Mapping geohazards to support climate adaptation on Yukon’s transportation network

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Abstract

The Government of Yukon’s Department of Highways and Public Works and the Yukon Geological Survey are jointly developing a geohazard inventory and hazardous landform database to assess climate-driven hazards to Yukon’s transportation network. Climate-change effects, such as accelerating permafrost thaw and an increase in extreme precipitation events, are contributing to a rise in geohazards that threaten the reliability and safety of major road corridors. The inventory integrates field observations, remote sensing, historical reports, and maintenance history to identify ten types of geohazards and eight hazardous landforms associated with permafrost thaw and slope deformation. As of November 2025, 934 geohazard points and over 3000 hazardous landforms have been mapped on the road network. Preliminary results highlight subsidence, icing and river encroachment as the most widespread geohazards. Case studies from the North Canol Road, South Klondike Highway and Dempster Highway illustrate how permafrost degradation, slope instability and extreme weather interact to impact transportation infrastructure. The hazard inventory and associated risk-assessment tools will support proactive adaptation, monitoring, and mitigation planning across the Yukon’s road network.

Plain language summary

Much of Yukon’s road network is exposed to hazards from permafrost, steep mountain slopes or rivers, making these areas vulnerable to problems such as ground settling from permafrost thaw, landslides, rockfalls and flooding. As climate changes, these hazards are becoming more common and more damaging, creating challenges for keeping roads safe and open. To help manage associated risk, the Yukon Geological Survey and the Government of Yukon’s Department of Highways and Public Works are creating a territory-wide geohazard inventory and hazardous landform map. Using field inspections, imagery and road maintenance history, the project identifies where hazards are occurring, how they are changing over time, and which locations pose the greatest risk to roads. This information will help the Government of Yukon plan maintenance, prioritize risk mitigation projects, and reduce long-term costs. Furthermore, this will improve safety and reliability for people who travel these roads, and to the communities that are served by them.

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Introduction

The Yukon Geological Survey (YGS) and Highways and Public Works (HPW) are collaborating to create a geohazard inventory and hazardous landform database for Yukon roadways. Climate change in the Yukon is accelerating permafrost thaw and increasing extreme weather events such as extreme precipitation (Vincent et al., 2015), thereby raising the risk of geohazards such as slope failures, river flooding, erosion, and permafrost subsidence (Huscroft et al., 2004; Lantuit et al., 2008; Perrin and Jolkowski, 2022; Grenier et al., 2024). This trend poses increasing maintenance and safety challenges for transportation corridors as extensive segments of the territorial road network are built across permafrost terrain, along steep mountainous areas, or adjacent to rivers. Disruptions to the transportation network can delay other crucial systems such as food distribution (Perrin and Jolkowski, 2022) and fuel transport. Given the importance of road networks in the Yukon for community and resource access, there is a need to track geohazards to support proactive adaptation, maintenance planning, and risk reduction.

The Yukon's road network spans thousands of kilometres, stretching from the northern extent of British Columbia to the Arctic Circle. The climate is characterized as subarctic continental, marked by dry conditions, short cool summers, and long, cold winters having some of the greatest temperature extremes in Canada (Smith et al., 2004). Mean annual air temperatures range from about -2°C in the southern valleys to below -10°C along the Arctic coast. Annual precipitation varies widely with topography, from 250–300 mm in low-lying valleys to over 600 mm in higher mountain ranges, as orographic barriers influence the movement of maritime and Arctic air masses (Smith et al., 2004).

Permafrost is widespread across the Yukon, transitioning from continuous permafrost in the north, to discontinuous and sporadic zones in the south (Fig. 1; Smith et al., 2004). The thickness and temperature of permafrost vary considerably with latitude, elevation and surficial materials. Ground ice content varies considerably based on permafrost distribution, surficial geology, glacial history and paleo-vegetation (O'Neill et al., 2019). Ground ice content is often high in glaciolacustrine and organic-rich sediment, whereas materials like fluvial and glaciofluvial gravel are commonly ice poor. Permafrost degradation and thaw-related geohazards are increasingly evident across central and southern Yukon, particularly in response to climate warming and surface disturbance.

Recent analysis of maintenance-cost records for the territorial highway network in the Yukon revealed a clear linkage between climate-driven changes in permafrost environments and escalating infrastructure costs. Schetselaar and Burn (2024) show that annual climate-related maintenance expenditures (e.g., snow removal, icing control, landslide/washout repair) increased from approximately C$6.6 million in 1994–1999 to C$10.2 million in 2017–2022 (in constant 2021 dollars), with an average annual growth of roughly C$169 000. They further demonstrate that highway sections situated in extensive discontinuous and continuous permafrost zones incur per-kilometre maintenance costs more than 50% higher than those in areas of sporadic or isolated permafrost patches (Schetselaar and Burn, 2024).

Our geohazard inventory focuses on all major transportation corridors within the Yukon, and mapping has been completed for almost all high and medium-high priority roads (Fig. 1). Given the growing risks associated with climate-driven geohazards, a comprehensive inventory is crucial for ensuring the long-term stability and safety of the Yukon's major transportation corridors.

Methodology

This project consists of two spatial datasets: the geohazard inventory and the hazardous landform database. The geohazard inventory is a point layer that identifies segments of the road that are at risk of being impacted by a geohazard. The hazardous landform database is a series of polygons that are within 250 m of either side of the road. Each polygon delineates the extent of a landform, many of which are associated with a geohazard point (Table 1).

The spatial datasets are maintained in a GIS-based relational database, which enables integration with existing highway asset management systems and facilitates visualization of geohazard locations, and potential impacts to the road. Mapping of roads is prioritized based on traffic usage, and social and economic functions.

