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Recommended citation

Huntley, D., Bobrowsky, P., Rotheram-Clarke, D., Cocking, R., and Joseph, J. 2020. Understanding prairie landslides: current research in the Assiniboine River valley, Manitoba-Saskatchewan (2019-2020); Geological Survey of Canada, Open File 8735, 24 pages. <https://doi.org/10.4095/326821>

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

Abstract

The mandate of Inter-Departmental Letter of Agreement 5170 (IDLA-4755) between Natural Resources Canada (NRCan) and Transport Canada (TC) was to research and monitor landslides where vital railway infrastructure and operations, public safety, and the environment are at risk. IDLA-4755 combined research and development of landslide monitoring technologies in the Thompson River valley, British Columbia with new activities in the Assiniboine River valley along the borders of Manitoba and Saskatchewan, and other sites in Canada. This report focuses on the 2019-2020 results and interpretation of: a) monitoring with real-time kinematic global navigational satellite system (RTK-GNSS); and, b) photogrammetry using unmanned aerial vehicles (UAV) and commercially available software in the Assiniboine River valley.

Keywords

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

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Cover illustration: Geological Survey of Canada field crew in the Assiniboine River valley, Manitoba (October 2019). Oblique photograph captured by a Phantom 4 unmanned aerial vehicle, view to southeast.

1. Introduction

Rail is the dominant method for moving Canada's import and export commodities to marine terminals on the east and west coasts, and into the USA. 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, a significant portion of which must cross the landslide-prone Assiniboine River valley on the border of Manitoba and Saskatchewan (**Figure 1-1**).

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 Assiniboine River valley. 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. The socioeconomic importance of this transportation corridor, along with the need to understand and manage the safety risk related to the landslides that threaten this route, make the Assiniboine River valley a research priority for Natural Resources Canada (NRCan), Geological Survey of Canada (GSC), and the Transport Canada Innovation Centre (TC-IC), as mandated by Inter-Departmental Letter of Agreement 5170 (IDLA-4755).

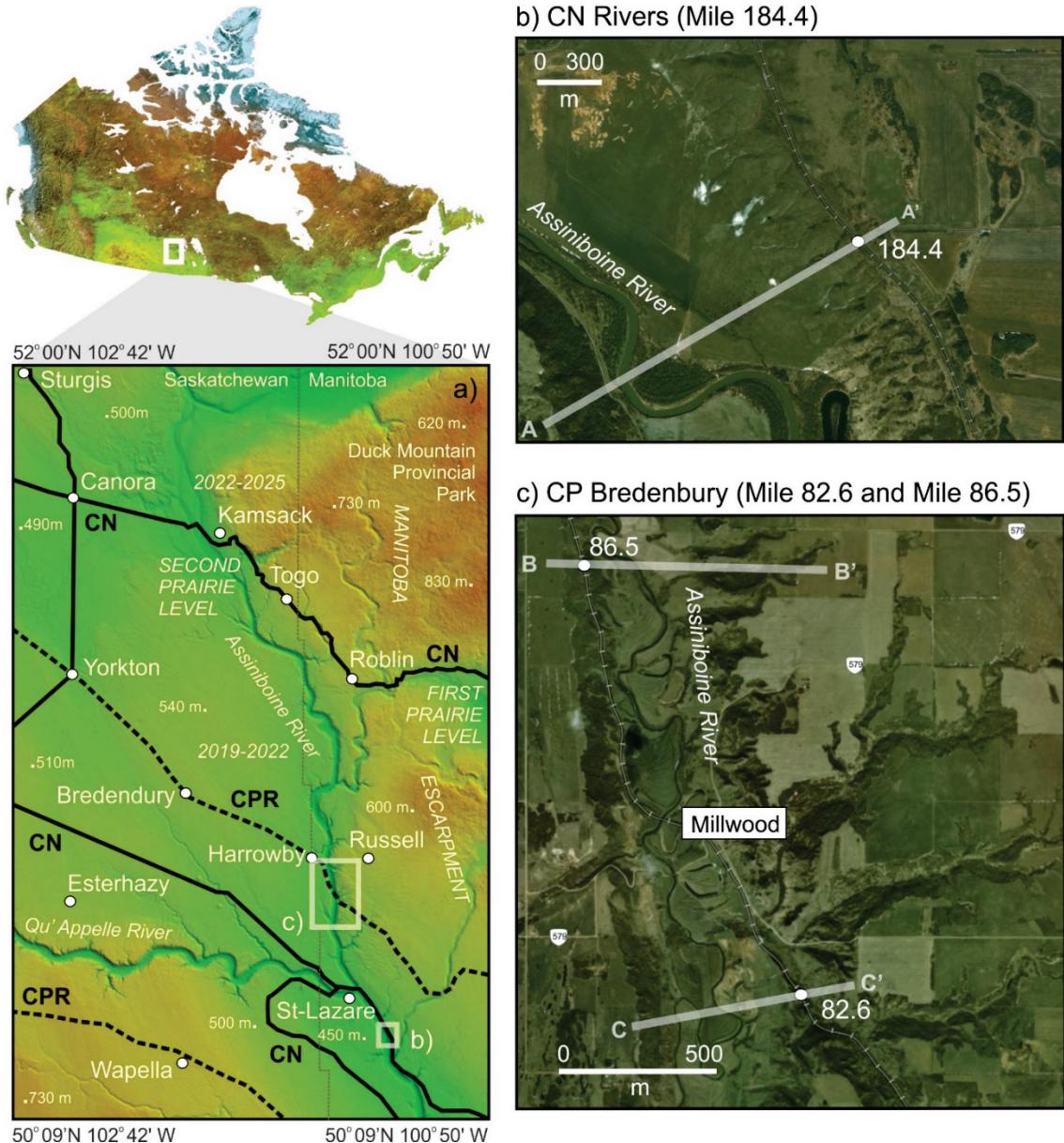


Figure 1-1 New study areas showing railway routes and major landforms and areas of interest to CN and CPR: a) major geomorphic elements (after Klassen 1972; Christiansen 1979) crossed by the CN and CPR tracks (source DEM: SRTM); b) Worldview image for CN area of interest (Rivers Subdivision, Mile 184.4) (base map source: [arcgis.com](#)); c) Worldview image for CPR area of interest (Bredenburg Subdivision, Miles 82.6 and 86.5) (base map source: [arcgis.com](#)); Digital elevation model derived from SRTM data and processed in Global Mapper™.

1.1 Research Objectives of IDLA

Since 2013, the Geological Survey of Canada (GSC), with international and national partners, has pioneered innovative research and monitoring of landslides in the Thompson River valley, British Columbia. This research and development (R&D) is funded by TC-IC, and activities contribute to the success of the

Railway Ground Hazard Research Program (RGHRP). This national 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 affected communities through outreach workshops (Figure 1-2).

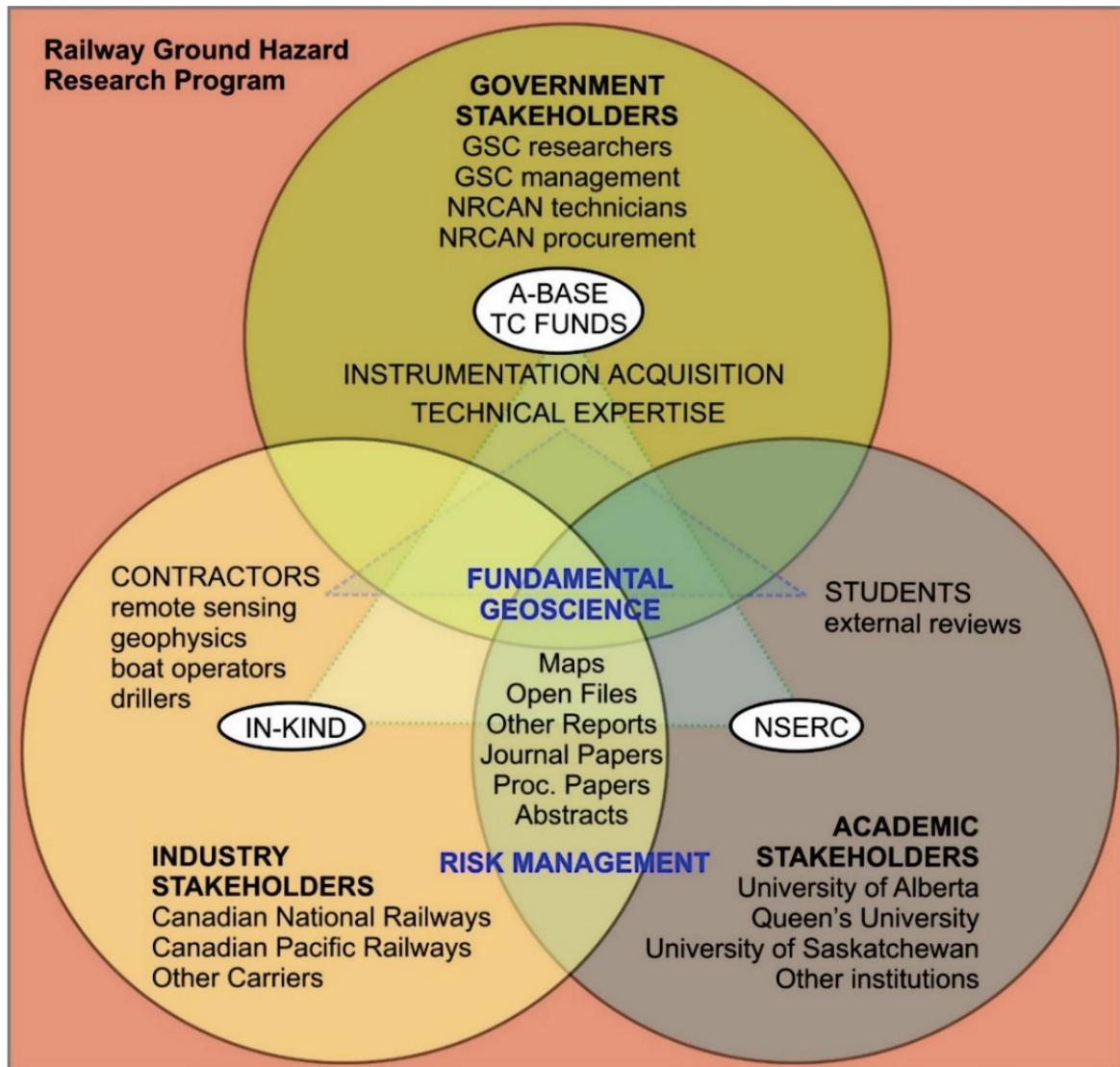


Figure 1-2 Modified Venn diagram representing the contributions and interactions of key stakeholders in the Railway Ground Hazard Research Program, with funding structure.

