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1 Hydrogeological and geophysical properties of the very slow-moving Ripley Landslide,

2 Thompson River valley, British Columbia

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16 Abstract

Landslides along a 10-km reach of Thompson River south of Ashcroft, British Columbia have 17 repeatedly damaged vital railway infrastructure and threaten salmon runs, potable water 18 supplies, cultural heritage features, and public safety. Government agencies, universities and 19 the railway industry are focusing research efforts on a single test site – the very slow-moving 20 Ripley Landslide - to better manage geohazard risk in this corridor. We characterize the 21 22 landslide's composition through hydrogeological and geophysical mapping. Field mapping and exploratory drilling distinguished ten hydrogeological units in surficial deposits and fractured 23 24 bedrock. Electrical resistivity tomography, frequency domain electromagnetic conductivity measurements, ground penetrating radar, seismic primary wave refraction and multispectral 25 analysis of shear waves; in conjunction with down-hole measurement of natural gamma 26 27 radiation, induction conductivity and magnetic susceptibility provide a detailed, static picture of soil moisture and groundwater conditions within the hydrogeological units. Differences in 28 electrical resistivity of the units reflect a combination of hydrogeological characteristics, 29 temperature and solutes. Resistive earth materials include dry glaciofluvial outwash and non-30 fractured bedrock; whereas glaciolacustrine clay and silt, water-bearing fractured bedrock, and 31 saturated to partly saturated till and outwash are conductive. These new hydrogeological and 32 geophysical datasets enhance understanding of the composition and internal structure of this 33 34 landslide and provide important context to interpret multi-year monitoring underway in the 35 valley. Continuous real-time monitoring of electrical resistivity, now underway, will help characterize water-flow paths and possible relationships to independently monitor pore 36 pressures and slope creep. 37

38

39 Keywords

40 Surficial mapping; geophysical surveys; landslide; geohazard monitoring; British Columbia

41 Introduction

The ten-kilometre stretch of Thompson River between Ashcroft and Basque Ranch, British 42 Columbia (BC) has experienced numerous landslides since the mid-1800s (Fig. 1). In light of 43 threats to trans-continental transportation, Stanton (1898) investigated the earliest of these 44 events in one of the first landslide studies in the Canadian Cordillera. Subsequent rapid failures 45 occurred during the twentieth century (Porter et al. 2002; Clague and Evans 2003) and 46 47 numerous landslides along this reach continue to creep (Eshraghian et al. 2008; Journault et al. 2018). Such instabilities have the potential to impact both of Canada's national railways, 48 49 portions of Trans-Canada Highway, arable land, fisheries, and the community of Ashcroft (Fig. 1 a). They also provide insight into landslide risk of several communities similarly situated 50 along the inner gorge of Thompson River such as Spences Bridge, and as far south as Lytton 51 52 at the confluence with Fraser River, where repeated failures have generated displacement waves or landslide dams (Drysdale 1914; Porter et al. 2002; Clague and Evans 2003). 53

54

Since 2013, Ripley Landslide has been used as a research test site to advance understanding of 55 the composition, behaviour, and associated risks of similar but generally larger landslides along 56 this stretch of Thompson River. The landslide occurs in unconsolidated valley fill on the east 57 bank of the river, seven kilometres south of Ashcroft (Fig. 1 b), and due to the small size (~3.3 58 ha) and continuous activity, it is an ideal target for geohazard characterization and monitoring 59 60 (Fig. 1 c, d; Bobrowsky et al. 2014, 2017). Completed and ongoing investigations at this site focus on monitoring of landslide motion and environmental conditions, through a combination 61 of slope instrumentation, real-time global navigation satellite system (GNSS) tracking, repeat 62 63 unmanned aerial vehicle (UAV) surveys, and spaceborne RADAR interferometry (InSAR) (Bunce and Chadwick 2012; Macciotta et al. 2014; Hendry et al. 2015; Journault et al. 2018). 64 The resulting insights are guiding future landslide monitoring and geohazard mitigation efforts 65

66 in the inner gorge of Thompson River and along similar reaches of Fraser River downstream67 (Bobrowsky et al. 2018).

68

To investigate the composition of the landslide, we undertook a field-focused program 69 70 combining hydrogeological mapping, stratigraphic analysis of borehole logs, geophysical testing (Huntley and Bobrowsky 2014; Huntley et al. 2017a), along with laboratory 71 72 characterization of sediments and their electrical properties. Based on this work, we here characterize hydrogeological, geophysical variability and electrical properties of Ripley 73 74 Landslide. These details provide important context for interpreting instrumental and remotely sensed records from the Ripley test site; and for understanding causal mechanisms and function 75 of this and similar landslides along Thompson River. 76

77

78 Background: Landslides of the Thompson River Valley

79 *Physiology, geology and climate*

Thompson River occupies a broad, approximately 1 km-deep, locally steep, bedrock valley. 80 Basement rock near Ashcroft comprises various units of the late Paleozoic to early Mesozoic 81 Cache Creek Terrane and the largely Mesozoic Quesnel Terrane that are respectively of oceanic 82 and island arc affinity (Monger and McMillan 1989; Gordey et al. 1991; Beatty et al. 2006). 83 The youngest rocks, predominantly clastic sedimentary rock of the Jurassic Ashcroft 84 85 Formation, are sporadically exposed along Thompson River for 10 km south of Ashcroft (Monger and McMillan 1989; Beatty et al. 2006). Above ~500 m elevation, slopes are locally 86 mantled by colluvium or drift. Valley-bottom benchlands, reaching up to 350 m elevation, have 87 88 been incised by Thompson River since the last glaciation, forming an inner gorge with steep slopes up to 125 m high. 89

Thick (50 m to 150 m) Pleistocene valley-bottom fill is well exposed along post-glacial terrace 91 scarps of Thompson River and its tributaries (Ryder 1976; Clague and Evans 2003; Johnsen 92 and Brennand 2004). These sediments include multiple glaciolacustrine units, separated by till 93 and outwash gravel recording at least three glaciations: the last (Late Wisconsinan) glaciation, 94 the penultimate glaciation (Early Wisconsinan), and an earlier glaciation (Ryder et al. 1991; 95 Clague and Evans 2003). The upper part of the sediment sequence was deposited during 96 deglaciation, when repeated glacial lake stages occupied the valley (Fulton 1969; Ryder 1976; 97 Johnsen and Brennand 2004), and shortly after deglaciation when the valley bottom was 98 99 choked by paraglacial sedimentation (Church and Ryder 1972).

100

Modern climate and river discharge, measured respectively 65 km east of Ashcroft at 101 102 Kamloops and 40 km down Thompson River from Ashcroft near Spences Bridge, reflect seasonally variable weather conditions and hydrology. Precipitation (~250 mm, annual 103 average) is concentrated in May to September (20 mm to 40 mm, monthly) when it falls as 104 rain, and in December and January (20 mm to 30 mm, monthly) when it falls mainly as snow. 105 The driest months are February to April (http://climate.weather.gc.ca/ [2018 URL]). The valley 106 bottom is within the drought-prone Very Dry Hot subzone of the Bunchgrass biogeoclimatic 107 zone (Nicholson et al. 1991; <u>www.for.gov.bc.ca</u> [2018 URL]). Thompson River discharge 108 reflects spring snow melt and rainfall variation. Base flow varies annually from <200 m³/s to 109 ~600 m³/s, with a freshet peak in late May or June of <2,000 m³/s to >4,000 m³/s 110 (http://wateroffice.ec.gc.ca [2018 URL]). The river changes in elevation at Ripley Landslide 111 by over 5 m (264.5 m to 269.8 m elevation) in response to spring melt in the surrounding 112 mountains (Schafer et al. 2015). River levels are at their minimum between early January and 113 early March; and start to rise in late April to early May, continuing through until late July. By 114 early August, river levels are starting to fall. 115

117 Landslides and their drivers: initial conditions

The presence of steep slopes in bedrock and overlying fill flanking Thompson River is a 118 necessary condition for landslide activity. During deglaciation and early post-glacial (i.e., 119 paraglacial) time, rapid trunk valley incision in the Interior Plateau, resulting from glacio-120 eustatic rebound and first time exposure of poorly consolidated sediments, formed over-121 122 steepened slopes. Large, retrogressive rotational and translational landslides occurred during the Holocene (Ryder, 1976; Clague and Evans 2003). Although Pleistocene valley fill was 123 124 preconditioned for failure by rapid incision of unconsolidated glacial units, landslides were most likely triggered by elevated porewater pressure during particularly wet intervals in 125 prehistoric times. Post-glacial climate of the southern Interior Plateau has fluctuated between 126 127 warmer and cooler than present conditions, but was always generally dry (Hebda 1982; Mathewes and King 1989; Hebda 1995). Even at its wettest, between 6000 and 4000 years ago, 128 climate was not much moister than today (Hebda 1995). Thus, unconsolidated valley-bottom 129 sediments were likely relatively dry through much of the Holocene and remained marginally 130 stable until the 1860s when irrigation, necessary for agriculture on benchlands above the river, 131 began (Stanton 1898; Clague and Evans 2003). 132

133

Historic failure of Pleistocene units involve one of three mechanisms (Porter et al. 2002; Clague
and Evans 2003; Eshraghian et al. 2007, 2008): 1) very slow (2 cm/yr to 10 cm/yr) rotational
sliding of large, intact blocks; 2) very slow (2 cm/yr to 10 cm/yr) translational sliding of blocks
with little rotation; or 3) rapid flow slides and slumps, where fills disaggregate while moving
down slope (>2 m/hr). Additionally, extremely rapid (>5 m/s) and very rapid (> 3 m/min) rock
falls and debris falls initiate on steep valley walls (cf. Cruden and Varnes 1996), particularly
in the Black Canyon. Although many landslides failed rapidly in the past, those that are

141 currently active are very slow-moving, reactivated compound features (Porter et al. 2002;142 Clague and Evans 2003; Eshraghian et al. 2007, 2008).

