Constraints on glacier bedrock roughness from spectral analysis of glacier forefields

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Motivation

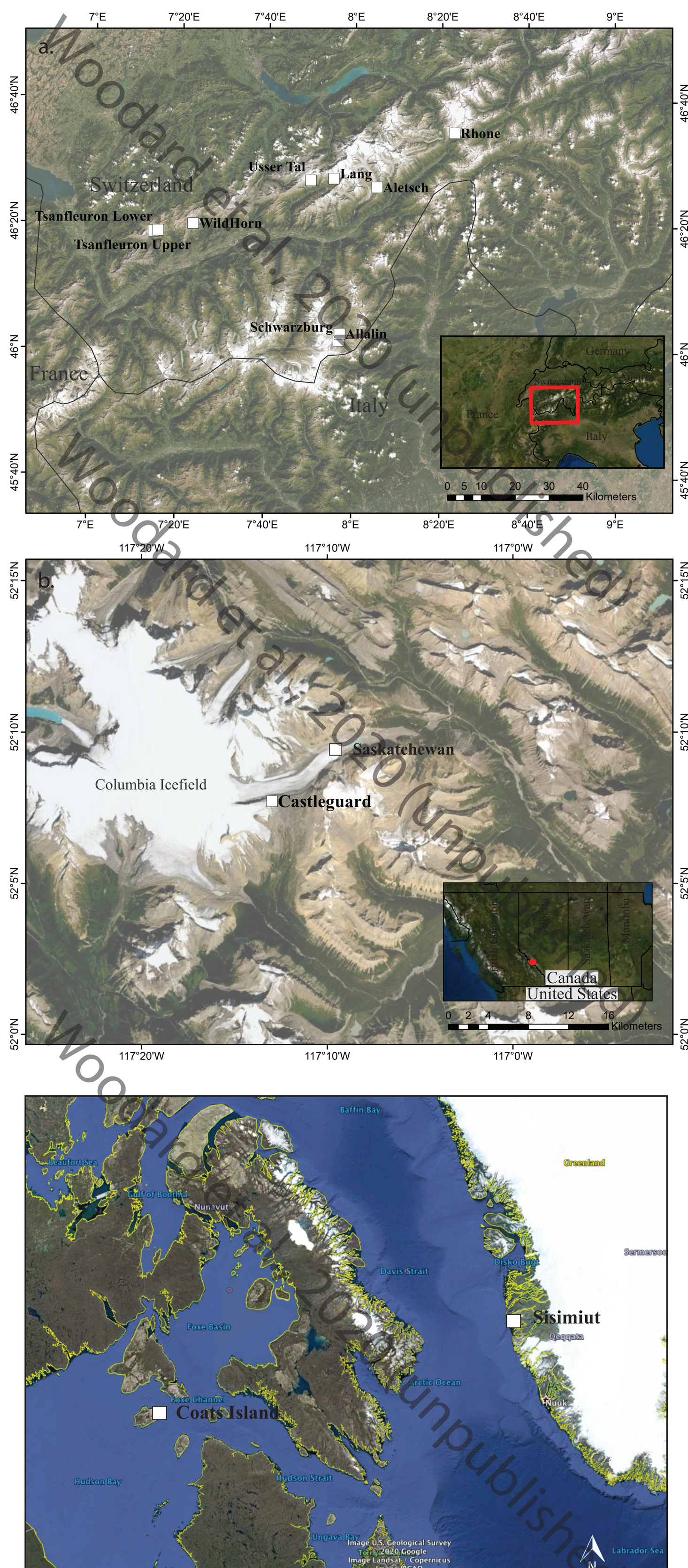


Figure 1: Locations of the recently exposed bedrock forefields in Switzerland (a) and Alberta, Canada (b), and the arctic (c) analyzed in this study. Satellite imagery from 2016 DigitalGlobe database and USGS.

Viscous creep and regelation are the two main sliding mechanisms thought to control ice flow over a hard bed. Most sliding models only consider the creep component and assume the effects of regelation are negligible. However, recent studies (Hansen and Zoet, 2019; Rempel and Meyer, 2019) have shown that the drag attributed to regelation may be substantially larger than previously thought. Here we estimate the magnitude of drag acting on the bed due to regelation by evaluating two different regelation models on elevation data from recently exposed forefields.

