

# Additional Tools for the Study of Variable Water Content Effects on a Slow-Moving Landslide



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## ABSTRACT

Monitoring of water content has continued across the head scarp of the slow-moving Ripley Slide, located approximately 8 kilometers south of Ashcroft in the province of British Columbia. In-place electrical resistivity tomography (ERT) data visually indicates the infiltration of water into tension cracks. The ERT data is verified by matric suction measurements at various locations along the head scarp. Water isotopes from core samples collected during a shallow drilling program were used to estimate rate of recharge, source water, and evapotranspiration effects. Small scale hydraulic conductivity within the vadose zone via Guelph permeameter tests supported recharge rates estimated from water isotope testing. Variable water content in the head scarp region is shown to influence strength parameters seasonally and should be considered for stability analysis in arid to semi-arid regions.

## RÉSUMÉ

La surveillance de la teneur en eau s'est poursuivie sur la tête de la rampe Ripley Slide, située à environ 8 kilomètres au sud d'Ashcroft, dans la province de la Colombie-Britannique. Les données de tomographie de résistivité électrique (TRE) sur place indiquent visuellement l'infiltration d'eau dans les fissures sous tension. Les données TRE sont vérifiées par des mesures d'aspiration matricielles à divers endroits le long du couvre-chef. Les isotopes d'eau des carottes prélevées au cours d'un programme de forage à faible profondeur ont été utilisés pour estimer le taux de réalimentation, les effets d'alimentation en eau et l'évapotranspiration. La conductivité hydraulique à petite échelle dans la zone vadose via les tests au perméamètre de Guelph a corroboré les taux de recharge estimés à partir des tests d'isotopes d'eau. Il a été démontré que la teneur en eau variable dans la région du couvre-chef influait de façon saisonnière sur les paramètres de résistance et devrait être prise en compte pour l'analyse de la stabilité dans les régions arides à semi-arides.

## 1 INTRODUCTION

The Ripley Slide is one of several metastable, translational, and retrogressive landslides in the Thompson River Valley south of Ashcroft, British Columbia, Canada. The slide affects three mainline tracks owned and operated by Canada's major railway companies, Canadian National and Canadian Pacific (Eshraghian et al., 2007; Hendry et al., 2015). Landslides of this type are an ongoing problem throughout the corridor and have presented a major challenge to the railways since their introduction to western Canada in the late 1800s (Stanton, 1898; Bishop, 2008). The corridor is the main route for rail traffic between the western sea ports and the rest of Canada, providing a vital service link for the Canadian economy.

Previous research has focused on understanding and analyzing slope movements based on a variety of factors. Studies have attempted to determine the impact of historical and ongoing irrigation on the upper terraces (Stanton, 1898) and regional groundwater flow effects (Hodge and Freeze, 1977; Bishop, 2008). The Ripley Slide has a complex glacial geology that controls the landslide geometry. Initial landslide movement in the region is thought to have been triggered by the Thompson River's deep incision into the Pleistocene fill during the early Holocene epoch (Huntley and Bobrowsky, 2014). The

rapidly downcutting Thompson River developed steep valley walls and appears to have exposed weaker layers that act as geologic controls for landslide movement (Clague and Evans, 2003; Eshraghian et al., 2007). Groundwater movement, focused in unconformities between glacial sequences, increases during late fall and through the winter which results in elevated pore pressures along the failure surface (Porter et al., 2002). During the winter months, the river elevation drops to its yearly minimum which can impact the rate of slope movement (Eshraghian et al., 2008; Hendry et al., 2015).

The current study has focused on monitoring seasonal changes in water content within the near surface unsaturated zone. Direct measurements of matric suction are collected and compared to indirect measurements from an in-place ERT system. The current paper demonstrates the application of some additional techniques to determine groundwater source, infiltration rate, and movement patterns.

## 2 BACKGROUND

As with many of the landslides in the region, the Ripley Slide sat dormant with minimal movement for many years. However, a track siding and retaining wall were

constructed in 2005 that caused reactivation of the slide mass. Track settlement resulted in additional ballast placement during the fall of 2006 and spring of 2007 (Bobrowsky et al., 2014). Bunce and Chadwick (2012) reported cumulative horizontal movement between 2.55 and 54.75 mm/year across the visible slide extents. The highest movement rates were documented in the vicinity of the retaining wall structure. Subsequent rates of movement have exceeded 100 mm/year at certain times of the year (Hendry et al., 2015).