The main objective of IDLA-4755 is to gain a better understanding of landslides through multi-year monitoring in 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 critical transportation infrastructure along strategically important sections of the national railway network, while

also protecting the natural environment, community stakeholders and Canadian economy. The GSC will apply multi-scale methodologies to provide the fundamental geoscience required to evaluate fixed and automated monitoring technologies (conventional and emerging) along these strategically important sections of the national railway network. The compendium of monitoring technologies and best-practices applied to these contrasting study areas will enable key stakeholders (i.e., Canadian National Railways – CN, Canadian Pacific Railways - CPR, University of Alberta – UA, University of Saskatchewan – USASK, Manitoba Geological Survey - MGS) to develop robust solutions for the management, remediation, and mitigation of active landslides driven by seasonal extreme weather events and longer-term climate changes.

In the coming year(s), the various monitoring technologies operational from 2013-2020 will be further tested in British Columbia, and installed at new sites in the Assiniboine River valleys (**Figure 1-1**), and possibly elsewhere, in order to: 1) better understand controls on landslide movement and 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 harsh environmental conditions.

2. New Horizons: Understanding Prairie Landslides

RGHRP partners have had considerable success monitoring slope instability in the Thompson River valley, British Columbia, with conventional and emerging remote sensing, global positioning, and borehole technologies (e.g., Macciotta et al. 2014; Hendry et al., 2015; Schafer et al. 2015; Journault et al. 2017; Journault et al. 2018). These methods, combined with terrain mapping (Huntley and Bobrowsky 2014) and geophysical surveys (Holmes et al. 2018; Huntley et a. 2019a, b) have provided necessary sub-surface information to understand the spatial and temporal variations in landslide activity (Holmes et al. 2020, in press; Huntley et al. 2020a, in press). 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 1-1**). CN and CPR have main lines traversing valley slopes, side-wall terraces, and floodplains prone to slow-moving landslides and floods. Railway infrastructure, including tracks and bridges, rolling stock, and public safety are at risk in these areas.

2.1 Geological Setting of the Assiniboine River valley, Manitoba-Saskatchewan

The Manitoba Escarpment - reaching elevations >800 m in Duck Lake Provincial Park - and Assiniboine River valley separate the western limit of the First Prairie Level (<500 m elevation), and eastern limit of the Second Prairie Level (>500 m elevation) (**Figure 1-1**). The escarpment is composed of the Cretaceous Odanah Shale Member of the Pierre Formation (Young and Moore 1994). Hummocky and undulating terrain with kettle lakes indicate that stagnant debris-rich ice mantled glacially eroded shale in upland areas (Klassen 1979; **Figure 1-1**). This ice mass likely represents the southwestern limit of northern ice from the Hudson Dome of the Laurentide Ice Sheet (Dyke et al. 1982). Parkland and mixed-grass prairie vegetation with neutral to moderately alkaline black soils develop on loamy (i.e., silt, clay and sand) tills (Saskatchewan Soil Survey 1991).

Much of the area of interest, now converted to agricultural fields and pastures, is a glacial drift-mantled, low-relief plain underlain by older, weak clay-rich marine shales of the Cretaceous Pierre Formation. This drift cover can be up to 100 m thick, and is characterized by gentle to moderate slopes, streamlined and hummocky ridged terrain with kettle lakes (Klassen 1979; **Figure 2-1**). These landforms are consistent with southeast ice flow of an Assiniboine Lobe of the western Caribou Dome of the Laurentide Ice Sheet (cf. Dyke et al., 1982). Southward-draining spillways incised in till plains are indicators of outflows from recessional ice margins and proglacial lakes confined to reaches of the Assiniboine River valley and First Prairie Level below 460 m elevation during deglaciation (Klassen 1979; **Figure 2-1**). Late-glacial valley incision reached a maximum depth of 380 m elevation in response to changing regional base level driven by glacio-isostatic rebound (Klassen 1972; Christiansen 1979).

Postglacial alluvial fills in the Assiniboine and Qu'Appelle spillways are thought to be <50 m thick (Christiansen 1979), and indicate a marked decrease in deposition rates following glaciation. Modern Assiniboine and Qu'Appelle rivers are classic underfit meandering streams with broad floodplains, scroll bars, splays, oxbow lakes, and wetlands (**Figure 2-2**). Alluvial sediments transported down-valley are deposited overbank and in-channel. Thick accumulations of colluvium and alluvial fan deposits occur along the valley walls as a result of sheetwash and slumping (Klassen 1972).

2.2 Landslides and glacial tectonics in the Assiniboine River valley

Generally, till slopes are relatively stable up to 25° to 33° (Sauer 1978). For example, in the lower Qu'Appelle River valley, slope failures are only common where stream erosion reaches the drift-shale contact, or where springs form along buried geological contacts. In valley exposures, Late Wisconsinan till unconformably overlies deformed bedrock. Brecciated, sheared, folded and faulted siliceous shale beds of the Odanah Member are exposed along the Qu'Appelle River valley between 460 m and 490 m elevation. Below 460 m elevation, lies undeformed marine shales of the Pierre Formation. This stratigraphic relationship is interpreted as evidence of ice-thrusting and glacial rafting of a >10 km² “megablock” of bedrock (Sauer 1978; Christiansen 1979), possibly sourced from the nearby Manitoba Escarpment and transported by a pre-Late Wisconsinan lobe of the Laurentide Ice Sheet (**Figure 2-2 a-c**). Where exposed, glaciotectonized shale is brittle and breaks with conchoidal fractures. Joints and bedding planes are stained with iron and manganese weathering products indicating groundwater flow (Mugridge and Young 1983).

Glacial geology and penetrative bedrock structures are proposed as primary controls on the distribution of unstable slopes along major valleys and coulees. At least five large landslides in the Qu'Appelle valley cut through the megablock east of Esterhazy toward St-Lazare, with slow-moving failures confined to disturbed clay shale (Sauer 1978). For the Assiniboine River valley, the extent of glaciotectonized shale buried beneath unconsolidated glacial deposits is not defined, and argues for surficial mapping in combination with deep penetrating boreholes and geophysics where landslides are impacting infrastructure. Active, slow-moving landslides (rotational slumps) in the study area (**Figure 2-2 b, c and d**) are confined largely to the Assiniboine River spillway, although valley slopes of coulees are also prone to slumping, soil creep, and gully erosion. Shallow rotational slumps along the flanks of spillways and coulees are triggered by loss of soil suction and shear resistance in weathered till, alluvium and colluvium during and following precipitation events (Blatz et al. 2004). Closer scrutiny of existing borehole logs and outcrops along railway embankments are required to determine whether sub-till shale units are glaciotectonized.

