m/s, with a range in site averages from 318 to 458 m/s. SPT N values range from ~20 to >50.

Thick flow tills have been identified at two sites: GBC 10x, where it was identified in core (Levson and Best, 2017), and MASW site SL3, where a 20 m thick till with SPT N values between 14 and 35 is present. At the latter site, both N values and cone penetration test tip resistance decrease toward the base of the till section, showing passage into less dense material. V_{sav} for flow tills is 341$\pm$66 m/s, with site averages of 333 and 344 m/s.

Tills interpreted as lodgment tills of the last glaciation occur at five sites: in cores of GB15-3 and 15-4, GBC10x and 13 (Hickin *et al*., 2016a, Levson and Best, 2017), and at MASW site SL2-6, where it was interpreted on the basis of a sharp downward increase in SPT N and V_s. V_{sav} is 502$\pm$94 m/s, with site averages of 447 and 582 m/s.

Tills interpreted older than the last glacial maximum are represented in seven occurrences in four boreholes: GB15-1 and 15-4, and GBC10b and 13 (Hickin *et al*., 2016; Levson and Best, 2017). V_{sav} is 660$\pm$158 m/s, with site averages ranging from 493 to 824 m/s. These can be subdivided into those interpreted from core as lodgment (four intervals in GB15-1 and 15-4, and GBC 10b and 13) and flow tills (4 intervals in GBC 10b and 13). V_{sav} in lodgment till is 709$\pm$152 m/s with site averages ranging from 560 to 824 m/s, and in flow till is 593$\pm$111 m/s with site averages from 493 to 729 m/s.

Given the complexity of glacial successions, it is probably overly simplistic to interpret the older lodgment tills as being definitively older that the last glaciation, but clearly V_s increases noticeably in deeper tills. Of more significance is the marked V_s difference between flow tills of the recessional phase of the last glaciation and earlier flow tills – 341$\pm$66 m/s compared to 593$\pm$111 m/s, reflecting the significance of glacial compaction.

[6] At MASW site SL2-6, the N value increase occurs shallower than the V_s increase. For the purposes of this section, the low and high velocity tills are considered till of the last glaciation.

Advance Phase Deposits of the Last Glaciation and Earlier Deposits

Deposits older than the last glacial maximum other than tills are represented at eight sites: GB15-1, 15-2, 15-4 and 15-5, MASW site SL2-5, and GBC 10b, 10x and 13). The sediments comprise glaciolacustrine silts clays and very fine sands, with V_{sav} of 420±26 m/s and a range of site averages from 387 to 454 m/s; glaciolacustrine and glaciodeltaic silty sands and sands, with V_{sav} of 529±190 m/s and a range of site averages from 390 to 751 m/s; and glaciofluvial sands and gravels with V_{sav} of 519±117 m/s and a range of site averages from 478 to 840 m/s. No SPT data were available at these sites. However, sands, silts, and clays interpreted to be older than the last glacial maximum were noted in several geotechnical boreholes, where N values ranged from 15 to >50.

In these deposits, V_s variation is not simply a function of grain size, but also the degree of glacial compaction. This is illustrated by the Groundbirch boreholes 15-1 to 15-5, which were drilled to investigate a narrow paleovalley. GB15-1, 15-3 and 15-4 were located on the flanks of the paleovalley and drilled to bedrock (Table 6). The Quaternary succession underlying the recessional phase deposits of the last glaciation in these boreholes includes lodgment tills, glaciofluvial gravels and sands, with V_{sav} of 665±110 m/s, and site averages of 582 to 725 m/s. GB15-2 and 15-5 were drilled in the axis of the paleovalley and, although being drilled deeper, failed to reach bedrock. Deposits underlying the recessional phase deposits of the last glaciation consist of glaciolacustrine silts, clays, sands and some gravels and minor tills. V_{sav} is much lower, at 420±26, and with site averages are 426 and 419 m/s. The V_s profile is highly uniform, with no variation between silt, sand and gravel intervals. At the latter two sites, the Late Wisconsin glacier most likely advanced into a lake, and it is probable the glacier was partly buoyed up by the lake waters or supported by the walls of the paleovalley, resulting in less glacial compaction.

Overall, the V_{sav} of all deposits compacted by glacial ice, comprising all lodgment tills of the last glaciation and earlier deposits is 516±158, with site averages ranging from 422 to 725 m/s.

Bedrock

Bedrock V_s was recorded at eight sites: four boreholes (GB12-2, GB15-1 and 15-3, GBC6a) and four MASW sites (SL-1, SL-4, SL2-3 and SL2-4). The bedrock surface is commonly highly weathered, and weathering to depths of 20 m has been reported. Weathered and unweathered bedrock intervals in boreholes were identified from core descriptions and wireline logs. In most MASW profiles, V_s increases downwards over a 15 to 20 m interval to level off at high V_s, with the latter being interpreted as unweathered bedrock (Figures 10 and 11).

Weathered bedrock intervals are represented at boreholes GB12-2 and GB15-3, and MASW sites SL-1, SL-4, SL2-3 and SL2-4. V_{sav} in these intervals is 572$\pm$164 m/s, with site averages ranging from 457 to 740 m/s. Those in Upper Cretaceous interbedded sandstone and shale intervals are somewhat higher than those in Sully and Kaskapau shales, with site averages ranging of 680 and 740 m/s in the former, and 457 to 677 m/s in the latter. The lowest site average occurs at SL2-3, where the weathered interval exceeds 30 m in thickness (Figure 10b). V_s shows little increase with depth in the upper 12 m averaging 368 m/s, below which V_s increases sharply. In geotechnical boreholes near SL2-3, SPT N values are generally >50, but some near 30 have been reported in the highly weathered shales.

Unweathered bedrock sections are represented in GB12-2, GB15-1, 15-3, GBC6a, SL-1, SL-4, and SL2-4). Excluding borehole GBC6a, V_{sav} is 947$\pm$187, with site averages ranging from 772 to 1208 m/s. In Sully and Kaskapau shales (GB12-2, GB15-1, 15-3, SL-4, and SL2-4), V_{sav} is 938$\pm$202, with site averages ranging from 772 to 1208 m/s. In Dunvegan interbedded sands and shales, (GB12-2 and SL-1), V_{sav} is 996$\pm$124, with site averages of 868 and 1104 m/s.

At three MASW sites (SL2, 5 & 6), where the adjacent borehole was not deep enough to encounter bedrock, unweathered bedrock was interpreted at the base of the profile where the V_s values are high, as they are at those sites where bedrock was confirmed. Interpreted bedrock V_s at these sites ranges from 724 to 871 m/s (Figures 10a and 11b).

V_{sav} in the Sikanni Sandstone at GBC6a is V_{sav} is 1549±287 m/s. Below a thin weathered interval with a V_s of 1159±167 m/s, V_s averages 1772±51 m/s in unaltered sandstone. These values are much higher than other bedrock V_s values, most likely because of greater depth of burial of the Sikanni sandstones compared to the Dunvegan sandstones. Not only is the Sikanni older, but succeeding formations are thicker in the western parts of the project area. However, the logged interval in this borehole is only 2 m, and does not include any interbedded shales.

V_{s30} AND SITE CLASS ASSIGNMENTS FOR THE SURFICIAL GEOLOGICAL MAP UNITS (MAP 2)

Based on the V_s model and V_{s30} determinations, Site Classes have been assigned to the surficial geological map units. The results are shown on Map 2, and details are discussed below.

Figure 12 shows the distribution of V_{s30} values for all the V_s sites by surficial geological unit. The results are generally what would be expected from the V_s model, with the Holocene alluvium and recessional phase glaciolacustrine and glaciofluvial units being in Site Class D, and glacial and glaciolacustrine veneer units being in Site Classes B and C. Departures are not because of incorrect mapping, but reflect the geological variability of these units. MASW site SL2-6 is represented twice on the chart because the profile at the south end, adjacent to the geotechnical boreholes is significantly different than at the north end.

