Engineering geology, electrical resistivity tomography and displacement monitoring of the Dawson City landslide,Yukon.

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ABSTRACT
The Dawson City landslide is a pre-historic slope failure located at the northern city limit of Dawson City, Yukon. The landslide occurred at the faulted contact between an older ultramafic rock unit that is thrust on top of a younger metasedimentary rock unit. The fault damage zone results in the very blocky nature (five main discontinuity sets) of the failed rock mass and led to an initial pseudo-circular slope failure mechanism. The landslide deposit is composed dominantly of ultramafic rocks. A series of split trees, disturbed soil exposing stretched roots, and trenches, all indicate movement in both the headscarp and deposit. Monitoring since 2006 confirms annual surface displacement rates in these areas in the cm to decimetre range. A 200 m long electrical resistivity tomography profile conducted in the lower part of the deposit is interpreted as a thick active layer over permafrost, suggesting that ongoing deformation is due to the creep of permafrost containing ground ice. As such, the lower part of the landslide can be regarded as a rock glacier.

RÉSUMÉ
Le glissement de Dawson City est un glissement de terrain préhistorique situé à la limite nord du village de Dawson City au Yukon. Le glissement s'est produit au contact de faille entre une unité de roche ultramafique plus âgé qui chevauche une unité de roche métasédimentaire plus jeune. La zone de dommages de failles se traduit par la nature très fracturée (cinq familles de discontinuités principales) de la masse rocheuse et qui mena à un mécanisme initial de rupture de pente pseudo-circulaire. Le dépôt de glissement de terrain est composé principalement de roches ultramafiques. Une série de tronc d'arbres déchirés, sol perturbés exposant des racines étirées et de tranchées suggèrent tous qu'il y a présentement des mouvements dans l'escarpement et le dépôt. La surveillance des déplacements depuis 2006 confirme des taux de l'ordre de centimètres à décimètres par année. Les résultats d'un profil long de 200 m utilisant la tomographie de résistivité électrique dans la partie inférieure du dépôt de glissement furent interprétés comme représentant la présence d'une couche active profonde au-dessus du pergélisol, ce qui suggère que les déformations dans cette section sont dues à la reptation du pergélisol qui contient de la glace de sol. Par conséquent, la partie inférieure du glissement peut être considérée comme un glacier rocheux.

1 INTRODUCTION

The Dawson City landslide (also known as the Moosehide slide) is a pre-historic mass-movement located just north of the town limit (Fig. 1). An unpublished radiocarbon date from the Geological Survey of Canada suggests that the main initial slope failure occurred before 1740 B.P. (GSC-2781; Hughes, 1979). This date was obtained from a wood sample recovered in a temporary borrow pit in the lower part of the landslide deposit (Fig. 2).

The Dawson City landslide was first described by Tyrell (1910) who suggested that the landform is not necessarily the result of a single large rapid slope failure but could be the result of continuous small rock falls due to frost shattering. The colluvial deposit would have acquired its elongated form due to rock glacier deformation and/or a seasonal-ice creep derived from springs in the headscarp and in the debris (a process he termed chrystocrene). While acknowledging that the landform resembles a rock glacier, Hughes (1979) noted that other rock glaciers in the map-area occur at elevations of > 1,500 metres above sea level (a.s.l.) (Vernon and Hughes, 1966). The Dawson City landslide is currently interpreted as a landslide on the latest surficial geology map by McKenna and Lipovsky (2014).

This paper summarizes previous work by Brideau et al. (2007a and b) on the characterization of the engineering geology and geomorphology of the Dawson City landslide and updates the displacement monitoring results for an unstable section of the headscarp and movement in the debris (Brideau et al., 2012). In addition, a new geophysical investigation in the landslide debris suggests the possibility of permafrost containing ground ice.

