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GSC Open File 8046

Preliminary investigations of unconsolidated sediments overlying the Leech River fault zone, southern Vancouver Island, British Columbia

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Abstract

The Leech River fault zone lies near the city of Victoria, British Columbia. Although this fault zone has been considered to be inactive for millions of years, two large paleo-earthquakes have been identified on its eastern extension, only 40 km from the city. Confirmation of an active fault in proximity to an urban centre or a part of critical infrastructure would fundamentally change the analysis of seismic hazard. To determine the occurrence of more recent faulting, younger sediments overlying the faulted bedrock were surveyed by high resolution Lidar topography, ground penetrating radar, electrical resistivity, and shallow seismic reflection lines. Targeted areas included surface scarps and transects crossing the bedrock structure in search of disturbed sediment that may be attributed to recent faulting. Preliminary results do not find conclusive evidence of active faulting in the youngest sediment dating from postglacial time, at least in the upper 5 to 10 m; however, the seismic reflection survey found deeper, faulted deposits dating from at least the last glaciation and warrant further investigation.

Introduction

As part of an ongoing assessment of the seismic hazard posed by the Leech River Fault Zone (LRFZ) near Victoria, Vancouver Island ((Massey et al., 2005; Fig.1), the Geological Survey of Canada (NRCan) conducted shallow geophysical surveys on unconsolidated sediments overlying the fault zone.

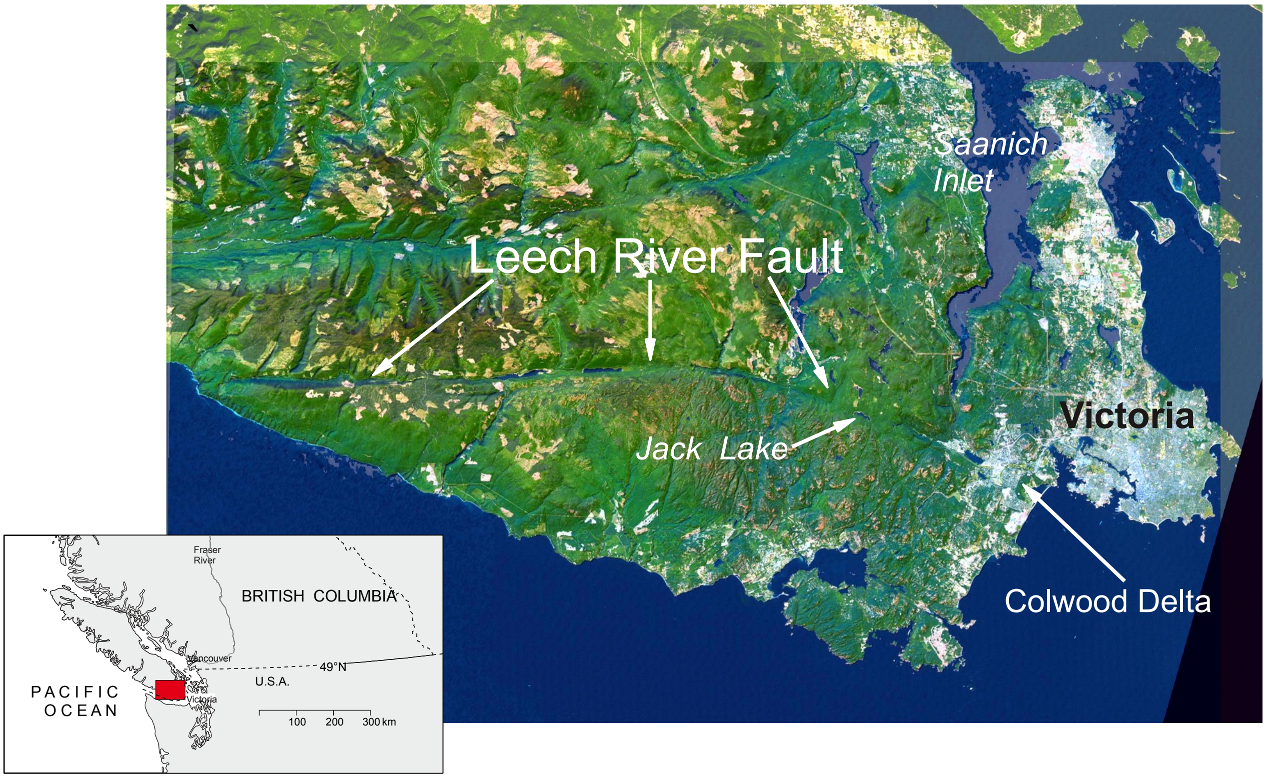

Figure 1: Landsat image shows the long narrow valley marking the Leech River fault zone trending towards the Victoria metropolitan area. Built-up areas appear grey on the image. On its eastern end the trace of the Leech River fault lies beneath thick glacial outwash sediments which comprise the Colwood delta.

The LRFZ passes through the rapidly expanding communities of Colwood and Langford, including a hydroelectric dam and reservoir farther west. The apparent southeastern extension of the Leech River Fault zone, known as the Devil's Mountain fault zone, has been active with two damaging paleo-earthquakes 40 km east of Victoria in Washington State (Johnson et al., 2003), but it is not known if this activity also extended to the Leech River Fault. Recently, Barrie and Greene (2015) mapped the Devil's Mountain fault zone on the sea floor within 4 km of the Victoria waterfront. Currently, it is believed that movement along the LRFZ ceased in late Oligocene time (Fairchild and Cowan, 1982). The goal of this study was to search for evidence of recent activity along the LRFZ by using geophysical techniques to determine if any younger deposits overlying the fault zone may have been disrupted by seismic activity The eastern part of the fault zone is overlain by sediments comprising the Colwood delta, an isostatically raised glaciofluvial deposit formed during the retreat of the last glaciation (Fig.2). The targeted areas were surface lineaments identified on high resolution bare-earth topography derived from light detection and ranging data (Lidar) acquired by NRCan (James et al., 2010). Although every attempt was made to locate the geophysical survey lines across the lineaments, extensive urban development restricted line locations to parks and open areas. The main survey tools were ground penetrating radar, capacitively coupled resistivity and a single seismic reflection line across the mouth of Esquimalt Lagoon along Ocean Boulevard (Fig.2).

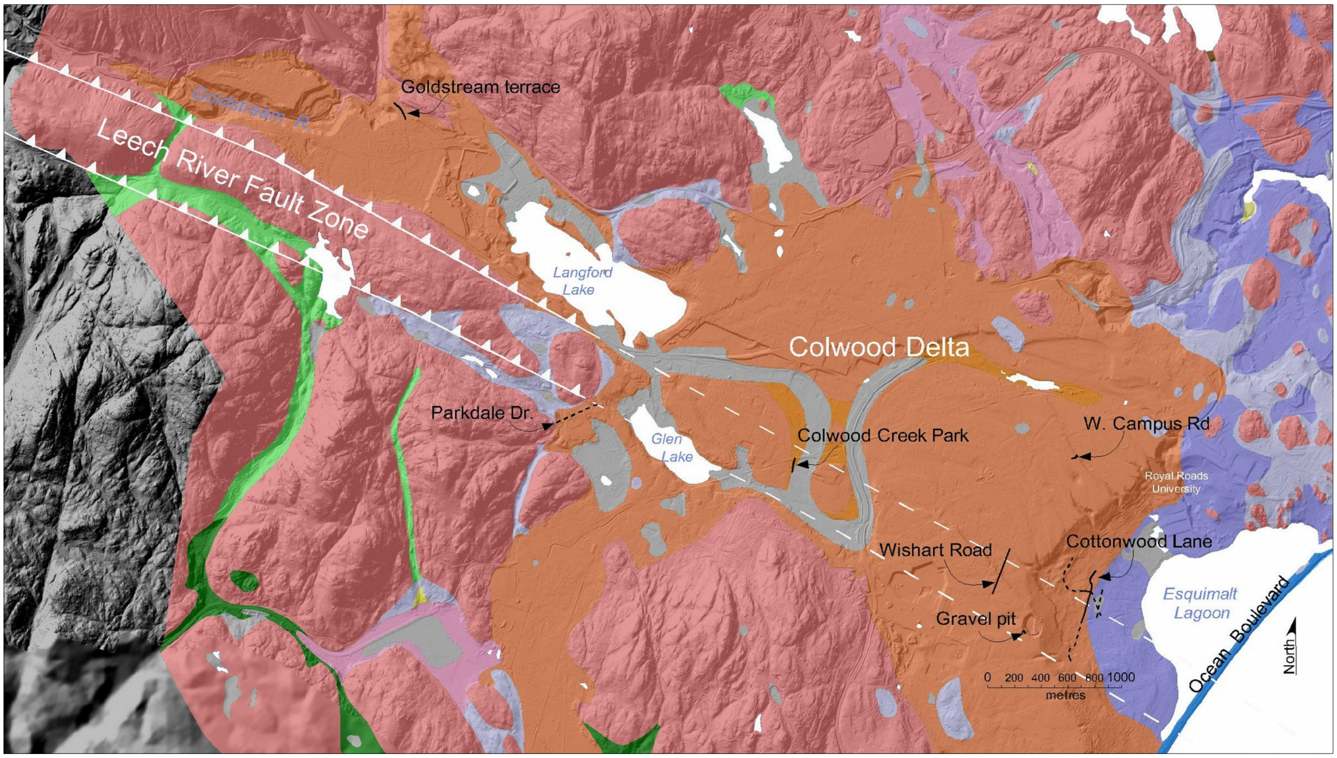

Figure 2: Surficial geology overlying the Leech River fault zone in the Colwood delta region showing the location of GPR and ground resistivity survey lines. The thrust faults and assumed projection are from Massey et al., 2005. Colour Legend: pink – bedrock; orange – thick sand and gravel; light and dark green – till veneer and till respectively; light and dark blue – fine marine veneer and mud respectively; violet – lacustrine deposits; yellow – alluvium; grey – organic deposits; brown – fill (derived from Monahan and Levson, 2000).

The pristine surface of the Colwood delta has been extensively modified by commercial development in modern times and even since historic times many naturally occurring lineaments and scarps were commonly used roadways because of better drainage. This makes it especially difficult to determine the genesis of surface lineaments in the current landscape. Moreover, several natural processes besides faulting can produce surface lineaments. For example, channel scarps can be cut by meltwater streams or postglacial drainage. In order to extract what may have been the original surface of the Colwood delta, a detailed analysis of the surface morphology was made using the high resolution Lidar. An image combining slope maximum dip direction and slope aspect reveals an extensive network of braided channels covering the surface of the delta, as would be expected in a glaciofluvial environment (Fig. 3). Although the possibility of fault scarps cannot be discounted, this analysis suggests that the dominant natural lineaments on the delta were produced by glaciofluvial activity.

