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Permafrost in mountainous regions of Canada

Stephan Gruber and Christopher R. Burn
Carleton University, Ottawa, ON, Canada
Lukas Arenson
BGC Engineering Inc., Vancouver, BC, Canada
Marten Geertsema
British Columbia Ministry of Forests, Lands and Natural Resource Operations, Prince George, BC, Canada.
Stuart Harris
University of Calgary, Calgary, AB, Canada
Sharon L. Smith
Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada
Philip Bonnaventure
Department of Geography, University of Lethbridge, Lethbridge, AB, Canada
Bronwyn Benkert
Northern Climate ExChange, Yukon Research Centre, Yukon College, Whitehorse, YK, Canada

ABSTRACT
About one third of the global permafrost region is situated in mountainous terrain, and in Canada, large areas underlain by permafrost have mountainous topography. Although mountain topography and terrain-related mass movements yield a much greater diversity of ground materials and temperatures per unit area than encountered in polar lowlands, the governing physical principles are the same. Permafrost in mountainous regions thereby enriches the variety of permafrost-related phenomena encountered beyond what is typically found in lowland areas. Permafrost thaw in mountains is relevant as it may increase the potential for geohazards such as debris flows, rock falls, rock avalanches, and displacement waves. There are also implications for hydrology, water quality, and ecosystems. We argue for better integration of permafrost research in mountainous regions with mainstream permafrost research and education in Canada.

RÉSUMÉ
Environ un tiers des terrains à pergélisol sont situés en zones montagneuses. Au Canada, de vastes zones à pergélisol ont des reliefs montagneux. Bien que les topographies montagneuses et mouvements de masse associés produisent une plus grande diversité de matériel et de température par unité de surface que celle observée dans les plaines polaires, les principes physiques les gouvernant demeurent les mêmes. Le pergélisol des zones montagneuses vient donc enrichir la diversité des phénomènes liés au pergélisol au-delà de ce qui est typiquement observé dans les plaines. Le dégel du pergélisol en régions montagneuses est important car il peut accroître le potentiel de risques géologiques tels que les coulées de débris, les chutes de pierres, et les éboulements de rochers. Il a également des implications pour l'hydrologie, la qualité de l'eau, et les écosystèmes. Nous recommandons une meilleure intégration des travaux sur le pergélisol en régions montagneuses au sein de l'éducation et la recherche généraliste sur le pergélisol au Canada.

1 INTRODUCTION

Nearly half of the Canadian land mass is underlain by permafrost, and a significant proportion of this is in mountainous terrain (Figures 1 and 2). In contrast to Scandinavia and the Alpine countries, little is known about permafrost in the mountains of Canada. The bias towards lowland areas in research and public perception of permafrost in Canada is due to a number of factors. These include concentration of settlements in valley bottoms, little historical use of high mountains, preferential development of infrastructure in gentle terrain, and the easier operation of machinery for investigations on gentle slopes.

Given the prevalence of permafrost in mountain regions in Canada (e.g., western Canada, eastern Arctic), its characteristics are important for understanding the impacts of future environmental change in Canada, supporting the development and operation of infrastructure in mountainous regions, and reducing local and off-site geohazard risk associated with permafrost thaw.

We argue for a better integration of permafrost research in mountainous and other areas in Canada. To this end, we outline the general characteristics and relevance of permafrost in mountain areas, provide a synopsis of past research on permafrost in Canadian mountains, and identify research and development needs.

2 BACKGROUND

The term *mountain permafrost* evolved from *alpine permafrost,* which was introduced into the mainstream literature by Fujii and Higuchi (1978), who summarized the literature back to Antevs (1932). In the Circum-Arctic Map of Permafrost and Ground Ice Conditions, classes of permafrost extent are given consistently for all terrain types (Brown et al. 1997). Lowland and mountain regions are only distinguished with respect to overburden thickness and ground ice.