In a general way, V_{s30} decreases as depth to bedrock increases, as higher V_s bedrock is replaced by lower V_s Quaternary sediments (Figure 13). However, V_{s30} for any particular depth to bedrock depends on which Quaternary units are present, as shown by the two points near 20 m depth. At the higher V_{s30} site (MASWS SL2-6, south end) till is at surface, whereas at the lower V_{s30} site (SL2-3), 11 m of glaciolacustrine silt occurs. Deeper than 30 m, bedrock V_s does not contribute to V_{s30}.

Bedrock

Few areas have been mapped as bedrock, and these are in the Foothills part of the map area, and along the Sikanni Chief and Buckinghorse Rivers. Bedrock in the Foothills area is likely to comprise Lower Cretaceous and older sedimentary rock that has been more deeply buried than most bedrock investigated for this project. V_s is likely to be comparable to the Sikanni at Borehole GBC6a, where the V_{sav} is 1549 m/s. Elsewhere bedrock V_s is generally between 760 and 1200 m/s. Although bedrock is exposed in the valleys of the Peace River and its tributaries, the areas of bedrock exposure are too small to be resolved at the current mapping scale. This map unit is assigned to Site Classes A and B, with nil to very low amplification susceptibility rating.

Glacial

The Glacial map unit is widespread and includes most areas where topography is controlled by bedrock (Figures 2 and 3). Sediments overlying bedrock are primarily till, although a few metres of glaciolacustrine silt and clay commonly occur, particularly at lower elevations, and colluvium may be present. Depth to bedrock is commonly only a few metres and usually less than ten. It can vary by up to 15 m across a single industrial site, such as a gas plant or related facility. However, unconsolidated sediments in this map unit can be up to 60 m thick adjacent to valleys of rivers and creeks, both the larger valleys where glaciolacustrine and related sediments have been mapped, and smaller valleys with deposits of areal extent too limited to be resolved at the scale of mapping. The sediment fill in these valleys is commonly complex, but generally includes thick late stage glaciolacustrine sediments and till. Accordingly, tens of metres of unconsolidated sediment could be present in this map unit adjacent to any valley.

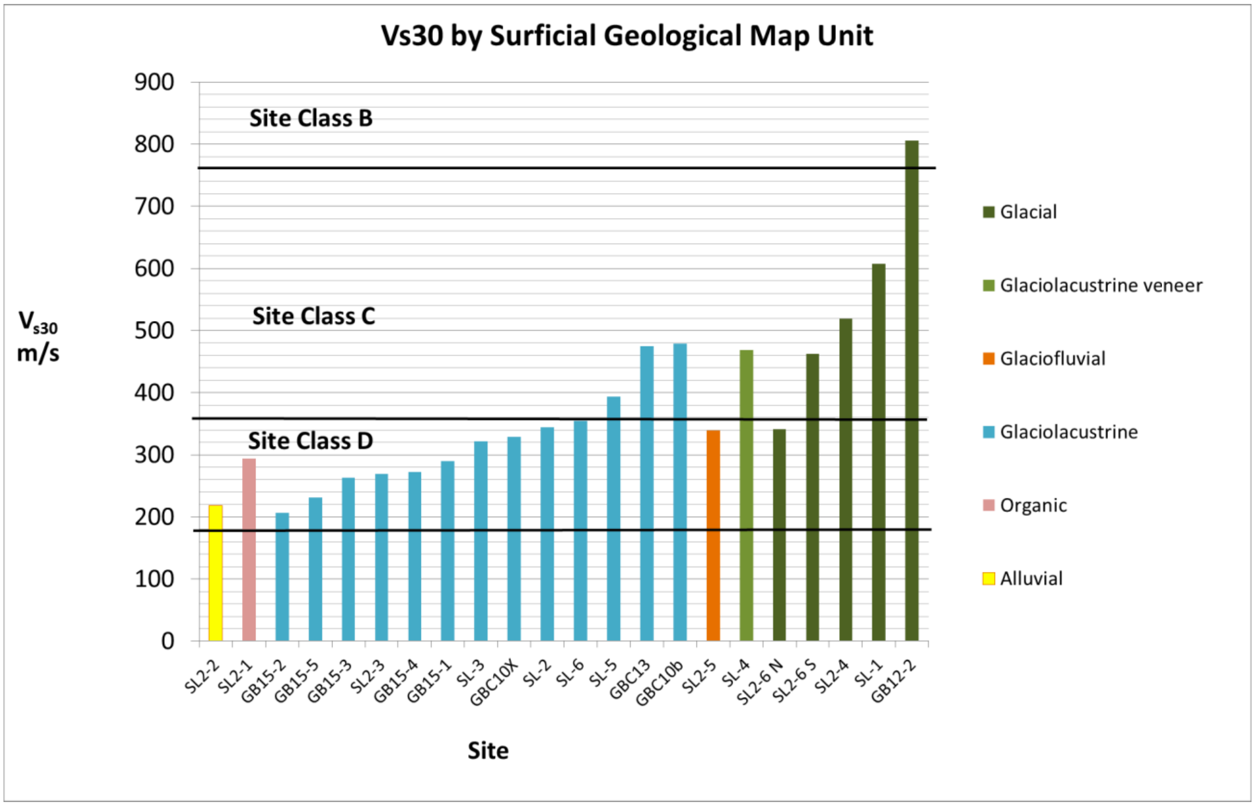

Figure 12. V_{s30} by surficial geological map unit. Note that MASW site SL2-6 is represented twice, because the geological profile at the south end, adjacent to the geotechnical boreholes, is significantly different than at the north end.