143

Possible anthropogenic triggers for historical landslides (Fig. 1 b) include: 1) irrigation of 144 terraces, first by leaky unlined ditches beginning in 1868, and then by confined pipes since the 145 1960s; and 2) excavation of lower slopes during the construction and expansion of rail lines 146 147 beginning in the 1880s and continuing into this century (Stanton 1898; Clague and Evans 2003; Bunce and Chadwick 2012). Artesian groundwater pressures linked to precipitation further 148 149 contribute to instability (Porter et al. 2002). Stratigraphy exerts a first order control on the distribution, geometry and rate of landslides along the inner gorge. Most failures occur along 150 weak, sub-horizontal shear zones within glaciolacustrine clay and silt units, confined between 151 overlying till and underlying gravel deposits and bedrock (Porter et al. 2002; Eshraghian et al. 152 2007, 2008; Bishop et al. 2008). Thin, highly plastic clay beds dominate the geomechanical 153 behaviour of the glaciolacustrine units due to their low strength (Porter et al. 2002). The 154 weakest clay zones have residual shear strengths, and were probably previously sheared during 155 glacial overriding and syndepositional landslide events (Porter et al. 2002; Bishop et al. 2008). 156

157

Thompson River influences landslide activity in the inner gorge in several ways. Deep post-158 glacial incision was first required to expose weak, failure-prone units at the base of the fill 159 160 sequence and provide kinematic freedom for failure (Porter et al. 2002; Clague and Evans 2003; Eshraghian et al. 2007; Bishop et al. 2008). Ongoing channel migration promotes toe instability 161 (Porter et al. 2002) and alters landslide toe geometry (Eshraghian et al. 2008). Dropping river 162 level exerts a complex control on landslide stability, reflecting increased hydraulic gradients 163 within the basal glaciolacustrine unit, particularly along rupture surfaces within it (Eshraghian 164 et al. 2008), and loss of toe loading (Porter et al. 2002; Eshraghian et al. 2008; Hendry et al. 165

2015). Probably because of several of these effects on toe stabilization, creep commonly
accelerates shortly after flood events and during river stage drop following the freshet (Porter
et al. 2002; Macciotta et al. 2014; Schafer et al. 2015).

169

170 Ripley Landslide Test Site

Ripley Landslide is approximately 220 m wide (N-S) by 150 m long (E-W) with an estimated 171 volume of 400,000 m³ (Fig. 1 c). The landslide has been active since at least 1951, but 172 displacement across the slide body increased after 2005 when a rail siding was constructed 173 174 across its middle portion (Bunce and Chadwick 2012). During construction, embankments were extended upslope and a lock-block retaining wall, separating the Canadian National 175 Railway (CN) and Canadian Pacific Railway (CP) tracks, was installed (Fig. 1 d). Pronounced 176 sagging of the retaining wall and bulging of lock blocks has occurred since 2005 (Huntley et 177 al. 2016). To accommodate continual lateral and vertical displacement across the landslide, 178 both rail companies periodically add ballast, in addition to lifting and re-aligning their tracks. 179

180

181 Landslide monitoring

Numerous conventional and experimental continuous monitoring technologies (Fig. 1 c, d) 182 provide insight on the activity, deformation mechanisms, and potential acceleration triggers of 183 Ripley Landslide. Each of these techniques record increased landslide activity in winter, when 184 river and groundwater levels are lowest (Macciotta et al. 2014; Hendry et al. 2015; Schafer et 185 al. 2015; Journault et al. 2018). Four permanent GNSS monuments installed across the 186 landslide in 2008 (Fig. 1 c) record cumulative annual displacement on the order of 100 mm/yr 187 to 200 mm/yr, which peaks from autumn to winter (Bunce and Chadwick 2012; Macciotta et 188 al. 2014; Hendry et al. 2015). InSAR results from 2013 to 2015 indicate similar magnitudes 189 and spatial-temporal patterns of displacement (Huntley et al. 2017b; Journault et al. 2018). 190

Ground movement concentrated within the centre of the sliding mass averages 39 mm/year, 191 with fastest displacements detected upslope from the railway tracks and on the southern flank. 192 Average and maximum line of sight displacement rates (equivalent to the downslope direction 193 for the west-facing test site) of INSAR corner reflectors (Fig. 1 c) and other coherent targets 194 (e.g., buildings, large boulders) are 49 mm/year, and 77 mm/year, respectively; with greater 195 displacement from November to March (Huntley et al. 2017b; Journault et al. 2018). Fibre 196 197 Bragg grating (FBG) and Brillouin optical time domain reflectometry (BOTDR) monitoring of the retaining wall from 2013 to 2015 detected ~ 2 mm of accumulated strain in the wall, 198 199 including displacement of individual blocks at its southern end (Fig. 1 d), with peak activity occurring in the fall and winter months (Huntley et al. 2016; 2017c). 200

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Subsurface borehole monitoring combining ShapeAccelArray (SAA) inclinometry with piezometer head levels indicate that the main slide body is failing along sub-horizontal, weak, basal shear surfaces in highly plastic clay beds (Macciotta et al. 2014; Hendry et al. 2015; Schafer et al. 2015). The central and northern parts of the slide are translating sub-horizontally $(2.1^{\circ} \text{ to } 2.5^{\circ})$ whereas the southern portion near the lock-block retaining wall has a steeper (28°) slide surface.

208

209 Knowledge gaps

Although earth material stratigraphy, textures and penetrative planar structures are important controls on sub-surface porosity, permeability and hydrology in the Thompson River valley (Evans 1984; Porter et al. 2002; Clague and Evans 2003), it remains unclear how these factors influence the style, timing and rate of slope displacement (i.e., form and function) at Ripley Landslide. Landslide monitoring reveals limited information on the subsurface range of earth materials, structures and hydrological behaviour. A suite of conventional terrain mapping, geophysical methods, field sensors and laboratory techniques were tested in this challenging
environment to address significant knowledge gaps in the nature and distribution of surficial
earth materials, their stratigraphic relationships and internal structure of the landslide.

219

220 Methods and Results

Investigations at the Ripley Landslide test site have three aims: 1) characterizing material 221 222 composition, particularly beneath railway infrastructure; 2) quantifying spatial and temporal characteristics of displacements; and 3) assessing the degree of infrastructure damage. The 223 224 present study relates principally to the first objective, and provides important context for better addressing the second and third objectives. Landslide form and function in the Thompson River 225 valley are strongly influenced by sub-surface porosity, permeability and hydrology, which are, 226 227 in turn, influenced by the stratigraphic order of earth materials, textures and penetrative planar structures. To help determine the degree to which these controls influence the nature, extent 228 and activity of Ripley Landslide, we combined terrain mapping, stratigraphic analysis of 229 borehole logs, and several geophysical techniques to characterize hydrogeological variability 230 at the test site. 231

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233 Hydrogeological mapping

Surficial earth materials and landforms were mapped in ArcGIS using ortho-rectified and georeferenced digital natural colour air photographs taken by a Phantom IV UAV during repeat photogrammetric overflights in September 2016, September 2017 and September 2018. The resulting imagery was sufficient to resolve cobble-sized boulders and anthropogenic features (<5 cm across) at a flight elevation 50 m above ground level. During desktop terrain analysis, visual interpretation of imagery relied on the recognition and separation of geological features using colours, tones, surface textures, patterns, shapes, sizes, shadows and field associations.

Fieldwork was undertaken periodically between 2013 and 2019 to ground-truth air photo 241 interpretations, and to describe sedimentological characteristics that could not be determined 242 by remote mapping. With over 80 field stations and 11 boreholes on and adjacent to the 243 landslide, hydrogeological units were defined on the basis of lithofacies and landform 244 associations, texture, sorting, colour, sedimentary structures, degrees of consolidation, 245 stratigraphic contact relationships, geological age, and other distinguishing characteristics 246 247 described on site (Fig. 2 a-l). Fig. 3 depicts the surface and vertical (stratigraphic) distribution of hydrogeological units and landforms at Ripley Landslide and adjacent terrain; more detailed 248 249 unit descriptions are provided in Huntley and Bobrowsky (2014). Key hydrogeological characteristics of these units are highlighted in Tab. 1. Drainage classes and permeabilities were 250 qualitatively determined from field assessments of porosity, unit thicknesses, earth material 251 textures, penetrative planar structures and slopes driving hydraulic gradients (Tab. 1). 252

253 Observations of textures and porosity variations in hydrogeological units

Pleistocene and Holocene sediments unconformably overlie fine-grained, massive crystalline 254 255 andesite (unit 1a, **Fig. 2** a) and fine-grained, flow-banded crystalline rhyolite (unit 1b) with low or negligible intercrystalline porosity, and welded clast-supported agglomerates with a low 256 257 vugular porosity (Fig. 2 b; Tab. 1). The oldest Pleistocene deposits (unit 2) are up to 6 m thick 258 and include intercalated centimetre-thick beds of clay, silt, sand, gravel and diamicton (Fig. 3) with moderate intergranular porosity. This basal unit is disconformably overlain by up to 12 m 259 of silt-clay couplets (i.e., varves) with dropstones and stratified diamicton with low 260 261 intergranular porosities (Fig. 2 c, d). Units 2 and 3 are glaciolacustrine in origin and were deposited during the retreat phase of a penultimate glaciation and advance of the Late 262 Wisconsinan Cordilleran Ice Sheet, respectively. Glaciolacustrine units are over-consolidated, 263 deformed, eroded and overlain by unit 4, a massive, matrix-supported diamicton up to 5 m 264 thick composed of silt, clay, erratic boulders and ice-rafted blocks of locally derived bedrock, 265

interpreted as a (subglacial) lodgement till (Fig. 2 e). Consolidation of unit 3 causes silt and 266 clay particles to densely pack, resulting in an increase of effective stress, combined with a 267 decrease in void ratio, water content, and permeability (Le Meil 2017). The permeability of 268 glaciolacustrine units is anisotropic, with horizontal permeability (along the rhythmite beds) 269 an order of magnitude larger than the vertical permeability (across beds). Heterogeneities 270 caused by fissures and sand laminae intersecting the glaciolacustrine silt and clay significantly 271 272 enhance the bulk permeability of units 2 and 3. Till has a low vugular porosity due to the presence of isolated weathered igneous and sedimentary clasts and sand-filled voids within the 273 274 fine-grained matrix. Field observations, borehole logs and geophysical data all indicate that unit 4 till contains ice-rafted bedrock blocks. Silt-rich glaciolacustrine sediments (unit 5, Fig. 275 2 f), containing centimetre-thick sand beds with moderate intergranular porosity, conformably 276 277 overlies till. During summer months, salt crusts form where solute-rich groundwater seeps and evaporates from exposed sand-rich beds in units 3 and 5 along railway embankments and river 278 cutbanks. Above unit 5 lies >5 m of massive and crudely stratified beds of open framework, 279 clast-supported boulder and sand-rich gravel (unit 6, Fig. 2 g). This coarse-grained 280 glaciofluvial unit has a high intergranular porosity. 281

