NORTH-EAST BC SONIC DRILLING PROJECT
PHYSICAL LOG
DESCRIPTIONS AND INTERPRETATIONS

GEOSCIENCE BC REPORT 2017-16

Prepared for Geoscience BC

By Vic Levson, Ph.D., P.Geo.
Quaternary Geosciences Inc.
&
Mel Best
Bemex Consulting International
Victoria, BC
August 31, 2017

TABLE OF CONTENTS

EXECUTIVE SUMMARY

This report summarizes the results of a sonic drilling program conducted to evaluate a model of Quaternary and bedrock geology of the Montney gas field study region. The model was based on a map of the Quaternary geology of the study area compiled by Quaternary Geosciences Inc. and an airborne electromagnetic (AEM) survey conducted by Aarhus Geophysics. The AEM survey provided relatively high resolution, resistivity data for five areas and 11 test well sites were selected in these areas. In the 2017 program, a total of ten sonic holes were drilled at eight different sites (3, 6a, 7, 10b, 10x, 11, 12 and 13), including two groundwater monitoring wells drilled at sites 6a and 10x. Quaternary paleovalley fill sediments were encountered in all the wells providing a first level of verification of the geological model. All the wells were drilled in paleochannels mapped previously using gamma logs and water well data with predicted bedrock depths generally greater than 10 m. Bedrock occurred at greater than 10 m in all the wells except well 6a where shallower bedrock was expected. Minimum bedrock depths estimated from the closest wells to any one site and from resistivity data were either accurate or understated paleochannel depths, as expected. Likewise, the Quaternary stratigraphy encountered was generally as predicted except for some minor variations due mainly to large distances from the drill sites to the nearest interpreted well logs. Interpretations of stratigraphic sequences based on resistivity data also were generally accurate except that some stratigraphic units were too thin to be detected at the resolution of the AEM survey, especially at greater depths. Sand and/or gravel units were encountered at all the wells except sites 3 and 11 where these units were expected at greater depths than drilled. At site 3, the presence of water-producing gravels about 20 m below the well bottom was confirmed at a nearby geotechnical drill hole. Granular materials encountered in most of the wells were water-bearing but they were either too thin or too fine-grained to warrant installation of groundwater monitoring wells (except at wells 6a and 10x) as lengthy periods of time are required for well completions in these types of sediments. In summary, the sonic drilling program confirmed the presence of paleochannels at all drill sites as deep or even deeper than estimated, and stratigraphic predictions based on the geological and geophysical model also were generally accurate with mainly minor exceptions such as the presence of thin beds at depth. Granular deposits were encountered at most sites and many of these units were water-bearing but not thick or permeable enough to allow for sufficiently rapid well completions.

INTRODUCTION

This report describes a sonic drilling program conducted in the spring of 2017 as part of the GeoscienceBC Peace Project. The Peace Project is a collaborative effort involving Geoscience BC[1], the Ministry of Forests, Lands and Natural Resource Operations (FLNRO), the Ministry of Environment, the BC Oil and Gas Commission, the Ministry of Natural Gas Development, Progress Energy Canada Ltd., ConocoPhillips Canada, Northern Development Initiative Trust, and the BC Oil & Gas Research and Innovation Society, with additional support from the Peace River Regional District and the Canadian Association of Petroleum Producers. The objective of Geoscience BC's Peace project north of Fort Saint John is to provide a regional

[1] Geoscience BC is an independent, non-profit organization that generates earth science in collaboration with First Nations, local communities, government, academia and the resource sector. Our independent earth science enables informed resource management decisions and attracts investment and jobs. Geoscience BC gratefully acknowledges the financial support of the Province of British Columbia.

overview of the Quaternary and shallow bedrock geology of the area. A secondary objective is to locate potential aquifers within the study area.

OBJECTIVES

The main objective of the present work is to test a model of the Quaternary and bedrock geology of the study region by conducting a sonic drilling program. The model is based mainly on a on a map of the Quaternary geology of the study area compiled by Quaternary Geosciences Inc. (Petrel Robertson Consulting Ltd., 2015) and on the results of a 21,000 line-km SkyTEM airborne electromagnetic (AEM) survey conducted by Aarhus Geophysics (Brown et al., 2016). The AEM survey was carried out with a traverse line spacing of 600 m (trending ENE) and a tie line spacing of 2400 m and resistivity cross-sections and depth slices were produced for the entire area (Brown et al., 2016). A brief description of the time-domain AEM survey and data processing was provided by Best and Levson (2016). The Quaternary geology mapping was based on existing surficial geology maps, topographic data, water wells and depth to bedrock data inferred from over 1200 gamma logs that were corrected for casing effects using a procedure described by Levson (2014). The Quaternary/bedrock contact and the depths of any potential sand and gravel aquifers within the Quaternary section were interpreted for each gamma log. Water wells were used when the data quality was sufficient to provide additional information on stratigraphy and depth to bedrock. These results were overlain on the compiled surficial geology map of the region (Figure 1).

To test the model, eleven areas were originally selected as potential sonic drilling sites (Best and Levson, 2016; Figure 1). Areas of relatively complex stratigraphy occurring in relatively shallow sections were intentionally selected to maximize the stratigraphic information obtained and minimize costs. The locations of the test areas were selected based on Quaternary geology, resistivity depth maps and sections, road accessibility, and proximity to existing petroleum and water wells for calibration purposes. The objective of the study was to test the validity of the geological model and not specifically to locate aquifers. Sonic drill hole locations were originally selected to include a wide geographic distribution, varying geological complexities, areas with existing well data, high resolution resistivity data, a variety of potential aquifer types, sites requested by First Nations and areas with nearby road access. Best and Levson (2016) provide a rationale why each area was selected as well as a prognosis on expected resistivity values and geological formations versus depth for each of the proposed locations.

STUDY AREA

The study area (Figure 1), defined by GeoscienceBC, is in the Peace River district in northeast British Columbia and is part of the NE BC Aquifer Characterization Project study area. Active gas exploration in the region has focused mainly on the Montney Formation and the study area covers the central and northern parts of the Montney play area which extends from the Alberta border northwesterly into the Rocky Mountain Foothills. The study area extends north of the Peace River to the Sikanni Chief River drainage area and is bounded approximately by Ft. St. John to the east and Hudson Hope to the west.

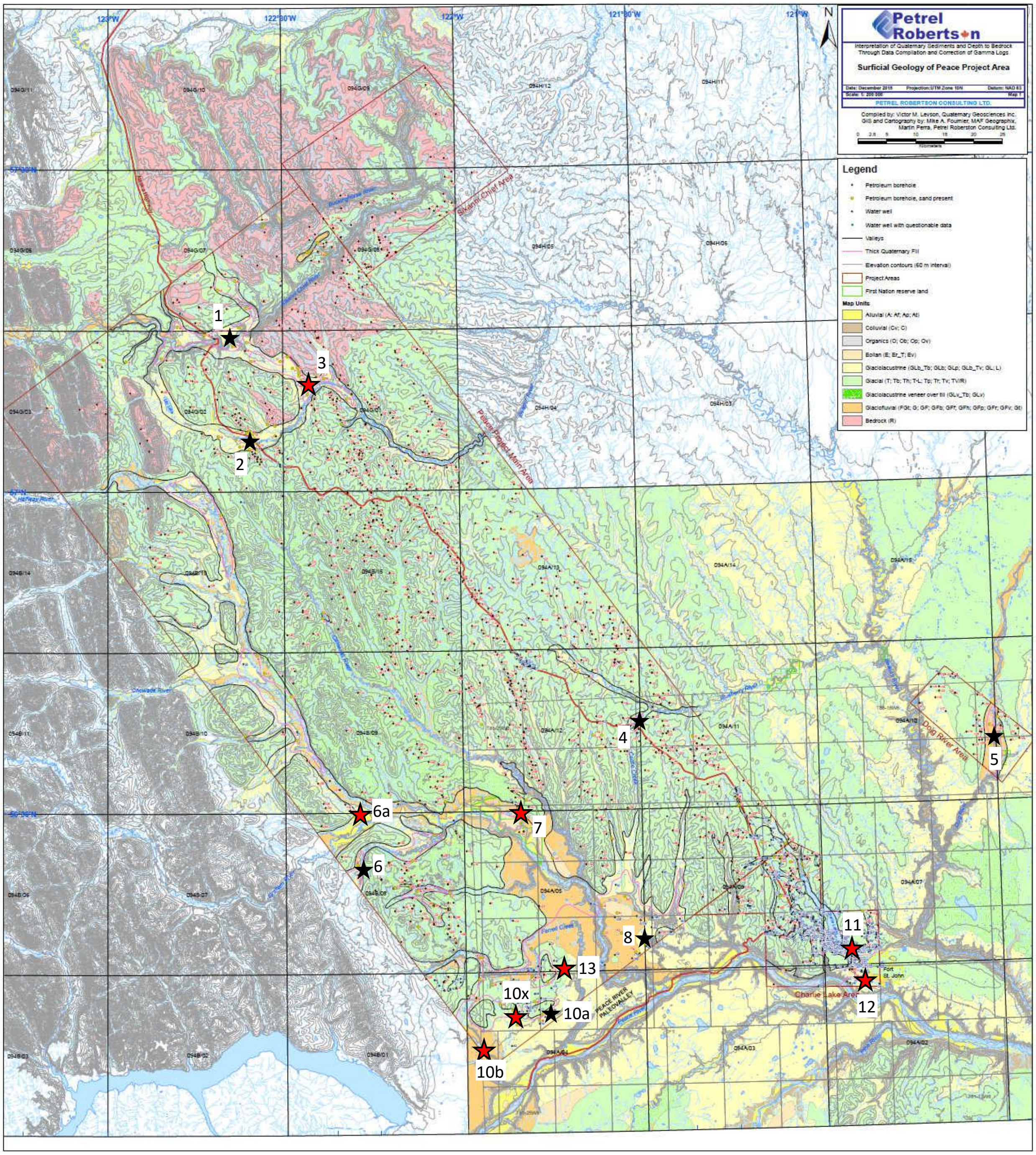

Figure 1. Surficial geology map with interpreted paleovalley locations outlined in black; original locations of selected test well areas not drilled shown as black stars; completed sonic drill sites shown in red.

RESULTS OF 2017 SONIC DRILLING PROGRAM

A total of 10 wells were drilled at eight different sites during the 2017 sonic drilling program, including two monitoring wells. Water-bearing sediments were found at many of the sites but only two (6a and 10x) produced enough water to warrant installing monitoring wells for FLNRO. Figure 2 shows the location of the 8 areas where wells were drilled during the 2017 program. Many of the original eleven areas selected as test sites could not be accessed due to poor road conditions during the spring field season and difficulties in obtaining land owner permission. In addition, none of the sites selected on First Nations reserves were approved for drilling (e.g. Site 5). Sites 3, 6a, 7, 11 and 12 were all located in the original areas planned. Site 10b was located close to the original site but was moved from the east side of Lynx Creek to the west side where access was better. Site 10a was relocated to site 10x to aid in a collaborative project with researchers from the University of British Columbia who were interested in locating a relatively shallow aquifer. Site 8 was moved northwestward to site 13, a location selected by hydrogeology researchers from Simon Fraser University. Site 2 was the only other original location not drilled, due to poor access, limited budget and time constraints at the end of the program.

Descriptions of the Quaternary geology and resistivity structure of each original well location are described in detail by Best and Levson (2016) and that information is not duplicated here. The descriptions included surficial geology data, gamma log interpretations from nearby gas wells, and water well logs where available. The locations of the proposed well were shown on resistivity depth slices and cross-sections from the Aarhus inversions.