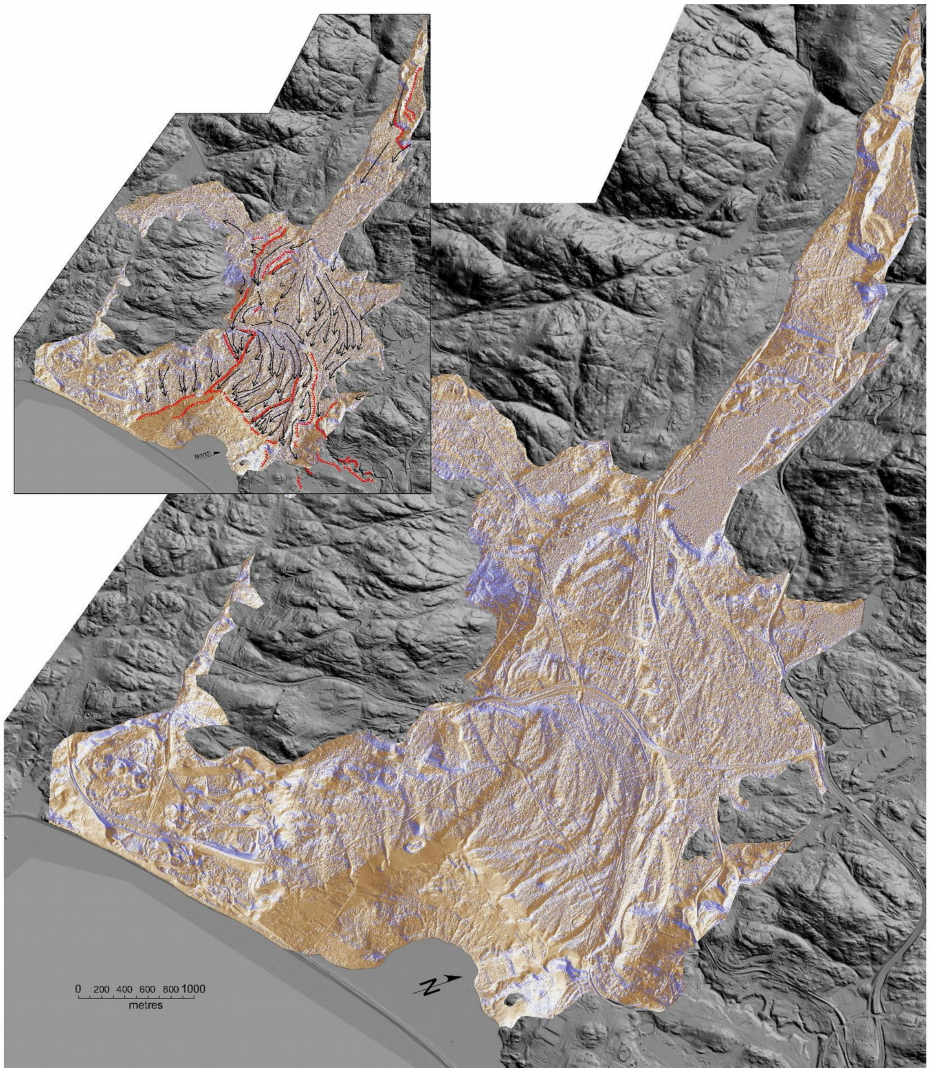

Figure 3: An analysis of slope and aspect on the Colwood delta shows an extensive braided channel morphology. Prominent thalwegs and scarps are mapped in the inset.

Methods

Three geophysical techniques were used in this study to detect either lateral or vertical changes in the physical properties of the subsurface materials. It was hoped that the derived models of the geologic structure would identify disturbed bedding that could be attributed to faulting. The main parameters measured were capacitive-coupled electrical ground resistivity (ohm-mapper) and electromagnetic (EM) radiation with ground penetrating radar (GPR). The ohm-mapper uses current antennae to emit an electric field and potential antennae to measure the electric field in the vicinity of the current flow. Depth penetration depends on ground conductivity and antennae array geometry. GPR instruments measure the two-way travel times and amplitudes of reflected pulsed electromagnetic radiation. Spatial variations in the travel times and amplitudes of EM radiation are caused by reflections from various subsurface horizons. Lastly, the shallow seismic reflection survey measured travel times and amplitudes of seismic energy to derive acoustic velocity and density of the subsurface. Further descriptions of these geophysical methods and their utility in geomorphological studies are found in Gilbert (1999).

Preliminary investigations of the unconsolidated sediments overlying the LRFZ began in September, 2006 with ground resistivity transects across selected scarps and lineaments identified in the Lidar digital elevation model (DEM). Subsurface resistivity was measured with a capacitively coupled resistivity meter (OhmMapper, Geometrics Ltd., San Jose, California) using an in-line (dipole-dipole) method where a streamer of several receivers are pulled along the ground providing an almost continuous apparent resistivity profile simultaneously. The resistivity data were inverted and 2-D resistivity sections generated using the RES2DINV program (Geotomo Software). Several of the initial transects were subsequently probed with GPR the following year.

In 2007, GPR lines were run using a pulseEKKO PRO unit from Sensors and Software Inc., with followup lines done in 2008 using an older EKKO PRO unit owned by the GSC. In order to assess the tradeoff between the level of detail versus the depth of penetration in the sediments, three different antennas were used during this survey (200, 100 and 50 MHz). The GPR data were processed using 'EKKO View Deluxe' software by Sensors and Software Inc. Some of the lines are composed of smaller segments stitched together because of unexpected interruptions during data logging. Except for the Royal Roads gravel pit survey, all the lines where topographically shifted according to elevations derived from the Lidar using an average velocity of 0.10 m/ns (approximate average for gravel) for estimating the depth. All the images shown in this report were processed with similar gain and migration protocols. The lines were located by GPS logging but it was found that the lines could be more accurately positioned from the digital ortho-photographs acquired during the Lidar survey, and elevations in this report are in metres above sea level (m asl) as calculated during the Lidar survey (James et al., 2010).

In 2012, a seismic reflection survey was done across the mouth of Esquimalt Lagoon using the GSC's multi-component reflection profiling system (Microvibe/LLandstreamer), which consists of a portable vibrator followed by an array of geophones towed behind a vehicle (Pugin et al., 2002; Fig.4). The seismic line was located so as to cross the apparent seaward projection of the LRFZ.

Figure 4: GSC Seismic Landstreamer on Ocean Boulevard, a causeway across the mouth of Esquimalt Lagoon.

Survey lines

The following sections describe each line and provide preliminary interpretations of the results. Figures 2 and 5 show the location of the GPR, seismic, and resistivity survey lines in the vicinity of the LRFZ where it is projected to underlie deposits comprising the Colwood delta. The Jack Lake and 13K Road GPR lines lie about 7 km west of the area of Figure 2. The precise location of each line, including links to each GPR and ground resistivity profile, is plotted in the Google KMZ files found in the Appendix. The Appendix also includes the raw GPR and resistivity data, SEG-Y files of the seismic line and converted GPR files, and plots of each processed profile. The main study areas near the Royal Roads University are shown in Figure 5.

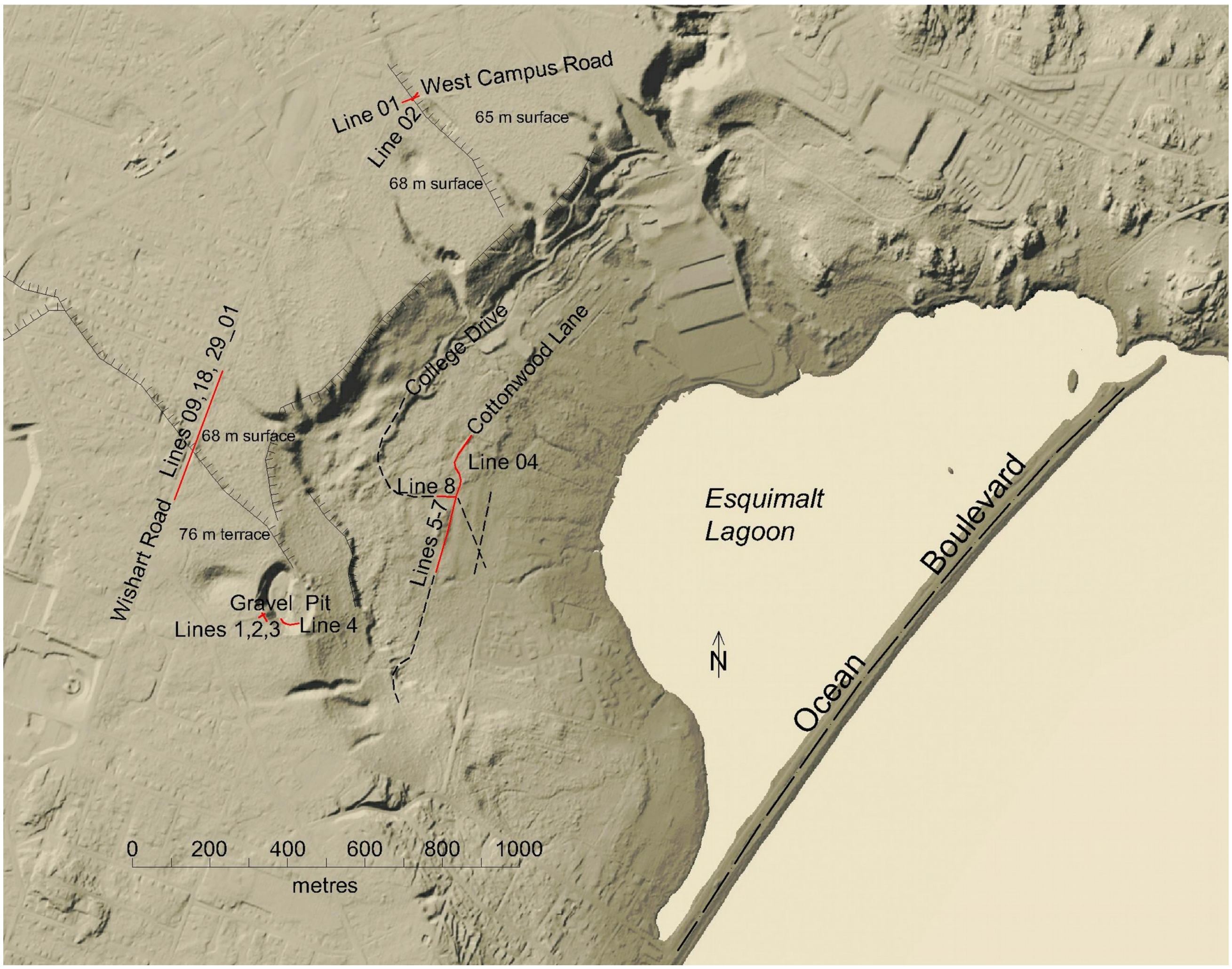

Figure 5: GPR lines (red lines) on the Colwood delta in the vicinity of Royal Roads University. Dashed lines represent ground resistivity lines and scarp lines delineate distinct terraces on the delta. The long dash-dot line shows the location of the seismic line along Ocean Boulevard. Surface elevations are metres above sea level derived from the Lidar survey.