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The oldest Holocene deposits, unit 7 (Fig. 2 h), consist of interbedded stratified diamicton and 283 open framework, clast-supported cobble-gravel incised into unit 6. This basal sequence fines 284 285 upward to massive centimetre-thick sand and silt beds with moderate intergranular porosity. Bedding lies sub-parallel to surface slopes ranging from $>3^{\circ}$ to $<8^{\circ}$ on alluvial fans, and $>8^{\circ}$ to 286 <12° on alluvial cones. Slopes >12° are covered in postglacial coarse-grained colluvium with 287 a high intergranular porosity (unit 8, **Fig. 2** i). Moderate slopes from $>12^{\circ}$ to $<26^{\circ}$ are covered 288 in a veneer of stratified diamicton and clast-supported cobbles, boulders with interstitial sand 289 and silt. Moderately steep bedrock slopes from $>26^{\circ}$ to $<35^{\circ}$ are covered in a veneer of clast-290

supported talus blocks. Modern alluvial floodplain sediments (unit 9, Fig. 2 j) are open 291 framework, clast-supported boulders and sand with a high intergranular porosity, confined to 292 elevations lower than 270 m. Surface water is quickly removed during heavy or prolonged 293 rainfall, and boulders and sand are permanently saturated by river water at shallow depth (<2 294 m) on the active flood plain. Bedrock, glacial and alluvial sediments (units 1-5 and 9), 295 excavated during track construction, are unconformably overlain by a linear deposit (<5 m 296 297 thick) of open framework, clast-supported cobble and boulder ballast and a lock-block retaining wall (unit 10) with high intergranular porosity (Fig. 2 k, l). 298

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300 <u>Penetrative structures observed in hydrogeological units</u>

Unit 1 has moderate fracture porosity (**Tab. 1**). Fine-grained crystalline andesite (unit 1a) has 301 302 two dominant sets of vertical joints, trending W and NW; overlying rhyolite and volcaniclastic rocks (unit 1b) have vertical fractures trending NW and SW. Volcaniclastic rocks dip eastward 303 into the slope. These penetrative features are an expression of the regional folding and faulting 304 history. Surface weathering rinds and mineral alteration are observed along exposed surfaces, 305 including open fractures. Surface exposures and borehole logs reveal overlying 306 glaciolacustrine units 2 and 3 have low to moderate fracture porosities with discrete zones 307 where clay-rich beds are intensely cracked, fissured and sheared (Fig. 3). Sub-till silt and clay 308 beds with contorted layering and loading structures indicate deformation during the overriding 309 of glacial lake deposits by ice during the last glaciation (Fig. 2 c, d, e). Cross-cutting (and 310 younger) penetrative structures are observed at depths between 5 m and 15 m below surface. 311 confined to unit 3. Below 270 m elevation. sub-horizontal planar surfaces dip from 5° to 30° 312 W toward and underneath the river (Fig. 3, Tab. 1). These structures are interpreted as 313 translational-rotational shear planes related to current landslide movement. Slide scarps, 314 crescentic tension cracks on the slide body and surface relaxation (unloading) fractures along 315

railway embankments are sub-vertical, penetrate deep into the slide body (greater than 2 m
depth) and cross-cut multiple units (Fig. 2 e, f). These penetrative structures impart a moderate
to high fracture porosity in till diamicton (unit 4), silt-rich glaciolacustrine beds (unit 5),
postglacial alluvium (unit 7), colluvial sediments (unit 8), and anthropogenic materials (unit
10). Coarse-grained glaciofluvial deposits (unit 6) and modern alluvial floodplain sediments
(unit 9) have no penetrative planar structures (Tab. 1).

322

323 Geophysical field mapping

324 The objective of the geophysical surveys was to measure contrasts in the physical properties of unconsolidated sediments and bedrock, interpreted in the context of the known lithological units 325 on site (Huntley and Bobrowsky 2014; Huntley et al. 2017a, b). Geophysical surveys were 326 327 undertaken between 2013 and 2015 using a combination of terrestrial and waterborne electrical resistivity tomography (ERT), frequency domain electromagnetic conductivity measurements 328 (FEM), ground penetrating radar (GPR), seismic primary wave refraction (PWR) and 329 multichannel analysis of surface waves (MASW); in conjunction with down-hole measurement 330 of natural gamma radiation (GR), induction conductivity (IC) and magnetic susceptibility (MS) 331 in boreholes located directly adjacent to the CPR tracks (Fig. 3; Tab. 2). Geophysical traverses 332 were spaced across the breadth of the landslide and Thompson River to ensure reasonable 333 diversity in coverage of the subsurface variability (Fig. 4). Terrestrial cross-sections extended 334 335 from behind the landslide head scarp to the channel bank (November 2013). River survey lines trended parallel to the shoreline (November 2014), and were traversed using a metal-hulled jet 336 boat towing a non-metallic white-water raft containing the geophysical equipment. With regard 337 to geoelectrical properties, five terrestrial ERT lines used a Wenner-Schlumberger array with 338 48 electrodes spaced 5 m apart. Four waterborne ERT lines used a reverse Wenner array with 339 an electrode spacing of 10 m (Huntley et al. 2017a; Huntley et al. 2019a). Apparent resistivity 340

datasets were merged into a single file and interverted using the RES3DINV inversion program
 (geotomosoft.com 2017; Huntley et al. 2019b).

343

A Proactive Infrastructure Monitoring and Evaluation (PRIME) resistivity monitoring system 344 was installed on the Ripley Landslide in November 2017 (Holmes et al. 2018). This system, 345 which provides near-real time 4-D resistivity data, consists of two intersecting Wenner arrays 346 347 (one 91 m long with 45 electrodes, the other 54 m long with 27 electrodes, all evenly spaced). The PRIME system is connected to the internet via a modem and allows for remote data 348 349 acquisition. When calibrated with soil moisture measurements and laboratory testing of earth materials, continuous data collection allowed for changes in subsurface condition to be 350 monitored over time (cf. Merritt et al. 2014; Uhlemann et al. 2017), and improves understanding 351 of seasonal changes in the hydrogeological regime of the landslide (Huntley et al. 2019c). 352

353

354 Soil moisture monitoring

The importance of soil suctions (negative pore water pressure) on slope instability has long 355 been recognized (Fredlund et al. 1976). Soil suctions increase the strength of soil and help 356 stabilize slopes. However, transient near-surface changes in suction pressures, as a result of 357 climatic conditions, may be sufficient to induce slope movement. In November 2017, two 358 Decagon MPS6 soil suction meters were installed in the headscarp of Ripley Landslide to a 359 360 depth of 2 m (Sattler et a. 2018); another three experimental meters were placed in November (Fig. 4). The potential use of resistivity as a proxy for suction has been previously suggested 361 (Piegari and Di Maio 2013). In the coming years, the relationship between these parameters 362 will be investigated using preliminary PRIME and soil suction sensor data from unit 3. 363

364

365 ERT results and hydrogeological units

An unprecedented level of insight into the internal composition and structure of the landslide 366 has been gained from the terrestrial, waterborne and borehole geophysical surveys (Tab. 2). 367 The ERT surveys provide the most complete and deepest penetrating information regarding the 368 internal structure of the landslide (Huntley et al. 2017a, b; Huntley et al. 2019a, b). The FEM 369 only images the upper 10 m, but results are consistent with ERT data, and add additional useful 370 information on the near surface resistivity/conductivity distribution (Huntley et al. 2017a, b; 371 372 Huntley et al. 2019a, b). Seismic surveys provide information on earth material stiffness at depth. GPR data show interesting results (Huntley et al. 2017a), but there are difficulties in 373 374 interpretation due to the predominance of clay-rich sediments, and numberous diffracting centres, mostly boulders at various depths (Tab. 2). 375

376

The terrestrial-based ERT survey undertaken in November 2013 and waterbourne ERT survey 377 completed in November 2014 are presented with PRIME data from November 2018 in a fence 378 diagram showing the range of electrical properties of the landslide (Fig. 5). Since the surveys 379 were completed at the same time of year, differences arising due to the influence of seasonal 380 changes in weather conditions on the electrical properties were minimised by selecting 381 November as the month of observation, and ensures that the electrical properties are 382 comparable, although completed in different years. Data from the terrestrial-based ERT lines 383 were inverted in 3D using Res3DInv (geotomosoft.com 2017), taking account of the offline 384 385 variation in topography in the topographically complex area of the slide. This improved the correlation between each of the lines, reducing the mismatch in resistivity values at depth. The 386 waterbourne survey data were inverted in 2D using Res2DInv (geotomosoft.com 2017). The 387 lines are displayed in ParaView® alongside the PRIME ERT lines (Fig. 5). 388

Combined terrestrial and waterborne 2D ERT datasets are visualized as a pseudo-3D model of 390 resistivity values using ParaView® software (Fig. 6). Competent bedrock (unit 1) has a high 391 apparent resistivity value, >110 Ω m (Fig. 6). Weathered bedrock and colluviated fine-grained 392 beds at the base of unit 2 are moderately resistive (80 Ω m to 110 Ω m). Overlying areas with 393 low resistivity values (<80 \Omegam) are correlated with the oldest Pleistocene glaciolacustrine 394 sediments, units 2 and 3 (Fig. 6). Unit 4 lodgement till appears as a moderately resistive (80 395 396 Ω m to 110 Ω m) silt, clay and boulder diamicton up to 5 m thick (Fig. 2 e). Silt-rich glaciolacustrine sediments (unit 5, Fig. 2 f) have low resistivity values (<80 Ω m). Overlying 397 398 glaciofluvial outwash (units 6 and 7, **Fig. 2** g) are moderately resistive (80 Ω m to 110 Ω m) when undersaturated (dry). Coarse, rapidly drained colluvium (unit 8) has a high apparent 399 resistivity value >110 Ω m (Fig. 6). Modern alluvial floodplain sediments (unit 9, Fig. 2 j) are 400 saturated (wet) through much of the year and return high apparent resistivity values (Fig. 6). 401 Coarse ballast (unit 10), when undersaturated (dry), has a high apparent resistivity >110 Ω m 402 (Fig. 6). 403