The locations of sites drilled in the 2017 sonic drilling program and the main reason for targeting each site are provided in Table 1.

Site #	Description of drill target	UTM_E	UTM_N
3	possible infilled paleovalley between Sikanni Chief and Beatton rivers	532791	6337064
6a	north-trending resistivity feature on glaciofluvial terrace	546650	6262600
7	inferred old paleochannel of the Halfway River	570755	6262065
10b	probable old paleochannel of Lynx Creek	564660	6220787
10x	possible paleochannel indicated by a sinuous, high resistivity feature	570720	6225047
11	potential small buried aquifer SE of Charlie Lake	628484	6237717
12	large valley infill of the Peace River paleovalley	627050	6234063
13	inferred deep paleovalley of Farrell Creek indcated by resistivity sections	579293	6234812

Table 1. Locations and UTM coordinates of 2017 wells drilled (NAD 1983 UTM Zone 10N) *N =north, S = south.

SITE 3

Well 3 is in a broad topographic saddle between the Sikanni Chief River and Beatton River valleys. The site was selected to test for the presence of a buried paleochannel that formerly may have connected the two modern river valleys, based on the hypothesis that the Sikanni Chief River previously flowed southeastward through this saddle into the Beatton River drainage, rather than to the northeast as it does today. Interpretation of gamma logs from several gas wells in the valley suggest the presence of a potentially deep (>40 m) Quaternary paleochannel there. In addition to a topographic low, the saddle between the two valleys is a resistivity low (Figure 2), probably reflecting the presence of fine-grained paleovalley-fill sediments. Based on two gamma logs and resistivity data from the area, Best and Levson (2016) inferred the Quaternary valley-fill to be mainly glaciolacustrine sediments overlying till and basal sands and gravels. Well 3 was drilled about 1.7 km north of the originally selected site along a seismic line.

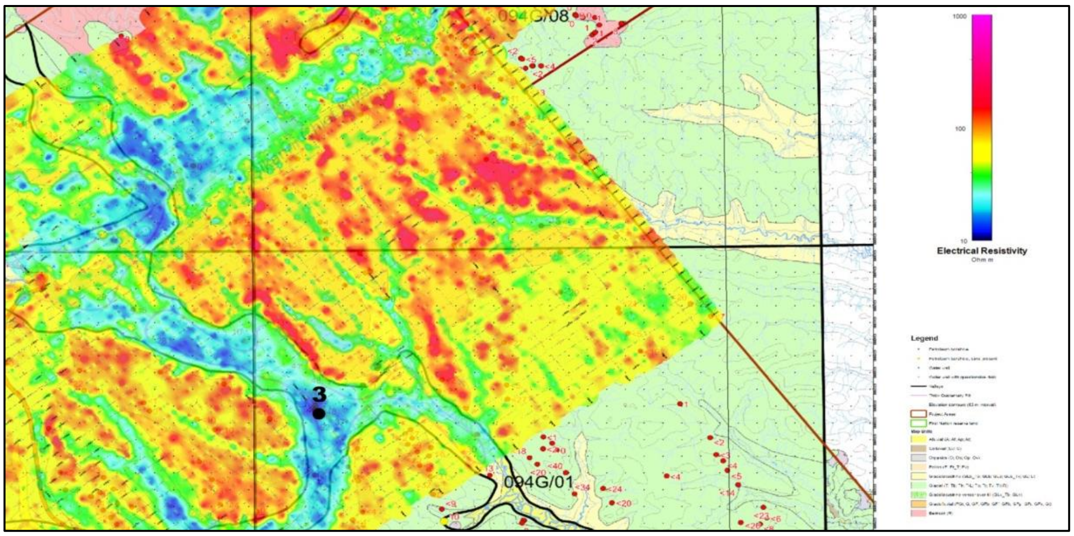

Figure 2. Resistivity depth slice (15-20 m) showing the locations of well 3 and the inferred paleovalley trending northwesterly between the Sikanni Chief valley to the north and the Beatton River valley to the south.

Geology and Interpretation

Well 3 is characterized by a 28-m thick sequence of laminated clays and silts that gradually coarsen downwards into bedded silts, clays, fine sands and stony muds (Figure 3). The silts and clays are laminated to massive and contain minor pebbles interpreted to be glacial dropstones (Figures 4 and 5). These sediments are inferred to be medial to distal glaciolacustrine deposits overlying proximal glaciolacustrine muds, sands and glacially-derived subaqueous debris flow deposits. A massive sandy-silt diamict, interpreted to be a basal till, occurs at the base of the hole from about 28-32 m. The diamict is matrix-supported, dense to very dense, and very poorly sorted. It contains about 10-20% pebble-sized clasts that generally get larger with depth. Clast lithologies are both local (e.g. sandstone, siltstone and shale) and far travelled (e.g. carbonates and quartzites) and the presence of striae confirm glacial transport. Unfortunately, the drill casing seized in the hole in the last drill interval and further drilling would have required re-drilling the hole with a larger diameter casing. Due in part to budget and time constraints, the decision was made to case the well and move to the next site. The main objective of the well, to determine if a buried valley was present at the site, was confirmed by the thick in-fill sequence of glaciolacustrine and glacial sediments. Although the base of the hole was above the buried gravel horizon, the presence of highly productive water-bearing gravels under till has been confirmed in the valley from recently acquired geotechnical data (Monahan, Pers. Comm., 2017). In addition, the site was remote and FLNRO would not likely monitor the site even if an aquifer was encountered.

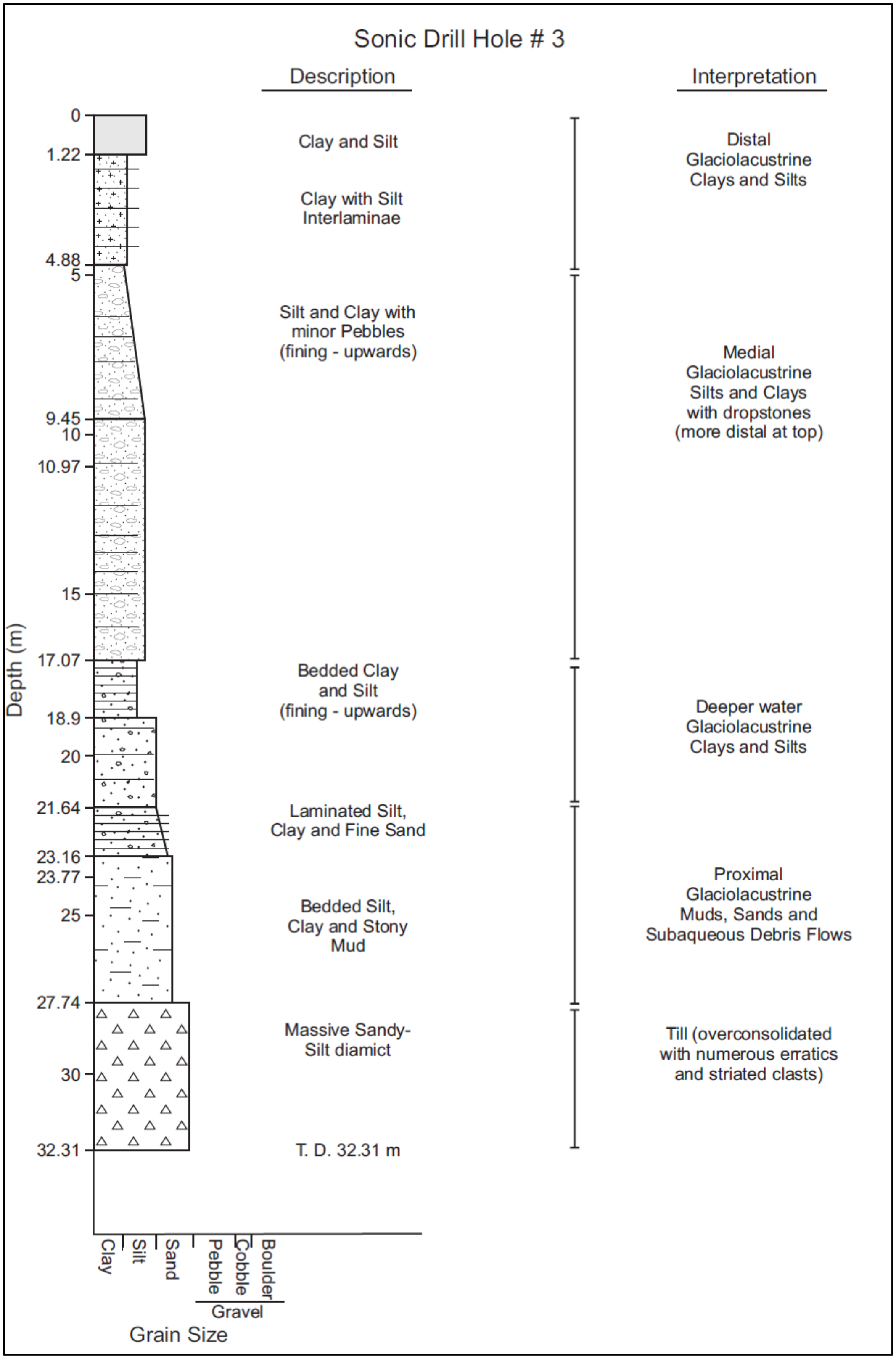

Figure 3. Stratigraphic log and interpretation of main units at sonic drill hole 3

Figure 4. Soft clays and silts with minor pebble at a depth of about 15.5 m (48-50ft & 52-54ft) in sonic drill hole 3 interpreted to be glaciolacustrine sediments (scale in inches)

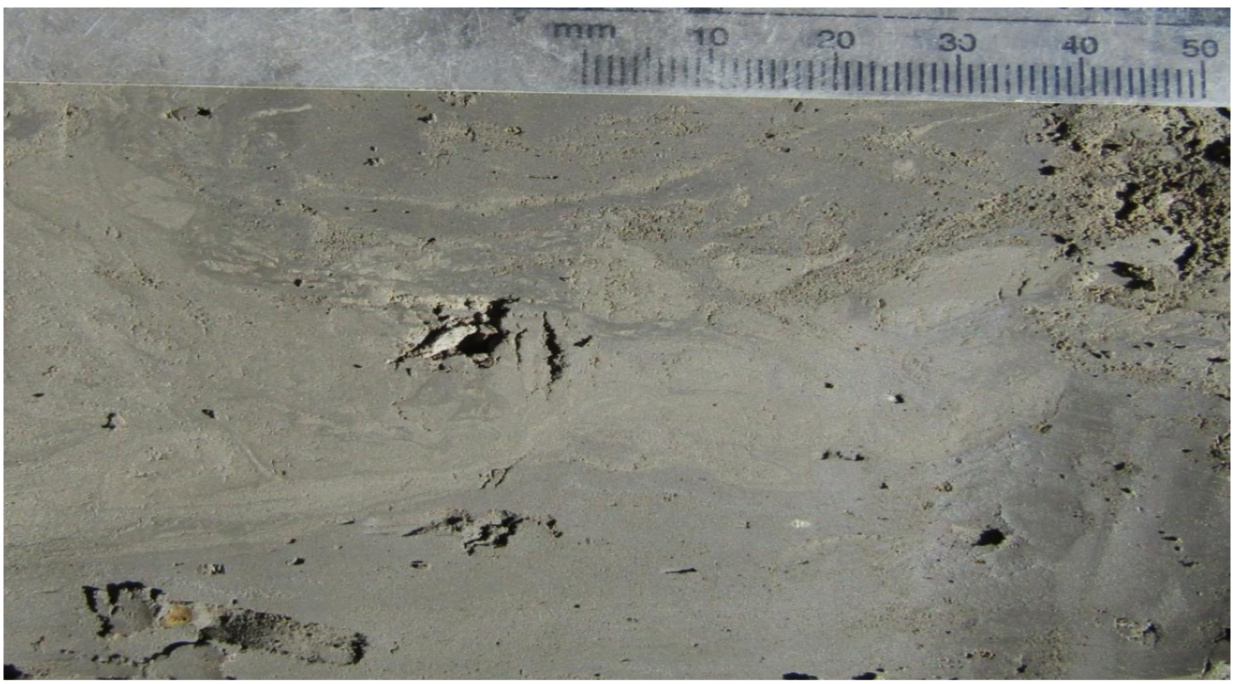

Figure 5. Close-up view of thin silt laminae (light grey) in thicker clay beds (dark grey) in sonic hole 3; deformation mainly from drilling; note small pebble in photo centre (scale in mm)

Comparison with model data

Resistivity data for site 3 shows high resistivity materials at surface on the mountains on either side of the paleovalley interpreted to be Dunvegan sandstones by Best and Levson (2016). The presence of these sandstones was confirmed in the field at a borrow pit in a bedrock ridge on the west side of the paleovalley.

