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doi:10.4095/293453

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Recommended citation
Huntley, D.H. and Bobrowsky, P.T., 2014. Surficial geology and monitoring of the Ripley Slide, near Ashcroft, British Columbia; Geological Survey of Canada, Open File 7531, 21 p. doi:10.4095/293453

Surficial geology and monitoring of the Ripley Slide, near Ashcroft, British Columbia

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Abstract
New geoscience information is presented that will help reduce the economic, environmental, health and public safety risks that landslides pose to the national railways operating through part of Canada's western Cordillera. Knowledge of the nature and stratigraphic relationships of surficial earth materials leads to a better understanding of some controls on mass wasting near Ashcroft, British Columbia, and in particular at the Ripley Slide: an active, slow-moving translational failure situated along a critical section of the national transportation corridor. This work compliments and will help guide other aspects of a multi-year international investigation of this landslide.

Keywords: Ripley Slide, Canadian National Railway, Canadian Pacific Railway, British Columbia, geohazards, slope stability, landslide, surficial geology, mapping, ground motion monitoring, GPS, InSAR corner reflectors, fibre optic sensing, shallow geophysical survey, risk management,

Introduction
As Canada's economy continues to grow, there will be an increasing demand for safe and secure transportation of natural resources, agricultural products, manufactured goods, people and other cargo using the national network of railways. Landslides in the Cordillera of southern British Columbia (**Figure 1**) are costly geological hazards that have challenged railroads in the mountains of western Canada since the late 19^{th} Century. Pronounced economic and environmental repercussions occur when railways are severed and infrastructure is damaged by landslide activity.

In southern British Columbia, both Canadian National (CN) and Canadian Pacific (CPR) railways run along the lower valley slopes of Thompson and Fraser rivers. Up to 80 trains per day, some with lengths up to 4 km, run through these valleys. Landslides in this transportation corridor have the potential to stop the flow of exports and imports to, and from the Port of Vancouver and thus the rest of Canada, resulting in economic losses that grow exponentially with the duration of service interruption (Bunce and Chadwick, 2012). In addition, both Thompson and Fraser rivers are highly sensitive aquatic ecosystems subject to contamination and long-term environmental damage by train derailment. Domestic passenger services and international tourism would also have the potential to be adversely impacted by outages due to landslides along this section of the CN-CPR corridor.

The aim of this contribution is to present new geoscience data that will compliment other ongoing monitoring of the Ripley Slide in the Thompson River valley south of Ashcroft, British Columbia. This collaborative research (e.g., Bobrowsky et al., 2014) aims to reduce the economic, environmental, health and public safety risks that landslides pose to the railway network operating through Canada's western Cordillera (**Figure 2**).

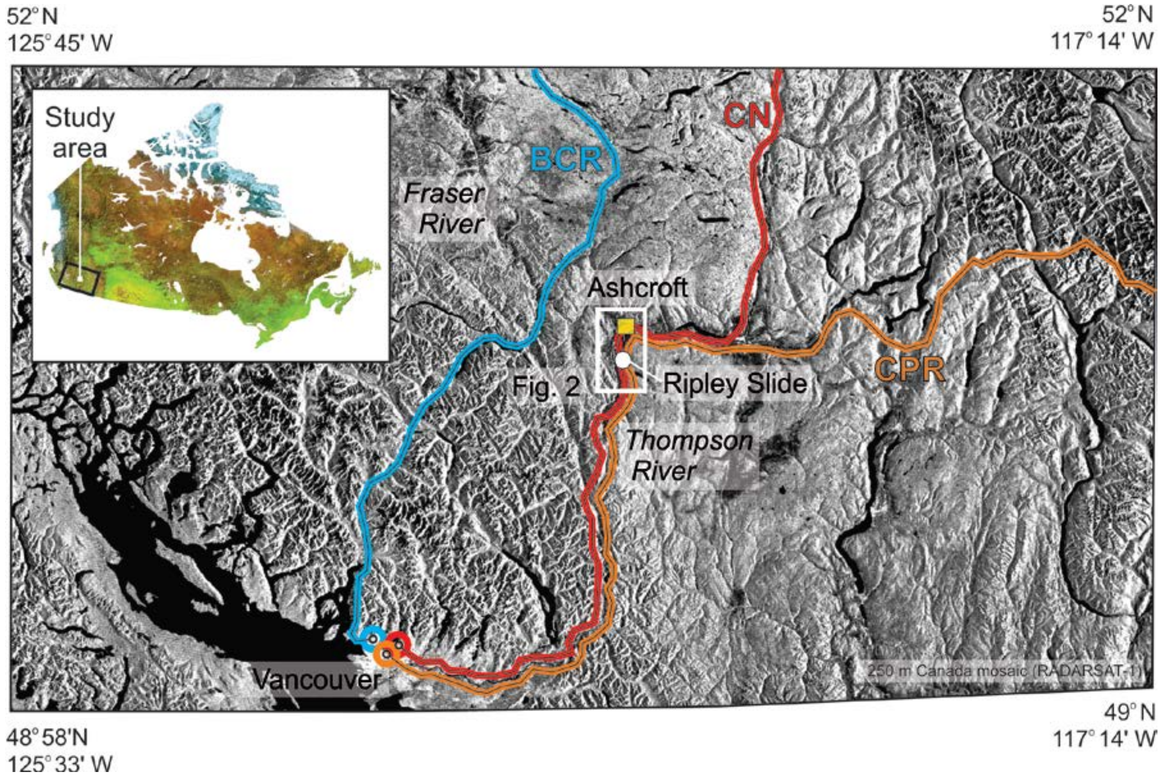

Figure 1 Major rail routes through the southern Cordillera of British Columbia (BCR – BC Rail; CPR – Canadian Pacific Railway; CN – Canadian National railways); with location of Ripley Slide south of Ashcroft.

Study area

The Thompson River valley south of Ashcroft is an important part of the British Columbia transportation corridor for both CN and CPR. Well-documented landslides along a ten kilometre stretch of the valley have been impacting critical infrastructure, arable land, fisheries and other natural resources since the 1880s (**Figure 2**).

Pleistocene fill in the Thompson River valley in the vicinity of the Ripley Slide consist of deposits related to least three glaciations (Ryder et al. 1991; Clague and Evans, 2003). A thick accumulation (50 m to 150 m) of Pleistocene materials is preserved in the valley; and is well exposed along terrace scarps formed by the post-glacial incision of Thompson River and its tributaries (Ryder, 1976; Johnsen and Brennand, 2004). This valley fill includes multiple glaciolacustrine units separated by till and outwash gravel.

The complex glacial geology is a significant control on the distribution, geometry and rate of landslide activity in the valley. Large rotational and retrogressive translational landslides were initially triggered by deep incision of Pleistocene fill in the Thompson River valley during the early Holocene (Clague and Evans, 2003; Eshraghian et al., 2007; 2008). Possible anthropogenic triggers include the irrigation of terraces beginning in the 1860s, and the excavation of lower landslide slopes during the construction and expansion of CN and CPR tracks in the late 1800s and early 1900s (Clague and Evans, 2003). At present, Thompson River affects landslide stability by changing: 1) pore water pressure in the slope mass and in particular in relation to rupture surfaces; 2) supporting force on landslide toes; and 3) through cutbank erosion, thereby affecting the geometry of the landslide.