Royal Roads Gravel Pit

Four GPR lines were run at a decommissioned gravel pit in Royal Roads Forest (Hatley Park

Reserve), City of Colwood (Fig. 5). The excavation exploited stratified gravels underlying the delta terrace that forms a level surface at 76 m asl. It is likely that the excavation began at the eastern edge of the terrace and the pit now extends about 140 m to the west. There are no corresponding ground resistivity surveys at this site.

Figure 6: Coarse, crudely-stratified gravel exposed near the top of the gravel pit. The notebook is 20 cm high. See Fig.5 for location.

GPR lines 1 and 3 run directly over the exposure parallel to the cliff edge in a SSE – NNW direction. Line 1 is along the cliff edge, while Line 3 is about 2.5 m from the edge. Line 2 extends away from the cliff edge at a right angle to Lines 1 and 3 (Fig. 5).

The location of these lines across the terrace surface above the gravel pit face, provided a means to compare GPR profiles with actual pit-face exposures and hence to assess the accuracy of the technique on the Colwood gravels. Lines 1, 2 and 3 were run at 200 MHz with a 10 cm step size for high resolution. This pit is thought to expose typical sediments comprising the Colwood glaciofluvial delta that overlies the LRFZ. The cliff edge on the west side exposes about 20 m thickness of coarse gravel and sand. Indistinct cross-bedding defines large troughs 5-10 m wide and 1-2 m thick. The uppermost 1.5 m of the exposure (Fig. 6) shows well-rounded clasts (mean size of ~ 2 cm) with crude trough cross-bedding and a few interbedded sand lenses (3 cm by 50 cm). Clast-supported cobble layers, and a 1 m thick pebbly-gravel layer are exposed laterally along the cliff-face to the south-east. These beds are interbedded with thicker sand lenses that have an apparent dip to the south-east. The lower slope in the gravel pit is largely covered.

Table 1. Royal Roads Forest gravel pit GPR line summary.

Line	Frequency (MHz)	Length (m)	Trace position (m) and Comment
28_Line1	200	13.2	12.9 – low overhanging branch
28_Line2	200	17.6	8.3 – large root across traverse
28_Line3	200	19.5	17.0 – Ln2 intersection
28_Line4	100	51.25	34.5 – track turns into pit

Results

GPR Lines 1-3 penetrate up to ~ 7 m below the surface with a pattern of reflectors that appear to mimic the sedimentary structure exposed along the cliff edge. Orthogonal Line 2 is in good agreement with a correspondence of individual reflectors identified in Lines 1 and 3 that identify broad troughs in 3D with a foreset bed dip of up to 20° to the east and north-east (Fig. 7).

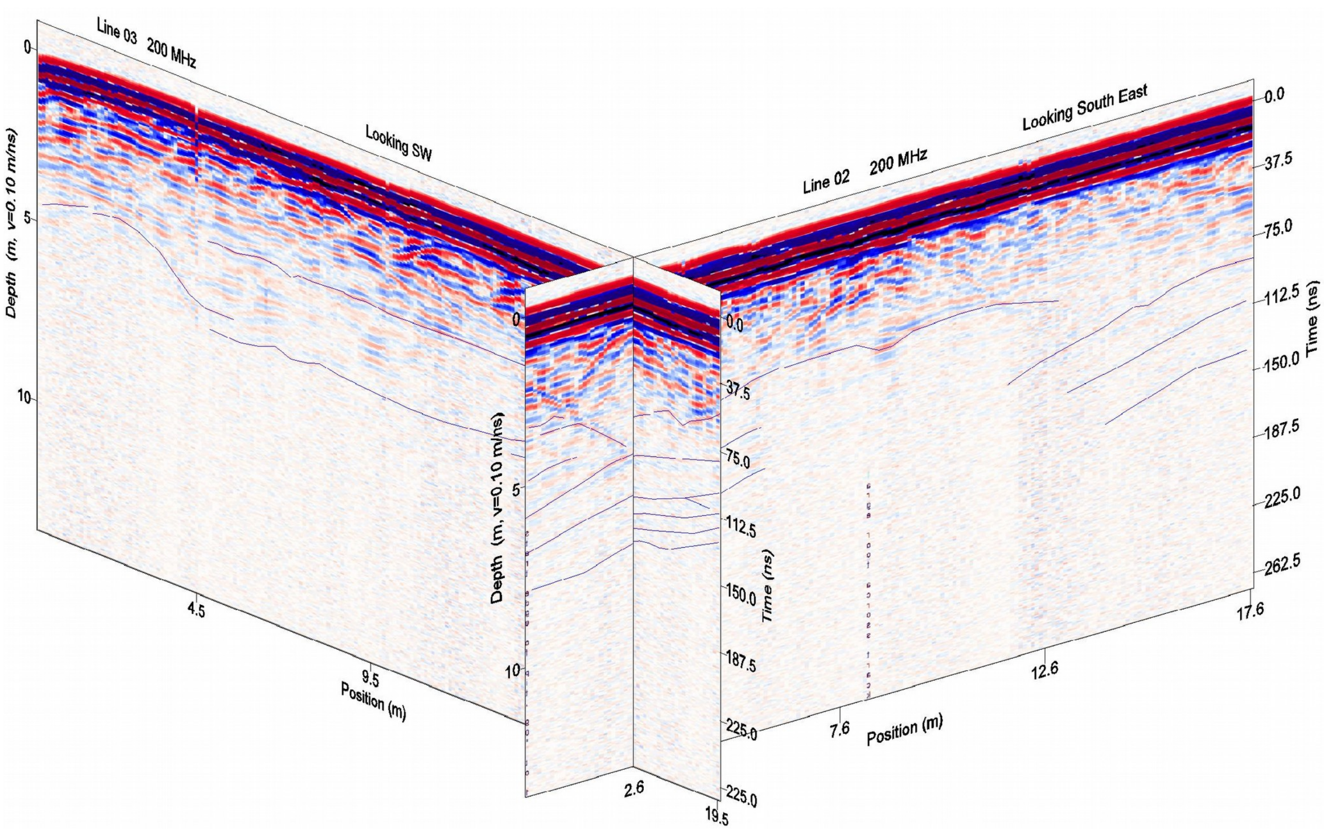

Figure 7: Gravel pit GPR lines 2 and 3. The dark blue lines, drawn between about 3-7 m depth, show the trend of some prominent reflectors.

Line 4 is located on a road leading down into the pit, curving sharply to the north in the last 15 m. The GPR image shows individual reflectors extending for 15-17 m with an apparent dip to the south at ~17° (*see* Appendix: Gravel_pit_Ln4.jpg). The reflectors are thought to show tabular cross-bedding in the gravels, with individual beds extending to at least 10 m depth. Hence, these strata are likely delta foreset beds indicating an eastward progradation of the Colwood delta in this area. In general the 100 MHz line detects reflectors at least 5 m deeper than the 200 MHz lines 1, 2 and 3.

In summary, the images derived from the GPR survey realistically portray bedding structures exposed on the gravel pit walls. Consequently, the GPR survey should be able discern any fault structures that should cross-cut the survey line within the uppermost 10 m of sediment on the Colwood delta.

Wishart Road

Two resistivity and 3 GPR lines were run along the east side of Wishart Road adjacent to Hatley Park Reserve where the roadway cuts across a prominent scarp that marks the edge of a relatively flat surface at about 78 m asl (Fig. 5). The road cuts into the edge of the terrace where at least 2 m of material has been removed to reduce the grade in the roadbed. GPR Lines 09 and 18 start on the same delta surface as the gravel pit GPR lines and run northward over the terrace edge to the next lower surface at 68 m asl (Fig. 5), using 50 and 100 MHz antennas respectively. A third line, (Line 29_1) using a 200 MHz antenna, was imaged only from the foot of the scarp. The resistivity lines, D3Ln0 and D3Ln1, follow the same route as GPR lines 09 and 18, using transmitter to receiver spacings of 10 and 5 m respectively (Fig. 5; *see* KMZ files).

*Table 2. Wishart Road GPR line sum*mary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
Line 09	50	0	Start of line on top of scarp down gravel path along fence to bottom of terrace
		115	At top of slope break; starting down steep part of terrace; just before road cut; road cut rises slightly in elevation
		193	Adjacent to old wooden culvert with wire; no diffraction noted on radar
		208.5	Bottom of steep terrace front; tapered slope; gradual decrease in dip; moving onto flatter ground
		282.5	End of line near the speed hump at bottom of hill
Line 18	100	0	Start at top of scarp
		58	Edge of flat terrace top
		92	Old culvert hoops
		259.75	End at X-walk sign
Line 29_1	200	0	Start at the base of the scarp and continue east to crosswalk
		33.2	Near fire hydrant
		73.9	Crosswalk sign
		78	End with receiver at the east edge of cement sewer on the south side, just after crosswalk.

Table 3. Wishart Road OhmMapper Resistivity line summary.

Line	No. of receivers	Operator offset (m)	Receiver dipole (m)	Rope length (m)	Transmitter dipole (m)	Total Length	Range (Ω·m)
D3Ln0	4	5.32	5	10	5	358.8	192-4747
D3Ln1	4	5.32	5	5	5	356.2	159-5351

Results

GPR lines 09 and 18 both have a very similar pattern of reflectors. Both lines starting on the upper, 76 m elevation delta surface, show distinct tabular cross-bedding at depth with an apparent northward dip. Although the true dip is not visible in 3D, the beds have a similar orientation to the ones imaged at the Royal Roads gravel pit, and hence indicate a general progradation of the terrace to the north east (Fig. 8; see Appendix for detailed plots).