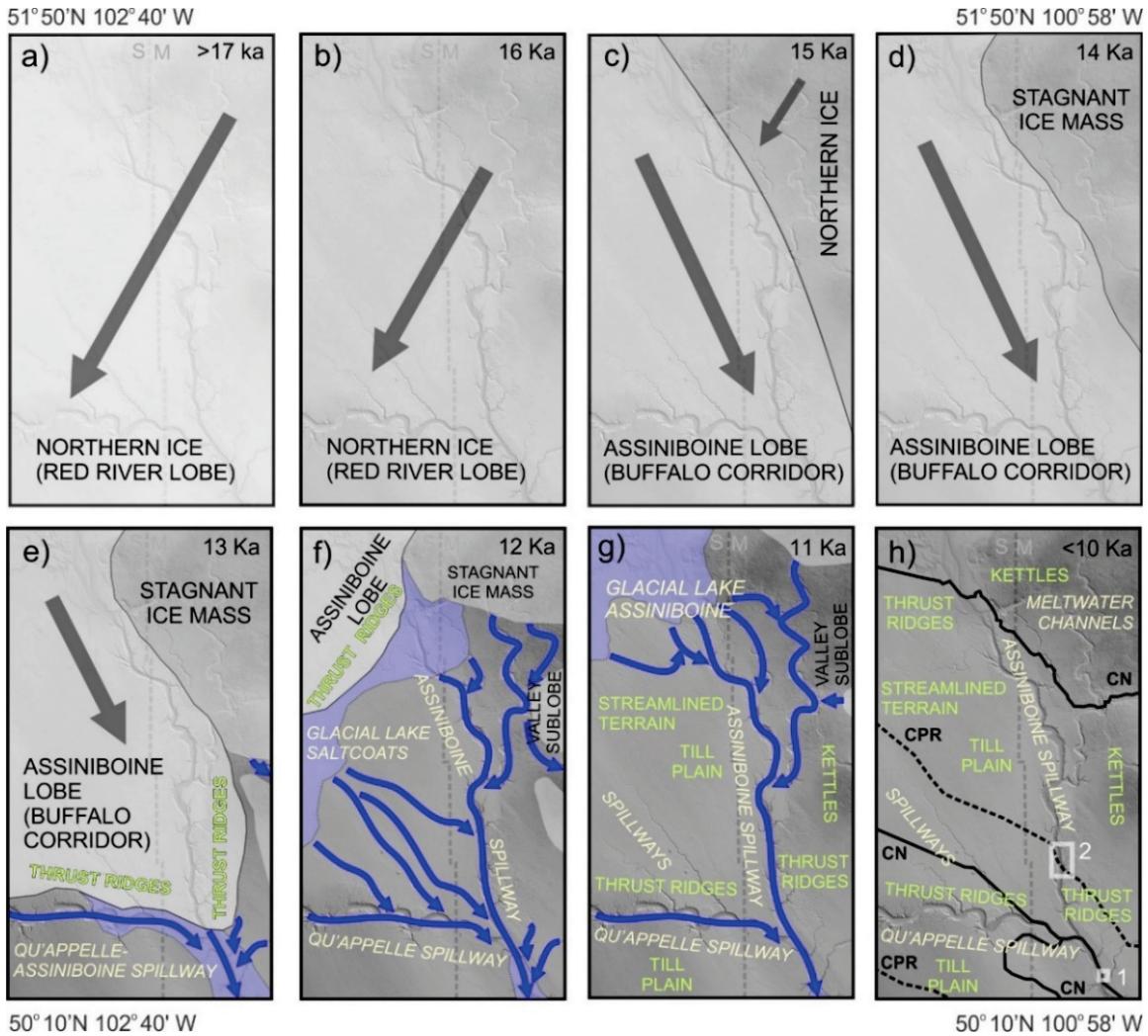


Figure 2-1 Postulated Late Wisconsinan glacial history of the study area: a, b) At the close of the last glacial maximum, from before 17 Ka (>21,000 calendar yBP) to 16 Ka (~19,000 calendar yBP), the Red River lobe of the western Caribou Dome of the Laurentide Ice Sheet flowed southwest over the region, eroding weakly consolidated Cenozoic and Mesozoic bedrock, and deranging pre-existing drainage networks; c) after 15 Ka (~18,000 calendar yBP), the northern ice mass stagnates while the Assiniboine Lobe becomes active, flowing to the southeast; d) deglaciation *ca.* 14 Ka (~16,000 calendar yBP) with the Assiniboine Lobe forming thrust moraines along the margins of ice-free terrain that is locally inundated by higher stages of glacial lake Agassiz and incised by ice-marginal spillways draining retreating ice; e) further retreat of the Assiniboine Lobe is accompanied with the formation of an ice-marginal proglacial lake system connected to glacial lake Agassiz by spillways dissecting deglaciated terrain, *ca.* 13 Ka (~14,000 calendar yBP); f) glacial lake Assiniboine forms with further retreat of the Assiniboine Lobe, *ca.* 12 Ka (13,000 calendar yBP) and is drained by overflow spillways feeding the Assiniboine and Qu'Appelle spillways; g) glacial lake Assiniboine drained by overflow spillways feeding the Assiniboine and Qu'Appelle spillways, *ca.* 11 Ka (12,000 calendar yBP); h) by 10 Ka (~11,000 calendar yBP), the study areas, indicated by the two white rectangles, are ice-free but glacial deposits and landforms are subject to periglacial modification until vegetation cover is established in post-glacial times, and later by anthropogenic activities.

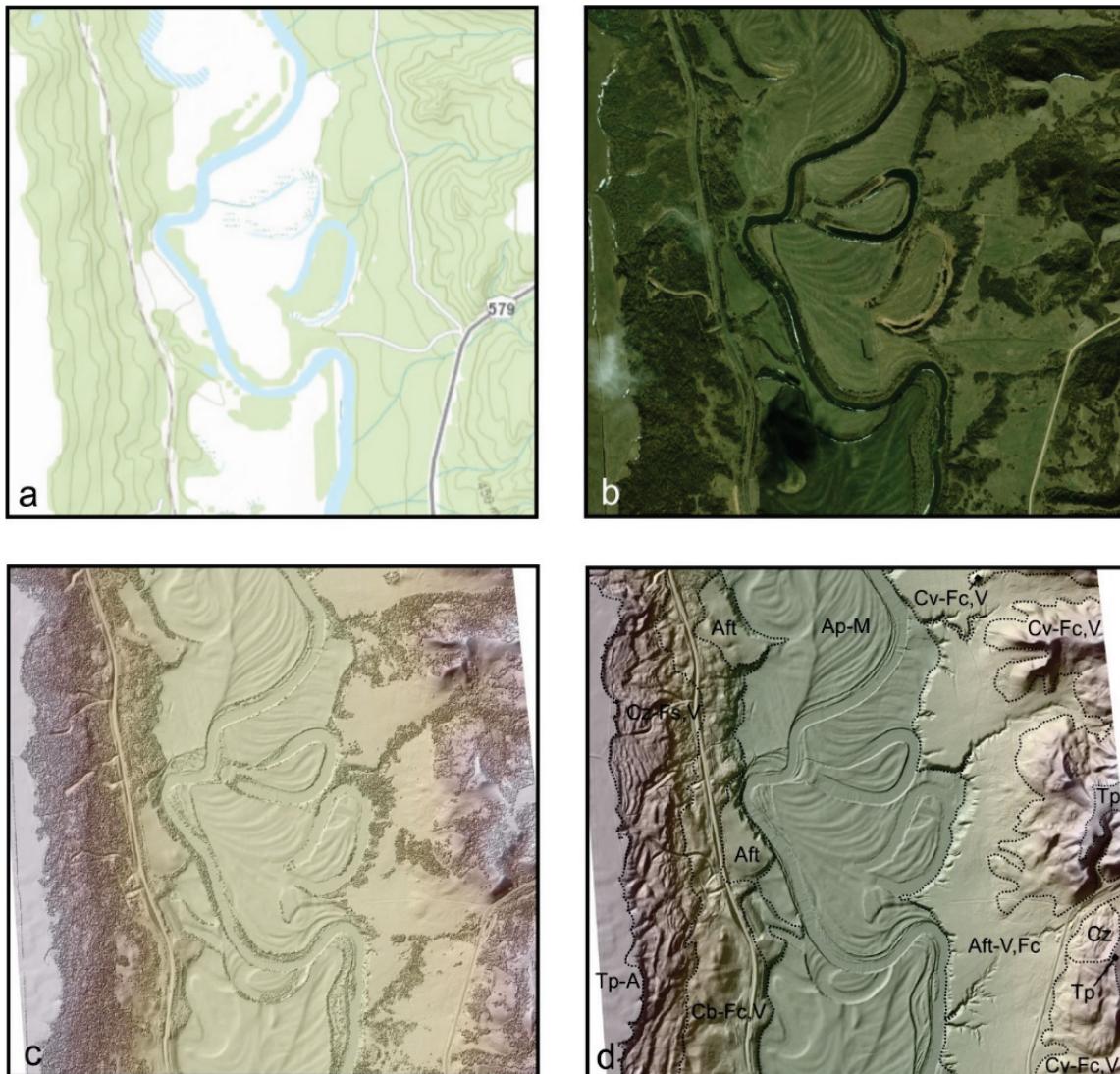


Figure 2-2 Contrasting views of the terrain in the vicinity of Millwood (Harrowby study area c) as depicted on: a) a topographic map (source, arcgis.com); b) Google Earth image; c) LiDAR imagery (1 m resolution) with vegetation and surface features; d) the LiDAR bare earth model with preliminary terrain classification (after Howes and Kenk 1998). Ap-M = alluvial flood plain, modified by meandering Assiniboine River. Aft-V, Fc = alluvial fan terraces, modified by gully erosion and hillslope creep. Cv-Fc,V = colluvial veneer (<2 m thick), modified by hillslope creep and gulley erosion. Cz-Fs,V = active landslide, modified by slow rotational slumping and gulley erosion. Tp-A = till plain, modified by anthropogenic activity (farming, road cuts, railway cuts and embankments). The linear feature on the left is the rail line (image processing by R. MacLeod).

The geological and geomorphological settings of the Assiniboine and Qu'Appelle River valleys are markedly different from those of the Thompson River valley. Whereas slope failures at the British Columbia test site occur within clay-rich glaciolacustrine deposits, landslides in the Saskatchewan-Manitoba border region occur in both weak (clay-rich) shale beds and glacial valley deposits. In the Thompson River valley, small ice-rafted blocks and glacially sheared sediments contribute to slope instability (Huntley and Bobrowsky 2014; Huntley et al. 2019a, b). For the Assiniboine and Qu'Appelle river valleys, ice-rafted megablocks of weak, glacially deformed shale are prone to failure, in addition to glacial valley fill (**Figure 2-3**).

