The Role of Permafrost in the 2002 Ten Mile Creek Debris Torrent, Yukon, Canada

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Yukon Energy, Mines and Resources

Yukon Geological Survey

Introduction

In June 2002, a catastrophic debris torrent travelled 4.7 km down Ten Mile Creek, descended 500 vertical metres and crossed the North Klondike Highway, 12 km southeast of the town of Carmacks (Figure 1).

Field evidence indicates that the debris torrent was triggered by a blow-off or permafrost-detachment style of landslide that occurred on a moderate slope in the headwaters of Ten Mile Creek (Figures 2 & 3). The landslide is attributed to elevated pore pressure beneath thin permafrost during the spring snowmelt season.

This mechanism of failure is unique in comparison to other permafrost-related landslides (i.e. retrogressive thaw failures and active-layer detachments) documented in the region (Lipovsky et al. 2006, Lipovsky & Huscroft 2007, Lyle 2006).

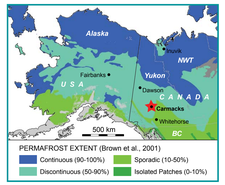


Figure 1. The debris torrent initiated 15 km southwest of the town of Carmacks.

Figure 2. The debris torrent initiated in the headwaters of Ten Mile Creek, and flowed 4.7 km down to the North Klondike Highway.

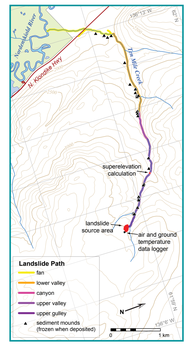


Figure 3. Location map showing path of debris torrent and key site features.

Landslide Description

Source Zone Landslide Features:

- located at 1084 m elevation on moderately steep (27°) north-facing slope
- boreal forest cover consisting of low shrubs, mosses and mature spruce trees
- bowl-shaped scar up to 160 m wide by 100 m long (Figure 4A)
- steep headwall is 12-31 m high with active retrogression (Figure 4A)
- springs flow from the floor of the bowl

Debris Torrent Features:

- Following the initial failure, an ensuing debris torrent descended 500 m in elevation and traveled 4.7 km down the narrow v-shaped valley of Ten Mile Creek.
- The main debris lobe came to rest after crossing the North Klondike Highway, clogging its culvert and filling the adjacent ditch with debris.
- Superelevation measurements taken on a channel bend in the runout zone (Figure 4B) indicate that the torrent traveled at a maximum velocity of 11 m/s (40 km/hr) with a peak discharge of 1300 m3/s.
- Along much of the debris torrent path, a swath of trees averaging 35 m wide was cleared through mature forest adjacent to the former stream channel (Figure 4C).
- Silty loam diamicton (with 35-43% coarse fragments) was deposited up to 1.3 m thick along most of the debris torrent path, except within a 600-m long canyon segment confined by steep rock walls. Hardened debris was also found up to 6 m high up tree trunks adjacent to the flow path (Figure 4D).
- Ongoing remobilization of these deposits by subsequent stream flow has caused sedimentation of local salmon habitat at the mouth of the creek where it flows into Nordenskiold River (Figure 4E).

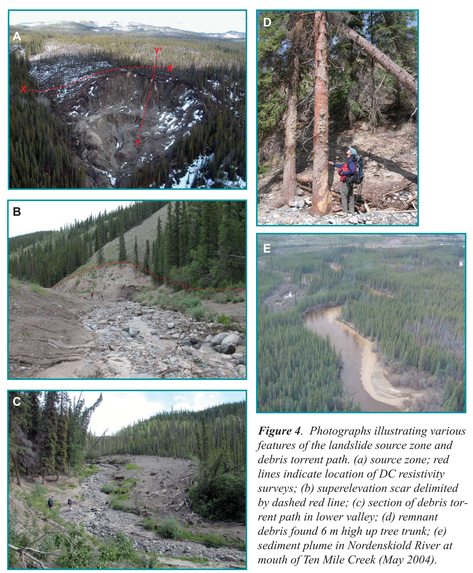


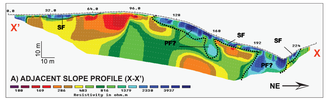
Figure 4. Photographs illustrating various features of the landslide source zone and debris torrent path. (a) source zone; red lines indicate location of DC resistivity surveys; (b) superelevation scar delimited by dashed red line; (c) section of debris torrent path in lower valley; (d) remnant debris found 6 m high up tree trunk; (e) sediment plume in Nordenskiold River at mouth of Ten Mile Creek (May 2004).