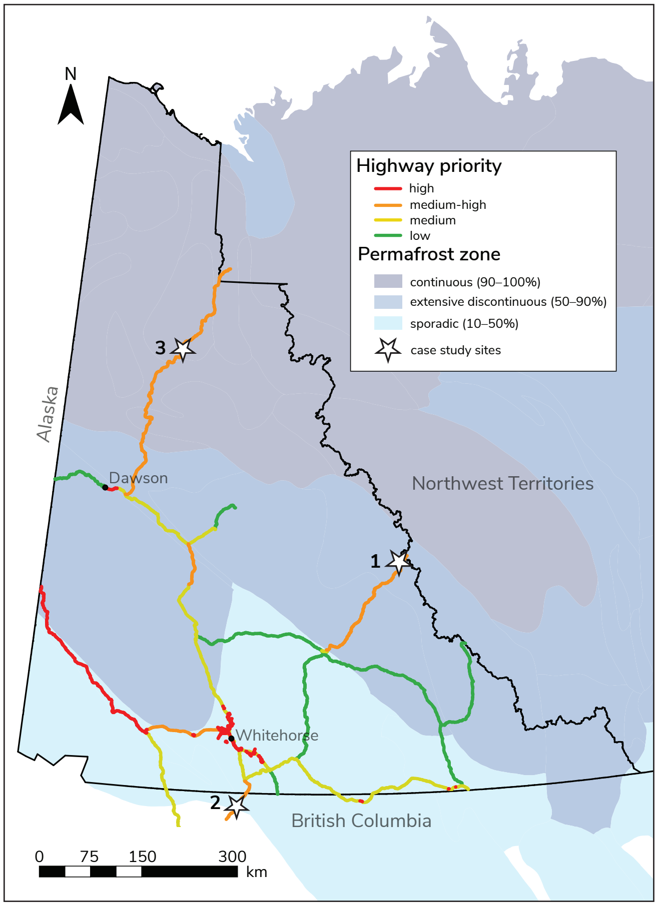

***Figure 1.** Permafrost zones, case study locations, and priority of road network within the Yukon. Case studies: 1 – North Canol Road rock glacier; 2 – South Klondike Highway debris flow; 3 – Dempster Highway embankment failure.*

The geohazard inventory identifies ten primary geohazard types: fast and slow-moving landslides, rockfalls, snow avalanches, erosion, subsidence, washouts, flooding, icing, and encroachment (Table 2). Each geohazard is recorded as a geolocated point along the road network and linked to a detailed attribute table describing its type, location, affected road length, activity state, and associated risk variables.

The hazardous landform database identifies seven types of landforms: fast and slow-moving landslides, avalanche paths, gullies, ice-wedge polygons, permafrost mounds, and thermokarsts (Table 1). Each landform is mapped as a polygon and assigned a landform type, location, imagery type and date, surficial material, and activity state. The landforms are tied to polygons and are assigned a date so they can be re-mapped once new imagery or lidar becomes available. This allows for tracking the change in extent over time. In the database, geohazard points are linked to the mapped landforms that they are associated with.

There are three main steps in creating the geohazard inventory: (1) identifying geohazards, (2) inspecting geohazards, and (3) assessing geohazard risk.

Identifying geohazards

Geohazards are identified using multiple information sources, including academic and consultant reports, highway maintenance staff observations, field inspections, satellite imagery, and lidar datasets. Data collection focuses on both historical and active geohazard sites, ensuring that the inventory captures long-term hazard activity as well as recent events.

Many geohazard points are also linked to polygons in the hazardous landform database that delineate the spatial extent of the underlying process and track its evolution over time. These landforms are delineated using lidar, high-resolution satellite imagery, and field-based mapping. Polygons representing active processes, such as subsidence due to ice-wedge thaw, are linked to a geohazard point if they pose a threat to the road. These polygons are temporally variable and allow for monitoring of spatial change, thereby improving understanding of hazard evolution.

Inspecting geohazards

Targeted field inspections were conducted in the summer of 2025 on high, medium-high, and medium priority roads to verify remote-sensing interpretations, update activity states, and record field measurements such as slope geometry and surface displacement. Sites will be revisited on a regular monitoring cycle, and updates will be recorded directly in the database. This iterative process ensures that the geohazard inventory reflects current field conditions and provides a foundation for ongoing risk assessment.

Assessing geohazard risks

Risk matrices are being developed for each of the ten geohazard types (Table 3). The risk matrices include two components: hazard and consequence. Hazard is the product of another two components: magnitude and frequency. Magnitude is the size of

Table 1. Landform types with their definitions and associated geohazard.

Landform	Definition	Associated geohazard
fast-moving landslide	Scar from rapid sliding or flowing of material (disintegrating or cohesive soil, debris, mud, rocks, etc.) downslope.	fast-moving landslide
slow-moving landslide	Ground that is slowly deforming or creeping downslope (e.g., rock glacier, solifluction).	slow-moving landslide
avalanche path	Path where snow and ice, as well as entrained debris, move rapidly downslope by flowing or sliding.	avalanche
gully	Narrow ravines that are parallel and sub-parallel produced by shaping of consolidated and unconsolidated materials by various processes (Resource Inventory Branch, Ministry of Environment, Lands and Parks, 1997). Can be a thermokarst gully.	erosion
ice-wedge polygons	A polygon on the ground surface outlined by connected ice wedges (massive ice feature) beneath its borders (Lewkowicz et al., 2024; Lewkowicz et al., 2025).	subsidence
permafrost mound	Any mound-shaped landform produced in periglacial environments by frost action. Includes palsas, lithalsas, pingos and peat plateaus.	subsidence
thermokarst	Landforms resulting from ice-rich permafrost thaw (Lewkowicz et al., 2025). Includes depressions, ponds and beaded streams.	subsidence

a potential event, and frequency is the known or estimated rate of event occurrence over a length of time. In the case of rockfall, magnitude would consider the potential size of blocks that could fall based on joint configuration and the size of historical rockfall. Frequency would be estimated based on highway maintenance records, the recency of rock debris in the ditches, and the condition of the rock mass.

Consequence is assigned a number from one to six which describes the potential impact of an event to the condition of the road. For example, permafrost subsidence that affects an asset such as a culvert will be assigned a higher consequence rating than subsidence where no major asset is present.

Magnitude, frequency and consequence are estimated based on variables measured in the field, collected through conversations with highway maintenance staff, and determined from remote sensing data. These variables change with the type of geohazard. As such, a risk assessment will be completed for each geohazard separately. This basic risk assessment will highlight high-risk geohazards, and inform prioritization of monitoring and mitigation projects, allowing for improved risk management.

Preliminary results

As of November 2025, 1670 km of the 4828 km of highway, community roads and resources roads maintained by the Government of Yukon have been mapped for geohazards. This includes the South and North Klondike, Alaska and Dempster highways, and the North Canol Road. The geohazard inventory includes a total of 934 recorded geohazard points (Fig. 2).