The rôle played by glacially-rafterd terrain in controlling groundwater flow and regional landslide distribution and behaviour will be addressed in this study (**Figure 2-3**). Pre-sheared, brecciated, folded, faulted and jointed shale beds are expected to be more porous and permeable than undeformed (underlying) shale and (overlying) clay-rich morainal deposits. A new understanding of the regional stratigraphy can be provided through detailed terrain mapping (using UAV imagery with ground control), combined with geophysical surveys (e.g., ERT, borehole gamma, induced polarity and magnetic susceptibility), and laboratory investigation of geotechnical properties (e.g., hydraulic conductivities, shear strength) at the UA and USASK. In addition to field mapping (led by the GSC and MGS), monitoring groundwater and shear surfaces in well-logged boreholes with piezometers and slope inclinometers (led by UA and USASK partners) will be essential for characterizing hydrogeological units, and observing how river and weather conditions recharge aquifers and influence slope stability.

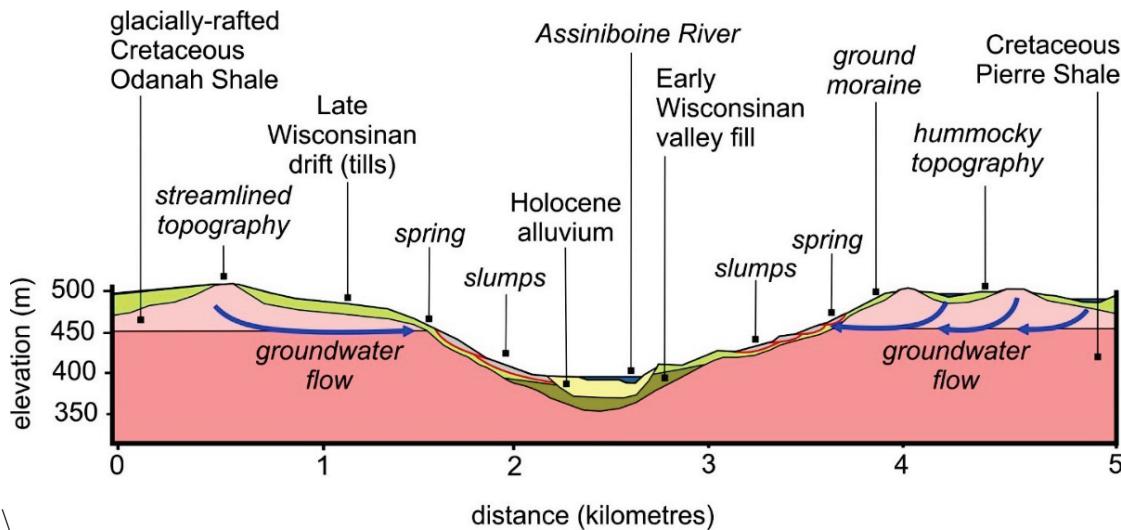


Figure 2-3 Simple stratigraphic model of the Assiniboine and Qu'Appelle river valleys showing hypothetical relationship of landslides to groundwater flow paths through earth materials in the study area (after Klassen 1972; Sauer 1978).

3. Research Action Plan: Methods, Results, and Discussion

(Collaborators: GSC, TC-IC, CN, CPR, MGS, UA, USASK)

The primary research objective for the 2019-2020 field season was to begin to understand how landslides impact Canada's railway network in the Assiniboine River valley, along the Saskatchewan-Manitoba border (**Figure 1-1**). Geohazard mapping and change detection studies, started in 2019, identify terrain units and geohazards susceptible to extreme weather events and changing climate (past, current and future). The rôle of the Late Quaternary history and dynamics of the southwestern sector of the Laurentide Ice Sheet in determining the distribution and activity of landslides will also be explored. Surficial geology mapping shall determine whether megablock ice-thrust terrain (cf. Sauer 1978; Christiansen 1979) is exposed along the Assiniboine River valley in the three areas of interest (**Figure 1-2**). Glacially deformed bedrock units (pre-sheared and over-pressured) lying beneath porous and impervious glacial deposits are posited as a pre-

condition for slope failure, and as a control on landslide activity. 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). Applied mapping will classify geohazard risks to potentially vulnerable railway resources and other transportation infrastructure (e.g., roads, and bridges). This fundamental geoscience information will help build more robust risk tolerance, adaptation, 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.

3.1 ACTIVITY 1: GNSS surveying and geohazard mapping

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 (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 (Hendry et al. 2015; Schafer et al 2015). Similarly, geological mapping (and compilation of extant data sources) will help to establish the physical setting of landslides, and inform other aspects of study in the Assiniboine River valley.

3.1.1 Site recognition

Reconnaissance fieldwork in the Assiniboine River valley was undertaken at the end of August (24-31), 2019 to identify target landslides for investigation, evaluate options for site access, and to establish logistic links. Three landslide test sites were selected (**Figure 1-1**, **Figure 3-1**): 1) a CN area of interest, **Rivers Subdivision, Mile 184.4**; 2) a CPR area of interest, **Bredenbury Subdivision, Miles 82.6 & 86.5**; and 3) a CN area of interest near **Kamsack (Togo Subdivision, Mile 73.1)**. Of the three areas visited, the CN River Subdivision site (Mile 184.4) has the most reliable access: a farm lane running parallel to the track which crosses unstable slopes (**Figure 3-1 a, b**). The CPR Bredenbury Subdivision sites (Miles 82.6 & 86.5), and Togo locations, are only accessible by hi-rail. For safety and logistical reasons, the ease of access at CN Mile 184.4 makes this the primary research landslide target for IDLA-4755 activities.

3.1.2 GNSS surveying

Fieldwork from October 6-12, 2019 focused on establishing a permanent global navigation satellite system (GNSS) benchmark, and permanent ground control points at CN Rivers Subdivision, Mile 184.4 for all future survey requirements (**Table 3-1**; **Figure 3-2**). The geospatial information collected is summarized in **Table 3-1**.

3.1.3 Terrain mapping and geohazard identification

Hydrogeological units were defined on the basis of lithofacies and landform associations, unit thicknesses, earth material textures, degree of sorting, weathered and non-weathered colours, sedimentary structures and penetrative planar structures, degrees of consolidation, stratigraphic contact relationships, estimated geological age, and other distinguishing characteristics (cf. Klassen 1979; Howes and Kenk 1987; Deblonde et al. 2018). Surficial maps and cross-sections depict the surface and vertical (stratigraphic) distribution of hydrogeological units, landforms and geohazards in the areas of investigation.



Figure 3-1 Reconnaissance views of study sites: a) CN Mile 184.4, Rivers Subdivision, view west (NRCan photo 2020-271); b) CN Mile 186.2, Rivers Subdivision, view south (NRCan photo 2020-272); c) CPR Mile 82.6, Harrowby Subdivision, view north (NRCan photo 2020-273); d) CPR Mile 86.5, Bredenbury (Harrowby) Subdivision, view north (NRCan photo 2020-274); e) CN tracks outside of Kamsack, Togo Subdivision, view east (NRCan photo 2020-275); f) Grain elevator at CN siding in Kamsack – a key role for both CN and CPR is the transportation of agricultural produce to global markets (NRCan photo 2020-276).

Table 3-1 Baseline survey: geographic location and elevation of ground control points (GCP) at CN Mile 186.2; using WGS1980 coordinate system, UTM zone 14; prime base station – “gopher1”.

GCP	Northing	Easting	Height (Ellipsoidal)
1a	5563981	351208.3	367.938
1b	5563952	351229.3	367.776
1c	5563935	351241.3	367.624
1d	5563899	351260.8	367.988
2a	5564052	351306.1	378.95
2b	5564014	351335	382.321
2c	5563997	351347.7	382.141
2d	5563964	351368.7	381.958
3a	5564097	351381.1	395.503
3b	5564076	351414.1	393.37
3c	5564061	351427.5	392.962
3d	5564029	351448.7	395.281
4a (base)	5564159	351429.9	407.269
4b	5564117	351463.6	406.979
4c	5564102	351476.8	404.421
4d	5564069	351501.3	401.827
5a	5564184	351474.7	413.214
5b	5564150	351501.7	412.123
5c	5564135	351516.1	412.663
5d	5564107	351543.9	414.257
6a	5564203	351521.4	422.651
6b	5564176	351536.3	423.19
6c	5564160	351548.1	424.549
6d	5564129	351572.7	424.459
gopher1	5564241	351533.1	435.547

