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Mapping the Amplification of Seismic Ground-Motion Hazard in the Montney Play Area, Northeastern British Columbia

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Introduction

The recent increase in seismicity in northeastern British Columbia (BC) has been attributed to the increase in hydraulic fracturing and subsurface fluid injection by the petroleum industry (Atkinson et al., 2016; Babaie Mahani et al., 2017). Although the increase in seismicity is well documented, the associated ground motion has not been studied until recently. Furthermore, it remains poorly understood how surficial sediments in this region could effect the amplification and attenuation of ground motions. Understanding where there is a greater likelihood of damaging ground motions to occur is paramount for public safety and protection of infrastructure. By using surface and subsurface geological and geophysical data, areas that are prone to amplified ground motion can be mapped, thereby providing key information for public safety and the natural gas sector.

Ground-motion amplification is a complex phenomenon, but can be estimated by the average shear-wave velocity (V_s) in the upper 30 m (V_{s30}). The National Earthquake Hazards Reduction Program (NEHRP) in the United States has defined five site classes based on V_{s30} (Table 1; Building Seismic Safety Council, 2003) and these have been adopted by the National Building Code of Canada. Of these, significant amplification can occur in Site classes D and E.

The objectives of this project are to

- map NEHRP site classes in the Montney play area of northeastern BC, and
- acquire sufficient V_s data in the area to develop a V_s model for shallow geological materials, for use in future earthquake studies in the region.

The project area was defined on the basis of 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). This paper presents the results of this study to date, which include surficial geological map compilation, subsurface geological database compilation and acquisition of new V_s data.

Geological Summary

The project area lies in the plains and foothills of northeastern BC. The valleys of the Peace River and other major rivers are incised up to 200 m in this area. Bedrock consists mainly of gently dipping Cretaceous shale and sandstone (Stott, 1982; McMechan, 1994).

At least three glaciations have occurred in the area (Mathews, 1978a; Hartman and Clague, 2008; Hickin et al., 2016b). Laurentian ice extended over most of the eastern part of the area, with Cordilleran ice extending out from the Rocky Mountains front and coalescing with the Laurentide Ice Sheet during the Late Wisconsinan (Hickin et al., 2016b). Deposits of nonglacial fluvial sand and gravel (including Holocene deposits) and advance-phase deposits of

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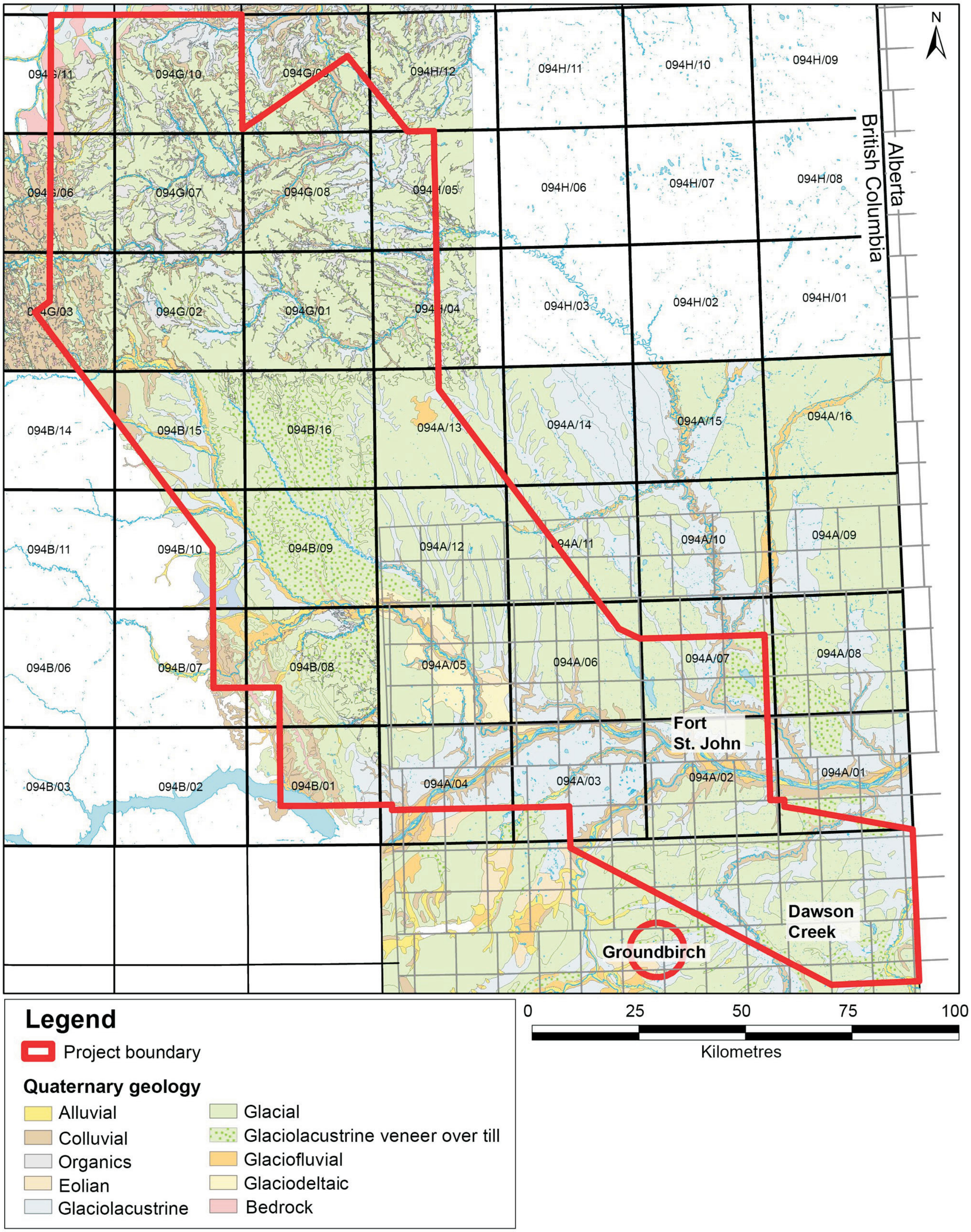

