MULTI-PARAMETER ASSESSMENT OF SLOPE MOVEMENTS IN GLACIOLACUSTRINE SEDIMENTS, QUESNEL RIVER VALLEY, BRITISH COLUMBIA, CANADA

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Abstract

A detailed site investigation of a landslide on the upper Quesnel River is undertaken as part of a regional assessment of landslide activity. Along side more conventional stratigraphic and sedimentological investigative measures, geophysical surveying techniques are utilized to aid in the description of the internal structure of the landside and surrounding terrain This paper presents some of the preliminary results and interpretations of ground penetrating radar and direct current resistivity surveys and relates geophysical interpretations to the geologic structure of the terrace and landslide. They have proven their utility for subsurface mapping of landslides at two different scales. In addition, it is believed that surfaces of rupture have been imaged by both methods.

Résumé

Une investigation détaillée du site d'un glissement de terrain le long de la rivière Quesnel a été conduite dans le cadre d'une évaluation régionale de l'évaluation de l'aléa. En plus d'une reconnaissance stratigraphique et sédimentologique conventionnelle, le site du glissement de terrain a fait l'objet d'une investigation géophysique afin de décrire la structure interne de la zone affectée par le glissement de terrain et des secteurs adjacents. Cet article présente une interprétation préliminaire des résultats obtenus par géoradar et par résistivité en courant continu, et fait le lien entre l'interprétation des données géophysiques et les structures géologiques du glissement de terrain et de la terrasse. Ces techniques ont montré leur utilité pour cartographier en subsurface des glissements de terrain à deux échelles différentes. Il est en outre possible que la surface de rupture ait été localisée par les deux méthodes utilisées.

1. INTRODUCTION

An above average number of landslides occurring along the Quesnel River in the Cariboo region of British Columbia threaten fish stocks, small placer operations, homesteads and important historical sites within the river valley. Moreover, the landslides often have significant economic impact on pulp mill operations located along the river's lower reaches. Stratigraphical, sedimentological and geophysical investigative techniques as well as GIS and 3D modeling have been used to inventory and better understand the slope processes that affect the region.

Collectively, such methods provide an excellent opportunity to test their virtues as landslide assessment tools. The critical factor here is the ability to verify geophysical interpretations against observable subsurface geological deposits. The observations and data generated here provide an exceptional case study for multi-parameter assessment of landslides.

2. STUDY AREA

The study area is located approximately 50 kilometres southeast of Quesnel, near the township of Likely, British Columbia (Fig. 1a). Surficial mapping was conducted for the Hydraulic map sheet (National Topographic System map sheet 93A/12) whereas the stratigraphic and landslide components of the research are focused on valley fill sediment confined to the valleys of the Quesnel and Cariboo rivers.

Furthermore, the site-specific mapping and geophysical surveys that are the focus of this paper were carried out on the Quesnel Forks Landslide. The landslide is located at the confluence of the Quesnel and Cariboo Rivers (52° 40' N, 121° 40' W) opposite to the historical town site of Quesnel Forks (Fig. 1a).

The Quesnel and Cariboo rivers drain the Quesnel and Cariboo lakes respectively, and represent the major drainage in the region: the Cariboo River being a tributary of the Quesnel River. The Quesnel River valley is an east-west trending feature that averages 280 metres in depth and 1.5 kilometres in width. Flow within the valley is to the west, with the river dropping some 90 metres over a distance of 32 kilometres. The Cariboo River valley also trends roughly east-west and is similarly incised but is generally narrower than the Quesnel River valley.

The Quesnel Forks Landslide occurred in a glaciofluvial terrace that is approximately 70 metres above current base level (Fig. 2). The terrace is bound to the north, east and west by the Quesnel River (Fig. 1b). To the south, an abrupt transition occurs from the flat terrace to a steep bedrock-cored knob that rises more than 240 metres above the river.