Although some landslides failed and moved rapidly in the past, they are presently all are slow-moving reactivated compound features (Porter et al., 2002; Clague and Evans, 2003; Bishop et al., 2008; Eshraghian et al., 2007; 2008; Bunce and Chadwick, 2012). For most, movement occurs along weak, sub-horizontal zones of glaciolacustrine clay and silt confined between overlying till and underlying gravel deposits and bedrock. Movement is accommodated by one or more failure mechanisms, including: 1) slow-moving (2 cm to 10 cm/yr) rotational slides with large back-tilted blocks; 2) slow-moving (2 cm to 10 cm/yr) retrogressive translational slides with little rotation; and 3) rapid debris slumps involving flowage and sliding of landslide material (Clague and Evans, 2003).

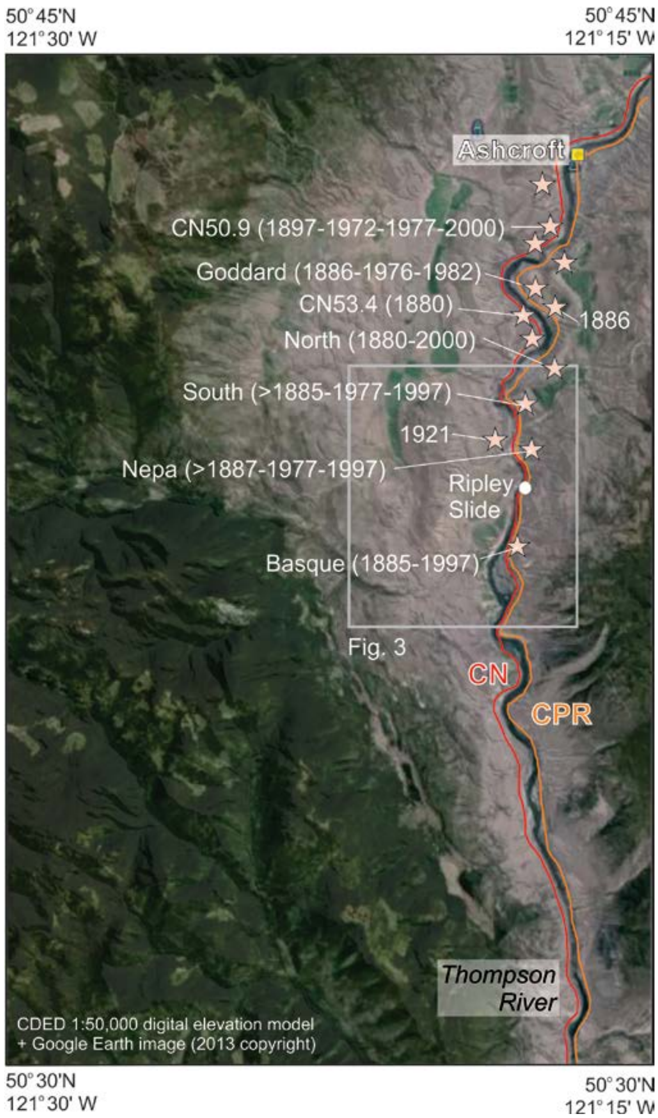

Figure 2 Significant landslides along Thompson River south of Ashcroft with approximate dates of activity (after Porter et al., 2002; Clague and Evans, 2003; Bishop et al., 2008; Eshraghian et al., 2007; 2008; Bunce and Chadwick, 2012).

Ripley Slide

The Ripley Slide is a small (area ca. 220 m x 150 m, volume 400,000 m^3), slow-moving landslide that is known to have been active since 1951 (Bunce and Chadwick, 2012; **Figure 3**). Although movement was slow in the late 20th Century, cumulatively it was sufficient to open numerous tension cracks in the main body of the landslide and cause a visible shift in the fence line of the CPR track by the early 2000s (Bunce and Chadwick, 2012).

In 2005, a rail siding that required upslope cuts and embankment widening was extended across the landslide. Slope modification included the construction of a retaining wall between the CN and CPR tracks at the southwest limit of the toe slope and in the vicinity of GPS-3 (**Figure 4**). During the autumn of 2006 and spring of 2007, track lifting between 10 mm to 20 mm as often as every three to six weeks was required; and a back scarp of a 40,000 m^3 portion of the landslide became visible in the excavated cut slope east of GPS1 (**Figures 3** and **4**). Results from GPS monitoring indicate that the Ripley Slide is in a continual cycle of alternating between stability and instability. The landslide experiences small increments of movement over time, with documented cumulative horizontal movement rates ranging from 2.55 mm/year at GPS-1, to 36.5 mm/year at GPS-2 and 54.75 mm/year at GPS-3 that are consistently to the WNW (Bunce and Chadwick, 2012; **Figure 4**).

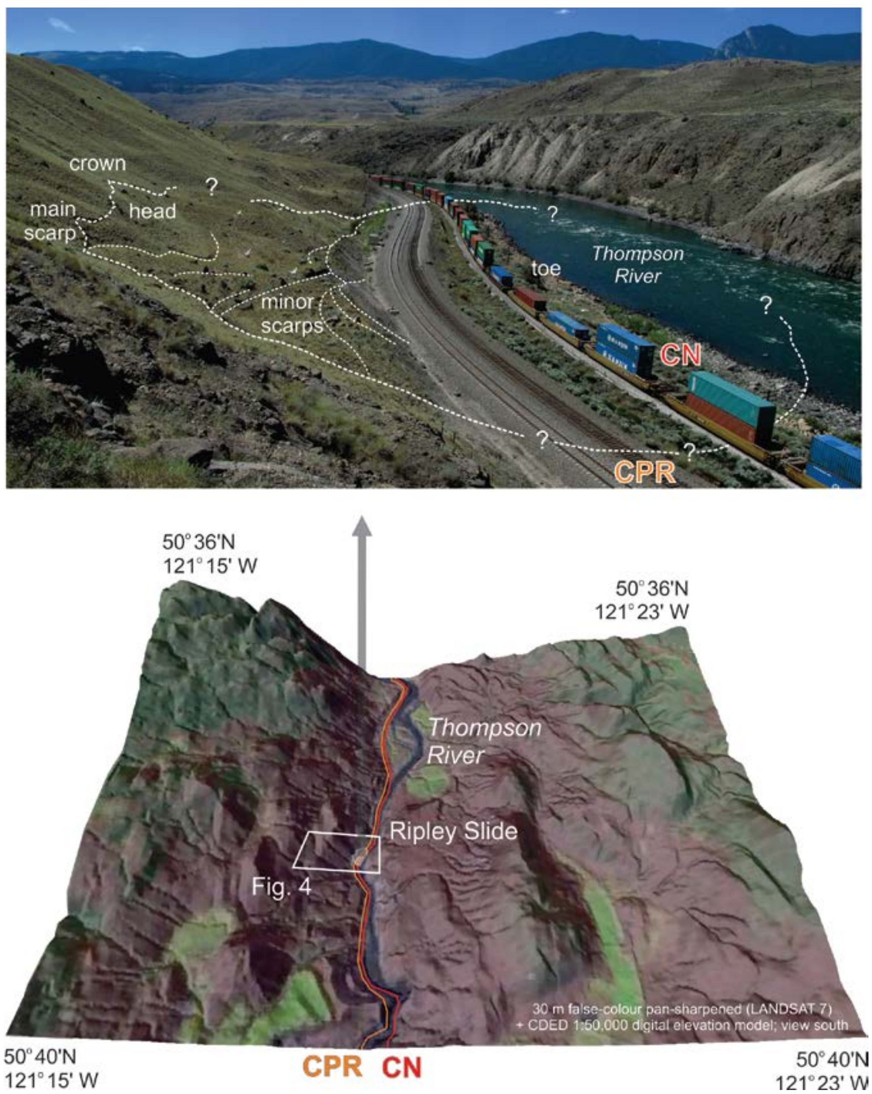

Figure 3 Ripley Slide: a) Location on a DEM generated from CANVEC files (www.geobase.ca); b) Ground view south of landslide, showing the main elements in relation to CPR and CN tracks and Thompson River.