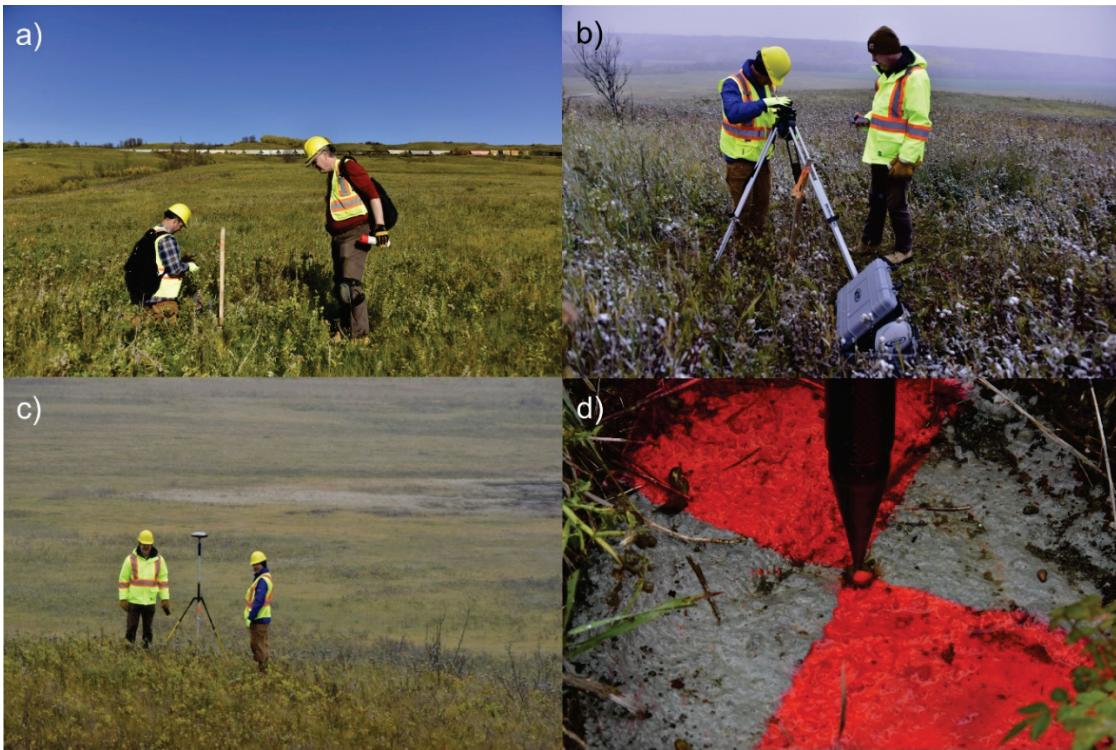


Figure 3-2 RTK-GNSS base survey at CN Mile 186.2: a) identification of GCPs (NRCan photo 2020-277); b) establishing base station (NRCan photo 2020-278); c) collection of location points for GCPs with RTK rover unit (NRCan photo 2020-279); d) detail of concrete GCP with fluorescent target marking (annual clearing of vegetation and soil will be required) (NRCan photo 2020-280).

3.1.3.1 CN Rivers Subdivision, Mile 184.4 (Figure 1-1 a, b)

East of Assiniboine River, a single CN track with sidings crosses a glaciofluvial spillway comprising an undulating bedrock plain (Ru-C) draped by gravel-rich glaciofluvial outwash (GFp-C). Both surficial units are extensively modified by meltwater erosion and ice-marginal depositional processes. At the Assiniboine River, the track turns north and descends the eastern valley side wall, crossing two coulees before encountering the floodplain. Valley sidewalls are draped in clay-rich till and colluvium (Tr.Cz-V, Fs, Fc) modified by gully erosion, slow-moving rotational slumps, and soil creep on moderate to steep slopes ($>18^\circ$). The CN track crosses the Assiniboine River at the confluence with Qu'Appelle River, encountering silty sand-rich alluvial floodplain and fan deposits, modified by meandering channels (Ap-M, Af). At St-Lazare, the track continues westward along the north side of the Qu'Appelle River valley (**Figure 3-3**).

At Mile 184.4, the CN track is cut into a moderate valley slope of $<18^\circ$ (**Figure 3-4 a, b, c**). Exposures of clay-rich mudstone and siltstone facies of the Cretaceous Odanah Shale (R) are confined to the 2-3 m-high railway cutbank upslope of the track. Although the contact with underlying Pierre Shale units is not exposed, saturated soils observed below the track may be an indication of groundwater seepage along the upper geological contact (cf. **Figure 2-3**). These weakly consolidated and poorly cemented bedrock formations were incised during the last glaciation to form a broad south-draining trough, then blanketed by subglacial and ablation tills composed of clay-rich diamicton containing Laurentide erratics (**Figure 3-4**).

d). Valley-side till deposits (**Figure 3-4 a, c, d**) are <20 m in thick, and have corrugated or lobate surface expressions reminiscent of recessional moraine ridges modified by solifluxion processes (Tr-V, Fs, Fc).

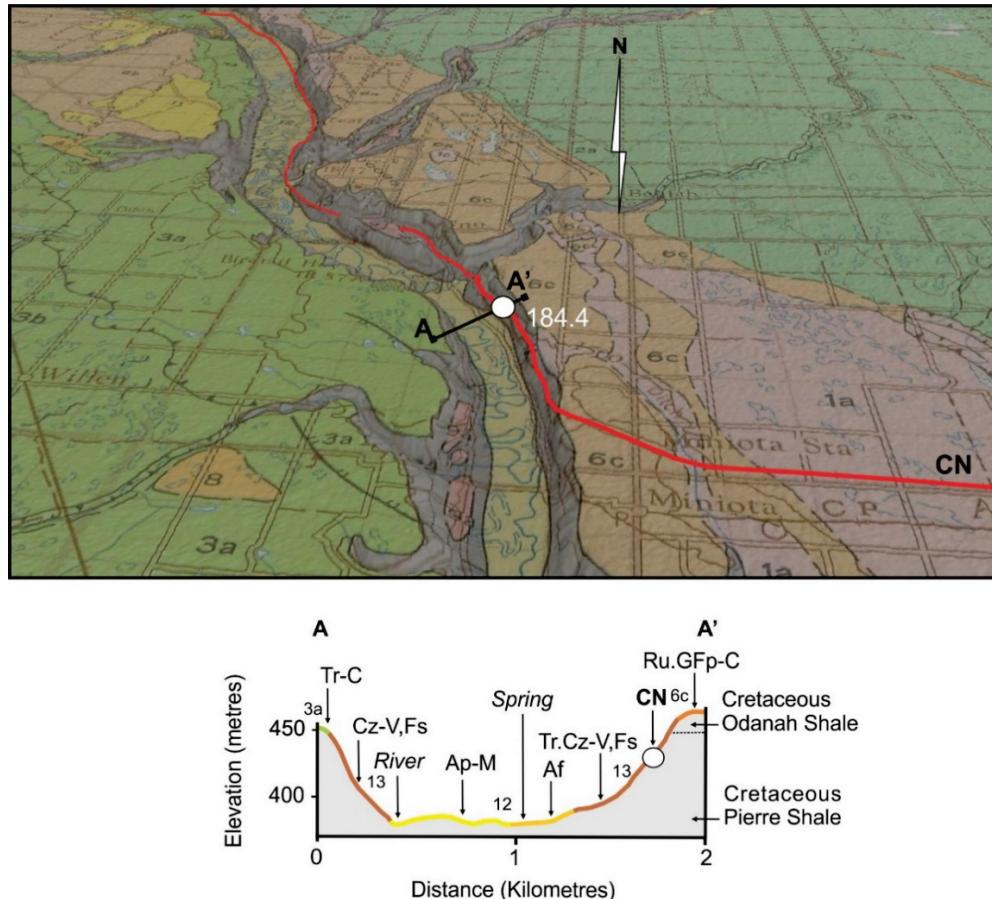


Figure 3-3 Cross-section across the Assiniboine River valley in the vicinity of the landslide site at CN Rivers Mile 184.4. Terrain units from Klassen (1979): 1a (Rp-C) – bedrock plain, modified by meltwater erosion; 3a (Tr-C) – corrugated till, modified by meltwater erosion; 6c, 8 (GFp-C) – glaciofluvial outwash, modified by meltwater erosion and deposition; 12 (Ap-M, Af) – alluvial floodplain and fan deposits, modified by meandering channels; 13 (Cz-V, Fs, Fc) – undifferentiated colluvium, modified by gulley erosion, slow-moving rotational slumps in drift and shale, and soil creep on moderate to steep slopes (>18°).

Till slopes are actively modified by gulley erosion, slow-moving rotational slumps in drift and shale, and soil creep (Cz-V, Fs, Fc). Unstable terrain is bounded by ephemeral gullies that incise the valley side and drain to alluvial fans (Af) that prograde over the floodplain (Ap-M). The numerous shallow rotational slumps remobilizing boulder clay-rich till and underlying clay-rich bedrock from above the track to the valley floor produces a hummocky or lobate surface expression where ground displacement is active (**Figure 3-4 a-e**). Characteristically, the head scarps of shallow slumps are arcuate in planform, listric in cross-section, and up to 3 m deep (e.g. **Figure 3-5 a**). Slump toes form lobes up to metre in height that are observed overriding grassy slopes, forest soils, and tree boles (**Figure 3-5 b**). A distinctive feature at Mile 184.4 is a linear scarp at the toe slope, ranging in height from 0.5 m at the north end to 1.5 m high in south, which runs the width of the slide zone (**Figure 3-4 c, e**). Riverwards, the toe slope is saturated from at least

late August to early October, and zones of seepage are observed along the upper margin of the active floodplain (**Figure 3-4 e**).