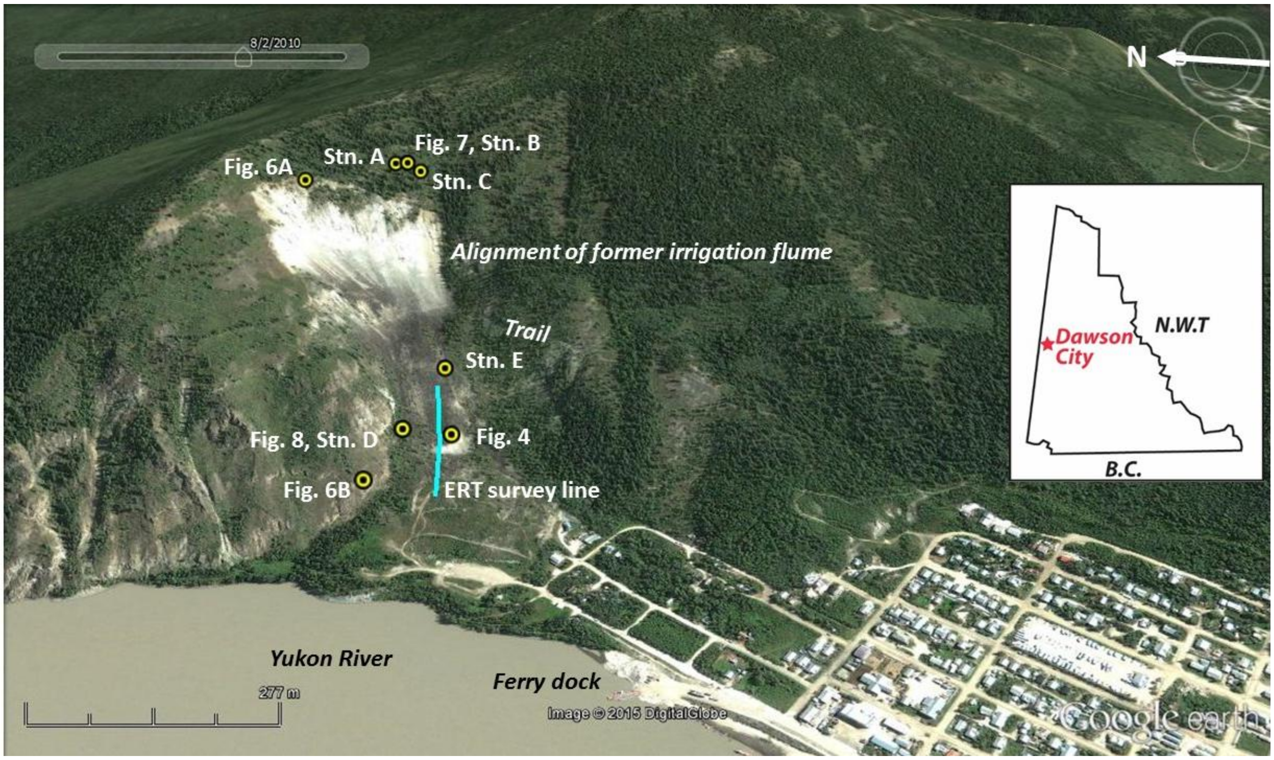

Figure 1: Overview of the Dawson City landslide (Google Earth imagery from 2010).

2 REGIONAL SETTINGS

The townsite of Dawson City is located on a fluvial terrace on the east bank of the Yukon River (elevation 320 m a.s.l.). To the east of the townsite, the slope steepens and rises to a rounded summit known as Midnight Dome (elevation 850 m a.s.l.). The study area is part of the Klondike Plateau physiographic region (Yukon Ecoregions Working Group, 2004). The region is also part of eastern Beringia (Froese et al., 2009) and has not been glaciated for the last 3.2 Ma (Duk-Rodkin, 1999).

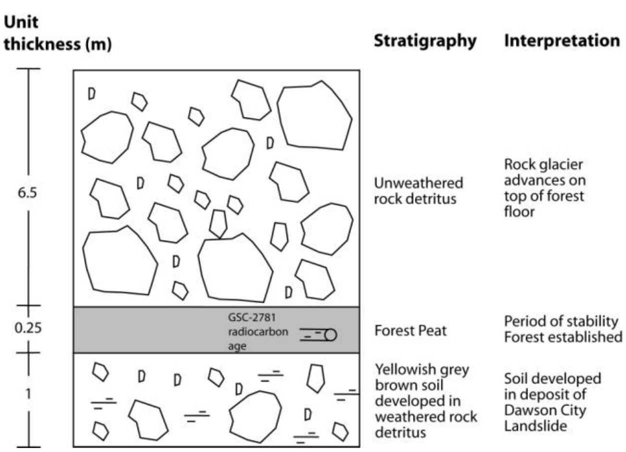

Figure 2: Interpreted stratigraphy at radiocarbon sample site within the Dawson City landslide deposit.

The present climate is continental with warm summers and cold winters and a mean annual air temperature at Dawson airport (1981-2010) of -4.1°C (Environment Canada 2015). Since 1948 the average winter temperature in the Yukon and northern British Columbia has increased by 5.4°C (Environment Canada, 2013) to the detriment of permafrost and other periglacial features (e.g. Laxton and Coates, 2011). Winter snowfall ranges from 50-80 cm (some recent years had snowfalls at the top of this range), but snow melts quickly in April from west- and south-facing slopes. The Klondike Plateau lies within the zone of widespread but discontinuous permafrost (Yukon Ecoregions Working Group, 2004) but trends in air temperatures with elevation mean that the highest probability of permafrost below treeline is beneath the valley floor (Bonnaventure et al., 2012).