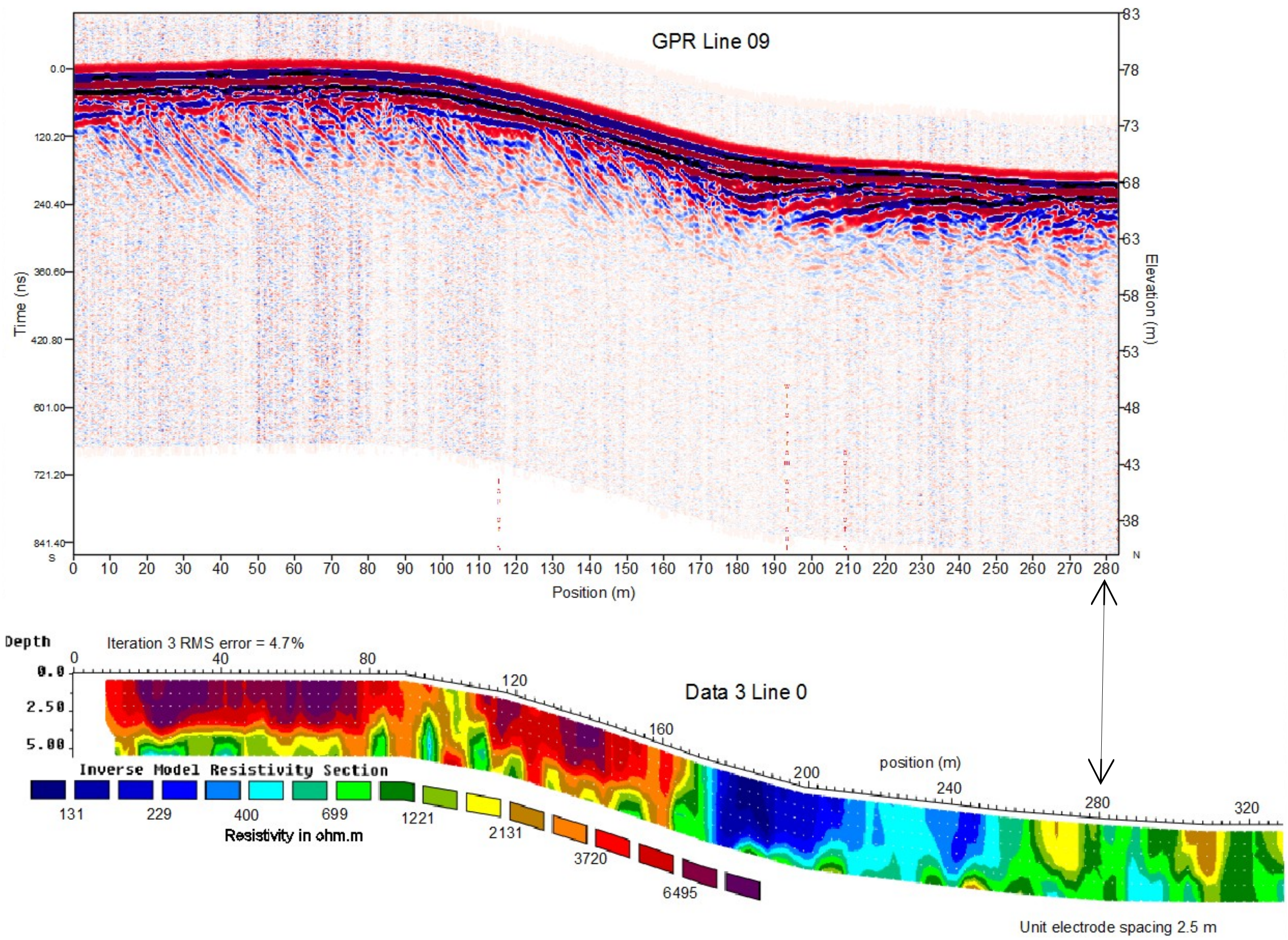

Figure 8: GPR line 09 (top) and resistivity line (D3Ln0), running SSW to NNE along the same transect line on Wishart Road (see Fig. 5 or KMZ files for location; vertical exaggeration: x3 for GPR and x4 for resistivity section).

The dipping beds underlying the upper terrace surface appear to be covered by a 1m thick layer of horizontally bedded material. Moving to the north, off the terrace, this layer thickens to 6-7 m at the base of the slope and no underlying tabular cross-bedding is discernible. Moving further away from the slope, the upper layer appears to thin to about 1 m again ~100 m from the edge of the terrace. The uppermost layer is interpreted to be a disturbed layer related to road construction, although colluvium may make up some of the thicker material at the base of the slope. In the north part of the survey lines, the uppermost layer appears to be underlain by faint trough cross-bedding.

A further comparison of GPR Line 09 and Line 18 shows that the 50 MHz antenna, penetrated up to 12 m below the surface, whereas the penetration was only 8 m for the 100 MHz antenna (Line 18), with only a minor increase in resolution. Likewise, Line 29_1, which ran along the same path as the last 75 m of Line 18 only penetrated a maximum of 5 m depth. None of the lines show any abrupt discontinuities in the bedding indicating any faults. However, all the lines have discrete segments where the penetration suddenly deepens or shallows. It is not known if this is related to deeper structures (*see* Section plots/Wishart Road in the Appendix*)*.

Finally, although lines 09 and 18 have very similar patterns, it should be noted that when positioned relative to ground control points, the patterns do not line up accordingly. The exact cause of this positioning error is not known, but each of the lines had a different step size related to the antenna frequency, resulting in a cumulative positioning error in one of the lines.

The subsurface resistivity section (bottom of Figure 8) shows high resistivity values over the upper surface and slope face in the upper 4 m of sediment, corresponding to well-drained gravels, whereas the colluvium at the foot of the slope has low values likely reflecting more poorly drained finer sediments. Line D3Ln1, running along the same path as D3Ln0, shows a similar pattern but with ~1m less penetration in the resistivity profile. The resistivity of both lines increases to the north, away from the scarp, but a number of service lines crossing the road in this area likely complicate the resistivity pattern.

West Campus Road

Two GPR lines traversed across a gentle scarp separating a 68 m delta terrace from a 65 m asl terrace surface within the Royal Roads University grounds along West Campus Road (Fig. 5; *see* Section plots/West Campus Road in the Appendix). The scarp roughly parallels the scarp surveyed along Wishart Road, 1 km to the southeast, and coincides with a gully incised into the seaward edge of the delta terrace. A rectangular pit along the base of the scarp immediately south of the road was probably used to extract gravel in the past. Line 01 ran parallel to the road, about 2 m off the north edge of the pavement. Line 02 started on pavement and obliquely crossed Line 01, following a foot path to the north west. There are no accompanying ground resistivity lines in this area.

*Table 4. West Campus Road GPR line sum*mary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
Line 01	200	0	Start of line on the west end
		16.9	Receiver flipped over
		31.1	Near telephone pole
		45.9	End off scarp in swale

Line 02	200	0	Start at south end
		4	End of pavement
		21.2	Line ends in swale

Results

Line 01 and 02 penetration with 200 MHz antenna was about 5 m below the surface (*see Appendix)*. In general, the reflection pattern in Line 01 shows a pattern suggesting broad trough cross-bedding in the sediment. Line 01 also shows a few hyperbolic reflections that could represent a few larger boulders within the gravel. However, numerous contorted reflections in the upper few metres suggest that the bedding was disturbed during road construction despite the line being located off the road proper. The southern end of Line 02 started on the road and the penetration was only 2 m over the pavement. The penetration increased abruptly once off the pavement. The deeper reflectors of Line 02 show parallel beds with an apparent south-west dip. These beds are not very extensive and are only evident again as indistinct reflectors at the northern end of Line 02. If the dipping reflectors represent delta foreset beds, it confirms that the lower 65 m asl terrace is an erosional surface cut into the higher terrace sediments.

College Drive and Cottonwood Lane

College Drive and Cottonwood Lane survey areas lie at the foot of a prominent delta terrace within the Royal Roads Forest (Hatley Park Reserve; Fig. 5). The Lidar bare-earth DEM shows the terrace ending at a prominent scarp at 68 m asl. The forested slope below the scarp is hummocky with subdued ridges and characteristics of old slump deposits. The surveyed part of College Drive is mostly underlain by this slump material. Figures 8 and 9 are 1:10,000 scale plots of the survey lines with corresponding resistivity sections and GPR profiles. The locations of the sections are only approximate because they were plotted along a straight line but the actual survey tracks were curved. The surface drainage indicated on the figures was modeled using the Lidar DEM.

Resistivity line D1Ln0 on College Drive starts at the intersection with Cottonwood Lane and goes west until the sharp northward bend in the road. Lines D1Ln4 and D1Ln5 continue northward from the bend in the road to the gate at the park boundary. Lines D1Ln4 and D1Ln5 were run along the same track but in opposite directions and show that the measured resistivity pattern is consistent (Fig. 9).