Earlier studies have been conducted using borehole programs and instrumentation monitoring that have been centred near the base or middle of the slide mass. Site accessibility and steep terrain are the primary motivation for the location of previous monitoring points. However, the depth of the tension cracks in the upper reaches of the landslide appear to be shallow and the slip surface may mirror the steep topography of the valley walls (Schafer, 2016). As a result, shallow borehole investigations in the head scarp region may prove useful at the Ripley Slide to study the impact of temporally changing water content.

Periodic changes in movement rate at the Ripley Slide appear to be seasonally motivated. While seasonal changes in Thompson River stage are significant, on the order of 8 m (Hendry et al. 2015), other factors could have an important role in triggering a change in the movement rate. For example, during a precipitation event, river elevation will tend to rise quickly. An increase in river elevation will improve landslide stability. However, infiltration of precipitation runoff will cause a loss of matric suction in the tension cracks that reduces landslide stability. Therefore, it is important to consider both factors, especially when the river elevation is near its minimum prior to a precipitation event.

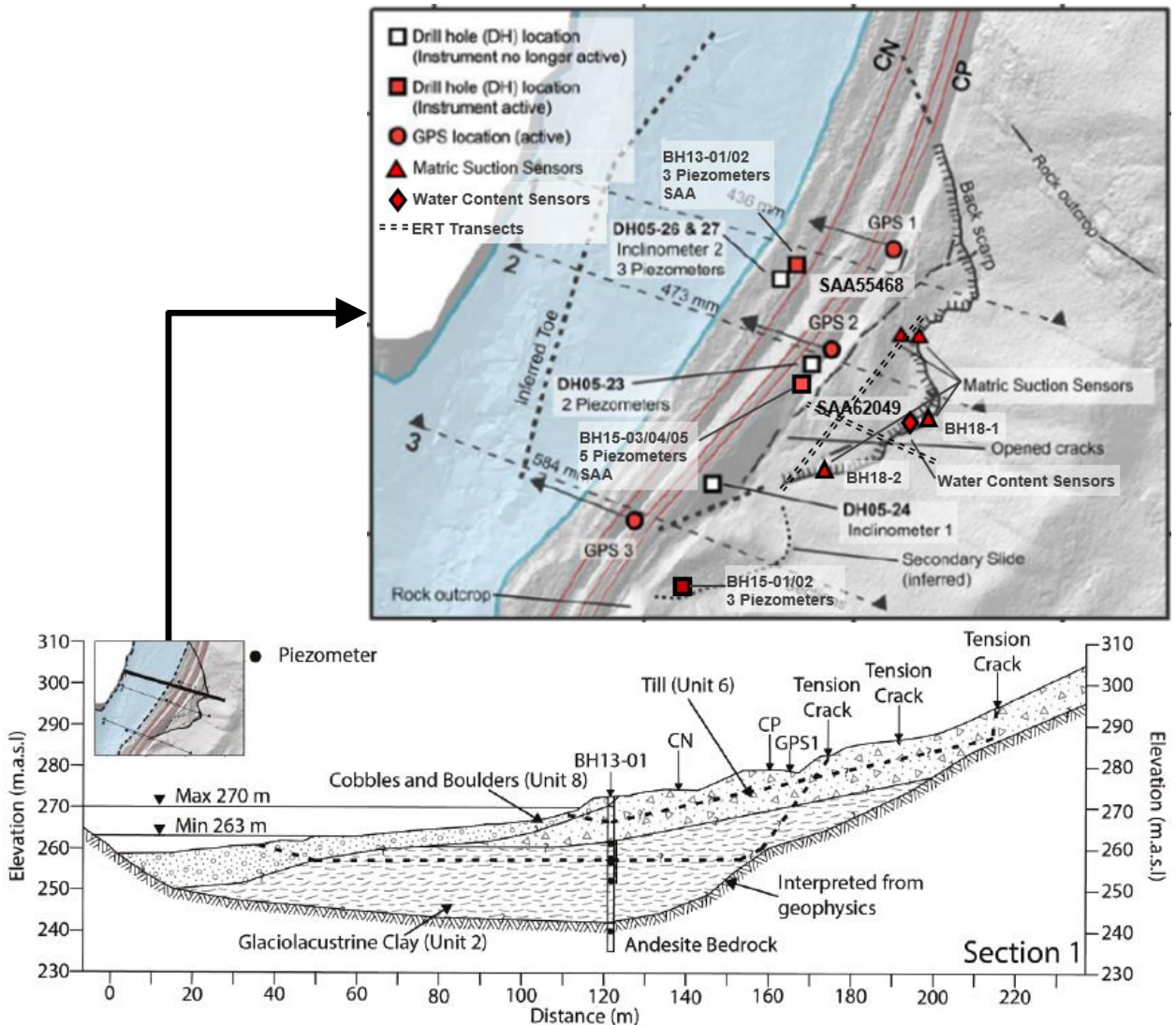


Figure 1. Ripley Slide showing landslide extent (after Schafer, 2016)

### 3 INVESTIGATION AND DISCUSSION

Site access is a major hindrance to any investigation focused in the head scarp reaches of the landslides occurring in the Thompson River Valley. The present research program focuses on the impacts of unsaturated soil mechanics and its influence on slope stability in arid regions. As such, testing methods must be applicable in the presence of negative pore pressures where water content is minimal.