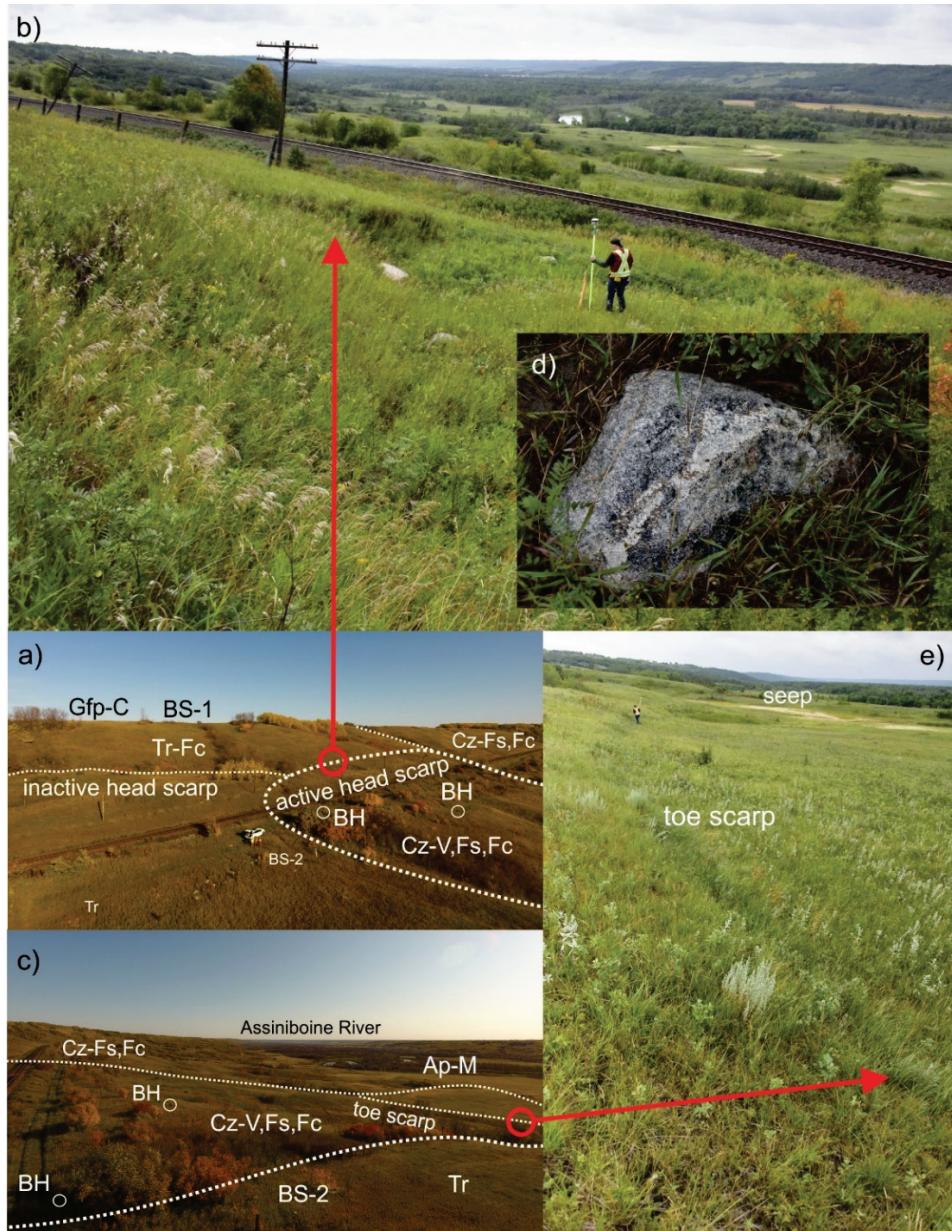


Figure 3-4 Oblique aerial and ground views of the slump-slide complex of Rivers Subdivision CN Mile 184.4: a, b) head scarp features and upper valley wall with CN track traversing the middle slope (bedrock exposed in railway cutbanks), view to southeast (b, NRCan photo 2020-281); c) middle and toe slope, view to south with Assiniboine River valley; d) granite-gneiss erratic boulder interpreted as a Laurentide erratic (NRCan photo 2020-282); e) toe scarp and shallow detachment above the modern flood plain, saturated ground conditions are observed here and perennial seeps are also observed at the break of slope (NRCan photo 2020-283).



Figure 3-5 Details of: a) a rotational head scarp (NRCan photo 2020-284); b) toe slope lobe at CN Mile 186.4 (NRCan photo 2020-285).

3.1.3.2 CPR Bredenbury Subdivision, Miles 82.6 & 86.5 (Figure 1-1a, c)

At Binscarth, a single CPR track with sidings runs northwest, descending a steep grade along a tributary coulee, into the Assiniboine River valley. At Millwood, the track crosses the actively meandering river, makes a northerly ascent up the west side of the valley, then turns west for Harrowby (**Figure 3-6**). East of Assiniboine River, the CPR track crosses glacially streamlined (drumlinized) bedrock plain (Rd). Descending a coulee with moderate to steep side slopes ($>18^\circ$), the track is incised into clay-rich till modified by gully erosion, slow-moving rotational slumps, and soil creep (Cz-V, Fs, Fc; **Figure 3-7 a**). Crossing at Millwood, the track encounters silty sand-rich alluvial fans, and terraced floodplain deposits modified by meandering channels (Af, Ap-M, **Figure 3-7 a, b**). On the west side of the valley the track is

again incised into clay-rich till modified by gully erosion, slow-moving rotational slumps, and soil creep (Cz-V, Fs, Fc; **Figure 3-7 c, d**).

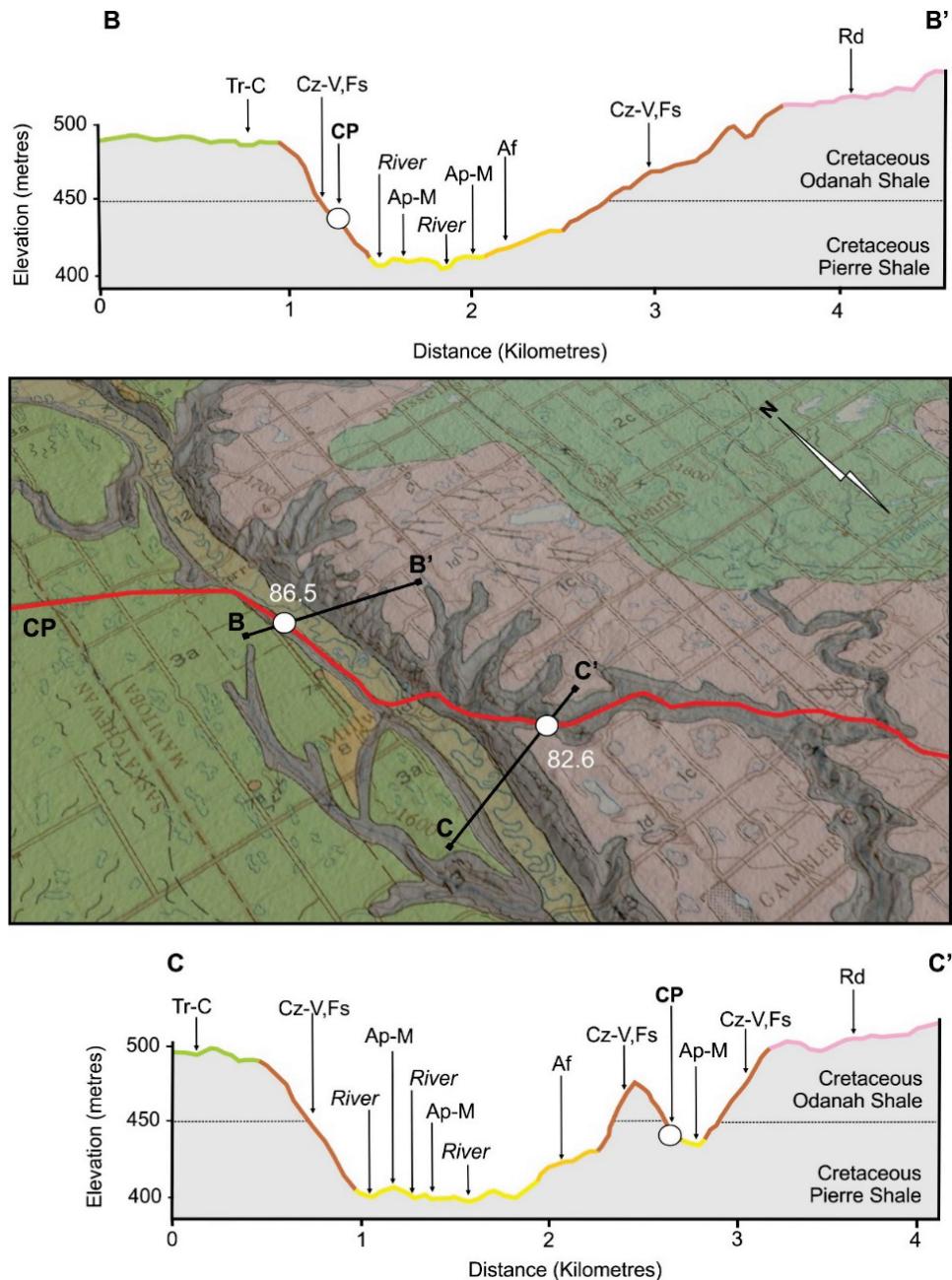


Figure 3-6 Cross-section across the Assiniboine River valley in the vicinity of the landslide sites at CP Bredenbury Miles 82.6 and 86.5. Terrain units from Klassen (1979): 1a, b (Rd) – bedrock plain, drumlinized; 3a (Tr-C) – corrugated till, modified by meltwater erosion; 12 (Ap-M, Af) – alluvial floodplain and fan deposits, modified by meandering channels; 13 (Cz-V, Fs, Fc) – undifferentiated colluvium, modified by gully erosion, slow-moving rotational slumps in drift and shale, and soil creep on moderate to steep slopes ($>18^\circ$).

Although Cretaceous Odanah and Pierre shales (R) are not well exposed on valley sidewalls, saturated soils above the track may be an indication of groundwater seepage along their contact (cf. **Figure 2-3**). The numerous shallow rotational slumps remobilizing till and underlying bedrock produces a hummocky or lobate surface expression where ground displacement is active from above the track to the valley floor (**Figure 3-7 a**). West of the Assiniboine River valley, an undulating till blanket with moraine ridges is modified by meltwater erosion (Tr-C; **Figure 3-7 c**). Logistical constraints and weather conditions precluded ground observations of the rotational slumps impacting the CPR track at Bredenbury Mile 82.6 & Mile 86.5 in 2019. During summer, heavily forested east-facing slopes obscure ground conditions and limited observations trackside, and from the CPR hi-rail (**Figure 3-7 a, b**). Ground conditions were still not possible to assess due to early snow cover during fall fieldwork (**Figure 3-7 c, d**).