Table 1
Forefield Specifications

Forefield	Lithology	Glacier Type
Rhone	Granite	Valley
Aletsch	Granite	Valley
Allalin	Grano-diorite	Valley
UsserTal	Diorite	Valley
Lang Upper	Schist	Valley
Schwarzburg	Granitic gneiss	Valley
Castleguard	Limestone	Valley
Tsanfleuran_Upper	Limestone	Valley
Tsanfleuran_Lower	Limestone	Valley
WildHorn	Limestone	Valley
Saskatchewan	Limestone	Valley
Sisimiut	N/A	Ice sheet
Coats Island	Granitic gneiss	Ice sheet
Limestone X	Limestone	N/A

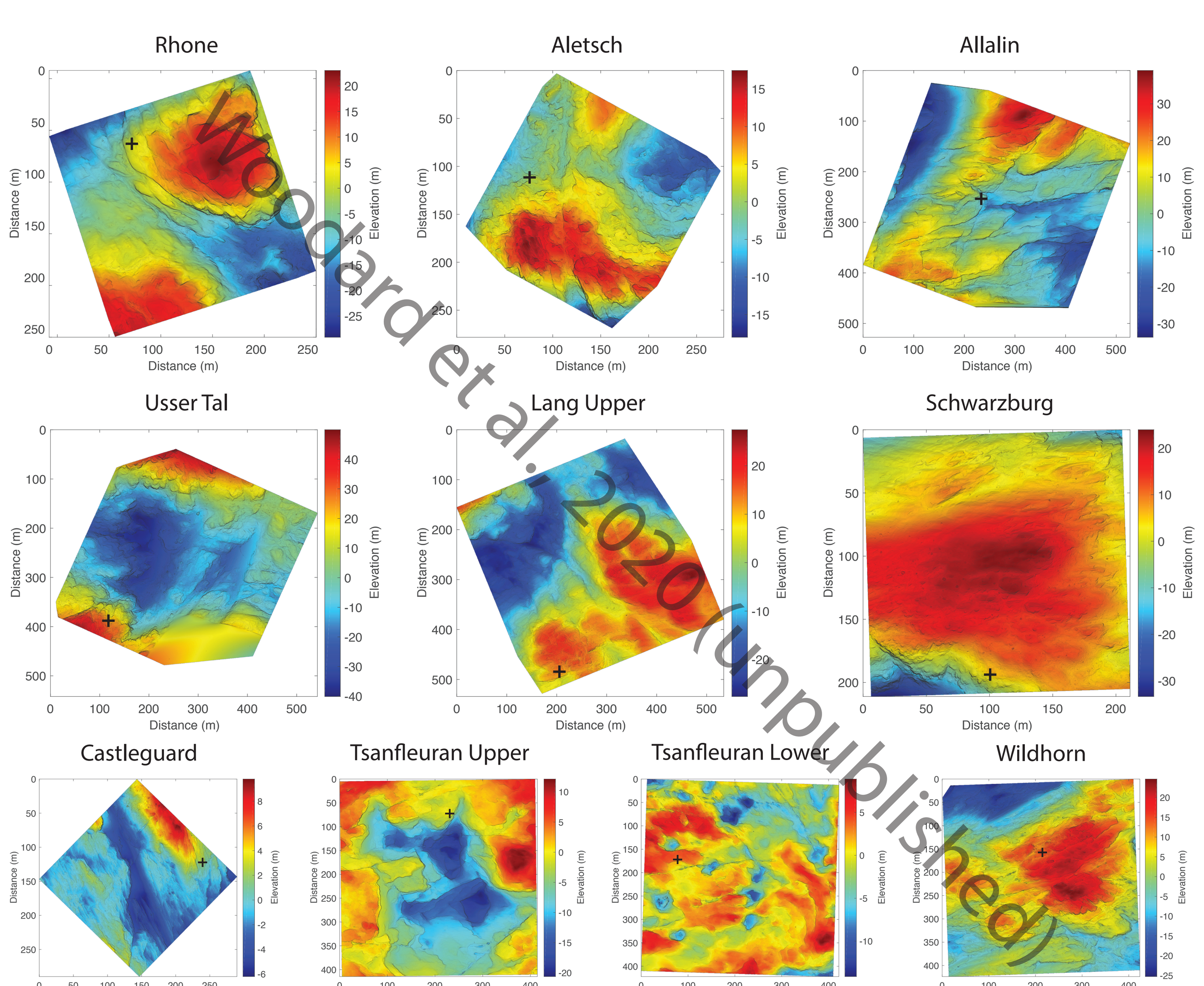


Figure 2: Shaded relief maps of ten valley glacier forefields used in this study. Ice flow direction is from left to right across the x-axis.

Methods

Elevation data was compiled from digital elevation models (DEMs) created from terrestrial lidar scans, photogrammetry using photos from a drone, white light interferometer scans, and SETM surface models. Scales of DEMs range from ~1000 to 0.00001 m. We then calculated the mean along flow power spectra of the DEMs following the methods outlined by Perron et al., 2008. Natural terrains tend to increase in amplitude with longer wavelengths and is commonly fitted with an inverse-power law of the form $P(f) = \psi f^{-\beta}$ or $P(f) = \psi f^{-(1+2h_u)}$. Where P is the spectral power, f is frequency, ψ is a constant, β is the spectral slope and hu is the Hurst exponent (note that $\beta = 1 + 2h_u$).

Forefields constitute a variety of differing lithologies and tectonic regimes. Two forefields are from exposed bedrock that was glaciated by ice streams, while the other forefields are near valley glaciers.