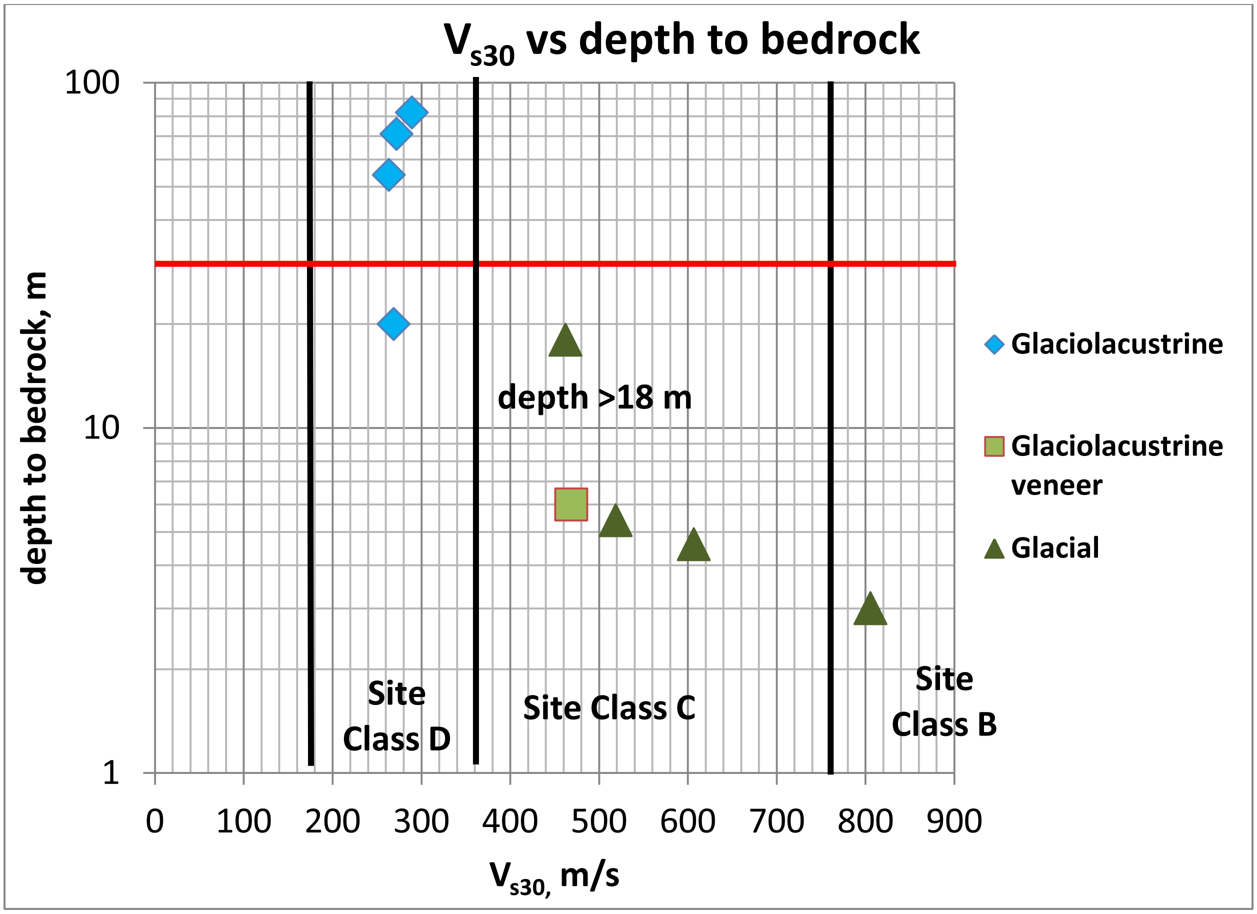

Figure 13. Depth to bedrock vs. Vs30 for Vs sites where depth is known from borehole data. Note that the south end of SL2-6 where the depth is >18 m is added to complement the description of the Glacial map unit. Note also the red line that marks depth of 30 m, beyond which bedrock V_s does not contribute to V_{s30}.

V_{s30} at five sites ranges from 341 to 806 m/s, from Site Class D to B (Figure 12). The lowest is at the north end of SL2-6, where the low values are possibly due to a small bog. At the remaining sites, V_{s30} increases from 463 to 806 m/s with decreasing depth to bedrock, from >18 m at the south end of SL2-6 to 3 m at GB12-2 (Figure 13). Because the unconsolidated sediment is dominated by till and usually less than ten m thick, it is assigned to Site Classes B and C, with a very low to low amplification susceptibility rating. However, it can include areas of Site Class D adjacent to valleys where the glaciolacustrine, glaciodeltaic, organic and eolian map units have been mapped, and in valleys and bogs in which deposits are too small to be resolved at the scale of mapping.

Glaciolacustrine Veneer

The glaciolacustrine veneer map unit is similar to the glacial map unit, and occurs in areas where topography is bedrock-controlled. It has been designated on the basis of thin glaciolacustrine deposits being recognized overlying till, but there is considerable overlap. Adjacent to the glacial map unit, it is commonly mapped on slopes below the hill crests, where the glacial map unit is mapped, and occupies minor valleys. The sediment overlying bedrock consists of both till and glaciolacustrine silts and clays, Bedrock depth is commonly only a few metres. However, as in the glacial map unit, it can increase to up to 70 m adjacent to valleys of rivers and creeks, both the larger valleys where glaciolacustrine and related sediments have been mapped, and smaller valleys with deposits of too limited areal extent to be resolved at the scale of mapping. As with the glacial map unit, tens of metres of unconsolidated sediment could be present in this map unit adjacent to any valley.

V_{s30} has been measured at only one site, where it is 469 m/s, and the sediment thickness is representative of most of the map unit (Figure 12). Consequently, this unit is assigned to Site Class C, with low amplification susceptibility rating. Like the glacial map unit, it includes areas of Site Class D adjacent to valleys where glaciolacustrine and related sediments have been mapped, and in valleys and bogs where deposits are too small to be resolved at the scale of mapping. Areas of Site Class B may also occur where depth to unweathered bedrock is very thin.

Glaciolacustrine

The glaciolacustine map unit occupies benches of level ground adjacent to major river valleys and the upstream reaches of many minor ones (Figures 2 and 3). Modern streams have incised through these deposits during the late Pleistocene and Holocene to form their present valleys. Sediment thicknesses are generally in the order of tens, and locally hundreds of metres. The sedimentary fill consists of recessional phase glaciolacustrine silts, clays and very fine sands, till of the last glaciation and, in the thicker sections, earlier glacial and non-glacial deposits. Peat deposits less than one metre thick occur locally at the surface. Recessional phase glaciodeltaic sediments occur locally in the westernmost part of the map unit adjacent to the Peace River, and thick recessional phase flow tills occur locally. The thickness of the glaciolacustrine silts varies from a few metres to 90 m near Hudson Hope, and along the Peace River varies from an average of 30 m in the west to 17 m in the east (Mathews, 1978a). Glaciolacustrine clay thicknesses in excess of 40 m have been reported in geotechnical boreholes adjacent to the Beatton River. Thicknesses are generally greater than 10 m, although thinner sections can occur along the margins of the map unit adjacent to the glacial map unit, and along minor valleys. In the Groundbirch boreholes, the glaciolacustine silts are 11 to 30 m thick and are underlain by 11 to 30 m of sands also interpreted to have been deposited in a glaciolacustrine setting (Hickin *et al.*, 2016a).

V_{s30} at thirteen sites varies from 207 to 479 m/s, from Site Class D to C (Figure 12). All but three sites are in Site Class D. In those in Site Class C, the higher V_{s30} is due to thin glaciolacustrine sections: 6 m at MASW site SL-5 and 9 and 12 m in boreholes GBC13 and 10b, respectively. Furthermore, the latter two are in the area of a late stage re-advance of Cordilleran ice where the V_{sav} of glaciolacustrine deposits is significantly higher than the unit average – 319 compared 231 m/s (see V_s model in Table 9; Mathews, 1978a; Levson and Best, 2017).

This map unit is assigned to Site Class D with a moderate amplification susceptibility rating. Areas of Site Class C can also occur where the glaciolacustine section is thin along the margins of the map unit adjacent to the glacial map unit, and along minor valleys. The threshold thickness is approximately eight metres in most of the map unit, but likely increases to 15 m in the area where glaciolacustrine sediments have been partially compacted due to the late stage re-advance of Cordilleran ice. Based on the distribution of surface flutings, this area extends from west of Farrell Creek across the southwest part glaciolacustrine plain between the Peace and Pine Rivers (Mathews, 1978a, b). V_s data are limited to the part of the area west of Farrell Creek, and geotechnical data are limited to a single borehole near the Pine River. SPT values at this site are higher than average for glaciolacustrine deposits (13-25) and are consistent with a low degree of glacial compaction. Acquisition of additional V_s and geotechnical data is necessary to better understand and map the effects of the late stage Cordilleran re-advance in this area.

Glaciodeltaic

The Glaciodeltaic map unit has been mapped along benches of level ground adjacent to the Halfway River and the upper reaches of Farrell Creek, and is laterally equivalent to the glaciolacustrine map unit. As in the glaciolacustrine map unit, the modern streams have incised through these deposits during the late Pleistocene and Holocene to form their present valleys. Depth to bedrock varies from a few metres to 179 m. The sedimentary fill consists of recessional phase glaciodeltaic sands and interbedded silts, till of the last glaciation and, in the thicker sections, earlier glacial and non-glacial deposits.

No V_s data are available in this map unit. However, glaciodeltaic sands have been reported in one borehole (GBC10x, Levson and Best, 2017), and similar recessional phase sands occur in five Groundbirch boreholes (GB15-1 to 15-5; Hickin *et al*., 2016a). V_{sav} for these is 298 m/s. This map unit is assigned to Site Class D with a moderate amplification susceptibility rating. Areas of Site Class C can also occur where the glaciodeltaic section is thin along the margins of the map unit adjacent to the glacial map unit. The threshold thickness is likely to be approximately 15 metres.