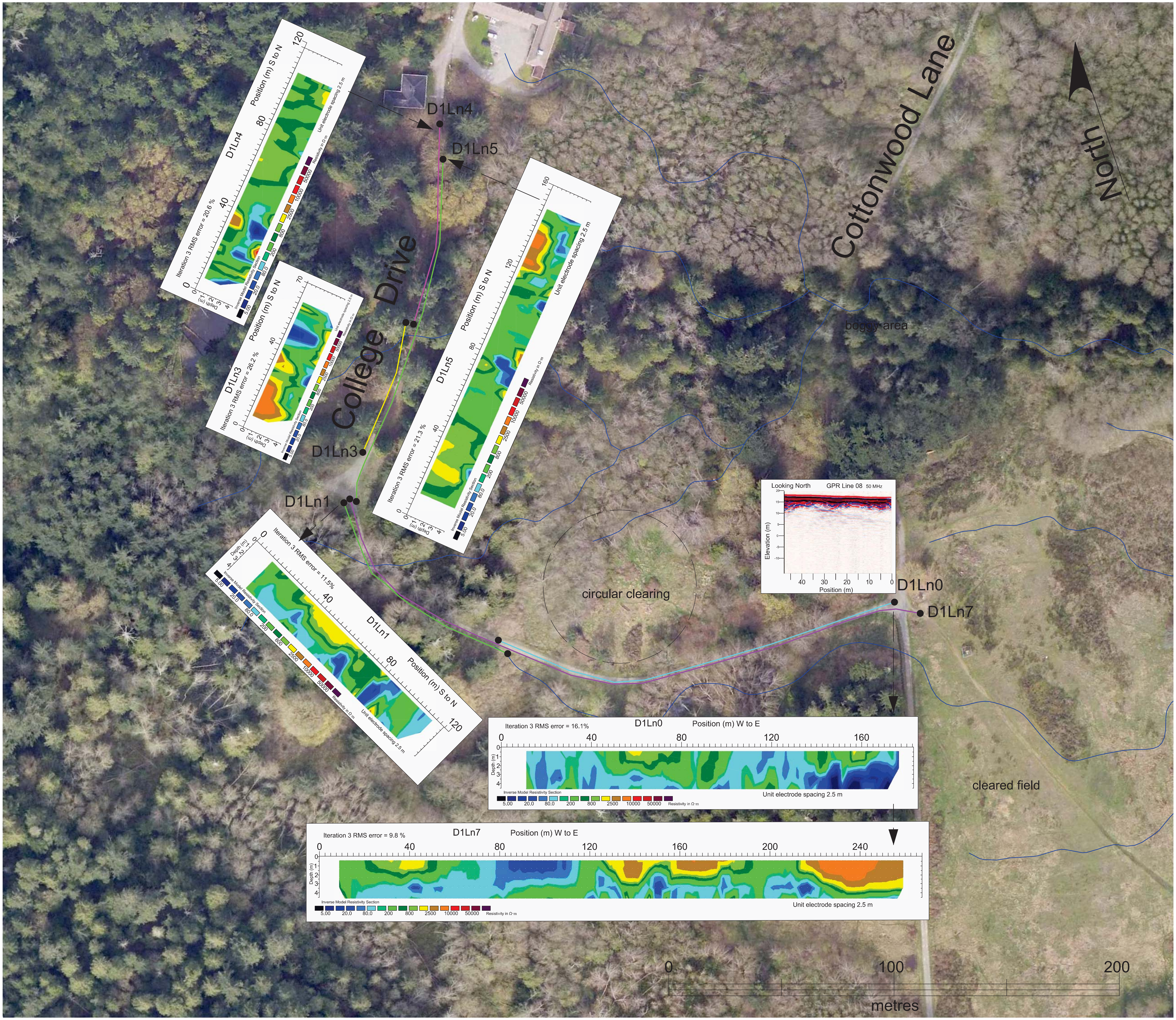

Figure 9: OhmMapper resistivity and GPR lines along College Drive, Royal Roads forest reserve.

Resistivity lines (D1Ln9, and D2Ln0 to D2Ln8) were run along Cottonwood Lane, marking the approximate western boundary of a gently sloping surface that runs down to Esquimalt Lagoon ~375 m away (Figs. 4, 9). This low-lying area is underlain by fine-grained marine sediments of undetermined thickness (Fig.2) and 4 resistivity lines (D2Ln9 to D2Ln12) cross this open area.

Four GPR lines (lines 4 to 7) trend north to south along Cottonwood Lane (Figs. 5, 9). Line 4 starts at the gate to Royal Roads University at about 19.5 m asl, and curves down to an open field at about 17 m asl. GPR lines 5, 6, and 7 were merged into a single line extending SSW from the end of Line 4. The merged profile (Lines 4-7) Line 8 starts near the south end of Line 4 and runs west up the slope for 47.5 m towards the hummocky area and coincides with the easternmost part of ground resistivity line D1Ln0 (Fig. 9).

Table 5. Cottonwood Lane GPR line summary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
Lines 4-7	50	0	Start of line at gate
		12.5	Culvert
		21.5	2 shots taken without advancing
		52	End of swamp
		75	2 shots taken without advancing
		117	Coming out of the forest into the clearing; one alder tree on left side of line; trail turns back to right
		157	Maple tree; near intersection of road
		173	Last good trace before transmitter failed; end Line 4 in swampy area
		173.5	Start Line 05: ~15m from Maple tree; stepped back so as to continue from end of Line 04; Heading SW; past intersection
		234.5	High frequency reflections at depth; Messed with gain; Close to forest on the NW side of road; Not sure if real stratigraphy or diffractions from trees
		291	Leaving wooded area on the right side of trail into open area with metal well casings ~10m off trail
		344.5	End of field; moving into alder and equisetum; wetter ground
		347	Started Line 7 at the end of the good traces ended in Line 06; heading down the hill into the swamp (Bee Creek)
		373.5	End of Line 7
Line 8	50	47.5	Perpendicular to main trail; start at intersection next to maple tree; heading up towards the scarp

Table 6. Royal Roads Forest OhmMapper Resistivity line summary.

Location	**Line**	**No. of receivers**	**Operator offset (m)**	**Receiver dipole (m)**	**Rope length (m)**	**Transmitter dipole (m)**	**Total Length**	Range (Ω·m)
College Drive	D1Ln0	5	7.57	5	5	5	142.5	0.6-799
College Drive	D1Ln1	5	7.57	5	5	5	104.2	16-1175
College Drive	D1Ln3	5	7.57	5	5	5	63	5-2344
College Drive	D1Ln4	5	7.57	5	5	5	127.5	24-2353
College Drive	D1Ln5	5	7.57	5	5	5	145.0	18-2098
College Drive	D1Ln7	5	7.57	5	5	5	293.5	5.5-3759
Cottonwood Lane	D1Ln9	5	5.32	5	5	5	135.0	15-8187
Cottonwood Lane	D2Ln2	4	5.32	10	5	5	351.2	36-1432
Cottonwood Lane	D2Ln3	4	5.32	10	5	5	46.2	85-7552
Cottonwood Lane	D2Ln4	4	5.32	10	5	5	123.8	52-9529
Cottonwood Lane	D2Ln5	4	5.32	5	5	5	456.3	9-3520
Cottonwood Lane	D2Ln6	4	5.32	5	5	5	216.3	23-8432
Cottonwood Lane	D2Ln7	4	5.32	5	5	5	198.7	17-21064
Cottonwood Lane	D2Ln8	4	5.32	5	5	5	73.7	58-1925
Hatley Park field	D2Ln9	4	5.32	5	5	5	223.8	46-6301
Hatley Park field	D2Ln10	4	5.32	5	5	5	221.2	47-1990
Hatley Park field	D2Ln11	4	5.32	5	5	5	191.2	53-10922
Hatley Park field	D2Ln12	4	5.32	5	5	5	211.2	66-3183

Results

The resistivity profiles penetrated to a depth of ~ 5 m below the surface with inverted values ranging from less than 1 to 21 thousand ohm metres (Ω·m). In general, low values can be expected for clay or fine alluvium with a high moisture content, whereas well-drained sand and gravel would have high measured resistivity, but the highest values would be expected in bedrock. For comparison, average resistivity estimates reported from bore holes in northeastern Ontario were 47 Ω·m for clay, 123 Ω·m for till, and 251 Ω·m for sand (Palacky and Stephens, 1990).

In general, the ground resistivity sections have a mottled pattern with an absence of continuous layers suggesting stratified beds of unconsolidated sediments. This may be because most of the survey lines were taken along the roads and in some places the roadbed has more than 2 m of fill and culverts cross underneath the road. The exact positioning of some of the lines is not possible because the sections were plotted as straight lines whereas some of the survey lines followed the curves in the road. This means that identifying specific ground features with corresponding resistivity patterns is confounded. Nevertheless, there is broad correspondence between resistivity and local surface drainage. Poorly drained areas tend to have low resistivity, as observed where the survey lines crossed boggy areas. Higher resistivities were measured in gravelly stream crossings where the channel is underlain by well-drained sediments.

College Drive resistivity lines D1Ln3, 4 and 5 show generally similar patterns where they overlap (Fig. 9), although their relative positions are only approximate, as noted above. This part of the roadway, paralleling the slope, appears to be built along a broad ridge crest of slumped material. The ridge itself has moderate resistivity of 200-500 Ω·m, higher values relating to a better drained and/or coarser grained road bed. Smaller areas of 20 Ω·m or less may be due to wetter areas directing drainage under the roadway. Surveys of these areas may also be detecting drainage pipes buried beneath the roadbed; however no underlying pipes were observed here during the survey.

Line D1Ln7, on College Drive, runs east to meet Cottonwood Lane, descending about 6 m in elevation. The western end of this line appears to have more resistive sediments (200-2000 Ω·m) layer overlying a less resistant layer (≤150 Ω·m). The contact is abrupt and dips westward into the slope. This layering may indicate material that was sheared and stacked from downslope mass wasting. However, the extent of anthropogenic alteration in this area may be significant because the Lidar DEM shows a level circular clearing, 34 m in diameter, just north of D1Ln7. Although lines D1Ln0 and D1Ln1 were along the same path as D1Ln7, the resistivity profiles are only broadly similar and it is not known why the eastern ends of D1Ln0 and D1Ln7 are so dissimilar (Fig. 9). GPR line 8 coincides with the east end of resistivity lines D1Ln7 and D1Ln0. The GPR reflection profile shows lenticular beds resembling trough cross-stratification, the unit thickening from about 4 m to 8 m depth to the east.

The sediments underlying Cottonwood Lane were imaged by 9 resistivity sections and 4 GPR profiles (Fig. 10). The open field west of Cottonwood Lane was traversed by 4 resistivity lines, an area thought to be underlain by fine marine sediments (Fig.2). In general the resistivity sections are well reproduced where the lines overlap.