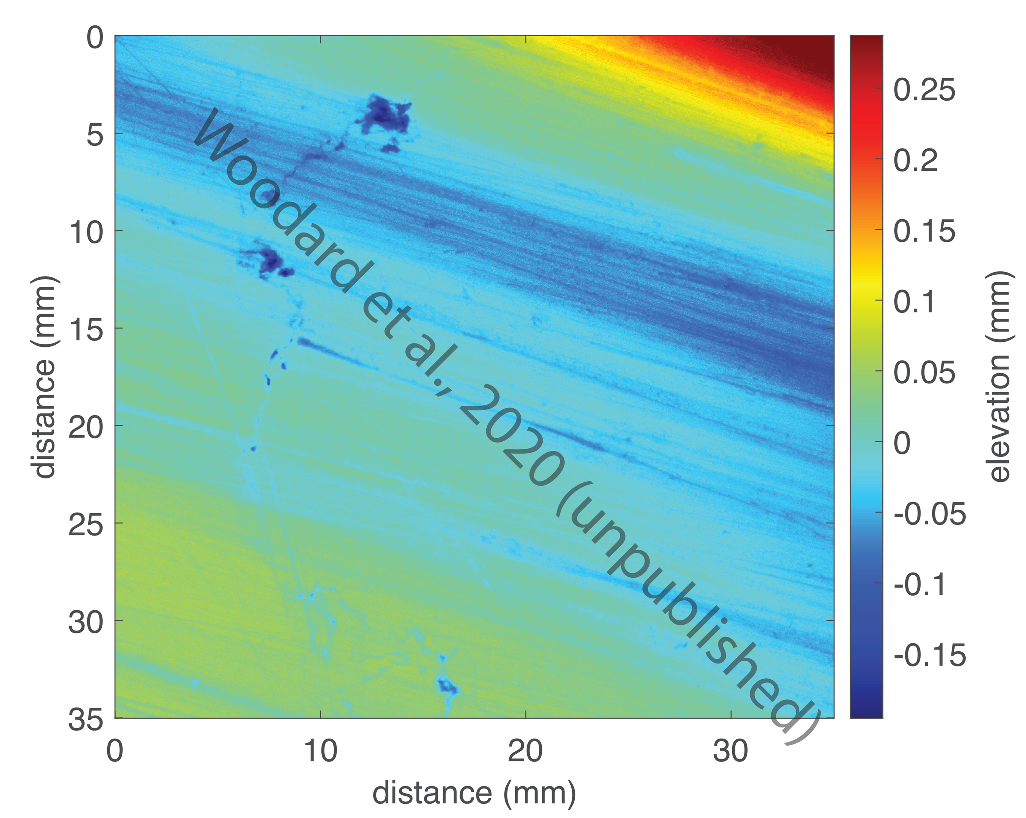
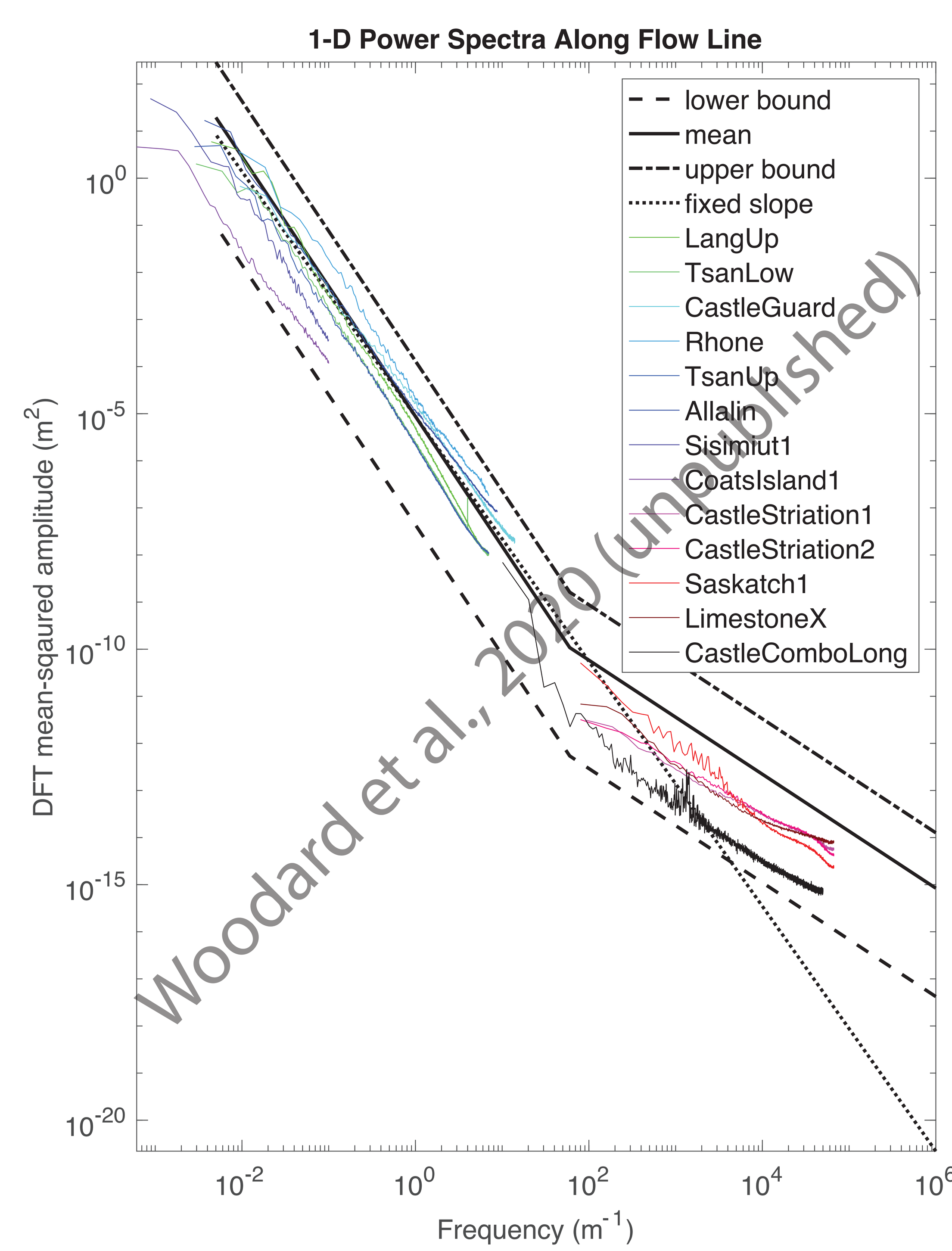


Figure 3 (left): Digital elevation model of a striated sample from Castleguard forefield taken with a white light interferometer.

