The Dawson City landslide (Dawson map area, NTS 116B/3), central Yukon

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ABSTRACT

A pre-historic pseudo-circular rock-slope failure at the northern edge of Dawson City, Yukon occurs in altered ultramafic rocks. The middle section of the landslide debris continues to move down-slope, as is evident from sheared trenches, stretched roots and split trees along its edges, and a steep snout exposing fresh material. Dendrochronological analysis demonstrated that the split trunk of one tree has displaced over the last 40 to 45 years at an average movement rate of 4.5 cm/year. This moving section of the debris could be characterized as a rock glacier or as an earth flow, although our present observations and measurements do not confirm either mechanism. A block upslope from the headscarp of the landslide exhibits signs of recent movement. To assess the movement rate of the different sections of the landslide in the future, a monitoring array was set up and an initial set of measurements was taken in July, 2006.

RÉSUMÉ

Une rupture pseudo-circulaire préhistorique de talus rocheux s'est produite dans les matériaux ultramafique à la limite nord de Dawson City, au Yukon. La section du milieu des débris d'éboulement continue à se déplacer vers le bas de la pente, comme le font fois des tranchés cisaillées, des racines étirées, et des arbres fendus le long de leurs limites, et le nez de cette section qui expose des matériaux de débris frais. Une analyse dendrochronologique a démontré qu'un tronc d'arbre déchiré s'est déplacé pendant les 40-45 dernières années avec un taux moyen de mouvement de 4.5 cm/a. Cette section des débris pourrait être considérée comme un glacier de roche ou une coulée de terre malgré que nos observations à se stade-ci ne nous permettent pas de confirmer l'un ou l'autre de ces mécanismes. Un système de monument de levé a été mis en place et un relevé initial fut effectué en juillet, 2006 pour évaluer les taux de déplacement des différentes sections du glissement dans le future.

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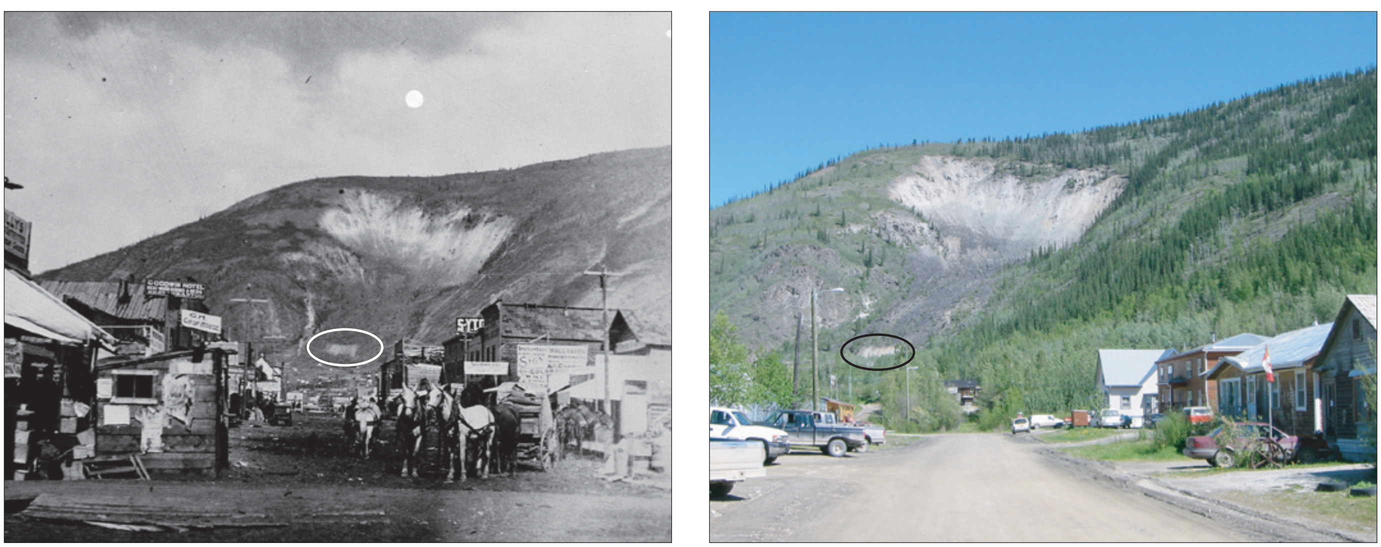
INTRODUCTION

The Dawson City landslide (also known as the Moosehide slide) is a dominant feature of Dawson's city-scape (Fig. 1). Due to its close proximity to the north edge of the town (Fig. 2), a variety of human land use activities have periodically taken place on the landslide debris. During the goldrush-era housing shortage (Brand, 2002), the landslide deposit and its flanks were temporarily occupied. In about 1908 (see Tyrrell, 1910), a flume was built across the upper talus to carry water to the town from Moosehide Creek; its foundation remains to this day. In the late 1970s, the lower third of the landslide deposit was quarried for coarse fill and rip-rap, and was subsequently re-contoured. During the 1990s, this area has been used as a temporary campground. High above this activity, the rock cliffs (hereafter called the headscarp) spawn occasional rockfall, which has accumulated at the base of the headscarp in a deposit (hereafter called the 'landslide debris deposit') with a furrowed character. A trail popular with summer hikers crosses the debris train below the headscarp. The surface of the landslide debris deposit slopes, steeply at intervals, down to the uppermost streets at the north edge of the town, where it terminates in a steep-sided front. Local inhabitants have wondered whether another catastrophic slide will ever occur and whether the debris will continue to encroach on their property. At the same time, earth scientists have long speculated about how the slide initiated and what the present mechanism of movement is.

The observations in this article reflect fieldwork performed primarily by the first author and his assistants during the summers of 2005 and 2006, as well as discussions among the other authors. Statistical and laboratory analysis of rocks (first author) and organic material (third author) reflect thesis-related research. A second phase of the study was initiated in 2006 when survey pins were inserted in the debris train and on opposite sides of an expanding tension crack above the headscarp. By periodically and precisely remeasuring their positions, we hope to be able to detect and monitor small ground movements in the future. This monitoring will provide a better understanding of the magnitude and direction of displacement, and therefore the mechanism of movement.

REGIONAL GEOGRAPHIC AND CLIMATIC SETTING

The townsite of Dawson City is located on fluvial terrace on the east bank of the Yukon River (elevation 308 m). East of 8th Avenue (the highest street and furthest east of the river), the slope steepens and rises to a rounded summit known as Midnight Dome (elevation 850 m). This feature is a relatively small mountain in the Klondike



View down 2nd Avenue, *ca.* 1900. **View down 3rd Avenue, 2005.**

Figure 1. *Northward view of the landslide in ca. 1900 and in 2005, showing little change in the headscarp. Note that the pale snout (circled on the figure) of the middle to lower section of the debris has moved downslope. The historical photograph was obtained from the archive at the Dawson City Museum and is part of the collection of Mrs. Ellen Northrop Shannon.*