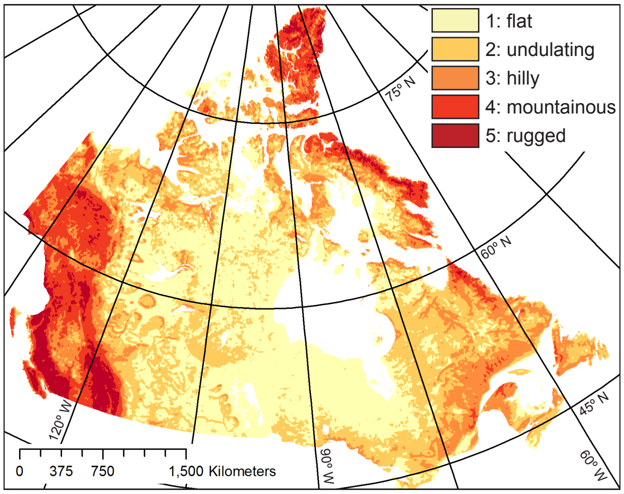

Figure 1. Terrain ruggedness map of Canada (Gruber 2012). Equivalents to the classes shown are: Rugged (5): e.g., Mt. Robson in Banff National Park; Mountainous (4): Pelly mountains, NE of Whitehorse; Hilly (3): Iqaluit; Undulating (2): Yellowknife; Flat (1): Mackenzie delta.

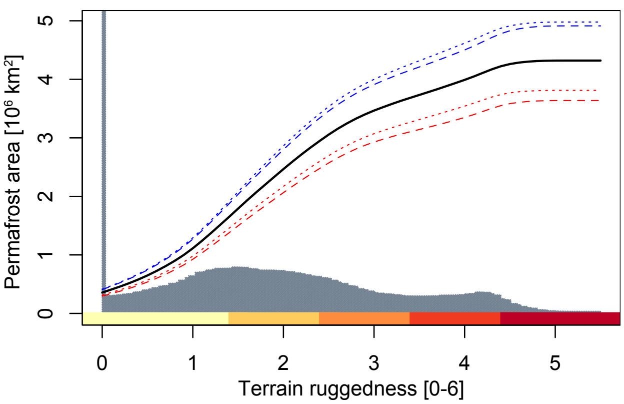

Figure 2. Estimated permafrost area (lines) in Canada as a cumulative function of terrain ruggedness. Blue and red dotted and dashed lines are conservative and anti-conservative estimates illustrating the uncertainty range of this simulation. Grey bars show shape of density function. Based on Gruber (2012).

The concept and definition of *alpine* or *mountain permafrost* remain somewhat problematic. Rugged terrain with steep slopes can occur at any elevation, as in the fjords of Baffin Island, but Gorbunov (1988) suggested an arbitrary elevation of 500 m as the lower limit for mountain permafrost. Parts of the Qinghai-Tibet Plateau at ~4500 m elevation, however, are fairly flat. Likewise, processes such as cold air drainage occur in dissected table lands with limited relief, such as in central Yukon. Instead, the effect steep topography has on permafrost characteristics is the critical factor (Gruber and Haeberli 2009).

The same physical processes govern permafrost phenomena in mountainous regions and in gentle topography. Nevertheless, permafrost in mountains has a number of distinctive characteristics, particularly the extreme environmental gradients (due to elevation change, insolation, avalanches, etc.) that result in juxtaposition of conditions otherwise found over distances of hundreds or thousands of km. Furthermore, permafrost and glacial environments often coexist and interact in mountains, while outside mountain regions, glacier and permafrost research are primarily related in the context of Quaternary history.

A number of phenomena are prominently or exclusively observed in mountainous areas, such as: thermal effects of air advection in slopes composed of coarse materials (Harris and Pedersen 1998), compaction of avalanche snow and debris into ice-rich permafrost (Gruber and Haeberli 2009), rock glaciers (Haeberli et al. 2006), intense sediment dynamics including rock fall and debris flows, groundwater movement (Muir et al. 2011), and extended unsaturated zones. These phenomena originate from the high potential energy available in mountain terrain, while temperature inversions and cold air drainage are important components of mountain climates in winter (e.g., Harris 1983).

Initially, maps and schematic diagrams, such as in Fujii and Higuchi (1978), were used to illustrate the probable distribution of permafrost in mountains. Areas included the summits of the Rocky Mountains south to New Mexico, scattered occurrences in Quebec and New York State, and patches on the southern margins of the Qinghai-Tibet Plateau, south of the Tanggula Range. Subsequently, Harris (1986) provided a south to north view of permafrost distribution in the eastern ranges of the Rocky Mountains from 40˚ to 70˚ latitude (New Mexico to the Arctic Coast). Gruber (2012) has represented the relation of permafrost extent and mean annual air temperature, as used by the IPA map (Brown et al. 1997), through a simple mathematical model and produced a global grid of permafrost zonation at 1-km resolution.