Figure 1. Surficial geological compilation map of northeastern British Columbia, assembled from existing maps (Lord and Green, 1971, 1986; Lord, 1973, 1977; Green and Lord, 1975; Mathews et al., 1975; Mathews, 1978a, b; BC Ministry of Environment, 1980, 1986, 1987, 1988a, b; Reimchen, 1980; Bednarski,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

Table 1. National Earthquake Hazards Reduction Program (NEHRP) site classes (Building Seismic Safety Council, 2003).

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

the last two glaciations indicate a repetitive pattern of fluvial incision and deposition followed by deposition of glaciolacustrine silt as the drainage was blocked by advancing Laurentian ice. After retreat of the ice, renewed fluvial incision cut deeper following each glaciation, so that the modern Peace River channel is incised through the earlier Quaternary deposits into bedrock.

Most Pleistocene interglacial fluvial sediments and advance-phase glaciolacustrine deposits are restricted to 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 (Mathews, 1978a). Each surficial unit has a characteristic geomorphic expression. Upland areas, where topography is controlled by bedrock, are underlain mainly by till or colluvial deposits. Low relief areas, bordering and extending up major valleys, are underlain by recessional-phase glaciolacustrine silt, clay and fine sand and equivalent glaciodeltaic sand deposited where major drainages were blocked by retreating Laurentian ice (Figure 2). Terraces flanking major valleys are underlain by later glaciofluvial sand and gravel representing the earliest phases of postglacial fluvial incision. Modern fluvial sand and gravel occupy river valley bottoms.

Figure 2. 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 ‘Ma’ Murray Community School, where site SL-6 of the multichannel analysis of surface waves (MASW) program is located.

Surficial Geological Map Compilation

A surficial geological map of the study region (Figure 1, Table 2) 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 Survey of Canada (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). Polygon map data for all areas were obtained digitally and compiled in GIS format. 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. In addition, some map unit designations were changed as a result of field investigations conducted in June 2017.

Subsurface Geological Data Compilation and Interpretation

There are three sources of subsurface geological data: 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 3.

Gamma-ray logs run through surface casings to very shallow depths are an important source of subsurface geological data for Quaternary studies. Top of bedrock can generally be picked with reasonable confidence where highly correlative Cretaceous strata are truncated and overlain by Quaternary sediments. Normalization for surface

Table 2. Surficial geology units defined in the study area, northeastern British Columbia.