The most prevalent geohazard is subsidence, with 446 mapped occurrences, followed by icing (144) and encroachment (97). Other notable categories include fast-moving landslides (71), rockfalls (50), snow avalanches (51), washouts (50), slow-moving landslides (15), and erosion (10; Fig. 3).

Additionally, 3093 hazardous landforms have been delineated along 2257 km of road. The roads that have been mapped are the Alaska Highway, the North and South Klondike highways, the Dempster

Table 2. Geohazard types in the inventory and their definitions.

Geohazard	Definition
fast-moving landslide	Rapid sliding, flowing or descent of material (disintegrating or cohesive soil, debris, mud, rocks, etc.) downslope.
slow-moving landslide	The slow deformation or creep of ground downslope (e.g., rock glacier, solifluction).
rockfall	The detachment and subsequent falling, rolling or bouncing of individual rock fragments or clusters.
avalanche	Snow and ice, as well as entrained debris, moving rapidly downslope by flowing or sliding (Resource Inventory Branch, Ministry of Environment, Lands and Parks, 1997).
erosion	The shaping of consolidated and unconsolidated materials by various processes, producing long narrow parallel and sub-parallel ravines (Resource Inventory Branch, Ministry of Environment, Lands and Parks, 1997). Can be a thermokarst process.
subsidence	Sinking of the ground surface due to the thaw of underlying ice-rich permafrost.
encroachment	Progressive erosion of riverbanks caused by meander migration or rapid erosion caused by abrupt channel diversion.
washout	Rapid erosion of a road embankment from a creek or river in flood, or from a beaver dam failure.
flooding	When the water level in a river of lake rises above its banks and floods the surrounding land, or when the groundwater table rises resulting in standing water.
icing	Groundwater that freezes at the ground surface, or river water that freezes above the ice cover as it is forced up by pressure, causing thick sheets of ice to form.

Table 3. Evaluation matrix used for assessing risk of geohazards along roadways. Consequence and hazard levels are determined based on set variables that are observed in the field, measured from remote sensing data, or noted during conversations with highway maintenance staff.

Hazard	Very high - 6	Low (6)	Significant (12)	High (18)	Very high (24)	Very high (30)
	High - 5	Low (5)	Moderate (10)	Significant (15)	High (20)	Very high (25)
	Significant - 4	Low (4)	Moderate (8)	Significant (12)	High (16)	High (20)
	Moderate - 3	Very low (3)	Low (6)	Moderate (9)	Significant (12)	Significant (15)
	Low - 2	Very low (2)	Low (4)	Low (6)	Moderate (8)	Moderate (10)
	Very low - 1	Very low (1)	Very low (2)	Very low (3)	Low (4)	Low (5)
		Minor - 1	Moderate - 2	Significant - 3	Major - 4	Catastrophic - 5
		Consequence				

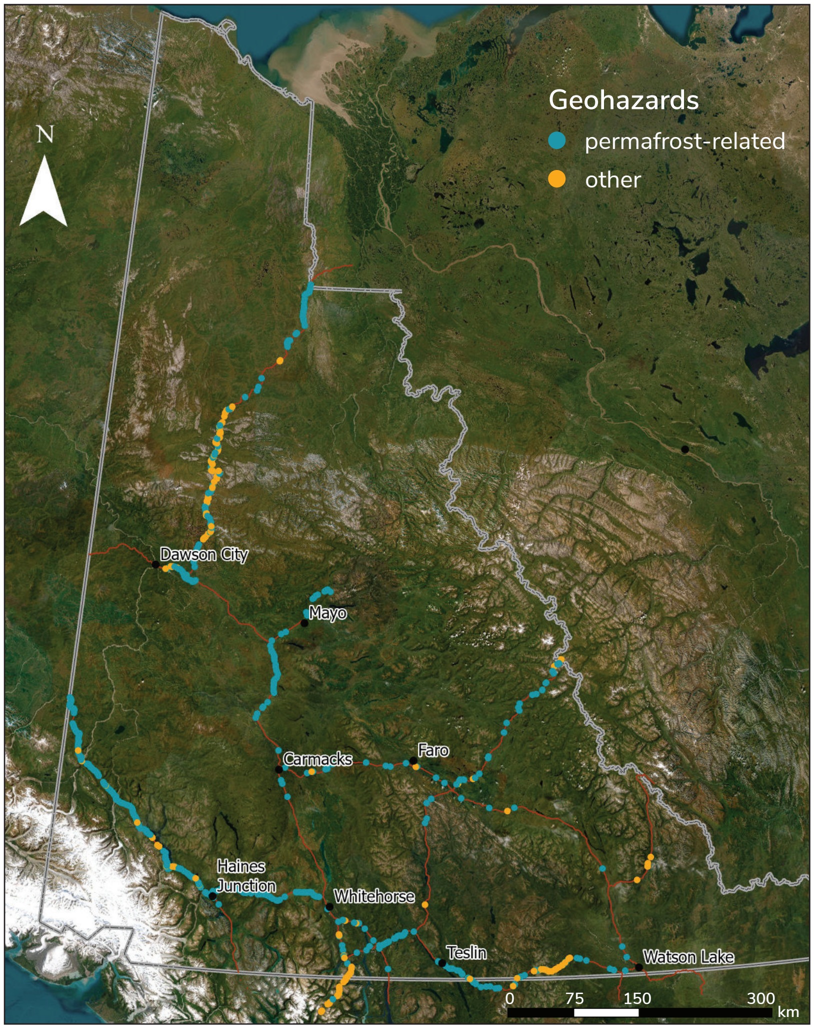

Figure 2. *Map of Yukon highways and resource roads with permafrost-related geohazards noted in blue and other geohazards noted in orange.*