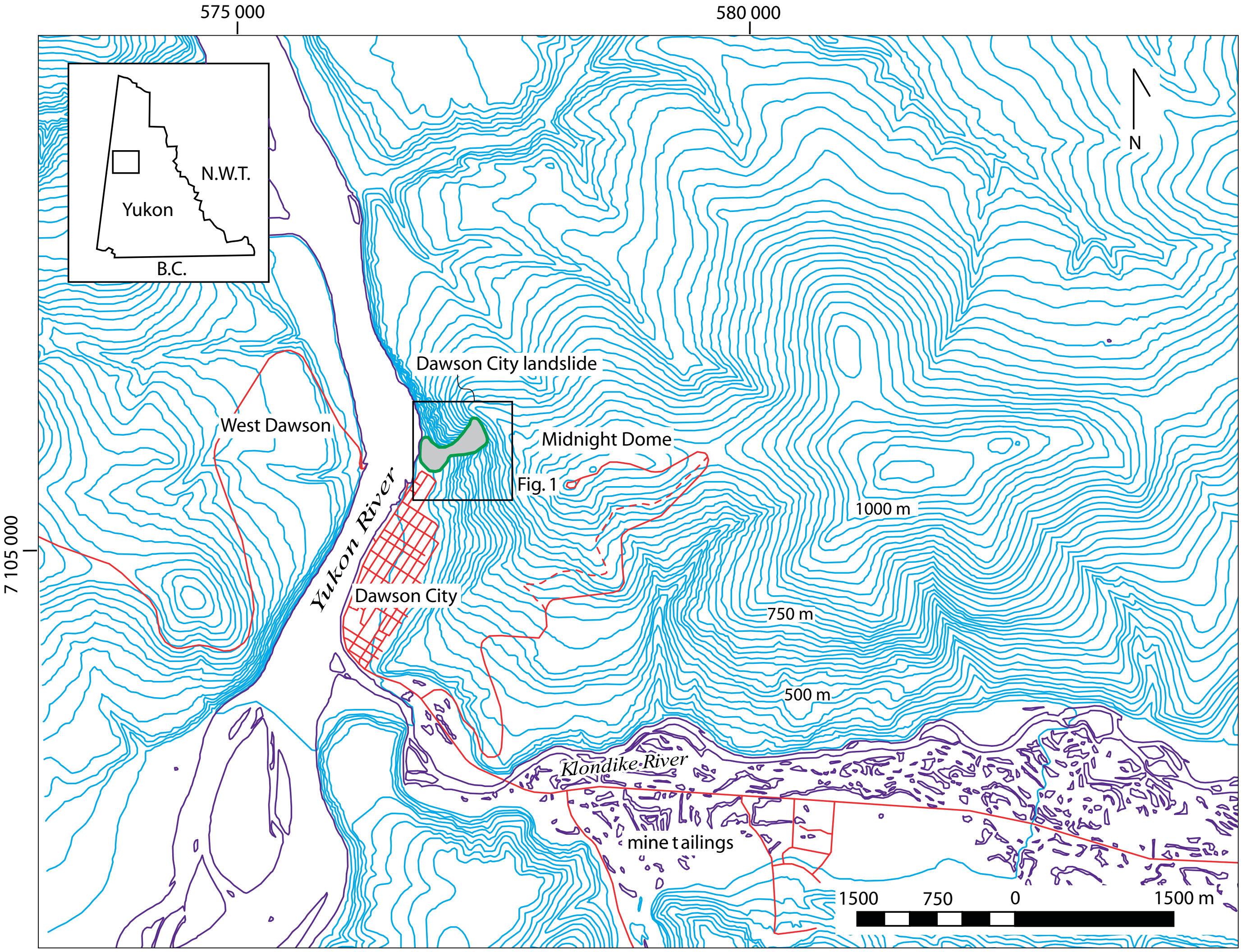


Figure 2. *Location map of the Dawson City landslide at the northern edge of town (modified from Brideau et al., in press).*

Plateau physiographic region. The region is unglaciated and part of eastern Beringia (Froese *et al*., 2000, 2001), so upper slopes are typically deeply weathered and outcrop is rare (Duk-Rodkin, 1996).

The present continental climate consists of warm summers and cold winters. Weather records yield an annual average air temperature of about -5°C (Wahl *et al*., 1987), but during the last decade this average has increased by several degrees (Environment Canada[3]) to the detriment of permafrost and other periglacial features. Winter snowfall ranges from 50-80 cm (some recent years had snowfalls at the top of this range), but snow melts quickly from west- and south-facing slopes in April. During most summers, the forest floor barely dries out between rainstorms, although some summers are very dry which makes them more prone to forest fires. Stable rock surfaces support thick lichen (although some ultramafic substrates are nutrient-poor for plant growth), and dense mixed (spruce-birch) second-growth forest occurs on thin soils, several tens of centimetres thick. Soils are composed of colluvium generally derived from local weathered bedrock intermixed with silty aeolian deposits (loess) and organic matter (Bond and Sanborn, 2006), and they are commonly modified by cryoturbation.

The Klondike Plateau lies within the zone of widespread but discontinuous permafrost (Yukon Ecoregions Working Group, 2004).

The Dawson City landslide involves two rock types: metasedimentary rock from the Yukon-Tanana Terrane and ultramafic rock of the Slide Mountain Terrane. These units are interpreted as a volcanic-arc assemblage overthrust by a sliver of oceanic crust, respectively (Mortensen, 1988a; Colpron, 2006).

[3] *http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html*

FIELD OBSERVATIONS AND MEASUREMENTS

The Yukon River cuts into the northwest-trending spur of Midnight Dome; the headscarp of the Dawson City landslide forms a southwest-facing bowl on the south side of that spur (Fig. 2). 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 rectangular headscarp is approximately 300 m wide and 100 m high. Directly below the headscarp a talus apron slope extends about 80 m in length, grading from sand near the top to boulder-sized particles at its base. Coarse debris extends below the talus for up to 550 m, dropping about 200 m in elevation. The landslide debris deposit begins as a gently sloping boulder field, becoming steeper in several locations where rock outcrops constrict the mid-section. It then widens and flattens toward the toe of the debris and terminates in a steeply sloping face that exhibits freshly exposed sediment. Linear extensional features such as tension cracks and trenches surround the headscarp and the margins of the landslide debris deposit.

From the lobate shape of the debris deposit and the abundance of very coarse blocks, we believe the initial slope failure event was a catastrophic rock slide. The upper part of the debris has been subsequently buried by ongoing piecemeal rockfall, which still continues today. Since the initial failure, the upper half of the debris has continued to move slowly downslope, as indicated by its wrinkled and furrowed surface, and trees growing on or adjacent to the debris with split or curved trunks. We address several possible failure mechanisms following descriptions of the landslide's morphological components.

HEADSCARP

The headscarp of the Dawson City landslide consists of abundantly fractured rock with an average slope angle of 60° and some nearly vertical faces up to 20 m high. Small amounts of rockfall have been observed after human disturbance, heavy rains or during freeze-thaw cycles. However, only small-magnitude mass movement has occurred at the headscarp during the past century because neither the stone flume located immediately below the headscarp, nor the footpath located at the base of slope, have been obliterated.

The headscarp is composed of altered ultramafic rocks. Serpentinite predominates (70-90%) with hornblende pyroxenite, gabbro and calcite also being present in variable amounts. Mottled green-black and orange rock surfaces with belt-buckle texture indicate alteration of original olivine to iddingsite; thin sections of this rock also revealed minor calcite (~5%), chlorite (~5%), pyroxene (0-5%) and magnetite (~1%). The ultramafic rock is laced with incipient and open fractures. Fresh surfaces of the rock are difficult to obtain and most faces are fracture surfaces coated with serpentine. We believe the gabbroic rock is medium crystalline, with no evidence of ductile strain.

