Understanding permafrost in bedrock slopes of intermediate steepness

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Introduction

- Investigation into permafrost thaw in bedrock slopes has focused on near-vertical bedrock and neglected slopes with an intermediate steepness of about 30–70°
- Intermediate slopes are heterogeneous, with spatially and temporally variable debris, vegetation, and snow. Access is challenging, and simulation of permafrost presence has received little attention
- Identification of intermediate slopes from digital elevation models (DEM) skews to lower slope angles in Canada, leading to underrepresentation of said slopes
- Aim to better understand what is known and can be anticipated about spatial and temporal patters in these intermediate slopes

Where are intermediate bedrock slopes in Western Canada?

A 90m digital elevation model covers Canada. It can be used to calculate slope.

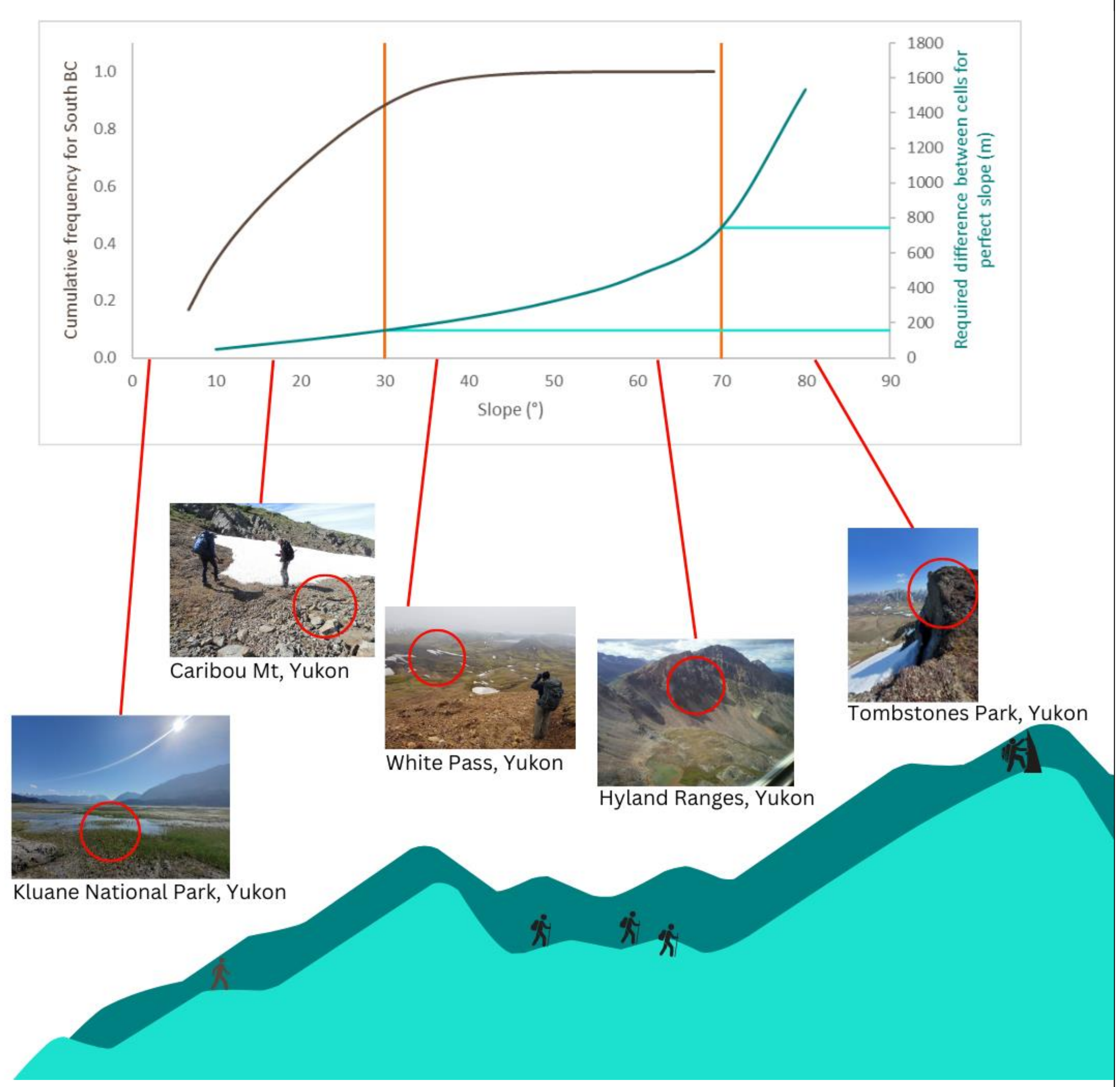

Figure 1: Brown line) Cumulative frequency of slope angles in Southern British Columbia (fig 2A). 90m DEM calculated only 10% of slopes falling between 30-70° (orange lines).
Blue line) Slope calculations will preference lower slope angles, and the required difference between DEM cells for a perfect slope increases with the tangent of the slope. To represent a slope of 70°, a difference of 750m between cells is required - this is why we may not see more of those slopes in the brown line. For a specific example of how higher slope angles are misrepresented, refer to fig 2.