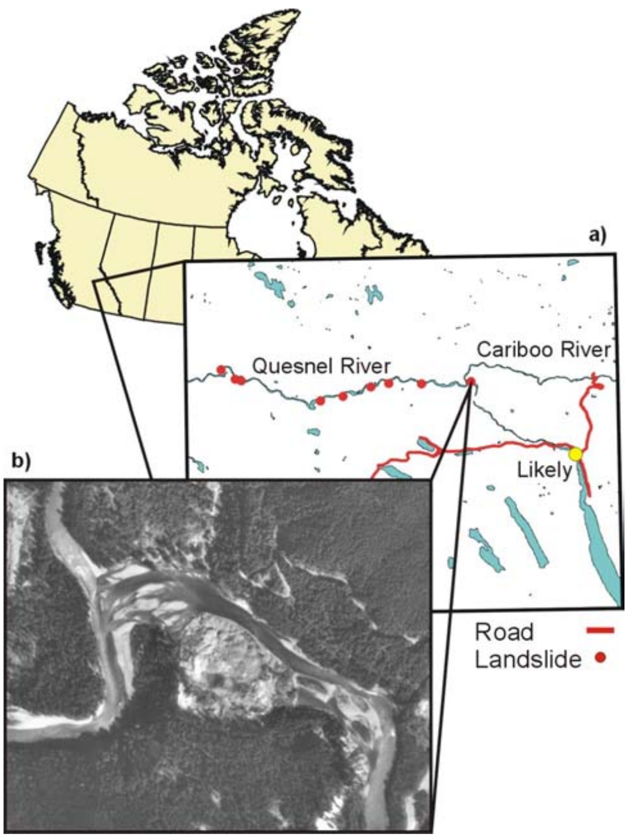


Figure 1. Map showing the location of the study area, and a) the distribution of landslides along the Quesnel River and b) an orthophoto of the Quesnel Forks Landslide.

Figure 2. Oblique photo of the Quesnel Forks Landslide.

3. TERRACE STRATIGRAPHY

The stratigraphy of the terrace at the Quesnel Forks Landslide was determined during surficial mapping of the landslide and is summarized in figure 3. The majority of the sequence is related to advance-phase ponding of the Quesnel River valley during the Fraser Glaciation. The exception is the upper most unit (A) that is recessional glaciofluvial and forms the cap of the terrace.

Unit G: This is the oldest unit in the sequence and is not visible at the site of the landslide. It is described from exposures on the opposite side of the river and its presence is inferred based on pre-failure photographs.

It is a well-compacted unit of interbedded fine, silty sand and clay that grades upwards to interbedded medium and coarse sand. Bedding ranges from lamina to beds on the order of ten centimetres. The upper surface of many sand beds is marked by ripple structures whereas the lower boundary often contains rip-up clasts. The base of the unit is highly contorted.

The unit is greater than 2.5 metres thick. Its basal contact occurs below the river level and is not visible. The upper boundary is formed by an undulating, erosive contact with a Holocene, recessional glaciofluvial gravel similar to unit A.

Unit F: The lowest unit exposed at the landslide is pebble gravel with a coarse sand matrix that fines upwards to medium pebble sand; 2 metres is exposed. Locally, lenses of clast-supported pebble gravel are present. Though there are rare clasts up to 50 centimetres in diameter, the average clast size is 0.5 centimetres. Clast shape ranges from rounded to sub-angular, with an average of sub-rounded. The unit exhibits crude stratification that strikes 230° with a true dip of 18° to the SW. The base of the unit is covered by debris from the toe of the slide.

Unit E: Overlying unit F is well-compacted, laminated, medium to coarse sand. Laminae are up to 1 cm thick and strike 200° with a true dip of 20° to the SW. The sand is orange with possible weak iron cementing. The upper 10 cm of the unit fines from medium sand to silt. The basal contact is gradational over 1 metre. The unit is approximately 12 metres thick.

Unit D: Consisting of massive clay with fine sandy clay pockets, this unit represents the largest part of the stratigraphic section. It is approximately 22 metres thick and has a sharp basal contact.

Unit C: This unit is moderately compact and consists of laminated, medium sand. Laminae are locally discontinuous and horizontal. The unit is approximately 10 metres thick and forms a sharp, erosional, undulating contact with the underlying clay.

Unit B: This unit pinches out to the east and west and is thickest in the centre of the landslide where it is 7 metres thick. It is a lenticular unit of well-bedded, well-sorted pebble gravel. It has an open framework and is a clast-supported unit that is heavily cemented with calcite. Beds strike 310° with a true dip 22° to the NE. The unit fines to the west from pebble gravel to coarse, immature sand that is not cemented. The lower contact is sharp and erosional.

Unit A: The uppermost unit that forms the terrace is a cobble, boulder gravel with a pebble matrix. Clasts are up to 3 metres in diameter and range from rounded to sub-angular in shape. On average they are 25 centimetres in size and sub-rounded. The lower contact is undulating and erosional. The unit is up to 7 metres thick and generally thickens to the east.