From a meteorological perspective, the Ripley Slide is in a semi-arid region with extreme summer temperatures and heavy evapotranspiration. The climate suggests that meteorological events could have a significant influence on landslide movement for several regional landslides.

#### 3.1 Visual Study

In addition to a dry climate, the tension cracks along the head scarp form a series of progressive slip surfaces gradually appearing further up the steep valley walls (Figure 2). The progressive expansion of the failure mass along a shallow slip surface would indicate that a large part of the driving mass is under the influence of unsaturated soil mechanics.

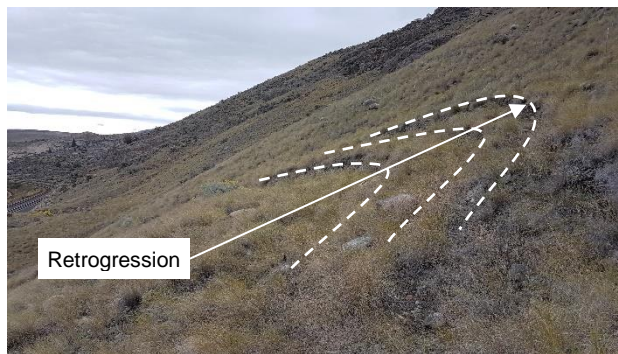


Figure 2. Series of retrogressive tension cracks

The movement of successive arc-shaped slices along the steep valley wall is an unsaturated soil mechanics problem influenced by the matric suction developed in the near-surface soil. Matric suction, or negative pore pressure, is directly related to the soil's water content by the soil water characteristic curve (SWCC) relationship (Fredlund and Rahardjo, 1993). Low water content induces high matric suction which stabilizes the soil overlying bedrock on steep valley walls. As the water content changes, the matric suction changes. A SWCC was developed for this site and is presented in a previous paper by the authors (Sattler et al., 2018). Infiltration of water due to precipitation, snowmelt, or runoff can increase the water content and lower the matric suction generated in the soil.

The Thompson River has steep, sloping valley walls with erosional cuts directing flow from upper terraces to the river at the base of the valley. During rainstorm events or snowpack melting, runoff is channeled through these erosional features which have been carved out over the last few thousand years. Most of the slopes are barren and

blanketed by short native grasses. However, within the erosion gullies taller vegetation tends to appear more frequently (Figure 3).

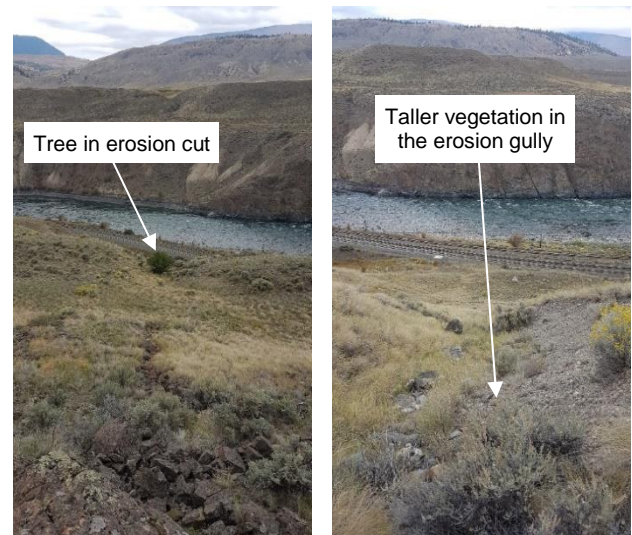


Figure 3. Upper terrace with erosion cut marked by vegetation (left) and view down the gully (right)