Also confirmed, was the presence of a relatively thick package of low resistivity, near-surface layers in the valley interpreted to be mainly glaciolacustrine and glacial sediments. These sediments were inferred from resistivity data to be about 57 m thick and, based on interpretation of gamma logs from two nearby gas wells, underlain by 5-10 m of sands and gravels. This interpretation has also been confirmed by nearby drill hole data that reveals a 7.5 m thick, water-bearing gravel unit under till producing 50-75 gals/min at a depth of 51-58.5 m (Monahan, *op. cit.*).

SITE 6a

Site 6a is located on a terrace just west of the confluence of the Halfway and Graham rivers (Figure 1). The area was selected because of an unusual north-trending highly resistive unit in the area that cross-cuts the south-easterly strike of bedrock formations in the region (Figure 6). The drill site is well within the target area as it is located within about 100 m of the originally selected site.

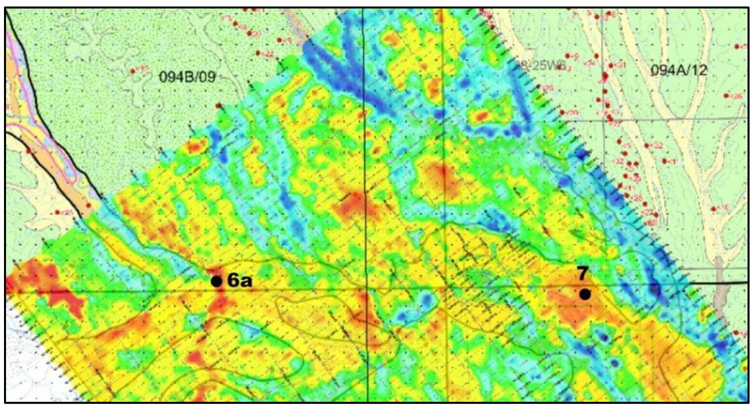

Figure 6. Location map of sites 6a and 7 on the 15-20 m resistivity depth slice

Geology and Interpretation

A stratigraphic log for well 6a is provided in Figure 7. The well was drilled to a total depth of 14 m (46 ft) and encountered 6.7 m of coarse gravels overlying sandstone. The gravels are interpreted as glaciofluvial terrace gravels and they are capped by a thin overbank silt (Figure 8). The gravels are clast-supported, pebble to cobble gravels with a sandy matrix. Clasts are rounded to well rounded and of varied lithologies (mainly sandstone, siltstone, quartzite and limestone) indicating that they were deposited in a glaciofluvial system flowing out of the Rockies. The gravels form a series of 1-4 m high terraces that gradually step down towards the Graham River. The lowermost terrace is mainly sandstone bedrock. Interestingly, the lowermost 1.5 m of the gravels are best described as pebbly muds or a mud breccia. They are mainly silts and clays with abundant (~10-20%) pebble-sized shale clasts. They may have formed by initial erosion of shaley bedrock by the glaciofluvial system or they may represent drill disturbance of a thin shale unit overlying the sandstone.

Sandstone was encountered in the drill holes at a depth of 6.7 to 14.2 m. The sandstone is fine-grained, very well sorted, quartz rich and well laminated (Figure 9). It is locally broken along planar fractures with some relatively intense, rubbly fracture zones. The sandstone was water-bearing with water probably following fractures and possibly shale partings. The initial hole produced about 20 gallons/minute of clear water. The monitoring hole was drilled only a few metres away but produced only about 10 gallons/minute of relatively silty water. Continued pumping gradually improved the water clarity. Static water level was about 15.5 m below the ground surface.

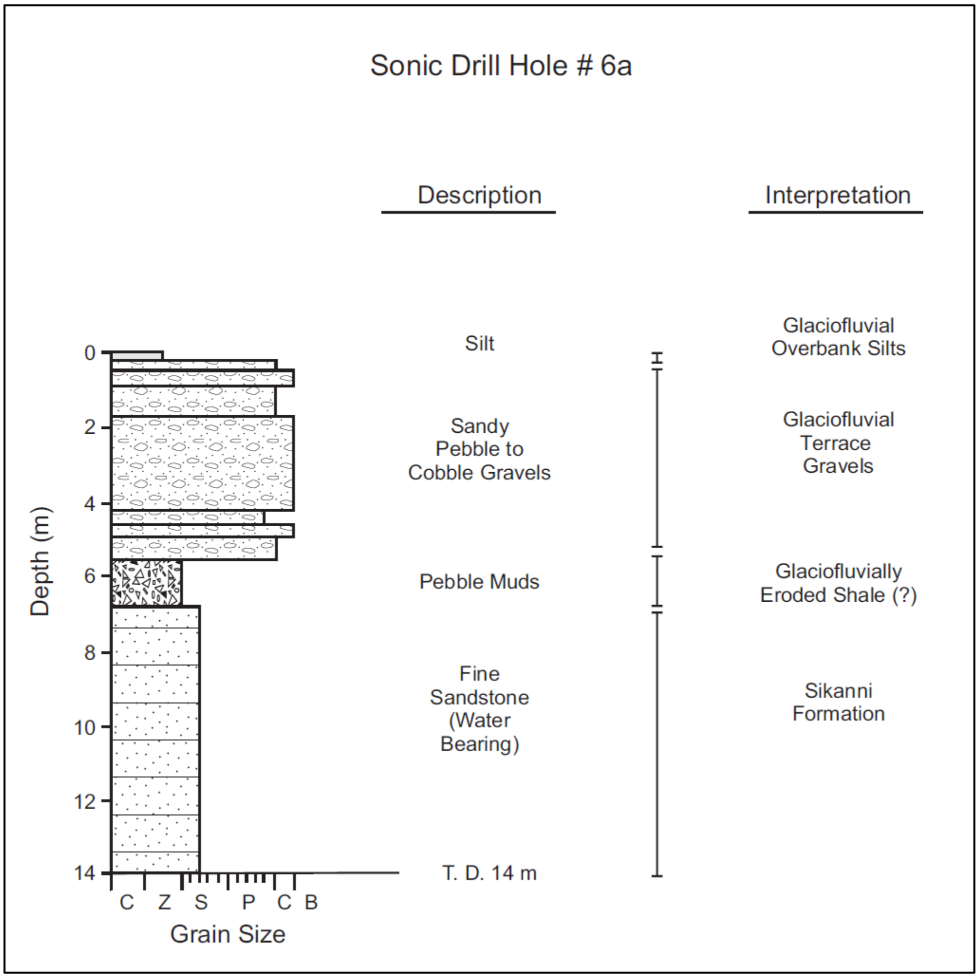

Figure 7. Stratigraphic log and interpretation of main units at sonic drill hole 6a

Figure 8. Thin overbank silt overlying quartzites and sandstone rich gravels in the upper metre at sonic hole 6a

Figure 9. Fractured sandstone bedrock with minor shale partings in drill hole 6a at a depth of about 12 m (top 38-40 ft) and 13.5 m (bottom 43-45 ft)

Comparison with model data

The north-trending resistivity feature in the area of site 6a was interpreted to represent glaciofluvial gravels that are coincidentally aligned with other resistive units such as sandstones (Best and Levson, 2016). This interpretation was confirmed by the drill data at site 6a as well as by the presence of coarse gravel terraces and sandstone outcrops all along both the Halfway and Graham rivers in the area. A water well about 1 km north of the site indicated several metres of gravel and sand over bedrock with a static water level of 18 ft (5.5 m). Other water wells in the area also report high static water levels and appear to be developed in bedrock (Best and Levson, 2016). This information was confirmed here by a shallow water table at drill hole 6a and by water production in the upper part of the bedrock sequence.

SITE 7

Site 7 is east of the Halfway River reserve near along a small gas well access road. The site is about 200 m from the original proposed drill site. The site is within an extensive belt of glaciofluvial sediments that occur on a high bench distant from the modern river valley (Figure 1). The main target for the drill hole was a thick, aerially extensive, resistive unit (>50 ohm-m) that occurs within the Halfway River valley (Figure 6). The unit was tentatively interpreted to consist of glaciofluvial sands, sand and gravels and possibly sandstone (Best and Levson, 2016). The unit was overlain by several metres of low resistivity sediments (32-50 ohm-m) interpreted to be glaciofluvial silts and underlain by more than 60 m of very conductive material (22-32 ohm-m) inferred to be shale. The glaciofluvial sediments mapped in the area were interpreted to be mainly deltaic sands (Mathews, 1976).

Geology and Interpretation

Site 7 is dominated by an 18-m thick sequence of fine to very fine sands and silts overlying an additional 25 m of interbedded silts, clays and fine sands (Figure 10). The uppermost fine sands and silts (Figure 11) are interpreted here as distal deltaic (bottomset or lower foreset) sands and glaciolacustrine silts. They are underlain by about 25 m of deep water glaciolacustrine silts and clays with interbedded very fine sands (Figure 12) inferred to be turbidite deposits. Silt and clay laminae throughout the sequence (Figure 13) support a relatively deep, quiet water depositional environment with an upward-increasing sand concentration due to input from a prograding delta. Load (ball and pillow) structures, deformed laminae and beds, and sharp lower contacts all support a turbidite origin for the sandy beds. The basal part of the glaciolacustrine sequence consists of an additional 10 m of pebbly silts and clays interpreted to be subaqueous debris flow deposits and deep-water muds with dropstones. Thin laminae throughout support a subaqueous origin and striae on some clasts indicate a glacial source for the dropstones. Sonic drill hole 7 bottomed out in about 5 m of silty clay diamict interpreted to be subglacial till (Figure 10). The diamict is massive, matrix-supported, dense to very dense and contains mainly subangular to subrounded sandstone, siltstone and shale clasts with some erratic lithologies and striated clasts.