Figure 4 (below): Along flow power spectra of glacial forefields. The four bold black lines show lower bound (dashed line), mean (solid line), and upper bound (dash-dot line) fits to the compiled spectra and a fixed spectral slope (dotted line; hu = 0.8) used in the regelation models. Note the break in slope at ~30 m^-1.



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Rempel, A. W., & Meyer, C. R. (2019). Premelting increases the rate of regelation by an order of magnitude. Journal of Glaciology, 65(251), 518–521. https://doi.org/10.1017/jog.2019.33

Regelation Models

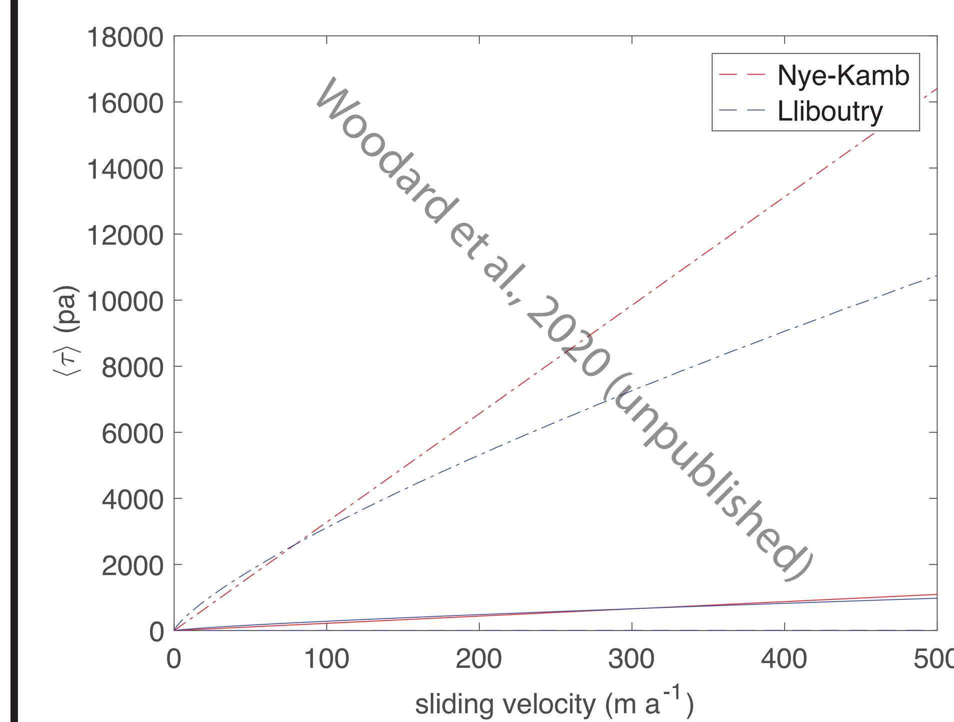

Figure 5: Regelation models of Nye-Kamb and Lliboutry. Line style (i.e. dashed, solid, or dash-dotted) correlates with the spectral bounds in Figure 4 used in the models. Note that the dashed lines are along the x-axis (i.e. approximately zero).

