Testing a theory of subglacial cavity formation from observations of deglaciated bedrock at Castleguard Glacier, Alberta, Canada

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Introduction

Water-filled cavities, where the basal ice of sliding glaciers separates from bedrock, modulate subglacial hydrology and glacier sliding speed. Accurately assessing the factors that control cavity size is thus a central goal in efforts to model the dynamics of sliding glaciers and ice sheets. Retreat of Castleguard Glacier (Fig. 1) has exposed its former bed (Fig. 2), allowing us to analyze the relationship between limestone step height and associated cavity size.

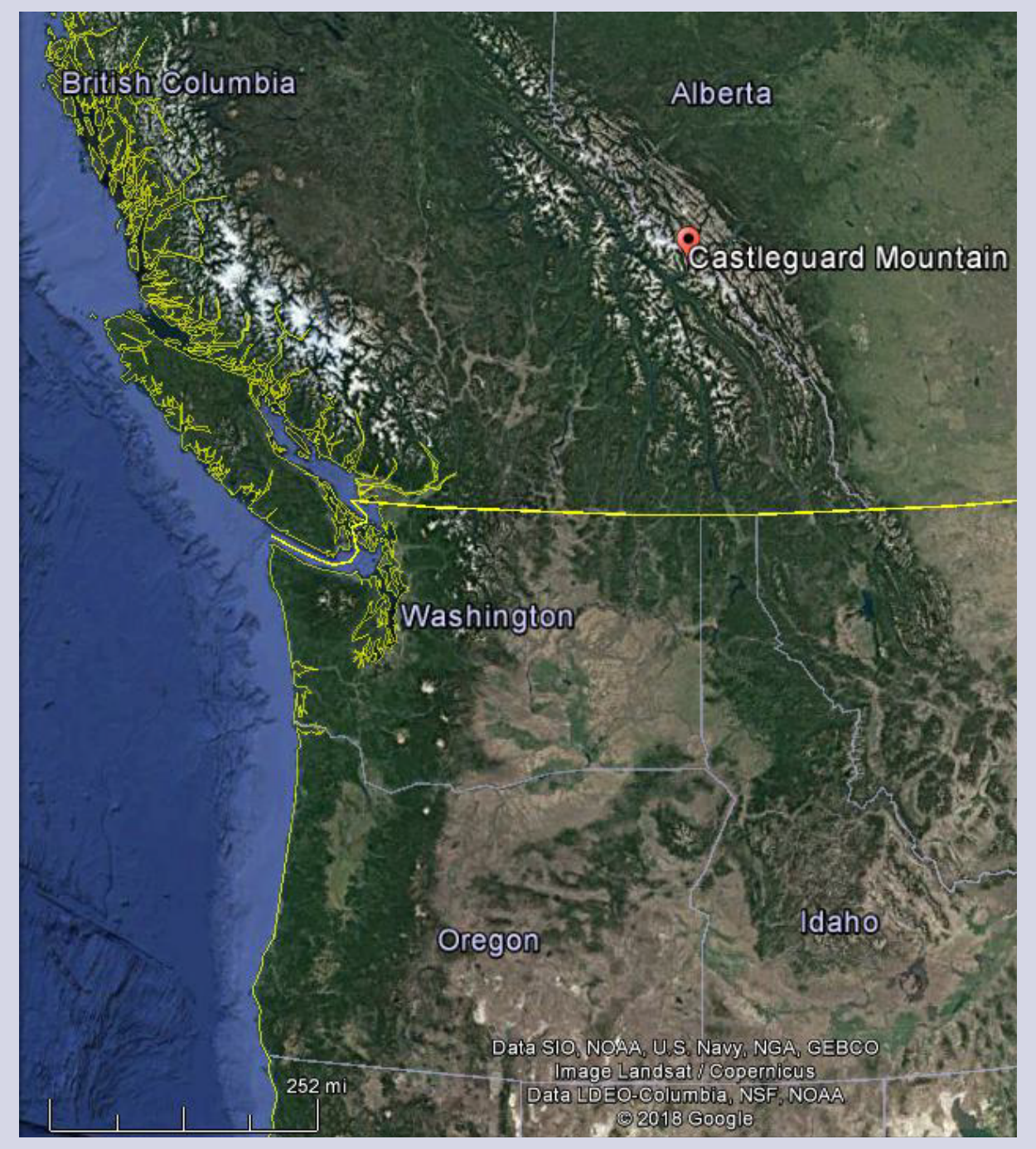


Figure 1. (above) Location of Castleguard Glacier on Castleguard Mountain in the Canadian Rockies.