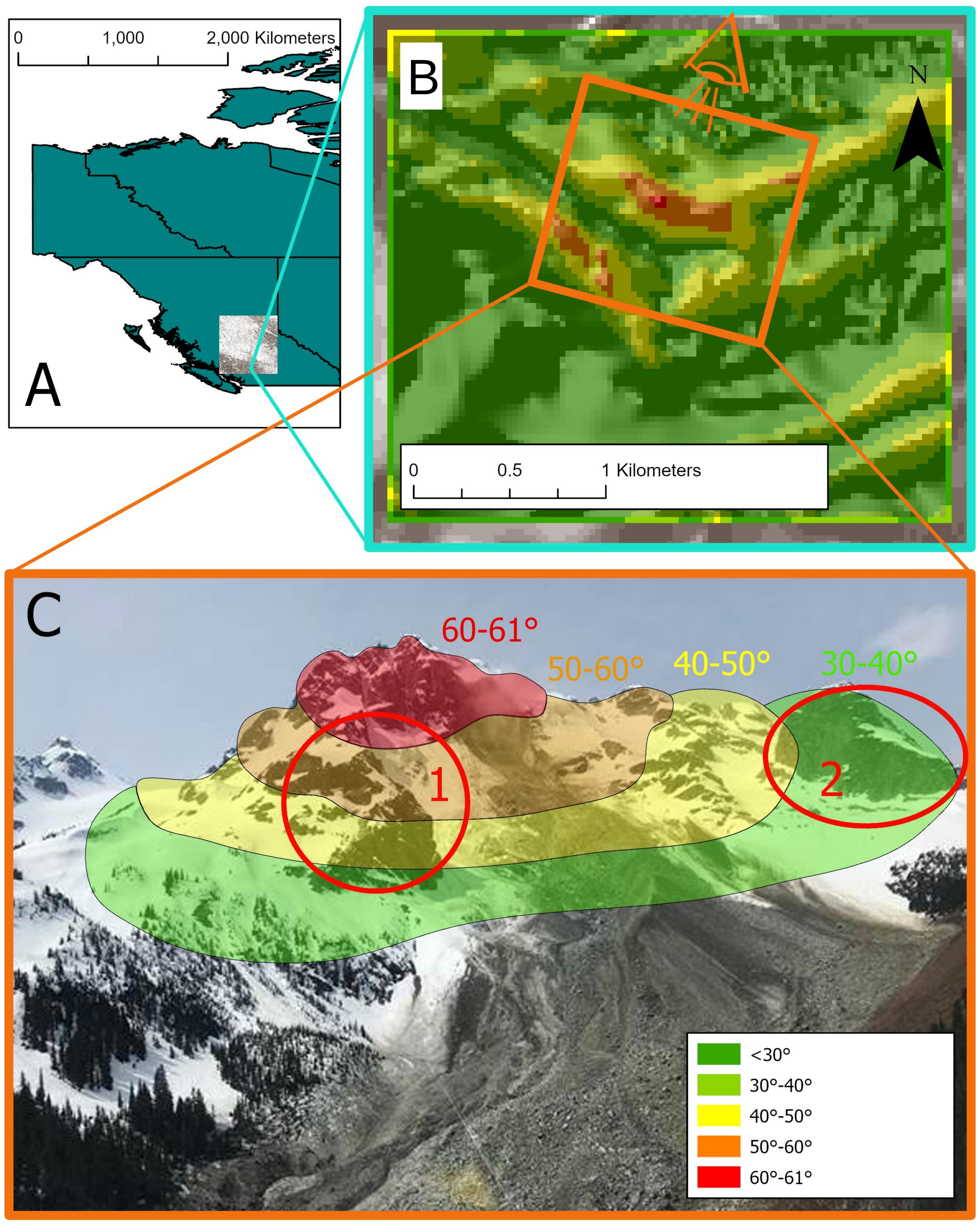

Figure 2: A) Western Canada, with the region covered by DEM in fig 1 (Southern BC).
B) Slope angles on Joffre Peak, BC, from 90 DEM.
C) Estimated bands of slope angles from B on a 2019 image of the north side of Joffre Peak, with mass movement event. The DEM does not represent slopes accurately. Error 1 demonstrates how the DEM-derived slope does not represent overall steep slopes, while error 2 demonstrates a smoothing of features smaller than the DEM grid.

What phenomena should we consider?

- **Snow and ice:** accumulation on ground that is perennial or seasonal. These can vary in composition, structure, behavior, and stability
- **Soil:** has little to no unsaturated pore space and circulation at depth, and has ability to retain water
- **Debris:** has a significant unsaturated pore space that allows circulation at depth, has little ability to retain water to support vegetation
- **Vegetation:** flora that grow on the soil and debris

What do we know about these slopes?

Slope	<30°	30°-40°	40°-50°	50°-60°	60°-70°	70°-80°	>80°
Snow and ice	Snow accumulation creates insulation [1, 2]			Sloughing of deep snow begins [2, 3]	Thin snow cover cools through increased albedo[4]		Little accumulation of snow [5]
			Presence of ice aprons, indicating permafrost presence [6]				
Soil	Soil increases water content and ability to have latent heat [7]			Soil does not adhere at these slopes			
Debris	Debris influences snow accumulation at depth, resulting in cooling of the rock face [5, 8]				Debris does not adhere at these slopes		