Glaciofluvial

This map unit has been mapped in two settings: late recessional phase glaciofluvial terraces on the flanks of major valleys, and local kame deposits at higher elevations (Mathews, 1978a). Only the glaciofluvial terrace deposits have been observed in boreholes and outcrop (Figures 2 and 4). Sediments in this map unit consist of glaciofluvial gravels and sands, capped by and and locally interbedded with a few metres of silt and sand. The deposits are up to 30 m thick in terraces beside the Peace River, but may be thinner adjacent to smaller rivers. These deposits overlie either bedrock or sediments preceding the last glaciation.

V_{s30} has been measured at one site, where it is 339 m/s (SL2-5; Figures 4 and 12). The thickness of the glaciofluvial section here is approximately 30 m. This unit is assigned to Site Class D, susceptible to moderate amplification. However, areas of Site Class C will be present where the glaciofluvial section is thinner, and the threshold thickness is likely to be 20 m.

Eolian

The eolian map unit consists mainly of Late Pleistocene and Early Holocene sand dunes and loess veneers. It occurs primarily in southwestern part of the project area, overlying and adjacent to sandy glaciolacustrine and glaciodeltaic deposits, which were the eolian sediment sources (Mathews, 1978a).

No V_s or geotechnical borehole data are available for this map unit. As it generally occurs above glaciodeltaic and glaciolacustrine deposits, it is assigned to Site Class D, susceptible to moderate amplification. However, areas of Site Class C may be present where the recessional phase deposits are relatively thin. The threshold thickness is likely to be in the order of ten to fifteen metres.

Organic

The organic map unit is mapped where peat occurs at the surface. Reported peat thicknesses are generally less than three metres (Hansen, 1950), and the maximum observed in geotechnical boreholes obtained for this study is one metre. However, thicker sections may occur in areas without geotechnical borehole control. This map unit has been identified in the northern part of the project area, and occurs in two settings. The first is in areas of low relief in and adjacent to river valleys, where organic units commonly are bordered by the glaciolacustrine map unit, and in these areas the sedimentary succession beneath the peat is the same as that in the glaciolacustrine map unit. The sedimentary succession is generally in the order of tens of metres thick, and consists of recessional phase glaciolacustrine silts, clays and very fine sands, till of the last glaciation and, in the thicker sections, earlier glacial and non-glacial deposits. Recessional phase glaciolacustrine clay thicknesses in excess of 40 m have been reported in geotechnical boreholes adjacent to the Sikanni Chief River, near MASW site SL2-1. Thicknesses are generally greater than 10 m, although thinner sections can occur along the margins of the map unit adjacent to the glacial map unit. The second setting for the organic map unit is in low lying areas in the uplands, where they are surrounded by the glacial map unit. No geotechnical data are available in this setting.

V_{s30} has been measured at one site, where it is 294 m/s (SL2-1; Figure 12). This site is adjacent to the Sikanni Chief River, where a ~30 m thick section of glaciolacustrine silts and clays is present. On the basis of this point and the similarity with the glaciolacustrine map unit, this map unit is assigned to Site Class D, susceptible to moderate amplification. However, as in the glaciolacustrine map unit, areas of Site Class C can also occur where the glaciolacustine section is thin along the margins of the map unit adjacent to the glacial map unit, and along minor valleys. As no data are available from the upland setting of this map unit, it is conservatively assigned to Site Class D as well.

Colluvial

The colluvial map unit has been mapped to include slope deposits, as well as unconsolidated Quaternary sediments and bedrock exposed along steep valley walls and areas adjacent to bedrock in areas of higher relief in the Foothills (Figure 2). The map unit may also include minor alluvial and glaciofluvial deposits along narrow valley bottoms.

As a variety of unconsolidated and bedrock lithologies are represented in this map unit, no specific Site Class can be assigned. However, this map unit is assigned a moderate to high hazard rating, because of potential slope instability. Numerous landslides have occurred along the steep valley walls of deeply incised rivers in the area, and have originated in both advance phase glaciolacustrine silts of Glacial Lake Mathews and Cretaceous shale bedrock (Mathews 1972a; Fletcher *et al*., 2002; Thomson and Cruden, 2010). In particular, major slides have occurred along the Peace River at Taylor, Bear Flat, Attachie, and most recently at Old Fort south of Fort St. John.

Alluvial

The alluvial map unit is mapped to include the floodplains, mid-channel islands and bars of modern rivers, but may also locally include lower glaciofluvial terrace deposits (Figure 2). Some alluvial fans are also included. Sediment thicknesses vary with the size of the river, and are up to 20 m thick in the case of the Peace River. At MASW site SL2-2 on the Sikanni Chief River, alluvial deposits are 10 m thick. The deposits consist of sands and gravels, interbedded and capped by silts.

V_{s30} has been measured at one site, where it is 218 m/s (SL2-2; Figures 5 and 12). This site is anomalous, in that the fluvial sands and gravels are underlain by approximately 25 m of low V_s material (V_{sav} 231 m/s), which is interpreted to be glaciolacustrine. Nonetheless, with a measured V_{sav} of 196 m/s for the modern alluvium at this site, most occurrences of this map unit are most likely to be in Site Class D, susceptible to moderate amplification. Areas of Site Class C may occur where the thickness of alluvium is less than approximately eight metres.

COMPARISON OF RECORDED GROUND MOTIONS WITH GEOLOGICAL MAPS UNITS

Based on recent recordings of earthquakes ranging from M 1.5 to 3.8, Babaie Mahani and Kao (2018a) generated local ground motion prediction equations for two areas within the project area – Graham and Septimus. Ground motions from a modified version of their database (A. Babaie Mahani, personal communication) are compared with the geological map units. This database comprises 232 seismic events and 1071 records. The locations of the seismograph stations are shown on Maps 1 and 2.

Initially, the geometric means of both horizontal components of peak ground acceleration (PGA) and peak ground velocity (PGV) were determined for each record. These were divided by the expected ground motions calculated using the ground motion prediction equations in order to determine apparent amplifications. The mean and median of the apparent amplifications were then calculated for each seismograph station for all events recorded by the station (Tables 10 and 11). Finally, the mean and median of the apparent amplifications were calculated for all stations within each geological map unit. Plots of the mean and median PGA and PGV amplifications sorted by site, geological map unit and magnitude, and plots of the geometric mean PGA and PGV vs. distance are shown in Appendix 12.

Babaie Mahani and Kao (2018a) place more weight on PGV due to the short duration and high frequency content of these events. Consequently, we focus on PGV here. Note that the ground motion prediction equations generated by Babaie Mahani and Kao (2018a) are relative to a V_{s30} of 760 m/s. Because their estimated V_{s30} for every station is less than that, most records show some level of amplification. We also focus on mean rather than median amplifications, as the mean is based on all the data, whereas the median is more influenced by those in the middle of the distribution.

Graham Area

The Graham area is located in the southwest part of project area, and extends from Farrell Creek north to the valley of Townsend Creek, a tributary of the Cameron River. The database includes 636 records of 141 events at 15 sites. The range of magnitudes is from M1.5 to 3.8. The station locations and averaged amplifications are summarized in Table 10, and the mean PGV amplifications sorted by site, geological map unit and magnitude are shown in Figure 14.