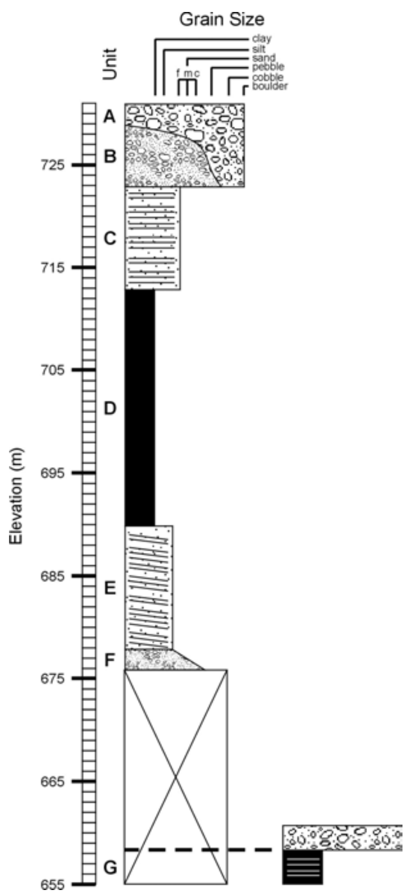


Figure 3. Stratigraphic log of the Quesnel Forks Landslide.

4. LANDSLIDE CHARACTERISTICS

There are nine prominent failures along the Quesnel River between Quesnel Forks and the western edge of the study area, approximately 32 kilometres down-river. In addition, several small failures are present. Estimated volumes of displaced material range from thousands of cubic metres for smaller slides to several hundreds of thousands of cubic metres. Site investigations focusing on the stratigraphy and surficial characteristics were carried out on each of the nine large failures.

Eight of the nine slides are primarily flow type failures. Two of these have rotational blocks located near the head scarp but which play a minor role in displacement. Two of the failures are also known to have dammed the Quesnel River for short periods of time. All eight slides are found on the outer, erosive side of river bends.

Flow material is primarily saturated, very fine-grained sand and clay. Its source is advance-phase lacustrine sediment from the Fraser Glaciation and less frequently till.

The ninth landslide is the Quesnel Forks Landslide that is a dormant, advancing, composite, very rapid, dry earth slide-debris flow, according to the classification of Varnes (1978) and Cruden and Varnes (1996). The earth slide consists of two major rotated blocks that show displacements of approximately 6 and 51 metres in the vertical direction and 9 and 70 metres in the horizontal direction, respectively. The debris flow component of the landslide blocked the Quesnel River for several hours until the earth dam breached, leaving the upstream reach of the river 1 to 2 metres higher (Rodman 1996). The earth slide-debris flow has a rupture width of 340 metres and a total length of approximately 400 metres. The upper block remains heavily forested whereas the lower block and toe are mostly free of both post- and pre-slide vegetation.

As with other landslides in the region, the dominant failure material is the advance-phase glaciolacustrine sediment. Still, several differences exist: overall the units are more massive; the clay unit (unit D) is not laminated and is the thickest unit of clay observed during fieldwork; it is the only site where the highly cemented gravel (unit B) is found; and it is the only landslide that does not occur on the erosive side of a river bend.

5. GEOPHYSICAL METHODS

Geophysical mapping methods offer a rapid and non-invasive approach to subsurface investigations where other techniques may be too costly, impractical or non-existent. They exploit discontinuities of physical properties within the material surveyed. In general, a large change in characteristics between the target and the surrounding material results in a recognizable high-amplitude signal. The choice of which property best identifies the target becomes an important factor for the selection of a surveying technique.

Geological factors that must be considered are the expected depth, structure and orientation of the target and the nature and thickness of the overburden. In the case of some landslides the changes in properties brought about by slope failure act as a guide for defining the target (Palmer and Wesgarber 1988).

The desired targets at the Quesnel Forks Landslide are the internal structure of the terrace and landslide and the recognition of the surface of rupture.

As described in sections 3 and 4, the Quesnel Forks Landslide has a large variation in material and morphology both with depth and at the surface. Furthermore, the topographic relief and expected structure of the landslide adds to the complexity of choosing an appropriate survey method. For these reasons, three different methods were applied: ground penetrating radar (GPR), DC resistivity and seismic reflection and refraction using both P- and S-waves. At the time of submission, the seismic data had not been fully processed and so are omitted from this discussion.