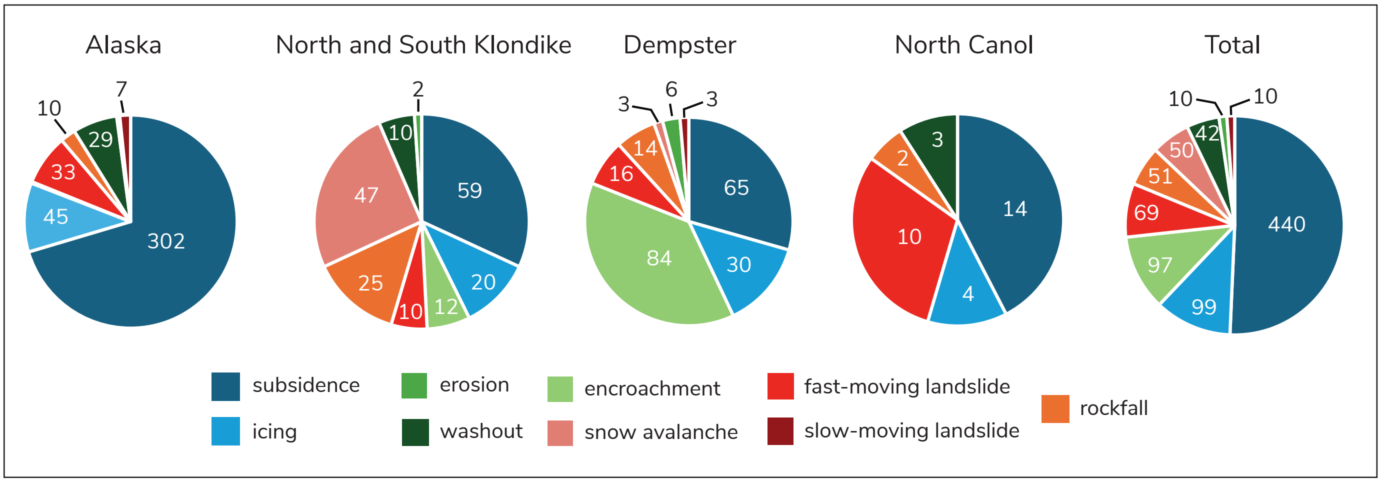

Figure 3. *Number of occurrences of each geohazard type by highway/road. Geohazard types not listed did not have enough mapped occurrences to be visible in the chart.*

Highway, and the North Canol Road. To date, the landform with the most mapped occurrences is thermokarst, which has been identified 1529 times. Following thermokarst is fast-moving landslides (572), permafrost mounds (335), ice-wedge polygons (253), gullying (88), avalanches (85), and slow-moving landslides (59; Fig. 3).

Case studies

North Canol Road rock glacier encroachment

Macmillan Pass is a mountainous region located at the border between the Yukon and Northwest Territories (NWT). There is a high density of rock glaciers in this area, many visible from the North Canol Road. A rock glacier is a tongue-shaped mass of ice-rich debris that creeps downslope through internal deformation. Rock glaciers are mapped in the geohazard database as slow-moving landslides. A rock glacier was identified very close to the road at KM 455 of the North Canol Road, approximately 5.6 km southwest of the NWT border (Figs. 1 and 4). This feature is located between Fireweed Metals' Macpass and Mactung projects, so there is frequent vehicle traffic along this section of the road.

The toe of the rock glacier on the North Canol Road has encroached onto the road, and regular debris clearing is required by maintenance crews to ensure the road is passable (Fig. 5). The toe of the rock glacier is up to 18 m thick on the road surface. Old tension cracks were visible in the 1949 and 1974 air photos near the top of the rock glacier; however, more recent tension cracks were captured in 2013 satellite imagery and formed sometime between 1974 and 2013; these are shown in lidar imagery from 2019 (Fig. 6).

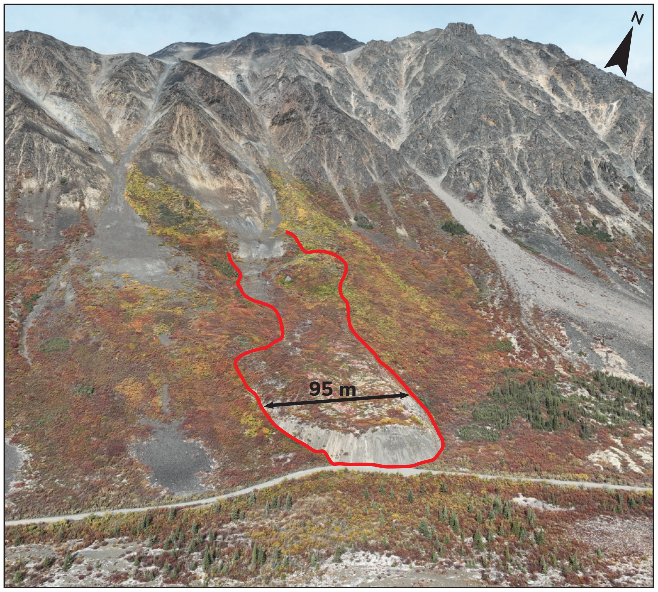

Figure 4. North Canol Road rock glacier, outlined in red.

Average displacement rates can be tracked using available lidar, satellite imagery and historic air photos. Two historic air photos of this area were available for 1949 and 1974, lidar was flown for 2012 and 2019, and high-resolution satellite imagery was available for 2013 and 2024. Using these we were able to calculate mean movement rates for each period bracketed by the imagery. From 1949 to 2024 the toe of the rock glacier advanced toward the road by a total of 13.8 m, on average. Advance is not uniform across the front of the rock glacier. In recent years there is greater advance on the western side of the toe, while there is little or no movement on the eastern side. Total displacement from 1949 to 1974 of the centre of the toe of the rock glacier was 19 m. From 1949 to 1974, the displacement across the toe of the rock glacier was 2.15 m, or an average of 0.09 m/year. Between 1974 and 2012, the toe of the rock glacier moved 6.47 m, or an average of 0.17 m/year. From 2012 to 2019, the advance

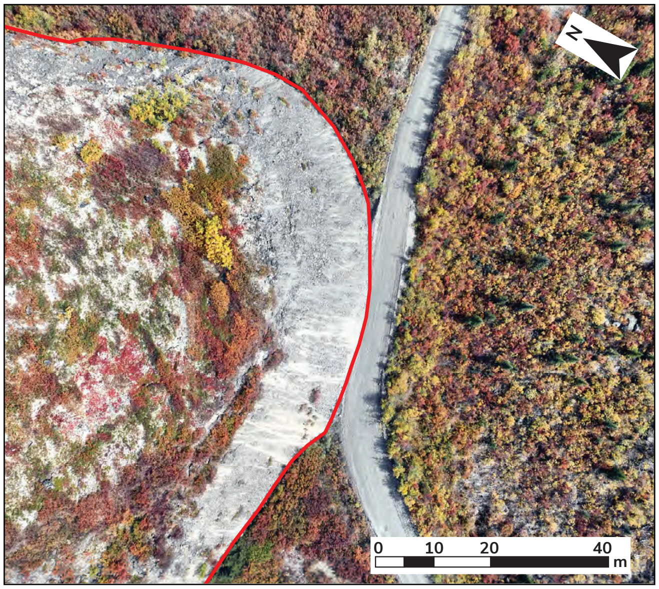

Figure 5. Birdseye view of the toe of the rock glacier (outlined in red) and its relative position to the North Canol road in September 2025.