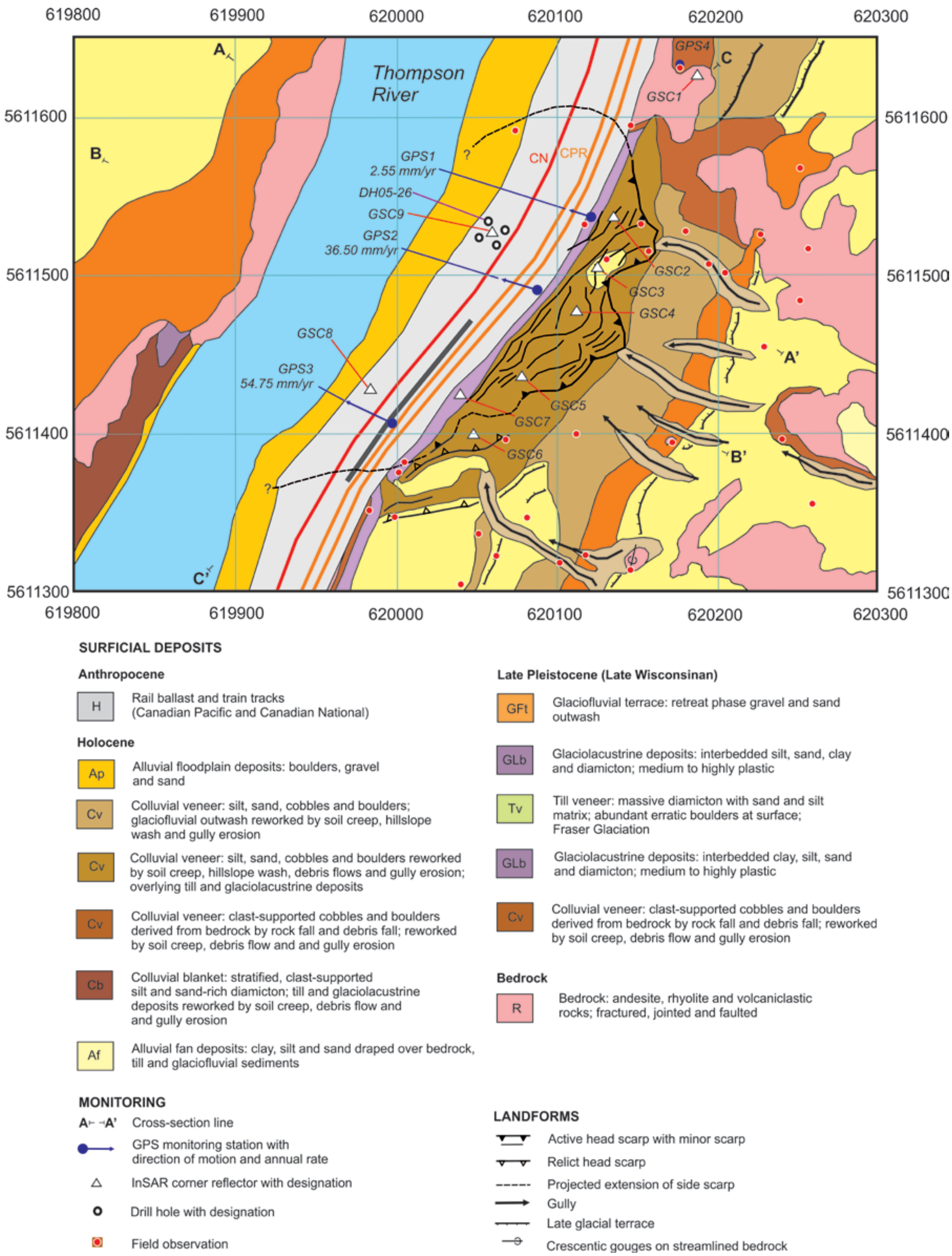

Figure 4 Provisional surficial geology and landforms of the Ripley Slide and adjacent terrain. Also showing the location of **Figure 15** cross-sections.

The Ripley Slide currently poses a significant hazard to onsite infrastructure since both CN and CPR tracks run adjacent to each other along the slide's entire breadth. On average some 80 trains per 24 hour period travel through the area and therefore cross this particular landslide. Locomotives traverse the landslide at a precautionary maximum speed of 30 km/hr; so in the event of a derailment, the potential is low for injury and death of engineers, conductors, passengers and other individuals. Potential environmental damage to Thompson River and groundwater by spilled dangerous goods is also minimized at this speed (Bunce and Chadwick, 2012). Unfortunately, as the magnitude and frequency of landslide activity increases, the frequency of track maintenance and costs rise. Consequently, the economic repercussions of a severed railway here remain pronounced.

There are three strategies for railways to reduce the risks associated with landslides in the Thompson River valley: 1) avoid landslide-prone terrain – not possible at the Ripley Slide and surrounding area; 2) stabilize the landslide – an unresolved and prohibitively costly geotechnical problem at this and other landslides in the Thompson River valley; and 3) monitor for unsafe ground movement – the most cost-effect approach for this landslide (Bunce and Chadwick, 2012). To this end, a large international consortium of research partners has embarked upon a detailed multi-year study to investigate the Ripley Slide (Bobrowsky et al., 2014). This Open File report will compliment and help guide other aspects of the investigation: for example, sound subsurface geology information is necessary to properly interpret drill/core samples, geotechnical logs and geophysical data at later stages of the landslide-monitoring program.

Glacial Geology

There are significant gaps in our knowledge of the nature of surficial earth materials, their stratigraphic relationships, and in the controls on the style of mass wasting at the Ripley Slide. This contribution addresses such uncertainties by providing new information on the distribution and stratigraphy of glacial deposits and bedrock in a reach of the Thompson River valley approximately 7 km south of Ashcroft (**Figure 3**). For the purpose of this study, the Ripley Slide is approximately centred in a 500 m (E-W) x 350 m (N-S) map area (**Figure 4**).

Surficial earth materials and landforms were mapped in ArcGIS using LANDSAT 7 satellite imagery (http://glovis.usgs.gov/ [URL 2013]), Google Earth imagery (Digital Globe, 2013), RADARSAT-1 and RADARSAT-2 images, and digital elevation models generated from CANVEC shape files (http://geogratis.cgdi.gc.ca/geogratis/ [URL 2013]) and ground-based LiDAR. Visual interpretation of imagery relied on the recognition and separation of geological features using tone, colour, gray-scale, surface texture, pattern, shape, size, shadow, field associations, spectral and spatial resolution.

Fieldwork was undertaken in the spring, summer and autumn of 2013 to ground-truth surficial geology polygons interpreted from satellite and LiDAR imagery, and to describe characteristics that could not be determined through remote mapping. On the ground, surficial units were defined on the basis of facies and landform associations, texture, sorting, colour, sedimentary structures, degree of consolidation, and stratigraphic contact relationships observed at 52 field stations. The distribution of undifferentiated bedrock, glacial deposits, post-glacial sediments and landforms is depicted on **Figure 4**. From oldest to youngest, the mapped earth materials include: Mesozoic bedrock; Pleistocene colluvium, glaciolacustrine sediments, till, glaciofluvial sediments; in addition to Holocene colluvial deposits, alluvial sediments and anthropogenic fill (e.g., railway ballast, lock-block retraining wall, culverts).