Several types of linear features were observed upslope from the headscarp. These include tension cracks (bounded by discontinuities in the bedrock), trenches (distinct lows in the topography), antislope (uphill-facing) scarps and ridges (Fig. 3). The length of the linear features varies between 5-100 m, their width between 0.5-8 m, and their observed depth between 0.2-3 m. Circular and rectangular depressions (length x width x depth: about 0.5 x 1.0 x 0.75 m) were observed behind the headscarps. These may be anthropogenic features (prospecting pits, caches, or dwelling structures) because they lack structural orientation and are close to the existing trail. Similar features were previously described in archeological reports of the area surrounding Dawson City (Brand, 2002; Thomas Heritage Consulting, 2005).

A tension crack outlining a potentially unstable block is located above the central portion of the headscarp. The location of this block is conceptually represented in Figure 4 and is shown on the map of linear features in Figure 3. Disturbed vegetation, exposed soil horizons, stretched roots and split trees were interpreted as indications of recent movement along the tension crack.

SIDEWALLS AND ADJACENT SLOPES

Directly beneath the headscarp, bedrock outcrop is obscured by talus and landslide debris, but a promontory on the north side and sidescarp on both sides of the landslide consists of brown to dark grey carbonaceous phyllite, amphibolite schist and minor quartzite. These rocks contain quartz (25-70%), mica (muscovite and biotite; 5-30%), chlorite (0-20%) and calcite (0-20%); thin sections also show minor amounts of opaque minerals (0-5%), epidote (1%) and zircon (1%). These rocks are more coherent than the ultramafic rock higher up and reveal discrete zones of high strain with oriented platy minerals and thin planes of mylonite. In places the strain zones have been folded (Fig. 5).

The contact between the ultramafic and underlying metasedimentary rocks was mapped on a regional scale

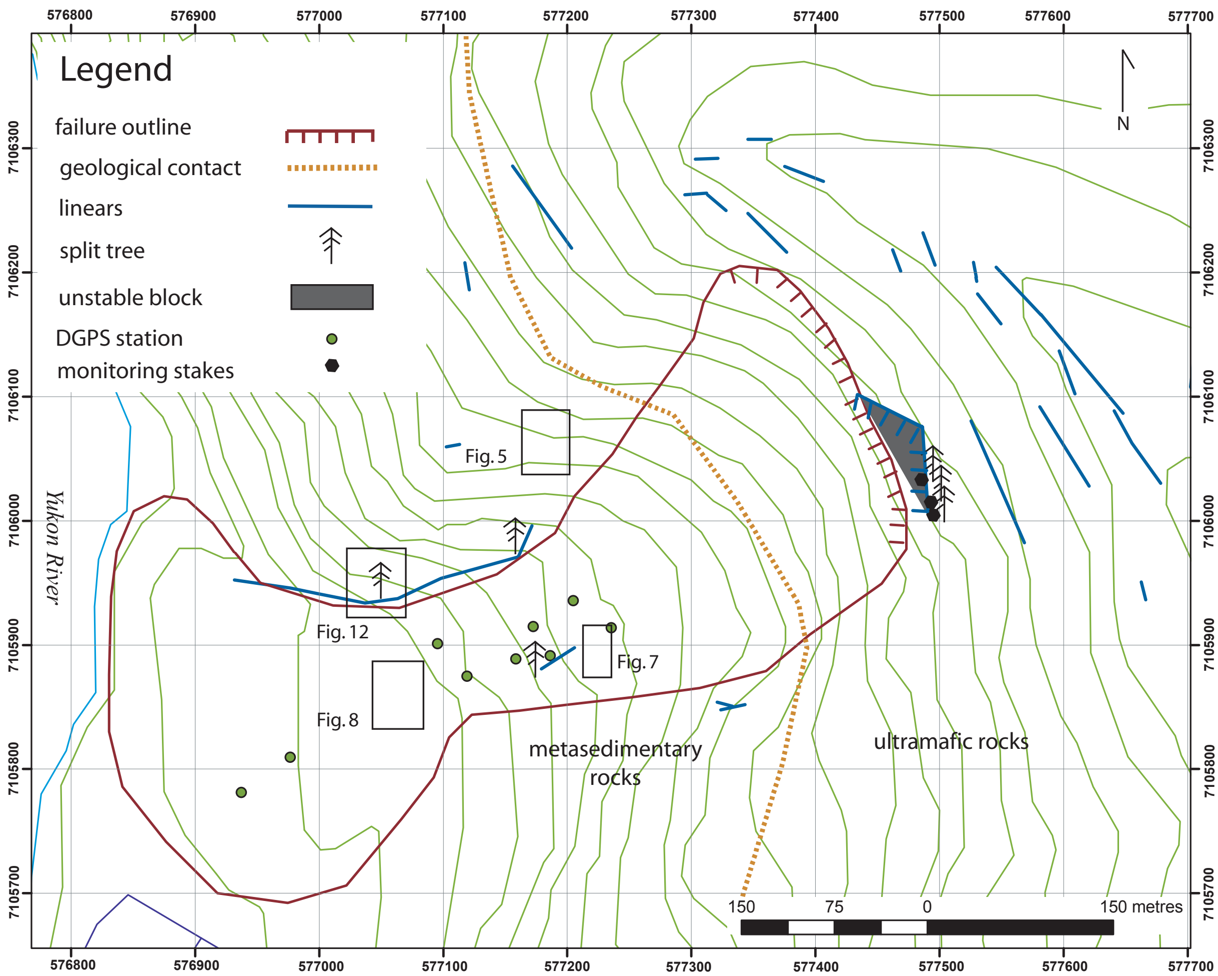


Figure 3. *Distribution of measured linear features, showing their orientation and length (modified from Brideau et al., in press).*

