Natural Resources Canada Ressources naturelles Canada

**GEOLOGICAL SURVEY OF CANADA**
**OPEN FILE 8743**

# Understanding Plateau and Prairie landslides: research plans for the Thompson River valley, British Columbia, and the Assiniboine River valley, Manitoba-Saskatchewan (2020-2025)

**D. Huntley, D. Rotheram-Clarke, R. Cocking, J. Joseph, and P. Bobrowsky**

**2020**

Canada

GEOLOGICAL SURVEY OF CANADA
OPEN FILE 8743

# Understanding Plateau and Prairie landslides: research plans for the Thompson River valley, British Columbia, and the Assiniboine River valley, Manitoba-Saskatchewan (2020-2025)

**D. Huntley, D. Rotheram-Clarke, R. Cocking, J. Joseph and P. Bobrowsky**

**2020**



Permanent link: https://doi.org/10.4095/327127

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

## Recommended citation

Huntley, D., Rotheram-Clarke, D., Cocking, R., Joseph, J., and Bobrowsky, P., 2020. Understanding Plateau and Prairie landslides: research plans for the Thompson River valley, British Columbia, and the Assiniboine River valley, Manitoba-Saskatchewan (2020-2025); Geological Survey of Canada, Open File 8743, 25 p. https://doi.org/10.4095/327127

Publications in this series have not been edited; they are released as submitted by the author.

## Abstract

A new Interdepartmental Memorandum of Understanding (IMOU-5170) between Natural Resources Canada (NRCan), the Geological Survey of Canada (GSC), and Transport Canada Innovation Centre (TC-IC) from 2020 to 2025 is presented in this Open File. IMOU-5170 combines on-going research and development of landslide monitoring technologies along strategically important sections of the national railway network in the Thompson River valley, British Columbia, and the Assiniboine River valley along the borders of Manitoba and Saskatchewan. This work is ultimately applicable to other sites in Canada, and elsewhere around the world where vital railway (or other socioeconomic) infrastructure and operations are potentially at risk from landslides.



**Keywords**

Geological Hazards, Climate Change, Landslide Monitoring, Railway Infrastructure, Risk Reduction, Thompson River, British Columbia, Assiniboine River, Manitoba-Saskatchewan


## 1. Introduction

Vital railway infrastructure and operations are at risk from landslides across much of Canada. A particularly vulnerable section of the Canadian National (CN) and Canadian Pacific (CPR) railway corridors runs through the Thompson River valley between Ashcroft and Spences Bridge in southern British Columbia (**Figure 1**; Bobrowsky 2013; Bobrowsky 2018). Rail is the dominant method to move Canada's export bulk commodities to Pacific northwest marine terminals, for example Vancouver, Squamish, Prince Rupert and Kitimat. Service efficiency and capacity are vital for a sustainable national railway system transporting Canadian grain, coal, oil, potash and other natural resources to the global market. The Port of Vancouver is the third largest port in North America by tonnage, and Canada's busiest container port. In 2017 alone, the port handled 142 million tonnes of cargo, which enabled the trade of approximately $200 billion in goods. All CN and CPR rail traffic into and out of the Port of Vancouver must pass through the Fraser River Canyon and Thompson River valley corridor. The economic importance of the Thompson River valley corridor, along with the need to understand and manage the safety risk related to the landslides that threaten this route, make this project a strategic priority for CN and CPR. Another strategic section of the national railway network is the landslide-prone terrain of the Assiniboine-Qu'Appelle river valleys, Saskatchewan-Manitoba (**Figure 2**). Here, similar to the Thompson River valley, sections of rail track and other infrastructure traverse active landslides or active flood plains where gradual, continuous slope movements (and occasional rapid failures) affect their safe and reliable operation.

Global socioeconomic recovery and rehabilitation will be strongly reliant upon transportation networks that are resilient to the adverse impacts of climate change and weather-driven geohazards (e.g., landslides, avalanches, floods and wildfires). For Canada, like many countries, national railway networks will be the dominant mode for transporting land-locked natural resources to, and from deep-water marine terminals; and commuters and tourists to, and from urban centres. Resilient railway transportation networks require sustainable, cost-effective management of service operations to meet future socioeconomic needs, and ensure protection of the natural environment. Where transportation corridors traverse unstable terrain, critical rail infrastructure is at risk of damage, and presents potential local and national economic, social, and environmental challenges. The economic importance of the Thompson River and corridors, along with the need to understand and manage the safety risks related to landslides make on-site investigations a strategic priority for governments, the rail industry, and academia. Monitoring unstable slopes and infrastructure at risk is a cost-effective hazard management practice that also provides important geoscience information to help develop appropriate mitigation and adaptation measures.

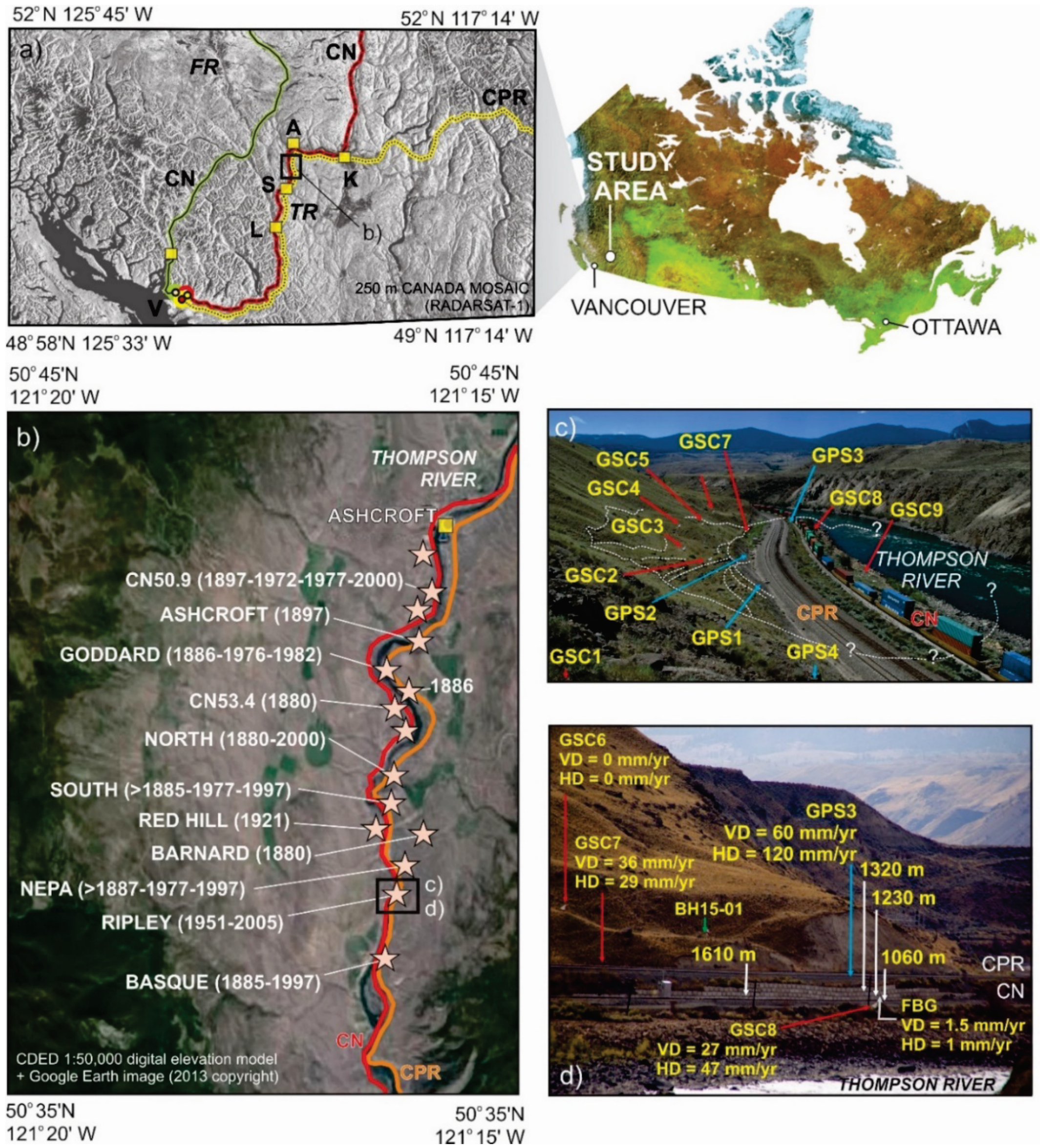


**Figure 1** The study area. a) Rail transportation corridors in southwestern British Columbia with location of the Thompson River valley area of interest: **A** – Ashcroft; **K** – Kamloops; **L** – Lytton; **S** – Spences Bridge; **V** – Vancouver; **FR** – Fraser River; **TR** - Thompson River. b) 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 location of GNSS monitoring stations (GPS1-4), InSAR corner reflectors (GSC1-9), and the monitored retaining wall dividing the CN and CPR tracks - view to south (NRCan photo 2020-290). d) South flank of landslide with sagging retaining wall separating CN and CPR tracks with displacement vectors for FBG, GNSS and InSAR stations; strain points detected by BOTDR (white arrows and distance in metres from datum); **VD** – vertical displacement; **HD** – horizontal displacement detected by FBG (grey arrow with displacement values expressed as mm/yr); and location of BH15-01 (green arrow) (NRCan photo 2020-291).

## 2. Research Objectives of IMOU

Historically, landslides and other geohazards (e.g., rock falls, debris flows, avalanches, floods, and wildfires) have resulted in train derailments and service disruptions in both the Thompson and Assiniboine transport corridors. Railway infrastructure and operations are expected to face unique challenges in design, monitoring, adaptation, mitigation, reclamation and restoration in a scenario of future extreme weather events and climate change. Seasonal and spatial variations in precipitation, temperature, river levels and groundwater recharge are perceived as the dominant controls on landslide activity in both valley systems. An understanding of the geographic distribution and temporal range of earth materials and geological hazards, and their potential responses to climate change is essential for a resilient and accessible transportation network, but also to protect the natural environment, local communities, land-use practices, and the national economy.