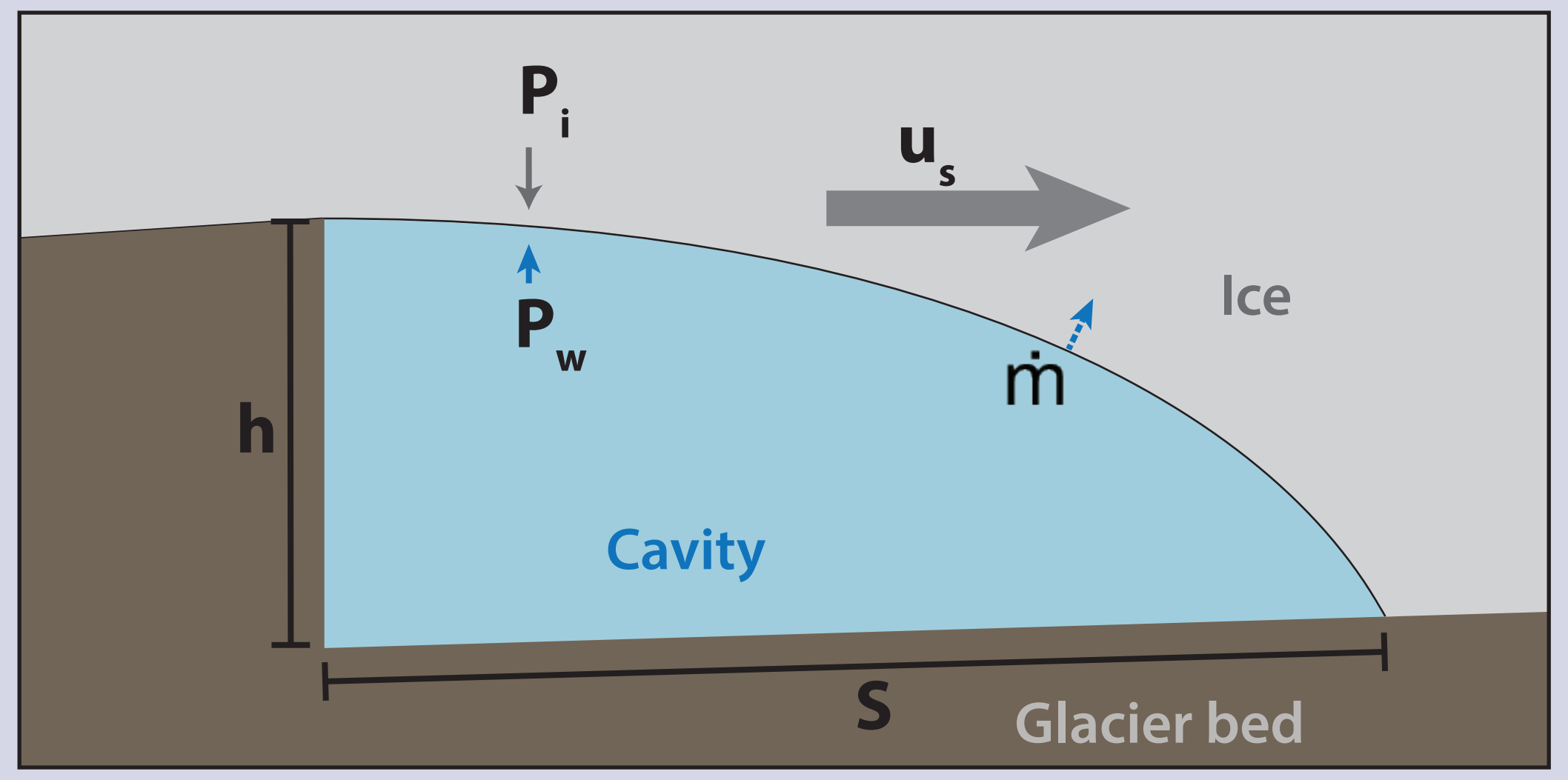
Figure 2. (left) Castleguard Glacier forefield, characterized by limestone steps.

Theoretical Relationship for Cavity Geometry

A simple theoretical relationship (Equation 1), tested experimentally, describes cavity length as a function of step height, sliding speed, effective pressure and the flow-law parameters of temperate ice (Fig. 3).

$$S = 4\left(\frac{(u_s+\dot{m})h}{2\pi}\right)^{\frac{1}{2}}\left(\frac{B}{P_i-P_w}\right)^{\frac{n}{2}}$$

Equation 1. Theoretical relationship derived by Iverson and Petersen (2011) based on a model by Kamb (1987).