Local Permafrost Conditions

Ten Mile Creek is located within Yukon's extensive discontinuous permafrost zone (Figure 1). Permafrost is commonly found on north-facing slopes in this region, particularly beneath thick organic mats associated with boreal forest cover.

Surface Probing
Surface probing behind the landslide headwall in late summer 2004 indicated an active layer thickness of 42-86 cm where the organic mat was at least 40 cm thick. Where the organic mat was thinner, the permafrost table was not encountered within 1.05 m of the ground surface, however it was assumed to be present at greater depth. Thermistor measurements and lateral probing into the lower headwall did not detect permafrost in the glaciofluvial unit at this time (ground temperatures 1 m into the face were ~1°C).

DC Resistivity Surveys
DC resistivity surveys conducted in 2006 suggest that permafrost is up to 5 m thick on the gentle north-facing slope behind the landslide headwall, and up to 15 m thick on the steeper north-facing slope adjacent to the landslide source zone. The resistivity surveys also confirmed the absence of permafrost in the landslide headwall, implying that rapid lateral thaw has occurred since the failure occurred in 2002.



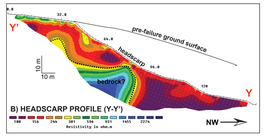


Figure 5. Resistivity profiles suggest that permafrost is between 5-15 m thick adjacent to the landslide source area. Locations of profiles are shown in Figure 4A. SF = seasonal frost; PF = permafrost.

Geomorphic Evidence
Surficial geological materials exposed in the landslide headwall consist of a stony till blanket up to 12.5 m thick overlying at least 22 m of glaciofluvial sand and gravel exhibiting prominent bedding structures. Local bedrock consists of Upper Cretaceous volcaniclastic and basalt lithologies.

At numerous locations up to 3.7 km downstream from the source zone (Figure 3), discrete blocks of sandy material deposited by the debris torrent and originating from the lower glaciofluvial unit show intact primary bedding structures (Figure 6).

In order to preserve these features over such a long transport distance, the sediment must have been frozen both before and during transport. This implies that permafrost must have extended into the sandy unit found at least 12.5 m below the ground surface in the landslide source zone.

Figure 6. Sediment mound formed of landslide debris found over a kilometer downstream from the source zone. The preservation of bedding inclined to the ground surface indicates that the material was frozen when it was transported.

Landslide Failure Mechanism

Unfrozen glaciofluvial sand and gravel exposed in the lower unit of the landslide headwall are highly permeable and porous, with a capacity to store and transmit a large amount of groundwater. This is confirmed by the presence of springs flowing from the floor of the landslide source zone scar.

Based on aerial photograph interpretation, these sediments are part of a larger geological unit consisting of bedded glaciofluvial deltaic materials that extend laterally further upslope and capture groundwater from the upper drainage basin.

As a result of this geomorphic configuration, the site of the landslide source area represents the location of greatest groundwater convergence within that basin. We therefore hypothesize that the base of the impermeable permafrost layer within these sediments confined groundwater flow and allowed high pore pressures to accumulate below the permafrost during the spring snowmelt period in June 2002.

During the same time period, no abnormal precipitation was recorded and no earthquakes occurred in the vicinity. We suggest that pore pressures increased until a threshold was reached that allowed rupture or "blow-off" (Cavers 2003) of the unfrozen materials and detachment of the entire permafrost layer above (Figure 7).