404

The PRIME system has provided new insight into the hydrogeological structure of the slope 405 (Fig. 7). The ERT models reveal a complex stratigraphy of coarse colluvial sediments (unit 8) 406 overlying massive silt-rich diamicton (unit 4) with tension cracks over 0.5 m wide and 1 m 407 deep, and highly fissured laminated silts and clays (unit 3) in which the landslide failure plane 408 409 lies. Large decreases in surface resistivity (>50%) by through (March to May) are due to an increase in moisture content are due to snowmelt and intense, short-duration precipitation 410 events. Temperatures are consistently above 0°C by this time, and despite a negative weekly 411 effective rainfall during this season, the additional moisture resulting from snowmelt is 412 sufficient to increase the moisture content of the slope. This demonstrates the need for 413 subsurface imaging in such locations where both temperature and precipitation control 414

groundwater hydrology, as this hydrogeological regime could not be predicted from weather 415 data alone. In addition, the spatial variations in resistivity changes are also revealed, which 416 again highlights the need for subsurface investigation. The propagation of the wetting front 417 along the failure plane is clearly shown in Fig. 7, indicating that the headscarp acts as a major 418 conduit for the flow of groundwater. Long-term monitoring of the slope will provide an insight 419 into the seasonal variations in subsurface moisture, and combining this with near-real time 420 421 displacement data will enable a long-term goal of developing moisture thresholds for failure to be realized. 422

423

424 Borehole geophysics results and hydrogeological units

Downhole natural GR levels, IC and MS surveys of boreholes BH15-01, BH15-02 and BH15-425 426 03 (Fig. 3 and Fig. 5) provide further insight into the sub-surface thickness of earth materials, depth to bedrock, groundwater conditions and failure mechanisms of the landslide. East of the 427 CPR tracks, the Mount Sopris MGX logging tool encountered 15 m to 17 m of glacial deposits 428 overlying basal bedrock in the boreholes (Fig. 5). West of the CN tracks, boreholes show around 429 30 m of till and clay-rich glaciolacustrine sediments overlying bedrock (Fig. 3 and Fig. 5). 430 These observations corroborate the terrestrial and waterborne geophysics results indicating the 431 main landslide body is located over a >20 m deep bedrock basin underlying the modern 432 Thompson River. 433

434

Natural GR logs show a relatively constant response (Fig. 3 and Fig. 5), interpreted to indicate the predominance of clays in the glacial deposits. Minor changes in readings throughout the borehole reflect small variations in sand, clay and silt content, and levels of Uranium, Thorium and Potassium in granitic and arkosic dropstones (units 2 and 3) and erratics (in unit 4) directly adjacent to boreholes. The IC logs show an initial progressive, but subtle rise in conductivity

values (Fig. 3 and Fig. 5) corresponding to an increase in clay content with depth. High 440 conductivity zones may indicate clay horizons in silt- and boulder-rich till (unit 4). At depth, 441 conductivity levels fall in response to a lower clay content at depth (unit 3), decreasing porosity 442 in stiff to hard silt-clay diamicton (unit 2), and electrically resistive andesite intersected in the 443 bottom of boreholes (unit 1). The MS logs show a consistently low response (Fig. 3 and Fig. 444 5) indicating a very low ferromagnetic mineral content in the surrounding glacial deposits 445 446 (units 2 to 5). The slight decrease in MS apparent near the base of each borehole corresponds to the intersection of unconsolidated glacial deposits with andesite bedrock (Tab. 2). 447

448

449 <u>Pertrophysical property relationships from sensor data</u>

Petrophysical property relationships of the materials comprising the landslide complement and 450 provide improved understanding and interpretation of field resistivity measurements. Field 451 suction-resistivity relationships have been estabilished by relating the resistivity of the head 452 scarp as revealed by the PRIME data with sensor data from the head scarp (Fig. 8). The daily 453 average suction is plotted alongside the daily average resistivity of the cells in the resistivity 454 model corresponding with the suction sensor location and depth. The location of the suction 455 sensor is shown in Fig. 4. Resitivity increases as suction increases. This relationship is 456 expected, as both suction and resistivity are known to increase as moisture content decreases. 457 A deviation from this trend is observed mid-January when daily resisitvity was higher than 458 459 expected. This is likely due to localized freezing at the surface which results in increased resistivity. This is supported by the weather data, which shows temperatures below 0°C around 460 this time. Therefore, there is an increase in resistivity despite the fact that effective rainfall was 461 positive during this period, which is usually associated with decreased resistivity. 462

Future work will build upon these relationships, and focus on laboratory investigations of the three different hydrogeological units present in Ripley Landslide (unit 3 - silt and clay; unit 4 - till diamicton; unit 8 – colluvial diamicton). The work will focus on the development of resistivity-moisture content, suction-moisture content, and resistivity-suction relationships for samples taken from each unit. Given the importance of temperature at this site, laboratory experiments will be carried out under a range of conditions, using temperatures recorded onsite as a basis for experimental design.

471

472 Discussion: Hydrogeological and Geophysical Properties of Ripley Landslide

Lying within the semi-arid Bunchgrass biogeoclimatic zone, slope stability at Ripley Landslide 473 is strongly influenced by local geological properties, hydrological conditions and channel 474 morphology. For much of the Holocene, infiltration of snow melt, precipitation and surface 475 runoff was very limited: generally, winters and springs are dry, and summer heat causes rapid 476 evaporation of precipitation (cf. Nicholson et al. 1991). Pleistocene and Holocene valley fill 477 was destabilized after irrigation of benchlands began in the 1860s, and inner canyon toe slopes 478 were excavated in the 1880s, 1950s and 2000s to accommodate CN and CPR tracks (Clague 479 and Evans 2003; Bunce and Chadwick 2012). Surficial mapping, borehole logs, and 480 geophysical surveys indicate the main landslide mass comprises a >20 m thick package of 481 Pleistocene and Holocene sediments, unconformably overlying bedrock, that extends from 482 483 under Thompson River to approximately 280 m elevation (Fig. 5 and Fig. 6). Permeability, porosity and drainage of bedrock and surficial units in the landslide are strongly influenced by 484 bed thicknesses, earth material textures, penetrative planar structures and slopes driving 485 hydraulic gradients. These properties constrain the interpretation of geophysical results (Tab. 486 2) and modelling of landslide form and function. 487

489 Drainage characteristics of hydrogeological units

490 At the surface, electrically resistive andesite (unit 1a), rhyolite and volcaniclastic rocks (unit 491 1b) are relatively well-drained where moderately permeable shallow bedrock fractures and 492 bedding planes allow downward percolation of water (**Tab. 1**). At depths >2 m, and elevations 493 lower than 270 m (i.e., below river level), bedrock fractures with low permeability are poorly 494 drained and remain saturated during high river stage (e.g., in spring and summer) or sealed.

495

More than 20 m of Pleistocene and Holocene sediment unconformably overlies unit 1 bedrock 496 497 (Fig. 3). Locally fractured and bedded sediments of unit 2 are imperfectly drained. Below 270 m elevation, coarser sediments remain saturated for much of year, especially during higher 498 river stages. Unit 3 is poorly drained in the sub-surface, with fine-grained sediments remaining 499 500 undersaturated for much of year. The exception would be during prolonged rainfall, snow melt, sustained confined groundwater flow and high river stage. Unit 4 diamicton and clay-rich 501 glaciolacustrine beds of unit 5 are imperfectly drained, with fractures allowing downward 502 infiltration of surface water and subsurface flow of groundwater. Both units become saturated 503 at depth during prolonged rainfall, snow melt and at high river stage (Tab. 1). At depth, vertical 504 fractures and sub-horizontal planes become saturated during prolonged rainfall or snow melt. 505

506

507 Upslope of the landslide, highly permeable coarse-grained glaciofluvial sediments (unit 6) are 508 rapidly drained. Percolating surface water and groundwater is quickly removed downslope, 509 with subsurface flow during heavy or prolonged rainfall, and snow melt indicated by the ERT 510 data (Huntley et al. 2019b). Moderately permeable unit 7 alluvial diamicton, silt and sand 511 deposits are well drained, and during snow melt and heavy or prolonged rainfall, percolating 512 water is readily removed downslope by subsurface seepage (**Tab. 1**). Highly permeable coarse-513 grained colluvial sediments (unit 8), alluvial floodplain deposits (unit 9), ballast, lock-block retaining walls and metal culverts (unit 10) are rapidly drained, with percolating surface water and groundwater quickly removed downslope, and subsurface flow occurring during heavy or prolonged rainfall and snow melt (**Tab. 1**).

517

518 Geophysical model of hydrogeological units

Pseudo-3D models capture resistivity, soil moisture and groundwater conditions in surficial 519 520 deposits and bedrock for the fall seasons of 2013 and 2014 (Fig. 5 and Fig. 6). This representation is interpretation-oriented, with the selection of resistivity thresholds at 80 Ω m 521 522 and 110 Ω m determined by observations of earth materials, and their hydrogeological properties at surface and in logged boreholes (Fig. 2 and Fig. 3). Electrically resistive earth materials 523 $(>110 \Omega m, red on Fig. 6)$ include undersaturated (dry) sand and gravel (unit 6), till diamicton 524 (unit 4) and competent bedrock (unit 1). Bedrock, clay, till and gravel saturated with 525 groundwater are all conductive bodies (<80 Ω m, blue on **Fig. 6**). Along the north and south 526 boundaries, a transition from bedrock to saturated clay-rich glacial sediments beneath the river 527 is recorded between 220 m and 240 m elevation by a drop in resistivity values to below 80 Ω m. 528 From 240 m to 270 m elevation, conductive earth materials (<80 Ω m) are bounded by resistive 529 zones (>110 Ω m) beneath the river and east valley slope (**Fig. 6**). This pattern is interpreted to 530 represent a north-south oriented bedrock palaeochannel fragment infilled with remobilized 531 glacial deposits (units 2 and 3). The 2D waterborne ERT dataset (Huntley et al. 2017a; Huntley 532 et al. 2019a) and pseudo-3D model (Fig. 6) show a significant portion of the landslide lying 533 below river level from approximately 270 m to 230 m elevation. The main slide body is 534 represented as an ovate conductive zone (<80 Ωm) containing inliers of resistive material (>110 535 Ω m) along the northern, eastern and southern flanks (Fig. 6). These latter features are 536 interpreted as locally derived bedrock blocks remobilized during glaciation. 537