The data show that there is relatively little difference in the mean and median PGA and the median PGV amplifications between geological map units, although mean PGA is 1.8 times higher in the glacial map unit than in the glaciolacustrine and alluvial map units (Appendix 12). In the glaciolacustrine veneer map unit, the values are skewed by the record of a single extreme event (M1.97) at station 13F in a small dataset (n=3). If this station is excluded, the mean PGA amplification for the glaciolacustrine veneer map unit is 1.95, comparable to the glaciolacustrine and alluvial map units.

station				amplification				depth to bedrock m	map unit	mapped Site Class
station ID	easting	northing	n	mean PGA cm/s^2	median PGA cm/s^2	mean PGV cm/s	median PGV cm/s			
13F	553650	6282263	3	139.53	3.99	71.28	3.98	0?	GLv	C
NBC 8, 1	536619	6270026	126	1.95	1.63	2.35	1.89		A	D
2	546579	6269512	120	1.99	1.71	2.13	1.84		GLv	C
3	541978	6262518	123	1.91	1.42	13.83	1.91	44	GL	D
4	533252	6260681	121	3.55	1.51	2.33	1.94		G	C
5	560755	6258148	2	0.97	0.97	1.54	1.54	<16	GLv	C
6	544617	6257402	123	3.45	1.56	2.93	1.97		G	C
7	551384	6253393	2	1.3	1.3	1.24	1.24	<11.5	GLv	C
8	558775	6249804	2	1.51	1.51	1.32	1.32	2	GLv	C
9	569962	6245465	2	0.88	0.88	1.07	1.07		G	C
10	551916	6245173	2	2.23	2.23	2.28	2.28	2	G	C
11	558202	6242071	2	1.1	1.1	1.22	1.22	<24.4	G	C
12	564473	6236440	2	2.39	2.39	3.01	3.01	<30	G	C
13	558312	6229449	2	2.89	2.89	4.05	4.05	<12.9	G	C
ALD72	557772	6250859	4	1.8	1.8	1.39	1.36		GLv	C

Table 10. Locations and average PGA and PGV amplifications for seismograph stations in Graham area, calculated from data provided by Babaie Mahani (Babaie Mahani and Kao, 2018a). Depth to bedrock from nearby borehole data. Abbreviations, PGA, peak ground acceleration; PGV, peak ground velocity; G, glacial; GL, glaciolacustrine, GLv, glaciolacustrine veneer; A, alluvial, n, number of events recorded. UTM coordinates NAD83 Zone 10N.

However, the mean PGV amplification shows a more significant differentiation by geological map unit (Figure 14). Station 3 in the glaciolacustrine map unit has a mean PGV amplification of 13.83, based on a dataset of 123 events. This is nearly four times higher mean PGV amplification than in the glaciolacustrine veneer map unit (six times higher if station 13F is excluded) and five times higher than in the glacial map unit. Gamma ray log data at Station 3 indicate a Quaternary thickness of 44 m, and it can be confidently assigned to Site Class D. With the exception of station 13F, where mean PGV is also skewed by the single extreme event, the stations in the glacial and glaciolacustrine veneer map units have lower mean PGV amplifications. Where known, bedrock depth at stations in these map units is a few metres, and these stations can be confidently assigned to Site Class C. Although the alluvial map unit is in general assigned to Site Class D, the alluvial section in the upper reaches of the Halfway River Valley may be thin, and so station 1 is most likely in Site Class C, as suggested by the lower mean PGV amplifications.

The events recorded by station 3 in Site Class D merit further discussion (n=123). The median PGV amplification is not significantly different from that at other stations, because in most events, PGV amplification is low. However, for 15 events PGV amplification exceeds 10 and reaches a maximum of 350, resulting in the high mean value. The highest peak velocities recorded at this station are between 1 and 2 cm/s and are for events between M1.5 and 2.5, not larger events. This pattern changes for events >M3 (n=5). In these both mean and median PGV are significantly higher than at other sites. The pattern shown for events <M3 is one of little amplification most of the time but extreme amplification some of the time. For larger events, high PGV amplification occurs more consistently.

In this context, the extreme amplification for one event at station 13F is not unique, as occasional extreme amplifications occur at station 3. However it is unknown from the small number of events recorded at site 13F whether this extreme amplification unusual or the norm.

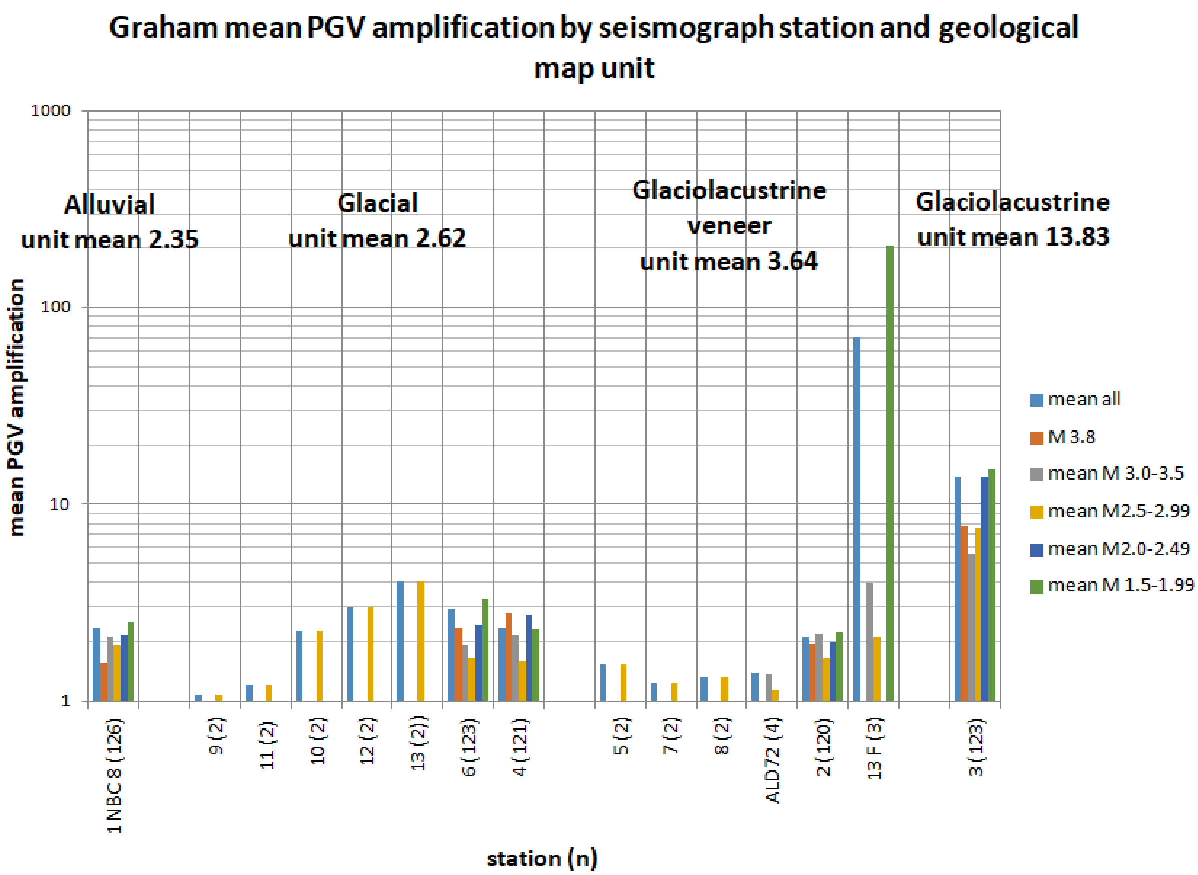

Figure 14. Graham area mean PGV amplification by seismograph station and geological map unit. Abbreviations: M, magnitude; n, number of seismic events.

Septimus Area

The Septimus area is located in the south-easternmost part of the project area. Except for station 1 (station NBC 7) in Fort St. John, all stations are located south of the Peace River. The database includes 435 records of 91 events at 20 sites. The range of magnitudes is from M1.5 to 3.0. The station locations and averaged amplifications are summarized in Table 11 and the mean PGV amplifications sorted by site, geological map unit and magnitude are shown in Figure 15.

The data demonstrate that mean PGV amplification in the glaciolacustrine map unit is 3.97, 1.3 to 2 times higher than in the glaciolacustrine veneer and glacial map units, respectively (Figure 15). However, there is considerable variability. PGV amplification is ~8 at stations 17 and 18, where depths to bedrock are 83 and 53 m, respectively, and which are probably in Site Class D. Amplification at station 1 (NBC 7) is 3.93. This station is co-located with MASW SL-5, where the V_{s30} is 394$\pm$17 m/s, at the lower end of Site Class C (Table 7). At this station, 6 m of glaciolacustrine clay overlies till, and bedrock is interpreted to be at 17 m (Figure 11b). Amplification is minimal at stations 4 and 16, where depths to bedrock are interpreted to be is 27 and <21 m respectively. These are probably in Site Class D, although the Quaternary stratigraphy is unknown.