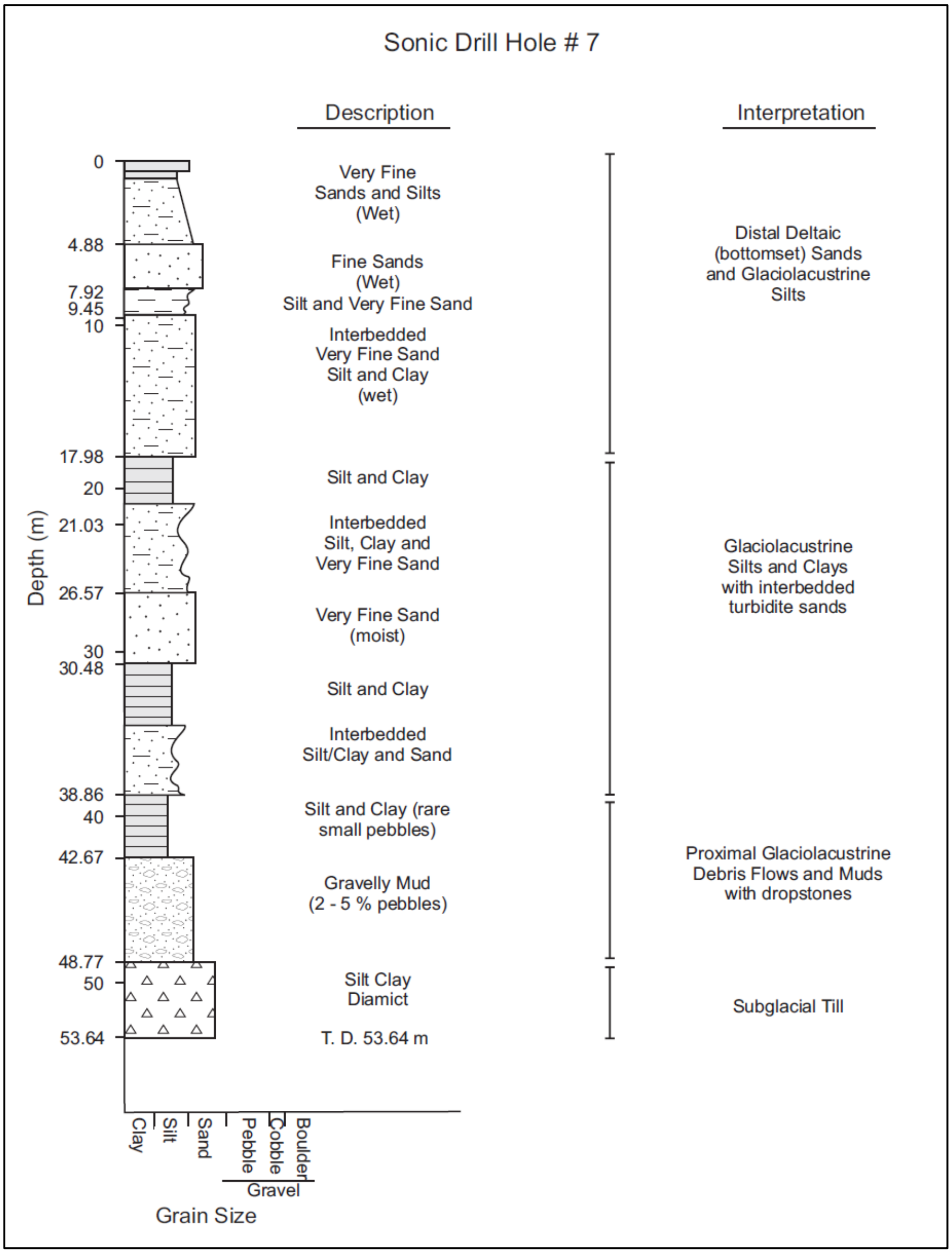

Figure 10. Stratigraphic log and interpretation of main units at sonic drill hole 7

Sand and silt beds in the upper 18 m of drill hole 7 are fully saturated and liquefy readily when disturbed (Figure 11). However, the sandy strata were dominated by fine to very fine sands; no medium to coarse sand or gravel beds were encountered. Although saturated, the permeability of the sands was too low to warrant a water test. Although no coarse sand or gravel units were encountered, it is likely that sands and gravels occur elsewhere in this deltaic sequence, probably closer to the centre of the valley where main feeder channels to the delta complex are more likely to be present.

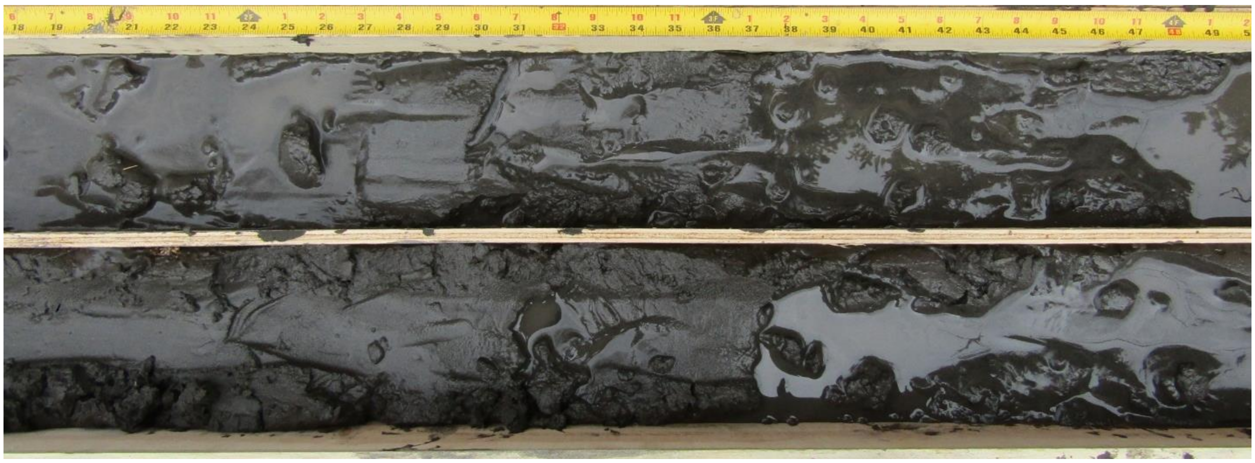

Figure 11. Liquified fine to very fine sands in sonic hole 7 at depths of about 13.5 m (top, 43-45 ft) and 14.3 m (bottom, 48-50 ft); scale in inches

Figure 12. Laminated silts and clays in sonic hole 7 at a depth of about 31.7 m (103-105 ft)

Comparison with model data

The subsurface geology at site 11 was interpreted by Best and Levson (2016) from a partial gamma log at a gas well about 0.5 km east of the proposed drill site. Glaciofluvial sands with thin clay interbeds and a few metres of basal sands and gravels were interpreted to be present at the gas well site and the depth to bedrock was determined to be uncertain. This interpretation was partially confirmed by the dominance of glaciofluvial sands with silt and clay interbeds in the drill core. The presence of gravels was not confirmed at the drill site but they are probably present elsewhere in the area as discussed above. Possible bedrock depths of about 12 m and 33 m were proposed by Best and Levson (2016) from the partial gamma log but both these depths proved to be too shallow at the location of well 7. However, since the interpreted gas well log is about 0.5 km closer to the side of the paleovalley, it is likely that the depth to bedrock shallows in that direction.

Figure 13. Close-up of well laminated silts and clays (dark grey) and fine sands (light grey) in sonic hole 7; deformation, especially on the lateral margins of the core, is assumed to be from drilling disturbance

The main objective of drilling well 7 was to investigate the resistive unit that occurs in the area at depths of about 7 to 31 m based on a nearby resistivity cross-section (Best and Levson, 2016). The resistive unit is overlain by several metres of low resistivity sediments interpreted to be glaciofluvial silts and underlain by more than 60 m of very conductive material inferred to be shale. Silts and very fine sands were encountered in the borehole in the upper several metres as predicted. Also confirmed was the presence of a thick sequence of conductive materials below about 31 m, although the composition of these materials was largely silts, clays and silt clay diamict (rather than shale as inferred). The main resistive unit itself is dominated by fine to very sands with a complexly interbedded sequence of silts and clays (Figure 10). The resolution of the AEM data was not sufficient to detect these fine interbeds but the relatively high, overall resistivity of the unit was confirmed by the dominance of resistive sands in the borehole.

SITE 10b

Area 10b is located along the southwestern margin of the Peace Block resistivity survey. The drill site was located on the west side of Lynx Creek, rather than the east side as originally planned due to access issues. The site is about 1 km west and 0.5 km south of the original site. The area was selected because of interest in the Quaternary stratigraphy of the area due to recent landslides in the region and because a broad area of sandy glaciodeltaic sediments had been mapped along the Lynx Creek drainage system by Mathews (1978). Resistivity maps and cross-sections show that the sediments in area 10b become more resistive with depth (Best and Levson, 2016). The upper 30 m of the section was interpreted to be mainly resistive late glacial glaciofluvial sediments. Moderately resistive material to a depth of 40 m was underlain by moderately conductive material inferred to be sandstone, siltstone and shale.

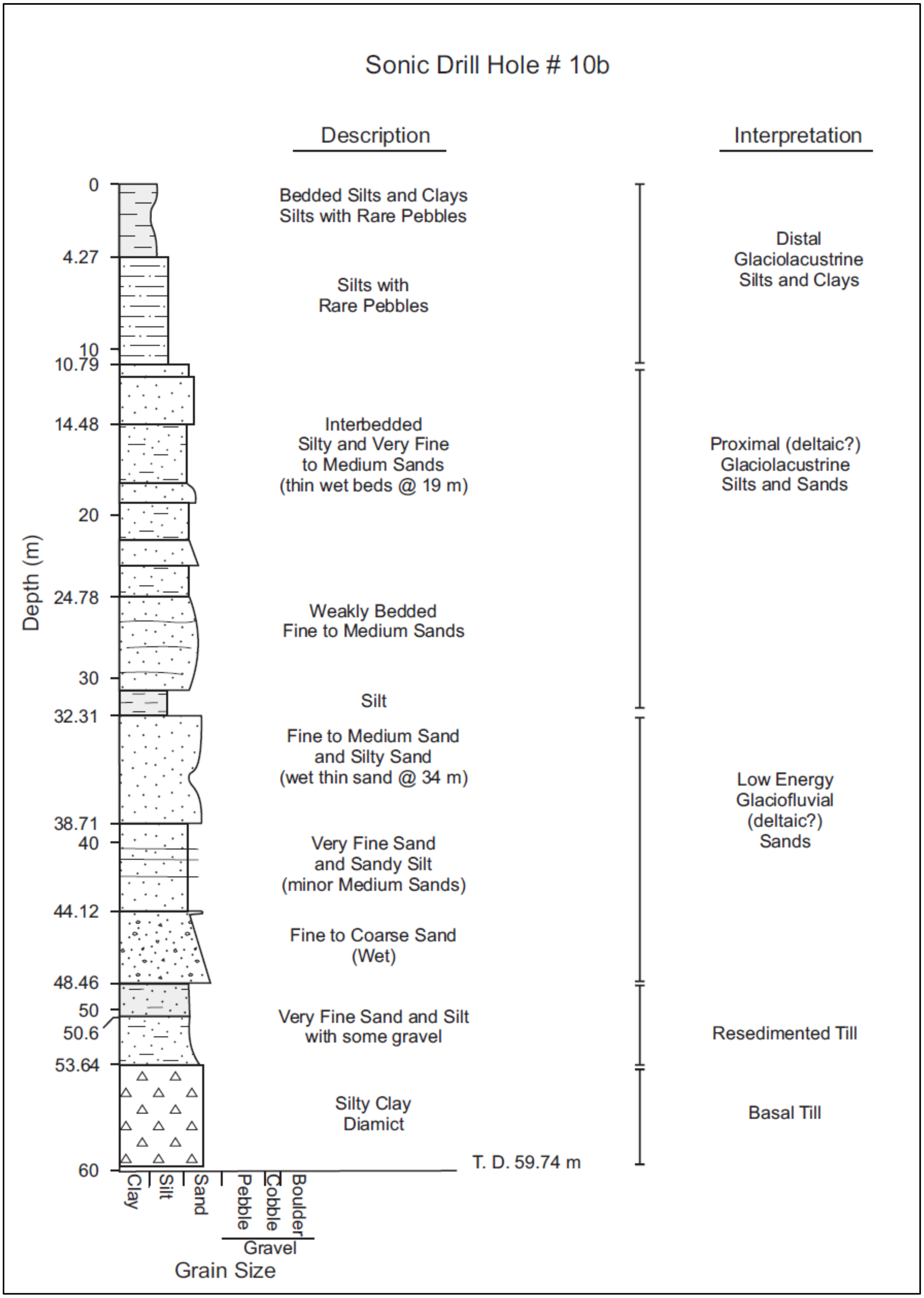

Figure 14. Stratigraphic log and interpretation of main units at sonic drill hole 10b