The Dawson City landslide involves two rock types: metasedimentary rock from the Yukon-Tanana Terrane and ultramafic rock of the Slide Mountain Terrane (Fig. 3). These units are interpreted as a volcanic volcanic-arc assemblage overthrust by a sliver of oceanic crust, respectively (Colpron, 2006).

3 LANDSLIDE DESCRIPTION

The top of the Dawson City landslide headscarp is located approximately 700 metres a.s.l. while the town of Dawson City and the toe of the deposit are located at 320 metres a.s.l. The rectangular headscarp is approximately 300 m wide and 100 m high. The rock cliff that forms the headscarp of the landside is the source of occasional rock falls and small debris avalanches which have accumulated at the base of the headscarp. A popular hiking trail crosses the debris talus below the headscarp. The surface of the landslide debris has a boulder carapace that terminates in a steep-sided gravelly front (Fig. 4).

The Yukon River cuts into the northwest-trending spur of the Midnight Dome, in which the headscarp of the landslide forms a southwest-facing bowl (Fig. 1). The landslide debris extends out of this bowl and downward, south of a rock buttress to the river, forming the northern boundary of the town. The hills on either side of the landslide have gently rounded tops, characteristic of the dome geomorphology of the Klondike Plateau, and steeper lower sections. The longitudinal break-in-slope corresponds approximately to the location of the buried contact between the ultramafic and the metasedimentary rocks. Weathered ultramafics are exposed in the headscarp while metasedimentary rocks are found only in the steep cliffs to either side of the landslide. A talus apron composed of sand and gravel-size material occurs near the base of the headscarp coarsening to boulder size over a downslope distance of approximately 75 metres. The surface of the landslide debris consists predominantly of ultramafic boulders with an average size of 0.3 x 0.3 x 0.3 m and a maximum of approximately 1.5 x 1.5 x 1.0 m. The total area of the different sections of the deposit is on the order of 100,000 m^2. The Dawson City landslide has a vertical displacement (ΔH) / runout distance (L) ratio of approximately 0.5 (arctan ΔH/L = 27°).

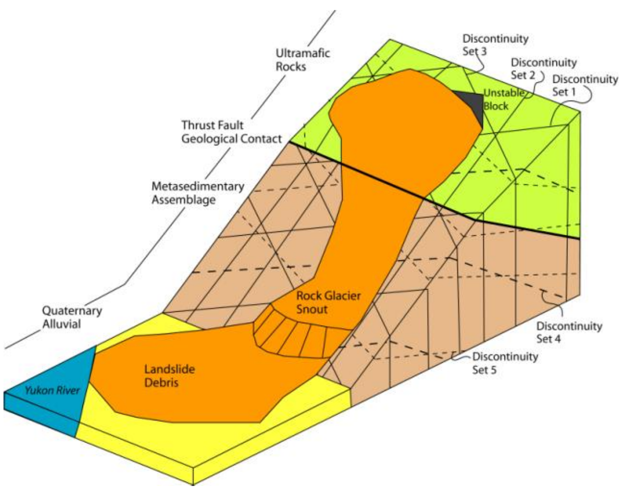

Figure 3: Conceptual block diagram of the main components of the Dawson City landslide.

The distinctive hummocky and lineated surface morphology of the middle to lower section of the landslide deposit is flanked by 100 m long furrows/trenches with pulled roots and split trees indicating active shear movement. The overall form of this section is tongue-shaped with low amplitude transverse arcuate ridges and longitudinal furrows in the upper accumulation area. While most of the rock debris material is black in colour and covered in lichen indicating that any overturning in the debris is slow, the steep-side front of this section is composed of a ~40° face of tan coloured, less weathered and sand to gravel-sized material that is actively sloughing (Fig. 4). The lower part of the landslide debris was quarried for aggregate in the 1970s and subsequently recontoured. Historical air photographs (NAPL A22199-99,100) show that the distal edge of the debris deposit originally displayed pronounced arcuate ridges.

4 ENGINEERING GEOLOGY

The strength of rock samples collected at different locations around the landslide was estimated in the laboratory using a point load apparatus. No uniaxial compressive tests were available to calibrate the relationship between the I_{s50} obtained with the uniaxial compressive strength (UCS). The I_{s50} were multiplied by 23 as suggested for core size of 50 mm in the ASTM (2008). The UCS estimates obtained for the ultramafic rocks at the landslide range from 56 to 340 MPa (average 195 MPa). The variability of the UCS values is attributed to the presence of veins and pre-existing fractures in the samples. A limited number of point load tests were performed on samples from the metasedimentary units. The metasedimentary samples were tested parallel (average UCS 97 MPa) and perpendicular (average UCS 300 MPa) to the dominant foliation plane (crenulation cleavage).