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 diamict and slump deposits	Slope deposits mainly along steep valley walls (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)
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)
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)
Glaciolacustrine veneer over till	Sand and silt; minor clay	Thin and discontinuous cover of glacial lake sediments (LGv), usually overlying till and other glaciogenic deposits
Glaciofluvial	Sand 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)
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
Bedrock	Mainly sandstone and shale	Exposed or thinly covered bedrock outcrops (R), usually sandstone

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 incorporated into the present study. An additional 1076 gamma-ray logs were similarly normalized and interpreted for the current project (Figure 3). 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. Furthermore, not all logs have been run continuously to surface and, in many places, attenuation of the gamma-ray signal by the conductor pipe obscures the lithological signature in the upper 10–30 m. Where the bedrock top lies above the top of the logged section, 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.

An edited database of water well logs of northeastern BC by Hickin (2013), derived from the BC Ministry of Environment WELLS database, was included in the Petrel Robertson Consulting Ltd. (2016) study, and additional data from Hickin's database is being incorporated into the present project. Lithological descriptions in the WELLS database vary greatly in quality, and some well locations are suspect. However, the depth to bedrock is usually reliably reported, and this is the parameter of most importance for this study. Fifteen hundred and sixty water well logs from this database have been used in this project (Figure 3).

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 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 in this area, as N values in this till range from 15 to >50. The low N values (<40) in some till may be due in part to being clay-rich, or being ablation or flow till rather than lodgment till. To date, 816 borehole logs from 174