Unit 1: Bedrock

Pleistocene deposits in the Thompson River valley infill in a deeply incised Paleogene landscape (65 Ma to 23 Ma old) consisting of topographic uplands and remnant sections of paleochannels with moderately steep (>25 to <35^{o}) to steep slopes (>35^{o}). Regional drainage in Eocene times (ca. 50 Ma to 40 Ma) was northward. Eocene paleovalleys were partly infilled as base levels increased during the Oligocene (ca. 36 Ma to 23 Ma) and Miocene (ca. 23 Ma to 6 Ma). Southward drainage through a proto-Thompson River valley began in the Pliocene (ca. 6 Ma to 2.6 Ma) prior to the Pleistocene glaciations, <2.6 Ma (Tribe, 2005). In the map area, bedrock outcrops on the middle and lower valley slopes east of Thompson River;

and at river level on the west bank (**Figures 4** and **5a**). Fine-grained, dark green-grey andesite is exposed in a bedrock cutbank at the north end of the railway corridor at elevations below 310 m. Above this elevation, intermediate volcanic rocks are overlain by flow-banded rhyolite and bedded pyroclastic rocks. Andesite, rhyolite and volcanic breccia belong to the Late Triassic (ca. 210 Ma) to Early Jurassic (190 Ma) Nicola Group; and represents the final stages of arc-related igneous activity in the southern Quesnellia tectonostratigraphic terrane (Monger and McMillan, 1984; Monger, 1985; Mortimer, 1987). Although no faulting is observed in outcrop, major fracture sets in andestite trend E and NW (**Figure 5a**). Fresh fractured surfaces show a thin (< 5 mm) altered rind, beneath which bedrock is unweathered. A NW-SE fracture set fracture is dominant in rhyolite and volcanic breccia on upper slopes. Volcaniclastic rocks dip $<20^{o}$ NNE (**Figure 5b**). Frost shatter is focused along fractures and bedding planes, and yields rectilinear angular blocks. Fracture networks in bedrock likely also facilitate groundwater recharge on gentler portions of slopes, below porous unconconsolidated deposits, in gullies and beneath the active channel.

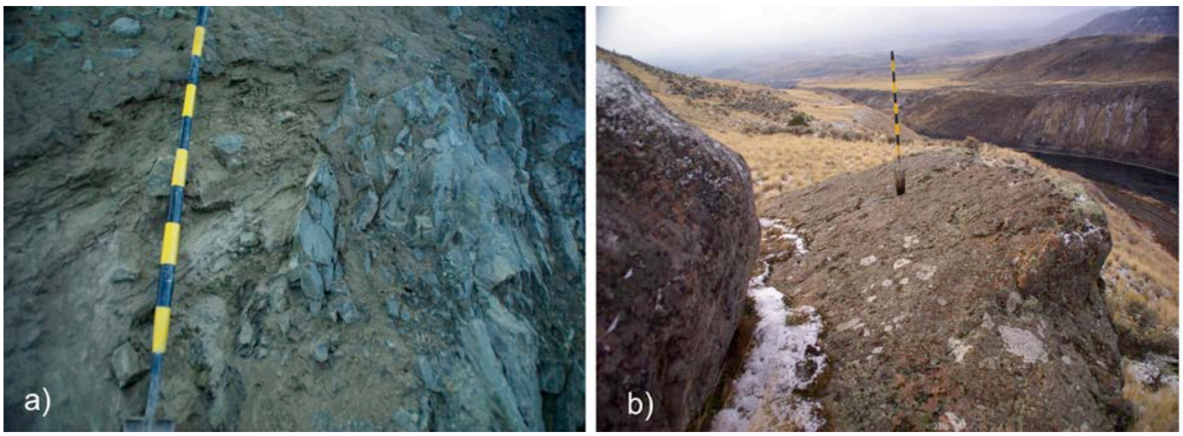

Figure 5 Unit 1, undifferentiated bedrock: a) Andesite, fine-grained crystalline igneous rock with dominant fractures 040/076/E (278 m elevation), 074/50/NNW, 136/78/W, 178/28/E; b) Rhyolite and pyroclastic volcanic rock, strike/dip/dip-direction 104/18/E (350 m elevation).

Unit 2: Colluvium (early glacial advance)

A basal unconsolidated unit, less than 2 m thick, is draped over andesite. This unit consists of massive and crudely stratified clast-supported diamicton(s) with sand-silt and clay-silt matrices (**Figure 6a**). These porous and permeable basal sediments are well-drained. Locally, planar bedded gravel and sand is preserved at the top of the unit, marking an abrupt transition in depositional conditions characteristic of Unit 3 (**Figure 6b**). This basal Pleistocene unit is interpreted to represent rock falls, debris falls and debris flows deposited in an ice-distal lake confined to the Thompson River valley. The lake was impounded downstream of the Ripley Slide by mountain glaciers, outwash and landslide debris damming the Fraser River valley during the advance stage of the Late Wisconsinan Fraser Glaciation (Ryder et al., 1991)

Unit 3: Glaciolacustrine sediments (late glacial advance)

Overlying basal colluvial sediments are rhythmically interbedded clay, silt, sand and diamicton. East of Thompson River, some 3 to 5 m of Unit 3 is exposed in the railway cutbank, and a further 25 m to 30 m of highly plastic clay lies beneath the valley floor (**Figure 7a**). Unit 3 is also exposed the steep cutbank west of the river (**Figure 4**). Silt and clay couplets, and interbeds of sand and diamicton range in thickness from less than a centimetre to several tens of centimetres. Dispersed through this unit are rare pebbles and cobbles interpreted as dropstones. Deposition of ice-rafted debris is also suggested by a massive clast-supported diamicton observed at the south end of the embankment. Similar to other landslides in the valley, visually, the clay-size fraction appears to exceed 70%, with illite likely the dominant clay mineral (cf. Porter et al., 2002). Fine-grained sediments of Unit 3 indicate low-energy deposition in a proglacial lake confined to the Thompson River valley prior to ice advance into the valley ca. 25 ka (Ryder et al., 1991; Clague and Evans, 2003). Contorted bedding and loading structures (**Figure 7b**) indicate soft-sediment deformation during landslide activity shortly after deposition; or that glaciolacustrine sediment was plastically deformed as the Cordilleran Ice Sheet flowed through the valley. With slope erosion and excavation of overburden, vertical unloading/relaxation fractures and bedding-parallel planar fissility readily develops in Unit 3. This fracture permeability and variations in porosity allow for sustained confined groundwater flow through the unit: along the railway embankment, saline groundwater is observed seeping and evaporating from sand interbeds during summer months.

Figure 6 Unit 2, colluvium: a) Basal clast-supported diamicton overlying fractured andesite (Unit 1), ca. 276 m elevation; b) Gravel-rich sand marking transition from pre-glacial landslide deposits to clay and silts deposited by suspension in glacial lake (Unit 3).

Unit 4: Fraser Glaciation Till (glacial maximum)

Unit 3 glaciolacustrine sediments are truncated, deformed and unconformably overlain by massive, matrix-supported and clast-supported diamictons (**Figure 8a, b** and **c**), interpreted as Late Wisconsinan Fraser Glaciation till (ca. 18 ka to 16 ka; cf. Ryder et al., 1991; Clague and Evans, 2003). In the study area, Unit 4 varies in thickness from less than 2 m to greater than 5 m, cross-cuts all older glacial deposits, and in places extends to bedrock. Andesite, rhyolite and volcanic breccia are glacially streamlined and polished. Striae were not observed, but crescentic fracture gouges indicate SSW iceflow in the valley (**Figure 4**). Fraser Glaciation till is a moderately to well-drained clay and silt-rich diamicton with erratic clasts ranging in size from cobbles to boulders (**Figure 8b**). Many lithologies are exotic to the map area, and include granitic, carbonate and metamorphic rocks from outside the Ashcroft region.