Geology and Interpretation

The upper 11 m at drill hole 10b is comprised of bedded silts and clays with rare pebbles interpreted to be distal glaciolacustrine sediments with rare dropstones (Figure 14). Crude bedding and clay laminae (Figure 15) indicate a relatively quiet, probably deep water depositional environment. The silts and clays are underlain by about 20 m of interbedded silty sands and very fine to medium sands (Figure 16) inferred to be proximal glaciolacustrine sediments, possibly glaciodeltaic in origin. The next 14 m of the borehole encountered interbedded silty sands and very fine to fine sands generally coarsening downwards into coarse sands with some gravel. These sandy units are interpreted as low energy glaciofluvial sediments, possibly glaciodeltaic in origin. The lowermost coarse sands have a sharp lower contact suggesting an erosional base to the sequence as a result of incision by an early glaciofluvial system. The lowermost unit at borehole 10b is a massive, silty clay diamict, inferred to be a basal till, and an overlying unit of very fine sand, silt and stony mud is interpreted to be resedimented till. The latter unit is massive to weakly bedded, poorly sorted, moderately dense, pebbly throughout and contains striated clasts. It grades into the underlying till which is massive, matrix-supported, fissile and very dense (Figure 17), all characteristics of basal till. Clasts are mainly subangular to subrounded siltstone, sandstone and quartzite indicating a Cordilleran orgin for the till.

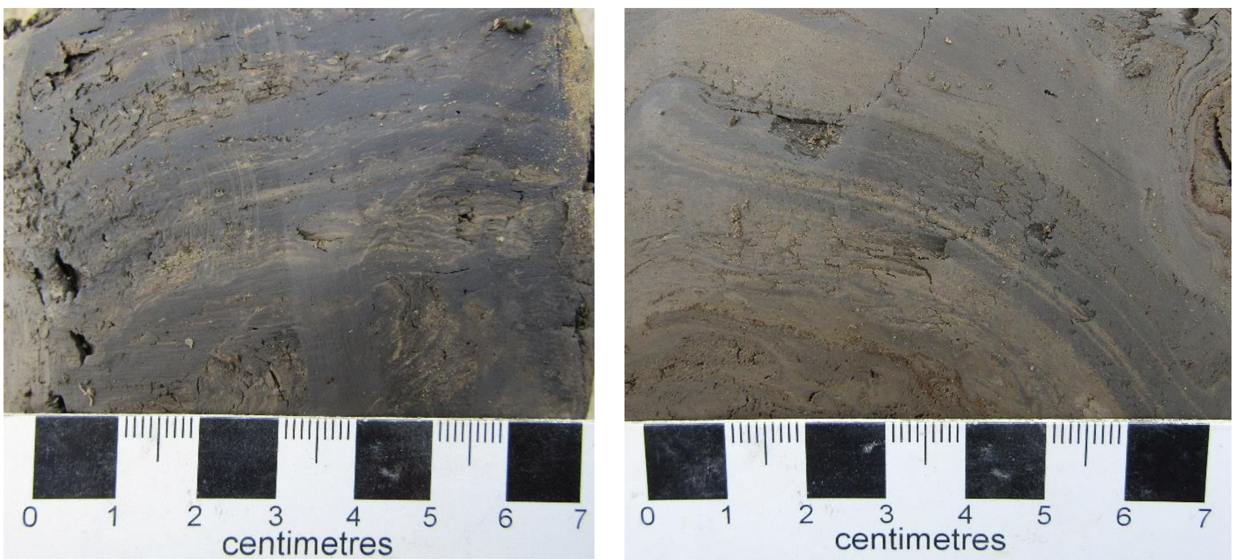

Figure 15. Close-up views of well laminated silts (light brown) and clays (dark grey) in sonic hole 10b at about 1.5 m (5 ft) depth (Left photo) and about 24.7 m (81 ft) depth (Right photo); deformation induced by drilling

Comparison with model data

The resitivity cross-section for area 10b (Best and Levson, 2016) shows a thin moderately resistive unit at surface that correlates with the uppermost silts and clays at the drill site. The presence of these silts and clays suggests that the surficial sandy deltaic unit mapped by Mathews (1976) should be glaciolacustrine rather than glaciofluvial. Several metres of massive to rhythmically bedded silts and clays were also observed in surface exposures in the area. The underlying glaciodeltaic sands extending to a depth of about 30 m correlates well with the main resistive body at the site inferred to be late-glacial glaciofluvial sediments (Best and Levson, 2016). The underlying silts, silty sands and very fine to coarse sands extend to a depth of about 48.5 m and likely correlate with moderately resistive materials extending to 40 m depth, originally interpreted to be sandstone. The greater thickness of these sandy materials at the drill site compared to the original site is likely because the two locations are well over a kilometre apart. The lowermost glacial sediments correspond to a moderately conductive unit observed in the resitivity data.

Figure 16. Close-up view of wet fine sand beds at about 19 m depth in sonic hole 10b

Figure 17. Massive, dense, matrix-supported diamict interpreted as basal till from a depth of about 58.5 m (190-194 ft) near the bottom of sonic drill hole 10b.

SITE 10x

Site 10x was not one of the original sites selected by Best and Levson (2016) but it was chosen in collaboration with researchers from the University of British Columbia who were interested in locating a relatively shallow aquifer. The site was selected because a moderately resistive unit with a broad channel-form or fan shape occurs near surface in the area (Figure 18). Northward, the shallow (<30 m deep) resistive unit narrows into a valley with a reported artesian water well. A produced aquifer was encountered at the site so a water monitoring well (well 10x-2) was drilled immediately adjacent to well 10x.

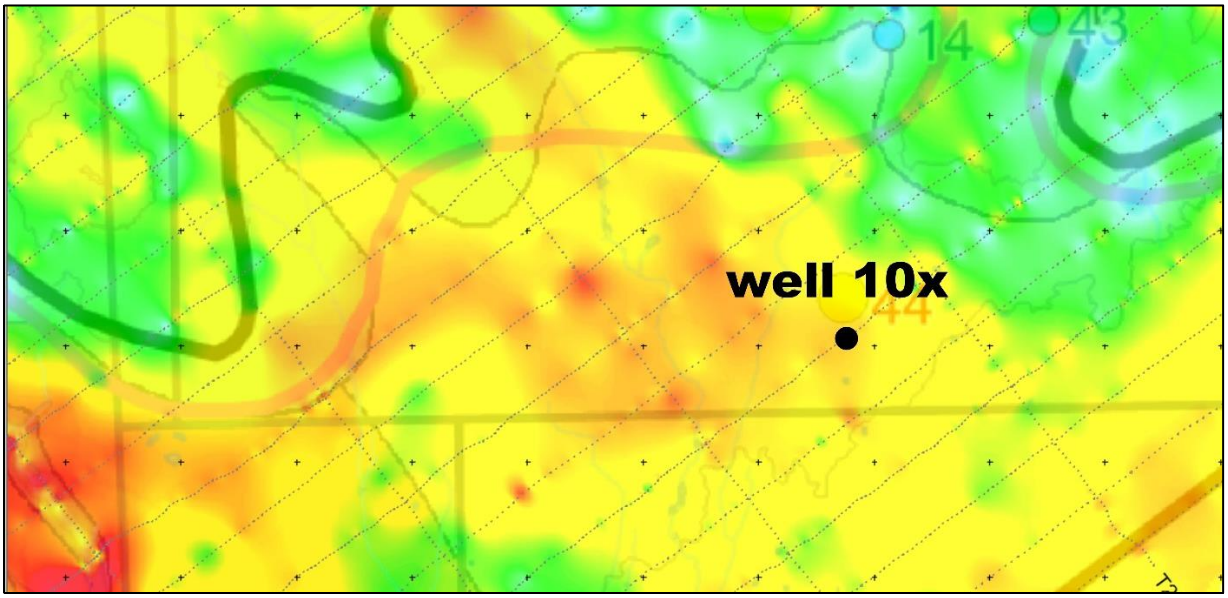

Figure 18. Location of well 10x on the 15-20 m resistivity depth slice

Geology and Interpretation

The surface geology at site 10x is characterized by a thin (about 1 m thick) glaciolacustrine veneer of pebbly fine sand overlying a glacial diamict that extends to a depth of about 12 m (Figure 19). The diamict matrix coarsens slightly downwards from a clayey silt to a sandy silt. The diamict is massive and matrix-supported (Figure 20) with increasing clast content and density with depth. Clasts are subangular to subrounded, of varied lithologies, and many are striated, faceted or bullet-shaped. The lower contact is very sharp (Figure 20). All these characteristics are typical of a basal till. The diamict is underlain down to a depth almost 23 m by a complexly interbedded sequence of very fine to fine sands, silts and pebbly silts. Most beds in this sequence are wet but a water test did not produce a significant volume of water, likely due to the relatively low permeability of the sediments. Fine sandy units are generally massive, well sorted, faintly bedded and of low density. Silty beds are moderately well sorted, pebbly, moderately dense and massive to horizontally bedded. The sediments generally coarsens-upward suggesting a prograding sequence, possibly a glaciofluvial fan unit fed by the buried system in the valley to the north. This sequence is underlain by about 2 m of moist to wet, pebbly fine sands (Figure 21). The sands are massive, poorly sorted with some silt, contain ~10% clasts of varied lithologies including one potassium feldspar granite. The matrix coarsens-down from fine sand at the top to a coarse sand at base of the unit. A water test on this unit produced about 10 gallons/minute with a static water level of about 2-3 m below ground level.