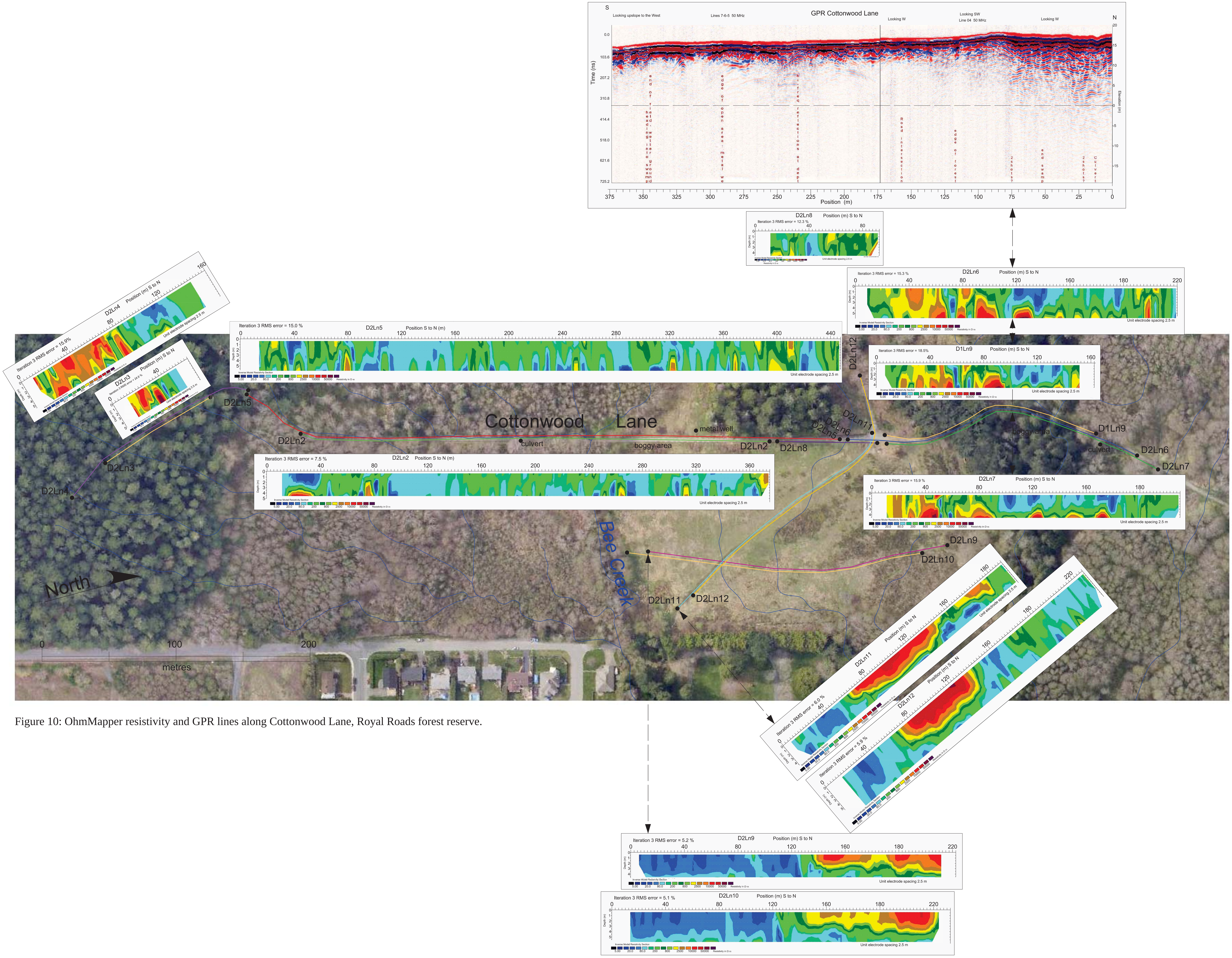

Figure 10: OhmMapper resistivity and GPR lines along Cottonwood Lane, Royal Roads forest reserve.

Lines D1Ln9, D2Ln6 and D2Ln7, in the northern part of Cottonwood Lane, have low to intermediate resistivity values (<200 Ω·m) extending to a depth of 4 m for about 80 m of the roadway. Like on College Drive, this zone coincides with a boggy area where surface streams converge. At least one culvert crosses under the road which may coincide with a small area of high resistivity underlying the area of low values, but its exact location in the sections is imprecise. Notably, the area of lower resistivity corresponds with a zone of deep subparallel reflectors on GPR Line 04 (Fig. 10). The northern part of the GPR line shows the horizontal reflectors extending to at least 15 m below the surface, but at position 75 m the reflectors end abruptly and penetration is reduced to about 5 m with a corresponding increase in resistivity to values exceeding 10,000 Ω·m. The cause of this lateral discontinuity is not known. The area of shallow penetration may be underlain by a bedrock protuberance but no outcrops occur in the area. Farther south on GPR Line 04, other smaller areas of slightly deeper penetration occur at positions 100 and 125 m. The deeper radar penetration at position 125 m appears to coincide with another zone of low resistivity.

On Cottonwood Lane south of the intersection with College Drive, resistivity lines D2Ln2, D2Ln5, and D2Ln8 are broadly similar where they overlap with moderate values between 80 to 300 Ω·m. Like north of the intersection, distinct areas with of lower resistivity (<150 Ω·m) seem to correspond with a zones of deeper radar penetration. For example, on GPR Lines 5-7 (position 225 to 260 m) high frequency reflectors extend down to a depth of about 15 m below the surface. There are also segments with lower resistivity in the southern parts of lines D2Ln2 and D2Ln5, but these areas do not have corresponding GPR coverage. Resistivity values rise at the southern end of Cottonwood Lane as the road traverses the fore slope of the delta terrace, rising about 19 m in elevation (D2Ln3, D2Ln4).

Resistivity lines D2Ln9, D2Ln10, D2Ln11 and D2Ln12 cross the field south of Cottonwood Lane, which is thought to be underlain by fine marine sediments. These lines show large areas of relatively low resistivity (<80 Ω·m) as would be expected in an area underlain by finer sediments. Nonetheless, the lines also reveal a distinct pattern of high resistivity that may depict a channel, about 4 m deep, that crosses the field in a northeast to southwest direction. Whether this is a man-made feature is unknown.

Ocean Boulevard shallow seismic line

As noted, Esquimalt Lagoon is underlain by the seaward extension of the LRFZ. Consequently the seismic line along Ocean Boulevard (Fig. 5) would be expected to cross the fault zone orthogonally (Fig.2) and is parallel to, and about 1100 m east of the GPR lines on Cottonwood Lane.

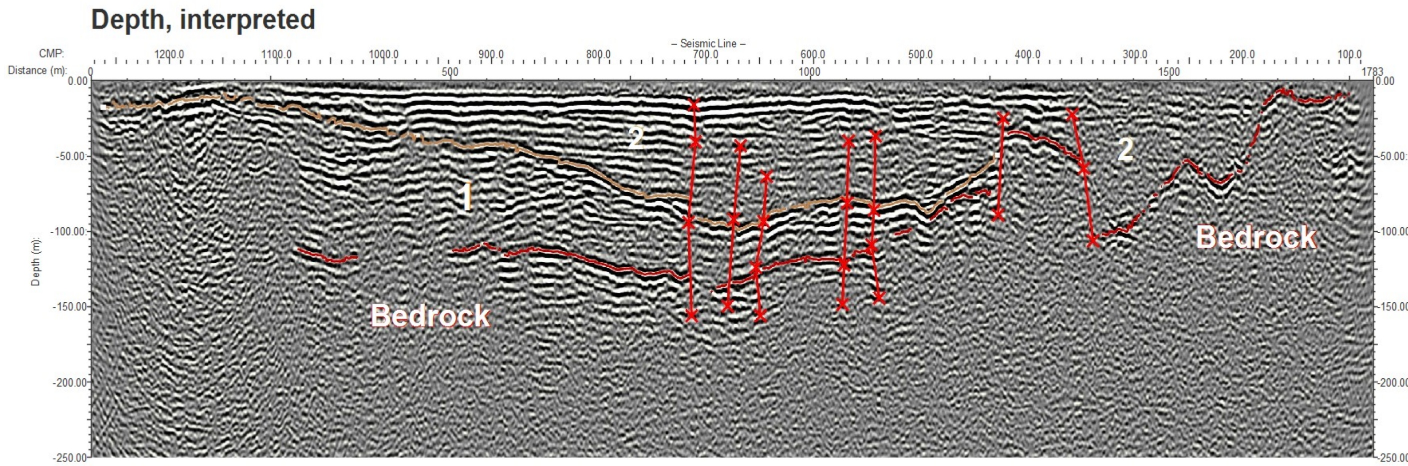

Figure 11: Shallow seismic line across Esquimalt Lagoon showing at least 140 m of sediment infilling a bedrock basin or trough. Apparent faulting in the bedrock propagates upward through two dense units (labelled 1 and 2), which are overlain by 3-4 m of less dense material forming the uppermost unit. Processing and interpretation by A. Pugin (GSC).

The interpreted seismic reflection survey across the mouth of the lagoon is shown in Figure 11. The P-wave reflection profile, processed and interpreted by A. Pugin (GSC), shows that unconsolidated sediments extend down to 140 m below sea level. The sediments appear to infill a bedrock basin, or trough, defined by surface bedrock outcrops adjacent to the lagoon. The uppermost 3-4 m is characterized by a poorly-resolved layer of low-velocity sediments (300 m/s) overlying two thick layers of relatively high velocity material (~2300 m/s). The high velocities of the thick layers are unusual for unconsolidated sediments suggesting that these units may be older compacted sediments (A. Pugin, pers. comm., 2012). This implies that only the thin uppermost layer constitutes postglacial material (equivalent in age to the Colwood delta). Consequently, the underlying deposits were probably overconsolidated by overriding ice during the last glaciation and, if their origin is glacigenic, they are likely basal till or a glaciomarine diamicton dating from at least the last glaciation (older than ca. 14,000 years ago).

With respect to neotectonics, the most important features on the seismic profile are a series of near-vertical discontinuities that appear to be faults propagating from the bedrock into the two overlying glacigenic units. As a first approximation this would imply that there may have been some movement on the LRFZ as recently as the last glaciation, but because the faults do not appear to penetrate the uppermost sediments, there was likely little or no movement here since post glacial time.

Lastly, the prominent bedrock protuberance seen on the north side of the seismic profile may be a fault bound ridge aligned with the northwest-southeast trend of the LRFZ. Therefore, it is possible that one or more such ridges underlie the sediments of the Colwood delta and may have been imaged by GPR Line 04 on Cottonwood Lane where there are abrupt discontinuities in the depth of radar penetration.

Parkdale Drive

The surface of the Colwood delta has a number of depressions occupied by lakes or wetlands. A number of these are related to melting out of buried glacial ice and other meltwater activity during deglaciation. Nevertheless, two broadly parallel troughs are aligned with the trend of the LRFZ – Fishers Field, a wetland park, and Glen Lake (Fig. 2). Two exploratory resistivity lines were run along Parkdale Drive, just north of Fishers Field where road crosses the trend of the LRFZ. At this location, the Colwood delta sediments end about 50 m to the north at the foot of a steep hill. Recent excavations at the foot of the slope exposed 3 m of cross-stratified sand and fine gravel overlain by at least 1 m of stony diamicton interpreted as slump material off a glacier (Fig. 12). Consequently, these indurated sediments probably predate the postglacial gravels of the Colwood delta.

Figure 12: Three metres of cross-bedded sand overlain by 1 m of diamicton north of Fishers Field.

Table 7. Parkdale Drive OhmMapper Resistivity line summary.

Line	No. of receivers	Operator offset (m)	Receiver dipole (m)	Rope length (m)	Transmitter dipole (m)	Total Length	Range (Ω·m)
D4Ln1	4	5.32	5	5	5	223.8	166-5738
D4Ln2	4	5.32	5	10	5	258.8	392-22821

Results

Lines D4Ln1 and D4Ln2 overlap but run in opposite directions. Although the patterns of resistivity are similar, it is inexplicable why the latter line has significantly higher values. In general, both lines show a 3-4 m layer of highly resistive material overlying a less resistive material. It is likely road fill that comprises much of the top layer; however it is possible that the two layers are the stony diamicton unit overlying the bedded sand unit that are exposed immediately to the north (Fig. 12).

