Ongoing displacement monitoring at the Dawson City landslide (Dawson map area NTS 116B/3)

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ABSTRACT

The Dawson City landslide is a prehistoric slope failure at the northern end of the town. It occurred along the faulted contact between an ultramafic unit from the Slide Mountain terrane and a metasedimentary unit from the Yukon-Tanana terrane. The very blocky nature (seven discontinuity sets) of the failed rock mass led to a pseudo-circular failure mechanism. Based on geomorphic observations suggesting moving masses in the headscarp and deposit, various monitoring techniques were begun in 2006 to confirm and quantify the rate of displacement. Data collected from five years of monitoring suggest that an unstable section in the headscarp is moving downslope at a rate of 4.3 to 11.9 cm/yr, whereas the lower part of the landslide deposit is moving between 8.5 and 20 cm/yr. XRD analysis of the silt and clay-size particles in the deposit revealed the presence of talc, chrysotile, and lizardite.

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INTRODUCTION

The Dawson City landslide (also known as the Moosehide Slide) is a prehistoric slope failure that defines the northern limit of the town (Fig. 1). Based on an unpublished radiocarbon date from O.L. Hughes of the Geological Survey of Canada (see Brideau *et al.*, 2007a) the landslide occurred more than 1740 years before present (pre 200 A.D.). This part of western Yukon is located within the Beringia refugium (unglaciated for approximately 2.6 Ma; Duk-Rodkin, 1996; 1999; Froese *et al.*, 2000). The present continental climate consists of warm summers and cold winters. The climate normal record for Dawson City (1971-2000) gives an average annual air temperature of -4.4°C and an average total precipitation of 324 mm (Environment Canada, 2011). Dawson City lies within the zone of widespread but discontinuous permafrost (Natural Resources Canada, 1993).

The engineering geology and geomorphology of the landslide has been described by Brideau *et al.* (2007a,b). The slope failure is interpreted as having occurred at, or near the geological contact between serpentinite and underlying metasedimentary rocks. The contact regionally represents the overthrust of a sliver of oceanic crust (Slide Mountain terrane) onto a volcanic-arc assemblage (Yukon-Tanana terrane; Mortensen, 1988; Colpron, 2006) but has not been located in outcrop in the slide area. Cliffs in the headscarp and rock exposures of the unstable block above it reveal the presence of seven discontinuity sets which facilitated a pseudo-circular slope failure (Brideau *et al.*, 2007a).

During their initial investigation Brideau *et al.* (2007a,b) identified zones of potential ongoing slope instability in the headscarp and movement in the landslide deposit (Fig. 1). Tension cracks and split trees were observed upslope from the current headscarp and atop the landslide deposit. Monitoring stakes were installed and precisely