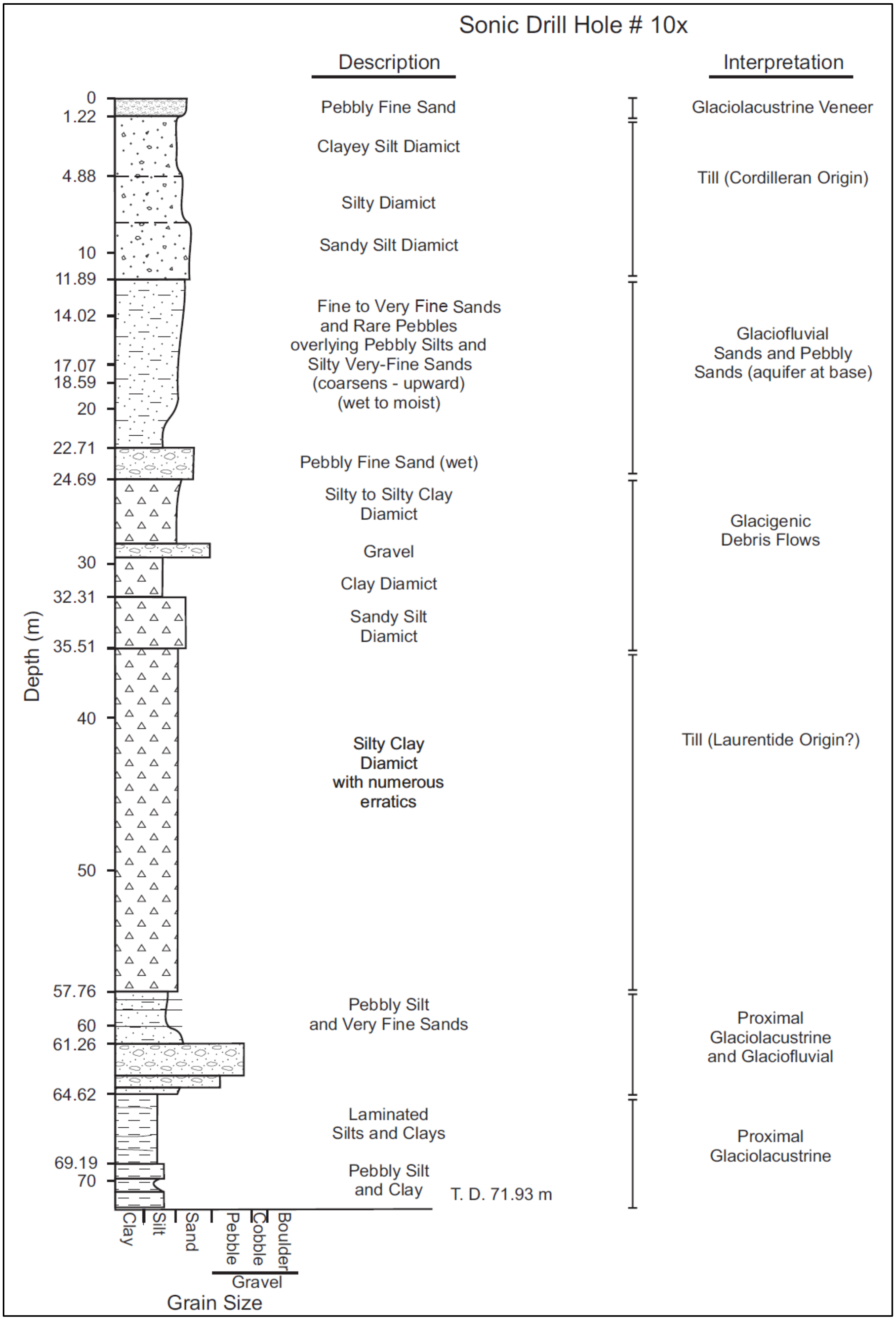

Figure 19. Stratigraphic log and interpretation of main units at sonic drill hole 10x

Figure 20. Massive, matrix-supported diamict in sharp contact with fine sands (contact is just left of center in the lower box); contact is at about 11.9 m (39 ft) at sonic drill hole 10x; scale in inches

Figure 21. Massive, soft, grey silts at about 21.5 m (top box, 70-71 ft) overlying moist to wet, pebbly fine sands at about 23 m depth (bottom box, 74.5-76 ft) in sonic hole 10x

Below the pebbly sands, the borehole is dominated by a thick sequence of glacial diamict from about 25 to 58 m depth (Figure 19). The upper 10 m consists of interbedded silty-clay to sandy-silt diamict and poorly sorted gravels inferred to be glacigenic debris flow deposits associated with a retreating Laurentide ice sheet. Diamict beds are massive, matrix-supported, moderately dense and contain about 5-30% clasts. Clasts are subangular to subrounded and mainly quartzite, carbonate, sandstone and shale. Density and clay content increase with depth. The lower 22 m of the diamict sequence consists of a massive, matrix-supported, dense to very dense diamict with striated and faceted clasts (Figure 22) interpreted as a basal till, probably of Laurentide origin. The till is underlain by interbedded pebbly silts, laminated silts and clays (Figure 23), bedded very fine sands and poorly sorted gravels interpreted to be mainly proximal glaciolacustrine sediments (Figure 19).

Figure 22. Striated and faceted clast in dense, massive diamict interpreted as basal till at a depth of about 51.8 m (170 ft) in sonic drill hole 10x; scale in inches

Figure 23. Well laminated, dense, silts and clays near the base of sonic hole 10x at a depth of about 60 m (197 ft); scale in inches

The overall interpretation for site 10x is that the lowermost glaciolacustrine sediments were deposited in the upper part of the Glacial Lake Mathews sequence which was subsequently over ridden by Laurentide ice. The retreating ice deposited a series of glacigenic debris flows. During a temporary ice-free period, fan sediments were deposited at the mouth of a glaciofluvial stream flowing southward from the valley to the north. The entire sequence was finally overridden by the Cordilleran ice sheet. The lower most part of the fan sequence is a pebbly sand that produced about 10 gallons per minute. Just 5 m away, the monitoring well was drilled and the pebbly sand unit there was slightly thicker (~2.5 m) and overlain by 1.5 m of interbedded fine to medium sand and some silty fine sand. The pebbly sands were also underlain by almost a metre of well sorted (clean) medium and fine sands. This type of lateral variation is typical of fan sequences.

SITE 11

Areas 11 is located northwest of Ft. St. John and southeast of Charlie Lake. The site is in a largely till covered area where a narrow paleochannel had been previously mapped. The site was selected in part because at least one spring was known to exist in the general area and a shallow resistive unit was observed on the resistivity cross-section. This was the first well drilled during the program and unfortunately there was no access into the originally planned site. The only accessible location was directly north of the original site on the crest of a small valley. Consequently, the target resistive unit was not encountered in the borehole.

Geology and Interpretation

The uppermost sediments at site 11 include almost 2 m of laminated clay, silt and minor sand underlain by about 6 m of pebbly muds with minor clay laminae (Figure 24). These sediments are interpreted to be distal glaciolacustrine deposits of Glacial Lake Peace grading downwards into more proximal glacial lake sediments. They are underlain by about 6 m of silty-clay diamict with minor clay laminae inferred to be glacigenic debris flows that were deposited in Glacial Lake Peace by the Laurentide Ice Sheet during the late stages of ice retreat. Clast content varies from about 10-20% and Laurentide erratics are present. The diamict is very dense and may include subglacial till within the sequence. Nine metres of massive, clay diamict with minor sands lenses below the silty-clay diamict are interpreted to be basal meltout till as indicated by moderate density, sand lenses and relatively low clast content (~5%). An additional 6 m of clays with about 1-2% pebble content occur in the lower part of the drill core. No laminae were observed in the clays and clasts are mainly large pebbles. The unit is interpreted to be a subglacial lake deposit. At the bottom of the borehole, a 6-m thick unit of very dense, massive, matrix-supported, clay-diamict is inferred to be a subglacial lodgement till (Figure 25). The till contains about 5-10% clasts including some red feldspar granites of Laurentide origin.

Comparison with model data

The subsurface geology of area 11 was initially interpreted from two nearby water well logs (Best and Levson, 2016). The closest log reported a thick package of fine sediments which is similar to what was encountered at the borehole. A second water well, located several hundred metres west of the drill site, reported clays and sands down to a depth of 31 m overlying 4 m of gravel and wet sand. The latter may represent a small paleochannel deposit but it was not encountered in the sonic borehole likely because of the distance between the two wells. The nearest gas well, about 2 km to the southeast had only a partial gamma log from which depth to bedrock could not be ascertained but it was estimated that silt, clay and sand extended to a depth of somewhere between 35 and 55 m. No bedrock was encountered in the borehole at 35 m so it is likely that 55 m may be a more reasonable estimate.

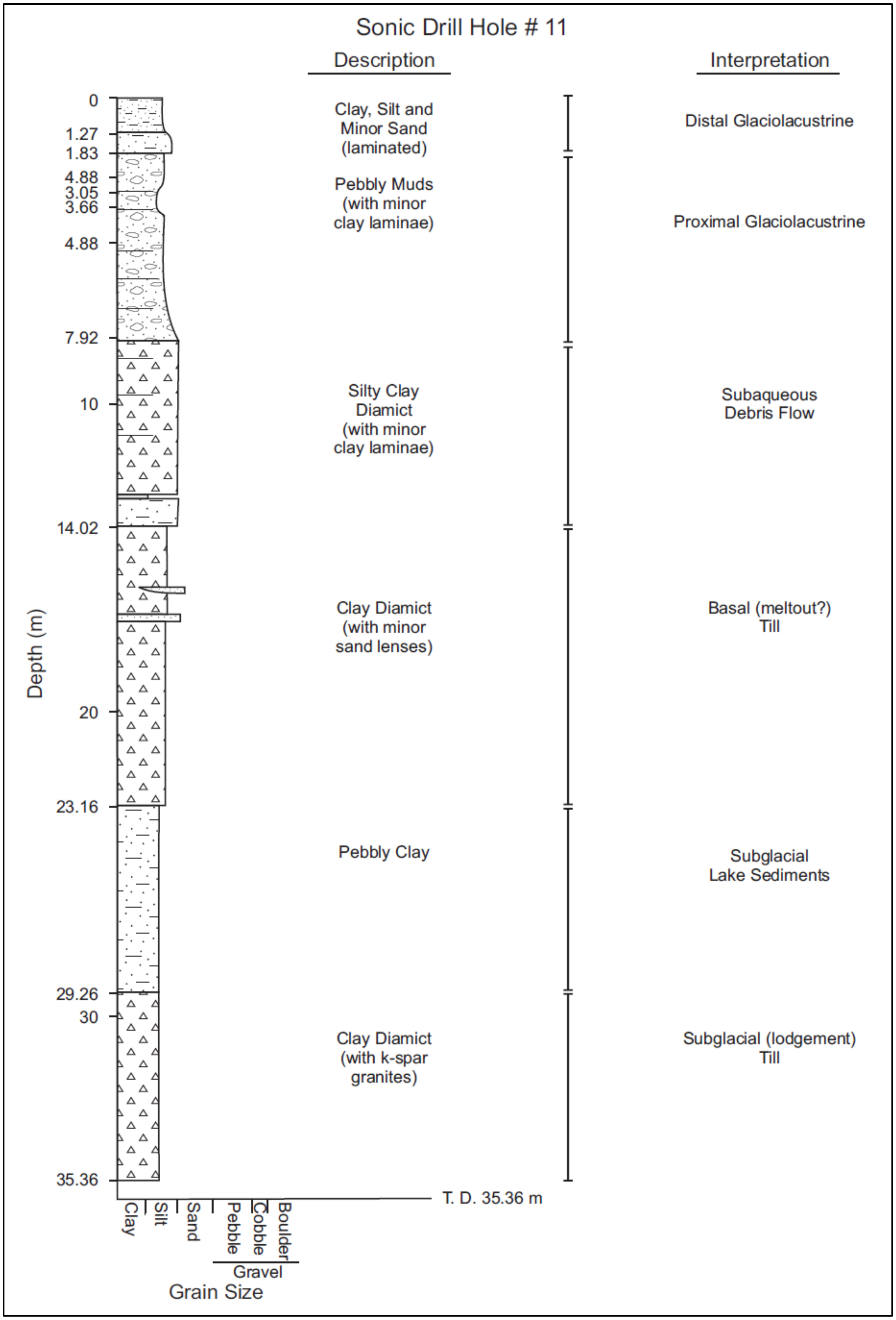

Figure 24. Stratigraphic log and interpretation of main units at sonic drill hole 11

Figure 25. Massive, matrix-supported, very dense, clay rich diamict at a depth of about 33 m in sonic hole 11 (depth interval shown: 104-107 ft, top box, and 108-111 ft, bottom box) interpreted to be subglacial lodgement till deposited at the base of the Laurentide Ice Sheet

SITE 12

Area 12 occurs west of Ft. St. John along the northern margin of the Peace River valley. The area has a continuous cover of glaciolacustrine silts and clays deposited in Glacial Lake Peace that partially infill an inferred large paleochannel of the former Peace River. Exposures along the river valley in the area reveal relatively thick sequences of Quaternary sediments. Site 12 is located about 250 m west of the original drill site.