Conductive zones logged in the boreholes (Huntley et al. 2017a) suggest an increase in water 539 content along tension cracks, fissures, fractures and shear planes within clay, silt- and boulder-540 rich till (unit 4) at around 5 m depth (Fig. 3). Deeper fissures recorded in the borehole logs and 541 field observations are not represented in the conductivity readings, suggesting lower water 542 content at these depths. Strong reflectors in GPR profiles (Huntley et al. 2017a) may also 543 represent saturated clay, silt (units 3 and 5), coarser diamictons (units 2 and 4), and bedrock 544 545 (unit 1) at depths < 20 m (**Tab. 2**). Higher conductivity (i.e., low resistivity, $< 80 \Omega$ m) values in units 2, 3 and 4 beneath the Thompson River detected by waterborne ERT (Tab. 2) may be 546 547 attributed changes in clay and groundwater content of sub-river units. Three zones of elevated terrain conductivity across the submerged landslide toe have been identified in the bathymetry-548 corrected waterborne FEM data (Fig. 6), These zones are interpreted to indicate areas where 549 artesian groundwater in units 2, 3 and 4 is discharging through the boulder lag (unit 9) covering 550 the river bed (Huntley et al. 2017a; Huntley et al. 2019a). 551

552

Upslope of the river floodplain and railway ballast, at elevations from 270 m to 295 m. 553 resistivity values >110 Ω m are intersected. This range in values is consistent with unsaturated 554 silt, sand and cobble colluvium overlying bedrock (Fig. 6). The distribution of these units 555 suggests a 290 m elevation limit to eastward headscarp retrogression and potential maximum 556 volume of approximately $0.8 \times 10^6 \text{ m}^3$ for the landslide. Above the head scarp, zones of higher 557 558 conductivity occur where soil water is migrating toward the water table through silt, sand and cobbles exposed by hill slope erosion (Fig. 6). Upslope of the landslide, zones of high resistivity 559 $(>80 \Omega m)$ in units 5, 6 and 7 occur where soil water is migrating toward the water table through 560 silt, sand and cobbles exposed by gully erosion (Tab. 2; Fig. 5). 561

562

563 Landslide function: observations of hydrogeology and geophysical data

Fluctuations in stream discharge and river level affect the stability of Ripley Landslide in three 564 ways: 1) by changing the porewater pressure on the rupture surfaces in units 2, 3 and 4; 2) by 565 changing the loading pressure on the submerged toe slope; and 3) by altering the slide geometry 566 through cutbank erosion, channel incision and toe scour. An increase in slope instability occurs 567 during years when the river level is elevated above average for longer than normal periods. 568 During spring run-off, high water levels provides temporary loading support at the landslide 569 570 toe, resulting in slower movement rates. Higher ground movement rates occur during autumn and winter when river discharge and groundwater levels drop, reducing load values on the slide 571 572 toe and porewater pressures in the main body (cf. Eshraghian et al. 2007; Hendry et al. 2015; Journault et al. 2018). 573

574

Elsewhere in the Thompson River valley, failing glaciolacustrine beds are highly plastic, with 575 plastic/liquid limits ranging from 45% to 90% and residual friction angles of 10° to 15° (Schafer 576 et sl. 2015; Le Meil 2017). Silt beds in units 2, 3 and 5 have higher overall residual shear 577 strength compared to clay beds, with values ranging from $>26^{\circ}$ to $<35^{\circ}$ (cf. glacial pond to 578 steep-dipping silt-rich debris flow diamictons draped over bedrock in Fig. 2 c). At Ripley 579 Landslide, field observations and borehole logs show that deformation and erosion by glaciers 580 or pre-historic slope movement have created pre-sheared discontinuities in units 2, 3 and 4 (Fig. 581 2 d) at a residual strength that predispose these sediments to failure (cf. Clague and Evans 2003; 582 583 Eshraghian et al. 2007; 2008). Fine-grained glacial sediments (units 2 to 4) have low permeability (**Tab. 1**) and exhibit subtle resistivity changes reflecting variations in total clay 584 and groundwater content across the slide body (Fig. 6). 585

586

587 Seasonal wetting and softening of clay beds may contribute to slope failure (cf. Clague and
588 Evans 2003). Surface and borehole monitoring indicate that much of the landslide moves very

slowly (cumulatively <55 mm/yr) on gentle (<2°) channel-sloping failure planes developed in 589 weak, highly plastic layers of fine-grained glaciolacustrine silt and clay (Fig. 3). Failure of units 590 2 to 5 occurs as shear strength is reduced in response to periods of saturation when the residual 591 friction angle of clay layers falls below the angle of slope (generally $<25^{\circ}$). The ERT data show 592 that these failing sediments are conductive ($< 80 \Omega m$), potentially saturated with groundwater, 593 and extend under the river (Fig. 6). Sediments of units 2 to 5 readily move, even on gentle 594 595 slopes, due to a reduction in shear strength with increasing saturation of sediments and penetrative structures. All other surficial units contain little clay, are non-plastic and permeable 596 597 to some degree. The presence of penetrative structures (e.g., tension cracks and slide surfaces), bedding thickness and porewater pressure in sand and gravel beds within glaciolacustrine units 598 influence the effective stress condition of the slope (cf. Clague and Evans 2003; Bishop et al. 599 600 2008). The residual friction angle of clay beds in glaciolacustrine units is stress dependant: high normal stresses promote alignment of clay particles during shear (Schafer et al. 2015; Le Meil 601 2017). Greater normal stresses beneath the main body of the landslide are expected where 602 InSAR and GNSS measurements show rates of movement are highest, and where geophysical 603 data indicate surficial deposits are >20 m thick. While the rate of movement is very slow, rapid 604 failure is possible under certain conditions. For example, when surface tension cracks fill with 605 infiltrating water (or snow) and landslide debris becomes saturated by rising river and 606 groundwater levels. 607

608

Waterborne geophysical surveys reveal that the landslide extends under Thompson River, where sediments are generally <20 m thick and river levels vary seasonally by >2 m. Finegrained beds (units 3 and 4) in the submerged toe are armoured from erosion by a lag deposit of modern fluvial boulders (unit 9) except where a deep trough and scour pool is carved by strong currents (**Fig. 4**). Here, bedding and sliding surfaces are exposed at the bottom or slightly

below the riverbed (<270 m elevation). For the submerged toe, shear rates are likely to be lower, 614 variable and stage-dependent (cf. Porter et al. 2002; Schafer et al. 2016). Scour holes and 615 cutbank erosion are evidence that the river continues to incise the channel floor (Fig. 4) when 616 rock fall debris (unit 8) constricts stream flow, locally increasing current velocity. Higher rates 617 of landslide movement might be triggered along deep-seated rupture planes if plastic clay beds 618 near the top of unit 3 (seen in borehole logs, e.g., Fig. 6) become exposed during channel 619 620 incision. Cutbank erosion is also producing over-steepened toe blocks along the main channel. If these blocks fail and are removed when river and groundwater levels are low, toe slope 621 622 unloading may contribute to rapid movement on rupture surfaces (cf. Eshraghian et al. 2007). Toe slope incision is occurring adjacent to where the highest ground motion rates are recorded 623 on the landslide (Macciotta et al. 2015; Hendry et al. 2015; Journault et al. 2018). This is also 624 625 where critical railway infrastructure is at risk (i.e., the lock-block retaining wall and tracks; Fig. 1 d). The seasonal addition of ballast, combined with longer, heavier and more frequent trains 626 crossing the main slide body may also contribute to subaerial loading. It is not known whether 627 these factors trigger increased movement during times of reduced shear strength. 628

629

Lastly, extreme weather events and climate change have the potential to exacerbate ongoing 630 landslide activity at the test site. Although the average rainfall in the area has increased since 631 the 1920s, there is no direct correlation with landslide activity (Porter et al. 2002; Eshraghian 632 633 et al. 2007). However, increased duration and magnitude of precipitation, loss of vegetation cover, reduced soil cohesion by wildfires and fluctuating river discharge could contribute to 634 sustained periods of groundwater recharge, increased porewater pressures in bedrock and 635 636 surficial units, higher seasonal river discharges and greater channel erosion triggering additional landslide activity in the Thompson River valley. Irrigation water does not directly contribute to 637 instability of Ripley Landslide since the surrounding slopes are still used as rangeland. 638

However, grazing limits the already sparse vegetation cover and cattle trails form intermittent
linear paths of disturbed soil forming narrow slope breaks that contour slopes. These conditions
contribute to infiltration of precipitation, snow melt and surface runoff into the unconsolidated
valley fill.

643

644 Summary and Conclusions

645 The overarching goal of our work is the mitigation of risks to public safety, the environment, and railway transportation infrastructure. Studies of Ripley Landslide provide important insight 646 647 into processes and behaviour of similar, but much larger, landslides between Ashcroft and Basque Ranch (Fig. 1). Like others landslides in the Thompson River valley (Porter et al. 2002; 648 Clague and Evans 2003; Eshraghian et al. 2007), seasonal movement occurs along sub-649 horizontal translational rupture surfaces corresponding to weak glacially sheared zones in 650 glaciolacustrine clay and silt (unit 3) and till (unit 4) (Fig. 3 and Fig. 5). This constant activity 651 has the potential to cause damage to railway tracks and disruption of service with risks to the 652 national economy, the local environment, and natural resources (e.g., potable water and 653 salmon). 654

655

Significant gaps in the knowledge of the nature of bedrock and surficial earth materials, their 656 stratigraphic relationships; and in the controls on the style of mass wasting have been addressed 657 here. By combining terrain analysis and modelling of multidimensional geophysical datasets, 658 we have revealed an unprecedented level of detail in the internal composition, structure and 659 hydrology of the very slow-moving Ripley Landslide. This paper helps to explain how 660 hydrogeological conditions influence the spatial and temporal patterns of surface water and 661 groundwater flow; and how future changes in climate and landscape conditions might influence 662 landslide activity along Thompson River. 663

