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

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Introduction

In June 2002, a catastrophic debris torrent initiated from a moderate north-facing slope in the headwaters of Ten Mile Creek, in central Yukon, Canada. Field evidence indicates that permafrost was a major contributing factor that caused an initial landslide which then triggered the debris torrent. The mechanism of failure in the initial landslide appears to be 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).

Setting

The landslide source zone is located at 1084 m elevation, 15 km southeast of the town of Carmacks in central Yukon, Canada (61°58′45.4″N, 136°08′20.7″W). Based on field observations and aerial photograph analysis of the terrain immediately surrounding the source zone, the pre-failure slope is estimated to have been moderately steep (up to 27°) with a typical boreal forest cover consisting of low shrubs, mosses and mature spruce trees.

The landslide left a bowl-shaped scar up to 160 m wide and 100 m long with a steep headwall 12–31 m high (Fig. 1). Springs flow from the base of a secondary slump scar in the floor of this bowl. 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 South Klondike Highway, clogging its culvert and filling the adjacent ditch with debris. Superelevation measurements taken on a channel bend in the runout zone indicate that the torrent traveled at a maximum velocity of 11 m/s (40 km/hr) with a peak discharge of 1300 m^3/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. Silty loam diamicton (containing 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. 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.

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. At numerous locations up to 3.7 km downstream from the source zone, discrete blocks of sandy material deposited by the debris torrent and originating from this lower glaciofluvial unit show intact primary bedding structures. 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 in the landslide source zone permafrost must have extended into the glaciofluvial unit found at least 12.5 m below the ground surface.

Local Permafrost Conditions

Ten Mile Creek is located within Yukon's extensive discontinuous permafrost zone. Permafrost is commonly found on north-facing slopes in this region, particularly

Figure 1. Aerial view of landslide source zone showing debris torrent channel exiting at lower left corner. Maximum height of the headwall is 31 m and the bowl is approximately 160 m wide.

beneath thick organic mats associated with boreal forest cover.

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 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 (Fig. 1). 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.

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 hypothesize, therefore, 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.

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 northeast allowing water to accumulate in a pond. However, we were unable to locate any evidence of such ponding in the field.

Local and regional climatic data show that at least four decades of climate warming have occurred in central Yukon since 1930. 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. Dataloggers were installed in 2005 to monitor the long-term air and ground surface temperatures above the landslide source zone.

Implications

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 this type of landslide. It also 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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