Geology and Interpretation

The uppermost sediments at site 12 include almost 8 m of laminated clays and silts and an additional 4 m of pebbly muds interpreted, respectively, to be distal glaciolacustrine deposits of Glacial Lake Peace underlain by more proximal glacial lake sediments (Figure 26). Clast content increases downwards in the pebbly muds from <1% to about 3%. These deposits are gradationally underlain by about 4 m of massive silty-clay diamict inferred to be basal till of the Laurentide ice sheet. The diamict is moderately to very dense, matrix-supported and contains about 10% clasts (Figure 27). Below the silty-clay diamict there is a 15-m thick sequence of gravelly and sandy-silt diamicts interbedded with sands and silty sands. The lower few metres of the sequence are mainly silts and clays grading down into pebbly muds with a dry pebble gravel at the base (Figure 28). The diamict beds are interpreted to be glacigenic debris flows and the interbedded sands and muds are likely proximal glaciolacustrine sediments deposited in Glacial Lake Mathews. The basal gravel may represent a subaqueous fan deposit deposited by water flowing into the lake from the advancing ice sheet. The remaining 22 m of the section are dense, laminated clays and silts with fine sand beds (Figure 29) inferred to be relatively distal glaciolacustrine sediments deposited in Glacial Lake Mathews before the arrival of the Laurentide ice sheet.

Comparison with model data

The subsurface stratigraphy in the area of site 12 was originally inferred from a gamma log at a gas well located about 1 km to the northeast of the original site (Best and Levson, 2016). The depth to bedrock was interpreted to be about 25 m below the surface but bedrock was not encountered in well 12. However, bedrock was observed in exposures along the river near the well site below a thick sequence of glacial and glaciolacustrine sediments. It is likely that the bedrock is shallower at the gas well to the north because it is located closer to the northern margin of the Peace River paleovalley. Gravels reported at depths of 7 to 32 metres, from a water well log about 2 km to the southwest of the drill site, probably reflect the pebbly muds, diamicts and gravels encountered at these same depths in the sonic borehole. The absence of water in gravels and gravelly sediments in both boreholes supports this interpretation.

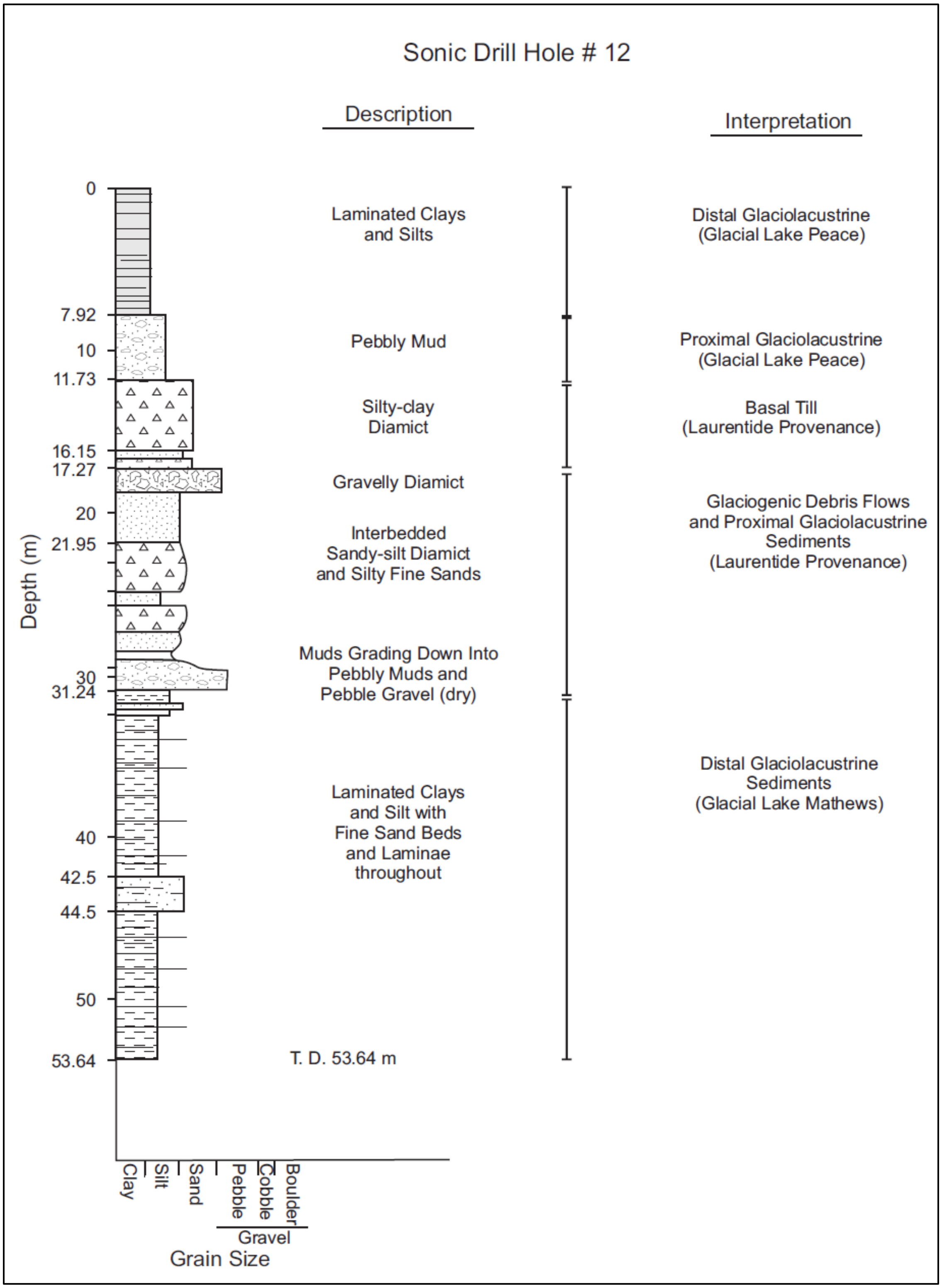

Figure 26. Stratigraphic log and interpretation of main units at sonic drill hole 12

Figure 27. Fine to coarse sand bed at about 16.5 m depth (lower box, 53-55 ft) in sharp contact with silty-clay diamict at about 14-16 m depth (upper boxes) in sonic hole 12

Figure 28. Dry sandy gravels at about 30 m depth (98-102.5 ft) in sonic hole 12; gravel top and bottom marked by trowel positions; scale in inches

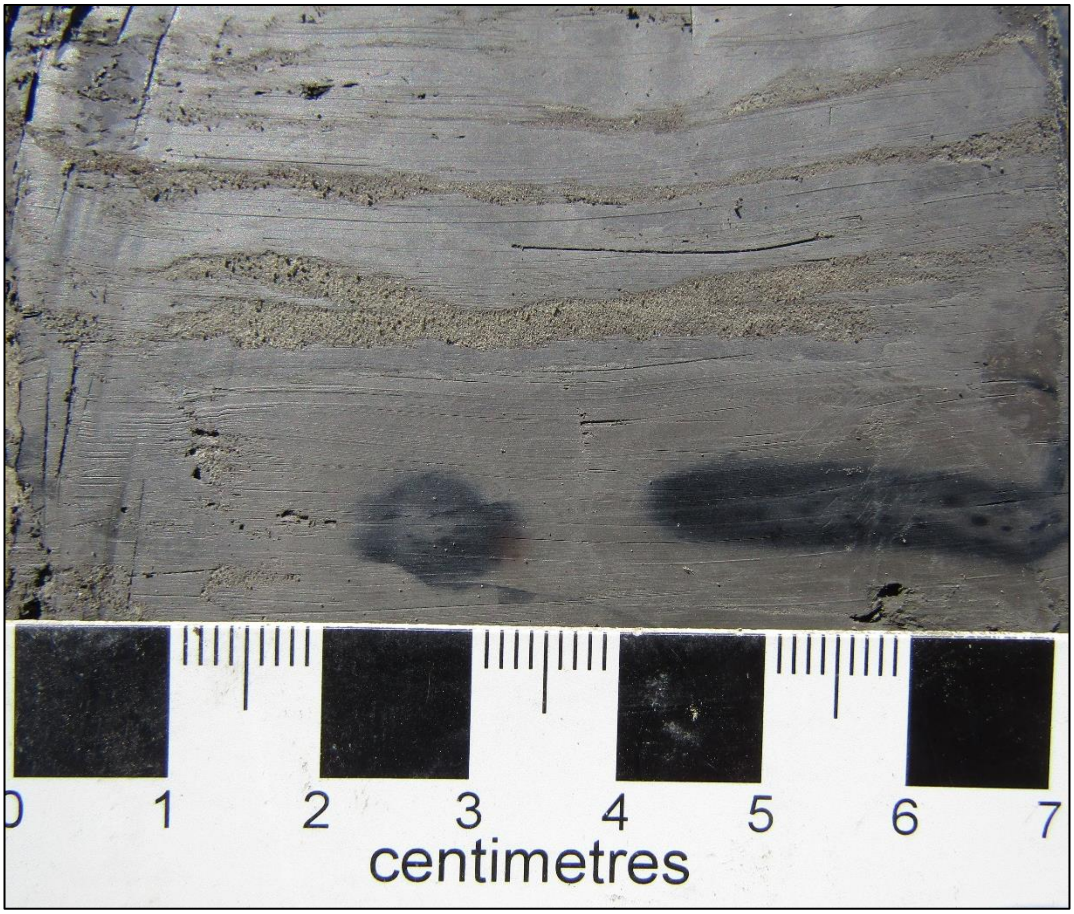

Figure 29. Dense, laminated, silts, clays and fine sands at a depth of about 50 m (134.5 ft) in sonic hole 12, interpreted to be sediments deposited in Glacial Lake Mathews; note black (organic?) zones at photo base

Comparison with model data

Resistivity data at well 12 shows an oscillation between moderately conductive and resistive materials interpreted as glaciolacustrine sediments with varying clay, silt and sand contents and glacial sediments (Best and Levson, 2016). The vertical changes in resistivity were interpreted to reflect textural variations in the paleochannel fill sequence inferred to include Glacial Lake Peace sediments overlying till and Glacial Lake Mathews sediments and confirmed by sonic hole 12. The upper 15 m of the resistivity section at the site was interpreted to be Glacial Lake Peace silts, sands and clays and till which corresponds well with the upper 16 m of sediments in well 12, also interpreted to be glacial lake sediments and till. Likewise, both the resistivity data and sonic core data indicated an underlying thick package of mainly fine sediments interpreted to be Glacial Lake Mathews sediments. Below a depth of 65 m, conductive material in the resistivity data was interpreted to be siltstone or shale.