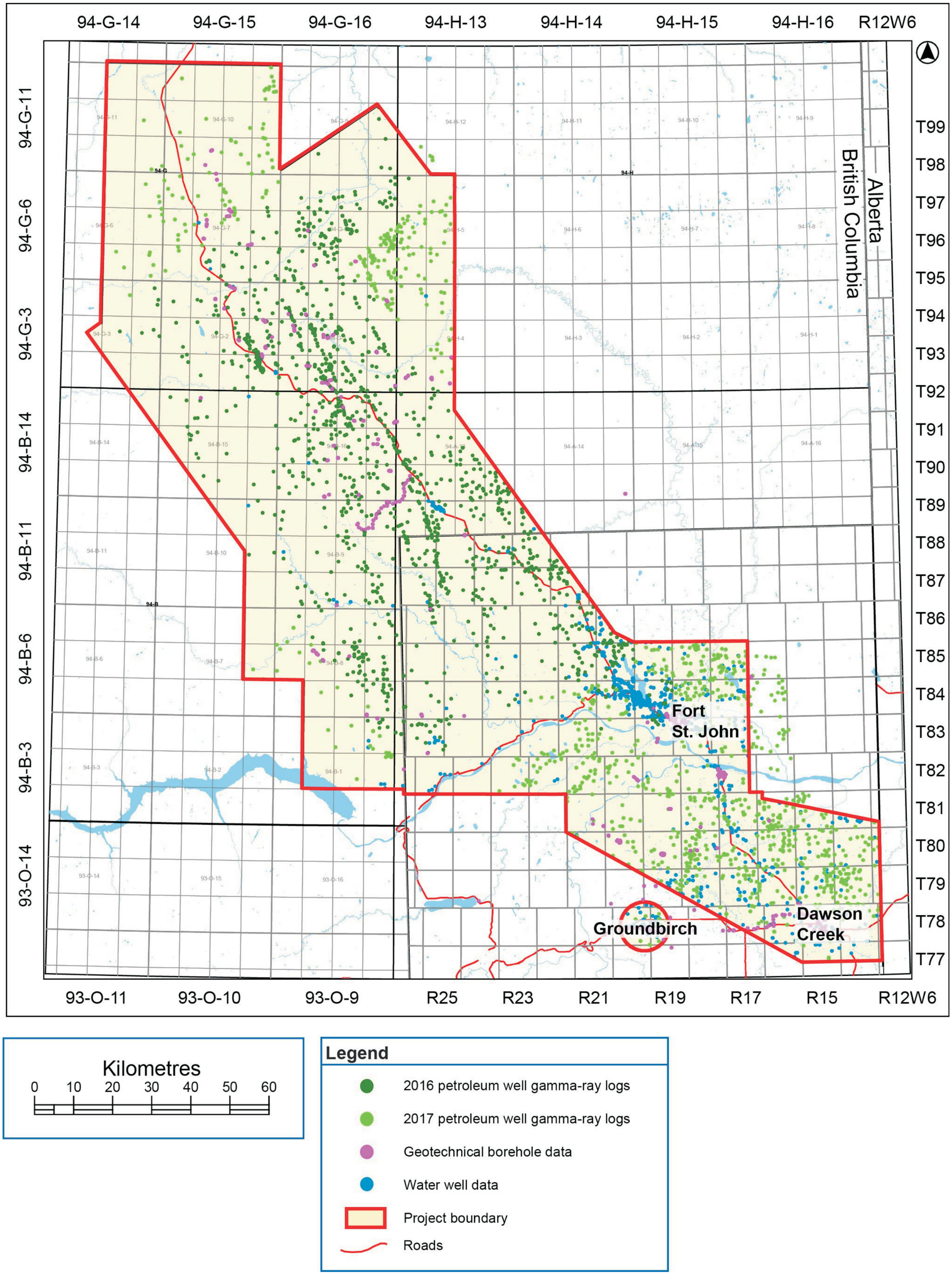

Figure 3. Petroleum well, water well and geotechnical borehole data locations in the study area, northeastern British Columbia.

sites have been obtained, of which 153 sites include borehole data deeper than 10 m. 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 labourious to collect and details cannot be routinely published.

Shear-Wave Velocity Data Acquisition

Three field programs have been conducted to date by Frontier Geosciences Inc. to determine the V_s of the shallow geological materials. Several correlations of SPT N values with V_s have been proposed (e.g., Hutchinson and Beird, 2016) but 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 this area provides more reliable data than correlations.

Downhole V_s logging by the vertical seismic profile (VSP) method was conducted in six cased boreholes in the Groundbirch area (Figure 1). This method is described further by Arsenault et al. (2012). The stratigraphy of these boreholes is well described by Hickin and Best (2013) and Hickin et al. (2016a), so that the V_s of each geological unit can be readily determined. In five of these boreholes, recessional-phase deposits of the last glaciation are 26–49 m deep and overlie till, which in turn overlies bedrock or earlier glaciogenic deposits. The sixth borehole penetrated 3 m of till over bedrock. The results of this program are summarized in Table 3, and an example is shown in Figure 4.

Table 3. Summary of downhole shear-wave velocity (V_s) data acquisition in boreholes at Groundbirch, northeastern British Columbia.

Borehole	DLS location	Depth logged (m)	Thickness of recessional-phase deposits (m)	Bedrock depth (m)	Geological map unit	V_{s30} (m/s)	Site Class
GB12-2	1-13-79-20W6*	31	0	3	Glacial	806	B
GB15-1	9-17-78-19W6	112	26	82	Glaciolacustrine	290	D
GB15-2	8-17-78-19W6	149	49	>147	Glaciolacustrine	207	D
GB15-3	8-13-78-20W6	70	36	52	Glaciolacustrine	263	D
GB15-4	12-4-78-19W6	67	26	71	Glaciolacustrine	272	D
GB15-5	16-7-78-19W6	100	45	>118	Glaciolacustrine	231	D

*L.S. 1, Sec. 13, Twp. 79, Rge. 20, W 6th Mer.

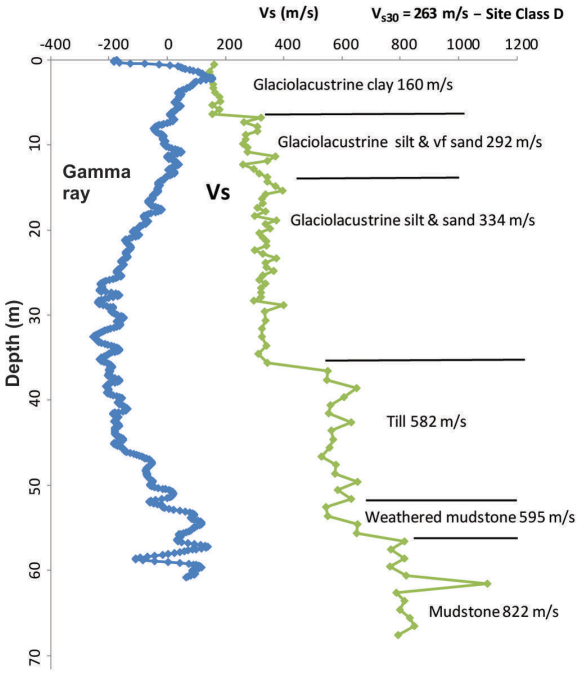

Figure 4. Shear-wave velocity (V_s) and gamma-ray logs from borehole GB15-3 at Groundbirch, northeastern British Columbia. Gamma-ray data from Weatherford, in Hickin et al. (2016a). Abbreviation: vf, very fine; V_{s30}, average shear-wave velocity in the upper 30 m.