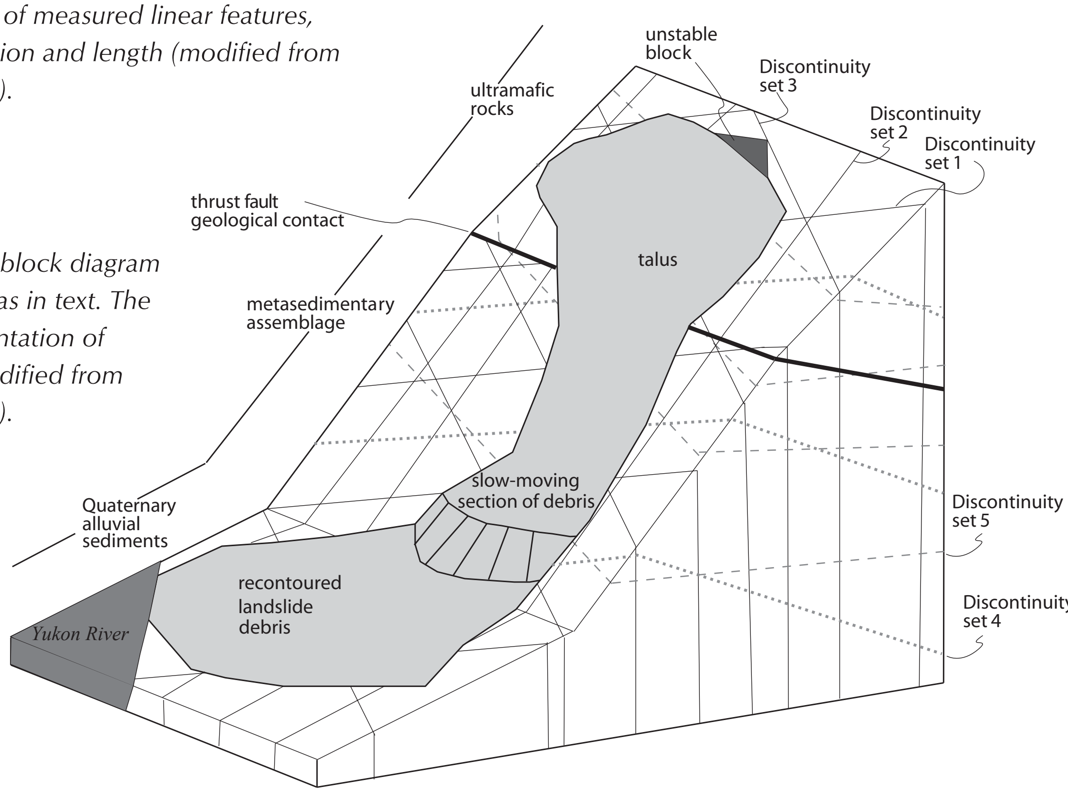


Figure 4. *Conceptual block diagram with features labeled as in text. The lines indicate the orientation of discontinuity sets (modified from Brideau et al., in press).*

by Green (1972) and deduced to be a horizontal to southerly shallow-dipping brittle shear zone (Mortensen, 1988a,b). Mortensen (1990) interpreted the ultramafic rock to be a tabular sliver thrust from the west or southwest over the metasedimentary-metavolcanic rocks.

Beneath the headscarp, the contact is covered by debris, but on either side of the headscarp, the contact is constrained to within a few metres by outcrops of contrasting lithology. We did not observe any brittle or ductile features attributable to movement on this contact, except that the underlying rock is pervasively strained as described above.

Discontinuity patterns and rock-mass quality was examined and described by Brideau *et al.* (in press). Measurements were made on accessible surfaces facing southwest and south. Five dominant and two subordinate discontinuity sets were recognized in the headscarp (Fig. 6, Table 1,). Discontinuity sets 1, 2 and 3 steeply dip to the southeast, southwest and west, respectively. Discontinuity set 4 dips 40-50° to the northwest. Discontinuity set 5 dips to the southeast at 30-40°, roughly parallel to composition banding in the ultramafic rocks. Discontinuity set 6 dips to the southwest at 60-80°. Discontinuity set 7 is sub-horizontal and therefore has a wide range of dip directions. Figure 4 conceptually illustrates the relationships between the geomorphology, bedrock geology, tectonic contact and orientation of the major discontinuity sets present at the Dawson City landslide.

TALUS

The upper section of the debris (Fig. 4) consists of an 80-m-long talus cone, with a steep slope (at the angle of repose). The talus particle sizes grade from sand and gravel at the top (near the contact with the weathered bedrock headscarp), to boulders up to 50 cm wide at its base. Here the slope gradient becomes gentler and the landslide debris deposit is first evident (i.e., boulders have been in place for a long period based on their lichen cover). Tension cracks 30-40 cm long and 10-20 cm deep are parallel to the contour lines and observed locally in the upper parts of the talus.

LANDSLIDE DEBRIS DEPOSIT

The landslide debris deposit is constricted in the mid-section by rock abutments spaced 100 m apart. The narrow passage provides a ‘choke’ on downslope movement, separating the ‘upper’ debris (a rubble field

Figure 5. *Folded metasedimentary rock on the western side of the landslide. See Figure 3 for location.*

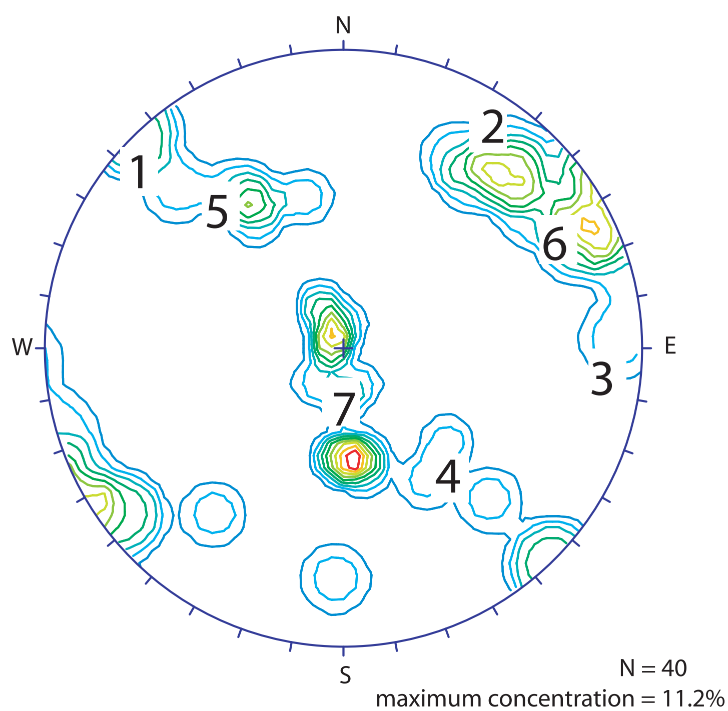


Figure 6. *Contoured stereonet of poles to discontinuity planes in the headscarp. The numbers refer to discontinuity sets discussed in the text (and Table 1 and Fig. 4) and N refers to the number of measurements included in this figure.*

Table 1. Summary orientation and roughness characteristics of discontinuity sets (see text for explanation; from Brideau et al., in press).

Discontinuity set	Dip (°)	Dip direction(°)	Primary roughness	Secondary roughness
1	80-90	130-140	planar	rough
2	80-90	220-230	planar	rough
3	70-80	260-270	planar	rough
4	40-50	330-340	undulating	rough (dominant) smooth (subordinate)
5	30-40	130-140	undulating	smooth
6	60-80	230-240	planar	rough
7	10-30	020-070	planar	smooth

above the constriction) from the 'lower' debris and wider spill area below. The middle to lower section of the landslide deposit consists predominantly of lichen-covered altered ultramafic boulders with an average size of 0.3 x 0.3 x 0.3 m and a maximum size of approximately 1.5 x 1.5 x 1.0 m. The tongue-shaped lower section is characterized by subtle transverse arcuate ridges and longitudinally sheared trenches about 100 m long with stretched roots and split trees spanning them. Localized pockets within the central portion of the middle to lower section of debris expose loose fresh soil. Although tree and shrub cover is sparse on the deposit, their spatial distribution commonly follows geomorphic features such as furrows and trenches (Fig. 7). The snout of this section of the landslide debris is composed of a steep (~40°) face of tan-coloured, less-weathered finer material (sand to gravel-sized) that is actively sloughing (Fig. 8). The steep