Research on permafrost in mountains initially focused on geomorphic phenomena in the European Alps (Barsch 1971), Scandinavia (Østrem and Ostrem 1964), North America (Luckman and Crockett 1978), and South America (Corte 1976), particularly rock glaciers (Johnson and Nickling 1979; Barsch et al. 1979). Haeberli (1973) demonstrated that the late-winter basal snow temperature (BTS) could indicate the occurrence of permafrost beneath a thick snow cover. Permafrost in Canadian mountains was first confirmed at Plateau Mountain in southwest Alberta (Harris and Brown 1978), and in Banff and Jasper National Parks (Harris and Brown 1982).

In the late 1990s there was a shift from the geographical approach towards more detailed understanding, measurement, and simulation of permafrost in mountains. In Europe, this was driven by recognition of geohazards related to permafrost thaw in densely populated mountains (Harris et al. 2009; Deline et al. 2014).

3 PERMAFROST IN CANADIAN MOUNTAINS

Research on permafrost in Canadian mountains has largely been related to rock glaciers, understanding spatial patterns of occurrence, and understanding temperatures and their change. Most studies have been conducted in the mountains of western Canada despite extensive mountainous terrain in eastern Canada and the High Arctic.

3.1 Rock glaciers

In the 1970s, interest in ice-cored moraines (Østrem and Arnold 1970) and rock glaciers in Canada arose simultaneously with research in Europe and the U.S. The research included measurements of temperature and movement in boreholes (Ragle et al. 1970; Johnson and Nickling 1979), and studies of the local distribution, characteristics, origin and movement of rock glaciers (Osborn 1975; Luckman and Crockett 1978; Johnson 1984).

3.2 Spatial distribution

Efforts to understand the distribution of permafrost in in the western Cordillera as a continuous probability field rather than in terms of distinct classes of extent were introduced by Lewkowicz and Ednie (2004) in the southern Yukon, who adapted BTS-based simulation used in the Swiss Alps (Gruber and Hoelzle 2001). Incorporation of direct evidence of permafrost occurrence from pits facilitated the development of 30-m resolution maps of permafrost probability for the Wolf Creek basin, near Whitehorse, YK. This study provided the basis to upscale field research in other areas within the Yukon and northern British Columbia, resulting in a regional model of permafrost probability covering an area of approximately 500,000 km^2 (Bonnaventure et al. 2012).

Wintertime inversions (Bonnaventure and Lewkowicz 2012; O'Neill et al. 2015) and cold-air drainage and pooling are more prevalent in Subarctic and Arctic mountain ranges than at the mid latitudes, and pose an additional challenge to regional modelling. Areas in northern and continental locations, where inversions are most frequent, show lowest air temperatures on mountaintops and in valley bottoms. Often, a forested zone, in-between, is bounded by an upper and a lower treeline. Lewkowicz and Bonnaventure (2011) accounted for spatial differences in surface lapse rates and inversions, to show that permafrost presence in continental high-latitude mountains is favoured in both valley bottoms and on mountaintops above treeline. Model experiments incorporating scenario-based climate change suggested a large potential for permafrost thaw in valley bottoms with concomitant effects on infrastructure (Bonnaventure and Lewkowicz 2013).

3.3 Temperature

Monitoring networks for observing permafrost thermal state and active-layer thickness are well developed for European mountains, especially in the Swiss Alps (e.g., PERMOS 2013) and the high elevation plateaus of central Asia (e.g., Zhao et al. 2010). In Canada however, comparable permafrost monitoring networks and long-term records are limited.

Measurements at a few sites in the western Cordillera were initiated in the 1970s in Alberta, BC, and Yukon (Harris 1990; Harris and Brown 1982), but until the recent International Polar Year (IPY), little was known about the thermal characteristics of permafrost in Yukon mountains outside the main valley floors. Efforts during and immediately following the IPY period resulted in the instrumentation of six boreholes at various elevations in the central and southern Yukon (Smith et al. 2010). As with much of the permafrost monitoring in northern Canada, sites have generally been established near existing or planned infrastructure or communities. Many of the Yukon alpine boreholes are in bedrock and are associated with potential mine developments. These boreholes complement about 30 others recently instrumented in valley bottoms along the Alaska Highway Corridor (e.g., James et al. 2013). The information from these sites has improved our knowledge of permafrost conditions in the southern half of Yukon, but the records are too short to characterize any recent trends in permafrost temperatures (Smith et al. 2010; Lewkowicz et al. 2011; Lewkowicz et al. 2012; Throop et al. 2012).