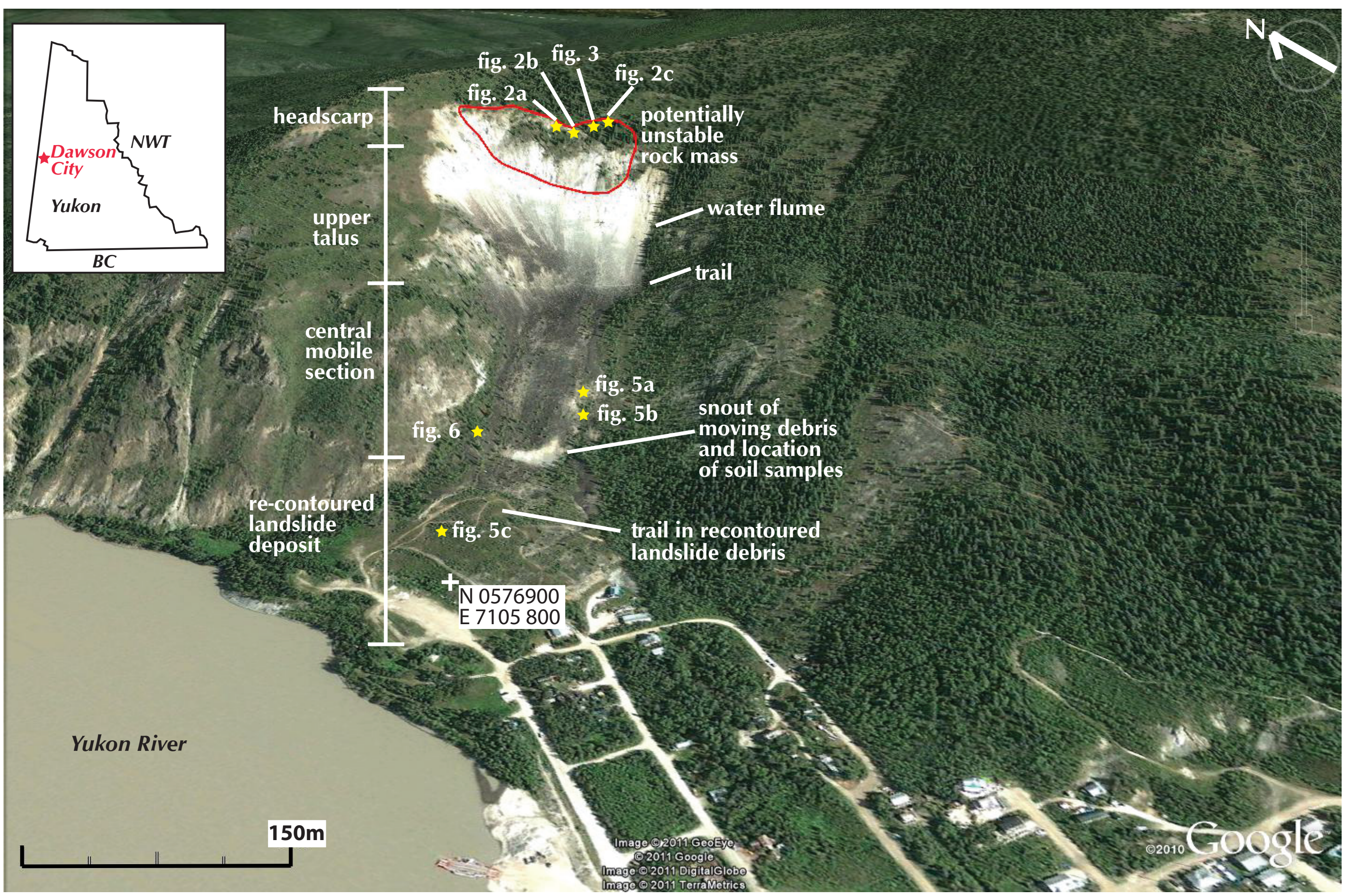

Figure 1. *Annotated oblique aerial view of the Dawson City landslide (Google Earth imagery; July 2010). Tension crack above the headscarp referred to in the text is outlined by the yellow stars denoting the location of figures 2, 3, 5 and 6.*

surveyed in 2006 (Brideau *et al.*, 2007b) to confirm and quantify subsequent displacements. The main focus of this paper is to present the displacement monitoring data collected during repeat surveys in 2009 and 2011. Also presented are additional soil property data and results of X-ray diffraction analysis on the silt and clay-sized particles from the snout of the slow-moving debris.

DISPLACEMENT MONITORING

HEADSCARP

Geomorphic evidence of ongoing movement (disturbed soil and vegetation) was identified by Brideau *et al.*, (2007a,b) along a tension crack approximately 200 m in length and upslope from the current headscarp (Fig. 1). Between this crack and the headscarp is an unstable rock mass. Assuming a length of 200 m, a width of 50 m, and a depth between 1 and 5 m, the volume of the unstable mass is between 10 000 and 50 000 m^3. It should be emphasized that the range in volume represents a first order approximation and further work is needed to refine the estimate. A number of trees located along this feature have had their trunks split (Fig. 2). One tree was photographed on four occasions between 2005 and 2011 and provides a time-series illustration of the movement along the tension crack over that period (Fig. 3). Several wooden and metal stakes were installed in 2006 to quantify the deformation rate. The displacement data presented in Figure 4 demonstrate that downslope movements of 4.3 to 11.9 cm/yr have occurred along a 40 m section of the tension crack.