Although mean PGV amplification is generally low in the glacial map unit, it exceeds ~4 at three of the thirteen stations - stations 10, 11 and 13. Depths to bedrock at these stations are <8, 11 and <10, respectively. Elsewhere in the glacial map unit, depths to bedrock are between 1 and 12 m at stations 3, 5, 6, 7, 8 and ND124. These stations are most likely in Site Class C. At stations 2 and 9, greater depth to bedrock interpretations have been made – 93 and 48 m, respectively. However the Quaternary stratigraphy is unknown at these stations and the Site Class is uncertain. In particular, station 9 is close to the glaciolacustrine map unit, and could potentially be in Site Class D.

The data from the two stations in the glaciolacustrine veneer map unit produce a mean PGV amplification 1.5 times higher than in the glacial map unit, perhaps reflecting a greater thickness of glaciolacustrine silt and clay than at most glacial unit stations. Bedrock depths at these stations are <30 and <16 m respectively, and they are located adjacent to the glaciolacustrine map unit.

station				amplification				depth to bedrock m	map unit	mapped Site Class
station ID	easting	northing	n	mean PGA cm/s^2	median PGA cm/s^2	mean PGV cm/s	median PGV cm/s			
1, NBC 7	633609	6237976	3	2.09	1.94	3.93	4.31	17	GL	D
2	642341	6218767	3	1.66	1.56	1.88	1.67	93	G	C
3	629346	6216117	81	0.47	0.35	0.52	0.45	7	G	C
4	646167	6216133	3	1.61	1.22	1.7	1.41	>27.9	GL	D
5	642620	6215980	3	1.49	1.56	1.12	1.11	<11.9	G	C
6	638709	6215540	2	1.44	1.44	1.22	1.22	<24.3	G	C
7	643475	6214661	1	1.36	1.36	1.44	1.44	0.6	G	C
8	642888	6213539	3	6.42	5.84	2.53	2.41	<3.1	G	C
9	644477	6212657	80	1.04	0.91	1.51	1.2	48.2	G	C
10	635644	6211968	81	3.23	2.95	3.87	3.81	<7.8	G	C
11	660961	6210478	1	11.23	11.23	6.93	6.93	10.9	G	C
12	630491	6209169	81	1.36	1.37	1.54	1.59		G	C
13	644916	6208862	5	17.41	4.86	9.5	2.87	<9.5	G	C
14	654608	6206659	1	3.41	3.41	2.85	2.85		GLv	C
15	639941	6204465	81	2.86	2.98	2.99	3.15	<16.4	GLv	C
16	675757	6201240	1	2.41	2.41	2.38	2.38	<21.1	GL	D
17	682394	6192222	1	7.99	7.99	8.26	8.26	83	GL	D
18	668550	6190313	1	7.04	7.04	8.21	8.21	53.2	GL	D
19, NBC 4	647102	6173760	2	0.81	0.81	1.43	1.43		G	C
ND124	628662	6217121	1	2.74	2.74	1.84	1.84	7	G	C

Table 11. Locations and average PGA and PGV amplifications for seismograph stations in Septimus area, calculated from data provided by Babaie Mahani (Babaie Mahani and Kao, 2018a). Depth to bedrock from nearby borehole data. Abbreviations, PGA, peak ground acceleration; PGV, peak ground velocity; G, glacial; GL, glaciolacustrine, GLv, glaciolacustrine veneer; n, number of events recorded. UTM coordinates NAD83 Zone 10N.

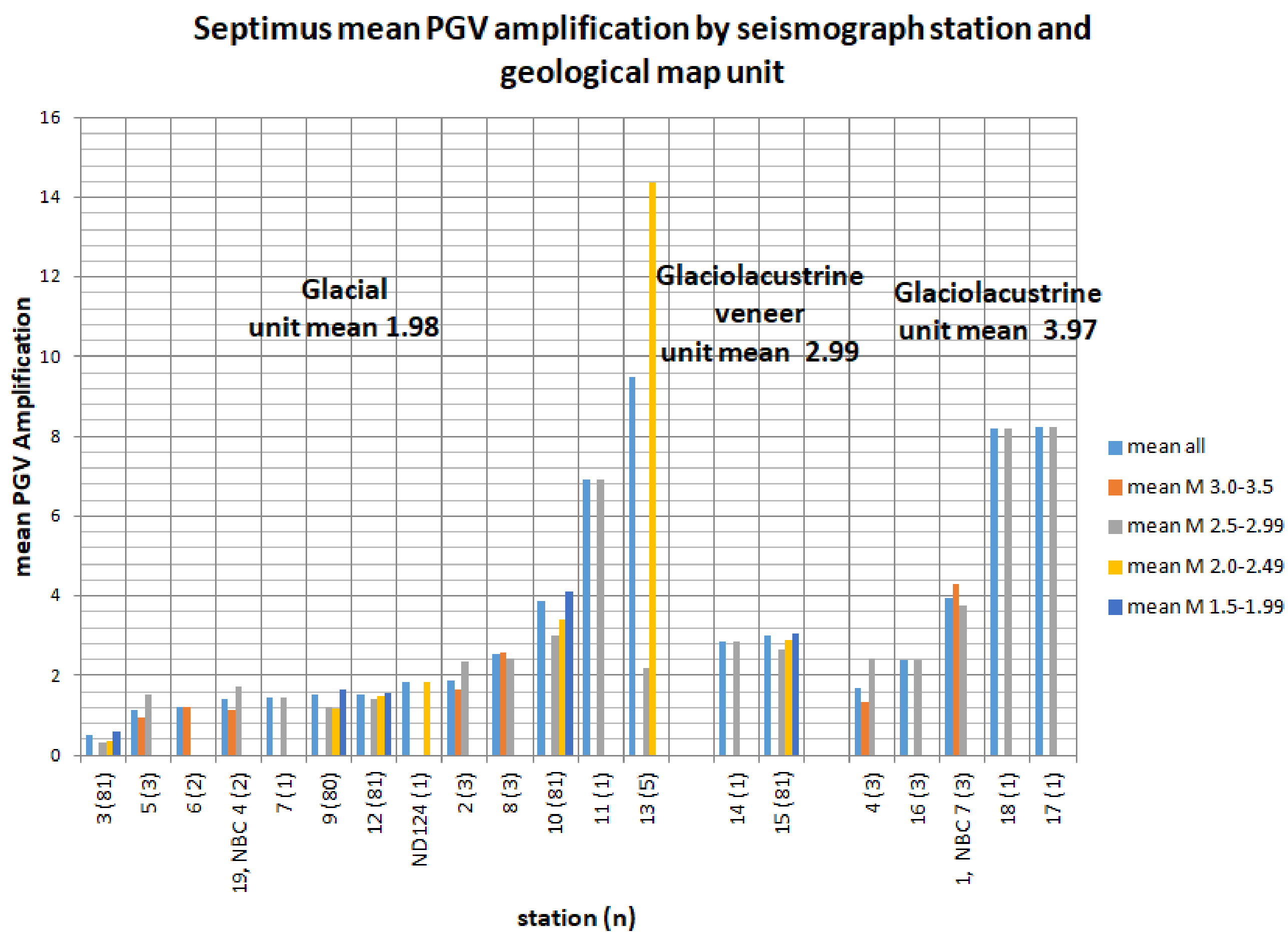

Figure 15. Septimus area mean PGV amplification by seismograph station and geological map unit. Abbreviations: M, magnitude; n, number of seismic events. Note that station 1, NBC 7 is co-located with MASW site SL-5.