5.1 Ground Penetrating Radar

During this study, the PulseEkko IV system from Sensors and Software was utilized with a 50 MHz antenna and receiver. The system was powered by a 12V motorcycle battery and controlled by a laptop computer running the DOS-based control module. The control box, battery and computer were mounted on a backpack for ease of mobility and connected to the transmitter and receiver with fibre optics cables.

Seven survey lines were run as indicated in figure 4. In total, data from 340 metres of survey line were collected using 0.5 metre spacing between shots and an antenna-receiver spacing of 2 metres. The antenna and receiver were oriented perpendicular to the survey line.

The location and topographic relief of each line was later surveyed using a theodolite station and global positioning system (GPS) to permit application of a topographic correction using the Sensors and Software software package.

5.2 Direct Current Resistivity

The Syscal IRIS DC resistivity system used here is a 48-channel instrument with the ability to collect multiple spreads. Electrodes were laid out using a 5-metre spacing in a Wenner configuration. Measurements were taken with an ‘a’ spacing ranging from 5 metres to 75 metres at 5-metre increments.

For survey lines longer than one spread of electrodes (48), the first 24 electrodes were moved to new positions leaving the remaining 24 electrodes in their former positions. Survey measurements were then carried out in a manner that allows for a continuous data set. This procedure was repeated until the end of the survey line.

DC resistivity surveying equalling a total distance of 4100 metres were surveyed along the 12 lined shown in figure 4. Topographic corrections and two dimensional model inversions were later applied using Res2Dinv v3.4 software from GEOTOMO Software.

6. SURVEY RESULTS

Only one GPR (Fig. 5) and five resistivity (Fig. 6) profiles are discussed here. Profile locations are shown in figure 4. Profile X-X’, the GPR profile, is located along a portion of DC resistivity profile A-A’.

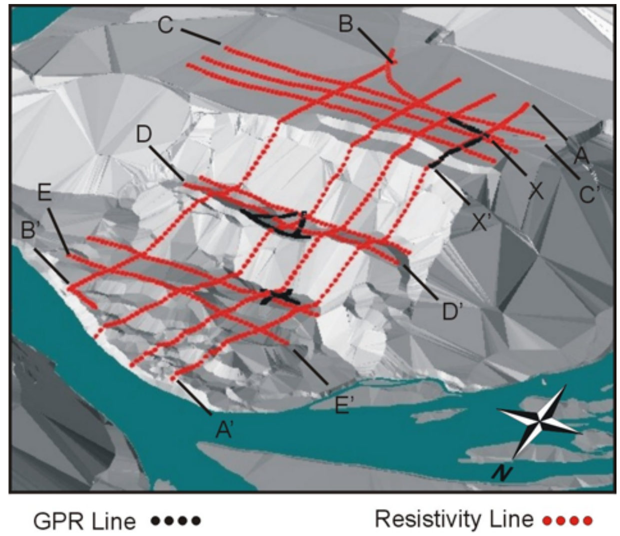


Figure 4. Geophysical survey lines on a digital elevation model of the Quesnel Forks Landslide.

6.1 Ground Penetrating Radar

Profile X-X’ is 73.5 metres long (Fig. 5) and begins on the undisturbed terrace and ends at the outer edge of the upper rotational block (Fig. 4). The area where data were not collected represents the steep face of the head scarp is located. Figure 5a is the uninterpreted raw profile whereas figure 5b is the interpreted profile.

There are two distinct radar facies in this profile. The first, 1 on figure 5b, consists of filled channel structures. It is 5 metres thick nearest X and thickens to approximately 7 metres towards the head scarp. There are two sub-facies that are based on the dip directions of the beds. Beds have an apparent dip between 10° and 13° towards the centre of the channels. Individual beds are approximately 70 centimetres thick.

The second facies (2) is less defined and consists of sub-horizontal hummocky beds. It is approximately 4 metres thick and, like facies 1, thickens towards the edge of the terrace to approximately 7 metres.

Below this, the signal is greatly attenuated. Weak, flat-lying reflections evident in this area (3), may be artificial or may represent horizontal beds in a more conductive material.

There are two steep, major events that are evident in the upper rotational block. The first extends from the edge of the block at the surface, downwards towards the head scarp (Fig. 5a, dotted line). This event passes through other, sub-horizontal reflections. The slope of the event was calculated and equals 0.105 metres per nanosecond, which is approximately equal to the velocity of a radar wave in the expected medium. It is postulated that this event is a reflection of the surface wave from the edge of the rotated block.