3.4 Other studies

A number of other studies have, directly or indirectly examined permafrost in mountain areas. For instance, climatic and geomorphic factors affecting retrogressive thaw slump initiation and activity on the Aklavik Plateau (Lacelle et al. 2010), and the influence of landscape change or disturbance and climate change on mass-movements in permafrost have been investigated (Lewkowicz and Harris 2005; Blais-Stevens et al. 2015). Recently, Kokelj et al. (2015) have described the role of increased rainfall in initiating terrain disturbance in Richardson Mountains and Peel Plateau. Lewkowicz (2001) measured time series of near-surface rock temperatures on northern Ellesmere Island.

4 RELEVANCE OF PERMAFROST IN MOUNTAIN REGIONS OF CANADA

The permafrost in Canadian mountains is of scientific interest as it occupies a large area, is subject to unique phenomena, and may exhibit distinct responses to environmental change. It is an integral part of Canadian nature and many of our iconic National Parks. It is relevant for research because it influences geohazards and, in some areas, water quality and ecosystems.

4.1 Geohazards

Permafrost brings many, and sometimes unique, geohazard challenges to engineering projects in mountainous terrain. As with landslides, permafrost challenges are expressed both on-site and off-site. On-site challenges are generally the easiest to understand and manage, as they relate to the underlying permafrost and issues such as subsidence or creep (Bommer et al. 2010). Problems induced by off-site permafrost, due to degradation of distant permafrost, are more difficult to characterize and predict (Huggel et al. 2012). This could be as simple as a rock topple-fall (Gruber and Haeberli 2007), or as complex as a rock slide transforming into a debris flow, entering a lake and causing a displacement wave and flood.

An early step in planning for permafrost-related hazards in mountains is predicting where permafrost might occur. There are several maps available for western Canada: a global layer (Gruber, 2012), a regional study of Yukon and northern British Columbia (Bonnaventure et al. 2012), and a provisional map for all of BC (Hasler and Geertsema 2013). Considerable infrastructure exists or is planned in the mountains of western Canada (Figure 3) including roads, railways, and mines. Proposed pipeline routes also traverse mountainous terrain, where geohazards and engineering challenges related to permafrost must be addressed.

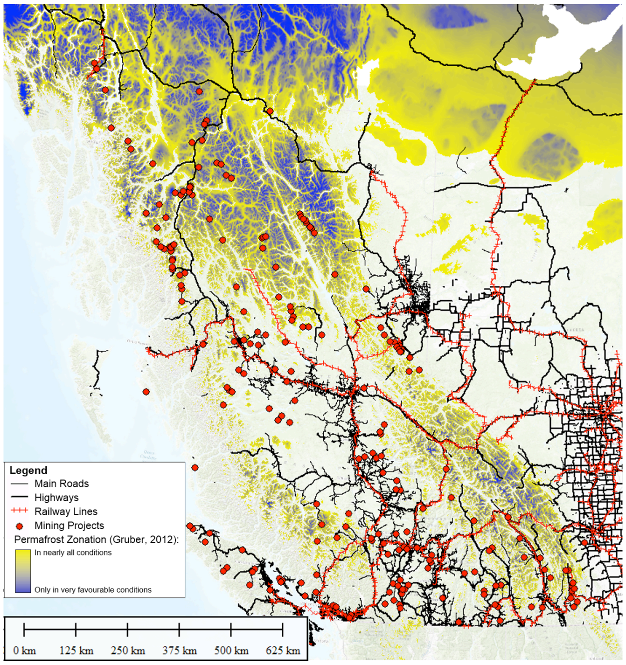

Figure 3. Transportation infrastructure, mining projects and permafrost in western Canada. Permafrost zonation from Gruber (2012).

While hazards due to permafrost degradation may not be immediately evident for foundations in bedrock, the creep and thaw of frozen fissures and joints have become major issues for some structures in these environments (Haeberli et al. 2010). In Canada, the number of such structures is currently still limited, but new projects are in planning or under construction, such as the Jumbo Glacier Resort in SE BC, which require understanding of permafrost related hazards. Once permafrost is anticipated, simulation studies, geomorphic mapping, geophysical surveys and geotechnical boreholes can be used to characterize distribution, cryostructure, thickness, and temperature of the permafrost. Understanding mechanical characteristics is also required to project future changes in the permafrost.