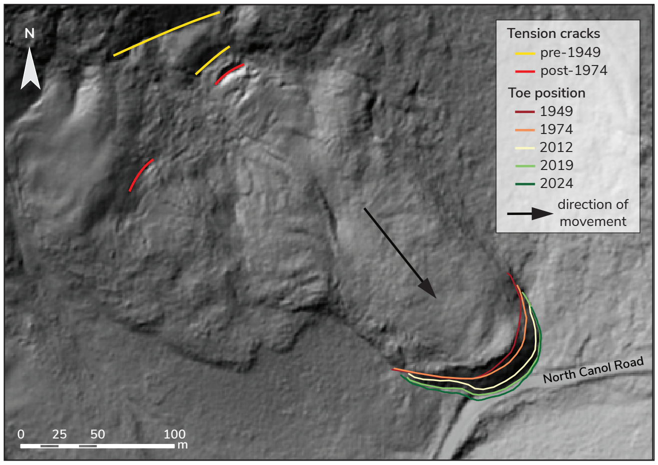

Figure 6. *Lidar image from 2019 of the North Canol rock glacier outlining the maximum toe positions from 1949 to 2024; tension crack locations are also delineated.*

of the rock glacier accelerated to an average of 0.49 m/year, and then dropped to an average of 0.35 m/year from 2019 to 2024 (Fig. 7).

The acceleration of the rock glacier in the last decade is likely related to increasing air temperatures in the Yukon, having a total mean annual air temperature increase of 2.5°C between 1948 and 2021, including notable increases beginning in the mid-1970s (Perrin and Jolkowski, 2022). The relationship between increasing air temperatures and accelerating rock glacier velocities has been observed for rock glaciers globally (Hu et al., 2025), suggesting that, with increasing air temperatures, this rock glacier may continue to accelerate and further encroach onto the road.

South Klondike Highway debris flow

Large sections of the South Klondike highway are built at the base of steep mountain slopes and are therefore prone to avalanches, rockfalls and landslides. A segment of the South Klondike Highway is within British Columbia, but the entirety of the Canadian side of the highway is managed by the Government of Yukon. As the only land route to the port city of Skagway, Alaska, this highway plays a crucial role in transporting fuel and other goods in and out of the Yukon.

In July of 2024, a heavy rainfall event of approximately 50 mm of precipitation over 24 hours triggered a debris flow that covered a 200 m section of the South Klondike Highway at KM 58 (Figs. 1 and 8a). Similar rainfall across the region caused widespread flooding, debris flows and rockslides, and at least one of these events closed the White Pass rail line. At KM 58, the road was closed for less than a day; however, it took seven weeks to fully remove debris, requiring a pilot car to shuttle traffic during this time. Most material originated from the lower part of a pre-existing drainage and its channel deposits (Fig. 8b), resulting in an estimated 63 000 m³ of debris deposited across the road and colluvial fan (Fig. 9).

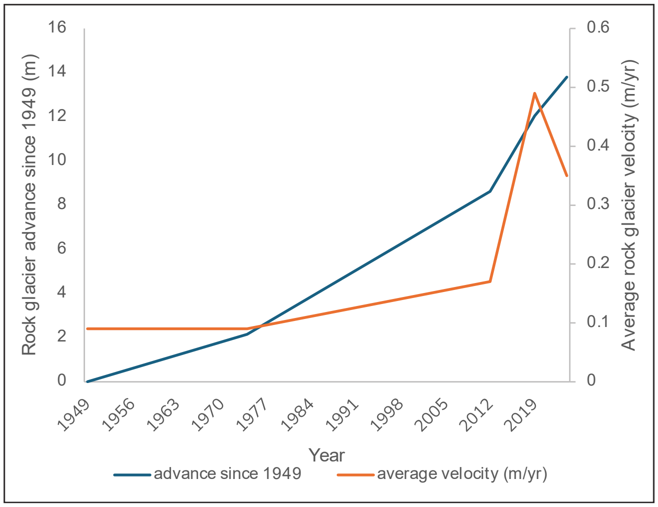

Figure 7. *Average velocity and maximum advance of the toe of the North Canol Road rock glacier since 1949.*

This is the second major debris flow at this site in a decade. A smaller event occurred in July 2014 after heavy rainfall triggered a debris flow and resulted in a 2-day road closure (Fig. 8c). For another event of this magnitude to occur at this site, a build-up of material in the channel will be required, suggesting that large events in consecutive years are unlikely.

This site is also a common avalanche path in the winter (Fig. 8d), and 52 avalanches were recorded between 1991 and 2020, resulting in two road closures (Tse and Adams, 2024). Recent work has estimated the frequency of size 3 avalanches (large enough to bury and destroy a car or break a few trees) to be every year, and the frequency of size 4 avalanches (large enough to destroy a large truck or several buildings) to occur every 10 years (Sharp, 2025).

With the expected increase of extreme weather events in the Yukon (Perrin and Jolkowski, 2022), debris flows remain a hazard at this site and may become a greater risk elsewhere on the Yukon's road network.