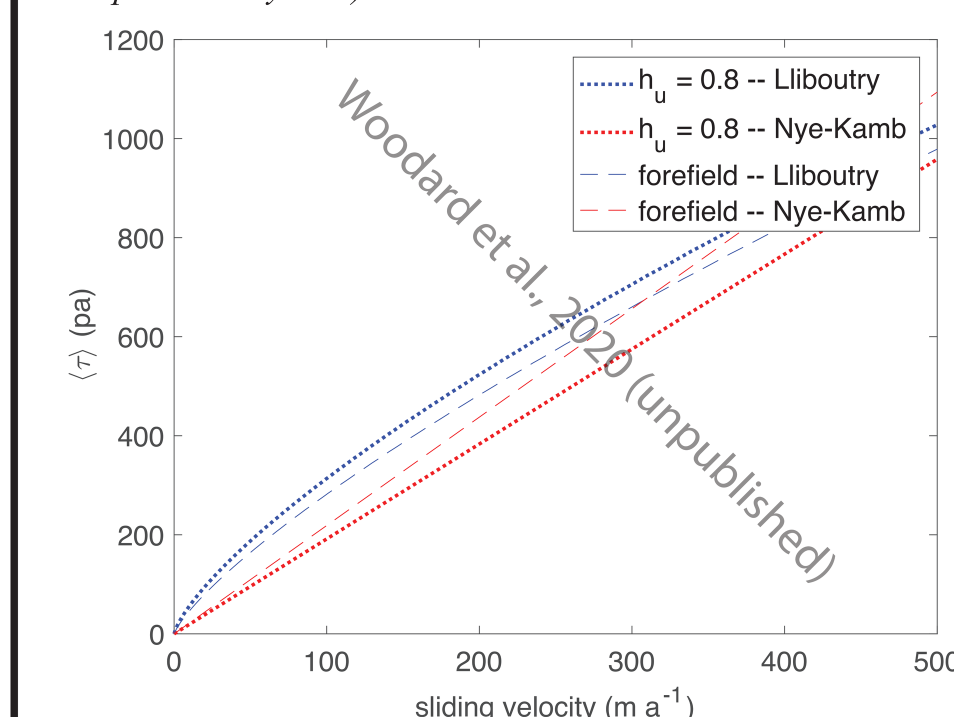

Figure 6: Regelation models of Nye-Kamb and Lliboutry comparing a fixed spectral slope (hu=0.8; dotted line in Figure 4) and the mean forefield spectra (solid line in Figure 4).

The regelation models by Lliboutry (1968) and Nye (1970) are used to constrain the proportion of basal drag attributed to regelation. Lliboutry's model accounts for the non-linear rheology of ice and the presence of cavities behind bumps in the bed. Nye's (1970) model is designed to solve for basal stress using the surfaces periodogram but assumes a Newtonian rheology for the ice and ignores the affects of cavities. Both models assume clean temperate ice and a small water film with a thickness O(10-6 m) that eliminates any shear traction on the bumps and drowns out bumps with bump spacing less than the film thickness. We also include the premelting component on all calculations following Rempel and Meyer, 2019.

The fractional amplitude of the actual bedrock relief (ar) is used to taper the regelation stress acting on the bed. Including premelting (Rempel & Meyer, 2019), ar is defined as

$$a_r = \frac{k^2}{k^2 + k_o^2}$$

$$k_o^2 = \left(\frac{\rho_l - \rho_i}{\rho_l}\right)\left(\frac{L\rho_i}{2BC_o(K_i + K_r)}\right)$$

Where k is the wave number, B is the mass ice viscosity, L is the latent heat of fusion, Ki and Kr are the thermal conductivities of the ice and rock, respectively, Co is a the melting point depression with pressured, and ρl and ρi are the densities of the water and ice, respectively.

Implications

Power spectra show a decrease in spectral slope (β) from -2.75 to -1.21 (hu = 0.88 and 0.11, respectively) after ~30 m^-1. This change suggests a change in the scaling relation of bedrock roughness and may reflect a change in the erosional mechanisms acting on the bedrock.

Our results suggest that regelation is only able to account for a up to ~17 kPa of basal stress with most forefields only reaching ~1 kPa for clean ice with velocities up to 500 m a^-1. Thus, neglecting the regelation mechanism in glacier sliding is reasonable for sliding models. However, inclusion of debris would likely increase the drag attributed to regelation.

Key Points

- The break in spectral slope on forefield bedrock suggest a change in erosional mechanisms acting on the bedrock.
- Clean ice regelation models run on real bedrock terrain suggest that drag due to regelation sliding does not exceed a few kilopascals under normal sliding conditions.
- Omission of regelation in clean ice flow models is an appropriate approximation.