A multichannel analysis of surface waves (MASW) program was conducted at six sites in Fort St. John and Dawson Creek, where geotechnical data was obtained. A 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). The stratigraphy at these sites ranges from 5 m till over bedrock to 11 m glaciolacustrine silt over till. The results of this program are summarized in Table 4 and an example shown in Figure 5. The Vs calculations are made to 30 m depth 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 4 for each site.

The results of these programs demonstrate that V_s in the recessional-phase deposits of the last glaciation is <350 m/s. Specifically, V_s ranges from 120 to 220 m/s in silt and clay, 200 to 290 m/s in silt and very fine sand, and 250 to 350 m/s in sand and gravel. In sediments that have been glacially overridden, V_s exceeds 400 m/s. As with the SPT data, a possible exception is till of the last glaciation, in which V_s ranges from 300 to 600 m/s. A V_s result of <400 m/s may occur because the till is clay-rich, or is ablation and flow till rather than lodgment till. In bedrock, V_s ranges from 500 to 1100 m/s. The lower values are in disturbed bedrock. Although it is often described as 'weathered bedrock', in many cases it is likely to have been disturbed by glaciotectonic processes.

As noted above, the NEHRP site classes are based on V_{s30}, which is calculated using the following formula:

$$V_{s30} = \Sigma h / \Sigma t$$

where h = each measured interval thickness, where Σh = 30 m, and t = the measured interval travel time, and $t = h/V_s$ for each interval.

The data show that sites underlain by recessional-phase deposits of the last glaciation (glaciolacustrine, glaciodeltaic and glaciofluvial units, Figure 1, Table 2), where sufficiently thick, are classified as Site Class D, and susceptible to amplification of seismic ground motions. Furthermore, where these deposits are thinner, amplification of short-period ground motions due to resonance may occur where the site period matches that of the dominant short-period ground motions. Structures with the same natural period as the site would potentially be most vulnerable to damaging ground motions. Anecdotal reports from local informants are consistent with these conclusions.

The site period (T) is calculated by the quarter wavelength rule:

$$T = 4H/V_s$$

where H = thickness of the low velocity geological unit, which may include several measured intervals, and V_s = the average shear-wave velocity of the low velocity geological unit.

The third field program is another MASW program, which is underway at the time of writing. This program is being conducted at six sites located between Parkland, south of the Peace River, and the Sikanni Chief River. The results of this and V_s data from dipole sonic logs run in boreholes drilled by Geoscience BC in 2017 (Levson and Best, 2017) will be combined with the data from this project to generate the final V_s model for the shallow geological materials.

Table 4. Summary of initial multichannel analysis of surface waves (MASW) program results. Abbreviations: N, number of hammer blows in standard penetration test; NRCan, Natural Resources Canada; V_{s30}, average shear-wave velocity in the upper 30 m.

Site	Location	Geological map unit	V_{s30} (m/s)	Site Class	Significance
SL-1	112th Avenue by Fort St. John Hospital, Fort St. John	Glacial	607 ±50	C	5–6 m till over bedrock
SL-2	94th Avenue, east of Pomeroy Sport Centre, Fort St. John	Glaciolacustrine	344 ±14	D	>7 m glaciolacustrine sediments
SL-3	10th Street bridge, Dawson Creek	Glaciolacustrine	322 ±24	D	4? m glaciolacustrine over >20 m till, N = 14–35 (thick low N till)
SL-4	Ecole Frank Ross Elementary, Dawson Creek	Glacial	469 ±23	C	8 m till over weathered bedrock
SL-5	Northern Lights College, Fort St. John	Glacial	394 ±17	C	6 m glaciolacustrine sediments over till, NRCan seismograph location NBC7
SL-6	Margaret 'Ma' Murray Community School, Fort St. John	Glaciolacustrine	355 ±11	C-D	11 m glaciolacustine silt over till