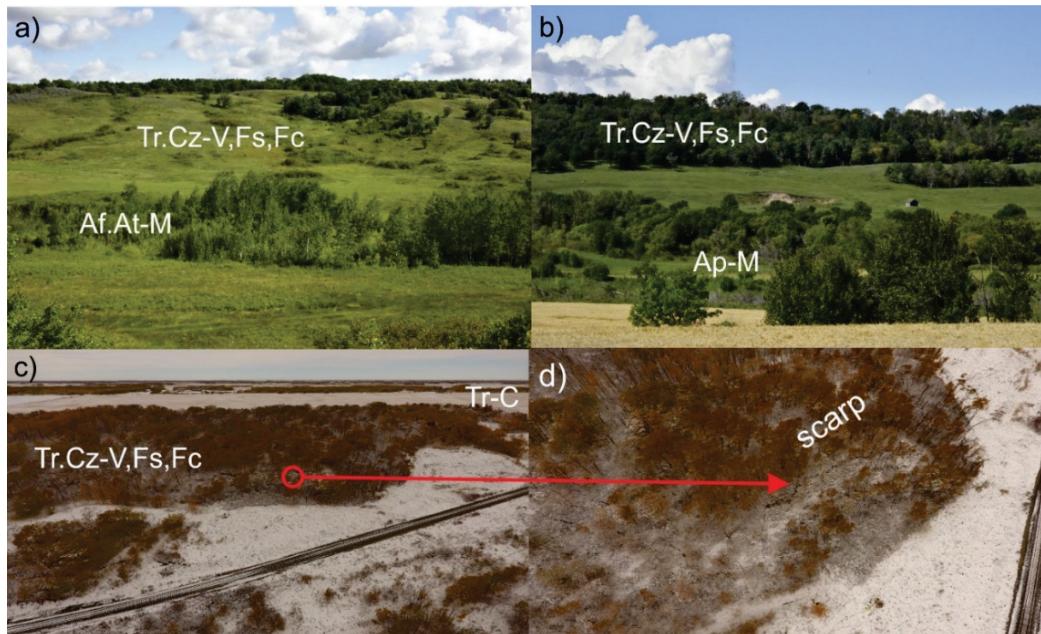


Figure 3-7 Oblique ground and aerial views of terrain in Bredenbury Subdivision: a) east side of coulee viewed from CPR Mile 82.6 (NRCan photo 2020-286); b) Assiniboine River valley at Millwood (NRCan photo 2020-287); c) oblique UAV aerial view of geoengineered slope and slump feature at CPR Mile 86.5; d) oblique UAV aerial view of back scarp of the CPR Mile 86.5 slump.

3.2 ACTIVITY 2: UAV photogrammetric change detection monitoring

The new study sites in the Assiniboine River valley are similar in areal extent to those in the Thompson River valley, BC. Consequently, UAV photogrammetric surveys offer an excellent opportunity to generate high-quality repeat Digital Surface Models (DSMs) that can be compared to characterize surface change of active landslides along the transportation corridor. Started in the fall of 2019, UAV surveys aim to capture changes in landslide morphology in the valley. Baseline survey flights were conducted from October 7-10, 2019 using the GSC's DJI Phantom 4 with a 12.4 MB RGB camera (**Figure 3-8 a**), with one operator and two observers (**Figure 3-8 b**).

3.2.1 CN Rivers Subdivision, Mile 184.4 (Figure 1-1 a)

The arrival of snow and sub-zero temperatures during October 2019 fieldwork curtailed detailed overflights of the CPR Bredenbury sites. UAV surveys focused on capturing the CN Mile 184.4 for Structure from Motion (SfM) modelling (Figure 3-9, Figure 3-10, and Figure 3-11).



Figure 3-8 UAV surveying in the Assiniboine River valley under varying weather conditions: a) CN Mile 186.2, Rivers Subdivision, October 9, 2020 (NRCan photo 2020-288); b) CPR Mile 86.5, Harrowby Subdivision, October 10, 2020 (NRCan photo 2020-289).

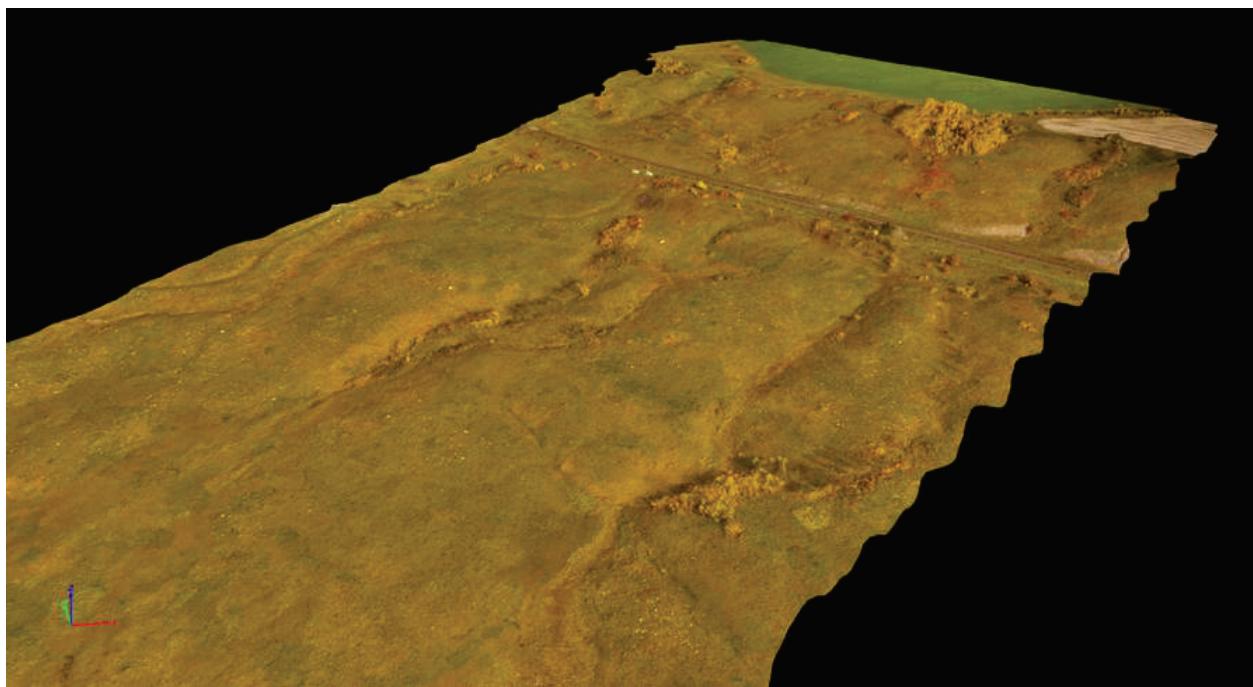


Figure 3-9 Overview SfM digital surface model (DSM) generated from October 2019 overflight of CN Mile 186.2, Rivers Subdivision (view NE).

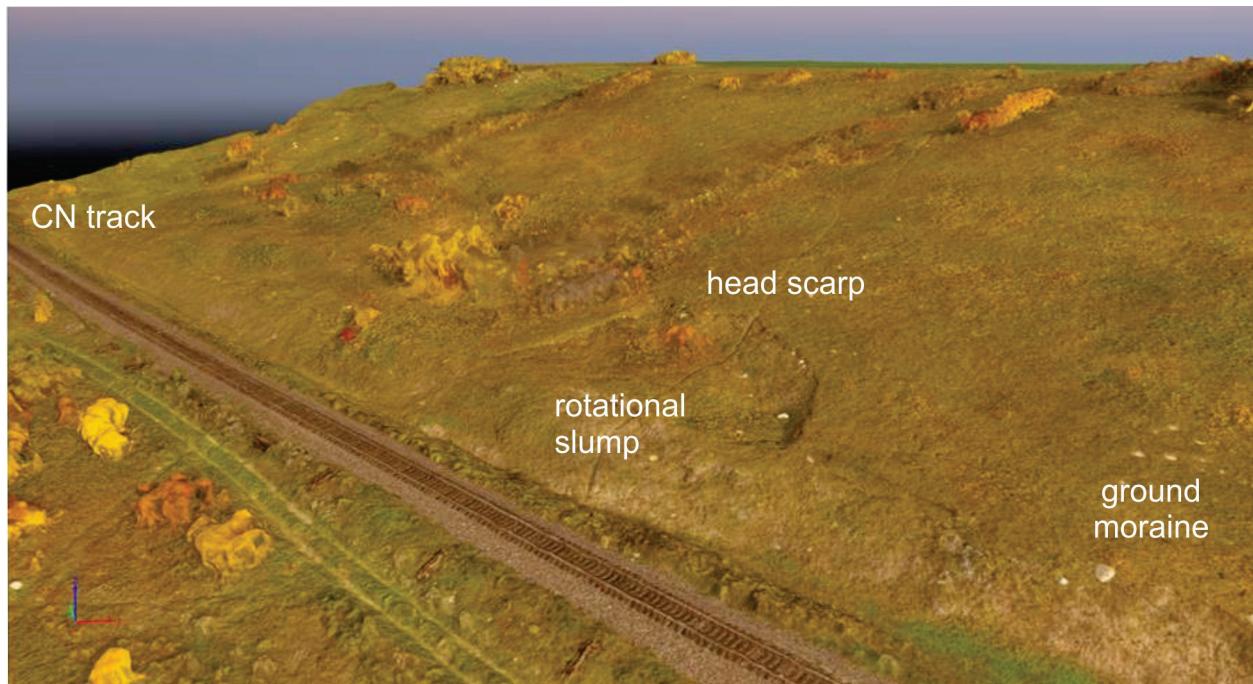


Figure 3-10 SfM digital surface model (DSM) of headscarp slump above CN track generated from October 2019 overflight of CN Mile 186.2, Rivers Subdivision (view NE).