P_i = overriding ice pressure
P_w = water pressure
u_s = sliding speed
$\dot{m}$ = melt rate
h = step high
S = cavity length

Figure 3. Subglacial cavity and step geometry with variables defined.

Methods

Dissolution features immediately down-glacier from limestone steps provide evidence of former water-filled cavities, while striations and $CaCO_3$ precipitate indicate ice-rock contact that defines the maximum extent of ice-bed separation (Fig. 4). We measured the heights and corresponding cavity sizes of several hundred steps using these features to delimit the maximum extent of subglacial cavities (Fig. 5).

Figure 5. Evidence of a former subglacial cavity defined primarily by $CaCO_3$ precipitate.

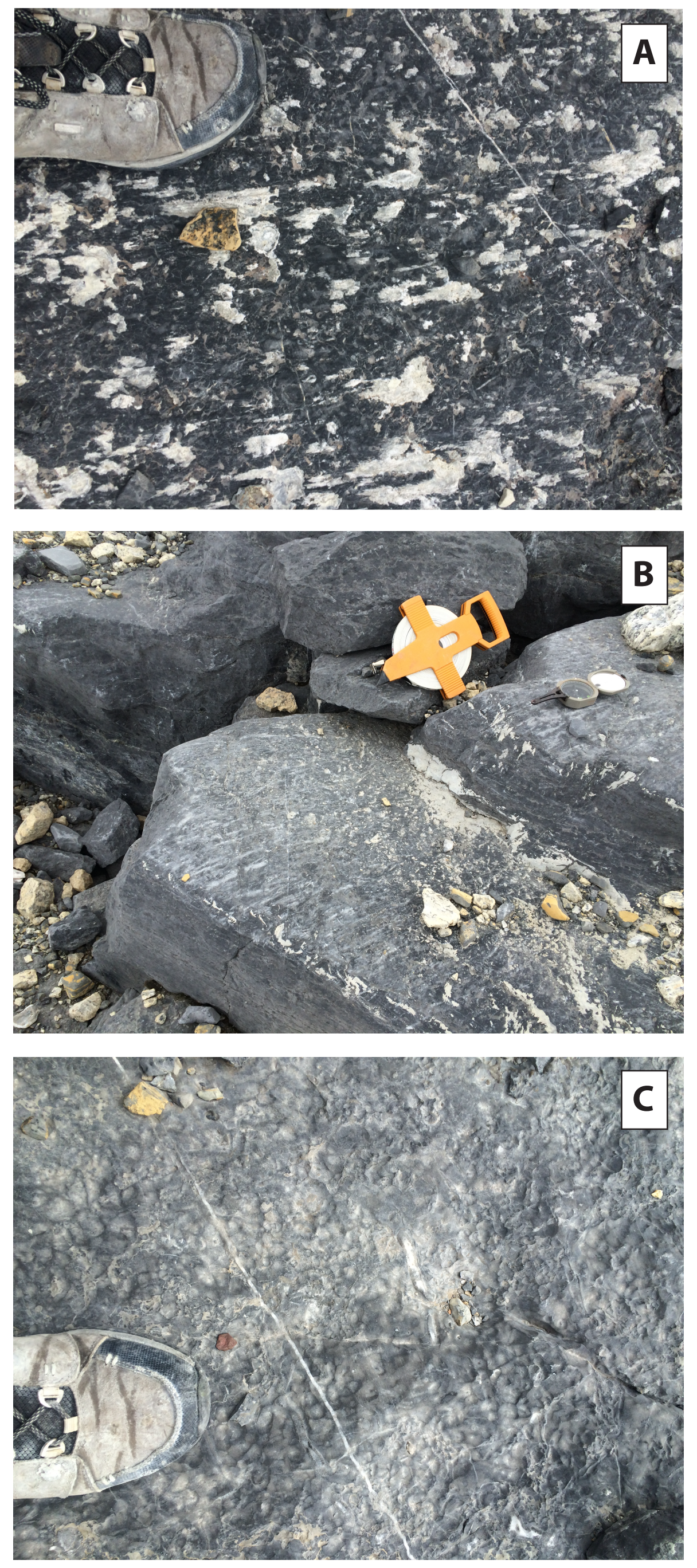


Figure 4. $CaCO_3$ precipitate (A) occurs only where ice is in intimate contact with the rock. Striations (B) reflect flow direction where ice was in contact with the rock. Dissolution pits (C) formed on the floor of water filled cavities.