Figure 4: Fresh steep-sided front of the mobile section of the landslide deposit (see Fig. 1 for location).

The orientation and characteristics of approximately 900 discontinuities were collected from 60 field stations. Discontinuity sets were defined for measurements from each geological unit for the planar features (joint, bedding and cleavage) that dissects the rock mass with a consistent orientation. The metasedimentary and ultramafic units contain five dominant discontinuity sets and two subordinate sets (Fig. 5).

The geological strength index (GSI) is a classification system that incorporates field observations of the structure and discontinuity surface conditions to quantify the rock mass quality (Marinos et al., 2005). The GSI estimates obtained at the Dawson City landslide vary from 60-70 for the blocky rock masses with good surface condition to 10-20 for the disintegrated rock masses with poor surface condition (Fig. 6). The spatial distribution of the GSI estimates failed to values reveal a pattern as both the lowest and highest were recorded in the northwestern side scarp and in the headscarp regions of the landslide.

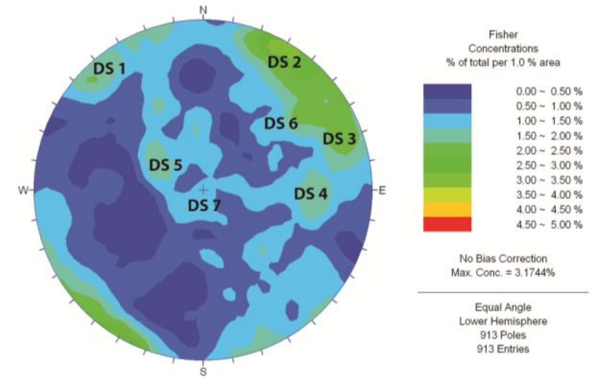

Figure 5: Stereonet of the discontinuities mapped in the scarps of the Dawson City landslide.

Three soil samples were collected from the steep-sided front of the landslide deposit shown in Fig. 4. The grain size distribution characterized the samples as a well to poorly-graded gravel. The plastic limit of the fine portion of these samples was between 36 and 45% and the liquid limit was between 69 and 79%, resulting in a plasticity index ranging from 20 to 43% water content. The linear shrinkage was estimated in one sample to be approximately 1%. XRD analysis of the silt and clay-size particles revealed the presence of talc, chrysotile and lizardite.

Lineaments, including several tension cracks, trenches, uphill-facing scarps and ridges were observed on air photographs and on the ground. The length of these features varies between 5-100 m, their width between 0.5-8 m; and their observed depth between 0.2-3 m. These lineaments can be observed up to 250 m behind the present day Dawson City landslide headscarp. The orientation of the lineaments and the discontinuity sets both have a preferential NNW-SSE trend and strike respectively with a minor concentration of features trending ENE-WSW. Discontinuity set 1 (DS 1) has a strike of NNW-SSE which is also corresponds to the dominant orientation of the linear features as they are approximately perpendicular to the maximum slope gradient (Fig. 5).

4.1 Initial slope failure mechanism

Brideau et al. (2007b) evaluated the kinematic feasibility of planar sliding, wedge sliding and toppling. They found that toppling and sliding were only marginally feasible and neither of these simple failure modes could explain the geomorphic features and rock mass characteristics observed at the site. The highly fractured nature of the outcrops (5 major and 2 subordinate discontinuity sets) is considered to result in a weak rock mass strength. A pseudo-circular failure mechanism, similar to those generally described in soil slope failure, is therefore considered to be the most likely initial rock slope failure mechanism.