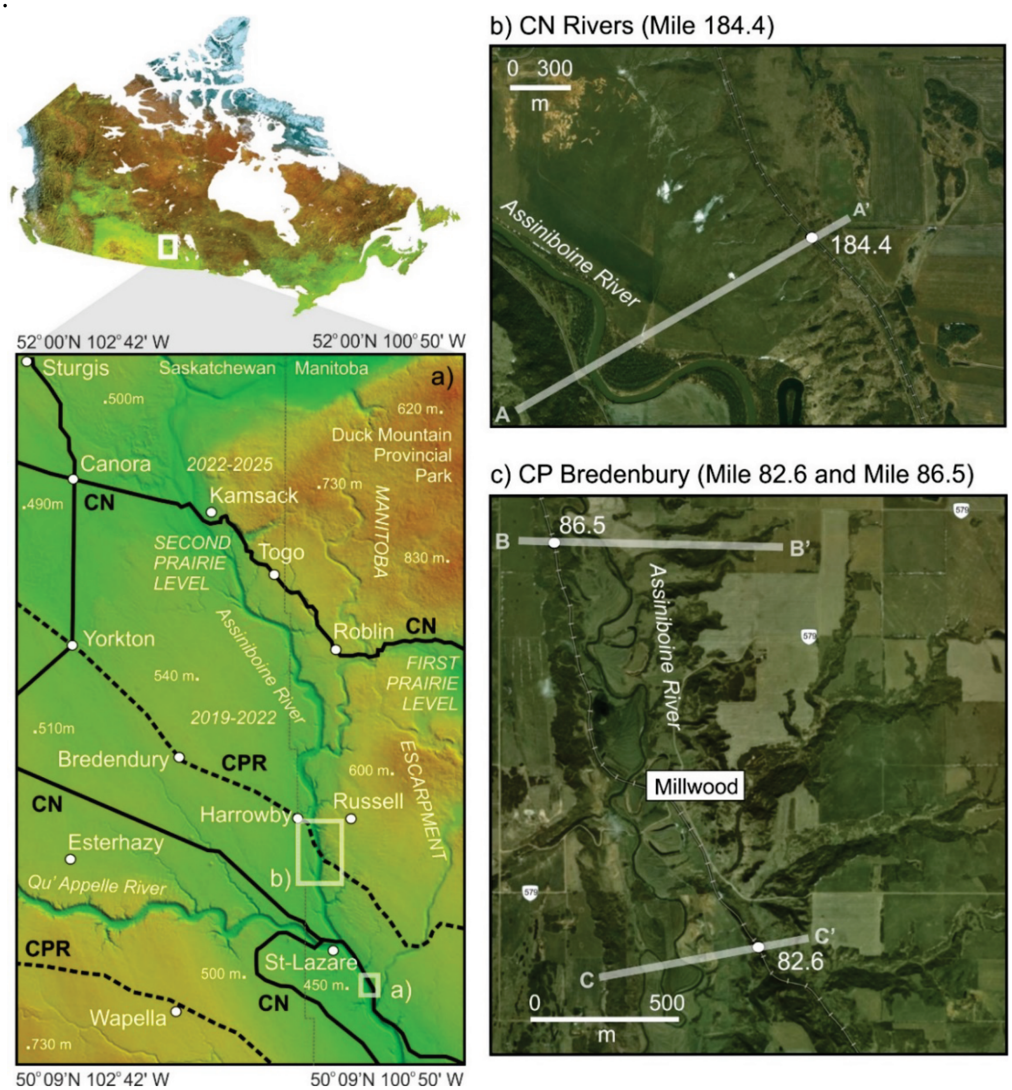


**Figure 2** New study areas showing railway routes and major landforms and areas of interest to CN and CPR: a) major geomorphic elements (after Klassen 1972; Christiansen 1979) crossed by the CN and CPR tracks (source DEM: SRTM); b) Worldview image for CN area of interest (Rivers Subdivision, Mile 184.4) (base map source: arcgis.com); c) Worldview image for CPR area of interest (Bredenbury Subdivision, Miles 82.6 and 86.5) (base map source: arcgis.com).

Since 2013, Natural Resources Canada (NRCan), through the Geological Survey of Canada (GSC), along with international and national partners, has pioneered innovative research and monitoring of landslides in the Thompson River valley. This research and development (R&D) is funded by the Transport Canada Innovation Centre (TC-IC), and activities contribute to the success of the Railway Ground Hazard Research Program (RGHRP). This program provides government agencies, university partners, and the national railway companies with vital information to understand geohazard risk, predict landslide movement, improve the safety, security and resilience of Canada's transportation infrastructure, and reduce such risks to the economy, environment, natural resources and public safety. In addition, the program disseminates knowledge to community members through outreach workshops (**Figure 3**).

The main objective of IMOU-5170 is to gain a better understanding of how extreme weather events and climate change influence landslide activity in the Thompson River valley, British Columbia, and the Assiniboine River valley, Saskatchewan-Manitoba. This fundamental geoscience information will contribute to more robust risk tolerance, remediation, and mitigation strategies to maintain the resilience and accessibility of critical transportation infrastructure along strategically important sections of the national railway network, while also protecting the natural environment, community stakeholders, and Canadian economy. In the coming year(s), the various monitoring technologies operational from 2013-2020 in the Thompson River valley will be further tested (**Figure 1**), installed at new sites in the Assiniboine River valley (**Figure 2**), and possibly elsewhere in Canada, in order to: 1) better understand controls on landslide movement, and the measure the impacts of extreme weather events and climate change; 2) compare, evaluate, and identify the monitoring technologies which provide the most useful information on why, how, and when landslides move; and 3) develop reliable real-time monitoring solutions for critical railway infrastructure (e.g., ballast, tracks, retaining walls, tunnels and bridges) able to withstand the harsh environmental conditions of Canada.

The compendium of monitoring technologies and best-practices applied to these contrasting study areas will broaden our understanding landslide responses to climate change, and enable key stakeholders (i.e., CN and CPR, University of Alberta – UA, University of Saskatchewan – USASK, Manitoba Geological Survey - MGS) to develop risk management, remediation, and mitigation solutions.

### 2.1 Extreme weather, climate monitoring, geohazards and vulnerable infrastructure

Over the next 50 years, measurable changes in temperature, precipitation, and other climatic factors are expected to display spatial variations across Canada (Weaver 2004; IPCC 2014). In western Canada and the Prairie provinces, a number of geohazards are anticipated to negatively impact terrain, leaving critical infrastructure vulnerable to loss or damage. Depending on location, climate change will trigger positive or negative feedback in groundwater recharge, flow and discharge, flooding and stream erosion, the extent and duration of wildfires, magnitude and frequency of landslides, in the permafrost regime, and the distribution of wildlife and vegetation (Bruce and Cohen 2004; Smith and Burgess 2011; Weaver 2004; IPCC 2014). Communities are also vulnerable, with populations susceptible to disease and malnutrition as agriculture, traditional wildlife, and water resources become threatened (IPCC 2014; Lonergan 2004).

Increases in magnitude and frequency of landslides and other geohazards are expected as a response to rising precipitation amounts (as rain and snow), greater seasonal ranges in temperature and more extensive wildfires (Heginbottom et al. 1995; Evans and Clague 1997; Geertsema et al. 2006; Couture and Evans 2006; Wang and Lesage 2007). Erosion of exposed sediments is likely if wind strength and duration increases due to changes in storm systems, air pressure gradients, loss of vegetation and wildfires (Wolfe 1997; Wolfe 2001). Increasing precipitation, duration of rainfall, loss of vegetation, and wildfires will lead to an increase in magnitude and frequency of gully erosion on valley sidewalls (Sauchyn and Nelson 1999; Valentin et al. 2005); in addition to an increase in magnitude and frequency of flooding, erosion and deposition in rivers and streams (Knox 2000; Chen et al. 2006; St. George 2007; Chen and Grasby 2009).

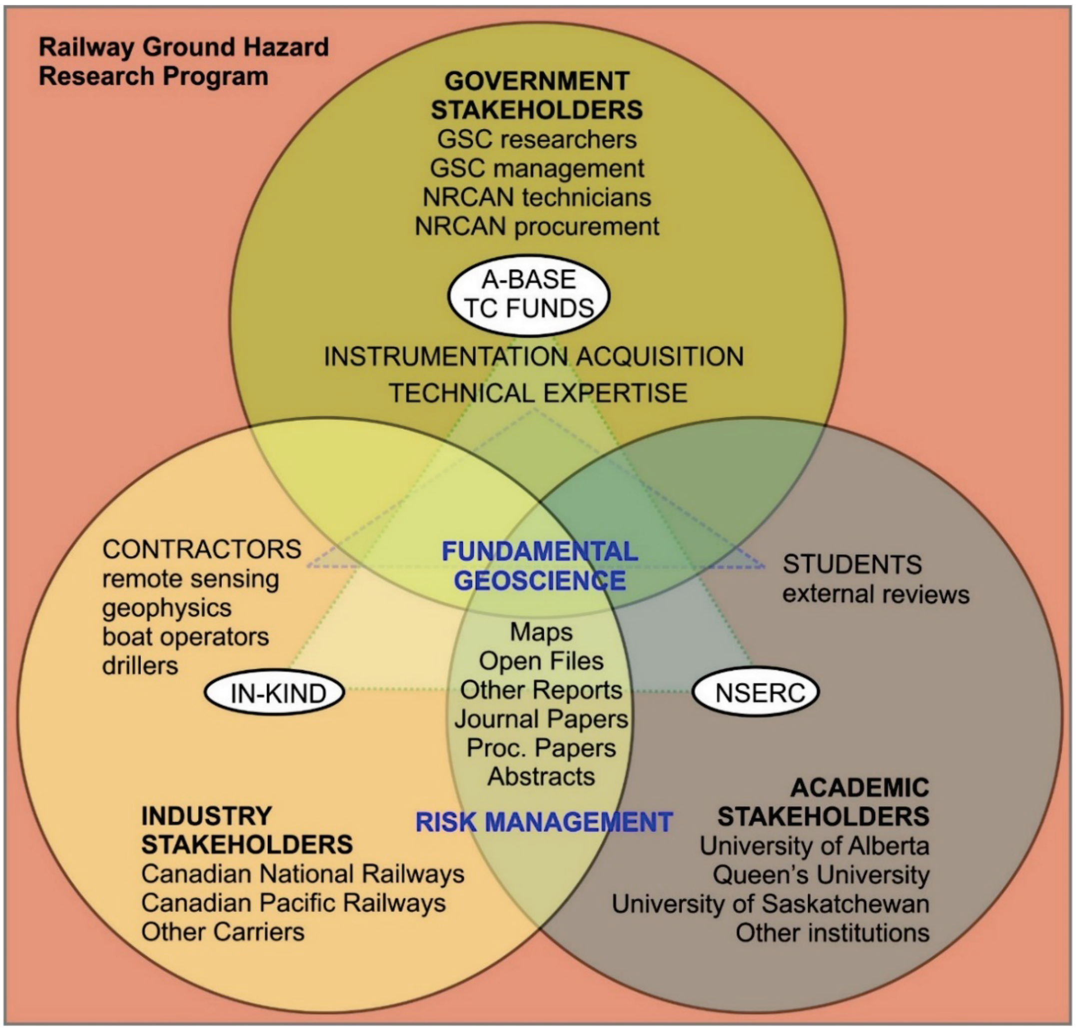


**Figure 3** Modified Venn diagram representing the contributions and interactions of key stakeholders in the Railway Ground Hazard Research Program, with funding structure.