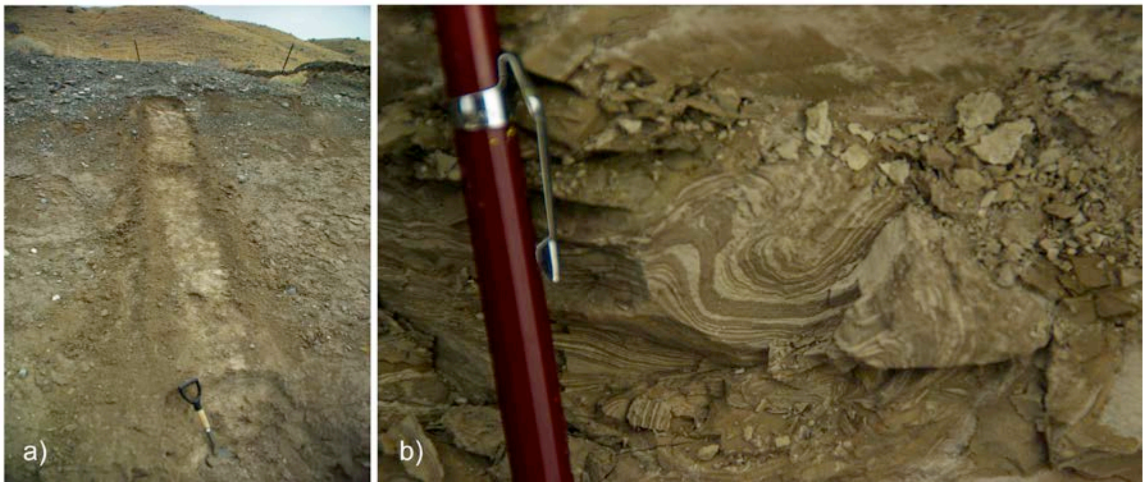

Figure 7 Unit 3, glaciolacustrine sediments: a) Rhythmically interbedded clay, silt and sand with rare dropstones, 278 m elevation; b) Soft-sediment glacial deformation (sub-till).

Figure 8 a) Unit 4, till exposed in headscarp at 280 m elevation b) Massive, matrix-supported diamicton overlain by veneer of hillslope colluvium (Unit 8); c) Detail of silt and clay-rich diamicton.

Figure 9 Unit 5, glaciolacustrine sediments: a) Cobble, pebble and sand-rich colluvial veneer (Unit 8) overlying interbedded clay and silt (Unit 5) and till (Unit 4); b) Detail of observation pit, silt-rich beds appear lighter; c) Bedding-parallel fissility and vertical slope relaxation fractures exposed in railway embankment.

Figure 10 Unit 6, glaciofluvial outwash: a) 340 m terrace escarpment and moderately steep upper slopes (32^o), rapidly drained; b) 340-350 m terrace abutting against bedrock; c) Gullied 340-350 m terrace, rapidly drained.

Unit 5: Glaciolacustrine sediments (early glacial retreat)

Above the main body of the Ripley Slide, Unit 5 is less than 2 m thick where observed in observation pits (**Figure 9a, b**) and along exposures on the rail embankment (**Figure 9c**). Clay and silt couplets, and interbeds of sand and diamicton range in thickness from less than a centimetre to several centimetres. Similar to Unit 3, as slopes are excavated (and unloaded with removal of colluvial overburden), vertical slope-parallel fractures readily develop, while strong sub-horizontal planar fissility develops in clay-silt couplets (**Figure 9c**). This fracture-fissility pattern likely favours rapid downward and lateral percolation of precipitation and surface runoff. Unit 5 is interpreted to be Late Wisconsinan in age, and deposited in glacial lakes Thompson-Deadman early during ice retreat (ca. 16 ka to 13 ka; Fulton, 1969; Ryder et al., 1991; Clague and Evans, 2003; Johnsen and Brennand, 2004).

Unit 6: Glaciofluvial sediments (late glacial retreat)

Bedrock, till and retreat phase glaciolacustrine units are overlain by a massive to crudely stratified boulder and sand-rich gravel (Unit 6). This unit forms a prominent terrace at 340 m to 350 m elevation (**Figures 4** and **10a, b**). Gravel is porous, rapidly drained and prone to gully erosion (**Figure 10c**). Unit 6 records the transition from glacial to proglacial conditions, and is interpreted to be deposited following catastrophic drainage of the ice, sediment and landslide-dammed lake confined to the Thompson River valley, ca. 13 ka to 11 ka (glacial lakes Thompson-Deadman; Fulton, 1969; Ryder et al., 1991; Johnsen and Brennand, 2004).

Unit 7: Alluvial fan sediments (early post-glacial)

Deposition of this unit marks the onset of post-glacial fluvial conditions in the late Pleistocene to early Holocene, ca. 11 ka to 10 ka. Unit 7 is graded to successively lower elevations reflecting falling post-glacial regional base-levels (**Figure 11a**; cf. Fulton, 1969; Clague and Evans, 2003; Ryder et al., 1991; Johnsen and Brennand, 2004). Alluvial fans (with surface slopes from 3^o to 8^o) and cones (slopes $>8^o$ and $<12^o$) drape bedrock, till and late-glacial flood deposits (**Figure 11b**). Observation pits expose diamicton and gravels fining upward to sand then silt, with this sequence generally less than a metre in thickness (**Figure 11c**). As sediment sources diminished and regional base-levels fell after 10 ka, the post-glacial drainage system deeply incised unconsolidated glacial deposits and bedrock, forming the distinctive benchland terraces, gullies and canyons of the modern Thompson River valley (**Figures 4** and **11a**).

Unit 8: Colluvial sediments (post-glacial)

Unit 8 includes post-glacial and Holocene colluvial deposits (ca. 11 ka to present) unconformably overlying valley fill on over-steepened slopes. On steep bedrock slopes, gelifraction is focused along slope-parallel fractures, and in places, the resulting detritus is transported down slope through rock fall and debris fall, to accumulate as talus and scattered colluviated blocks (**Figure 12a**). On moderately steep unconsolidated slopes exposed by the down-cutting Thompson River, glacial sediments are remobilized by debris fall, debris flows, slides, avalanches, soil creep, solifluction, gully erosion and surface runoff; and deposited as stratified, clast-supported gravels and sand-rich diamicton on the colluvial mid-slope (**Figure 12b**) and toe slope of the valley (**Figure 12c**).

Unit 9: Alluvial floodplain sediments (late post-glacial)

Unit 9 includes alluvial deposits of Thompson River below 265 m elevation (high bench-level of the active floodplain). The modern river channel is laterally eroding bedrock, till, glaciolacustrine and colluvial deposits; a scour pool beyond the inferred southwest limit of the landslide indicates the river is locally incising the channel bed. Floodplain deposits are predominantly boulder and cobble-rich rich, reflecting the fast-flowing conditions of Thompson River during spring and summer runoff (**Figure 13a**). Sand is deposited as a matrix within the framework of cobbles and boulders during low-flow conditions in autumn through winter (**Figures 4** and **13b**). The presence of horsetails (*Equisitales* sp.) between ca. 294 m and 296 m elevation indicates a zone of groundwater seepage through alluvial sediments active during autumn.

Figure 11 Unit 7, alluvial fan sediment: a) terraced fan, outwash and till deposits indicating falling base-levels in the Thompson River valley during early Holocene b) Alluvial cone; upper slope 12^{o}; c) Detail of moderately drained sand and silt draped over till and bedrock.