DISCUSSION

The V_s data show that areas underlain by Holocene and recessional-phase deposits of the last glaciation (alluvial, eolian, organic, glaciolacustrine, glaciodeltaic, and glaciofluvial map units), where sufficiently thick, are in Site Class D, and susceptible to moderate amplification of seismic ground motions. Areas of Site Class D can also occur in the glacial and glaciolacustrine veneer map units adjacent to major and minor river and stream valleys.

The comparisons of ground motions from recently recorded seismic events in the Graham and Septimus areas are generally consistent with this conclusion, with mean PGV amplifications in the glaciolacustrine map unit being 2 to 5 times higher than in the glacial map unit and 1.3 to 4 times higher than in the glaciolacustrine veneer map unit. However, there is considerable variability in each map unit. For example in the glaciolacustrine map unit, several stations exhibit average amplifications 4 to 5 times higher than the glacial map unit mean, but others do not exhibit significant amplification.

Furthermore, for most events <M3 recorded by the glaciolacustrine station at Graham, PGV amplification is not evident, the high mean amplification being driven by a small number of records with extreme amplification. Amplification occurs more consistently for events greater than M3.

High PGV amplification also occurs at some seismograph stations in the glacial and glaciolacustrine veneer map units where unconsolidated sediments are thin and are in Site Class C – stations 13F at Graham and 10, 11 and 13 at Septimus, where depth to bedrock is 11 m or less. The enhanced ground motions at these stations are likely due to three dimensional (basin edge) effects or resonance. Resonance occurs where the site period matches the period of the dominant ground motions. Structures with the same natural period as the site and the dominant ground motions would be most affected.

The dominant site period (T) is calculated by the quarter wavelength rule (Kramer, 1996; Finn and Wightman, 2003):

$T = 4H/V_s$, where

H = thickness of the low velocity geological unit, and

V_s = the average shear-wave velocity of the low velocity geological unit.

The natural period of a building can be approximated by 0.1 second per story (*e.g.* Rogers *et al*., 1994).

For recessional phase deposits 6 m thick with average V_s of 240 m/s, the site period would be 0.1 second. The small induced earthquakes described here are likely to be rich in short period energy. Consequently, areas where Holocene and recessional phase deposits of the last glaciation are thin and not in Site Class D, could be susceptible to amplification of short-period ground motions due to resonance. These areas could occur on either side of the boundaries between the glaciolacustrine, glaciodeltaic, glaciofluvial, organic and eolian map units on one hand and the glacial and glaciolacustrine veneer map units on the other. Along such boundaries, as earthquake magnitude increases and longer period ground motions become more significant, amplification due to resonance would shift to sites where recessional phase deposits are somewhat thicker.

The relatively high PGV amplifications at NBC 7 (Septimus station 1; MASW site SL-5), which is at the lower end of Site Class C, may be due to resonance, or could be due to topographic effect, as it on the top of a steep slope. Resonance may also account for the stronger ground motions at Septimus station 8 than at station 5, as reported by Babaie Mahani and Kao (2018b).

Minor damage reported from the August 2015 M_w 4.6 earthquake may be due to resonance or a basin-edge effect. In the Sikanni Chief River area, a small shed that was knocked off its foundations (M. Maple, personal communication, June 25, 2017) was located along the boundary of the organic/glaciolacustrine and glacial map units.

The magnitudes of the earthquakes in the database provided by Babaie Mahani (personal communication; Babaie Mahani and Kao, 2018a) are small, M1.5 to 3.8 at Graham and M1.5 to 3 at Septimus. The ground motions are correspondingly small: at Graham area maximum PGA and PGV are 0.05g and 1.8 cm/s respectively; and at Septimus, maximum PGA and PGV are 0.09 g and 0.65 cm/s, respectively[7]. These ground motions are just at or below the damage threshold, which corresponds to Modified Mercalli Intensity (MMI) VI, approximately PGA= 0.1 g (mean; range 0.05 to 0.3 g) and PGV~8 cm/s (mean; range 3.8 to 24 cm/s; Wald *et al*., 1999; Worden *et al*., 2012). However, induced earthquakes greater than M4 have occurred throughout the project area. The largest are the August 2015 M4.6 event, located 20 km southeast of Pink Mountain; the August 2014 M4.5 event, located 90 km north-northwest of Pink Mountain, and the May 1994 M4.3 event, located 10 km northeast of Fort St. John (Horner *et al*., 1994, Babaie Mahani *et al*., 2017a, b; Earthquakes Canada, 2018). For the August 2015 M4.6 event, Babaie Mahani *et al*. (2017a) estimated PGA=0.17 g at a station 5 km from the epicentre. In addition, a M5.4 event occurred 40 km north-northeast of Dawson Creek in April 2001 (Atkinson *et al*., 2016; Earthquakes Canada, 2018). Consequently, events larger than those included in the Babaie Mahani database are possible in this region, and their ground motions locally could exceed the threshold of damage (MMI=VI).

Amplification of seismic ground motions due to soil conditions should be expected on Class D sites for these larger events. The NBCC amplification factors for Site Class D firm ground PGA=0.1 g are 1.29 for PGA and 1.47 for PGV (Table 2; NRC, 2015). Seyhan and Stewart (2014) have developed equations for estimating amplification based on Site Class and firm ground PGA, and these are now incorporated into the

[7] These values are the geometric means of both horizontal components of PGA and PGV. The maximum values for a single component for PGA and PGV respectively are 0.06 g and 2.42 cm/s at Graham, and 0.12 g and 0.78 cm/s at Septimus.

current NEHRP provisions. These equations are used here to generate tables of amplification factors for levels of firm ground PGA down to 0.001 g, more representative of the stronger ground motions recorded in the Babaie Mahani database than the NBCC tables. The tables are included in Appendix 13, and summarized in Table 12. Note that their amplification factors are relative to V_{s30}=760 m/s, the Site Class B-C boundary, rather than Site Class C, as in the NBCC. These show that relative to V_{s30}=560 m/s (average Site Class C), amplification for a V_{s30}=250 m/s site (average Site Class D) at firm ground PGA=0.1 g is 1.33 and 1.67 for PGA and PGV respectively. Furthermore, they show that as firm ground PGA increases from 0.001 to 0.1 g, PGA and PGV amplifications (relative to 560 m/s) diminish by only 18% and 15%, respectively. However, it must be stressed that the amplification factors computed by the Seyhan and Stewart equations represent mean values. Their equations were developed from a large dataset with a high degree of variability, just as we see considerable variability in the amplifications within each geological map unit in this study.

Site Class	V_{s30} m/s	PGA							
		firm ground PGA, g							
		0.001	**0.005**	**0.01**	**0.02**	**0.03**	**0.05**	**0.1**	**0.2**
B	760	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	560	1.20	1.20	1.20	1.20	1.19	1.19	1.18	1.16
	450	1.56	1.55	1.54	1.53	1.51	1.48	1.42	1.34
	400	1.47	1.46	1.46	1.44	1.43	1.41	1.37	1.31
	360	1.56	1.55	1.54	1.53	1.51	1.48	1.42	1.34
D	300	1.74	1.73	1.71	1.68	1.65	1.60	1.50	1.37
	250	1.94	1.92	1.89	1.84	1.79	1.71	1.57	1.38
	200	2.22	2.18	2.13	2.05	1.98	1.86	1.63	1.36

Site Class	V_{s30} m/s	PGV							
		firm ground PGA, g							
		0.001	**0.005**	**0.01**	**0.02**	**0.03**	**0.05**	**0.1**	**0.2**
B	760	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
C	560	1.29	1.29	1.29	1.29	1.29	1.28	1.28	1.27
	450	1.87	1.86	1.86	1.84	1.83	1.80	1.75	1.68
	400	1.71	1.71	1.70	1.69	1.68	1.67	1.64	1.59
	360	1.87	1.86	1.86	1.84	1.83	1.80	1.75	1.68
D	300	2.18	2.17	2.15	2.12	2.09	2.04	1.95	1.83
	250	2.54	2.51	2.48	2.43	2.38	2.30	2.14	1.93
	200	3.06	3.01	2.96	2.86	2.78	2.63	2.35	2.02

Table 12. Site Amplification factors for PGA and PGV calculated from Seyhan and Stewart, 2014. Note that amplification factors are relative to V_{s30}=760, Site Class B-C boundary rather than Site Class C, as in the NBCC amplification factors.