In the Thompson River valley (**Figure 1**), CN and CPR have relied on remote sensing, global positioning, and borehole technologies to monitor the impact of extreme weather and climate change on slope instability (e.g., Macciotta et al., 2014; Hendry et al., 2015; Schafer et al. 2015; Journault et al. 2017). These methods, combined with terrain mapping (Huntley and Bobrowsky

2014; Huntley et al. 2020a), and geophysical surveys (Holmes et al. 2018; Huntley et al. 2019a, b; Holmes et al. 2020) have provided necessary sub-surface information to understand the climate-driven spatial and temporal variations in landslide activity. This effective multi-disciplinary approach can now be applied elsewhere in Canada where landslides are adversely impacting the national railway network. The Assiniboine River valley from near its confluence with Qu'Appelle River at St-Lazare, Manitoba, north to Kamsack, Saskatchewan is a critical section for both national railway carriers (**Figure 2**). CN and CPR have main lines traversing valley slopes, side-wall terraces, and floodplains prone to slow-moving landslides and floods. A negative socio-economic consequence of landslide activity in the Assiniboine River valley is that railway infrastructure, including tracks and bridges, and rolling stock safety are at risk of damage.

## 3. Research Action Plan

Outlines of R&D topics to be addressed by the 2020-2025 Activity Plan (to be approved by NRCAN, TC, and all key RGHRP partners) are presented in **Table 1** and **Table 2**. The prime research objective of the IMOU is to gain a better understanding of how extreme weather, climate change, and landslide hazards impact Canada's railway network, focusing on the Thompson River valley, British Columbia, and the Assiniboine River valley, Saskatchewan-Manitoba. This fundamental geoscience information will help build more robust risk tolerance, remediation, and mitigation strategies to maintain the resilience and accessibility of vulnerable transportation infrastructure along strategically important sections of the national railway network, while also protecting public safety, the natural environment, community stakeholders, and Canadian economy.

Two fields of R&D will meet this objective. 1) *Terrain Mapping* is mostly directed to describing landslide form, adjacent stable slopes and water bodies. This activity will incorporate surficial geology mapping, bathymetric and geophysical surveys and real-time monitoring of movement, groundwater, and geophysical properties in boreholes (**Figure 4**). 2) *Change Detection Monitoring* is mostly directed to describing landslide function using emerging airborne and spaceborne platforms, ground-based GNSS systems, fibre optics and climate variables (**Figure 4**). Geohazard mapping and change detection monitoring will identify terrain units and slopes susceptible to landslides, floods, and other geohazards triggered by extreme weather events, changing climate (past, current and future), and additional factors (e.g., slope engineering and agricultural practices).

In British Columbia, landslide mapping and monitoring in the Thompson River valley provides additional insight into the Late Quaternary Cordilleran Ice Sheet (Huntley and Bobrowsky 2014; Huntley et al. 2020a). In Manitoba and Saskatchewan, these methods will be applied to examine the history and dynamics of southwestern sector of the Laurentide Ice Sheet, and in particular whether megablock ice-thrust terrain (cf. Sauer 1978; Christiansen 1979; Blatz et al. 2004) is exposed along the Assiniboine River valley in the three areas of interest (**Figure 2**). Glacially deformed bedrock (pre-sheared and over-pressured) lying beneath porous and impervious glacial deposits are posited as a pre-condition for slope failure and control on landslide activity (Mugridge and Young 1983; Young and Moore 1994). This regionally distinctive geological setting should be considered along with the impacts of fluvial erosion, land management practices (e.g., slope modification, drainage) and climate change (e.g., precipitation, floods).

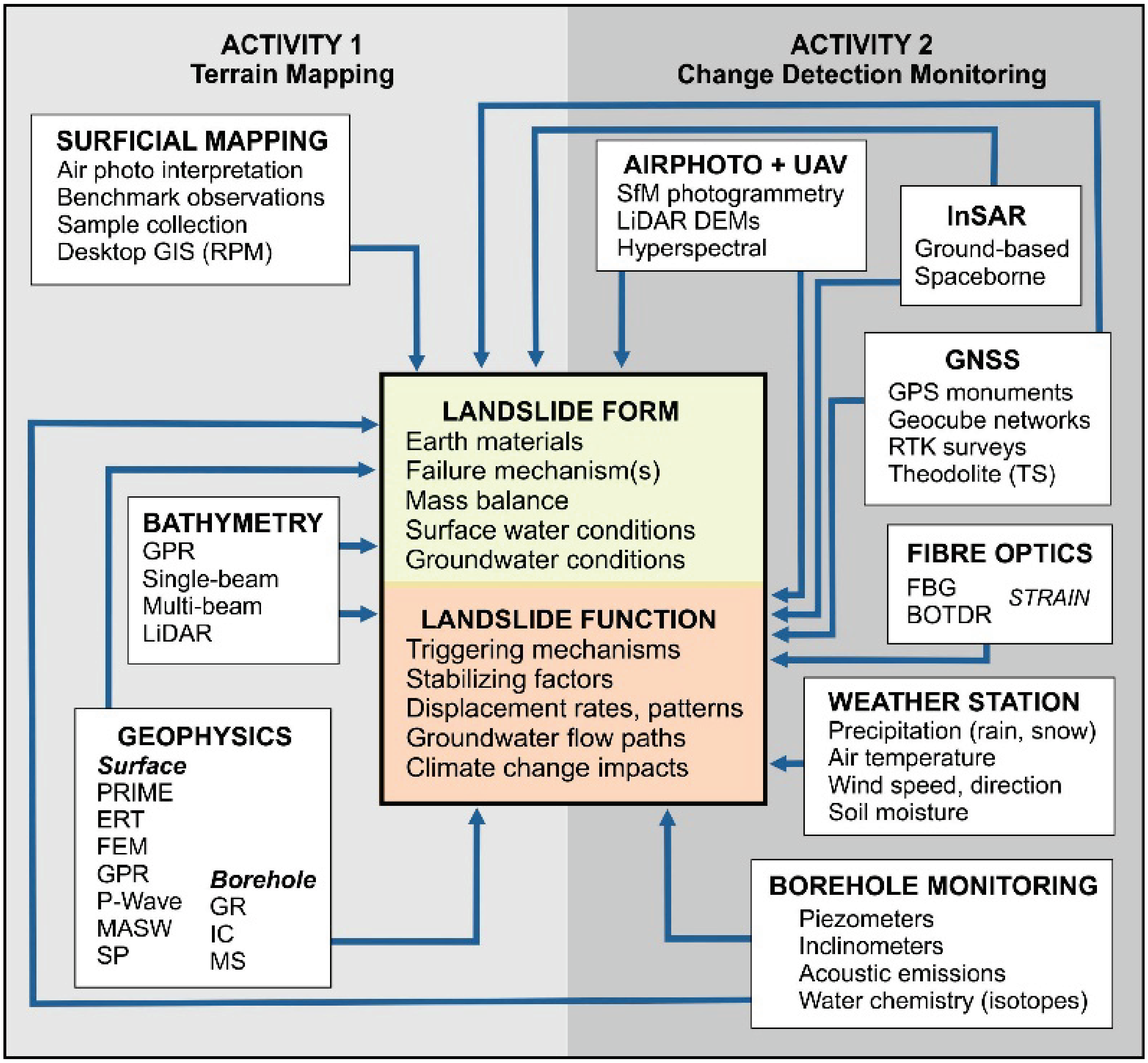


**Figure 4** Best practices for terrain mapping and change detection monitoring of landslide systems, based on experience in the Thompson River valley (2013-2020), and to be applied to the Assiniboine-Qu'Appelle river valleys (2020-2025).