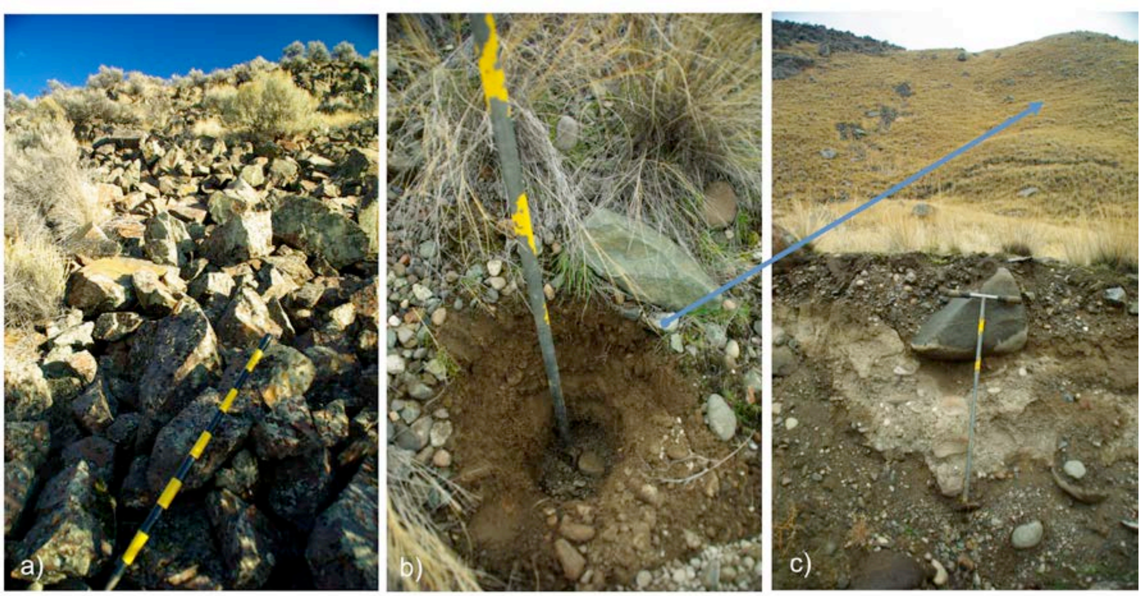

Figure 12 Unit 8 post-glacial colluvial deposits: a) Talus blocks derived from frost shattered rhyolite and volcaniclastic rock, slope 32^{o}; b) Glaciofluvial cobbles and sand remobilized by debris fall, soil creep and surface runoff on a 25^{o} slope above main body of landslide; c) Slide scarp exposing glaciofluvial boulders, cobbles and sand remobilized by rock fall, debris fall, soil creep and surface runoff on a 12^{o} slope, main body of landslide.

Figure 13 Unit 9, alluvial floodplain sediment: a) Modern floodplain deposit comprising sand, cobbles and boulders; b) Sand draping boulders, vegetation growth dominated by horsetails, indicating zone of seepage on the landslide toe.

Figure 14 Unit 10, anthropogenic deposits and features: a) Boulder-rich track ballast overlying alluvial floodplain on the landslide toe – note seepage in Unit 9 beneath ballast indicated by vegetation; b) CN (top left) and CPR tracks (centre) with cobble-rich track ballast; Lock-block retaining wall separating CPR (above left) and CN tracks (right).

Unit 10: Anthropogenic features (modern)
The CN and CPR tracks are positioned on a linear, low grade railway corridor along the eastern valley floor of Thompson River (**Figure 14a**). To accommodate this vital infrastructure, a 50 m to 100 m wide segment of toe slope was excavated in colluvium, alluvial sediments, till and underlying glaciolacustrine deposits. This corridor was infilled to varying depths (<20 m) with a base of weathered granodiorite boulders, overlain by cobble-sized ballast (**Figure 14b**) consisting of fine- to medium crystalline igneous and metamorphic rocks (e.g., granodiorite, rhyolite, amphibolite, phyllite). CN and CPR tracks are separated by a 3 m high retaining wall along the southern flank of the Ripley Slide, near GPS3 (**Figures 4** and **14c**). Unit 10 is the youngest surficial earth material, spanning construction of the railways in the late 1880s to the yearly addition of ballast to accommodate movement on the Ripley Slide as part of track maintenance.

Landslide cross-sections
Three interpretative cross sections across the map area (A-A', B-B' and C-C') were generated using the CANVEC DEM files and Global Mapper™ software (**Figures 4** and **15**). The distribution of Pleistocene units in cross-section is hypothetical, but based in part on observed stratigraphic relationships and knowledge of the internal structure of other landslides in the Thompson River valley (Porter et al., 2002; Clague and Evans, 2003; Bishop et al., 2008; Eshraghian et al., 2007; 2008; Bunce and Chadwick, 2012). Sediments logged in geotechnical drill hole DH05-26 have also been interpreted in the context of the stratigraphy described above (**Figure 15**).

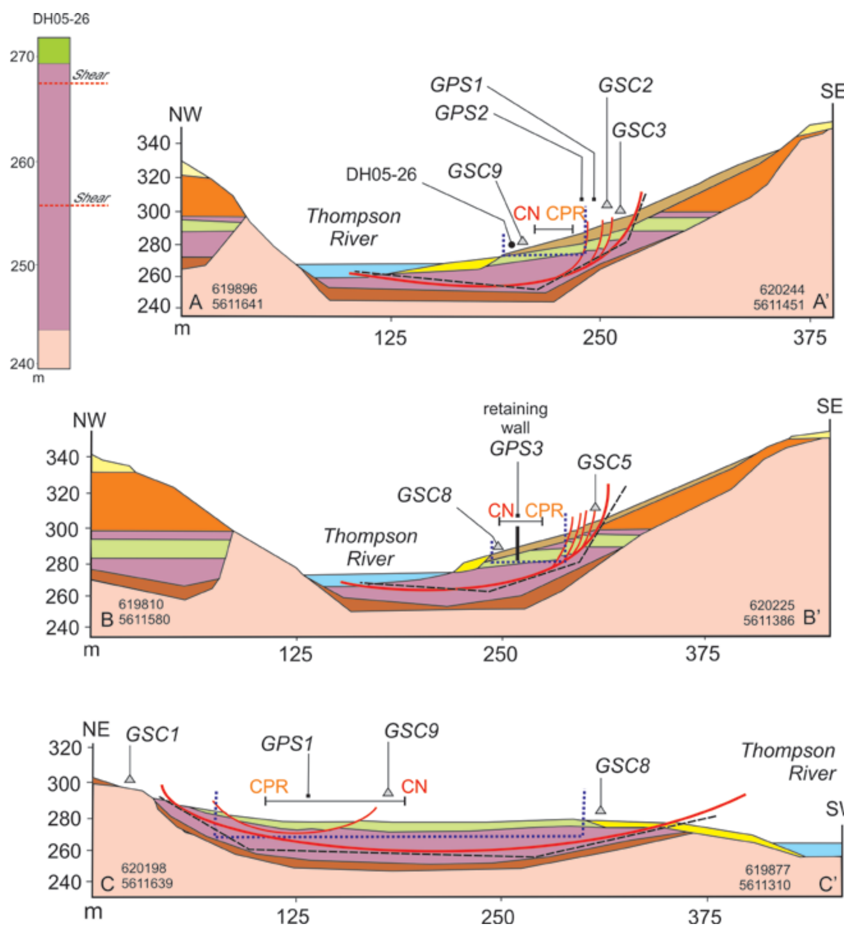

Figure 15 Hypothetical cross-sections across the Ripley Slide, showing stratigraphic relationships of earth materials depicted in **Figure 4**. Failure planes (illustrative only) of the translational slide are depicted as listric (red lines); however, movement could also be accommodated along rectilinear planes (dashed black lines); materials removed for railway right-of-way (dotted black lines). For locations of GPS stations (GPS1-3); InSAR corner reflectors (GSC1-9); and observation well (DH05-26) also see **Figure 4**.