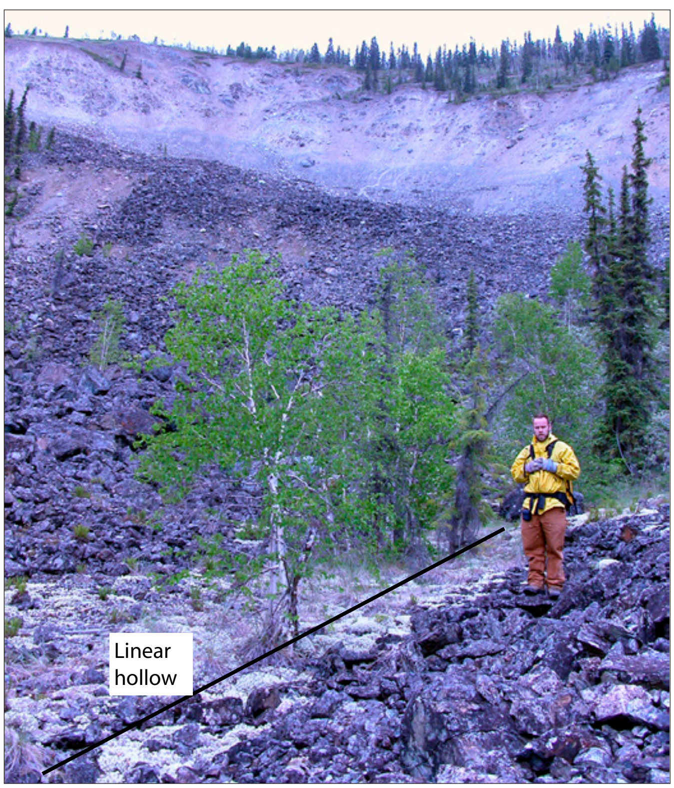


Figure 7. *View of the eastern edge of the moving section of debris. Note that the trees are preferentially growing in a linear hollow. See location on Figure 3.*

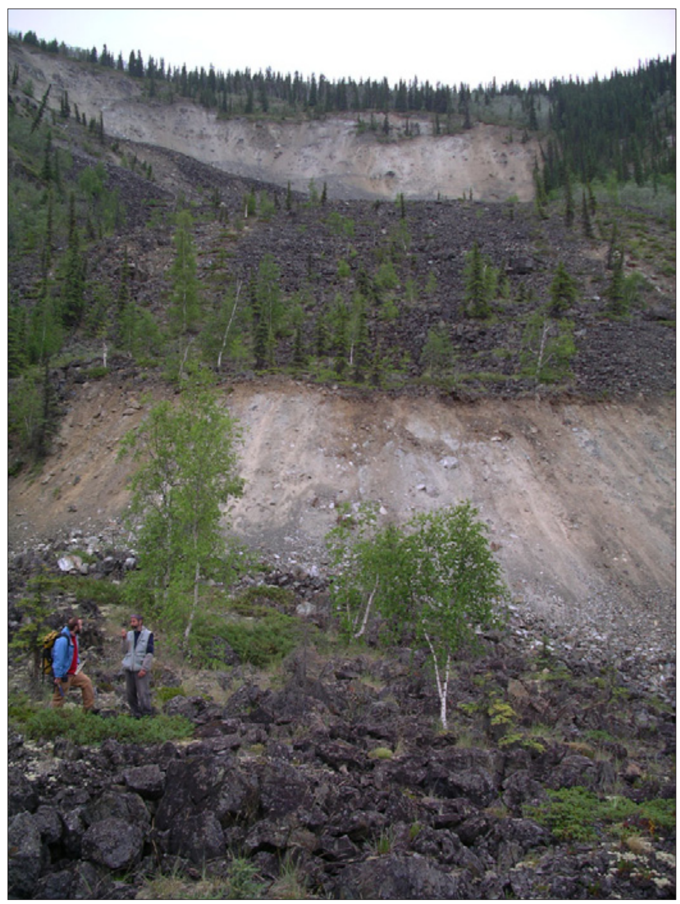


Figure 8. *Steep snout of the moving section of the landslide debris. It exposes ultramafic gravel and cobbles. Boulder fields above and below have thick lichen cover.*

fresh snout along with the sheared trenches, splitting trees and stretched roots indicate differential motion within the landslide debris (Fig. 4).

The lower section of the landslide debris is accessible from the north end of Front Street. From about 1906 until the 1940s, a level area provided the foundation for the Sisters of St. Ann's Mission, an impressive three-story wooden hospital. During the late 1970s, the back of this level area was excavated to fill in low-lying properties and supply rip-rap for the dyke that protects Dawson City from the Yukon River. The wisdom of increasing the slope of an unstable deposit by excavating the toe was questioned, and the City of Dawson subsequently recontoured the area. The original lobate morphology of this section of debris consisted of concentric compression ridges, as observed in pre-1970 aerial photographs. Further downslope, below the contoured area, the landslide deposit is overgrown with long grass and alder thickets, and the land surface drops steeply into the Yukon River.