**Table 1** Field methods for investigating unstable terrain in the Thompson River valley study sites for 2020-2025. *InSAR data archiving and processing undertaken by 3v Geomatics in 2020-2025.

| **Landslide study site**<br>***Slope description*** | **Terrain mapping** | **Surface change detection** | | | **Vibrating wire piezometers** | **Borehole inclinometry**<br>***SSI***<br>***SAA*** | **Climate variables**<br>***GSC-1 at Ripley*** |
|---|---|---|---|---|---|---|---|
| | | **UAV** | **InSAR*** | **GNSS** | | | |
| Nepa Crossover<br>*East side of valley unstable; embankments and retaining wall* | Surficial<br>Bathymetry | LiDAR<br>RGB | RADARSAT<br>SENTINEL | GNSS<br>RTK<br>TS | No ground instrumentation planned | | Precipitation<br>Temperature<br>Wind<br>Pressure |
| Ripley Landslide<br>*Both sides of valley unstable; embankments and retaining wall* | Surficial<br>Bathymetry<br>ERT<br>Boreholes<br>Gamma<br>IC<br>MS | LiDAR<br>RGB | RADARSAT<br>SENTINEL | GNSS<br>RTK<br>TS | Boreholes<br>- Main slide body<br>Thompson River | Boreholes<br>- Main slide body | |
| Red Hill Slide<br>*West side of valley unstable* | Surficial<br>Bathymetry | LiDAR<br>RGB | RADARSAT<br>SENTINEL | No ground instrumentation planned | | | |
| Barnard Slide and Creek<br>*East side of valley unstable; embankments* | Surficial<br>Bathymetry<br>ERT | LiDAR<br>RGB | RADARSAT<br>SENTINEL | GNSS<br>RTK<br>TS | No ground instrumentation planned | | |
| South Slide<br>*East side of valley unstable; embankments and retaining wall* | Surficial<br>Bathymetry<br>ERT<br>Boreholes<br>Gamma<br>IC<br>MS | LiDAR<br>RGB | RADARSAT<br>SENTINEL | GNSS<br>RTK<br>TS | Boreholes<br>- Main slide body | Boreholes<br>- Main slide body | |
| North Slide (Solar Slump)<br>*East side of valley unstable; embankments and retaining wall* | Surficial<br>Bathymetry | LiDAR<br>RGB | RADARSAT<br>SENTINEL | GNSS<br>RTK<br>TS | No ground instrumentation planned | | |
| Goddard Slide<br>*East side of valley unstable; embankments and retaining wall* | Surficial<br>Bathymetry | LiDAR<br>RGB | RADARSAT<br>SENTINEL | No ground instrumentation planned | | | |

**Table 2** Field methods proposed for investigating unstable terrain at the St-Lazare (CN), Harrowby (CPR) and Kamsack (CN) study sites for 2020-2025. *InSAR data archiving and processing undertaken by 3v Geomatics in 2020-2025.

| **Landslide study site**<br>***Slope description*** | **Terrain mapping** | **Surface change detection** | | | **Vibrating wire piezometers** | **Borehole inclinometry**<br>***SSI***<br>***SAA*** | **Climate variables**<br>***GSC-2 at Harrowby*** |
|---|---|---|---|---|---|---|---|
| | | **InSAR*** | **UAV** | **GNSS** | | | |
| St-Lazare<br>*Both sides of valley unstable; groundwater mitigation measures* | Surficial<br>Bathymetry<br>ERT<br>Seismic<br><u>Boreholes</u><br>Gamma<br>IC<br>MS | RADARSAT<br>SENTINEL | LiDAR<br>RGB | GNSS<br>RTK<br>TS | Boreholes<br>- Plains<br>- Side walls<br>- Valley floor<br>Assiniboine River | Boreholes<br>- Plains<br>- Side walls<br>- Valley floor | |
| Harrowby<br>*Both sides of valley unstable* | Surficial<br>Bathymetry | RADARSAT<br>SENTINEL | LiDAR<br>RGB | RTK<br>TS | Boreholes<br>- Plains<br>- Side walls<br>- Valley floor | Boreholes<br>- Plains<br>- Side walls<br>- Valley floor | Precipitation<br>Temperature<br>Wind<br>Pressure |
| Kamsack<br>*Stable with mitigation measures* | Surficial | RADARSAT<br>SENTINEL | LiDAR<br>RGB | RTK<br>TS | | | |

## 3.1 ACTIVITY 1: Geohazard Mapping

Primary collaborators: GSC, BGS, MGS, UA, USASK

### *A) Terrain Mapping and Fieldwork*

An understanding of the surficial and bedrock geology, including earth materials and structures, is essential for understanding landslide form and function. In the Thompson River valley, information obtained from terrain mapping, geophysical surveys and field observations (e.g., Huntley and Bobrowsky 2014; Huntley et al. 2019a, b) support borehole logging and inclinometer data suggesting landslides fail along a sub-horizontal, weak, basal shear surfaces in plastic glacial clay beds infilling bedrock basins (e.g., Hendry et al. 2015; Schafer et al 2015). Similarly, geological mapping (and compilation of extant data sources) in the Assiniboine River valley will help establish the physical setting of the landslides and help inform other aspects of the new study (see below).

THOMPSON RIVER VALLEY: Mapping efforts between 2020 and 2025 will focus on benchmarking field observations where needed, and desktop compilation of geographic and temporal datasets (e.g., ground control points, digital surface models, InSAR, GNSS stations), the production of Canadian Geoscience Maps for Ripley Landslide, South Slide, and other landslides in the transportation corridor (**Table 3**). These GSC map products will be useful working tools for industry and academic partners, contractors, and risk managers.

ASSINIBOINE RIVER VALLEY: In addition to the continuing mapping efforts in the Thompson River valley, beginning in the summer of 2020, fieldwork undertaken in the Assiniboine River valley will ground-truth terrain interpretations, and describe sedimentological characteristics that cannot be determined by remote mapping. The first task in the field will be to establish a permanent global navigation satellite system (GNSS) benchmark monuments and permanent ground control points (GCPs) for all survey requirements, including Total Station (TS) triangulation points. At field stations on, and adjacent to investigated landslides, hydrogeological units will be defined on the basis of lithofacies and landform associations, unit thicknesses, earth material textures, degree of sorting, weathered and un-weathered colours, sedimentary structures and penetrative planar structures, degrees of consolidation, stratigraphic contact relationships, estimated geological age, and other distinguishing characteristics. Resulting GSC Open File reports and Canadian Geoscience Maps will depict the surface and vertical (stratigraphic) distribution of hydrogeological units, landforms and geohazards in the areas of investigation (**Figure 2**, **Table 3**).

For the study sites in the Assiniboine River valley - the CN 184.4, and CP 86.5 and 82.6 sites (**Figure 2**), surficial earth materials and landforms will be desktop-mapped in ArcGIS using ortho-rectified and geo-referenced historical air photos, provincial LiDAR datasets, available satellite imagery, and digital natural colour air photographs taken by the GSC-operated Phantom 4 UAV during repeat photogrammetric overflights. The first of these was completed in October 2019. These data would be supplemented with LiDAR imaging of unstable slopes, collected with the USASK Velodyne VLP-16 Puck mounted on a DJI Mattrice 600 Pro Hexacopter. LiDAR will be an essential mapping tool since valley slopes and river floodplains promote prolific vegetation growth that present problems for optical terrain classification and structure from motion (SfM) software. A continuous LiDAR survey was flown in 2007 for the Province of Manitoba, covering the Assiniboine River valley from St. Lazare to Harrowby, and north to the provincial boundary with Saskatchewan. Potential provincial datasets will be sorted and compiled for processing (e.g., bare earth and canopy height models). Unfortunately, free LiDAR coverage is not available for Kamsack and adjacent reaches of the Assiniboine River valley in Saskatchewan.

After processing, UAV and LiDAR imagery should be sufficient to resolve vegetation type, cobble-sized boulders, and anthropogenic features (<5 cm across) at a flight elevations 50 m to 100 m above ground level. During desktop terrain analysis, visual interpretation of imagery will rely on the recognition and separation of geological features using colours, tones, surface textures, patterns, shapes, sizes, shadows, and field associations. Conventional terrain classification systems will be applied to allow comparison with landslides in the Thompson River valley and elsewhere (e.g., Resource Inventory Committee 1996; Howes and Kenk 1997; Huntley and Bobrowsky 2014; Deblonde et al. 2018). Terrain mapping will determine whether ice-thrusted (pre-sheared and over-pressured) bedrock, and overlying porous and impervious glacial deposits (cf. Sauer 1978; Christiansen 1979) are pre-conditions for slope failure and landslide activity.

### *B) Geophysical Mapping*

In collaboration with the BGS and provincial and university partners (**Table 3**), geophysical research objectives are to: 1) understand the impact of extreme precipitation events (monitored by the weather station) on slope stability at the site by comparing climate data with the results of the Geocube™ and InSAR installations; and 2) establish how surface water infiltration contributes to groundwater conditions on the slope by installing moisture meters and extensiometers across the slide body (monitoring sites selected from air photos and satellite images). Geophysical data collected by contractors (e.g., EBA-TetraTech, Advisian-Worley Parsons Group, Frontier Geosciences Inc.) will be processed, analysed and interpreted by colleagues at the British

Geological Survey, Queen's University, Belfast, in the UK, and University College, Dublin, in Ireland.

THOMPSON RIVER VALLEY: The proactive real-time infrastructure monitoring and evaluation (PRIME) system will continue to collect electrical resistivity data beyond 2020, and provide a more refined picture of moisture-driven processes for landslides in this semi-arid terrain (e.g., Holmes et al. 2020; Huntley et al. 2020a; Sattler et al. 2020; in review). In 2020-2021, the PRIME and climate datasets will be evaluated in the context of other monitoring results (e.g., Geocubes™, UAV change detection). These data will help researchers understand the mechanisms involved in landslide movement (e.g., precipitation and groundwater recharge). PRIME and climate time-series data will help reduce the costs of maintenance and improve the effectiveness of mitigation plans in the Thompson River valley.

ASSINIBOINE RIVER VALLEY: Experience at Ripley Landslide indicates that electrical resistivity tomographic methods reveal the most information about earth materials and groundwater conditions at depth (Huntley et al. 2018a; Huntley et al. 2019a, b). Beginning in 2020-2021, fieldwork will focus on repeat electrical resistivity tomographic (ERT) monitoring and shallow seismic surveys (undertaken by the GSC, universities and geophysics contractors) to characterize the long-term hydrological behaviour of geological units in the landslides of the Assiniboine and Qu'Appelle river valleys. At the CN 184.4 site, an array of fixed electrodes will be permanently positioned across the unstable slope to capture dynamic changes in electrical resistivity of the hydrogeological units over repeat visits through the duration of the study (~5 years). Such datasets will help better define surface water and groundwater flow paths in the landslide(s), and their relationship to fluctuating pore-water pressures and landslide activity. In turn, this will improve our understanding of soil strength, and landslide stability when landslide movements are detected by other monitoring techniques.