After one such rainstorm event, the site was traversed on foot to document erosion and potential flow paths. The upper terraces have numerous rock outcrops which show a consistent presence of moss and lichen that attach themselves to exposed bedrock. The occurrence of flowing water is apparent in some locations due to the raveling of fine material leaving behind coarse-grained material. In many flow paths, lichen has been removed from these exposed bedrock surfaces suggesting the movement of water (Figure 4). These erosion channels intersect the Ripley landslide further down the slope and funnel water directly into the head scarp tension cracks (Figure 5).



Figure 4. Raveling of fine material and removal of lichen



Figure 5. Flow path directed into landslide head scarp

### 3.2 Stable Isotope Determination

In October 2018, two additional boreholes were drilled and instrumented to monitor matric suction at locations further south along the Ripley Slide head scarp (Figure 6). These boreholes will be used to supplement the existing monitoring network and investigate the potential for varying soil suction across the head scarp due to different infiltration paths and topographic changes. When the additional boreholes were drilled, soil samples were collected at equal intervals and sealed for transport to the University of Saskatchewan. The soil samples were subjected to stable water isotope testing to determine infiltration source and degree of evaporation (fractionation).



Figure 6. Two additional boreholes for matric suction monitoring. BH 18-1 (top) and BH 18-2 (bottom)

The measurement of stable isotopes has gained momentum in recent years and provides valuable information about water held in the pore spaces of geotechnical samples. The sealed bag samples were inflated with dry air and left for three days to equilibrate. After equilibration, they were analyzed with a Picarro L1102-I cavity ring-down spectrometer (CRDS) (Figure 7). The method, known as direct vapour equilibration and laser spectrometry (DVE-LS), was developed in 2008 and has been shown to accurately determine deuterium ( $^2\text{H}$ ) and oxygen-18 ( $^{18}\text{O}$ ) isotope concentrations using core samples with volumetric water contents down to 5% (Wassenaar et al., 2008).

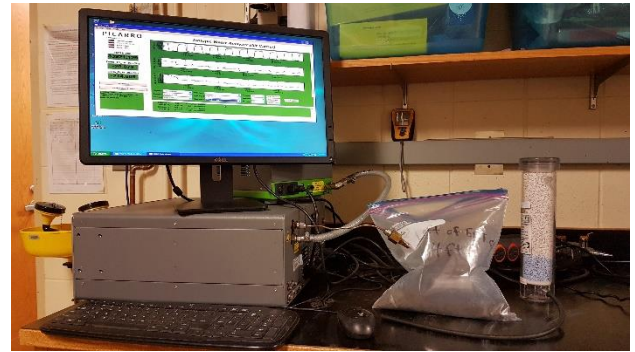


Figure 7. Water isotope analysis with Picarro cavity ring-down spectrometer

This method proved to be suitable for testing of unsaturated samples collected from the Ripley Slide. The same testing methods were conducted by Schafer (2016) near the toe of the Ripley Slide to delineate water isotope profiles at depths greater than 6 m. During Schafer's investigation, a water sample was collected from the Thompson River for comparison. In the present study, samples were collected from a nearby creek, the river, and precipitation that occurred during the 2018 site investigation. The isotope signature for the stable isotope analysis shown in Figure 8 shows some degree of fractionation due to evaporation for BH 18-1 when compared to the Western Interior meteoric water line determined by Clark and Fritz (1997).

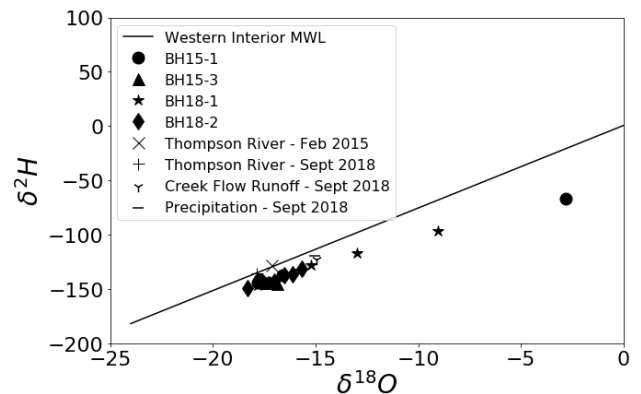


Figure 8. Water isotope signature observed from core samples collected at the Ripley Slide

The water isotope concentrations from both site investigations are plotted with depth to show additional details about the subsurface groundwater movement (Figure 9). It should be noted that the shallow samples (0-2.5 m) were collected from further up the slope compared to the deep samples (6 – 18 m). While the two sample sets appear to match reasonably well, there could be some discrepancy between 2.5 – 6 m where the datasets intersect. This could be based on the water table depth and the associated capillary fringe at each of these locations.