The second event is deeper than the first and does not come to surface. If projected towards the surface, it intersects the edge of the head scarp as shown in figure 5b. It is interpreted as a real event.

6.2 Direct Current Resistivity

Profiles A-A' (Fig. 6a) and B-B' (Fig. 6b) are north-south lines that extend from the undisturbed terrace to the outer edge of the toe as shown in figure 4. The survey lines are 475 and 430 metres in length, respectively.

Profiles C-C', D-D' and E-E' are east-west lines and parallel the head scarp (Fig. 6c, d and e). The first is on the undisturbed terrace, the second on the lower rotational block and the third on the toe. They are 355, 230 and 230 metres in length, respectively.

From the profiles, six units are outlined on the basis of their resistivity. They are discussed below as resistivity units 1 through 6 and are depicted in figure 6. Some resistivity anomalies have been interpreted through during the selection of unit boundaries as they are thought to be artefacts associated with the inversion process.

Unit 1: The uppermost unit is highly resistive, having values greater than 1280 ohm·metres. Its thickness varies greatly over the surface of the landslide and terrace. Profiles A-A', B-B' and C-C' demonstrate that it is thinnest over the western section of the terrace (approximately 5 metres thick) and effectively pinches out to the southwest. The unit abruptly thickens at the 100-metre mark on profile C-C' to an average thickness of approximately 15 metres. Over the slide it is substantially thinner, although it remains up to 10 metres thick on the lower rotational block. The basal contact of the unit undulates.

Unit 2: A range of resistivity from 240 to 1280 ohm·metres defines this unit. It is generally associated with the more resistive overlying unit on the terrace and rotational blocks. It is approximately 15 metres at its thickest and only a few metres thick on the toe of the slide, where it appears at surface. Within the terrace it thickens to the east and pinches out to the west. Its basal contact strongly undulates.

Unit 3: Resistivity values between 0 and 120 ohm·metres characterize this unit. It is found as a thick (~20 metres) unit throughout the landslide and terrace and is shallowest in the western side of the terrace as well as within the landslide toe. Within the terrace, the base of the unit appears to be gently dipping towards the centre of the valley. It lies stratigraphically below units 1 and 2 and above unit 4.

Unit 4: This unit has a range of resistivity between 120 and 640 ohm·metres. It is found beneath unit 3 and is best seen in profile A-A'. The base of the unit is not evident in any profile. It is >30 metres thick.

Unit 5: Unit 5 is only found beneath the surface of the toe in profile A-A'. It thickens towards the centre of the valley from 10 to 20 metres thick. The upper surface is approximately 10 metres below the current river level and its presence in profile B-B' and E-E' is debatable. The resistivity values range between 80 and 240 ohm·metres.

Unit 6: The final unit displays resistivity values between 240 to 1280 ohm·metres. It occurs at the ends of profiles A-A' and B-B' and is a dipping feature that shallows towards the north. The base of the unit is not evident. It may also be present in profile E-E' although here the resistivity is substantially less, between 120 and 640 ohm·metres.

7. GEOPHYSICAL AND STRATIGRAPHIC INTERPRETATION

The interpretation of geophysical data based on the observed stratigraphy yields a structural model of the Quesnel Forks Landslide that is given as figure 7. The following discussion consists of two parts: the first deals with the structure of the undisturbed sediments that constitute the terrace and the second with the structure of the landslide.

7.1 Terrace

The terrace is the result of the depositional and erosional processes that have occurred in the valley during the last glacial cycle. Unit G through B are interpreted as being associated with advancing glaciers and valley ponding during the Fraser Glaciation whereas unit A was likely deposited during the recessional phase of glaciation.

The deepest unit is resistivity unit 6. It is interpreted as bedrock based on its high resistivity as well as the presence of bedrock at surface directly across the river from the toe of the landslide.

It is unlikely that unit G is present in the resistivity profiles over the terrace as the penetration depth is not sufficient. In addition, resistivity data becomes more generalized with depth making it more difficult to differentiate between units.

However, unit G is thought to be present below the toe of the landslide and is represented by resistivity unit 5 on profile A-A', B-B' and C-C' (Fig. 6). This unit may represent initial ponding of the valley during the Fraser Glaciation or possibly a similar environment during a previous glacial cycle.