At the CN 184.4, and CP 86.5 and 82.6 sites, it is proposed to core into the shale with waste canola oil (WCO). Recent testing of drilling with WCO by USASK found it made a ~10% difference in modulus measurement for laboratory testing: a significant increase over standard drilling methods. Samples are preserved by storing them in Schedule 80 PVC tubes filled with oil and re-pressurized to their *in situ* stresses. This new method will vastly alter the results of the lab testing, and the benefit is that we can target it on the zones that we are interested as opposed to just drilling a whole hole with the oil. For example, by targeting a couple of metres of shale above and below a shear zone, as well as the shear zone, we are only using the oil through limited sections of core. This is very cost efficient and beneficial. USASK is also looking to explore *in situ* pressure meter testing (strength and stiffness testing) to greatly augment the modulus and strength data needed for detailed numerical modelling. There is some very impressive technology now in Canada that could be well-used to determine not only the *in situ* parameters, but also the *in situ* stress fields in the horizontal direction. Standard downhole measurement of gamma, electromagnetic induction, and magnetic susceptibility will also be undertaken in existing and new boreholes to provide additional subsurface information (cf. Huntley et al. 2017a; Huntley et al. 2019a).

**Table 3** Geohazard mapping activities matrix 2020-2025 for the Thompson River valley, BC (TRV), and the Assiniboine-Qu'Appelle river valleys, SK-MN (ARV).

| Collaborating Institutions | Personnel Requirements and Rôles | Activity Group 1 Objectives | Projected Outcomes | Dissemination (i.e., presentations, publications) |
|---|---|---|---|---|
| Geological Survey of Canada | • 2 Research Scientists (Quaternary)<br>• 1 Physical Scientist (Geophysics)<br>• 2 GIS Technicians | **Terrain mapping and fieldwork** | Logistical support for ground-truth fieldwork, and GNSS surveys In (TRV and ARV) | **Conferences**<br><br>**Journal Publication** |
| British Geological Survey | • 1 Research Scientist (Geophysics)<br>• 2 Physical Scientist (Geophysics)<br>• 1 Ph.D. student (University of Belfast [UB], Northern Ireland) | **Geophysics (SP, ERT and PRIME)** | Procurement of cables, electrodes, data loggers, software for SP and ERT system, equipment and sample transfers, logistical support for systems maintenance, fieldwork (TRV and ARV)<br><br>Sole-source contracts for geophysical data acquisition, processing, analyses, and interpretation | **Government Documents**<br>*Open File Reports* and Canadian Geoscience Series maps (GSC, BGS)<br><br>**Academic Theses**<br>Student M.Sc., Ph.D. theses and publications<br><br>UA, USASK and UB senior authors |
| Department of Civil Engineering, University of Alberta | • 3 Professors / Research Engineers<br>• 1 M.Sc./Ph.D. Student | **Bathymetric survey** | Procurement of hydrographic equipment in support of fieldwork (TRV and ARV)<br><br>Sole-source contracts to CHS data collection and analysis (TRV and ARV) and FUNKTIONAL (specialized jet boat operation, TRV) | |
| College of Engineering, University of Saskatchewan | | **Geoscience Outreach** | Logistical support for conferences, workshops, and publications that aim to:<br><br>• Characterize three-dimensional ground displacement patterns of discrete locations<br><br>• Evaluate the utility of precipitation, ambient temperature, and soil moisture datasets<br><br>• Predict landslide activity based on comparison of geophysical results, meteorological records, and 3D-displacement measurements | |

### *C) Bathymetric Mapping*

As part of the current IMOU, experimental and conventional single-beam and multi-beam sonar systems are being tested under extreme flow velocity and low water temperature conditions in the Thompson River valley corridor to determine the utility of these systems for future bathymetric surveys elsewhere in Canada (e.g., Assiniboine and Qu'Appelle river valleys). Single-beam systems are less expensive and relatively easier to operate than multi-beam systems. The former also enable more rapid processing and output generation. However, single-beam depth sounding systems profile directly under the transducer, hindering spatial coverage and preventing imaging nearer shorelines. Multi-beam systems are more expensive and complicated, but improve bottom coverage enabling surveys to be completed faster and with greater detail. The equipment is technically challenging to operate and in shallow water, where limited water depth limits the swath width, causes the system to function similarly to a single-beam system.

THOMPSON RIVER VALLEY: The significance of a repetitive survey is that the high-resolution multi-visit dataset will establish the nature of the changes in river bottom morphology along the Thompson River valley where active landslides are being monitored (Huntley et al. 2018b). This knowledge will help evaluate the influence of Thompson River on landslide activity in the railway corridor. Completing the bathymetric survey, interpreting and publishing the results of this survey will be a focus of the 2020-2025 work plans (**Table 3**).

ASSINIBOINE RIVER VALLEY: Bathymetric research aims to evaluate the influence of river dynamics on landslide activity in the Assiniboine and Qu'Appelle railway corridors. A key question to be addressed will be whether the river influences landslide movement in a manner similar to that seen in the Thompson valley landslides (cf. Huntley et al. 2018b). Assiniboine and Qu'Appelle rivers differ markedly to Thompson River. Both are low gradient, slow-moving, highly meandering, underfit alluvial channels with floodplains occupying broadly incised glacial spillways. In contrast, Thompson River is predominantly confined to a steep gradient, fast-flowing, sinuous canyon carved into bedrock and glacial sediments during deglaciation and early postglacial times.

For the Assiniboine River valley, beginning in summer of 2021, bathymetry and back-scatter maps could be established with one or two passes of the Norbitt multibeam system (the same employed at Ripley Landslide) using a dingy or autonomous surface vehicle (ASV) with the beam set to full width given the slow-flowing nature of the Prairie river. Similar, repeat surveys in subsequent years would allow us to distinguish bedform morphology, and map changes related to fluvial and mass-wasting processes. The discovery of scour pools and meander cutbank erosion incising landslide toe slopes along the Assiniboine and Qu'Appelle rivers would be important for two reasons. Firstly, it would suggest that erosion in the pools and channel cutbanks removes support from the gentle to moderate colluvial toe slopes, likely contributing to their instability. Secondly, similar to Ripley Landslide, the scour pools can expose fractured and porous sediments and bedrock at the river bed improving hydraulic connectivity between the river and groundwater in the slide mass. Both of these apparent relationships will be investigated in more detail in the coming years as part of the IMOU.

### 3.2 ACTIVITY 2: Change Detection with InSAR, GNSS, UAVs, and Weather Stations

Collaborators: GSC, UA, USASK, MGS, 3v Geomatics

#### *A) InSAR monitoring*

Ground motion measured by space-borne InSAR produced results with precision comparable to GNSS measurements, but have the advantage of monitoring displacement over large areas (e.g., Huntley et al. 2017b; Journault et al. 2018). However, before RADARSAT-2 datasets can be broadly used for change detection across Canada, they must be compared along with other satellite platforms, and with low-cost UAV monitoring techniques (**Table 4**).

THOMPSON RIVER VALLEY: SAR remote sensing is effective in the Thompson River valley as a first approximation of ground hazard distribution and instability, and whether site investigation and additional testing is required. Collaboration, beginning in 2019 and continuing through 2020-2025, with InSAR specialists at 3v Geomatics in Vancouver will compare RADARSAT-2 results with data acquired from the EUROSPACE platform SENTINEL-1 with different spatial resolutions, view-angle capacities, and orbital paths. This partnership will use dedicated processing systems and specific processing algorithms that will together reduce processing time, and likely improve the quality InSAR results.

ASSINIBOINE RIVER VALLEY: Private sector collaboration would allow us to expand the area of investigation of landslide activity to include the Assiniboine River valley from St-Lazare to Kamsack (**Figure 2**). Additionally, it improves processing capabilities through access to advanced in-house InSAR processing software and to high-performance computers that will reduce computational time. The application of advanced processing techniques that consider both persistent scatterer targets and distributed targets (e.g., corner reflectors) will greatly improve the spatial density of displacement records. The main expected outcomes of this activity will be: 1) analysis of the vertical and horizontal deformation components, combining ascending and descending acquisition geometries of satellite data; 2) analysis of the historical datasets and integration with GNSS and UAV data collected *in situ*; 3) improving knowledge of the behaviour and characteristics of the studied landslides; and 4) definition of a sequence of thresholds representative of increasing states of activity to better risk manage landslides and other geohazards.

#### *B) GNSS Monitoring*

Permanent GNSS markers provide a baseline measure of landslide activity for the assessment of other monitoring techniques. For both Ripley Landslide and South Slide, GNSS displacement records capture full (i.e., three-dimensional) displacement vectors with high temporal resolution (Macciotta et al. 2014; Hendry et al. 2015). To this end, these localized high-resolution spatial data are complementary to remote sensing techniques that provide spatially expansive records of motion with generally lower accuracy (e.g., UAV photogrammetric surveys; Huntley et al. 2018b) or are restricted to line-of-sight components (e.g., InSAR; Journault et al. 2018). GNSS spatial data will be used to help understand the behaviour and drivers of slope instabilities affecting rail transport in the Thompson and Assiniboine river valleys (**Table 4**).

THOMPSON RIVER VALLEY: For 2020-2025, a goal will be to develop a monitoring protocol that captures patterns and rates of movement, and changes in landslide activity. As the Geocube$^{TM}$ networks on both Ripley Landslide and South Slide stabilize through 2020 and beyond, data collected (remotely and on-site, respectively) will be processed and presented to graphically show:

1) Displacement trends (grey-scaled or colour-graded by month, ArcGIS shapefiles)
2) 3D displacement (mm) -vs- Date (month, year)
3) Surface angle of movement (angle, degrees) -vs- Date (month, year)
4) Precipitation (mm) and 3D displacement (mm) -vs- Date (month, year)
5) Temperature ($^{o}$ C) and 3D displacement (mm) -vs- Date (day, month, year)

Key questions to be addressed starting in 2020 are: 1) whether the pattern of landslide activity captured by the Geocube$^{TM}$ system compares with other monitoring data (e.g., InSAR, UAV); and 2) are changes in groundwater levels monitored in four boreholes across the landslide related to changes in movement detected by the Geocube$^{TM}$ system?