Results

Measurements indicate centimeter to meter scale cavities, and striations show that the direction of ice flow was approximately perpendicular to steps. Lengths of cavities are nearly linearly related to the heights of steps (Fig. 6). This observation is in contrast with the theoretical relationship that indicates that cavity length should increase with the square root of the step height (Equation 1). Thus, for larger steps on the bed, observed former cavities are significantly larger than those predicted by the theory, and vice versa.

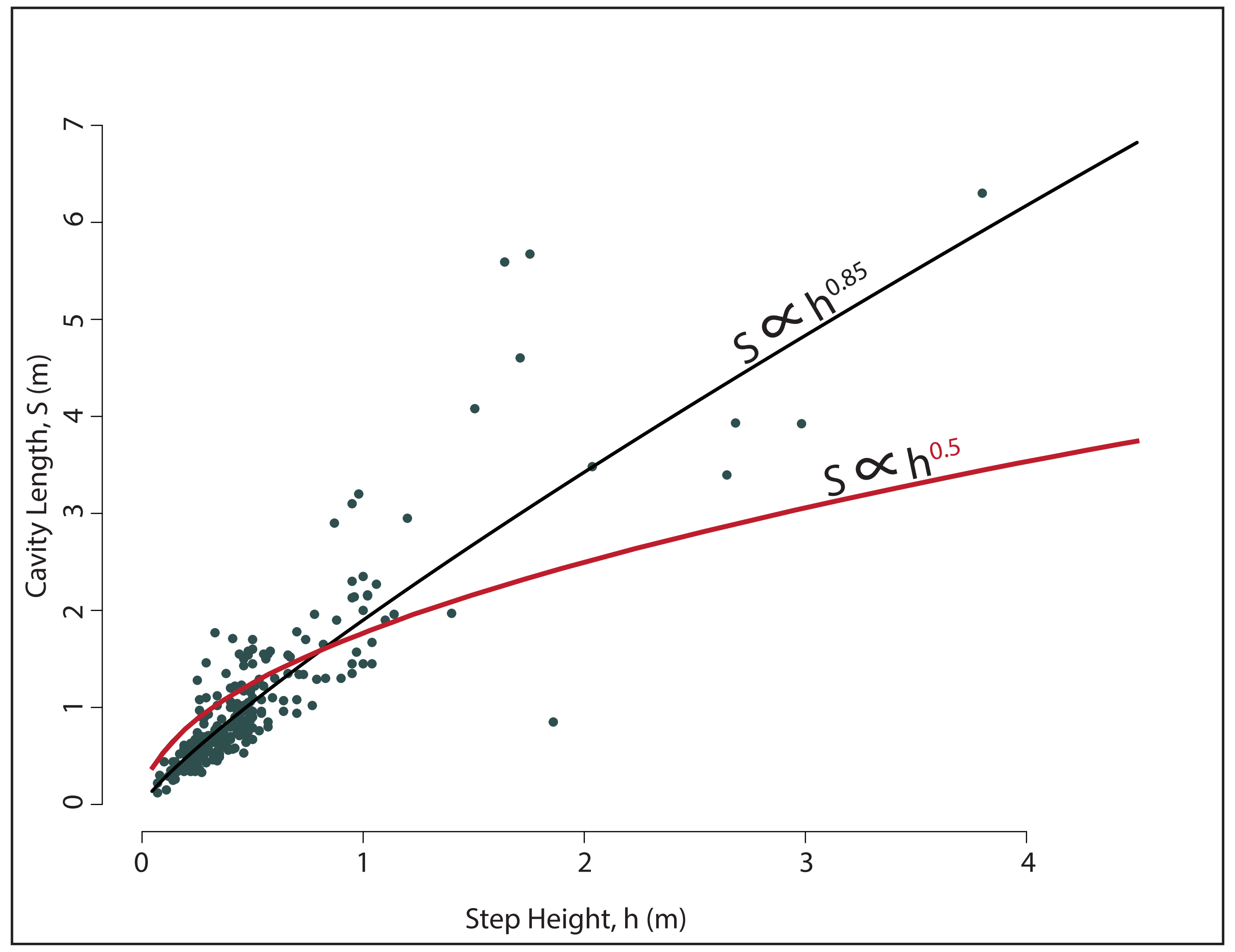


Figure 6. (right) Step measurements from Castleguard Glacier forefield with a power law best fit to the data, compared with the square-root dependence of Equation 1 (red).