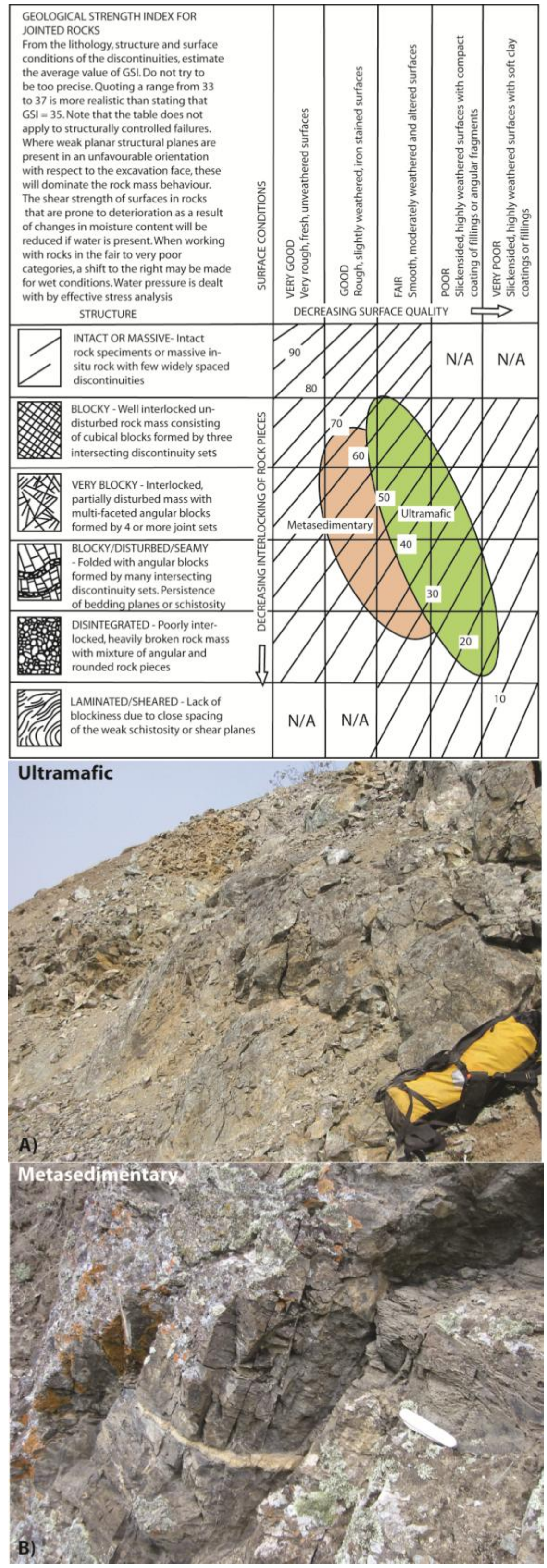

Figure 6: Rock mass quality of the two main geological units at the Dawson City landslide (see Fig. 1 for location).

5 DISPLACEMENT MONITORING

Brideau et al., (2007a and b) identified zones of potential ongoing slope instabilities in the headscarp and movement in the landslide deposit. These zones were delineated based on the presence of tension cracks, split trees and sheared trenches/furrows. Five monitoring stations, composed of stakes, were installed to quantify ongoing movement, four in 2006 and a fifth in 2011.

5.1 Headscarp

An approximately 180 m long tension crack with geomorphic evidence of ongoing movement (disturbed soil and vegetation) was identified by Brideau et al., (2007a and b) upslope from the current headscarp. The volume of the unstable rock mass is tentatively estimated between 45,000-90,000 m^3. This represents a length of 180 m with a width of 50 m and a depth between 5-10 m. It should be emphasized that this range of volumes is an approximation. Several trees located along this feature have had their trunks split (Fig. 7). Table 1 summarizes the displacement rates measured at stations A, B, C. The rates show that downslope movements of 2-12 cm/year have occurred along a 40 m section of the tension crack.

5.2 Landslide deposit

The landslide deposit can be divided in three sections: the upper talus, the central section and the lower re-contoured debris. The central section of the deposit is moving as evident from multiple geomorphic features that include split trees (Fig. 8), shear zones, tension cracks oriented perpendicular to the direction of movement, and measured displacements of 9-27 cm/year (Table 1, stations D and E). Field observations suggest that multiple strands might be present in the shear zone at the western edge of the central portion of the debris which means that the relative displacements might represent only part of the total movement. Brideau et al. (2007a and b) discussed the possibility that this central moving section of the debris represents an earthflow or rock glacier. Tension cracks and deformation of the newly created walking trail, suggest that deformation is also occurring in the lower recontoured section of the deposit.

Table 1: Observed displacement rate at each station. See Figure 1 for location of stations.

Interval	Stn. A cm/yr	Stn. B cm/yr	Stn. C cm/yr	Stn. D cm/yr	Stn. E cm/yr
2006-2009	4-7	7-8	N/A	20-23	N/A
2009-2011	8-12	7	5[1]	9-14	N/A
2011-2013	6-7	5-6	2	15-20	27

[1] Not measured in 2009, represents rate between 2006 and 2011.

6 ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)

6.1 Methodology

Several characteristics of the moving middle to lower section of the debris at the Dawson City landslide are common to both rock glaciers and earthflows, including its elongated lobate shape, sheared trenches and split trees, and formerly, arcuate ridges. The presence of the steep-sided active terminus, a bouldery "carapace" overlying gravelly diamicton, and a grain-size distribution dominated by gravel-size and larger material, however, support the rock glacier origin. The potential for creeping permafrost is also supported by the presence of perennially frozen ground beneath the adjacent town-site. A borehole