Colwood Creek Park

The Colwood Creek Park survey area is on part of the same broad delta surface that was imaged by GPR and resistivity lines on Wishart Road, about 1.73 km to the west and Glen Lake lies about half a kilometre to the east (Fig. 2). Six GPR lines were run along a trail within the park starting on Sunridge Valley Drive and ending at the Galloping Goose trail to the north. Unfortunately, technical difficulties during the survey resulted in some data loss. GPR Line 12 is only 88.5 m long, whereas the distance surveyed was 108 m. Moreover, because of frequent breaks in data collection, the higher resolution, GPR Lines 19-23 were merged to make a composite profile (Fig. 13).

*Table 8. Colwood Creek Park GPR line sum*mary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
Line 12	50	0	Start line on trail from Sunridge Valley Drive; Under power lines
		15	Offset line slightly to get around rocks that block the trail
		18	Back on line now
		63	Fault structure at depth?
		88.5	Finished line on the Galloping Goose at the crest of the rail bed; ~2 m of fill
Line 19-23	100	0	Start Line at Sunridge Valley Drive; move along trail to the north
		17.5	Start Line 20
		23.75	Start Line 21
		32.5	Start Line 22
		34.75	Start Line 23
		66	Fault structure at depth?
		115.75	End at Galloping Goose Trail

Results

Both the 50 and 100 MHz lines show a consistent pattern with penetration to about 7 m below the surface. Oblique and divergent reflectors suggest that the area is underlain by stratified gravels, as would be expected underlying the delta surface. Some hyperbolic reflections may be from larger boulders in the sediment. Short, chaotic reflectors at the northern end of Line 19-23 indicate at least 2 m of man-made fill underlying the Galloping Goose trail. The most interesting feature on both the radar profiles is the abrupt lateral discontinuity of some deeper horizontal reflectors that form a steep, fault-like structure at position 63 m on Line 12, and position 67 m on the composite Line 19-23 (the feature is not a suture point of the latter line). The feature warrants further investigation (*see* Appendix: Colwood_Crk_Pk_Ln12.jpg and Ln19-23).

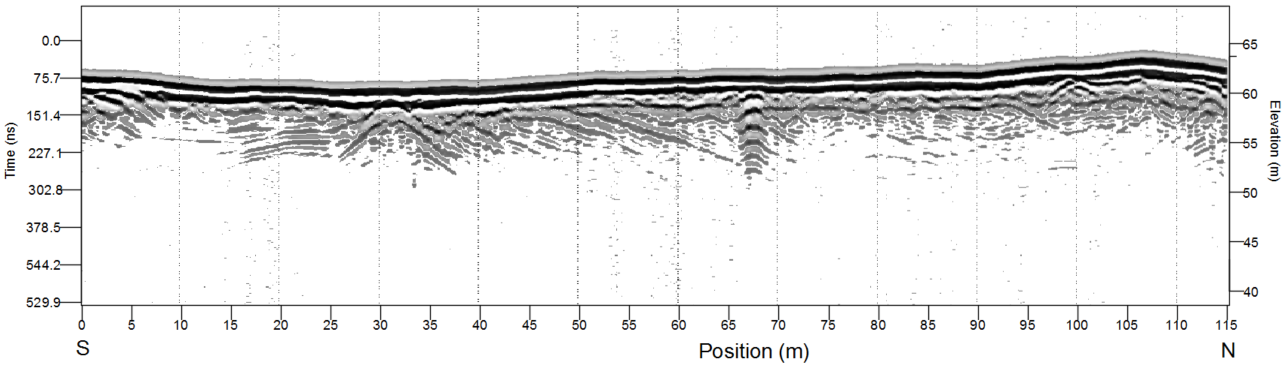

Figure 13. Merged GPR lines 19 to23, Colwood Creek Park.

Goldstream River Terrace

GPR Line 24 is located on a glaciofluvial terrace near the apex of the Colwood delta above the Goldstream River at 75 m asl. The site is immediately east of the point where the southwest-flowing river turns abruptly north to flow into Saanich Inlet (Fig. 2). This diversion is the result of stream capture that occurred after the head of Saanich Inlet became ice-free during deglaciation, opening up a shorter route to the sea. A river exposure on the north side of the terrace shows that the terrace is comprised of at least 45 m of well-rounded gravel and sandy diamictons, but any sedimentary structures are obscured by slopewash. A gravel pit about 700 m to the southwest exposes several metres of stratified gravel and sand (Fig. 14); as expected to underlie this area.

Figure 14: Cobbly gravel and coarse sand exposed in a gravel pit near Goldstream River.

*Table 9. Goldstream River terrace GPR line sum*mary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
Line 24	100	160.75	Line starts on the north end of the parking lot at the end of the road. Most of the line is on pavement, ending at Sooke Lake Road (Canyon Park Estates).

Results

GPR Line 24 shows subparallel reflectors and numerous hyperbolic reflectors dispersed through the profile to at least 10 m depth (Fig. 15). This pattern is interpreted to reflect stratified gravels with occasional large boulders scattered throughout. At position 109 m on the GPR line there is an abrupt phase change in the signal throughout the profile showing up as a vertical lateral discontinuity. The genesis of this feature is unknown, but it may be either an instrumentation artifact or anthropogenic because its position coincides with adjacent property lines.

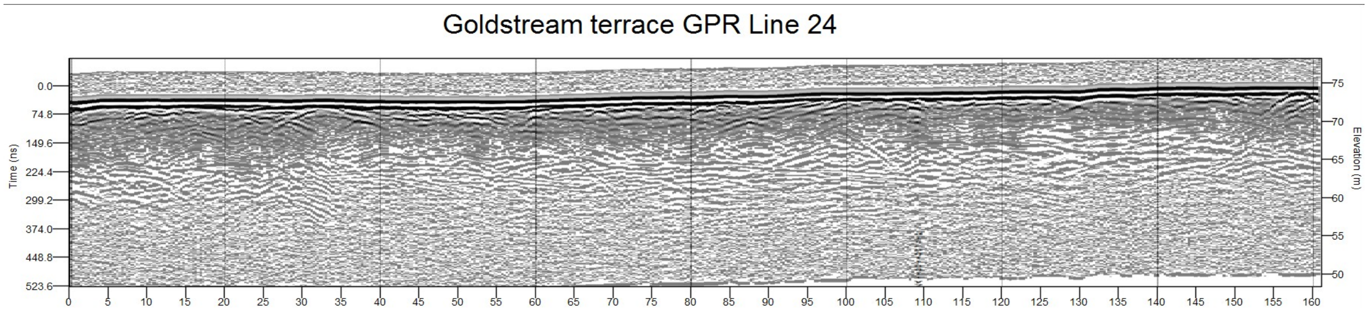

Figure 15: GPR Line 24 on a terrace above the Goldstream River.

13K Road

The 13K Road GPR site is located within the LRFZ, in a small boggy area at the foot of a rounded hill, about 750 m east of Jack Lake (Fig. 1). The hill is composed of glacially smoothed bedrock rising about 25 m above the site (Fig. 16). Glacial erosion was intense enough to shape the hill into an ovoid shape in plan view, with the long axis oriented nearly north to south, the main direction of former glacial flow. More intensely streamlined hills just north of Jack Lake attest to the dominant flow direction. However, sometime during deglaciation, there was a secondary glacial flow to the southeast within the LRFZ valley that crosscut the main ice flow. This flow was oriented in the same direction as the structural fabric of the underlying bedrock and etched the surface with fine parallel flutings (Fig. 16). Nevertheless, the crest of the hill has a prominent bedrock lineament forming a 2 m scarp (north side up) for about 220 m and there is a parallel ridge immediately to the northwest. The hill itself is mostly exposed bedrock with very little soil cover. Consequently GPR lines 16 and 17 were located in an attempt to cross the potential fault zone.

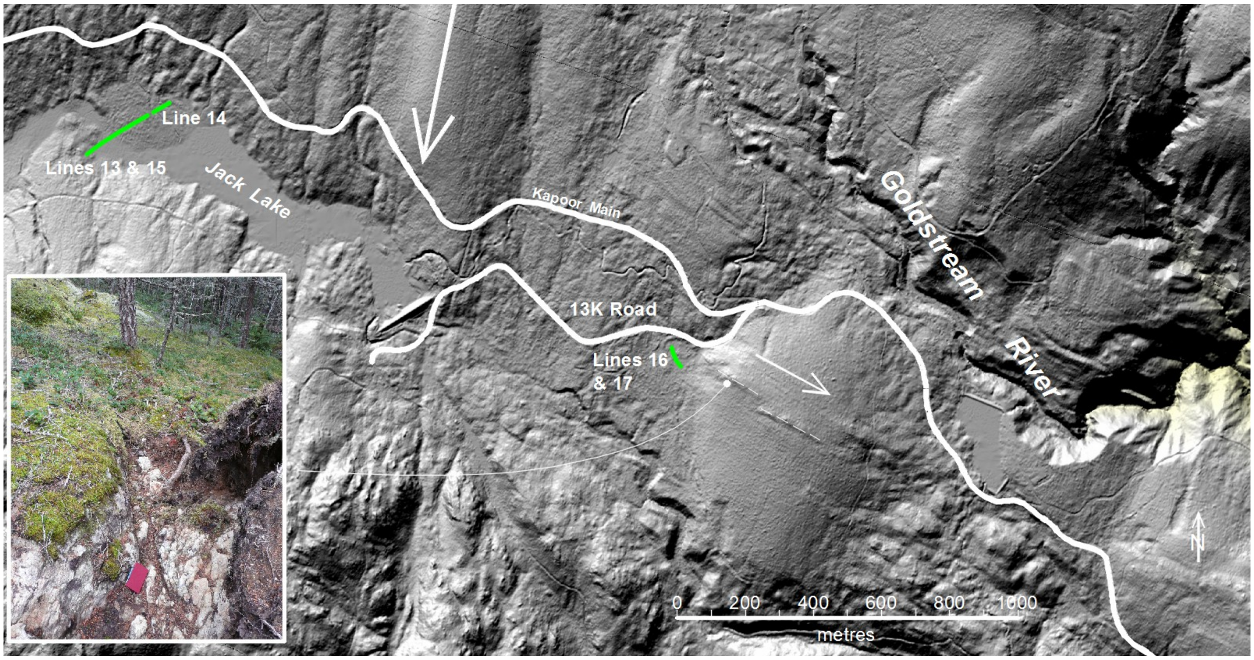

Figure 16: Location of the GPR lines near 13K Road and Jack Lake (green lines). The dominant ice flow from the last glacial maximum was from the north (large arrow), which was crosscut by a subsequent local ice flow within the LRFZ valley (small arrow). The dashed lines indicate prominent bedrock lineaments discussed in the text. Inset shows a steeply dipping fracture in the Metchosin Formation forming a step in the southern slope of the ridge. The photograph is looking approximately the southeast, along strike, with the fracture running from the bottom centre in the foreground to top centre of the photograph.