We infer that subsequent rapid drainage of stored groundwater supplied a large volume of water which facilitated the catastrophic debris torrent. Similar failure mechanisms are common in non-permafrost areas throughout western Canada where groundwater pressures are instead confined by surficial material stratigraphy rather than by frozen ground (Cavers 2003). Alternatively, the initial movement could have partially blocked a small stream channel to the north-east allowing water to accumulate in a pond. However, we were unable to locate any evidence of such ponding in the field.

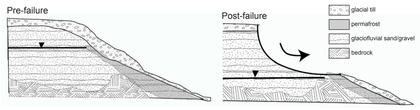


Figure 7. Schematic representation of surficial geology stratigraphy and landslide failure mechanism. We hypothesize that the permafrost layer restricted groundwater flow and allowed pore pressure to accumulate until a threshold value was reached which facilitated detachment of the permafrost layer.

Regional Climate Trends
Local and regional climatic data show that at least four decades of climate warming have occurred in central Yukon since 1930 (Figure 8). Any corresponding permafrost warming and/or thinning may have weakened the permafrost layer and lowered the pore pressure threshold required to initiate a failure and cause detachment. Data loggers were installed in 2005 to monitor the long-term air and ground surface temperatures above the landslide source zone.

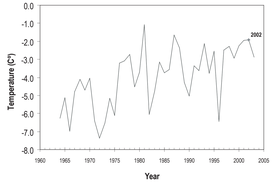


Figure 8. Annual air temperature trends in central Yukon since 1963. Data were compiled using climate records from Carmacks, Mayo and Pelly Ranch, and records from a weather station installed near the landslide source zone in 2005.

Implications

The blow-off/permafrost detachment mechanism of failure in the Ten Mile Creek landslide differs from other styles of permafrost-related landslides previously documented.

Key factors necessary to produce failures of this style include: large volumes of groundwater storage, concentrated groundwater convergence, and the presence of a thin permafrost layer.

Permafrost detachment failures can be recognised using several features, including: their bowl-shaped source zones; springs at the base of the slope; evidence of large volumes of water and high mobility; one-time occurrence (not poly-cyclic); and transportation of large blocks of frozen sediment.

The results of this study have important implications for future development and land use planning in the area as the geomorphic setting of the landslide source zone is widespread throughout much of central Yukon.

This case study illustrates that significant hazards are associated with these types of landslides, and highlights the need to perform detailed evaluations of basin characteristics, permafrost conditions and surficial material stratigraphy several kilometers upslope of any area targeted for human land use.

In particular, stream crossing designs and development on fans in permafrost regions should carefully consider the risk of debris torrents triggered by groundwater blow-off failures beneath frozen ground.

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References

Brown, J., O.J. Ferrians, Jr., J.A. Heginbottom, and E.S. Melnikov. 1998, revised February 2001. Circum-arctic map of permafrost and ground ice conditions. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology. Digital media.

Cavers, D.S. 2003. Groundwater blow-off and piping debris flow failures. 3rd Canadian Conference on Geotechnique and Natural Hazards, June 9-10, 2003, Edmonton, Alberta, Conference Proceedings: 151-158.

Lipovsky, P. & Huscroft, C. 2007. A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed, central Yukon. In: Yukon Exploration and Geology 2006, D.S. Emond, L.L. Lewis & L.H. Weston (eds.), Yukon Geological Survey: 181-195.

Lipovsky, P.S., Coates, J., Lewkowicz, A.G. & Trochim, E. 2006. Active-layer detachments following the summer 2004 forest fires near Dawson City, Yukon. In: Yukon Exploration and Geology 2005, D.S. Emond, G.D. Bradshaw, L.L. Lewis & L.H. Weston (eds.), Yukon Geological Survey: 175-194.

Lyle, R.R. 2006. Landslide susceptibility mapping in discontinuous permafrost, Little Salmon Lake, Central Yukon. M.Sc.E. Thesis. Queen's University. 351 p.

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