Detailed examination of Geocube$^{TM}$ records will provide insight on the rates and spatial pattern of creep as well as the timing, and possibly precursors of changes in creep behaviour. The resulting knowledge will help to characterize landslide hazard, and ultimately reduce landslide risk. The locations of highest creep rates as indicted by the Geocube$^{TM}$ networks will help identify where track damage can be expected if creep is continuous. Spatial variability in landslide motion will help inform the mechanism of the monitored landslides, such as whether failure involves complex interactions between structurally separate blocks, thus improving landslide characterization and mitigation efforts. Comparing displacement trends with proxy records of possible landslide drivers – including temperature, precipitation, river level and irrigation will help establish landslide warning threshold based on environmental conditions. Such comparisons will include detailed analysis of Geocube displacement histories spanning acceleration periods indicated by the CPR GNSS markers (at Ripley Landslide) in an effort to identify possible environmental triggers. If gradual acceleration is found to precede failure events, future Geocube-measured accelerated creep can be used to forecast impending failures.

ASSINIBOINE RIVER VALLEY: High resolution (millimetric) GNSS used at Ripley Landslide and South Slide (Geocubes), together with new systems to be developed by the UA, USASK and GSC, will help to understand the spatial and temporal distribution of movement and displacement across the Assiniboine landslides from year to year. At the CN 184.4, and CP 86.5 and 82.6 sites, networks of Geocubes will help to improve characterization of slope activity by combining three-dimensional displacement measurements with more spatially detailed line-on-sight displacements measured by, for example InSAR or UAV photogrammetry. In addition, networked GNSS data will help evaluate the utility of precipitation, ambient temperature, and soil moisture in predicting landslide activity based on comparison of three-dimensional displacement measurements with ERT results and meteorological records.

***C) UAV Change Detection***

UAVs allow flexible, inexpensive acquisition of low-altitude aerial imagery. Various off-the-shelf photogrammetric (SfM) software packages enable rapid production of high-quality digital surface models (DSM) from such images. Flying-height and battery restrictions limit the size of such surveys to areas on the order of magnitude of the largest landslides in the Thompson River valley (Huntley et al. 2018b). New study sites in the Assiniboine River valley are similar in areal extent (or perhaps an order of magnitude larger). Consequently, UAV photogrammetric surveys offer an excellent opportunity to generate high-quality repeat DSMs that can be compared to characterize surface change of active landslides along the transportation corridor. A number of issues may contribute to time delays in addressing sub-activity objectives in the coming years. Other project commitments limits access time to the GSC technical support required to fly UAVs, survey terrain, and process data in ArcGIS. In-house computing abilities are limited by stock computers and software, and limited data storage capabilities provided by Shared Services Canada. Aviation regulations are strictly enforced near railway property, requiring personnel with a flying license and controlled traverses avoiding the railway right-of-way. Lastly, wildfires and extremely poor air conditions during the 2017 and 2018 field seasons prevented flight and survey objectives. With changing climate and weather conditions, poor air quality may limit sortie times and ranges in the future.

THOMPSON RIVER VALLEY: Additional UAV surveys to be conducted from 2020-2025 will extend surface-change characterization of Ripley Landslide, South Slide and other active landsides in the valley (**Table 1**). Comparison of these subsequent surveys will allow exceptionally precise quantification of points and rates of movement. Also, a recent industry LiDAR survey collected in 2014 using a fixed-wing aircraft will be evaluated with benchmarked DSMs generated from seasonal high resolution air photographs and LiDAR taken from UAVs between 2016 and 2018. Three questions are to be addressed starting in 2020. The first is whether change detection results using photogrammetric methods are comparable to InSAR and other monitoring data (e.g., GNSS and Geocubes). From 2020-2025 (**Table 4**), geo-referenced UAV overflights are planned for summer, fall and winter to capture changes between the surface models, and comparison with DSMs generated in 2016, 2017, 2018, and 2019. These additional surveys will enable comparison of landslide motion over multiple periods, thus providing a further means to evaluate creep acceleration measured by CPR's GNSS markers. A second question is whether UAVs with high resolution hyperspectral imaging capabilities can they be used to remotely map the distribution and activity of landslides in the Thompson River valley (e.g., delimiting soil moisture and colluvial sediments with distinctive spectral signatures). Thirdly, the performance of UAV photogrammetry and UAV LiDAR surveys will be compared in detail.

ASSINIBOINE RIVER VALLEY: Starting in summer 2019, UAV surveys have aimed to capture changes in landslide morphology at the CN 184.4, and CP 86.5 and 82.6 sites in the Assiniboine River valley. Centimetre-resolution DSMs will be generated from the UAV surveys. Preliminary UAV results from the Thompson River valley are proof of concept (Bobrowsky et al. 2018). At Ripley Landslide, metre-scale features (e.g., boulders, corner reflectors) are clearly identifiable, and horizontal and vertical displacements of as little as 15 cm have been measured throughout the slide area. Zones within the landslide show an average cumulative movement of 230 mm between September 2016 and September 2017 (Huntley et al. 2020b). This imagery will be used in combination with other sources for terrain mapping purposes (see above). Repeat overflights in subsequent months and years will be conducted using the GSC's DJI Phantom 4 and USASK's DJI Mattrice 600 Pro Hexacopter. The reliable Phantom unit has a weight of 1.4 kg and includes a fixed payload consisting of a 12.4 MB RGB camera. The Mattrice weighs 9.5 kg (operating empty weight), and carries a 6 kg payload consisting of a Velodyne VLP-16 Puck LiDAR (16 channels, 300,000 points/second) and Zenmuse X3 RGB camera. Additional UAV surveys conducted beyond 2019 will extend surface-change characterization of the very slow-moving landslides in the Assiniboine and Qu'Appelle river valleys. Comparison of these subsequent surveys will allow exceptionally precise quantification of points and rates of movement. Vertical displacement modelling using the SfM would show mostly changes in vegetation: by using LiDAR, this problem is eliminated.

### 3.3 ACTIVITY 3: Monitoring Climate Change Variables

Collaborators: GSC, UA, USASK, MGS, 3v Geomatics

#### *A) Weather station installation*

Over the next 50 years, measurable changes in temperature, precipitation and other climatic factors are expected to display spatial variations across Canada (Weaver 2004; IPCC 2014). Depending on location, climate change will trigger positive or negative feedback in groundwater recharge, flow and discharge, flooding and stream erosion, the extent and duration of wildfires, magnitude and frequency of landslides, in the permafrost regime, and the distribution of wildlife and vegetation (Bruce and Cohen 2004; Weaver 2004; IPCC 2014). In western Canada and the Prairie provinces, a number of geohazards are anticipated to negatively impact terrain, leaving resources and infrastructure vulnerable to loss or damage. Communities are also vulnerable, with populations susceptible to disease and malnutrition as agricultural and traditional wildlife and water resources become threatened (IPCC 2014; Lonergan 2004). As a response to rising precipitation amount (as rain and snow), temperature ranges and wildfires, increases in magnitude and frequency of landslides and other geohazards are expected (Evans and Clague 1997; Geertsema et al. 2006; Couture and Evans 2006; Wang and Lesage 2007). Erosion of exposed sediments is likely if wind strength and duration increases due to changes in storm systems, air pressure gradients, loss of vegetation and wildfires (Wolfe 1997; Wolfe 2001). Increasing precipitation, duration of rainfall, loss of vegetation and wildfires will lead to an increase in magnitude and frequency of gully erosion on valley sidewalls (Sauchyn and Nelson 1999; Valentin et al. 2005); in addition to an increase in magnitude and frequency of flooding, erosion and deposition in rivers and streams (Knox 2000; Chen et al. 2006; St. George 2007; Chen and Grasby 2009).

THOMPSON RIVER VALLEY: In the Thompson River valley, a climate monitoring station has collected valuable data on precipitation, snow fall, air temperature since 2016, and from 2019, wind speed and wind direction. Beginning in 2020-2021, this multi-year climate-series will be compared with borehole monitoring results of groundwater levels and subsurface displacement, GNSS, UAV, and InSAR to investigate inter-annual variation in seasonal displacement rates. A research goal will be to establish the degree to which the amount and duration of precipitation (as snow and rain) events, and air temperature are important controls on ground displacement at the start of melt season in late winter-early spring (cf. Holmes et al. 2020).

ASSINIBOINE VALLEY: An important test for the new study sites is to determine the degree to which climate variables influence groundwater conditions and landslide activity (cf. Schafer et al. 2015; Holmes et al 2018; Holmes et al. 2020; Sattler et al. 2018; Sattler et al. 2020, in review). Fluctuations in temperature over the winter months may also contribute to intervals of ground thaw, changes in porewater pressures and landslide activity. These relationships will be tested over the coming years through validation of landslide deformation records (e.g., Geocube, UAV, and InSAR change detection monitoring) correlated to climate variables. The goal for 2020-2021 will the procurement and testing of components for a climate monitoring station (rainfall, snow, air temperature, wind speed and direction). Installation in the Assiniboine River valley will likely take place in 2021-2022, after which it will be possible to test whether a component of landslide movement can be attributed to local weather conditions (e.g., precipitation, air temperature, wind, barometric pressure).