All three sections show Pleistocene units infilling an incised bedrock terrain (Unit 1) interpreted as a buried paleochannel segment of Thompson River (**Figure 15**). Eroded remnants of units 2 and 3 are inferred to lie beneath the modern river channel bed. Drill hole DH05-26 shows two shear zones less than 10 m apart at ca. 260 m elevation in Unit 3, and ca. 268 m below Unit 4. Similar shallow and deep rupture surfaces 6.5 m apart are reported from other landslides in the valley (Eshraghian et al., 2007). These deformation zones correspond to sheared and deformed clay-rich glaciolacustrine beds, and the erosional contact with overlying till (Unit 4) exposed in railway cutbanks along the toe slope of the landslide (**Figure 4**). Other landslides in the Thompson River valley fail along planar to listric scarp planes that intersect sub-horizontal bedding (Porter et al., 2002; Clague and Evans, 2003; Bishop et al., 2008; Eshraghian et al., 2007; 2008). Two end-member interpretations of the internal architecture of the Ripley Slide are depicted: listric failure planes are shown in red; rectilinear failure planes are shown as dashed black lines (**Figure 15**). The objective of geophysical surveys will be to employ seismic reflection, ground penetrating radar, direct electrical current resistivity tomography and electromagnetic techniques to test the validity of the landslide architecture depicted in the cross-sections (**Figure 15**).

Landslide Processes

Insight into mass wasting processes at the Ripley Slide can be gained through an examination of other landslides in the Thompson River valley south of Ashcroft (**Figure 2**). Translational and rotational landslides move by two processes: 1) rapid movement with a high potential for risk of life caused by the propagation of a rupture surface in the opposite direction of retrogressive failure; and 2) slow reactivation of landslides on previously formed rupture surfaces without retrogression that may cause damage to railway tracks and disruption of service (cf. Eshraghian et al., 2007). The Ripley Slide is in a reactivation stage and moving at up to 55 mm/year along two sub-horizontal translational rupture surfaces corresponding to weak glacially-sheared zones in Unit 3 glaciolacustrine clay and silt (Bunce and Chatwin, 2012; **Figure 4**).

Initial conditions

The presence of steep slopes in bedrock and valley fill flanking Thompson River at the Ripley Slide site is a necessary condition for slope failure. During deglaciation and early in post-glacial times, rapid down-cutting of valleys, crustal rebound and sediment unloading led to the formation over-steepened slopes. Unconsolidated sediments were likely relatively dry through much of the Holocene, and remained marginally stable until the early 1800s and 1860s when irrigation of the benchlands began (Clague and Evans, 2003). Although irrigation water may be a contributing factor to mass wasting at other sites, it is not the case for the Ripley Slide where the surrounding slopes are still used as rangeland for cattle. Nonetheless, grazing practices have ensured vegetation cover remains sparse and cattle trails form intermittent linear paths of disturbed soil forming narrow slope breaks that contour slopes. These conditions contribute to the infiltration of precipitation and surface runoff into the unconsolidated valley fill. Pleistocene fill was further destabilized when valley toe slopes were excavated in the 1880s and 1950s to accommodate CPR and CN tracks (Bunce and Chadwick, 2012). Similar to other landslides south of Ashcroft, under-cutting of the toe slopes and changes to channel morphology during railway construction may contributed to movement at the Ripley Slide (cf. Clague and Evans, 2003).

Geologic conditions

Disturbance and erosion by overriding ice or early slope movement have created pre-sheared discontinuities in Unit 3 at residual strength that predisposed these sediments to failure (cf. Clague and Evans, 2003; Eshraghian et al., 2007; 2008). Elsewhere in the Thompson River valley, Unit 3 clay beds are highly plastic with plastic/liquid limits from 45% to 90%, and have residual friction angles of 10^{o} to 15^{o}. Silt beds in units 3 and 5 have higher overall residual shear strength compared to clay beds, with values ranging from 24^{o} to 33^{o} (cf. Porter et al., 2004; Bishop et al., 2008). The seasonal wetting and softening of clay beds may further contribute to failure: when wet, units 3 and 5 sediments readily fail, even on gentle slopes, due to a reduction in shear strength with increasing saturation (cf. Clague and Evans, 2003). All other surficial units contain little clay, are non-plastic and permeable.

Retrogressive failure of glaciolacustrine sediments, and reactivation of the Ripley Slide likely began as the shear strength was reduced in response to periods of wetting; and as the residual friction angle of units 3 and 5 fell below the angle of slope (often in excess of 25^{o}). The residual friction angle of clay beds in glaciolacustrine units is stress dependant: high normal stresses promote alignment of clay particles during shear. The effective stress condition of the slope is also influenced by bedding thickness and pore water pressure in glaciolacustrine units (cf. Clague and Evans, 2003; Bishop et al., 2008). This suggests rates of movement in Unit 3 is higher beneath the main body of the landslide where normal stresses are greater, than at the toe where shear rates are lower (cf. Porter et al., 2002). While the rate of movement during reactivation is currently slow, rapid failure may occur if surface tension cracks fill with surface water and landslide debris becomes saturated by rising groundwater and river levels; or if toe material is excessively removed through cutbank erosion and river-bed scour by Thompson River (cf. Eshraghian et al., 2008) or if further loading should occur (e.g., addition of ballast; longer, heavier, more frequent trains).

Hydrogeologic conditions
Pleistocene units 4 to 7 likely host an unconfined aquifer, recharged by infiltrating precipitation and surface runoff on the slopes above the Ripley Slide. Groundwater flows laterally and downward through porous till and glaciofluvial units (4 and 6); and through vertically fractured glaciolacustrine units (3 and 5) until it encounters fractured, non-porous bedrock (Unit 1) or sub-horizontal sub-shear zones in Unit 3. As with other landslides in the area, units 3 and 5 function as aquitards but also accommodate landslide movement along shear zones approximately corresponding to stratigraphic boundaries (**Figure 15**). Artesian conditions at the landslide toe suggest the presence of an aquifer in Unit 1 bedrock and Unit 2 diamicton, confined by Unit 3 clay and silt. Recharge sources include groundwater flow through buried paleochannels and along unconformities separating older glacial sequences (cf. Porter et al., 2002; Clague and Evans, 2003). This confined aquifer controls pore water pressures at the base of Unit 3.

River levels affect the stability of translational and rotational slides in the Thompson valley in three ways: 1) by changing the pore water pressure on the rupture surfaces in Unit 3 as discharge fluctuates; 2) by changing the supporting pressure on the toe slopes of landslides; and 3) by altering the slide geometry through cutbank erosion, channel incision and toe scour. Slope instability on a number of larger landslides occurs during years when Thompson River levels are elevated above average for longer than normal periods. During spring run-off, high water levels provide temporary support at landslide toes, resulting in slower movement rates. Higher ground movement rates occur during autumn and winter when river discharge and groundwater levels drop, reducing load values in the toe slope (cf. Eshraghian et al., 2007).

River erosion can also reactivate landslides. Many landslides in the valley have pushed colluvial debris (Unit 8) well into the river, constricting the channel and locally increasing flow velocity. As a consequence, Thompson River is prone to channel scour and cutbank erosion. Scour holes are evidence that Thompson River continues incising the channel floor. If down-cutting exposes other clay layers similar to the highly plastic clay beds near the top of Unit 3, then renewed, rapid to extremely rapid landslide activity could be triggered on new, deeper seated rupture planes. Cutbank erosion can also produce over-steepened toe blocks along the river. As these blocks fail and are removed by river flow, toe unloading can trigger rapid to very rapid movement on new, deeper rupture surfaces once river and groundwater levels fall (cf. Eshraghian et al., 2007).