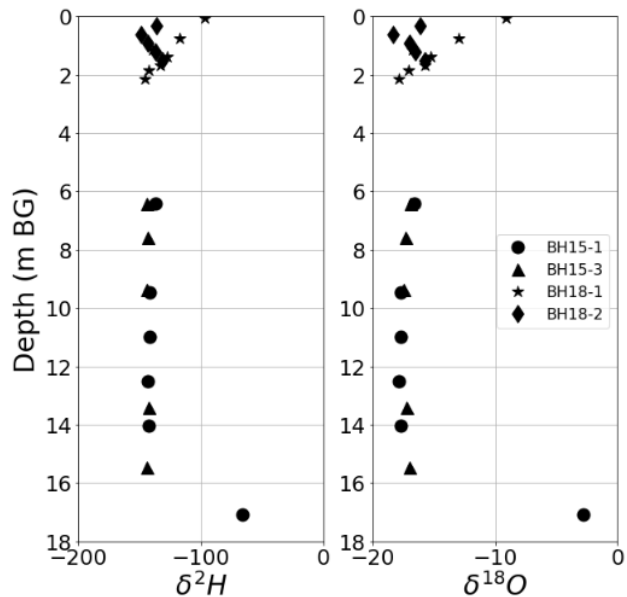


Figure 9. Deuterium and oxygen-18 isotope profiles with depth

The 2015 site investigation shows that the deuterium and oxygen-18 isotope concentrations are nearly constant with depth which indicates the presence of advection dominated flow below 6 m. The 2015 data matches the isotope signature shown by the Thompson River water samples taken from 2015 and 2018. Samples plotting further down the meteoric water line indicate isotopic depletion

However, the 2018 site investigation focused on the upper 2.5 m of the unsaturated zone and found variable concentrations for the stable isotopes. The tapering concentration in BH 18-1 indicates an active zone through which water content changes seasonally. The variable concentration can be attributed to temperature variation throughout the year. Cooler temperatures in the winter result in isotopically depleted precipitation whereas warmer temperatures cause isotopic enrichment (Stumpp et al., 2018). These cyclic variations can be traced with depth in the soil profile. Cook et al. (1992) demonstrated a method to determine diffusive infiltration rates based on the distance between concentration peaks and volumetric water content of the soil:

$$R = z \theta_D$$

[1]

where R is the recharge rate in m/year, z is the distance between peak concentrations of deuterium or oxygen-18 in m, and  $\theta_D$  is the volumetric water content (assumed to be constant).

A quick estimate for the recharge rate at the Ripley Slide from the stable isotope concentration profile with depth reveals a rate of approximately 350 mm/year. Due to hand auger refusal on cobbles, a deeper profile could not be generated.

The cyclic variations in BH 18-2 should taper off to a static concentration at greater depths due to the gradual transfer from diffusive vertical infiltration to non-vertical advective subsurface flow. BH 18-1 does not appear to have the same cyclic variation in stable isotope concentration. The profile seems to be dependent on the borehole location and topography. For example, BH 18-1 experiences more evaporation due to direct sunlight exposure and limited vegetation at the surface. On the other hand, BH 18-2 is tucked into the slope and often shadowed by the crest of the slope. This can effectively protect the location from higher rates of evapotranspiration. Furthermore, the incident angle of the sun changes throughout the year which can cause non-uniform patterns in the stable isotope concentration near the surface.

### 3.3 Guelph Permeameter

A total of six Guelph permeameter tests were conducted at several locations along the head scarp. These tests are highly scale dependent and are impacted by three-dimensional flow effects. However, they simulate a falling head test in the field and give the user a general idea of the rate at which water can infiltrate into the soil based on in-situ conditions (Figure 10). The test data indicated saturated hydraulic conductivity in the order of  $1e-7$  m/s.