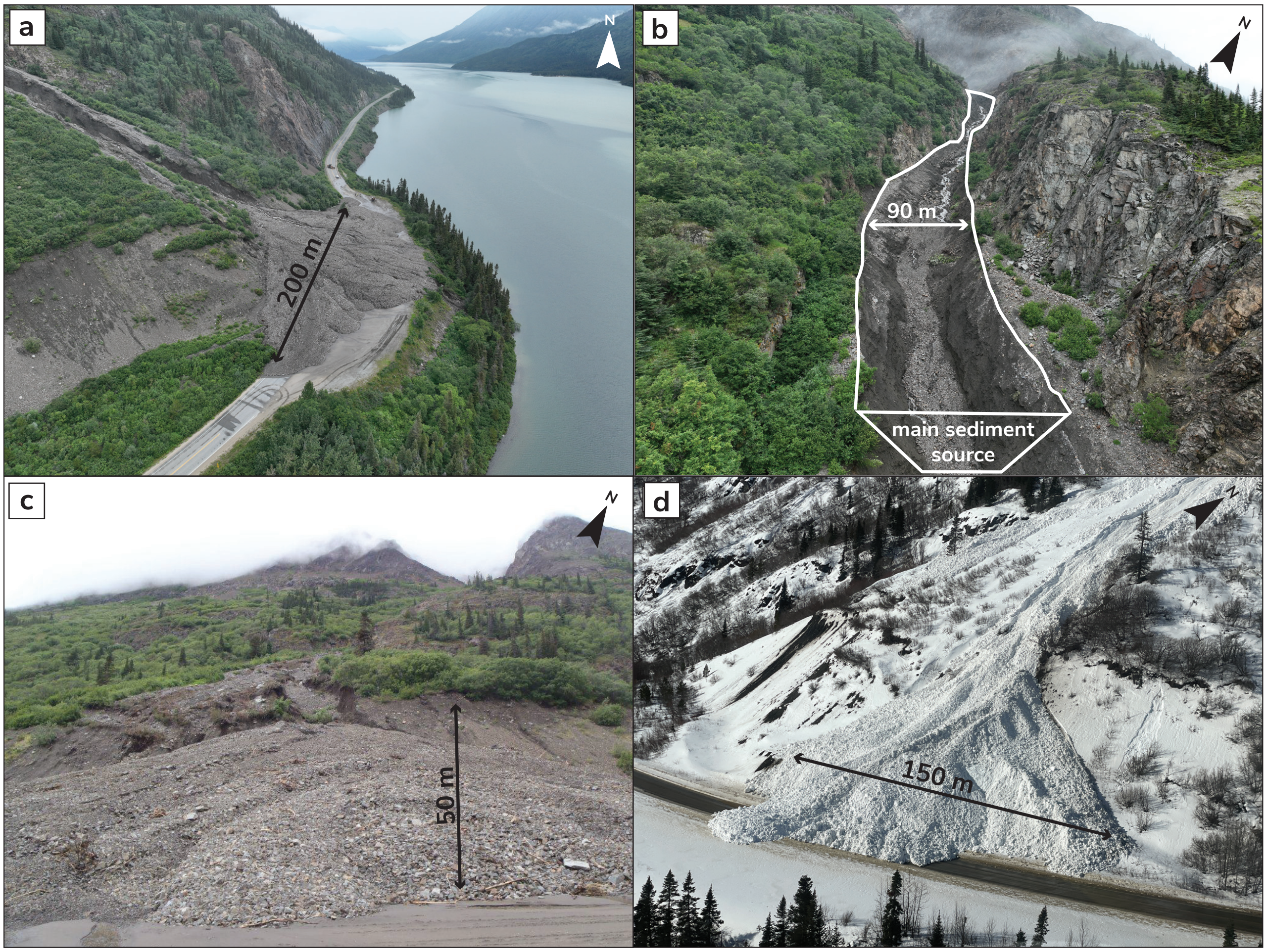

Figure 8. Photos of the South Klondike Highway KM 58 debris flow site. ***(a)*** *A photo from July 2024 of the debris flow fan covering the entire width and affecting a 200 m stretch of the highway (photo: Derek Cronmiller).* ***(b)*** *A photo from July 2024 of the scoured drainage resulting from the debris flow; the photo was taken above the road and near the apex of the debris flow fan (photo: Derek Cronmiller).* ***(c)*** *A photo of the toe of the debris flow fan taken from the road in July 2014 (photo: Paul Murchison).* ***(d)*** *A photo of an avalanche triggered by explosives taken in the spring of 2024; the avalanche followed the same path as the debris flow (photo: Colin MacKenzie, Snowshoot Productions).*

Dempster Highway embankment failure, KM 312

A road embankment failed at KM 312 of the Dempster Highway in August 2023 (Figs. 1 and 10a). A large crack initiated along the shoulder of the road, resulting in a vertical displacement of at least 1 m at one end. The embankment failure occurred on the downslope side of the road. At this location, the road intersects a small drainage where the embankment ranges in height from 2 to 4 m.

Material was added to the road in the fall of 2023 to stabilize the embankment before winter. The embankment remained stable (Fig. 10b) until September 2024, when it failed again. That fall, material was added to the toe to stabilize the slope; however, the embankment continued to fail with vertical displacement reaching up to 0.5 m (Fig. 10c). Repairs were not done until the following spring, resulting in a single lane closure at this location throughout the winter months. As of July 2025, there has been no significant movement observed at this site (Fig. 10d).

Prior to 2023, this embankment was stable. This section of the Dempster Highway is within the continuous permafrost zone and has historically shown little permafrost-related instability (Burn, 2015). The failure of the embankment at the end of summer (both in August 2023 and September 2024) suggests that the cause of failure is likely permafrost