At the test site, >20 m of glacial deposits with contrasting porosity and permeability are 665 preserved in a fractured bedrock paleo-channel basin. Bedrock and unconsolidated sediments 666 have been subaerially exposed by post-glacial valley incision, and during construction of the 667 railway corridor since the late 19th century. The pool and riffle channel morphology of 668 Thompson River at Ripley Landslide is significant because hydraulic conductivity between the 669 670 river, landslides and groundwater systems likely increases where fractured bedrock and glaciolacustrine units (containing impermeable silt-clay couplets, coarse porous beds, lateral 671 672 failure planes and vertical tension cracks) are continually exposed by fluvial erosion. Scour pools are also identified adjacent to irrigated benchlands along the study reach. These terraces 673 are potentially unstable and should be monitored together with active landslides for surface 674 subsidence, tension cracks and scarps to better manage geohazard risks in the Thompson River 675 valley. 676

677

Field observations (Tab. 1) and geophysical data (Tab. 2) indicate that Pleistocene units 4 to 678 7 host an unconfined aquifer recharged by infiltrating precipitation and surface runoff across 679 Ripley Landslide, and from the slopes above. Soil water and groundwater flow laterally and 680 downward through porous till and glaciofluvial sediments (units 4 and 6), and through 681 vertically fractured glaciolacustrine units (3 and 5), until it encounters fractured, non-porous 682 683 bedrock (unit 1) or sub-horizontal shear zones in unit 3. As with other landslides in the area, units 2, 3 and 5 function as aquitards, but also accommodate landslide movement and porewater 684 migration along shear zones approximately corresponding to stratigraphic boundaries (Fig. 5). 685 Artesian conditions at the landslide toe suggest the presence of an aquifer in unit 1 (bedrock) 686 and unit 2 (diamicton), confined by clay and silt layers in units 2 and 3 (cf. Macciotta et al. 687 2014; Hendry et al. 2015; Schafer et al. 2015). Recharge sources include groundwater flow 688

through buried paleochannels and along unconformities separating older glacial sequences (cf.
Porter et al. 2002; Clague and Evans 2003). This confined aquifer controls porewater pressures
at the base of unit 3.

692

A continuous (real-time) proactive infrastructure monitoring and evaluation (PRIME) system 693 has now been deployed to characterize the long-term hydrological behaviour of the landslide 694 695 by monitoring dynamic (pseudo-4D) changes in electrical resistivity (cf. Merritt et al. 2014; Uhlemann et al. 2017; Huntley et al. 2019b). To establish the petrophysical relationship linking 696 697 resistivity to moisture content, laboratory testing of three samples (units 3, 4 and 8), collected across the landslide, was undertaken at the British Geological Survey facilities at Keyworth, 698 UK. A continuous dataset will help to better define: 1) contributions from surface runoff, 699 700 precipitation, freeze-thaw cycles, and snow melt to seasonal variations in slope movement; 2) surface water and groundwater flow paths through the main slide body, the river and bedrock; 701 and 3) the relationship of fluctuating porewater pressures monitored in boreholes and landslide 702 activity. Relationships between suction and resistivity derived from field data (Holmes et al. 703 2018; Sattler et al. 2018) demonstrate the importance of changing moisture content (and 704 therefore changing suction and pore pressures) for resistivity, but given the wide range of 705 geological units present on the site, understanding the hydrogeological properties of each unit 706 will be pivotal in providing improved understanding of slope stability in the Thompson River 707 708 valley. As such, future work will focus on the laboratory testing of samples from different units of the Ripley landslide, building upon relationships identified in the field to establish 709 relationships between moisture content, suction and resistivity. These relationships will then 710 be used to better constrain the inversion of the ERT data. This new understanding will guide 711 the interpretation of multi-year monitoring datasets (e.g., GNSS, InSAR) and future efforts to 712 track landslide activity in the Thompson River valley. 713

714

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732 **References**

733 Beatty, T.W., Orchard, M.J., and Mustard, P.S. 2006. Geology and tectonic history of the

734 Quesnel terrane in the area of Kamloops, British Columbia. *In* Paleozoic evolution and

metallogeny of pericratonic terranes at the ancient pacific margin of North America,

736 Canadian and Alaskan Cordillera. Geological Association of Canada, Special Paper, 45: 483-

737 504

739	Bishop, N., Evans, S., Petley, D., and Unger, A. 2008. The geotechnics of glaciolacustrine
740	sediments and associated landslides near Ashcroft (British Columbia) and the Grand Coulee
741	Dam (Washington). In From Causes to Management. 4th Proceedings of the Canadian
742	Conference on Geohazards, 594 p
743	
744	Bobrowsky P., Sladen W., Huntley, D., Zhang, Q., Bunce, C., Edwards, T., Hendry, M.,
745	Martin, D., and Choi, E. 2014. Multi-parameter monitoring of a slow moving landslide:
746	Ripley Slide, British Columbia, Canada. In Engineering Geology for Society and Territory -
747	Volume 2, Landslide Processes, IAEG Congress, Springer Publishing, pp. 155-159
748	
749	Bobrowsky P., Huntley D., Neelands P, MacLeod R, Mariampillai D, Hendry M, Macciotta
750	R, Reeves H., and Chambers J. 2017. Ripley Landslide – Canada's premier landslide field
751	laboratory. Geological Society of America, Annual Meeting Abstracts and Proceedings
752	Volume, 1 p
753	
754	Bobrowsky, P., MacLeod, R., Huntley, D., Niemann, O., Hendry, M. and Macciotta, R. 2018.
755	Ensuring Resource Transport Safety: Monitoring Critical Infrastructure with UAV
756	Technology. Resources for Future Generations, Proceedings Volume and Abstracts,
757	Vancouver, Canada, 1 p
758	
759	Bunce C. and Chadwick, I. 2012. GPS monitoring of a landslide for railways. In: Eberhardt
760	E, et al (eds) Landslides and Engineered Slopes - Protecting Society through Improved
761	Understanding: 1373-1379
762	

763	Church, M., Ryder, J.M. 1972. Paraglacial sedimentation: a consideration of fluvial processes
764	conditioned by glaciation. Geological Society America, Bulletin 83: 3059-3072
765	
766	Clague, J. and Evans, S. 2003. Geologic framework for large historic landslides in Thompson
767	River valley, British Columbia. Environmental and Engineering Geoscience 9 (3): 201-212
768	
769	Cruden, D.M. and Varnes, D.J. 1996. Landslide types and processes. In Landslides,
770	Investigation and Mitigation. Washington Transportation Research Board, Special Report
771	247 : 36 -75
772	
773	Deblonde, C., Cocking, R.B., Kerr, D. E., Campbell, J.E., Eagles, S., Everett, D., Huntley,
774	D.H., Inglis, E., Parent, M., Plouffe, A., Robertson, L., Smith, I.R. and Weatherston, A. 2018.
775	Surficial Data Model: the science language of the integrated Geological Survey of Canada
776	data model for surficial geology maps. Geological Survey of Canada, Open File 8236, (ed.
777	version 2.3.14), 50 p, (2 sheets)
778	Drysdale, C.W. 1914. Geology of the Thompson River valley below Kamloops Lake, B.C. In
779	1912 Summary Report, Geological Survey, Department of Mines Sessional Paper, 26: 115-
780	150
781	
782	Eshraghian, A., Martin, C. and Cruden, D. 2007. Complex earth slides in the Thompson
783	River Valley, Ashcroft, British Columbia. Environmental and Engineering Geoscience XIII:
784	161-181
785	

786	Eshraghian, A., Martin, C. and Morgenstern, N. 2008. Movement triggers and mechanisms of
787	two earth slides in the Thompson River Valley, British Columbia, Canada. Canadian
788	Geotechnical Journal, 45: 1189-1209
789	

- 790 Evans, S.G. 1984. The 1880 landslide dam on Thompson River, near Ashcroft, British
- 791 Columbia. In: Current Research, Part A: Geological Survey of Canada Paper 84-1A: 655–658792
- Fredlund, D.G., Morgenstern, N.R. and Widger, R.A. 1976. The shear strength of unsaturated
 soils. Canadian Geotechnical Journal, 13: 261-275
- 795
- Fulton, R.J. 1969. Glacial Lake History, Southern Interior Plateau, British Columbia.
- 797 Geological Survey of Canada, Paper 69-37, 14 p
- 798
- Gordey, S.P., Geldzetzer, H.H.J., Morrow, D.W., Bamberm, E.W., Henderson, C.M.,
- 800 Richards, B.C., McGugan, A., Gibson, D.W. and Poulton, T.P. 1991. Ancestral North
- 801 America, Part A. In Upper Devonian to Middle Jurassic assemblages, Chapter 8 of Geology
- 802 of the Cordilleran Orogen in Canada, Geology of Canada, Geological Survey of Canada, **4**:

803 219-327

- 804
- Hebda, R.J. 1982. Postglacial history of grasslands of southern British Columbia and adjacent
- 806 regions. In Grassland Ecology and Classification Symposium Proceedings. British Columbia
- 807 Ministry of Forests, pp. 157-191
- 808
- Hebda, R.J. 1995. British Columbia vegetation and climate history with focus on 6 ka B.P.
- 810 Geographic Physique et Quaternaire, **49**: 55-79

812	Hendry, M., Macciotta, R. and Martin, D. 2015. Effect of Thompson River elevation on
813	velocity and instability of Ripley Slide. Canadian Geotechnical Journal, 52 (3): 257-267
814	
815	Huntley, D. and Bobrowsky, P. 2014.Surficial geology and monitoring of the Ripley Slide,
816	near Ashcroft, British Columbia, Canada. Geological Survey of Canada, Open File 7531, 21
817	p
818	
819	Huntley, D., Bobrowsky, P., Zhang, Q., Zhang, X., Lv, Z., Hendry, M., Macciotta, R.,
820	Schafer, M., Le Meil, G., Journault, J. and Tappenden, K. 2016. Application of Optical Fibre
821	Sensing Real-Time Monitoring Technology at the Ripley Landslide, near Ashcroft, British
822	Columbia, Canada. Canadian Geotechnical Society, GeoVancouver 2016 Annual Meeting
823	Proceedings Volume, 13 p
824	
825	Huntley, D., Bobrowsky, P., Parry, N., Bauman, P., Candy C. and Best, M. 2017a. Ripley
826	Landslide: the geophysical structure of a slow-moving landslide near Ashcroft, British
827	Columbia, Canada. Geological Survey of Canada, Open File 8062, 59 p
828	
829	Huntley, D., Bobrowsky, P. and Best, M. 2017b. Combining terrestrial and waterborne
830	geophysical surveys to investigate the internal composition and structure of a very slow-
831	moving landslide near Ashcroft, British Columbia, Canada. In Landslide Research and Risk
832	Reduction for Advancing Culture and Living with Natural Hazards - Volume 2, 4th World
833	Landslide Forum (ICL-IPL), Springer Nature, 15 p
834	