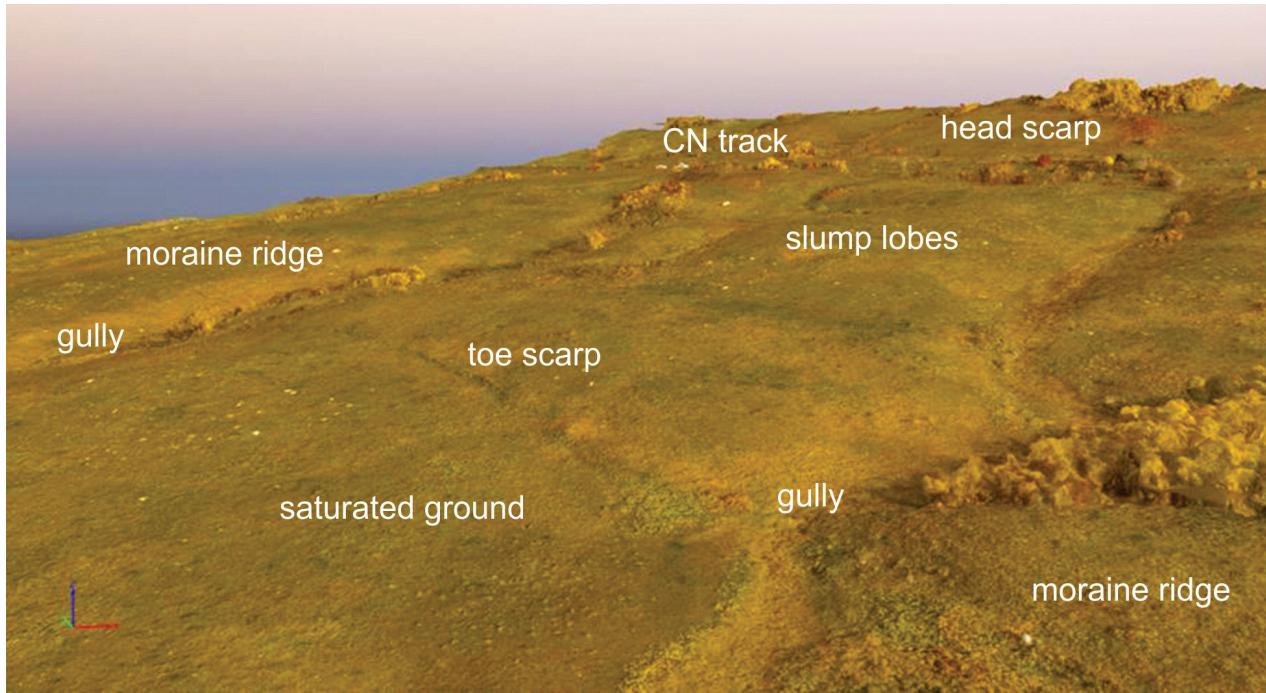


Figure 3-11 SfM DSM of slide toe and linear scarp feature, generated from the October 2019 overflight of CN Mile 186.2, Rivers Subdivision (view NE) downslope from **Figure 3-10**.

4. SUMMARY

The primary mandate of IDLA-4755 was to gain a better understanding of landslide hazards impacting Canada's railway network through: 1) *Terrain Mapping* described landslide form, adjacent stable slopes and water bodies using surficial geology mapping, bathymetric and geophysical surveys, and real-time monitoring of movement, groundwater, and geophysical properties in boreholes (**Figure 4-1, Table 4-1**). 2) *Change Detection Monitoring* described landslide function using emerging airborne and spaceborne platforms, ground-based GNSS systems, fibre optics and climate variables (**Figure 4-1, Table 4-1**).

Table 4-1 Research activity objectives achieved 2019-2020.

Work period	Location	Activity Theme	Activity Task and Outcome	Participants Collaborators
August 2019	Assiniboine River valley, MB	Site reconnaissance	<ul style="list-style-type: none"> Ground inspection at CN and CP landslides 	GSC, UA, USASK, CP, CN, TC 1 RES; 2 Ph.D.
September 2019	Phoenix, AZ	Geoscience Outreach	<ul style="list-style-type: none"> Presentation of results at GSA 	GSC, TC 2 RES; 3 PC
October 2019	Assiniboine River valley, MB	GNSS Technologies Climate variables UAV Change Detection	<ul style="list-style-type: none"> RTK survey of GCPs Photogrammetric survey of Assiniboine River valley slides 	GSC, MGS, CP, CN, TC 3 RES; 2 PC
December 2019	Carleton University Ottawa, ON	Geoscience Outreach	<ul style="list-style-type: none"> Presentation of results from installations and surveys at RGHRP Annual Workshop 	GSC, TC 2 RES

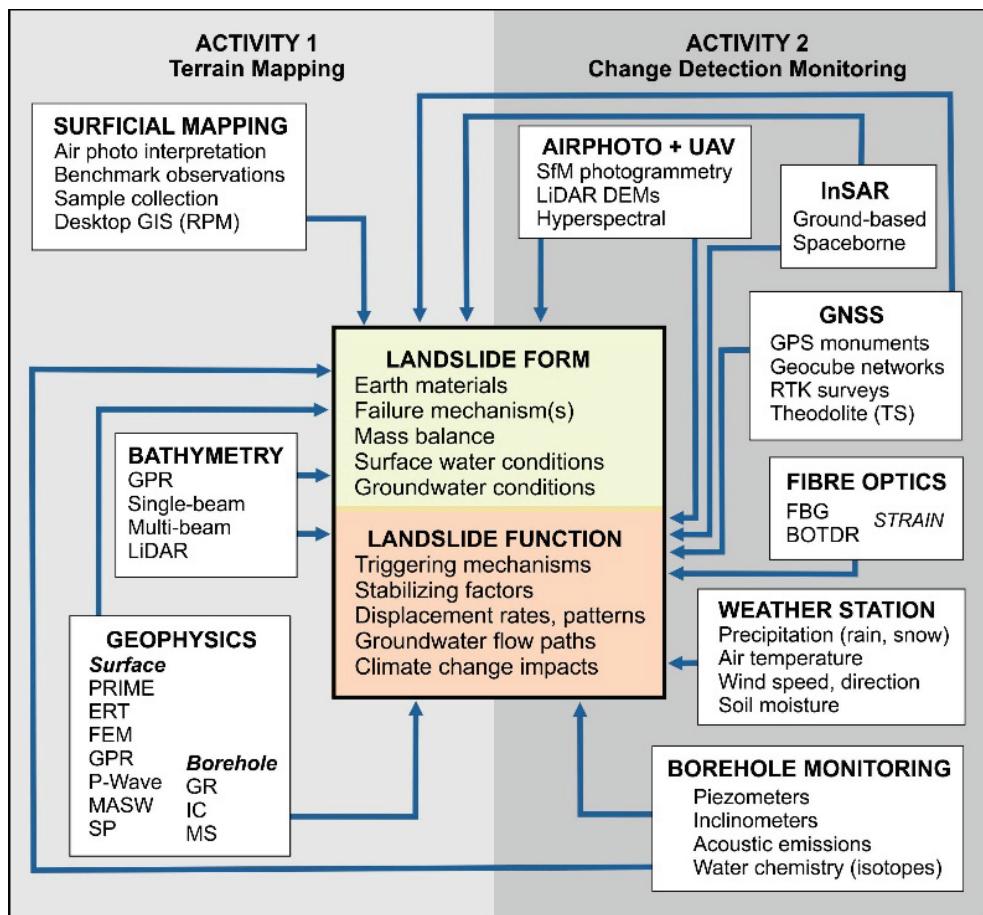


Figure 4-1 Best practices for terrain mapping and change detection monitoring of landslide systems, based on experience in the Thompson River valley, British Columbia (2013-2020), and to be applied to the Assiniboine-Qu’Appelle river valleys, Manitoba-Saskatchewan (2020-2025).

4.1 Going forward

IDLA-4755 focused on geohazard mapping and change detection monitoring in the Thompson River valley BC, successfully identifying 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). A new Interdepartmental Memorandum of Understanding (IMOU-5170) expands the scope of landslide studies to include the Thompson River valley (e.g., Huntley and Bobrowsky 2014; Huntley et al. 2020a-c, in press), and the Assiniboine River valley along the border of southern Manitoba and Saskatchewan. DSMs generated from UAV surveys as part of IDLA-4755 will be used in combination with other data sources (e.g., GNSS surveys, geophysics, borehole monitoring) for future terrain mapping campaigns and landslide change detection monitoring in the Thompson and Assiniboine railway transportation corridors (Huntley et al. 2020d, in press). Fundamental knowledge about landslide form and function generated by IDLA-4755 and IMOU-5170 is required to build robust risk tolerance, remediation, and mitigation strategies that maintain the resilience and accessibility of vulnerable transportation infrastructure along these strategically important sections of the national railway network; while also protecting public safety, the natural environment, community stakeholders, and Canadian economy.

5. Acknowledgement

This Open File was critically reviewed by Roger MacLeod and Adrienne Jones (GSC Pacific).

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