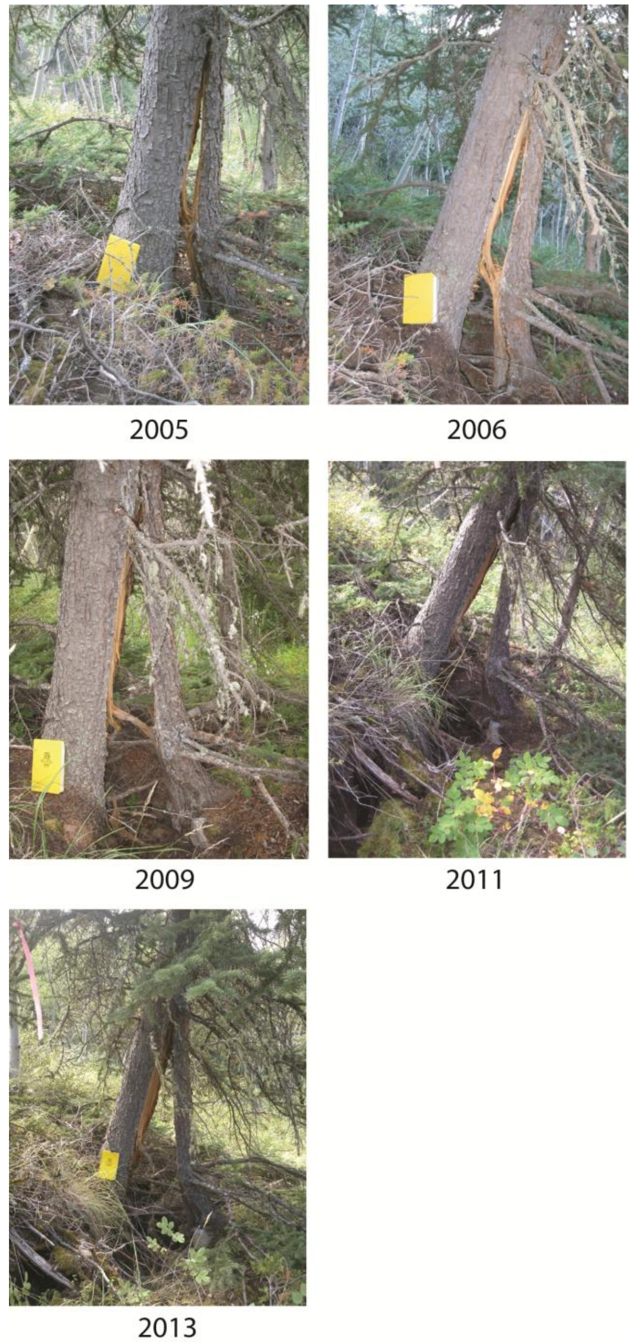

Figure 7: Time series of a split tree in the unstable section above the current headscarp (tree is located at Stn. B in Fig. 1).

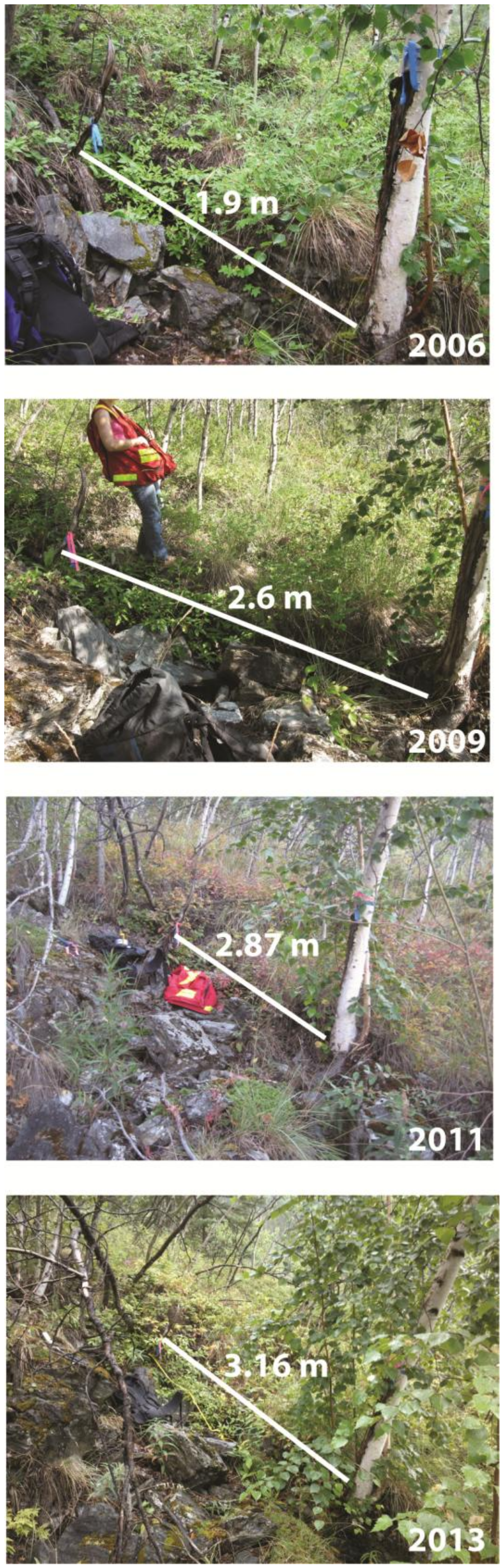

Figure 8. Time series of a split tree along the shear furrow along the northern edge of the deposit (See Stn. D in Fig. 1 for location).