835	Huntley, D., Bobrowsky, P., Zhang, Q., Zhang, X, and Lv, Z. 2017c. Fibre Bragg Grating and
836	Brillouin Optical Time Domain Reflectometry Monitoring Manual for the Ripley Landslide,
837	near Ashcroft, British Columbia. Geological Survey of Canada, Open File 8258, 66 p
838	
839	Huntley, D., Bobrowsky, P., Hendry, M., Macciotta, R. and Best, M. 2019a. Multi-technique
840	geophysical investigation of a very slow-moving landslide near Ashcroft, British Columbia,
841	Canada. Journal of Environmental and Engineering Geophysics, 24 (1): 85-108
842	
843	Huntley, D., Bobrowsky, P., Hendry, M., Macciotta, R., Elwood, D., Sattler, K., Best, M.,
844	Holmes, J., Chambers, J., Meldrum, P. and Wilkinson, P. 2019b. Application of multi-
845	dimensional electrical resistivity tomography datasets to investigate a very slow-moving
846	landslide near Ashcroft, British Columbia, Canada. Landslides, 16 (5):1033-1042
847	
848	Huntley, D., Bobrowsky, MacLeod R., Cocking, R., Joseph, J., P., Slatter, C., Elwood, D.,
849	Holmes, J., Chambers, J., Meldrum, P., Wilkinson, Hendry, M., and Macciotta, R. 2019c.

850 PRIME installation in Canada: protecting national railway infrastructure by monitoring

851 moisture in an active slow-moving landslide near Ashcroft, British Columbia. Geological

852 Survey of Canada, Open File 8548, 1 poster

853

Journault, J., Macciotta, R., Hendry, M., Charbonneau, F., Huntley, D. and Bobrowsky, P.

855 2018. Measuring displacements of the Thompson River valley landslides, south of Ashcroft,

B.C., Canada, using satellite InSAR. Landslides 15 (4): 621-636.

857

Le Meil, G. 2017. Characterization of a landslide-prone glaciolacustrine clay from the

859 Thompson River Valley near Ashcroft, British Columbia. Department of Civil and

- 860 Environmental Engineering, University of Alberta, Masters of Science in Geological861 Engineering, 182 p
- 862
- 863 Macciotta, R., Hendry, M., Martin, D., Elwood, D., Lan, H., Huntley, D., Bobrowsky, P.,
- Sladen, W., Bunce, C., Choi, E. and Edwards, T. 2014. Monitoring of the Ripley Slide in the
- 865 Thompson River Valley, B.C. Geohazards 6 Symposium, Proceedings and Abstracts Volume,

866 Kingston, Ontario, Canada, 1 p

867

- 868 Mathewes, R.W. and King, M. 1989. Holocene vegetation, climate, and lake-level changes in
- the Interior Douglas-Fir biogeoclimatic zone, British Columbia. Canadian Journal of Earth

870 Sciences, **26**: 1811-1825

871

- 872 Merritt, A., Chambers, J., Murphy, W., Wilkinson, P., West, L., Gunn, D., Meldrum, P.,
- Kirkham, M. and Dixon, N. 2014. 3D ground model development for an active landslide in
- Lias mudrocks using geophysical, remote sensing and geotechnical methods. Landslides, 11
 (4): 537-550

876

877 Monger, J.W.H. and McMillan, W.J. 1989. Geology, Ashcroft, British Columbia (92 I).

878 Geological Survey of Canada, Map 42-1989, Scale 1:250,000

- 880 Nicholson, A., Hamilton, E., Harper, W.L., Wikeen, B.M. Bunchgrass Zone Chapter 8. In:
- Meidinger, D. and Pojar, J. 1991. Ecosystems of British Columbia. B.C. Ministry of Forests,
 Special Report 6: 125-137
- 883

Piegari, E. and Di Maio, R. 2013. Estimating soil suction from resistivity. Natural Hazards
Earth Systems Science, 13: 2369-2379

886

- 887 Porter, M., Savigny, K., Keegan, T., Bunce, C. and MacKay, C. 2002. Controls on stability of
- the Thompson River landslides. In: Proceedings of the 55th Canadian Geotechnical
- 889 Conference: Ground and Water Theory to Practice, Canadian Geotechnical Society, pp.
 890 1393-1400

891

- 892 RES3DINV (2017 [URL]) Rapid 3-D Resistivity & IP inversion using the least-squares
- method, Geoelectrical Imaging 2D & 3D Geotomo Software Version 3.14, Available from

894 <u>www.geotomosoft.com</u> [accessed April, 2019]

895

Ryder, J.M. 1976. Terrain inventory and Quaternary geology, Ashcroft, British Columbia.
Geological Survey of Canada, Paper 74-79, 17 p

- 899 Ryder, J.M., Fulton, R.J. and Clague, J.J. 1991. The Cordilleran Ice Sheet and the Glacial
- 900 Geomorphology of Southern and Central British Colombia. Géographie physique et
- 901 Quaternaire, **45** (3): 365–377
- 902
- 903 Schafer, M., Macciotta, R., Hendry, M., Martin, D., Bobrowsky, P., Huntley, D., Bunce, C.
- and Edwards, T. 2015. Instrumenting and Monitoring a Slow Moving Landslide. GeoQuebec
- 905 2015 Challenges from North to South, 7 p
- 906
- 907 Stanton, R.B. 1898. The great land-slides on the Canadian Pacific Railway in British
- 908 Columbia. Proceedings of Civil Engineers 132 (2): 1–48

910	Uhlemann, S., Chambers, J., Wilkinson, P., Maurer, H., Merritt, A., Meldrum, P., Kuras, O.,
911	Gunn, D. and Dijkstra, T. 2017. Four-dimensional imaging of moisture dynamics during
912	landslide reactivation. Journal of Geophysical Research (Earth Surface), 122: 398-418
913	
914	
915	
916	
917	

Tables

Table 1 Hydrogeological characteristics of Ripley Landslide.

Hydro- geological Unit (thickness, m)	Earth material textures (and Porosity) Intercrystalline porosity Intergranular porosity Vugular porosity H (high porosity), M (moderate porosity) or L (low porosity)	Penetrative structures (and Porosity) Fracture porosity H (high porosity), M (moderate porosity) or L (low porosity)	Drainage (and Permeability) Rate at which surface water and groundwater flows through unit: H (high permeability), M (moderately permeability) or L (low permeability)
Unit 10 Anthro- pogenic materials (<2 m - 5 m)	Intergranular porosity (H) Open framework, clast-supported cobble and boulder ballast	 Fracture porosity (H) Displacement of concrete lock-blocks Sub-vertical crescentic tension cracks in ballast 	<u>Rapidly drained (H)</u> Percolating surface water quickly removed downslope during heavy or prolonged rainfall
Unit 9 Alluvial sediments (<2 m)	Intergranular porosity (H) Open framework, clast-supported boulders and sand		Rapidly drained (H) Percolating surface water quickly removed downslope during heavy or prolonged rainfall; permanently saturated at shallow depth (<2 m)
Unit 8 Hillslope colluvial sediments (<2 m)	Intergranular porosity (H) Talus blocks veneer steep bedrock slopes Stratified diamicton and clast-supported cobbles, boulders with interstitial sand and silt veneer unconsolidated slopes	 Fracture porosity (H) Sub-vertical crescentic tension cracks oriented N-S on slide body 	Rapidly drained (H) Percolating surface water and groundwater quickly removed downslope, with subsurface flow during heavy or prolonged rainfall
Unit 7 Alluvial fan sediments (<2 m)	Intergranular porosity (M) Basal interbedded stratified diamicton and open framework, clast-supported cobble- gravel, fining upward to massive sand and silt; cm-thick beds sub-parallel to surface slopes from 3° to 8° (fans) and >8° to <12° (cones)	 Fracture porosity (H) Sub-vertical crescentic tension cracks oriented N-S on slide body 	<u>Well drained (M)</u> Percolating surface water readily removed downslope, with subsurface seepage during heavy or prolonged rainfall
Unit 6 Glaciofluvial sediments (2 m to >5 m)	Intergranular porosity (H) Massive and crudely stratified, open framework, clast-supported boulder and sand-rich gravel beds, m-thick beds		Rapidly drained (H) Percolating surface water and groundwater readily removed downslope, with subsurface flow during heavy or prolonged rainfall
Unit 5 Glacio- lacustrine sediments (<2 m to 5 m)	Intergranular porosity (M) Pebble-rich sand; cm-thick interbeds	 Fracture porosity (M) Rhythmically interbedded silt, clay and diamicton, cm-thick with: Sub-vertical N-S unloading fractures parallel to exposed slope Sub-vertical crescentic tension cracks oriented N-S on slide body Fissile partings parallel to bedding, dipping W into bedrock basin 	Imperfectly drained (L) Seepage from exposed porous sand-rich interbeds indicated by salt crusts form at surface during summer months along the railway and river embankments; at depth, fractures become saturated during prolonged rainfall
Unit 4 Glacial till sediments (2 m to 6 m)	<u>Vugular porosity (L)</u> Massive, matrix-supported diamicton composed of silt, clay and boulders, isolated weathered clasts and sand-filled voids; m-thick beds	 Fracture porosity (M) Sub-vertical unloading fractures sub- parallel to exposed slopes, oriented N-S Sub-vertical crescentic tension cracks oriented N-S on slide body Sub-horizontal shear surfaces below 270 m elevation, dipping W into bedrock basin 	Imperfectly drained (L) Fractures allow downward and subsurface flow of groundwater; fractures become saturated at depth during prolonged rainfall and during high river stage
Unit 3 Glacio- lacustrine sediments (5 m to >15 m)	Intergranular porosity (M) Sand and gravel; cm-thick interbeds; uncommon	 <u>Fracture porosity (L)</u> Rhythmically interbedded clay and silt and diamicton, mm-thick with: Sub-vertical N-S oriented unloading fractures parallel to exposed slope Sub-vertical crescentic tension cracks oriented N-S on slide body 	Poorly drained (L) Sub-surface sediments remain undersaturated for much of year, except during prolonged rainfall, sustained confined groundwater flow and during high river stage