As in flat terrain, on-site analysis is important for assessing the integrity of embankments, foundations, dams, pipelines, and other infrastructure (TAC 2010; Bommer et al. 2010). This includes assessing effects of low temperature and permafrost foundations on, e.g., heap leach facilities (EBA 2011).

Off-site permafrost must be assessed both below and above planned infrastructure. In some cases, permafrost-related landslides can retrogress upwards, as with well sites in northern BC that were impacted by retrogressive landslides (Figure 4) (Geertsema and Foord 2014). Figure 5 shows the scar of a debris flow with exposed ground ice at the frontal area of a rock glacier in the south-eastern Rocky Mountains of Alberta (Arenson and Jakob 2014). Rock slides in northwestern BC (Figure 6) that transformed into far travelling debris flows ruptured natural gas pipelines (Geertsema et al. 2006). Similarly, Darrow et al. (2013) identified geohazards along the Dalton Highway in the Brooks Range of Alaska related to the creep of frozen debris lobes. Where permafrost occurs within forested areas, disturbances such as forest fires or timber harvesting exert additional control on geohazards.

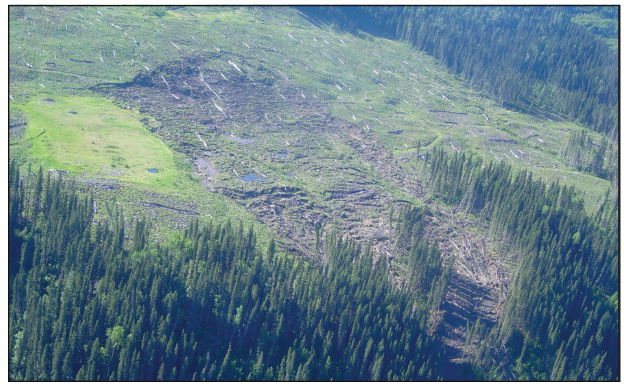

Figure 4. Temple Creek landslide (12+ ha) in close contact with oil and gas infrastructure in BC. It occurred on a slope of less than four degrees in clayey soil with sporadic permafrost and may have resulted as a hydrological response to timber harvesting. Image: M. Geertsema.

Figure 5. Debris-flow scar at frontal area of a rock glacier near Canmore, Canada. Photo: M. Jakob, July 2013.

Off-site assessments are inherently more challenging than on-site assessments because there are more uncertainties and the area of interest is larger. A permafrost-related landslide could come from a variety of locations within a catchment that may be tens of square kilometers in area. Furthermore, once a landslide occurs, other factors control whether it might reach infrastructure in the valley, whether it might be of sufficient magnitude to be damaging, and which of several processes might be involved.

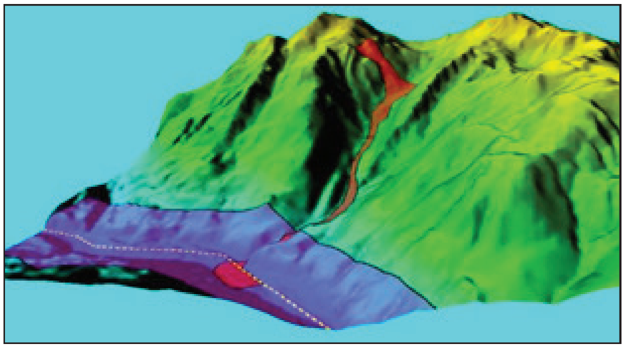

Figure 6. The landslide (red) started in a permafrost zone and ruptured a pipeline (dotted yellow line) more than four kilometres away in the valley bottom.

4.2 Hydrology and water quality

Permafrost and its thaw can affect hydrology via increasing hydrologic permeability following ice loss in pores and via the release of water stored in frozen material. This may change the hydrologic connectivity in a catchment and affect the rates and amounts of flow along differing paths (Hinzman et al. 2005). An increasing proportion of deeper groundwater flow has been postulated based on observations and computer simulation and linked with altered temporal runoff characteristics such as higher base flow (Woo et al. 2008; Bense et al. 2012). As the hydrologic regime changes from near-surface drainage to deeper flow paths following active layer thickening and talik formation, changed cycle times and their proportional contribution to stream flow may affect solute contents in surface and groundwater. Additionally, the thaw of previously frozen material releases solutes (cf. Kokelj and Burn 2003). This may be due to the release of ions stored in ground ice or, on longer time scales, by exposure of new material to leaching as thawing deposits become hydraulically more permeable. Water originating from areas of inferred permafrost degradation has been shown to exceed guidelines for drinking water quality with respect to heavy metals (Thies et al. 2013). These effects of permafrost on hydrology and water quality are likely most pronounced in small and arid catchments.