**Table 4** Change detection activities matrix 2020-2025 for the Thompson River valley, BC (TRV), and the Assiniboine-Qu'Appelle river valleys, SK-MN (ARV).

| **Collaborating Institutions** | **Personnel Requirements and Rôles** | **Activity 2 Objectives** | **Projected Outcomes** | **Dissemination (i.e., presentations, publications)** |
|---|---|---|---|---|
| Geological Survey of Canada<br><br>Canada Centre for Mapping and Earth Observation<br><br>3 v Geomatics | • 2 Research Scientists (Quaternary)<br>• 1 Physical Scientist (Geophysics)<br>• 2 GIS Technicians | **InSAR monitoring** | Sole-source contracts to 3v-GEOMATICS and TRE-ALTAMIRA for acquisition of satellite imagery for data acquisition, processing, analyses and archiving, procurement of satellite imagery (multispectral) and InSAR corner reflectors (TRV and ARV)<br><br>Logistical support for ground-truthing (TRV and ARV) | **Conferences**<br><br>**Journal Publications**<br><br>**Government Documents**<br>*Open File Reports* (GSC)<br><br>**Academic Theses**<br>Student theses and publications<br><br>UA and USASK senior authors |
| | | **GNSS monitoring** | Procurement of Geocube components from Ophelia (France) and GNSS components for in-house system<br><br>Logistical support for systems maintenance, fieldwork (TRV and ARV) | |
| | | **UAV change detection** | Procurement of UAVs, software, components enabling LiDAR and multispectral inventories<br><br>Logistical support for fieldwork (TRV and ARV) | |
| Department of Civil Engineering, University of Alberta | • 3 Professors / Research Engineers | **Monitoring climate change variables** | Procurement of total weather station (air pressure, temperature, rain gauge, snow sensor, anemometer and wind vane; insolation), moisture meters, | |

*Continued over …*

| | | | |
|---|---|---|---|
| College of Engineering, University of Saskatchewan | 2 M.Sc./Ph.D. Students | | Procurement of borehole inclinometers, piezometers, supporting hardware, software, data loggers, batteries, solar panels and data communication components (ARV)<br><br>Logistical support for routine maintenance of equipment, replacement and new units (TRV and ARV) |
| | | **Geoscience Outreach** | Logistical support for conferences, workshops, and publications that aim to:<br>• Characterize three-dimensional ground displacement patterns of discrete locations<br><br>• Evaluate the utility of precipitation, ambient temperature, and soil moisture datasets<br><br>• Predict landslide activity based on comparison of geophysics results, meteorological records, and 3D-displacement measurements |

## 4. Summary

Knowledge of landslide processes and controls on activity will help to mitigate risks and improve the safety and security of Canada's transportation infrastructure, economy, environment, communities and public. Field methods tested at Ripley Landslide and South Slide (**Figure 1**) will be applied to new study sites identified in Thompson River valley (**Table 1**), and at the CN 184.4, and CP 86.5 and 82.6 sites in the Assiniboine River valley (**Figure 2**, **Table 2**). **Table 3** and **Table 4** list the collaborating institutions, personnel requirements and roles, activity objected, project outcomes, and information dissemination plan. A proposed time-line for activities, deliverables, and operational budget is presented in **Table 5**.

### 4.1 Activities for 2020-2021

NRCan-GSC, TC-IC, and collaborators will address outstanding questions on the impact of past and future extreme weather and climate change, and to provide new information on landslide hazards in a timely manner to Railway Ground Hazard Research Program stakeholders (e.g., TC-IC, CN, CPR, UA). The fundamental geoscience knowledge generated through the proposed R&D will allow key industry stakeholders (e.g., CN and CPR) and university partners (e.g., UA and USASK) to develop robust solutions to measure, manage, and mitigate landslide geohazards and their consequences (**Figure 3**).

For 2020-2021, research activities will cover terrain analysis (desktop studies and fieldwork), and change detection monitoring (remote and on-site/*in situ*) in the Thompson River valley, British Columbia, and the Assiniboine River valley, Manitoba-Saskatchewan (**Table 5**). For the immediate future, the R&D focus will be: 1) acquisition of air photographs, satellite imagery, and other geospatial datasets for both study areas (and additional sites if necessary); 2) developing in-house (or at-home) functionality and capability using cloud storage and processing services; 3) developing desktop remote mapping protocols and data analyses, combining terrain studies with geospatial datasets to meet the IMOU mandate; 4) acquisition of climate station components (e.g., tipping-bucket rain gauge, air temperature sensor, snow depth gauge, anemometer and wind vane), borehole instrumentation and drilling requirements (e.g., piezometers, inclinometers, canola oil), and InSAR corner reflectors; and 5) communicating R&D through conferences, workshops, and publications (**Table 5**).

**Table 5** Proposed timetable for field investigations, desktop analyses, and project outputs (2020-2025). *Expected that partners will contribute in-kind funding in support for selected activities. Superscript [A] – project activities in the Thompson River valley. Superscript [B] – project activities in the Assiniboine-Qu'Appelle river valleys. Beyond 2022, other research sites may be included in the study.

| Project activity (collaborators) | 2020-2021 | 2021-2022 | 2022-2023 | 2023-2024 | 2024-2025 |
|---|---|---|---|---|---|
| **Terrain mapping** [A, B] surficial geology, geophysics (GSC, BGS, MGS) | Desktop mapping; Image acquisition; Cloud storage and processing Maintenance | Desktop mapping; ERT, Seismic; Bathymetry; Bench-marking | Desktop mapping; ERT; Bathymetry; Bench-marking | Desktop mapping; ERT; Bathymetry; Bench-marking | Desktop mapping |
| **GNSS** [A, B] fixed and mobile (GSC, UA, USASK, MGS) | Data acquisition; Cloud storage and processing; Maintenance | Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Decommissioning; Cloud storage and processing; Interpretation |
| **UAV overflights** [A, B] sites a, b, c (GSC, UA, USASK) | Data and software acquisition; Cloud storage and processing | Data acquisition; Cloud storage and processing; Interpretation | Data acquisition; Cloud storage and processing; Interpretation | Data acquisition; Cloud storage and processing; Interpretation | Cloud storage and processing; Interpretation |
| **InSAR*** [A, B] data, scenes (CN, CPR, 3v Geomatics, CCMEO) | Corner reflectors acquisition; Data acquisition; Cloud storage and processing | Corner reflector installation; Data acquisition; Cloud storage and processing; Interpretation | Data acquisition; Cloud storage and processing; Interpretation | Data acquisition; Cloud storage and processing; Interpretation | Cloud storage and processing; Interpretation |
| **Climate station data** [A, B] climate variables (GSC, MGS, USASK) | Component acquisition; Data acquisition Cloud storage and processing Maintenance | Climate station installation; Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Decommissioning; Cloud storage and processing; Interpretation |
| **Borehole Monitoring*** [A, B] piezometers, SSI, SAA (GSC, UA, USASK, MGS) | Borehole acquisitions; Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Borehole drilling*; Borehole installations; Downhole geophysics Data acquisition; Cloud storage and processing; Interpretation; Maintenance | Borehole installations; Data acquisition; Cloud storage and processing; Interpretation Maintenance | Borehole installations; Data acquisition; Cloud storage and processing; Maintenance | Decommissioning; Cloud storage and processing; Interpretation |
| **Publications** geoscience outreach (GSC, UA, USASK, MGS) | Conference abstracts Open File Annual Report Workshop Presentation | Conference abstracts Proceedings paper Open File Annual Report Workshop Presentation | Conference abstracts Proceedings paper Open File Annual Report Workshop Presentation | Conference abstracts Journal paper Open File Annual Report Workshop Presentation | Conference abstracts Journal paper Geoscience Map Annual Report Workshop Presentation |

## 5. Acknowledgements

This research was funded by the Transport Canada Innovation Centre and Natural Resources Canada. Fieldwork would not be possible without the support of Trevor Evans (Canadian National Railways, Kamloops, British Columbia), Danny Wong (Canadian Pacific Railways, Calgary, Alberta) and Jason Bojey (Canadian Pacific Railways, Kamloops, British Columbia). The Open File greatly benefitted from thorough and helpful critical reviews by Michael Hendry, Renato Macciotta and Jorge Rodriguez (Department of Civil Engineering, University of Alberta, Edmonton, Alberta). Dr. Andrée Blais-Stevens (GSC Vancouver) critically reviewed this Open File.

## 6. References

Blatz, J. A., Ferreira, N.J. and Graham, J. 2004. Effects of near-surface environmental conditions on instability of an unsaturated soil slope. *Canadian Geotechnical Journal*, Vol. 41, pp. 1111-1126

Bobrowsky, P. 2013. Recent advances in landslide monitoring. Paper presented at *CIRiDe-International Congress on Disaster Risk and Sustainable Development*, Catamarca, Argentina, 1 page

Bobrowsky, P. 2016. Ripley Landslide: a Canadian test site for landslide investigation and monitoring. *International Consortium on Landslides*, *Technical Presentation*, ICL Board Meeting, Paris, 1 page

Bobrowsky, P. 2018. IPL-202 Ripley Landslide Monitoring Project (Ashcroft, B.C., Canada). International Programme on Landslides, *Unpublished Annual Report*, 1 page

Bobrowsky, P. and Sladen, W. 2013. Installing Fibre Optics with the China Geological Survey. *NRCAN-ESS S&T Newsletter*, Issue #21 (NRCan Wiki online digital version only)

Bobrowsky, P., MacLeod, R., Huntley, D., Niemann, O., Hendry, M., Macciotta, R. 2018. Ensuring Resource Safety: Monitoring Critical Infrastructure with UAV Technology. *Resources for Future Generations*, Conference Abstracts Volume, Vancouver, Canada, 1 page

Bruce, J.P. and Cohen, S.J. 2004. Impacts of climate change in Canada (Chapter 4). In Coward, H. and Weaver, A.J. (editors); *Hard Choices: climate change in Canada*; Wilfred Laurier Press, 273 pages, ISBN 0-88920-442-X

Chen, Z. and Grasby, S.E. 2009. Detection of decadal and interdecadal oscillations and temporal trend analysis of climate and hydrological time series, Canadian Prairies. *Geological Survey of Canada* Open File 5782; 13 pages

Chen, Z, Grasby, S. E., Osadetz, K.G., Fesko, P. 2006. Historical climate and stream flow trends and future water demand analysis in the Calgary region, Canada. *Water Science and Technology*, Vol. 53, no. 10; pp. 1-11

Christiansen, E. 1979. The Wisconsinan deglaciation of southern Saskatchewan and adjacent areas. *Canadian Journal of Earth Sciences*, Vol. 16 (4), pp. 913-938

Clague, J.J. and Evans, S.G. 2003. Geologic framework of large historic landslides in Thompson River valley, British Columbia*. Environmental & Engineering Geoscience*, Vol. 9, pp. 201–212

Couture, R. and Evans, S. 2006. Slow-moving disintegrating rockslides on mountain slopes. In Landslides from massive rock slope failure: proceedings of the NATO Advanced Research Workshop on Massive Rock Slope Failure: New Models for Hazard Assessment. In Evans, S.G., Scarascia Mugnozza, G., Strom, A and Hermanns, R.L. (editors); *NATO Science Series, Sub-Series IV: Earth and Environmental Sciences*, Vol. 49, pp. 377-393

Deblonde, C. Cocking, R.B., Kerr, D.E., Campbell, J.E., Eagles, S., Everett, D., Huntley, D. H., Inglis, E., Parent, M., Plouffe, A., Robertson, L., Smith, I.R. and Weatherston, A. 2018. Science Language for an Integrated Geological Survey of Canada Data Model for Surficial Geology Maps (Version 2.3.14), *Geological Survey of Canada*, Open File 8236, 50 pages (2 sheets)