through the deposit would provide conclusive evidence of the presence or absence of permafrost containing ground ice, but would be expensive and difficult to drill.

ERT profiling was used in an attempt to infer frozen ground conditions beneath the deposit area. ERT is a geophysical technique that measures variations in the ability of the ground to conduct electricity along a transect, producing a two-dimensional image of changes in electrical conductance. In permafrost areas, the variations in conductance relate mainly to whether the ground is frozen or thawed because water is a good conductor of electricity and ice is a poor conductor. ERT profiling has been used extensively to investigate mountain permafrost in Europe (e.g. Kneisel et al., 2000, 2008; Hauck et al., 2004; Hilbich et al., 2008, 2009) and is growing in importance in North America as a technique for permafrost investigations in mountains and elsewhere (e.g., Lewkowicz et al., 2011).

Many ERT profiles show very clear differences relating to frozen ground conditions which can be correlated to surface changes in drainage, vegetation cover or land use (Lewkowicz et al., 2011). However, like all geophysical techniques, confidence in the interpretation increases where complementary information is available.

There is a major difference in the resistivity of water and ice, but there is not always a sharp line between the phase of water in soil pores (frozen or unfrozen) at temperatures above and below 0°C. Instead, percentages of unfrozen moisture gradually increase in the pores of frozen soils (especially in fine-grained ones - silts and clays) as their temperatures approach 0°C. Consequently, the difference in the electrical resistivity of frozen and unfrozen soils can be gradational rather than sharp (Lewkowicz et al., 2011). In addition, because there can be differences in the pore water salinity and in the conductance of the soil minerals, it is not possible to identify a single threshold resistivity value below which soils are definitely frozen and above which soils are definitely not frozen. However, values for sites in a given area are often quite stable. For the Dawson City landslide, a value of 1000 ohm m was considered to be appropriate based on the dry, coarse soils present.

The ERT profiling was undertaken on September 7, 2014 when the active layer would have been close to its thickest. An ABEM Terrameter LS profiling system was used with a Wenner electrode array (5 m spacing) along a 200 m profile (Fig. 9). The penetration depth of this array is approximately 30 m. UTM co-ordinates (relative to the WGS 84 datum) were taken using a hand-held Garmin Etrex Vista GPS. Relative variations in elevation along the individual profiles were measured in the field using an Abney level and are expected to have accuracies of ±2 m.

Resistivity profiles were topographically corrected using the Abney level surveys. Measured resistivity data were processed with RES2DINV software (Loke et al., 1996) using a robust inversion that can respond to the rapid transitions and high contrasts in resistivity (Loke et al., 2003) that occur between frozen and unfrozen ground. A reversed colour scheme was used to portray the profile so that blue represents high resistivities (generally indicative of frozen soils) and red represents low resistivities (ice-poor or unfrozen soils)