LABORATORY TESTS AND ANALYSES

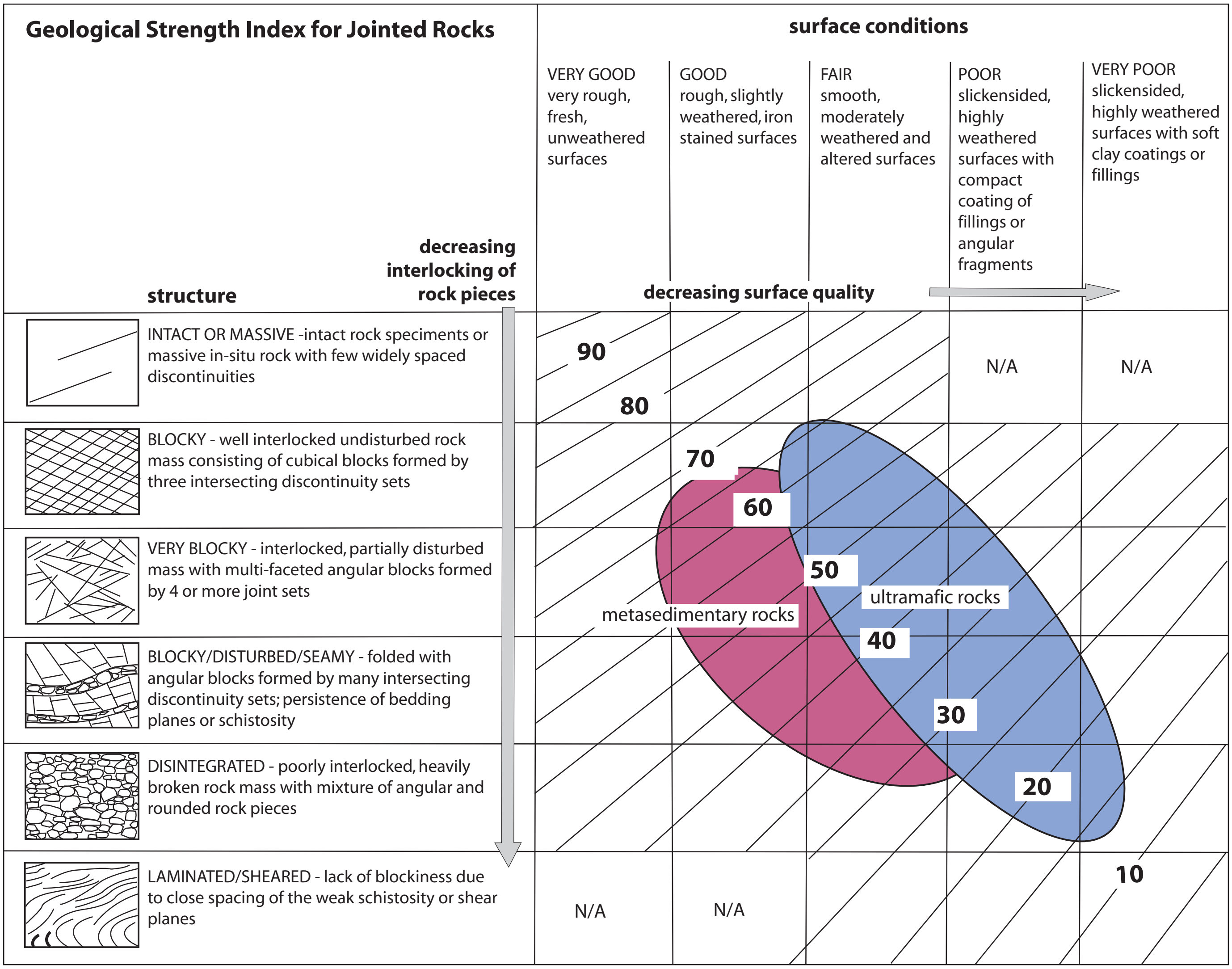
Rock strength

The rock-mass quality was estimated using the Geological Strength Index (GSI) (Hoek and Brown, 1997). The GSI is a quantitative measure of the structure (discontinuities, bedding and schistosity) and surface conditions (roughness, weathering and infillings) of a rock mass (Marinos and Hoek, 2000; Marinos *et al*., 2005). At the Dawson City landslide, 51 GSI estimates were obtained primarily from the headscarp and sidescarp, but also from outcrops on either side of the slope failure. The range of determinations, for both metasedimentary and ultramafic rocks, are encompassed in the shaded areas on Figure 9. The ultramafic rocks exhibit a large variability in rock-mass quality from disintegrated (GSI of 10-20) to very blocky (GSI of 60-70). Recent use of the GSI chart to characterize ultramafic rocks elsewhere in the world also demonstrated large variability in rock-mass quality (Marinos *et al*., 2006). While the discontinuity pattern for both the metasedimentary and ultramafic lithologies are similar, the higher discontinuity intensity and the poorer discontinuity surface conditions of the ultramafic rock result in the lower rock-mass quality values.

Intact rock strength was estimated by performing point load tests on hand samples collected in 2005 and 2006. The samples were cut using a rock saw to the standards outlined by the International Society for Rock Mechanics for the testing of irregular blocks (ISRM, 1985). The results of these tests are presented in Table 2 and compared with published unconfined compressive strength (UCS) values.

Table 2. *Point-load index values and corresponding uniaxial compressive strength estimates obtained from samples collected at the Dawson City landslide and previously published values for serpentinite (UCS = unconfined compressive strength; modified from Brideau et al., in press).*

Lithology	UCS minimum (MPa)	UCS average (MPa)	UCS maximum (MPa)	Reference	Test method
serpentinite	56 (I_{s50} 2.5)	195 (I_{s50} 8.9)	340 (I_{s50} 15.4)	this study	point load
altered serpentinite	NA	45	139	Coumantakis, 1982	uniaxial
fresh serpentinite	NA	95	268	Coumantakis, 1982	uniaxial
serpentinite	17	68	128	Kilic, 1995	uniaxial
serpentinite	34	78	127	Paventi *et al*., 1996	triaxial
serpentinite	17	149	295	Kilic *et al*., 1998	uniaxial
dunite (9% serpentinite)	147	NA	151	Escartin *et al*., 2001	triaxial
serpentinite	NA	66.5	NA	Glawe and Linard, 2003	uniaxial
serpentinite	NA	90 (I_{s50} 4.1)	NA	Glawe and Linard, 2003	point load
serpentinite	74	NA	166	Grasselli, 2006	NA



Notes on using the GSI: From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35.

Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock-mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

Figure 9. *Range of Geological Strength Index values observed at the Dawson City landslide for the metasedimentary and ultramafic rocks (from Brideau et al., in press).*

Soil material testing

Two samples were collected for preliminary analysis to determine the physical characteristics of the material making up the slow-moving feature. The samples were first sieved to determine the grain-size distribution (Fig. 10). The two samples consisted of 75 and 90% gravel (size range 2-4 cm), respectively, and their grain-size distribution is considered to be within the range of well graded gravel, but close to the boundary of poorly graded gravel (following accepted standards as outlined in Craig, 2004 and British Standard Institute, 1981).

The consistency of the two soil samples was then investigated by determining the liquid and plastic limits of the fine portion which passes through sieve #40 (425 μm) (according to ASTM, 2006). The consistency of remoulded soil varies in proportion to its water content. With high water content, the soil-water mixture behaves as a liquid, while with lower water content it behaves

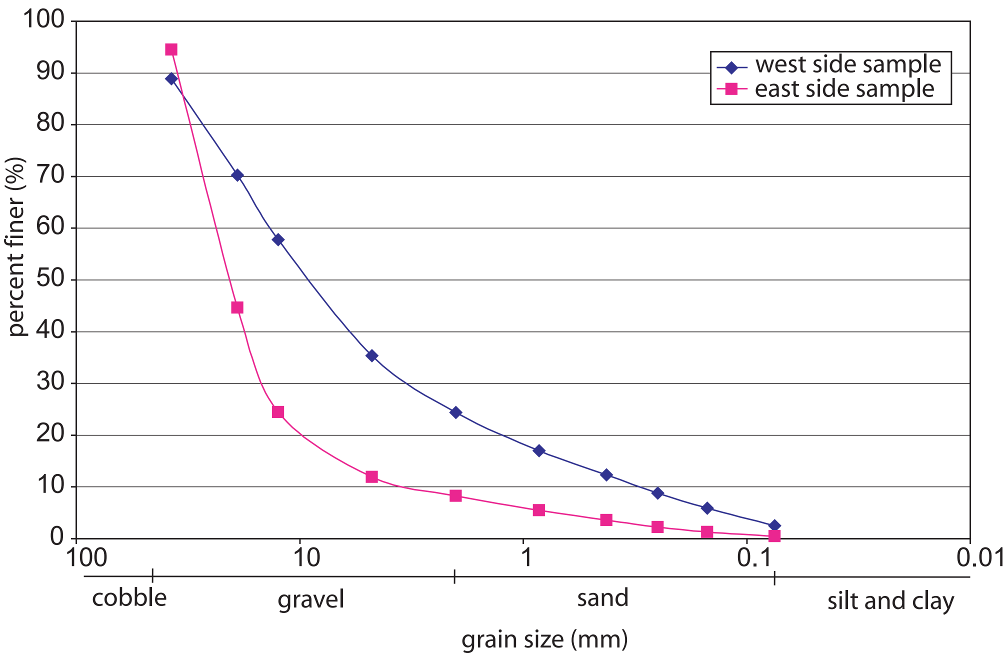


Figure 10. *Grain-size distribution curves of two samples collected from steep snout (see Fig. 6) of the moving landslide debris.*

plastically. With still lower water content, the soil behaves as a semi-solid to solid. The liquid limit is the water content at the boundary between liquid and plastic behaviour of a soil; the plastic limit is the water content at the boundary between plastic and semi-solid behaviour.