Vegetation	Vegetation can increase water content in the soil and ability to have latent heat, as well as snow retention [4]			Vegetation does not adhere at these slopes			

What hypotheses can be drawn from existing work?

Phenomena	Hypotheses and processes
Snow and ice	Snow acts as both an insulator and a coolant. As snow, it insulates. If it remains over years and transform to ice it acts as a coolant. Generally, the transition from insulator to coolant occurs with increasing slope.
Soil	Soil presence increases water content and latent heat in the ground, which increases surface offset. As slope increases, soil presence decreases.
Debris	There is less blocky debris at low slope angles, and none at high slope angles, with a maximum on intermediate slopes. Debris prevents snow accumulation at depth, leading to a cooling effect.
Vegetation	Vegetation decreases with increasing slope angle. It affects snow retention and energy balance, and increasing vegetation corresponds to increasing ground temperature.

Conclusion

- Bedrock slopes of intermediate steepness are impacted by multiple phenomena on a small spatial scale as compared to steep slopes
- Intermediate slopes heterogeneity harbour hazards that we have not studied
- Identification of intermediate slopes is impacted by skewing of DEM-derived slopes towards lower slope angles
- The effects of these factors will differ between climatic zones [9], and previous work based in Europe will likely apply differently in Canada
- Simulations which explore the influence of snow/ice, soil, debris, and vegetation will allow estimating plausible ranges of permafrost presence in slopes and which phenomena are key controls

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