Climatic conditions
Climate change and weather extremes have the potential to exacerbate ongoing landslide activity at the Ripley site. Although the average rainfall in the area has increased since 1920s, there is no direct correlation with landslide activity (Porter et al., 2002; Eshraghian et al., 2007). However, increased duration and magnitude of precipitation, loss of vegetation cover by wildfires and fluctuating river discharge could contribute to sustained periods of groundwater recharge, high pore water pressures in bedrock and surficial units, higher river discharge and greater channel erosion; all which could add to further activity of the Ripley Slide.

Summary

This contribution synthesizes existing geoscience data and knowledge, presents new geoscience information and summarizes our current understanding of landslide processes in the Thompson River valley south of Ashcroft where critical railway infrastructure is at risk. Knowledge of the glacial geology and stratigraphy in this reach of the Thompson River valley provides valuable insight into better understanding the nature and behaviour of the Ripley Slide: an active landform that is adversely impacting CN and CPR tracks and other rail infrastructure.

Valley fill at the Ripley Slide site consists of a wide range of sediments reflecting variability in the nature of their depositional environments over at least one glacial cycle during the Pleistocene. The occurrence and position of interbedded glaciolacustrine silt and clay is important with respect to local slope stability and infrastructure management because the horizontal component of the failure surface normally occur along weak, glacially sheared zones in Unit 3.

Similar to other landslides in the Thompson River valley, the Ripley Slide displays a retrogressive behaviour, where channel incision, as well as falling river and groundwater levels affect the significantly toe slope stability and mobility of the entire slide. Preserving mass at the toe of the landslide where frictional strength is higher than along other portions of the slip surface may help reduce landslide activity (cf. Porter et al., 2002).

GPS monitoring suggests peak movement of the Ripley Slide occurs from autumn to winter as river and groundwater reach minimum levels. Peak river flows, bank erosion, bed scour, and highest differential between river and groundwater levels occur from spring to summer (cf. Eshraghian et al., 2007; 2008; Bunce and Chadwick, 2012).

To summarize, ground movement and failure mechanisms of the Ripley Slide are a function of stratigraphic relationships of sub-surface units, toe erosion by Thompson River, river discharge levels, fluctuating groundwater conditions, anthropogenic slope excavation, and prolonged intervals and increasing frequency of ground vibration and loading of unconsolidated earth materials due to greater volumes of rail traffic.

Landslide monitoring

An extensive suite of monitoring technology is now being applied at the Ripley Slide that ranges from: 1) traditional applications including permanent monitoring using survey benchmarks, GPS stations and piezometers; 2) subsurface investigations involving drilling and shallow geophysical surveys; 3) novel technologies such as linear fibre optic sensing and vertical subsurface ShapeAccelArray (SAA) inclinometry for down-hole monitoring; 4) InSAR corner reflectors for satellite (RADARSAT-2) interferometry have been installed across the landslide and adjacent stable terrain (**Figure 16**); and 5) round-based SAR and LiDAR have also been deployed for ongoing comparative work (Bobrowsky et al., 2014).

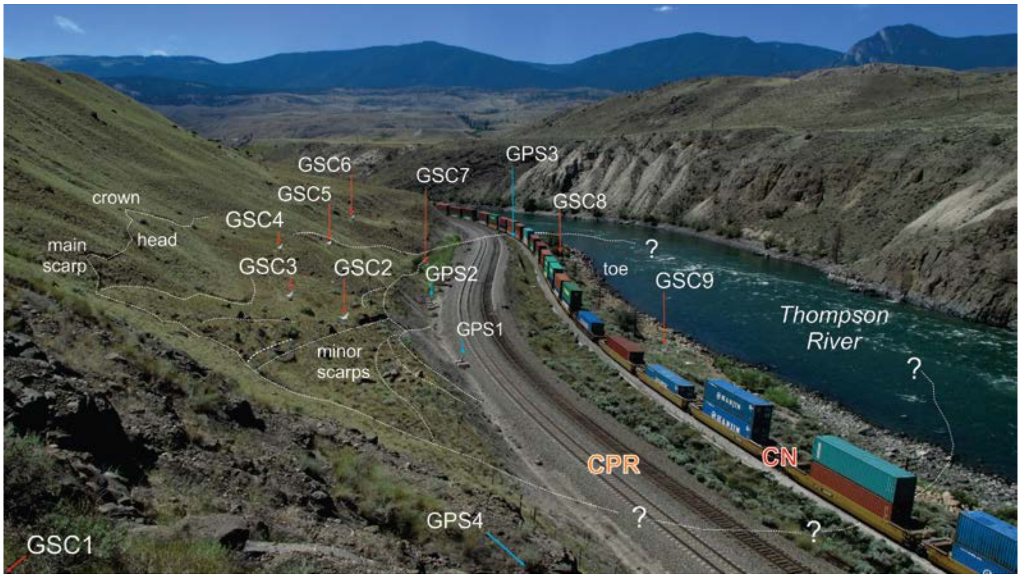

Figure 16 Location of GPS monitoring stations (Bunce and Chadwick, 2012) and InSAR corner reflectors. Fibre optic monitoring system is installed along the retaining wall separating the CPR and CN tracks.

Surficial geology mapping, borehole instrumentation and interferometric techniques reveal limited information on the subsurface nature of the Ripley Slide (**Figures 4** and **15**). Knowledge of the internal structure and composition of the landslide (to at least a depth of 50 m) as revealed by geophysical surveys will be of critical importance for interpreting the results gleaned from other monitoring applications. The optimal time for the geophysical surveys is in the autumn when river and groundwater levels are low. Direct current electrical resistivity and electromagnetic tomographic profiling techniques will be effective for detecting vertical and lateral variations and contacts between earth materials with contrasting electrical resistivities. For example, Unit 3 clay and silt with high pore water contents should be electrically conductive in contrast to gravel, till, bedrock and frozen ground which are more electrically resistive. Seismic reflection and ground penetrating radar will provide additional insight into the internal three dimensional architecture of the Ripley Slide.

The collective efforts and outputs associated with this extensive array of instrumentation and monitoring will help better manage this landslide and similar hazards elsewhere in Canada and internationally (Bobrowsky et al., 2014).

Acknowledgements

The project has benefited from management by Carmel Lowe, Adrienne Jones and Philip Hill (Geological Survey of Canada, Sidney, British Columbia) and Merrina Zhang (Transport Canada). Lionel Jackson (Geological Survey of Canada, Vancouver, British Columbia) critically reviewed the draft manuscript. The following colleagues were important team members and contributed by providing help in the field: Wendy Sladen and Baolin Wang (Geological Survey of Canada, Ottawa); Lionel Jackson (Geological Survey of Canada, Vancouver, British Columbia); Zhang Qing, Zhang Xiaofei and Lv Zhonghu (Centre for Hydrogeology and Environmental Geology, China Geological Survey, Hebei, China); Chris Bunce and Eddie Choi (Canadian Pacific Railway, Calgary, Alberta); Tom Edwards (Canadian National Railway, Edmonton, Alberta); Michael Hendry, Derek Martin, Renato Macciotta and Hengxing Lan (University of Alberta, Civil and Environmental Engineering, Edmonton, Alberta, Canada); and Ian Chadwick (ERD Consulting Ltd., Kamloops, British Columbia). Field safety was ensured by Gary Maximiuk and Roy Olsen (CPR) and Jennifer Kutchner and Mark McKay (CN). Accommodation for the duration of the project was furnished by the Ashcroft River Inn. Sue and Sandy at the Trackside Diner provided much needed nourishment; and essential blacksmith services were provided by John Bunce.

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