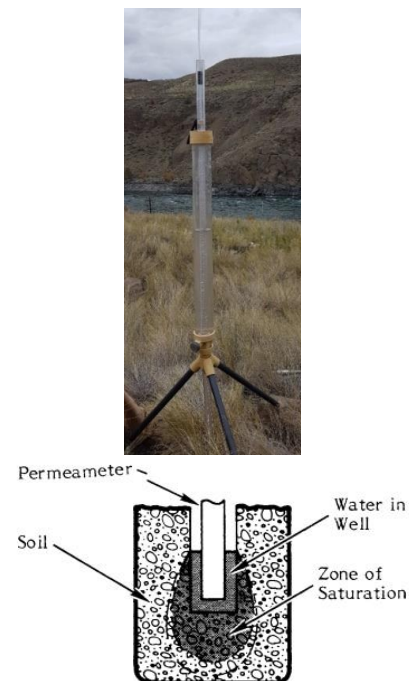


Figure 10. Guelph permeameter testing (diagram from Soilmoisture, 2008)

### 3.4 Comparison to ERT Results

Construction and initialization of the Proactive Infrastructure and Evaluation (PRIME) system was carried out between September and November 2017. The system employs in-place electrical resistivity tomography (ERT) developed by the British Geological Survey (BGS). The system monitors fluctuations in the electrical resistivity of shallow soils, which is directly related to the soil's in-situ water content. Changes in resistivity are determined by comparing ongoing data collection results to an initial background survey.

The ERT system has demonstrated the ability to visualize changes in resistivity (and the related changes in water content) with satisfying detail. Surveys have been conducted at one-week intervals beginning in December 2017. The data shows a thin zone of low resistance (high water content as indicated by cooler colours) near the surface between December 2017 and mid-February 2018 with isolated high resistance (low water content as indicated by warmer colours) pockets. Noticeable changes in resistivity began around mid-February continuing into March 2018. During this period, the upper tension crack became highly visible in the tomograph as infiltration from snowmelt increased the water content. Trail camera images collected over the same time period verify these observations (Figure 11).

### 3.5 The Big Picture

Climatic conditions have been shown to influence slope stability, not only in the saturated zone by varying pore pressures, but also in the unsaturated zone by changing matric suction (Leroueil, 2001). While well drained slopes may be more readily affected by low intensity rainfall events, poorly drained slopes can be significantly impacted by low intensity rainfall events (Rahimi et al., 2010). The Ripley Slide experiences reasonably low recharge rates as shown by stable water isotope data and verified by isolated in-situ Guelph permeameter tests. Furthermore, the climate is semi-arid causing the unsaturated zone to remain relatively dry, generating high levels of matric suction. Infiltration of precipitation or snowmelt can be expected to rapidly lower the matric suction generated in the near surface soils.

Rainfall, runoff, and evapotranspiration have been shown to influence the occurrence of landslides by previous authors in the literature (Blight, 1997; Wilson, 1999). Infiltration through unsaturated soils causing loss of suction is highly complex but has been shown to impact stability in several case studies (Leroueil, 2001). While a significant portion of the water balance may be composed of evaporation at the Ripley Slide, the steep valley walls may be expected to funnel runoff quickly through drainage channels during periods of low evapotranspiration (due to overcast skies during rainfall events). Monitoring changing water content must be conducted real-time and compared to meteorological data to determine the associated rate of impact.

The combination of several forms of instrumentation and exploratory techniques provides comprehensive observations of matric suction or water content and

develops a better understanding of groundwater movement patterns. Repetitive monitoring obtains a detailed temporal data record. A combination of water content or matric suction monitoring, meteorological data collection, and displacement monitoring has the potential to reveal how individual factors impact the overall stability of the Ripley Slide. The results taken from this investigation may be applied to slow-moving landslides with an extensive network of retrogressive tension cracks.

## 4 CONCLUSION

The present study focuses on methods of investigation used in other case studies that can help to identify the source of groundwater and movement patterns in the vadose zone. Cooperation between the U of S, U of A, GSC, and the BGS continues with the goal of increasing our understanding of mechanisms leading to reactivation or changing movement rates observed at several landslides within the Thompson River Valley. These landslides impact the transportation of goods for CP and CN as they intersect a major railway corridor.