LANDSLIDE DEPOSIT

The landslide deposit can be divided in three sections: the upper talus, the central moving section, and the lower re-contoured debris (Fig. 1). The upper talus represents the deposit of rockfall activity since the large prehistoric slope failure. The upper talus zone contains remnants of supports (carefully stacked, unmortared rock) for a flume that transported water (described in Tyrrell, 1910). Repeat aerial photographs document small debris avalanches between 1979 (National Air Photo Library A25131-76) and 1984 (National Air Photo Library A26718-97) that initiated from the headscarp and impacted the flume rock structure.

The central section of the deposit is currently moving. Evidence supporting this includes multiple geomorphic features such as shear zones (Figs. 5a. and 6), tension cracks oriented perpendicular to the direction of

Figure 2. *Split trees along the main tension crack located upslope from the current headscarp. See Figure 1 for the location.*

Figure 3. Expanding split tree located along tension crack upslope from current headscarp. See Figure 1 for location. UTM 7 NAD 83 coordinates 0577496E, 7106020N.

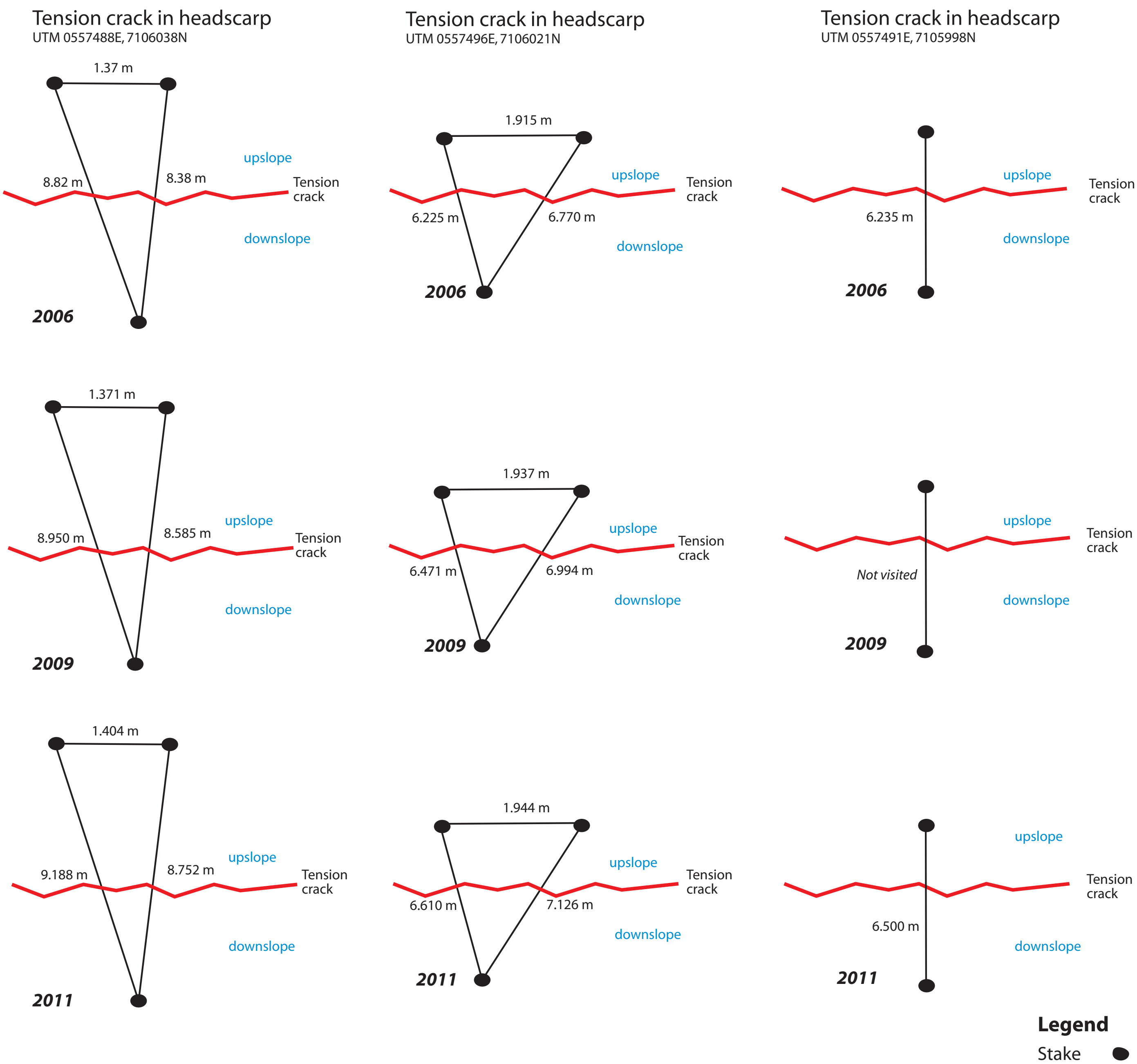

Figure 4. *Periodic measurement of displacement in arrays across tension cracks at the upslope edge of the unstable block (measurement at 3 sites). Jagged red line is approximate locus of tension crack.*

movement (Fig. 5b), and split trees (Fig. 6). In the western shear zone (Fig. 1), part of the trunk of a birch sapling was pulled from the main trunk by sliding downslope. The distance between the two parts of the tree was recorded in 2006, 2009 and 2011 (Fig. 6). Based upon the measurements the tension crack is opening at 8.5 to 20 cm/yr.

Field observations suggest that multiple sets of shear localization might be present in a shear zone at the western edge of the central portion of the debris. Geomorphic features observed in the field include several long (~100 m) linear zones with disturbed soil and vegetation. This means that the displacement values reported above might only account for part of the total movement. Brideau *et al.*, (2007a,b) discussed the