T*able 10. 13K Road GPR line sum*mary.

Line	**Frequency (MHz)**	**Cumulative Length (m)**	**Comment**
LINE 16	100	0	Starting on far side of swamp heading towards 13K Road; no standing water, tall grass; organic mud is surface sediment
		48.75	Lost transmitter under tree half way across the second part of the swamp (after fallen cedar tree) near end of swamp; starting another line where transmitter died so lines can be stitched together; last good trace was 194
LINE 17	100	15.25	Continues from Line 16

Results

GPR lines 16 and 17 were merged in Figure 17, which shows the profile from the south to the north. Radar penetration was only 5-6 m, perhaps owing to wet conditions below the surface or the presence of bedrock at shallow depth. The pattern of reflectors show a number of depressions that appear to be infilled with sediment with more or less parallel bedding. Two steeper depressions in the northern 20 m of the survey line have relatively undisturbed sediments about 1 m deep but the base of the depressions is underlain by a 2 m thick layer of reflectors having a chaotic pattern. The nature of these apparently disturbed sediments is not known but there is an old graded roadway only 25 m from the end of the survey line.

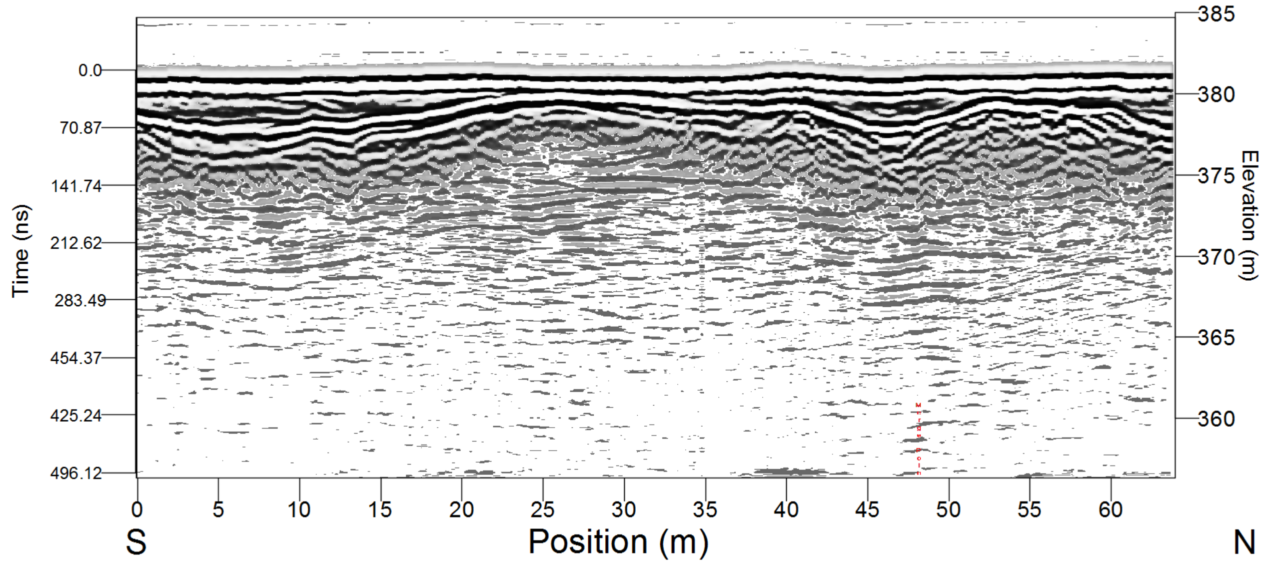

Figure 17: Merged GPR lines 16 and 17 south of 13K Road.

Jack Lake Reservoir

Three GPR lines cross the floor of the LRFZ valley at the north end of Jack Lake, a recently decommissioned reservoir (Figs. 1,16). Lines 13 and 15, shot at 50 and 100 MHz, respectively, were taken along the same transect line. The survey lines were over bouldery gravel that was recently exposed when the reservoir was drained. The gravel cover is of variable thickness as outcrops of bedrock occur near the southwest end of lines 13 and 15, whereas thicker sediments lie to the northeast where the survey lines cross an alluvial fan originating from Mavis Creek on the north side of the valley. Line 14 is a northeast extension of line 13, starting on the east side of Mavis Creek.

*Table 11. Jack Lake Reservoir GPR line sum*mary.

Line	Frequency (MHz)	Cumulative Length (m)	Comment
LINE 13	50	0	Line across reservoir, west to east; outcrop exposed in creek bed (foliation 320/50).
		47	Low spot; moist ground; no standing water; some small channels < 1 m wide.
		82	logs imbedded reservoir bottom
		119.5	Shot taken in mid air
		188.5	End of Line 13 at big stump and gully
LINE 14	50	53	Crossed gully (Mavis Creek) and started on far side; can just see edge of dam
LINE 15	100	0	Line runs along same track as Line 13
		38.25	Similar diffraction noted in both 50 and 100 MHz surveys at same location so could be used to reference lines
		50.5	Low spot a little farther along than the low noted in the 50 MHz survey; At first of little channels; Second little channel ahead
		183.25	End of Line. GPS position: 452443,5369634; Note, this position is about 9 m from the stump as located on the orthophoto. Stump is the end of Line 13.

Results

Based on radar penetration, the depth of the bouldery surface gravel extents from less than 5 m in the southwest to about 24 m in the northeast as the valley floor is crossed (Fig. 18). The many boulders observed on the surface are also present in the underlying gravel, as evidenced by many hyperbolic reflectors scattered throughout the profiles, especially in the higher-resolution profile (Line 15). Bedrock outcrops near the southwest end of the survey lines coincide with the shallower penetration; hence the base of reflectors confirms the sediment/bedrock interface. An abrupt step in the valley bottom at position 75 m may be a bedrock lineament that is oriented along the valley. Farther to the northeast, the bedrock surface becomes more jagged with narrow notch-like areas of deeper penetration at positions 100, 140 and 155 m, which may align with other lineaments oriented along the bedrock strike (Massey et al., 2005). At first approximation, unconsolidated sediments overlie the bedrock lineaments conformably, although the numerous hyperbolic reflectors from the boulders may have masked possible disturbances.

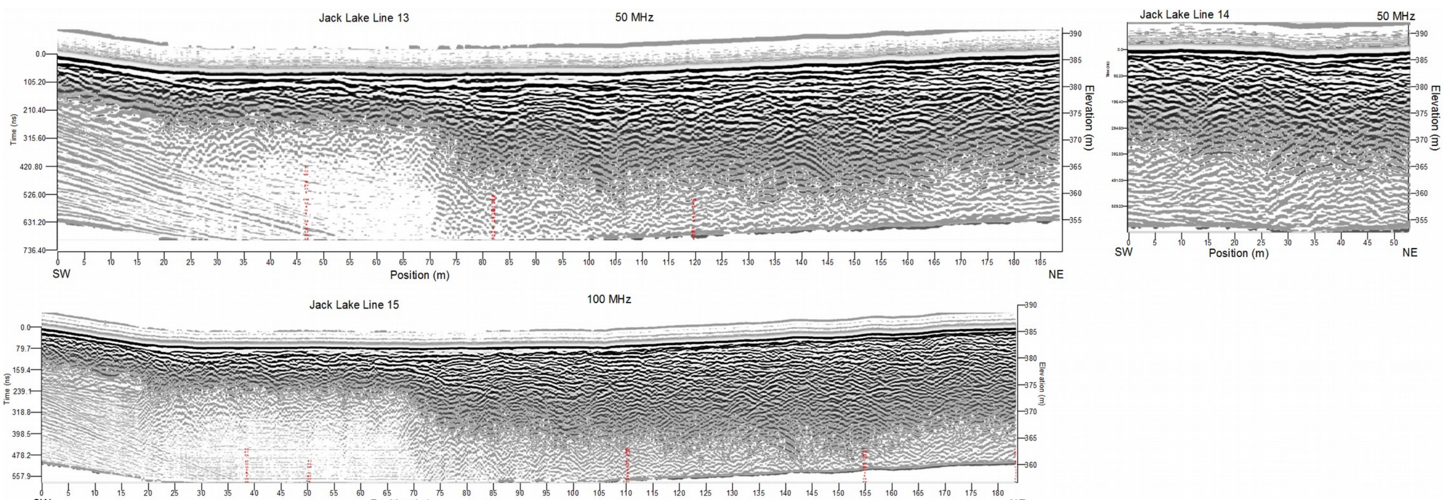

Figure 18: GPR lines across the Leech River valley north of Jack Lake. Lines 14 is a continuation of Line 13, whereas the higher resolution Line 15 runs along the same path as line 13.

Summary

Preliminary investigations of the unconsolidated sediments overlying the Leech River Fault Zone are presented in this report. The main goal of the study was to assess the feasibility of identifying faults in the relatively young glaciofluvial and postglacial sediments using ground penetrating radar (GPR), capacitively coupled resistivity, and a shallow seismic reflection survey. Potential lineaments identified on high-resolution Lidar topography provided target areas; however a detailed surface analysis revealed that the Colwood delta was dominated by a braided meltwater channel network complicating the analysis. In general, when surface exposures of the underlying deposits were present, it was found that the GPR profiles provided a good depiction the underlying gravel deposits and their structures. Soil moisture conditions and surface drainage seemed to have the greatest impact on the resistivity profiles, limiting their interpretation unless they were accompanied by GPR profiles.

The most definitive evidence of faulting was provided by the shallow seismic line across the mouth of Esquimalt Lagoon where steep fault structures, originating in bedrock > 100 m below sea level, cross-cut dense glacial deposits (likely till or glaciomarine diamicton). These faults, however do not appear to penetrate the poorly resolved uppermost few metres of sediment, which are thought to be postglacial (Holocene) in age. The depth of the faulted material in the lagoon suggests that both the resistivity and GPR surveys, which typically penetrated less than 10 m from the surface are of insufficient depth to detect deeper faults. Nevertheless, some of these profiles detected irregularities in the subsurface that warrant further investigation.

Acknowledgments

Many colleagues at the Pacific Geoscience Centre (GSC-Pacific) provided discussion and valuable input during this work. During the course of the field work, the help of Garry Rogers (PGC), Adrian Hickin and Travis Ferbey (BCGS) was greatly appreciated. André Pugin and crew (GSC-Northern) conducted the seismic line across Esquimalt Lagoon. Royal Roads University grounds keepers graciously allowed access to the forest reserve and the Capital Regional District granted permission to enter the Greater Victoria water supply watershed. The careful review and valuable suggestions by Lucinda Leonard (University of Victoria) was greatly appreciated.

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