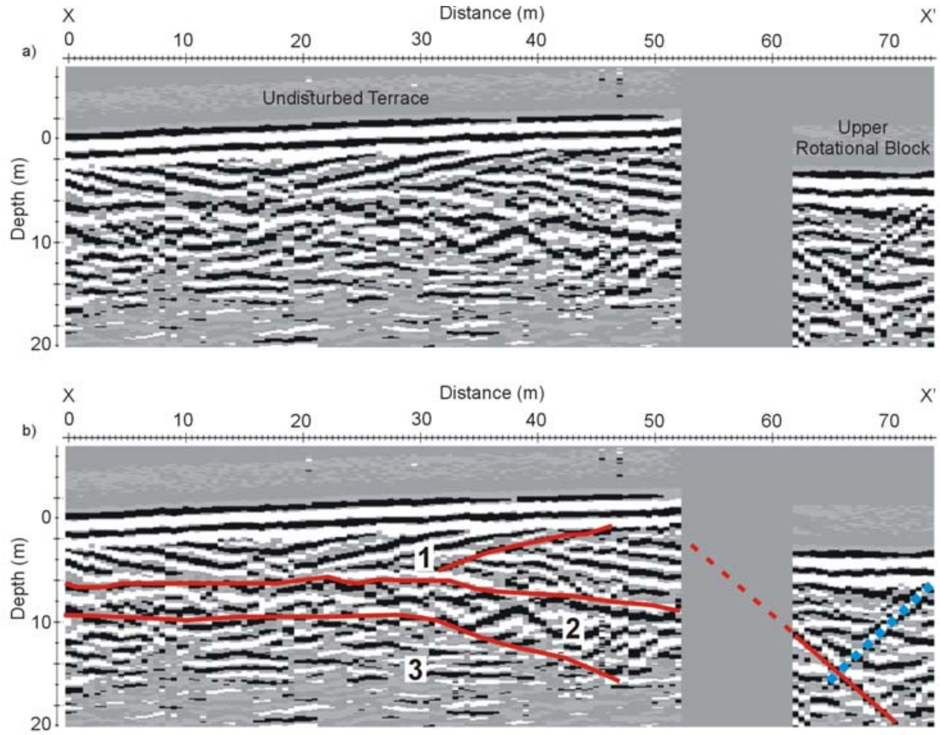


Figure 5. GPR profile of the terrace and upper rotational block. The profile is perpendicular to the head scarp.

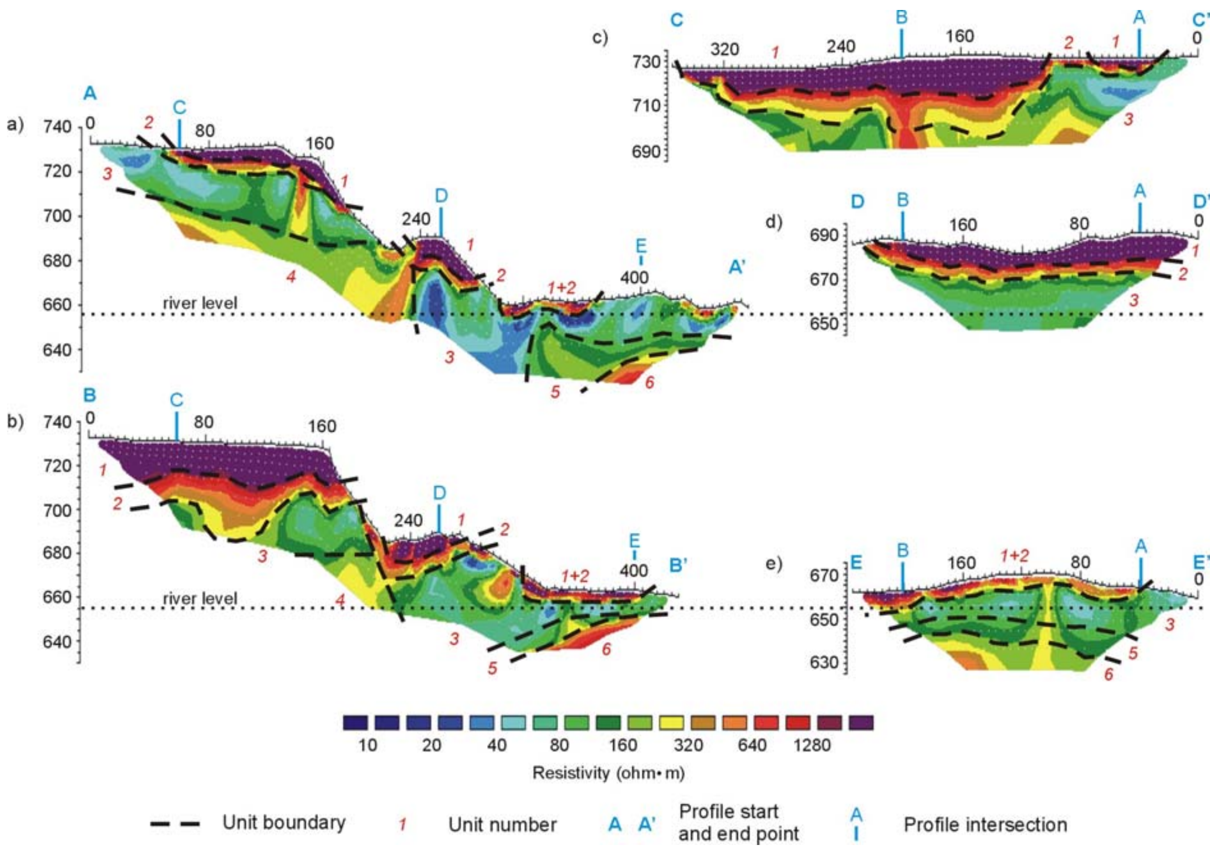
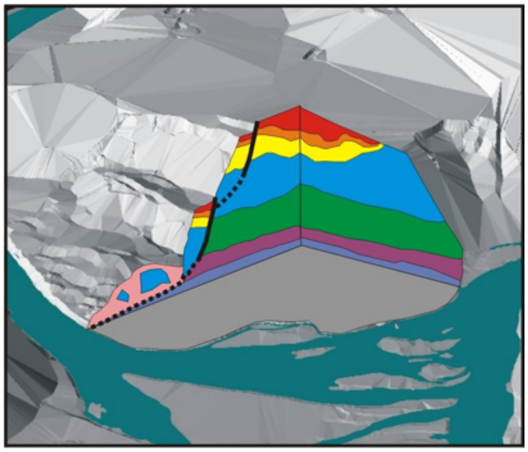