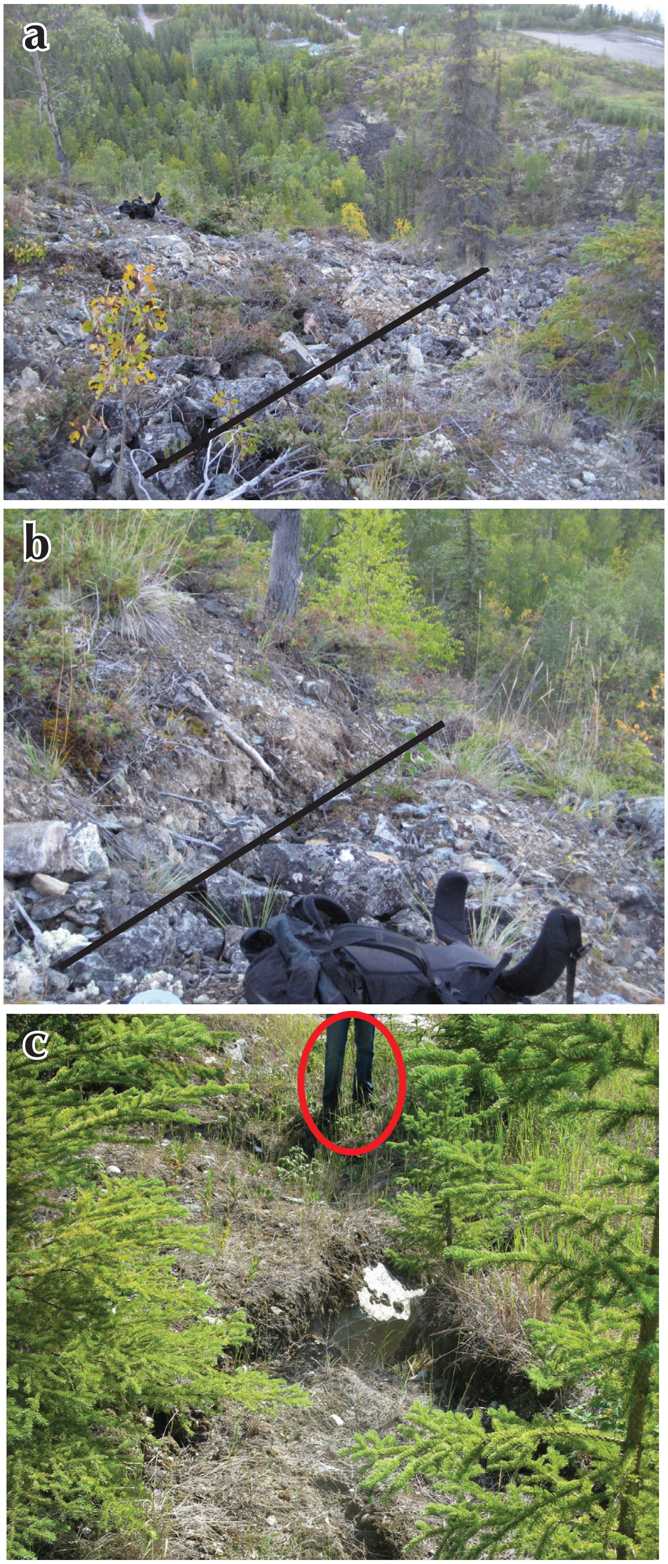

Figure 5. *Tension cracks observed in the* ***(a)*** *eastern shear zone,* ***(b)*** *upper landslide debris, and* ***(c)*** *re-contoured landslide debris. See Figure 1 for locations.*

possibility that this central moving section of the debris represents an earth flow or rock glacier.

The lower section of the deposit was re-contoured in the early 1980's after coarse aggregate had been quarried out. Observation of cracks in this area (Fig. 5c) during visits in 2009 and 2011 suggest that tensile deformation continues. A newly created walking trail is similarly affected. Although re-contouring decreased the average angle of slope, the base of the landslide deposit is creeping, or there is persistent instability within the deposit.

SOIL PROPERTIES AND XRD ANALYSIS

A soil sample was collected in 2011 from the steep scarp near the toe of the actively moving central section of the debris. The purpose was to supplement the geotechnical testing results presented in Brideau *et al.*, (2007b). A summary of the test results are presented in Table 1. The liquid and plastic limits represent the water content at which the sampled soil starts behaving as a liquid and plastic material respectively (Craig, 2004); the plasticity index represents the range of water content over which the soil behaves plastically, while the linear shrinkage represents the percent difference between the length of a sample at its liquid limit and when it is completely dry. The liquid and plastic limits testing was conducted according to the guidelines presented in ASTM (2010) while the linear shrinkage test followed NZS (1986). The plasticity index and liquid limit results indicate that the fine fraction of the deposit (<425 μm) has a high plasticity. By weight, the fine fraction represents approximately 2% of the samples. Brideau *et al.* (2007b) noted that the plasticity of their samples compared favourably to values reported by Bovis (1985) for earthflows in British Columbia. The 4% linear shrinkage value obtained in this study corresponds to a low shrink-swell potential (Holland and Richard, 1982).

An x-ray diffraction (XRD) analysis was conducted on the silt and clay-sized particles (<63 μm) of a sample collected from the snout of the slow moving part of the landslide deposit. The XRD analysis was undertaken to identify the types of clay present. The sample was brought into suspension using a sodium hexametaphosphate solution (4 g/L) to prevent the clay-size particles from flocculating. The clay mounts were then air dried on a thin glass slide, and scanned through the x-ray diffractometer. A peak analysis of the diffractogram was conducted against the ICDF powder database using the software Traces (GBC Scientific Equipment) and UPDSM (PSI international Inc.). Results of the analysis suggest the presence of talc, chrysotile, and lizardite.