The presence of tension cracks and erosion channels act to guide water into particularly stability-sensitive parts of the landslide as shown by stable water isotope sampling and ERT surveys. The Ripley Slide is highly susceptible to changes in water content because the area has a high soil moisture deficit instigated by an arid climate. The vadose zone remains dry with higher levels of matric suction for a large part of the year. However, loss of matric suction occurs readily with minimal changes in water content. These rapid changes are based on the shape of the soil water characteristic curve when the natural water content is near residual.

Ongoing research involving the application of novel instrumentation and exploratory techniques have shown the ability to recognize patterns of groundwater movement that have not been previously observed at the Ripley Slide. Seasonal changes in landslide movement rates and movement specific to meteorological events have been compared to water content and meteorological data to demonstrate the importance of vadose zone water content as an additional factor contributing to landslide stability in arid climates. Accounting for climatic controls can facilitate a more comprehensive understanding of these retrogressive slow-moving landslides.

## 5 ACKNOWLEDGEMENT

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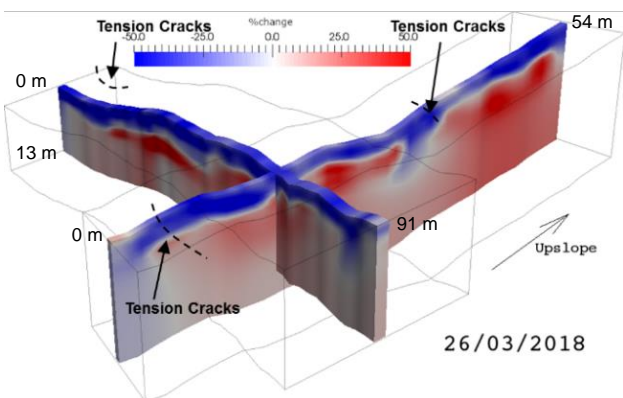
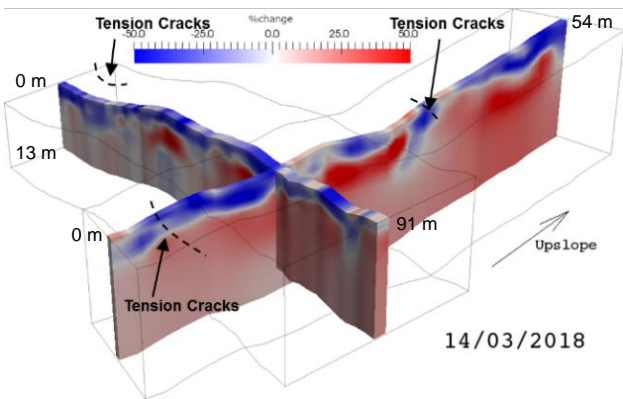
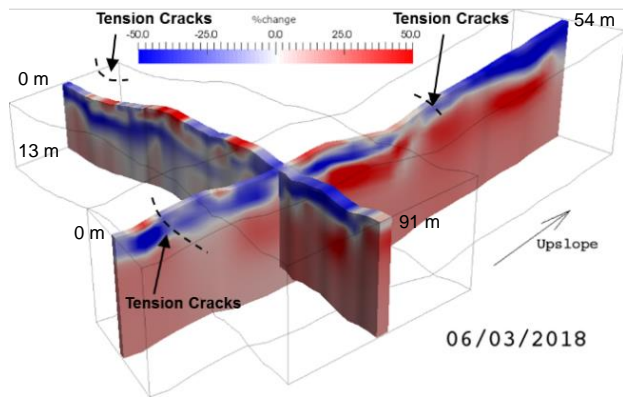
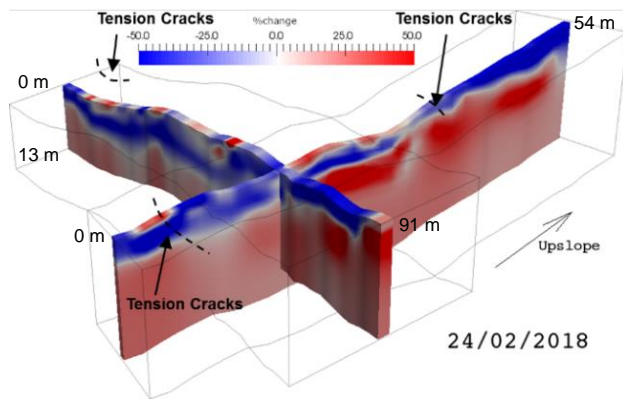


Figure 11. Spring 2018 ERT resistivity survey tomography and associated wildlife camera image

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