Discussion

Sizes of small cavities are overpredicted and sizes of large cavities are underpredicted by the theory (Equation 1). This implies that either melt rate ($\dot{m}$), water pressure (P_w), or sliding speed (u_s) may be systematically higher at larger cavities, and lower in smaller cavities.

$\dot{m}$ and P_w: The velocity of subglacial water decreases where it flows into larger cavities (Fig. 7). This velocity decrease lowers the melt rate and may increase water pressure, though not significantly.

u_s: Sliding speed could be preferentially higher near large cavities. Drag is reduced over a rough bed where large cavities result in small areas of ice-bed contact, which may cause locally higher sliding speeds (Fig. 8).

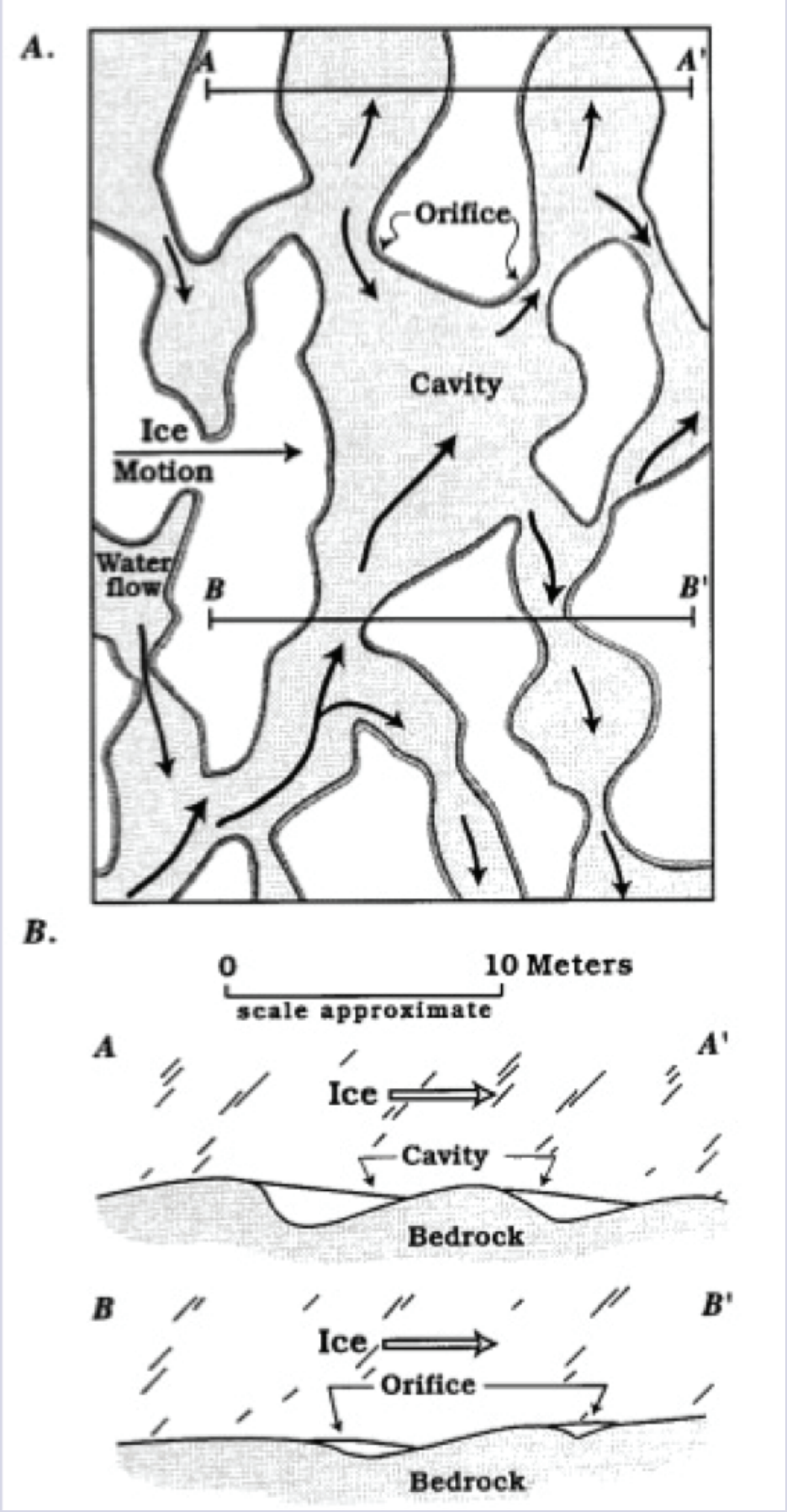


Figure 7. A subglacial cavity network. From Kamb, 1987.