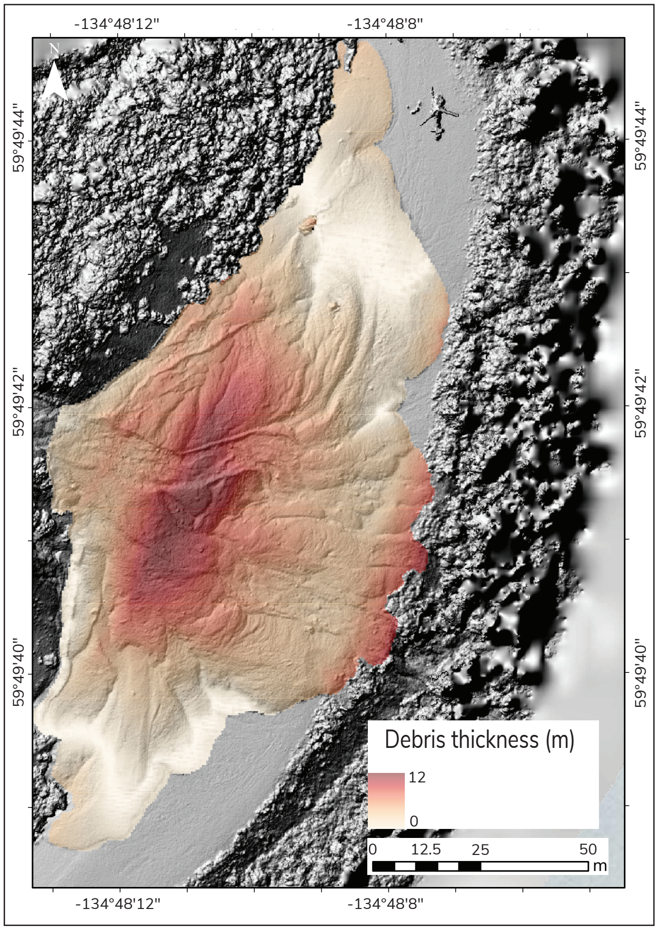

Figure 9. *Lidar imagery of change detection illustrating the thickness of the 2024 debris flow fan on the South Klondike Highway.*

related, as the depth of thaw is greatest in the fall. A possible contributing factor to this failure is the installation of a fibre optic line at the toe of the embankment in July 2022. Stripping of vegetation and the subsequent compression of the organic mat in permafrost terrain accelerates thaw and can lead to visible surface disturbance where ice is present (Brown and Grave, 1979; Fig. 11).

A geotechnical investigation was carried out at this site in the spring of 2025 (Singh and Ismail, 2025). The purpose of the work was to characterize soil, permafrost and geological conditions at the site to identify potential stabilization or mitigation options. Fieldwork included drilling four boreholes, three within the failure zone and one outside; depths ranged from 5.3 to 15.5 m (Figs. 12 and 13).

Subsurface conditions generally consisted of road fill overlying silt and clay (Fig. 13). The road fill in the failure zone varied in thickness from 2.7 to 4.4 m. Visible ice was identified in several boreholes, particularly between 3 and 6 m depth, indicating ice-rich and potentially thaw-sensitive materials. Boreholes 2 and 3, both located within the failure zone, contained the most visible ice. Although total ground ice content is difficult to determine due to the disturbance of ice during drilling, an estimated excess ice measurement was taken from a sample from both boreholes. The sample from borehole 2 taken at a depth of 4.2 m had a volumetric ice content of 58%, whereas the sample from borehole 3 taken at a depth of 4.9 m had a volumetric ice content of 55%.

Three factors are believed to have contributed to the embankment failure at this location:

1. High ground ice content, as was evidenced by greater ice content in the failure zone compared to outside of the failure zone.

2. Disturbance of vegetation and the ground surface during the installation of the fibre optic line, which likely caused ground ice melting and subsidence of the embankment toe.

3. A thick, steep embankment on a slope, which would have exacerbated the effects of the reduced soil strength at the toe as ground ice melted.

Conclusions

This geohazard inventory and hazardous landform database represents a key step toward understanding and managing the growing risks facing the Yukon's road network in a changing climate. The combined mapping of geohazard points and hazardous landforms has demonstrated that extensive sections of the territory's highways are affected by permafrost degradation, slope movement, and hydrological hazards, and have clear implications for maintenance costs and long-term infrastructure resilience. Case studies demonstrate how geohazards can significantly disrupt transportation corridors. With climate change, gradual processes such as creeping rock glaciers are undergoing significant accelerations, resulting in substantial impacts to the roadways. Extreme weather events can increase the frequency of large landslides such as the South Klondike Highway KM 58 debris flow. Surface disturbance can have significant effects on road stability, as seen at KM 312 of the