SITE 13

Area 13 occurs about 2.5 km northwest of the Farrell Creek road on private property (Figure 1). The site was not one of the original sites selected by Best and Levson (2016) but it was chosen in collaboration with hydrogeology researchers from Simon Fraser University who are attempting to model shallow aquifers in the region. The site was selected because resistivity sections in the area indicated the presence of deep paleovalley/channel features, possibly related to a former course of Farrell Creek, that could potentially host a good aquifer (Samantha Morgan, *pers. comm.* 2017). The drill site was located on a high bench west of the modern Farrell Creek valley in an area mapped as a deep paleovalley. The closest water well log to the site, about 3 km to the northwest, showed a depth to bedrock of 67 m. The surficial materials mapped in the area by Mathews (1978) are glaciofluvial sediments interpreted to be mainly deltaic sands.

Geology and Interpretation

The upper 10 m of core at sonic drill hole 13 are rhythmically bedded silts, clays and very fine sands (Figure 30) that grade downwards into crudely bedded, pebbly muds (Figure 31). They are interpreted as distal glaciolacustrine sediments with varved silts and clays grading down into more proximal glaciolacustrine sediments (pebbly muds). The pebble content of the muds increases from about 1% to about 10% at the base of the pebbly muds. These deposits are underlain by an additional 11 m of diamict with interbeds of pebbly silts and gravels. The lower 4 m is a massive diamict interpreted to be a basal till of Cordilleran provenance whereas the overlying diamict beds are inferred to be glacigenic debris flow deposits that are interbedded with glaciofluvial deposits. The lower diamict is massive, matrix-supported, dense and contains numerous erratics, all supporting a basal till origin (Figure 32). About 9 m of interbedded pebble to cobble gravels underlie the till (Figure 33). These gravels are likely glaciofluvial river gravels deposited in a paleovalley flowing from the Rocky Mountains. Immediately below the gravels about 1 m of well laminated clays and silts are interpreted to be glaciolacustrine muds. An additional 20 m of interbedded muds, pebbly muds, gravelly diamict and pebbly sands (Figure 34) underlie the gravels and are inferred to be glacigenic debris flow and mud flow deposits of Cordilleran provenance. The interbedded muds and pebbly sands may be of subaqueous or subaerial origin but the dominance of fine sediments, at least in the upper part of the sequence, suggests the former is more likely.

Figure 30. Rhythmically bedded silts and clays in sonic drill hole 13 at about 5.5-7.5 m depths (intervals shown: top box 18-20 ft, bottom box, 23-25 ft), interpreted to be varved glaciolacustrine sediments

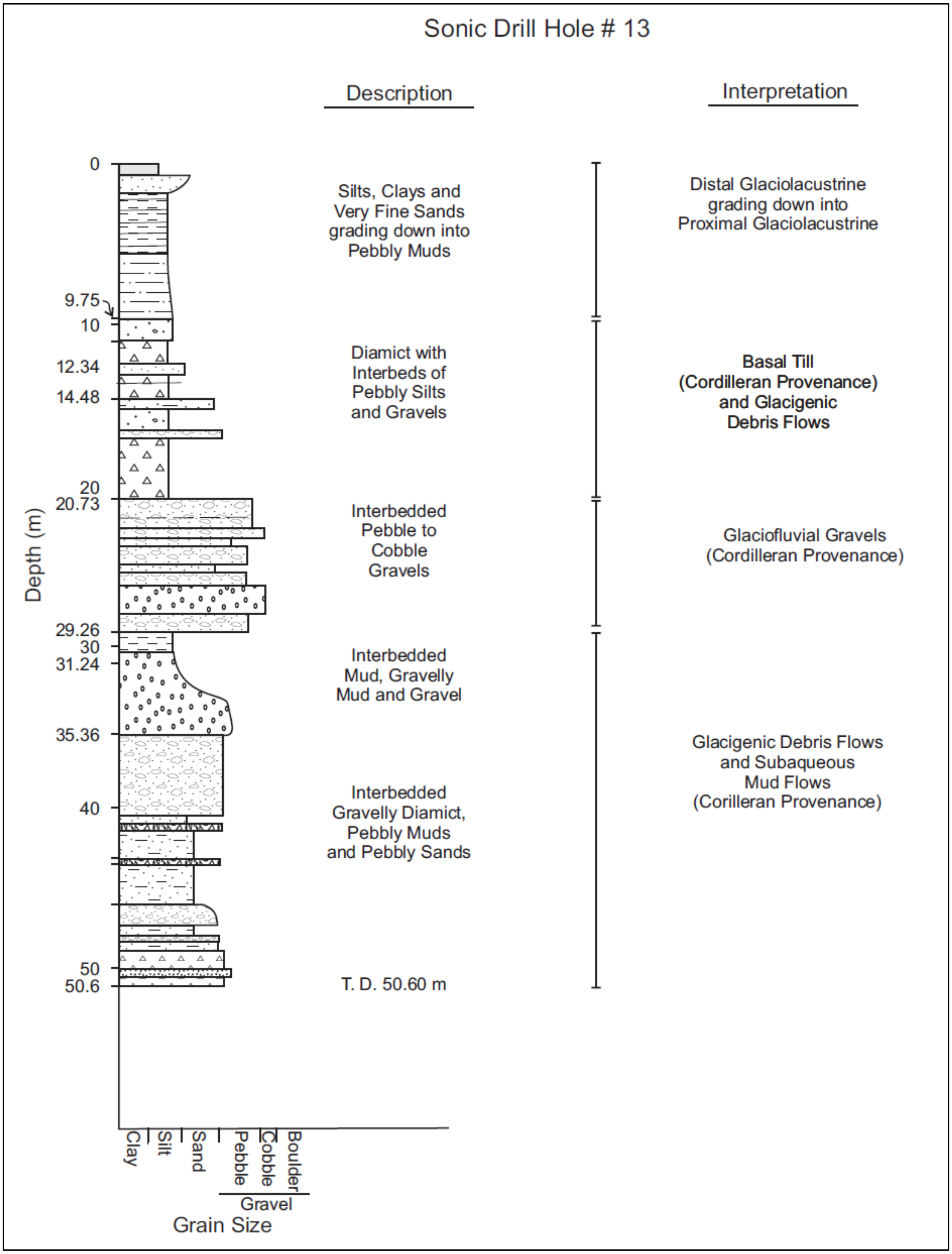

Figure 31. Stratigraphic log and interpretation of main units at sonic drill hole 13

Figure 32. Thin glaciofluvial gravel at about 16.8 m depth (upper box, 55-55.5 ft) in sonic hole 13 overlying massive, dense diamict at about 18-20 m (lower boxes, 59-61 ft and 63-65 ft), interpreted to be Cordilleran basal till

Figure 33. Interbedded pebble to cobble gravels at about 26-28 m depth (upper box 85.5-87 ft, lower box 90.5-92 ft) in sonic hole 13, interpreted to be glaciofluvial gravels of Cordilleran provenance

Figure 34. Massive, gravelly silts and fine sands at about 45.7 m (top box, 149-151 ft) interbedded with pebbly fine sands at about 47 m (bottom, 154-156 ft) in sonic hole 13, interpreted to be glacigenic debris flow deposits

Comparison with model data

Well 13 confirmed the presence of a deep paleochannel in the area, with Quaternary sediments to a depth of least 50 m. The resistivity section in the area (Line 122801) suggests a depth to bedrock of about 67 m which is the same depth as reported in the closest water well log. The presence of gravels at a depth of about 20-30 m and fine sediments at the top of the well also correspond well with the resistivity data. The latter is also confirmed by surface exposures of varved silts and clays observed in the field near the drill site. The gravels encountered in sonic well 13 were unfortunately dry indicating that the gravel unit is not hydraulically connected to an upslope recharge zone nor to the Farrell Creek aquifer. This is well illustrated by the resistivity section near the site (Line 122801) which shows a pocket of resistive material encased in relatively conductive sediments.

SUMMARY AND CONCLUSIONS

A total of 10 wells at 8 different sites were drilled and cored with a sonic drill with the main objective of testing the accuracy of a stratigraphic model developed from Quaternary geology data compiled by Quaternary Geosciences Inc. and an airborne electromagnetic (AEM) survey conducted by Aarhus Geophysics. The drilling results demonstrate that the stratigraphic model is accurate in most regards. Paleovalleys predicted by the model were encountered at all the sites and the expected stratigraphic sequences were confirmed. The paleovalleys are as deep as predicted and probably deeper at some locations. Only one well encountered bedrock due to the great depth of the paleovalleys and the difficulties associated with drilling deeply buried Quaternary sediments.

Although the drilling results demonstrate that stratigraphic model is generally accurate, there are inherent weaknesses because the model is largely based on interpretation of a single geophysical parameter (resistivity) as well as interpretation of single gamma logs (without other types of geophysical logs to provide corroboration). In addition, the resolution of the AEM survey decreases with depth so, for example, it does not resolve thin beds at depth. Finally, the subsurface geological database used to develop the model consists mainly of widely scattered points often requiring long-distance correlations between data points that are particularly tenuous due to the high lateral variability that is typical of Quaternary glacial sediments.

One well at each site, except site 11, was completed with a hollow PVC pipe to allow for down-hole geophysical logging at later dates. Two wells at sites 6a and 10x were drilled and completed as provincial water well monitoring stations. All the sonic core was boxed and stored at the provincial core storage facility in Charlie Lake.

ACKNOWLEDGEMNTS

This work could not have been completed without the generous financial assistance and support of GeoscienceBC and the British Columbia Ministry of Forests, Lands and Resource Operations. In particular, appreciation is extended to Carlos Salas (Vice President, Energy; Acting President & CEO, Geoscience BC) who managed the project and provided advice on numerous occasions. Special thanks are extended to Chelton van Geloven (Source Water Protection Hydrologist, Dam Safety Officer, Resource Management, Northern Area, Ministry of Forests, Lands and Natural Resource Operations) who provided invaluable help in project management, logistics, planning and locating well sites, obtaining land and road access permissions, decision-making, core preparation and storage, snow removal and even preparing awesome field coffee! This project would not have been a success without these efforts and countless others provided by Chelton. Thanks also to Dr. Aaron Graham Cahill (Research Associate, Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia) who provided advice in the field and in the selection of well site 10x. Appreciation is also extended to graduate students Samantha Morgan (Simon Fraser University) and Jessie Tse-Hua Chao (University of British Columbia) who assisted with core descriptions and preparation at sites 12, 10b and 10x. Samantha also provided the information for the selection of site 13. Last, but not least, the efforts and professionalism of the team from Mud Bay Drilling, especially the head driller Chuck and his assistants Johnny, Brandon and Marcus, were of course essential to the program and are much appreciated.

REFERENCES

Brown, B., Gisseloe, P., and Best, M., 2016: SkyTEM Airborne EM Systems for Hydrogeological Mapping in British Columbia in Geoscience BC Summary of Activities 2015, Geoscience BC, Report 2016-1

Best, M.E. and Levson, V.M., 2016: Peace Area Project - Well Selection for Testing Geological Model Based on Gamma and Airborne Electromagnetic (AEM) Studies; Final Report prepared for Geoscience BC by Bemex Consulting International and Quaternary Geosciences Inc.; 42 pages.

Levson, V. M., 2014: NE BC Aquifer Characterization Project – Gamma Ray Interpretation; Report prepared for Ministry of Forests, Lands and Natural Resource Operations, 31 p.

Mathews W.H., 1978: Surficial geology, Charlie Lake, Peace River District, British Columbia, (NTS 94A), Geological Survey of Canada, Map 1460A, Scale 1: 250,000.

Petrel Robertson Consulting Ltd., 2015: Interpretation of Quaternary sediments and depth to bedrock through data compilation and correction of gamma logs: Geoscience BC Report 2016-04.