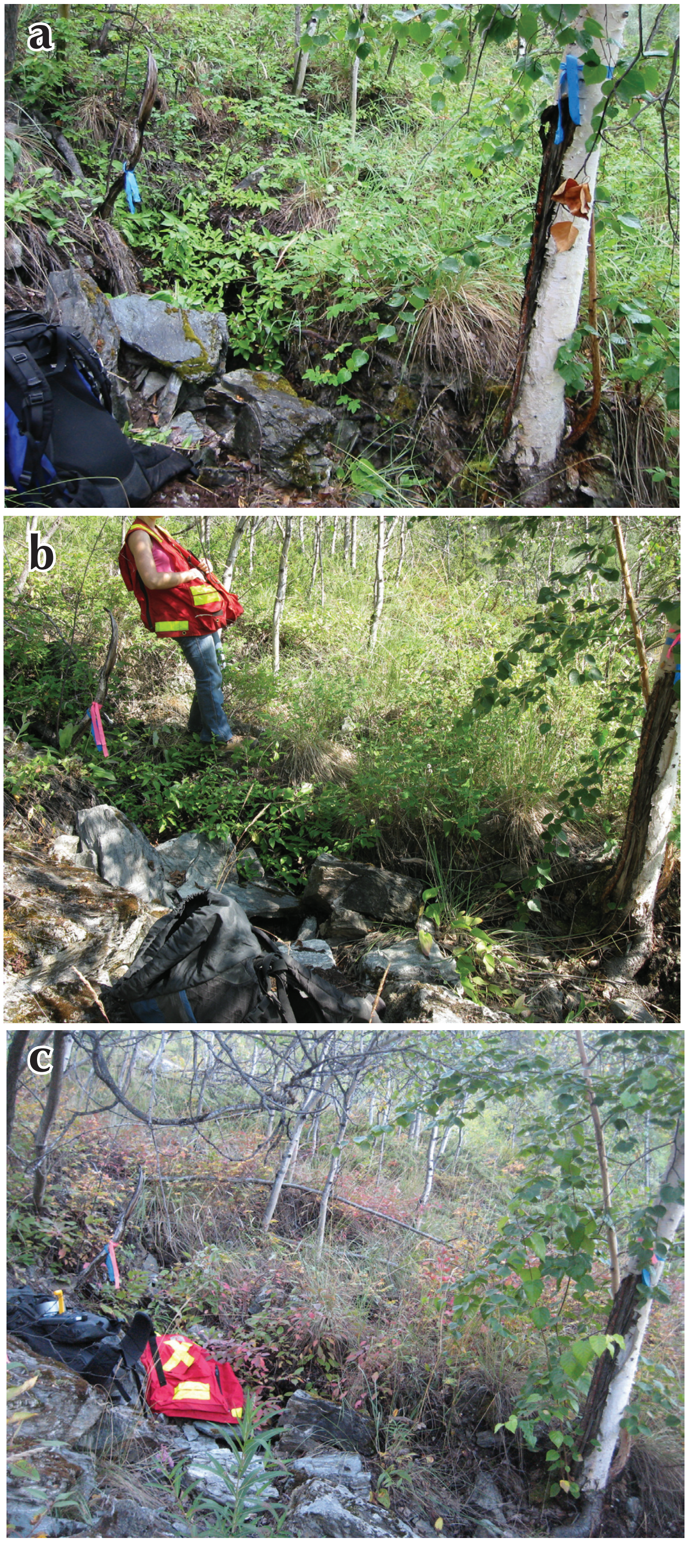

Figure 6. *Progressive separation of a split tree in the western shear zone of the moving landslide debris. See Figure 1 for location. UTM7 NAD83 coordinates 0577062E, 7105934N. The split of piece of trunk is on the left side of the photos, marked by a strip of blue (2006) or pink (2009, 2011) ribbon. The tree from which piece was split is at right.*