Geertsema, M., Schwab, J.W. and Blais-Stevens, A. 2006. Landslides impacting linear infrastructure in west-central British Columbia. In *Proceedings of the 1st Specialty Conference on Disaster Mitigation*, pp. DM 1- 10

Heginbottom, J.A., Dubreuil, M.A., Harker, P.T., Caron, A. Paul, P. and Rose, I. 1995. Canada Permafrost; *National Atlas of Canad*a, 5th Edition, Scale 1:7 500 000

Hendry, M., Macciotta, R. and Martin, D. 2015. Effect of Thompson River elevation on velocity and instability of Ripley Slide. *Canadian Geotechnical Journal*, Vol. 52(3), pp. 257-267

Holmes, J., Chambers, J., Donohue, S., Huntley, D., Bobrowsky, P., Meldrum, P. Uhlemann, S., Wilkinson, P. and Swift, R. 2018. The Use of Near Surface Geophysical Methods for Assessing the Condition of Transport Infrastructure. Civil Engineering Research Association, Special Issue on Structural Integrity of Civil Engineering Infrastructure, *Journal of Structural Integrity and Maintenance*, 6 pages

Holmes, J., Chambers, J., Meldrum, P., Wilkinson, B., Williamson, P., Huntley, D., Sattler, K., Elwood, D., Sivakumar, V., Reeves, H. and Donohue, S. 2020. 4-Dimensional electrical resistivity tomography for continuous, near-real time monitoring of a landslide affecting transport infrastructure in British Columbia, Canada. *Near Surface Geophysics*, 15 pages, doi.org/10.1002/nsg.12102

Howes, D.E. and Kenk, E. 1997. Terrain classification system for British Columbia (revised edition): a system for the classification of surficial materials, landforms and geological processes of British Columbia. *B.C. Ministry of Environment* Manual 10, 90 pages

Huntley, D. and Bobrowsky, P. 2014. Surficial geology and monitoring of the Ripley Slide, near Ashcroft, British Columbia, Canada; *Geological Survey of Canada*, Open File 7531, 21 pages

Huntley, D., Bobrowsky, P., Parry, N., Bauman, P., Candy, C. and Best, M. 2017a. Ripley Landslide: the geophysical structure of a slow-moving landslide near Ashcroft, British Columbia, Canada. *Geological Survey of Canada*, Open File 8062, 59 pages

Huntley, D., Bobrowsky, P., Charbonneau, F., Journault, J. and Hendry, M. 2017b. Innovative landslide change detection monitoring: application of space-borne InSAR techniques in the Thompson River valley, British Columbia, Canada. In: *Landslide Research and Risk Reduction for Advancing Culture and Living with Natural Hazards*, Volume 3, 4th World Landslide Forum (ICL-IPL), Ljubljana, Slovenia 29- May – 2 June 2017, Springer Nature, 13 pages

Huntley, D., Bobrowsky, P., Hendry, M., Macciotta, R., Elwood, D., Sattler, K., Reeves, H., Chambers, J., Meldrum, P. Holmes, J. and Wilkinson, P. 2018a. Using multi-dimensional ERT modelling to provide new insight into the hydrogeological structure of a very slow-moving landslide in glacial sediments, Thompson River valley, British Columbia, Canada. *Geological Society of America Annual Meeting*, Session T65, Abstract Volume, 1 page

Huntley, D., Bobrowsky, P., MacLeod, R. and Roberts, N. 2018b. New insights into form and function of very slow-moving landslides from bathymetric surveys of Thompson River, British Columbia *Geological Society of America Annual Meeting*, Session T53, Abstract Volume, 1 page

Huntley, D., Bobrowsky, P., Hendry, M., Macciotta, R. and Best, M. 2019a. Multi-technique geophysical investigation of a very slow-moving landslide near Ashcroft, British Columbia, Canada. *Journal of Environmental and Engineering Geophysics*; Volume 24 (1) pp. 85-108

Huntley, D., Bobrowsky, P., Sattler, K., Elwood, D., Holmes, J., Chambers, J., Meldrum, P. Holmes, J. and Wilkinson, P. Hendry, M. and Macciotta, R. 2019b. PRIME installation in Canada: protecting national railway infrastructure by monitoring moisture in an active landslide near Ashcroft, British Columbia. 32nd *SAGEEP, Environmental and Engineering Geophysical Society*. Proceedings Volume of the Annual Meeting, Portland, Oregon, USA, 1 page

Huntley, D., Holmes, J., Bobrowsky, Chambers, J., Meldrum, P., Wilkinson, P., Elwood, D., Sattler, K., Hendry, M. and Macciotta, R. 2020a. Hydrogeological and geophysical properties of the very slow-moving Ripley Landslide, Thompson River valley, British Columbia. *Canadian Journal of Earth Sciences*, 21 pages, doi.org/10.1139/cjes-2019-0187

Huntley, D., Bobrowsky, P., Cocking, R., Joseph, P., Neelands, N., MacLeod, R., Rotheram-Clarke, D., Usquin, R. and Verluise, F. 2020b. Installation, operation and evaluation of an innovative global navigation satellite system monitoring technology at Ripley Landslide and South Slide, near Ashcroft, British Columbia; Geological Survey of Canada, Open File 8742, 36 pages

Intergovernmental Panel on Climate Change 2014. Working Group II Report: Climate Change 2014 Impacts, Adaptation and Vulnerability. *IPCC 5th Assessment Report*; https://www.archive.ipcc.ch/

Journault, J., Macciotta, R., Hendry, M., Charbonneau, F., Bobrowsky, P., Huntley, D., Bunce, C., and Edwards, T. 2016. Identification and quantification of concentrated movement zones within the Thompson River valley using satellite-borne InSAR. *Canadian Geotechnical Society,* Proceedings Volume of GeoVancouver2016 Annual Meeting, 13 pages

Journault, J. Macciotta, R., Hendry, M., Charbonneau, F., Huntley, D. and Bobrowsky, P. 2018. Measuring displacements of the Thompson River valley landslides, south of Ashcroft, B.C., Canada, using satellite InSAR. *Landslides*. Volume 15 (4), pp. 621-636, DOI 10.1007/s10346-017-0900-1

Klassen, R. 1972. Wisconsin events and the Assiniboine and Qu'Appelle valleys of Manitoba and Saskatchewan. *Canadian Journal of Earth Sciences*, Vol. 9 (5), pp. 544-560

Knox, J.C. 2000. Sensitivity of modern and Holocene floods to climate change. *Quaternary Science Reviews*, Vol. 19, pp. 439-457

Lonergan, S. 2004. The human challenges of climate change (Chapter 3). In Coward, H. and Weaver, A.J. (editors); *Hard Choices: climate change in Canada*; Wilfred Laurier Press, 273 pages, ISBN 0-88920-442-X

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 Thompson River Valley, B.C. *Geohazards 6 Symposium, Proceedings Volume,* Kingston, Ontario, Canada

Mugridge, S-J. and Young, R. 1983. Disintegration of shale by cyclic wetting and drying and frost action. *Canadian Journal of Earth Sciences*, Vol. 20 (4), pp. 568-576

Resource Inventory Committee 1996. Terrain stability mapping in British Columbia: a review and suggested methods for landslide hazard and risk mapping. *Resource Inventory Committee Publications*, www.publications.gov.bc.ca (URL 2011)

Sattler, K., Elwood, D., Hendry, M, Macciotta, R., Huntley, D., Bobrowsky, P. and Meldrum, P. (2018) Real-time monitoring of soil water content and suction in slow-moving landslide. *GeoEdmonton 2018*, Proceedings Paper, 8 pages

Sattler, K., Elwood, D., Hendry, M., Huntley, D., Holmes, J., and Wilkinson, P. 2020 (in review). Effect of pore-pressure dynamics on progressive failure in clay shale landslides. *Landslides*, 17 pages

Sauchyn, D.J. and Nelson, H.L. 1999. Origin and erosion of the Police Point landslide, Cypress Hills, Alberta. In Holocene climate and environmental change in the Palliser Triangle: a geoscientific context for evaluation the impacts of climate change on the southern Canadian prairies; Lemmen, D.S. and Vance, R.E. (editors); *Geological Survey of Canada*, Bulletin 534, 1999; pp. 257-265

Sauer, K. 1978. The engineering significance of glacier ice-thrusting. *Canadian Geotechnical Journal*, Vol. 15 (4), pp. 457-472

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 2015* Paper, 7 pages

Smith, S.L. and Burgess, M.M. 2011. Permafrost and Climate Interactions. In Singh, V. P. and Singh, P. and Haritashya, U.K. (editors); *Encyclopedia of Earth Sciences*, Vol. 46, Pt. 15, pp. 852-857

St. George., S. 2007. Stream flow in the Winnipeg River basin, Canada: trends, extremes and climate linkages. *Journal of Hydrology*, Vol. 332, pp. 396-411

Valentin, C., Poesen, J. and Li, Y. 2005. Gully erosion: impacts, factors and control. *Cantena*; Vol. 63, pp. 132-153

Wang, B. and Lesage, K. 2007. Impact of climate change on slope stability in permafrost regions. *Proceedings of the 8th International Symposium on Cold Region Development*; 11 pages

Weaver, A.J. 2004. The Science of Climate Change (Chapter 2). In Coward, H. and Weaver, A.J. (editors); *Hard Choices: climate change in Canada*; Wilfred Laurier Press, 273 pages, ISBN 0-88920-442-X

Wolfe, S.A. 1997. Impact of increased aridity on sand dune activity in the Canadian Prairies. *Journal of Arid Environments*, Vol. 36, pp. 421-432

Wolfe, S.A. 2001. Eolian activity. In A synthesis of geological hazards in Canada; Brooks, G R (ed.); *Geological Survey of Canada*, Bulletin 548, pages 231-240, 1 sheet

Young, H. and Moore, P. 1994. Composition and depositional environment of the silicaceous Odanah Member (Campanian) of the Pierre Shale in Manitoba. *Geological Society of America,* Special Papers, Vol. 287, pp. 175-196