In global estimates of permafrost carbon pools, little information exists on mountain regions (Zimov et al. 2006). While likely of smaller magnitude than high-latitude carbon storage, valley fills or deposits of solifluction material are environments in which carbon can be accumulated and preserved over long time scales.

4.3 Public understanding and appreciation

National parks in “southern” mountains with extensive permafrost areas (Banff, Jasper, Kootenay, Mount Revelstoke, Glacier, and Yoho) received 54% (~6.8M) of all visitors to Canadian National Parks in 2013–2014. In contrast, northern permafrost areas received only 0.25% (~32,000) of the visitors, nearly all at Kluane National Park. Mountain parks are where most Canadians get close to permafrost. Correspondingly, these parks – and permafrost in mountains – provide a chance for engaging the public with permafrost science in general, as at the Tombstone Territorial Park Interpretive Centre, Dempster Highway, YK.

5 RESEARCH AND DEVELOPMENT NEEDS

A number of needs for research and development arise from the abundance and relevance of permafrost in Canadian mountains.

Improved understanding of processes and phenomena is required in key areas, including: (a) the temporal and spatial variation in ground temperatures and ground ice contents beneath mountain slopes; (b) changes to runoff and water quality following changes in permafrost and seasonally frozen ground; (c) incorporation of carbon into frozen deposits by solifluction and in valley fills; (d) interaction of vegetation and permafrost in mountains; (e) response of rock slope stability to permafrost degradation; (f) interaction of permafrost and groundwater flow in mountains.

Methods and technology are required for simulation studies and site investigations. These include: (a) back analysis of major geohazard events and the role of permafrost; (b) identification of priority areas for detailed geohazard investigation, e.g. in proximity to infrastructure; (c) simulation of permafrost characteristics in mountain terrain and their transient behaviour; (d) development of technologies that allow an efficient and reliable identification of areas susceptible to permafrost thaw; (e) homogenous repositories for permafrost monitoring data to enable digital querying.

Long-term monitoring of permafrost and related phenomena in mountains is required for informing research, industry, and governments, for understanding environmental changes, and for developing and testing computer models and other new technical developments.

Complementary baseline data suitable for supporting permafrost research in mountains is required for analysis and predictive simulation. This includes high-elevation meteorological stations, snow observations, stream flow and water quality measurements, as well as meteorological models and re-analyses.

Communication and integration of research results in planning and decision-making will help reduce risk and increase resilience as permafrost in mountainous regions poses risks for human habitation and infrastructure development. Successful approaches exist in Canada, and can be capitalized on. For example, the Yukon Permafrost Network (YPN 2011) serves as a forum for the research community, government, and industry. The ARQULUK program (Université Laval 2012) creates project committees with stakeholders, ensuring involvement of decision-makers in the development of research priorities.

6 SUMMARY AND CONCLUSION

Although mountain topography and its intensified redistribution of sediment and snow yield a much greater diversity of materials and temperatures per unit area than is encountered in cold lowlands, the physical principles governing permafrost phenomena in mountains are the same as in gentle topography. Permafrost in mountainous regions thereby enriches the variety of phenomena encountered beyond what is found in lowland areas. A combined view on permafrost in differing environments is useful for informing research and engineering. For this reason, the expression *permafrost in mountainous regions* is preferred over *mountain permafrost* as it avoids implying there is a separate category of permafrost.

Permafrost processes rarely act in isolation, especially in mountain regions. As a consequence, it is important to place research within the process chain underlying relevant risks (e.g., debris flow risk with surface hydrology; slope stability risk with avalanche forecasting). This requires integration of research. Thus, communication efforts should aim to facilitate collaborative action to address multidisciplinary questions.

Broadening Canadian permafrost expertise to increasingly include mountain environments – within and outside Canada may provide important insight into Canadian phenomena, and advantages for Canadian engineering firms supporting large projects in permafrost regions around the world.

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