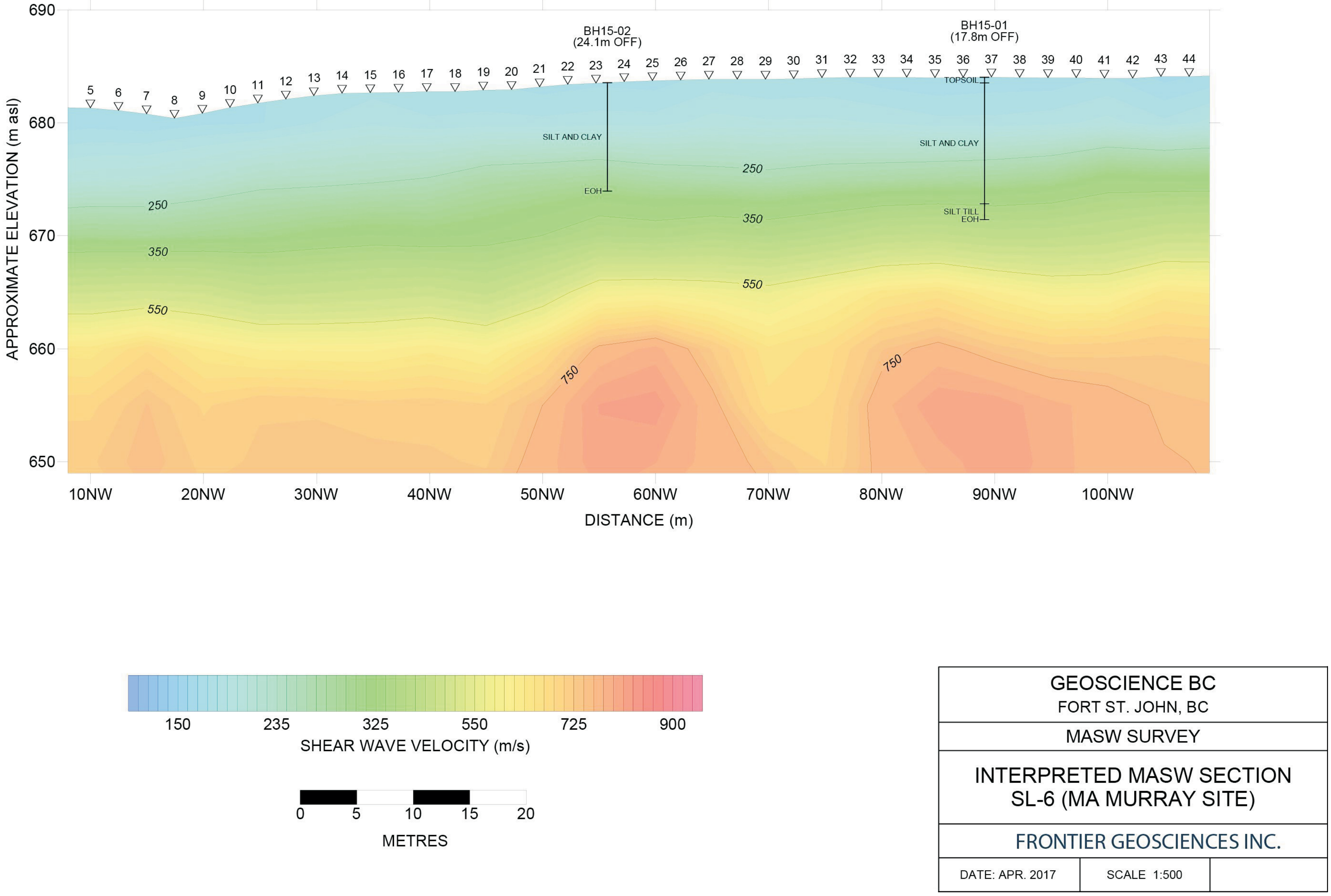

Figure 5. Multichannel analysis of surface waves (MASW) profile for site SL-6, Margaret 'Ma' Murray Community School, Fort St. John. Site Class C-D (Table 4) has been assigned due to shallow bedrock beneath 11 m of glaciolacustrine silt over an estimated 4–8 m of till (see also Figure 2). Abbreviation: BH, borehole; EOH, end of hole; NW, to the northwest; OFF, offset.

Summary and Conclusions

The principal results of this project to date are a) a compilation of surficial geological maps from a variety of sources; b) compilation and interpretation of a subsurface geological database comprising 2427 gamma-ray logs normalized for surface casing effects, 1560 water well logs and 816 geotechnical boreholes; and c) generation of new V_s data at 12 sites. Data obtained to date show that areas underlain by recessional-phase sediments of the last glaciation are potentially susceptible to amplification of seismic ground motions. Although data from modern sediments have not been analyzed at this time, it is anticipated that they will also be susceptible to amplification. By identifying areas where seismic ground motions may be amplified and thereby more likely to be damaging, this study is providing a tool for regional planning and mitigating the effects of induced seismicity to public safety and industrial infrastructure.

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