		 Contorted bedding and loading structures Fissile partings parallel to bedding, dipping W into bedrock basin Sub-horizontal shear surfaces below 260 m elevation, dipping W into bedrock basin 	
Unit 2 Glacio- lacustrine sediments (<2 m to 6 m)	<u>Intergranular porosity (M)</u> Sand, gravel, stratified clast-supported diamicton; cm-thick interbeds	 <u>Fracture porosity (L)</u> Silt, clay and matrix-supported diamicton; cm-thick; with: Fissile partings along bedding planes dipping W into bedrock basin 	Imperfectly drained (L) Fissile, bedded sediments remain saturated for much of year
Unit 1b Rhyolite ¹ and Volcaniclasti c rocks ² (>2 m)	Vugular porosity (L) ² Welded, clast-supported agglomerate <u>Intercrystalline porosity (L)</u> ¹ Fine-grained, flow-banded crystalline igneous rock ¹ .	 Fracture porosity (M) ²Bedding planes, <20° NNE ^{1,2}Dominant fracture sets, NW – SW Weathering rinds along fracture surfaces Fractures sealed at depth 	 ^{1,2}Well drained (M) Shallow bedrock fractures and bedding planes allow downward and subsurface flow of groundwater ^{1,2}Poorly drained (L) At depth, fractures saturated for much of year, or too tight for water flow
Unit 1a Andesite (>2 m)	Intercrystalline porosity (L) Fine-grained, massive crystalline igneous rock	 Fracture porosity (M) Dominant fracture sets, <i>E – NW</i> Weathering rinds along fracture surfaces Fractures sealed at depth 	Well drained (M) Shallow bedrock fractures and bedding planes allow downward and subsurface flow of groundwater Poorly drained (L) At depth, fractures saturated for much of year, or too tight for water flow

- **Table 2** Summary of modelled terrestrial and waterborne ERT, FEM, GPR and Seismic
- 925 properties of surficial units and bedrock at Ripley Landslide; * groundwater seeps / **
- 926 groundwater in fractures, partings and porous beds / *** downward percolating surface
- 927 waters; GPR reflectors, P point, L linear, S- strong, M moderate, W weak.

Hydro- geological Unit	Earth Material Description; structure; drainage	T-ERT Ωm	W-ERT Ωm	T-FEM Modelled conduct- ivity mS m ⁻¹ <i>Resistivity</i> Ωm	W-EM Modelled conduct- ivity mS m ⁻¹ Bathymetry corrected <i>Resistivity</i> <i>Qm</i>	T-GPR, W-GPR Origin, character, strength of reflectors	Seismic Refraction P-wave velocity m s ⁻¹	Shear Wave Velocity m s ⁻¹
Unit 10 */*** Anthro- pogenic	Cobble and boulder ballast; rapidly-drained	<500	-	<5 >200	-	Boulders P, S Unit contact L, W	250 - 600	240 - 280
Unit 9 */*** Alluvial May contain ground- water seeps	Boulders and sand; rapidly drained; saturated	<500	100 - 450	<5 >200	30 – 60 <i>33 - 17</i>	Boulders P, S Unit contact L, W	600 - 3500	240 - 280
Unit 8 */*** Colluvial	Blocks, gravel, sand, clast- supported diamicton; rapidly-drained	<500	-	<20 >50	-	Boulders P, M - S Unit contact L, W	250 - 600	100 - 240
Unit 7 */*** Alluvial	Sand, silt and minor gravel; well-drained	125 - 500	-	<20 >50	-	Basal contact L, W	250 - 600	100 - 200
Unit 6 *** Glaciofluvi al	Gravel and sand; rapidly- drained	125 - 500	-	<20 >50	-	Boulders P, M Basal contact L, W	250	100 - 280
Unit 5 */** Glacio- lacustrine	Silt and clay; deformed; imperfectly- drained	<125	-	>20 <50	-	Groundwater L, W - M Basal contact L, W - M	1400 – 2300	240 - 300
Unit 4 **/*** Till	Silt-clay matrix- supported diamicton; imperfectly- drained	125 - 500	25 - 150	>20 <50	15 – 30 67 - <i>33</i>	Boulders P, M Groundwater L, W - M Basal contact L, W - M	400 - 600	280 - 380
Unit 3 */** Glacio- lacustrine	Clay and silt; deformed; stiff to hard; poorly- drained	<125	25 – 100	>20 <50	15 – 30 67 - 33	Groundwater L, W - M Basal contact L, M - S	1400 – 2300	300 - 500
Unit 2 */** Colluvial	Clay, poorly- drained, stiff to hard; and blocks, gravel, sand, clast- supported diamicton; imperfectly- drained	<500	150 – 500	<20 >50	15 – 30 67 - 33	Basal contact L, M - S	600 - 3500	380 - 500
Unit 1 **/*** Bedrock May contain	Andesite, rhyolite and pyroclastic beds; weathered,	>500	1,000 - >3,000	<5 >200	<15 >67	No internal reflectors	3500 - 4000 (weathered)	500 - 700

	ground- water	fractured; well- drained	>4000 (pristine)
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Fig. 1 The study area. a) Rail transportation corridors in southwestern British Columbia with location of the
Thompson River valley area of interest: A – Ashcroft; K – Kamloops; L – Lytton; S – Spences Bridge; V –
Vancouver; FR – Fraser River; TR - Thompson River. b) Landslides of the Thompson River valley, with location
of Ashcroft, the railway transportation corridor and Ripley Landslide test site. c) Overview of the test site
highlighting the approximate limit of unstable terrain and submerged slide toe.



943 Fig. 2 Hydrogeological units of Ripley Landslide. a) Unit 1a- andesite: fine-grained crystalline igneous rock with 944 dominant fractures 040°/076°/E (278 m elevation), 074°/50°/NNW, 136°/78°/W, 178°/28°/E. b) Unit 1b - rhyolite 945 and pyroclastic volcanic rock: strike/dip/dip-direction 104º/18º/E (350 m elevation). c) Unit 2 - colluvial 946 sediments: interbedded clast-supported diamicton, sand and gravel overlying fractured bedrock (unit 1), ca. 276 m 947 elevation. d) Unit 3 - glaciolacustrine sediments: rhythmically interbedded clay, silt and sand with rare dropstones; 948 sub-till (unit 4) soft-sediment indicates glacial deformation, ca. 278 m elevation. e) Unit 4 - lodgement till: 949 massive, matrix-supported diamicton overlain by a veneer of hillslope colluvium (unit 8) exposed in headscarp; at 950 280 m elevation. f) Unit 5 - glaciolacustrine sediments: interbedded silt and clay overlying till (unit 4), silt-rich 951 beds appear lighter; bedding-parallel fissility and vertical slope relaxation fractures formed in exposed in railway 952 embankment. g) Unit 6 - glaciofluvial sediments: cobble gravel and sand; moderately steep slope (25 ° - 32°) is

953 gullied and drains a 340 m - 350 m elevation terrace abutting against bedrock (unit 1b). h) Unit 7 - alluvial fan 954 sediments: silt, sand and gravel deposited on outwash and till as terraced fans with slopes up to 12°; indicate falling 955 base-levels in the Thompson River valley during early Holocene. i) Unit 8 - colluvial sediments: erratic boulders, glaciofluvial cobbles and sand remobilized by debris fall, soil creep and surface runoff on slopes ranging from 25° 956 957 slope above the headscarp to 12° across the main slide body; on steeper portions of the slope (up to 32°), talus 958 blocks are derived from frost shattered rhyolite and volcaniclastic rock. j) Unit 9 - alluvial floodplain sediments: 959 boulders, cobbles and sand, sparse vegetation growth dominated by horsetails indicating zone of seepage across 960 the landslide toe. k) Unit 10 - anthropogenic features: boulder-rich track ballast overlying alluvial floodplain on 961 the landslide toe; CN (top left) and CPR tracks (centre); 1) Unit 10 - lock-block retaining wall separating CPR

962 (above left) and CN tracks (right).





Fig. 3 Surficial hydrogeological units and landforms of Ripley Landslide and adjacent terrain, showing location
 of boreholes and field observations; lock-block retaining wall – grey line. Borehole geophysical logging and data
 processing by Frontier Geosciences Inc.



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Fig. 4 Geophysical transects for November 2013 (red lines), November 2014 (yellow lines), and PRIME
 installation, beginning in November 2017 (green lines); other monitoring components shown include positions of
 logged boreholes (2005-2015), InSAR corner reflectors (2013 - present) and permanent GNSS stations (2010 -

971 present).



Fig. 5 Terrestrial ERT pseudosections (red transect lines A, B, C), waterborne ERT pseudosections (yellow transect lines 2, 3, 4, 5) and PRIME installation (green transect lines). Location of boreholes shown in relation to transect lines. Gamma radiation measured in counts per second (cps), induced conductivity measured in milliSiemens/m (mS/m) and magnetic susceptibility in parts per thousand (ppt). Also shown, location of elevated terrain conductivity readings located on submerged slide toe. Landslide extent (approximate) shown as dashed black lines on inset map.



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Fig. 6 Electrical resistivity tomographic depth slices of Ripley Landslide. Location of BH13-01 shown; graphic
 log captures changes in hydrogeological units at depth near the centre of the slide body. Solid blue line – east bank
 of Thompson River (TR). Solid green line - PRIME array. Red stars indicate elevated bathymetry-corrected EM
 terrain conductivity interpreted as artesian groundwater discharge zones exposed by river erosion. Data processing
 by Frontier Geosciences Inc.



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Fig. 7 Electrical resistivity tomography images generated from the PRIME data collected on the Ripley landslide.
The baseline image (December 05, 2017) highlights the lithological units present on site and shows key geomorphological features including failure surfaces and tension cracks. The image from May 02, 2018 shows the percentage change in resistivity from the baseline image, highlighting changes which took place following the onset of snowmelt on the site. Suction sensor locations are marked by the yellow stars. The suction sensors (yellow star) are located at 0.3 m, 0.6 m, 0.9 m, 1.2 m and 2 m below the surface.



Fig. 8 Relationship between resistivity and suction for the Ripley landslide head scarp. The average daily
resistivity is the average resistivity of cells of the PRIME model (Fig. 7) proximal to the suction sensors (within
1 m distance). The suction sensors are located at 2, 3, 4, and 6.5 ft depth from the surface, and their location
relative to the PRIME ERT lines is shown in Fig. 7.