Figure 6. Resistivity profiles both perpendicular to the head scarp (a and b) and parallel (c through e).



Strat.	A	B	C	D	E	F	G
Res.	1	1	2	3	4	4	5
GPR	1	2	3				

Figure 7. 3D structure model of landslide showing the stratigraphy (Strat.), resistivity (Res.) and GPR units correlated with each other.

Units E and F are interpreted as being part of resistivity unit 4 and are indistinguishable from each other by the resistivity method. They are the deepest units and underlay the entire terrace. The base of both units is not evident. Unit F was likely deposited in a fluvial environment whereas unit E may represent a transition to a lacustrine setting when the valley drainage became blocked.

At some point the proglacial lake deepened and unit D was deposited. It is identified as resistivity unit 3 based on its stratigraphic position and low resistivity values that are typical of clay. The unit gently dips towards the centre of the valley, coming to the surface of the terrace near the valley sides.

Unit C is a return to a higher energy depositional environment and is correlated with resistivity unit 2. Radar facies 3 is also interpreted as unit C though the possibility does exist that it is actually the top of unit D.

Unit C eroded the underlying clay, forming an undulating basal contact that is evident in both stratigraphic section as well as in resistivity profiles B-B’ and C-C’. In general, it thickens up-valley and pinches out down-valley. This unit may indicate advancing glaciers or the draining of the glacial lake.

The final resistivity unit (1) consists of two stratigraphic units: A and B. These two units are indistinguishable solely by the resistivity data. In contrast, the GPR data differentiates them based on their internal structure.

Unit B is interpreted as advance-phase glaciofluvial gravel deposited prior to the deposition of till in the area. Alternatively it may be associated with post-glacial outwash although this is unlikely as it is too well-sorted, containing no large clasts. It is represented by radar facies 2 in figure 5.

The uppermost unit is unit A. It is known from surficial mapping as it forms the majority of the surface area of the terrace. It is correlated with resistivity unit 1 based on its stratigraphic position and high resistivity values that are typical for dry gravel. The internal structure of the unit is evident in the GPR profile as facies 1 and is likely a series of channel fill structures deposited in a high-energy fluvial environment that was responsible for the formation of the terrace.

7.2 Landslide

The same stratigraphic and resistive sequences as in the terrace are seen in the rotational blocks of the landslide. The important information is the boundaries between units in the blocks and the undisturbed terrace.