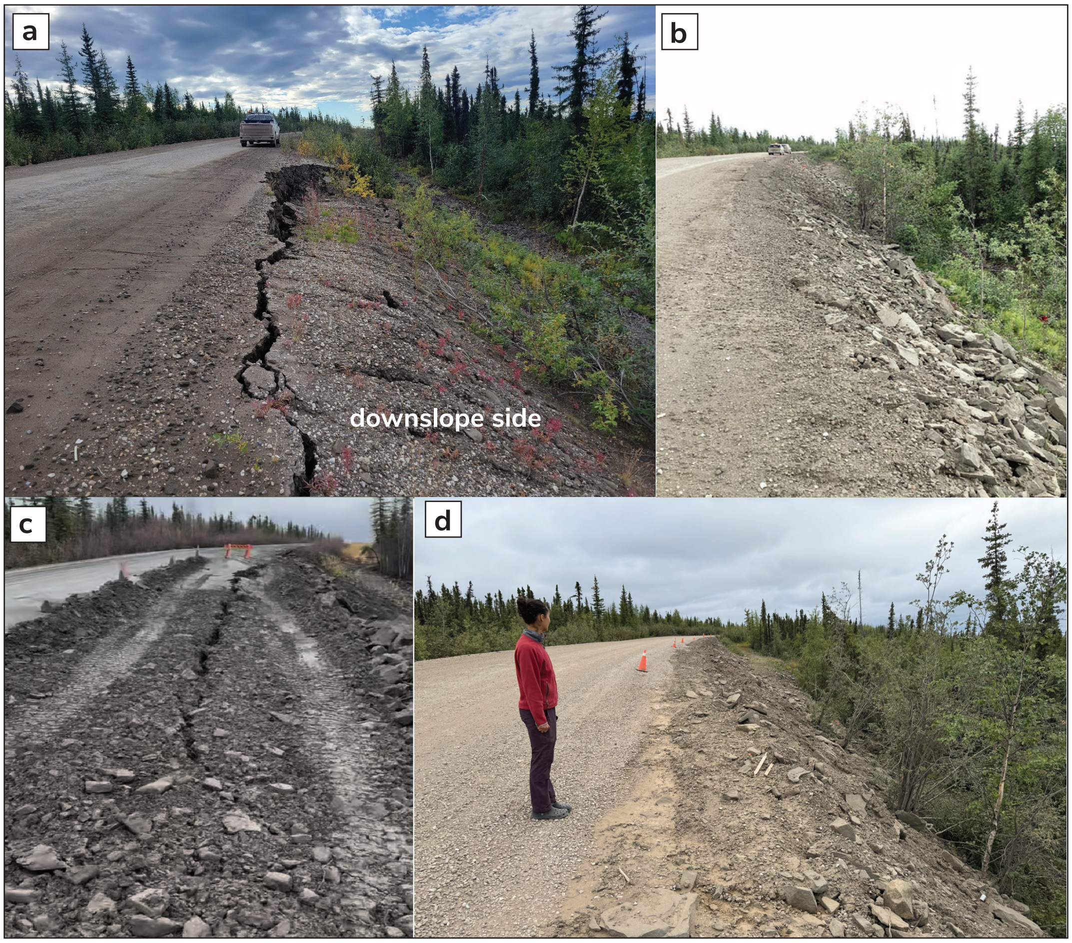

Figure 10. *The evolution of the embankment failure at KM 312 of the Dempster Highway:* ***(a)*** *the initial failure in August 22, 2023;* ***(b)*** *the repaired embankment in July 22, 2024 and minimal cracking;* ***(c)*** *the failed embankment in October 2024; and* ***(d)*** *the stabilized embankment in July 2025. Photo by Stephan Gruber.*

Figure 11. *An example of the installed fibre optic line in 2022 at KM 311.6 of the Dempster Highway. The photo was taken 100 m from the embankment failure, and the removal of vegetation is evident.*

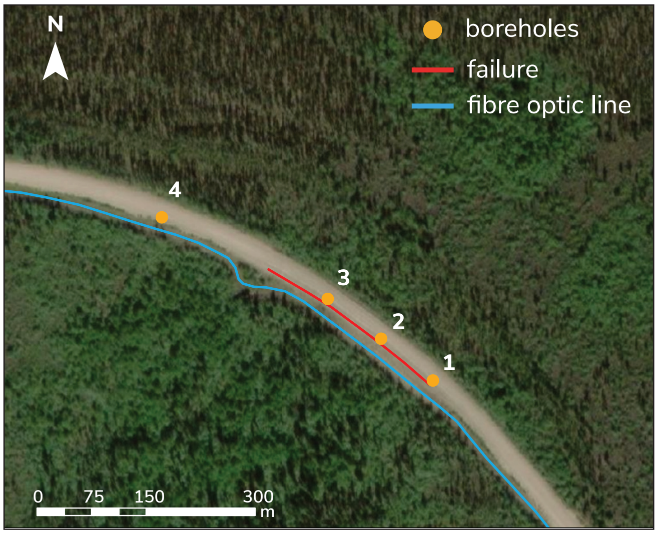

Figure 12. *Aerial photo of the embankment failure at KM 312 of the Dempster Highway and the location of the four boreholes drilled during the investigation.*

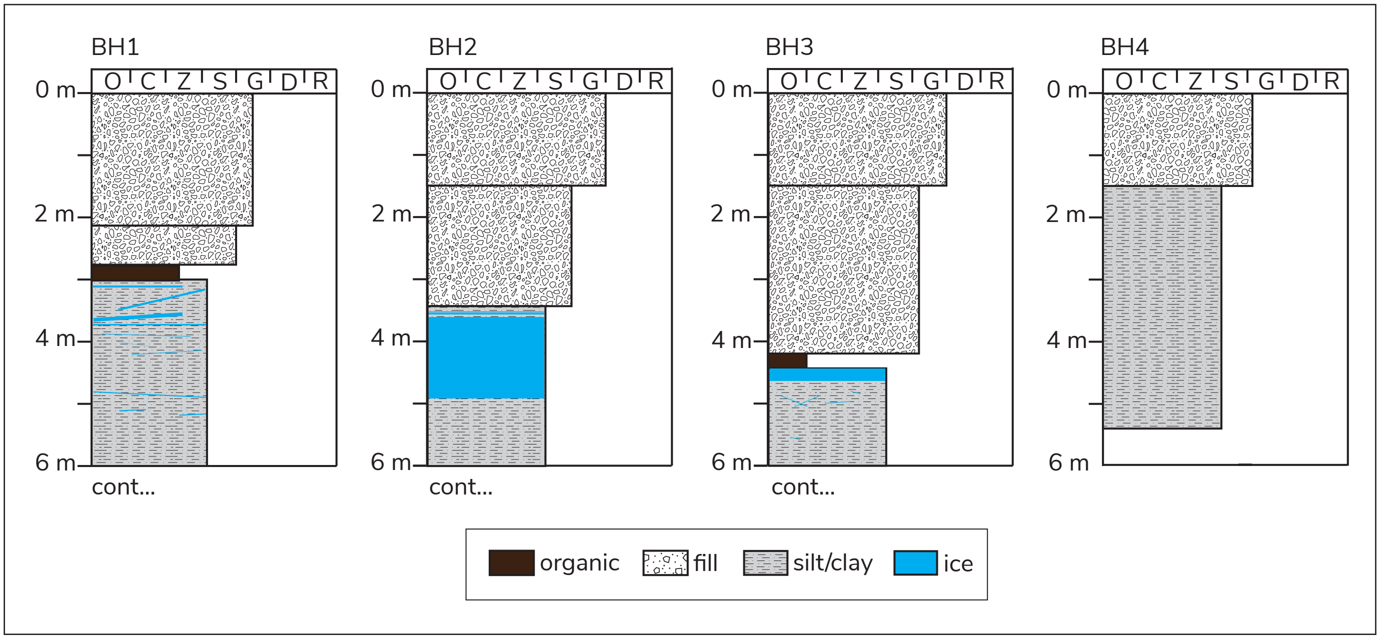

Figure 13. *Stratigraphic logs of the uppermost 6 m for the four boreholes drilled at KM 312 of the Dempster Highway. Borehole logs from Singh and Ismail (2025).*

Dempster Highway. Ongoing monitoring, regular field verification, and updated imagery will continue to refine the dataset and improve risk assessments. As the inventory expands to remaining highway sections, it will provide a foundation for prioritizing maintenance work, planning mitigation efforts, and supporting safe and reliable travel across the Yukon.

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