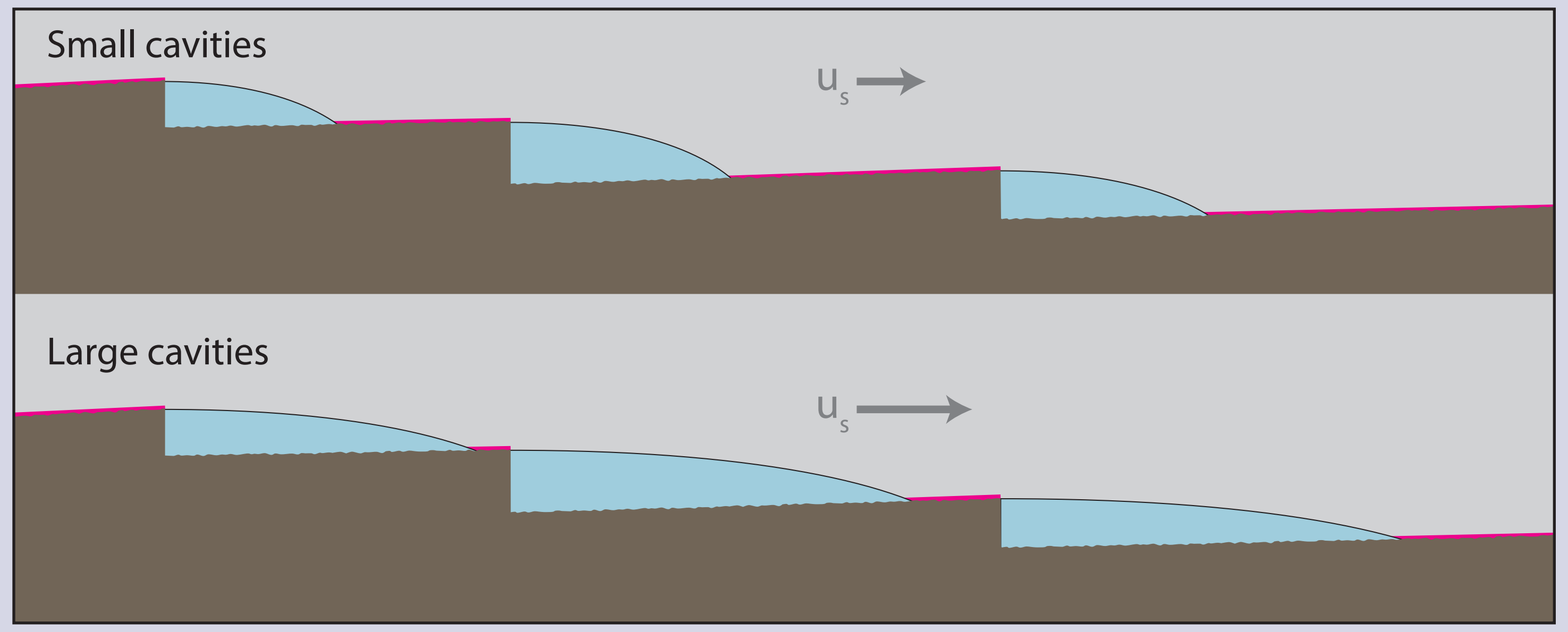


Figure 8. Larger cavities reduce drag by engulfing small undulations in the rock bed.

Conclusions

- $CaCO_3$ precipitate, striations, and dissolution pits can be used to delimit the sizes of former subglacial cavities.
- The observed relationship between step height and cavity length is more linear than that of a leading theoretical relationship tested experimentally (Equation 1).
- Sliding speed covarying with step height might help explain this difference.

References

Iverson, N., and Petersen, B., 2011, A new laboratory device for study of subglacial processes: first results on ice-bed separation during sliding: Journal of Glaciology, v. 57, p. 1135-1146.
Kamb, B., 1987, Glacier surge mechanism based on linked cavity configuration of the basal water conduit system: Journal of Geophysical Research, v., 92, p. 9083-9100.

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