For this project, plastic limits of 35.7% (eastern sample) and 37.2% water (western sample) were determined using a standard test (ASTM, 2006), where a thread of soil is rolled on a glass plate. Liquid limits of 79.1% (eastern sample) and 65.7% water (western sample) were determined using the cone penetrometer test. Figure 11 shows plasticity index (liquid limit – plastic limit) versus liquid limits for the two samples as compared to previously published values for earth flows in southern British Columbia (Bovis, 1985).

Such high plastic and liquid limit values are usually associated with smectite clays (the clay mineral group that is composed of pyrophyllite, talc, vermiculite, sauconite, saponite, nontronite and montmorillonite). The weathering of ultramafic rocks, however, commonly produces montmorillonite clay (Wildman *et al.*, 1968; Paradis and Simandl, 1996; Yagi *et al.*, 1996). Soil moisture has also been found to be important in the weathering of soils derived from serpentinite.

DENDROCHRONOLOGY

Split trees can occur on landslides where a tension crack in the soil underneath or proximal to a tree forces the trunk to split. Roots and trees also continue to grow and compensate for on-going slope deformation; trees tilted

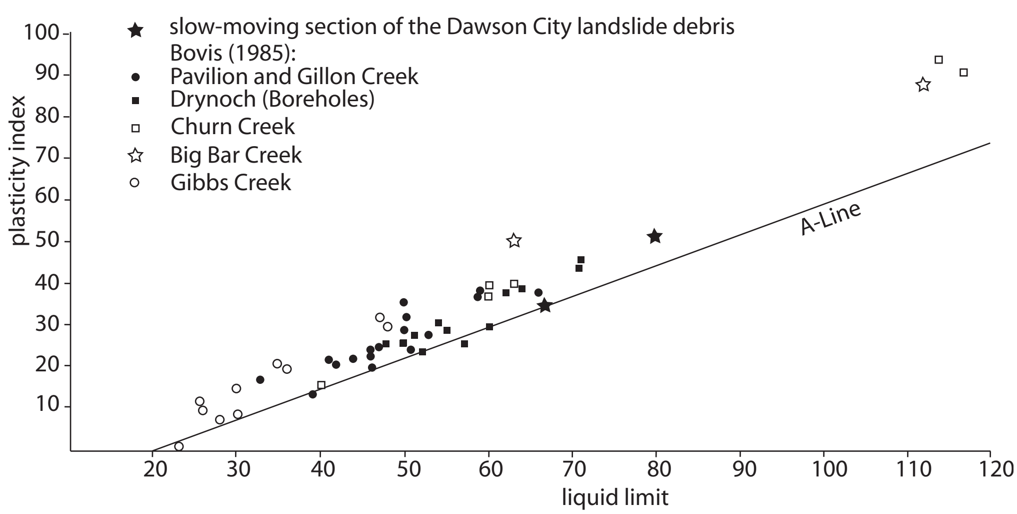


Figure 11. *Plasticity index vs. liquid limit plot for the soil samples collected from the snout of the moving debris at the Dawson City landslide compared with previously published values from Bovis (1985). Soil samples which plot above the A-line have mechanical behaviours dominated by clay while samples that plot below it have mechanical behaviours dominated by silt (British Standard Institute, 1981).*

by slope movements produce reaction wood on their downslope side in order to bend vertically again. Since this damage reflects slow and incremental movement (Wilford *et al*., 2005), the study of tree rings may be useful for constraining the age of a mass movement and can also indicate the progression of movement through an area.

Four split trees were examined to determine current movement rates of different portions of the Dawson City landslide. Split trees occur along sheared trenches, parallel to the edge of the middle to lower landslide deposit and above the active headscarp. These trees were cored in July, 2006 and are being examined as part of a larger dendrogeomorphology study on split trees. Tension cracks and trenches were also observed throughout the landslide site. In areas with thick organic soil, stretched roots spanned several tension cracks.

A small birch tree growing near the western margin of the moving section of the landslide debris is of particular interest (Fig. 3). A large root from this tree has been sheared from the trunk, which is now growing 1.9 m downslope of the sheared root (Fig. 12). A core was taken from the tree and indicates that the tree is between 40-45 years old. From this date, it can be interpreted that this portion of the northeast lateral tension crack has moved at least 1.9 m in less than 40 years. This suggests that the moving section of the debris has a minimum average differential movement rate of 4.5 ± 0.25 cm/yr.

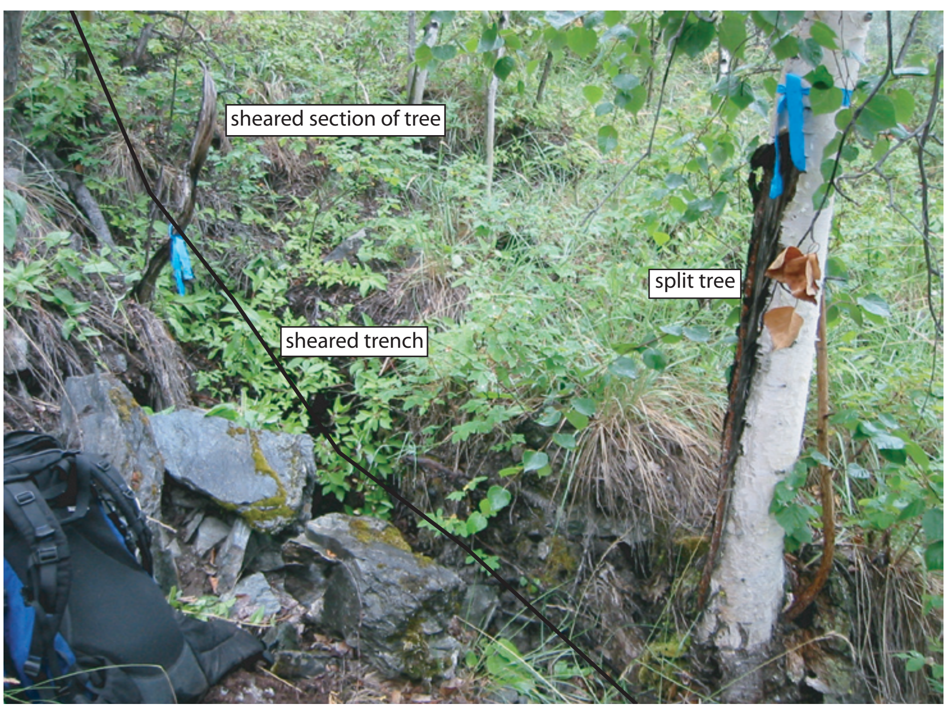


Figure 12. *Split tree that was cored along the western edge of the moving section of the landslide debris.*

MONITORING PROGRAM INITIATED

Several techniques are being attempted to monitor movement rates of the different sections of the Dawson City landslide. Three arrays of stakes (two on the 'stable' side and one on the 'unstable' side) were installed along the tension crack outlining a potentially unstable block above the central portion of the headscarp. A tape measure will be used to periodically measure the distance between the stakes on either side of the tension crack (Fig. 3). This approach should allow estimates of movement rate and direction with a precision of about 1 cm.