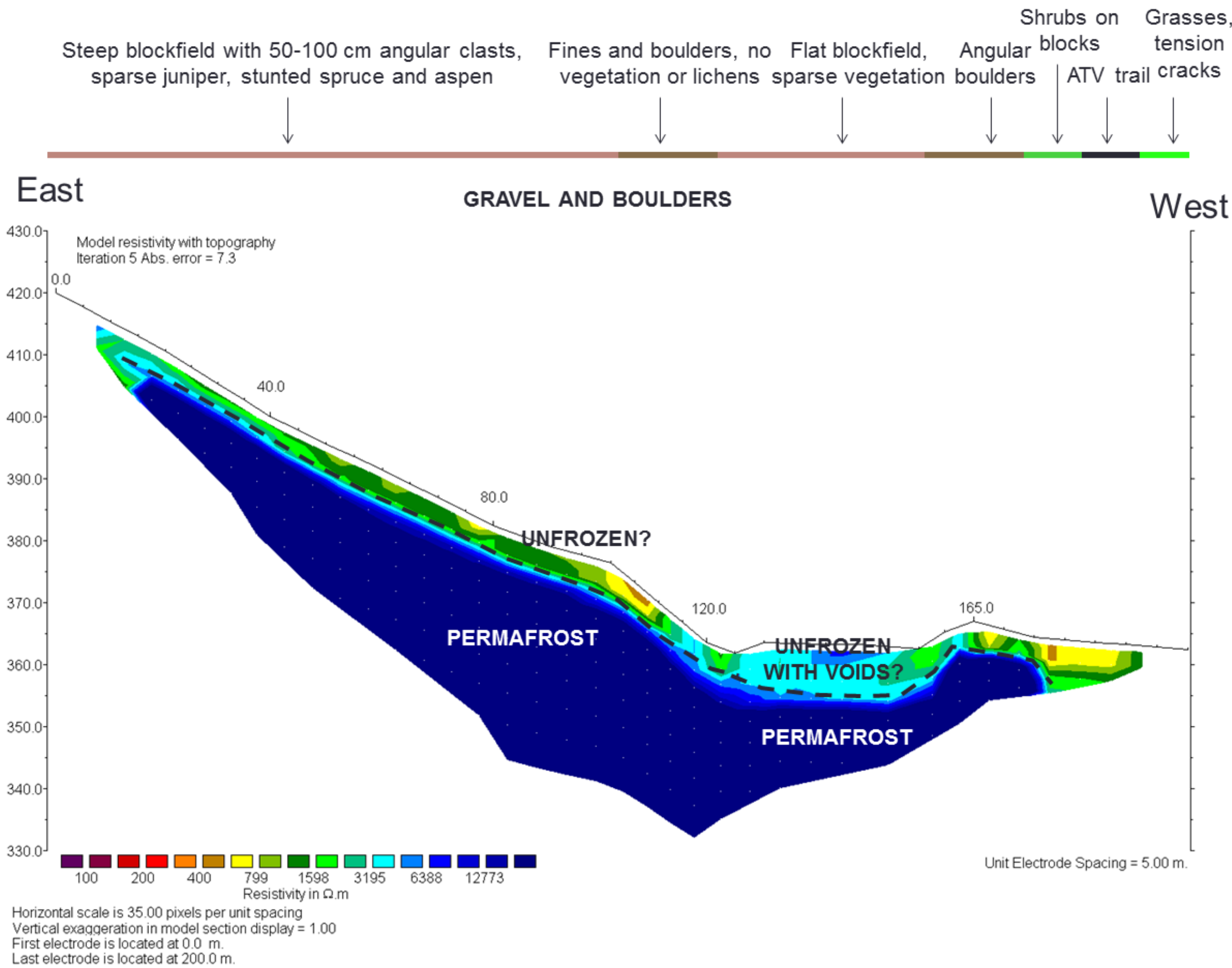

Figure 9: Electrical Resistivity Tomography (ERT) profile along the section of the landslide deposit suspected of moving as a rock glacier (see figure 1 for location). Dashed line represents the interpreted boundary between permafrost and the active layer and on the slope and follows the steep gradient in resistivities. Moderate resistivities beneath the flat blockfield are attributed to air-filled voids in the active layer rather than to frozen ground conditions.

6.2 Results and interpretation

The ERT profile shows a lower resistivity layer 3-5 m thick with values typically below 1000 ohm m overlying a very high resistivity layer that extends to the base of the profile at about 30 m depth (Fig. 9). The interpretation of the profile is a deep active layer overlying permafrost. The resistivities at depth which exceed 100 kilo-ohm m represent the highest values recorded in the Dawson area, and suggest significant ice but low unfrozen moisture contents that are associated with coarse materials. Permafrost temperatures are not known and may be lower than beneath the townsite (~-0.5°C) due to the cooling impact of the surface blocks, but given the slope and exposure, are unlikely to be less than about -1.5°C. ERT profiles of rock glaciers in the European Alps typically also exhibit very high apparent resistivities, in the 100 kilo-ohm m range or higher. The interpretation of the ERT, if correct, leads to the conclusion that the Dawson City landslide is moving as a result of the deformation of its core of permafrost by creep processes.

7 CONCLUSIONS

Detailed engineering geology mapping at the Dawson City landslide revealed that the initial rock slope failure occurred primarily in the highly fractured ultramafic rock mass which overlies a metasedimentary unit. The dominant slope failure mechanism is considered to be sliding along a pseudo-circular failure surface controlled by the low rock mass strength.

Repeated displacement monitoring between 2006 and 2013 demonstrated that a section of the headscarp is moving at a rate of 2-12 cm/yr while part of the middle to lower section of the deposit moved up to 27 cm/yr.

A longitudinal ERT survey along the moving middle section of the deposit found a high resistivity zone consistent with the presence of permafrost at a depth of 3-5 m extending to 30 m below the ground surface. This suggests that ongoing movements are the result of creeping permafrost and that the lower part of the landslide can be regarded as a rock glacier.

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