Table 1. *Summary of geotechnical properties for the soil fraction passing through a 425 μm sieve. Samples taken from the snout of the central actively moving section of the debris. See Figure 1 for location.*

	Sample A-2006	Sample B-2006	Sample 2011
Plastic limit (% water content)	35.7	37.2	44.5
Liquid limit (% water content)	79.1	65.7	64.9
Plasticity index (% water content)	43.4	28.5	20.4
Linear shrinkage (%)	NA	NA	4.0

DISCUSSION

Assuming a conservative measurement error of 1 cm, the data presented in this paper indicate displacements large enough to be outside the range of uncertainty and thus represent a true phenomenon. The duration of the displacement monitoring is, however, too limited to discuss trends, so we cannot currently quantify the risk associated with the unstable block in the headscarp area. Further monitoring should be used in conjunction with the progressive slope failure concept developed by Voight (1988; 1989) and Fukuzono (1990). This approach suggests that a log-normal plot of the inverse velocity *vs.* time since the monitoring was initiated can be used to estimate the time to failure which is represented by the x-axis intercept. This technique has been applied to open-pit and natural slope stability monitoring (Petley *et al.*, 2002; 2005; Crosta and Agliardi, 2003; Petley, 2004; Rose and Hungr, 2007).

Brideau *et al.*, (2007a,b) mapped a series of lineaments (tension cracks, trenches, ridges) over 200 m in length upslope from the present day headscarp. These features do not currently show evidence of movement, however all features observed and measured in this paper appear recent. It is unlikely that the displacement rates reported in this paper could be sustained for several decades without resulting in mass failure.

The average annual mean temperature between 1978 and 2007 appears to have increased >1°C for Dawson City (Fig. 7). This increase in mean annual temperature could have contributed to the renewed activity on the Dawson City landslide. It should be noted that the total annual precipitation does not appear to have changed significantly over that same period of time (Fig. 7).