On the lower and middle portion of the landslide debris, nine steel survey pins were installed in July, 2006. Their precise locations were measured using a Thales ProMar3-differential Global Positioning System (DGPS), with a field precision of <1 cm. The pins will be resurveyed annually (or more frequently if significant movement is detected) in order to characterize the movement rates and directions of the landslide debris. The locations of the survey pins are shown on Figure 3 and their locations are given in the Appendix 1. As described in the previous section, tree coring of split and bent trees is also being used to estimate movement ages and rates for both the lower landslide debris and the potentially unstable block above the headscarp.

DISCUSSIONS

LANDSLIDE FAILURE MECHANISM

Brideau *et al*. (in press) evaluated the kinematic feasibility of translational sliding, toppling or wedge failure. Our studies found that toppling and sliding are only marginally feasible, and neither of these simple failure modes can explain the geomorphic features and rock-mass characteristics observed at the site. While the intact rock strength of the material varied considerably (as estimated by the point load tests), it is the highly fractured nature of the outcrops (five major and two subordinate discontinuity sets) that results in a weak rock-mass strength. A pseudo-circular failure mechanism is therefore proposed to explain the failure mechanism similar to those generally described in soil slope failure. Numerical modeling using limit equilibrium and finite difference codes suggests that this type of circular failure is only possible with high pore-water pressures, and seismic acceleration.

MECHANISM OF SLOW MOVEMENT IN LANDSLIDE DEBRIS

The question of whether the slowly moving landslide debris should be considered an earth flow or a rock glacier is a challenging one. While several key characteristics that define earth flows and rock glaciers are exhibited in the Dawson City landslide, several others are lacking and there is no intermediate terminology to better describe the movement behaviour.

Rock glaciers are defined by Haeberli *et al*. (2006, p. 190) as "steadily creeping and perennially frozen ice-rich debris on a non-glacierised mountain slope". They usually have a lobate or tongue-shaped appearance extending outwards and downslope from talus cones or from glaciers (Martin and Whalley, 1987; Giardino *et al*., 1987). The fundamental dynamic process of rock glaciers is creep within permafrost (Haeberli *et al*., 2006). Rock glaciers can be talus-fed with further episodic inputs of re-worked clastic material from small debris flow/avalanches (Barsch, 1996).

Earth flows are defined by Hungr *et al*. (2001) as intermittent flow-like movement of plastic clayey earth. A ternary diagram of material making up earth flows presented by those authors reveals that up to 40% per weight can be composed of gravel-sized material. Earth flows in weathered fine-grained sedimentary material (siltstone and shale) and volcanic rocks have been described in southern British Columbia by Bovis (1985) and VanDine (1980). Hungr *et al*. (2001) suggest that a balance exists between material supply (from headscarp retrogression via slumps or falls) and material removal at the toe (from fluvial erosion or by anthropogenic action). They also suggest that pore pressure controls the rate of movement of earth flows.

Table 3 summarizes the key characteristics that are generally associated with earth flows and rock glaciers, and indicates which of them are found at the Dawson City landslide. Several characteristics of the middle to lower section of the debris at the Dawson City landslide are common to both rock glaciers and earth flows, including its elongated lobate shape and presence of sheared trenches and split trees. The presence of the steep snout at the terminus, a boulderly 'carapace'

Table 3. *Summary of characteristics of rock glaciers and earth flows, and evidence for their presence in the moving section of the Dawson City landslide debris (X indicates characteristic feature).*

Characteristics	Rock glacier	Earth flow	Observed in moving section of the landslide deposit in Dawson City
elongated shape with lobate terminus in plan view	X	X	yes
sheared trenches along edge of moving section	X	X	yes
split trees an indication of current state of activity	X	X	yes
ice-rich core	X		no
steep snout at terminus	X		yes
seepage in terminus zone	X		no
boulder 'carapace' overlying gravely diamicton	X		yes
occurrence at low elevation above sea-level		X	yes
occurrence on south-facing slopes	rare	X	yes
grain-size distribution dominated by gravel-size and larger material	X		yes
high plasticity index of fine material	unknown	X	yes

overlying gravelly diamicton, and a grain-size distribution dominated by gravel-size and larger material supports the rock glacier classification. However, the lack of an ice-rich core and seepage in the terminus zone, as well as the south-facing aspect and low elevation, provides more support for the earth flow classification. At this early stage in our investigations it is difficult to decide which classification is more dominant, but our field observations slightly favour a rock glacier interpretation.

CONCLUSIONS

The Dawson City landslide occurred predominantly in altered ultramafic rock that is heavily fractured with five dominant and two subordinate discontinuity sets. While the intact strength of the rock, as evaluated from point load tests, varies considerably its average value still corresponds to a strong rock. The fractured nature of the outcrop has reduced rock-mass strength, and led to probable pseudo-rotational failure.

Geomorphic evidence indicates that the middle to lower section of the landslide debris is currently moving. Preliminary dendrochonology results suggest that the minimum average movement rate is on the order of 4.5 cm/year. The moving debris exhibits traits common to both earth flows and rock glaciers. An array of survey pins was installed in July, 2006 to monitor and quantify movement of both the middle to lower portion of the debris and a potentially unstable mass of rock above the headscarp.

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Appendix 1. *Moosehide Slide Monitoring Network (July 26, 2006).*

Site No.	Occupation time (min)	Comments/Location	Easting	Northing	Elevation
			UTM Zone 7, NAD83		(m)
Moosehide Slide Differential GPS survey					
Dyke Bench Mark	32	NRCAN bench mark on dyke at south end of town	576126.770	7103962.889	334.426
Base Station	9 hrs 15 min	existing benchmark on dyke, at ferry landing	576735.886	7105541.625	333.434
MAB-06-18-1	30	rebar post in contoured debris	576937.413	7105781.203	361.822
MAB-06-18-2	21	rebar post in contoured debris	576976.878	7105809.586	373.597
MAB-06-18-3	24	rebar post at top of freshly exposed debris train toe	577096.079	7105900.851	399.512
MAB-06-18-4	18	rebar post on south flank near debris train toe	577119.580	7105874.333	405.826
MAB-06-18-5	26	rebar post halfway up debris train on south side	577158.807	7105888.599	428.911
MAB-06-18-6	32	rebar post in upper debris train, north flank	577172.752	7105914.620	441.403
MAB-06-18-7	28	wooden post in loose heaved material (significant fines)	577204.986	7105935.453	462.515
MAB-06-18-8	22	rebar post in stable levee on south flank	577235.723	7105913.771	467.829
MAB-06-18-9	25	rebar post on south flank, near fresh trench and split tree	577186.408	7105891.336	444.296
Handheld GPS coordinates					
MAB-06-18-10		1st crack monitoring site - big split spruce tree	577495	7106006	
MAB-06-18-11		2nd crack monitoring site - scarp about 1.5 m high	577493	7106012	
MAB-06-18-12		3rd crack monitoring site - scarp about 80 cm high	577486	7106033	