SUMMARY AND CONCLUSIONS

The principal objectives of this project were to assess and map the susceptibility to amplification of ground motions in the Montney play area of northeast BC, and to generate a V_s database and model of the stratigraphic units in the shallow subsurface for future studies. A surficial geological map was compiled from a variety of published sources. A subsurface geological database was collected comprising 2427 gamma-ray logs normalized for surface casing effects, 1831 water well logs and 885 geotechnical boreholes. These were interpreted to characterize the principal stratigraphic units of the shallow subsurface. New V_s data were acquired at 22 sites: downhole VSP logging in 6 cased boreholes at Groundbirch; MASW at 12 sites close to the Alaska Highway extending from Dawson Creek to the Sikanni Chief River; and dipole sonic logs in 4 boreholes in the Farrell Creek and Halfway River areas. These data were used to create a V_s model of the shallow stratigraphic units. The V_s model and the subsurface geological database were used to characterize and assign NEHRP Site Classes and amplification susceptibility ratings to the surficial geological units.

The geological and V_s data show that areas underlain by Holocene and recessional-phase sediments of the last glaciation, where sufficiently thick, are in NEHRP Site Class D, and potentially susceptible to amplification of seismic ground motions. The recorded ground motions of recent small seismic events are generally consistent with this conclusion. In the two areas examined, the mean PGV amplification of the glaciolacustrine map unit (Site Class D) as a whole is 1.3 to 4 times greater than that of any other map unit, and 2 to 5 times greater than that of the glacial map unit (Site Class C). However, within the glaciolacustrine map unit, considerable variability occurs, both between and within stations. Station mean PGV amplification varies from 4 to 5 times greater than the glacial map unit mean at some stations, to no greater than the glacial map unit mean at others. Furthermore, at one station with a large number of events amplification occurs only infrequently in small events, but occurs more consistently in events larger than M3.

Variability of amplification also occurs in the glacial and glaciolacustrine veneer map units, which are Site Class C. Although amplification in these units is generally low, high PGV amplification does occur at some stations. This is interpreted to be due to resonance or three dimensional site effects. Amplification due to resonance could be expected locally where Holocene or recessional phase deposits of the last glaciation are thin, such as along the boundaries of recessional phase deposits with map units dominated by shallow till or bedrock. Resonant amplification is suspected for all magnitudes considered in this study, including the August 2015 M4.6 event. However, resonant amplification is likely to shift from shallower to deeper soil sites along these boundaries as magnitude and dominant period increase.

The seismic events used to document amplification due to soil conditions have a low range of magnitude, and their ground motions are generally below the threshold of damage (~0.1 g). However, larger events, up to M4.6 with estimated PGA up to 0.17 g, have occurred. Although amplification decreases with PGA, published sources indicate that at firm ground PGA=0.1 g, amplification factors for PGA and PGV on Site Class D are 1.33 and 1.67, respectively. These are mean values, and higher amplifications could be expected locally.

Although most induced seismic events are too small to be damaging, rare stronger events have occurred locally. By identifying areas where seismic ground motions may be amplified, this study provides a high level tool for planning and mitigating the effects of induced seismicity to public safety and industrial infrastructure, as well as on public concerns about petroleum industry activity.

RECOMMENDATIONS FOR FUTURE WORK

This study is based on a compilation of surficial geological maps that were initially prepared at a scale of 1:250,000, and lack fine scale detail. Furthermore, the susceptibility to amplification of ground motions is dependent on subsurface conditions, which are indirectly indicated by the surface maps. The subsurface geological data collected was intended to be representative of the surficial map units, rather than exhaustive, and several potential sources of geotechnical and other borehole data were not fully accessed. Further work should include more extensive collection of geotechnical and other borehole data in order to refine the existing mapping, both to provide finer detail and be more representative of subsurface conditions. Fieldwork should also be included.

Additional V_s data should also be obtained to refine the V_s model of the shallow subsurface. In particular, the V_s of recessional phase deposits in glaciolacustrine plain between the Pine and Peace Rivers requires further investigation to determine the effects of the inferred late stage glacial re-advance over glaciolacustrine sediments.

New V_s data at key seismograph stations would also provide data to refine ground motion prediction equations. The Babaie Mahani and Kao (2018a) equations were based on correcting ground motions to a reference V_{s30} of 760 m/s. However, V_{s30} data were available to them at only one station, NBC 7 (Septimus 1), which was co-located with MASW site SL-5. At the other stations, they approximated V_{s30} from peak frequency (Hassani and Atkinson, 2016). This method relies on assumptions of the velocity of the resonating unit, assumptions that may not be met where tills and glacially overridden deposits overlie bedrock. Several of the site class estimates made using this approach are inconsistent with those interpreted from by this study, and new V_s data will help resolve those differences. In addition, new V_s data at these stations would improve our understanding of the relationship between our mapping and the observed amplifications at these stations. As noted above, V_{s30} data are available at only one station, and at the thicker soil stations, the Quaternary stratigraphy is imperfectly known.

Logging newly drilled boreholes with well described cores is the best, but the most time consuming and expensive option for acquiring new V_s data. Other options include logging existing cased boreholes, and Ministry of Environment observation wells are potential candidates (*e.g.* GB12-2 at Groundbirch). Of the downhole logging methods, VSP logging produced consistently better results than dipole sonic logging in shallow boreholes cased with PVC. MASW provides a rapid means to acquire new data at key sites, and being non-invasive is logistically simple, and should be a key part of any new V_s data acquisition program.

Studies to model the seismic site response for specific site conditions would also assist in understanding the variability of the observed seismic ground motions with specific map units (*e.g*. Esposito and Ciuvalu, 2018).

QUALIFICATIONS AND LIMITATIONS OF THE SITE CLASS AND SUSCEPTIBILITY TO AMPLIFICATION OF SEISMIC GROUND MOTION HAZARD MAP

- The map is intended for regional planning and assessment purposes only and should not be used for site-specific evaluations.

- The map reflects the relative variation in the susceptibility to the amplification of seismic ground motions due to the variation in shallow geological conditions. It does not address the seismic hazard directly because the regional variation in natural and induced seismicity is not considered.

- The map is based on a compilation of published surficial geological maps prepared at scales of 1:20,000 to 1:250,000, and is presented at a scale of 1:250,000. Consequently, the map lacks fine scale detail. Furthermore, the susceptibility to amplification of ground motions is dependent on subsurface conditions, which are indirectly indicated by the surface maps. Because of these factors, the map unit boundaries are approximate, may enclose smaller occurrences of other map units, and are subject to revision as more data become available. Furthermore, geological materials are variable, and deposits of a map unit may locally have unusual properties. Thus, the susceptibility at a specific site could be either higher or lower than that shown on this map.

- The susceptibility to amplification of ground motion hazard has been estimated on the basis of the National Earthquake Hazard Reduction Program (NEHRP) Site Classes (Building Seismic Safety Council, 2003), which are based on the average response of various types of soils. Variation in amplification factors within a site class is to be expected.

- This map does not fully address man-made alterations to ground conditions, nor considers the seismic stability of dams.

- This map does not directly address other earthquake hazards due to amplification of ground motion such as topography and three-dimensional effects, or earthquake-induced liquefaction and slope instability.

- This map cannot be used on its own to predict the amount of damage that could occur at any one site because other factors, such as building type and construction details, must be considered.

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