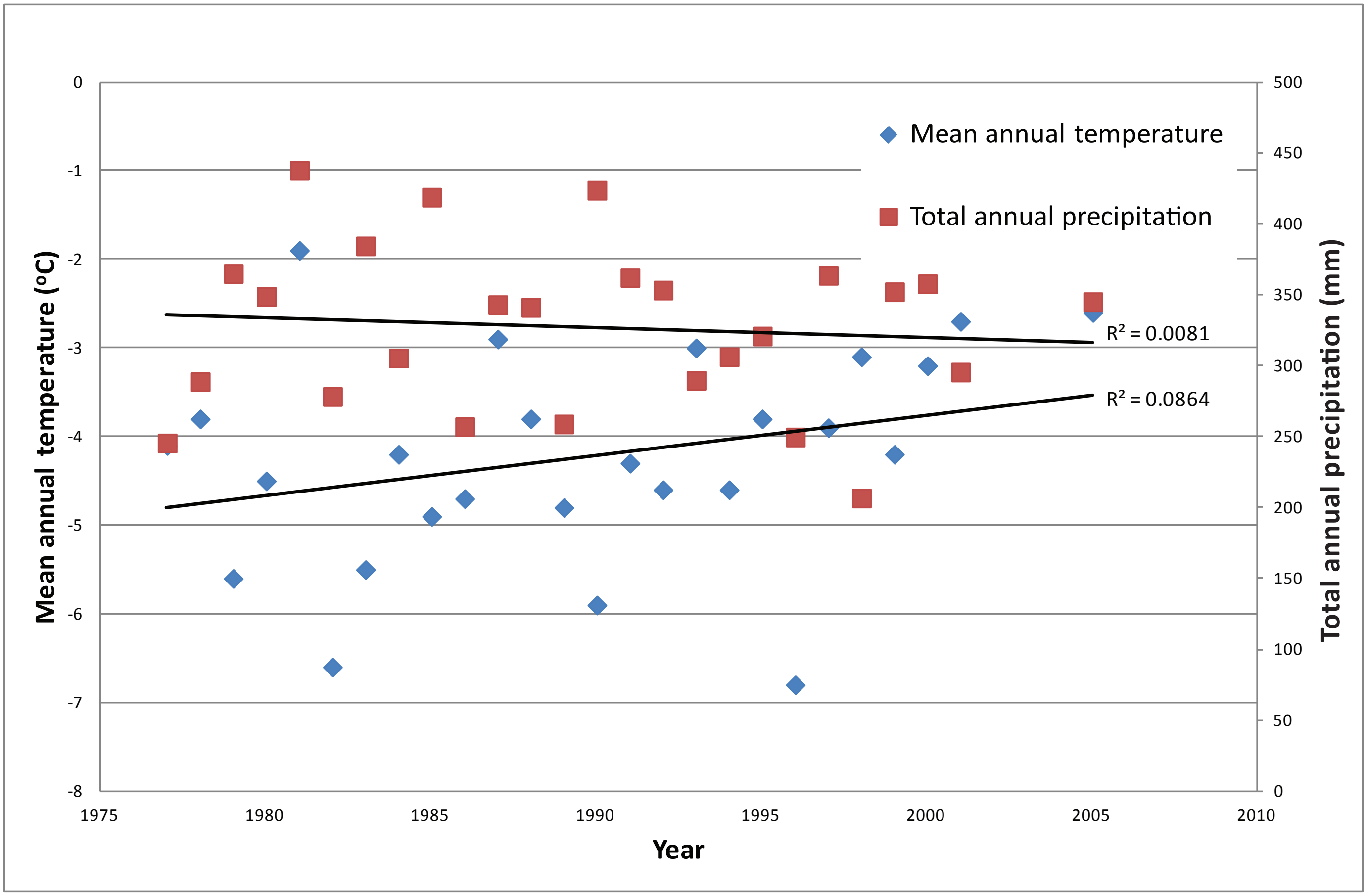

Figure 7. *Mean annual temperature and total annual precipitation at the Dawson City weather station (data from Environment Canada, 2011).*

Alternative mechanisms to explain the recent activity include progressive rock mass strength degradation (Guglielmi and Cappa, 2010), evolution stages of a large landslide (Zerathe and Lebourg, 2011) and stick-slip movement of the hillslope.

The new displacement values reported in this paper for the central section of the deposits (8.5-20 cm/yr) are greater than the initial value of 4.5 cm/yr estimated by Brideau *et al.* (2007b). This discrepancy is due to the assumption made by Brideau *et al.*, (2007b) that the tree had grown to its current size before being sheared off and as such the 4.5 cm/yr value represented a minimum displacement rate.

The DGPS station installed in 2006 in the deposit and listed in Brideau *et al.* (2007b) was intended to be resurveyed in 2011. Unfortunately only one metal rod could be located and it was out of the ground; this was attributed to the installed metal stakes being too short, smooth and thin for the coarse nature of the debris. The survey markers are assumed to have subsided into the ground or to have been frost-jacked out of it. It is recommended that if the DGPS approach is attempted again longer and larger survey stakes be used.

CONCLUSIONS

The results presented in the paper confirm that sections upslope from the headscarp and in the landslide debris are actively moving. Based upon five years (2006-2011) of displacement monitoring data, the unstable section in the headscarp is moving downslope at a rate of 4.3 to 11.9 cm/yr whereas the lower part of the landslide deposit is moving at a rate of 8.5 to 20 cm/yr. At this point the displacement time-series is too short to identify trends and continuing displacement monitoring is recommended.

Soil laboratory testing has determined that the fine soil fraction from samples of the snout in the central mobile section of the debris has high plasticity and low linear shrinkage values. XRD analysis of the mineralogy of the silt and clay-size particles of the component of the debris suggests the presence of talc, chrysotile, and lizardite.

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