The upper rotational block is best seen in figure 5. The steep reflective event recorded by the GPR within the rotational block is interpreted as the surface of rupture. By translating the block along this plane to its original surface elevation, congruency in reflective events is evident. Furthermore, a displacement of 6 metres in the vertical direction and 7 metres in the horizontal direction are measured, which is also in agreement with initial estimations based on topographic relief. As described in section 6, the plane dips approximately 41° to the north.

The surface of rupture of the lower rotational block can be estimated from profile B-B’ (Fig. 6b) for the east side of the landslide. Here, it is represented by the boundary between resistive units 3 and 4 in the terrace and units 2 and 3 in the rotational block. The surface of rupture is much steeper here, approximately 65° to the north. This plane dissects the upper clay unit (A) and so must shallow within a lower unapparent unit. Based on the available stratigraphy, the most likely candidate is the less permeable, interbedded silt and clay of unit G.

In addition, the beds in the lower rotational block in profile B-B’ show a rotation of approximately 21°. Profile A-A’ does not show this pattern as it appears the beds have not remained as intact as on the east side of the landslide.

Some structure can be seen in the toe of the landslide. In profiles A-A’, B-B’ and E-E’ distinct bodies of low resistive material are evident that may represent blocks of clay that remained intact during slope failure. Along sections of the surface of the toe, a thin layer of highly resistive material is found that consists of sand and gravel from units A, B and C.

If resistivity unit 5 is indeed unit G, then it is possible that the boundary between resistivity unit 3 and 5 is the surface of rupture. As such, the depth of disturbed material in the toe is up to 20 metres thick and is thickest on the west side of the landslide.

8. CONCLUSIONS

Preliminary analysis of stratigraphic and geophysical data collected at the Quesnel Forks Landslide indicate that such techniques used in tandem are effective tools for assessing the internal structure of landslides. The geophysical techniques presented here yield two scales of subsurface imaging.

GPR data show detailed internal structure of the upper 20 metres of the terrace and landslide. From these data, radar facies can be identified that are based on bedding characteristics of the units. In addition, the probable surface of rupture of a rotational block near the surface has been identified.

Data collected by way of DC resistivity are much more generalized than that of the GPR system. It is useful for determining the spatial distribution of stratigraphic units. Where the displacement of units along a rupture surface lead to adjacent units that contain a sufficient contrast in electrical properties, a rupture surface can be interpreted.

9. AKNOWLEDGEMENTS

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10. REFERENCES

Cruden, D.M. and Varnes, D.J. 1996. Landslide types and processes. *In* Landslides: Investigation and Mitigation. *Edited by* A.K. Turner and R.L. Schuster. Transportation Research Board, Special Report 247, pp. 36-75.

Davis, J.L. and Annan, A.P. 1989. Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy. Geophysical Prospecting, **37**: 531-551.

Dominic, D.F., Egan, K., Carney, C., Wolfe, P.J. and Boardman, M.R. 1995. Delineation of shallow stratigraphy using ground penetrating radar. Journal of Applied Geophysics, **33**: 167-175.

Hack, R. 2000. Geophysics for slope stability. Surveys in Geophysics, **21**: 423-338.

Mellett, J.S. 1995. Ground penetrating radar applications in engineering, environmental management, and geology. Journal of Applied Geophysics, **33**: 157-166.

Palmer, D.F. and Weisgarber, S.L. 1988. Geophysical survey of the Stumpy Basin Landslide, Ohio. Bulletin of the Association of Engineering Geologists, **25**(3): 363-370.

Rodman, R. 1996. Quesnel Forks, Erosion Assessment, Klohn-Crippen, Richmond.

Sharma, P.V. 1997. Environmental and engineering geophysics. Cambridge University Press, New York, 475 pp.

Sherrif, R.E. 1984. Encyclopidea dictionary of exploration geophysics. Society of Exploration Geophysists, Tulsa.

Varnes, D.J. 1978. Slope movement processes. *In* Landslides: Analysis and Control. *Edited by* R.L. Schuster and R.J. Krizek. Transportation Research Board, National Academy of Science, Washington, D.C., Special Report 176, pp. 11-33.

Ward, S.H. 1990. Resistivity and induced polarization methods. *In* Geotechnical and Environmental Geophysics. *Edited by* S.H. Ward. Review and Tutorial. Society of Exploration Geophysicists, Tulsa, 1, pp. 147-189.