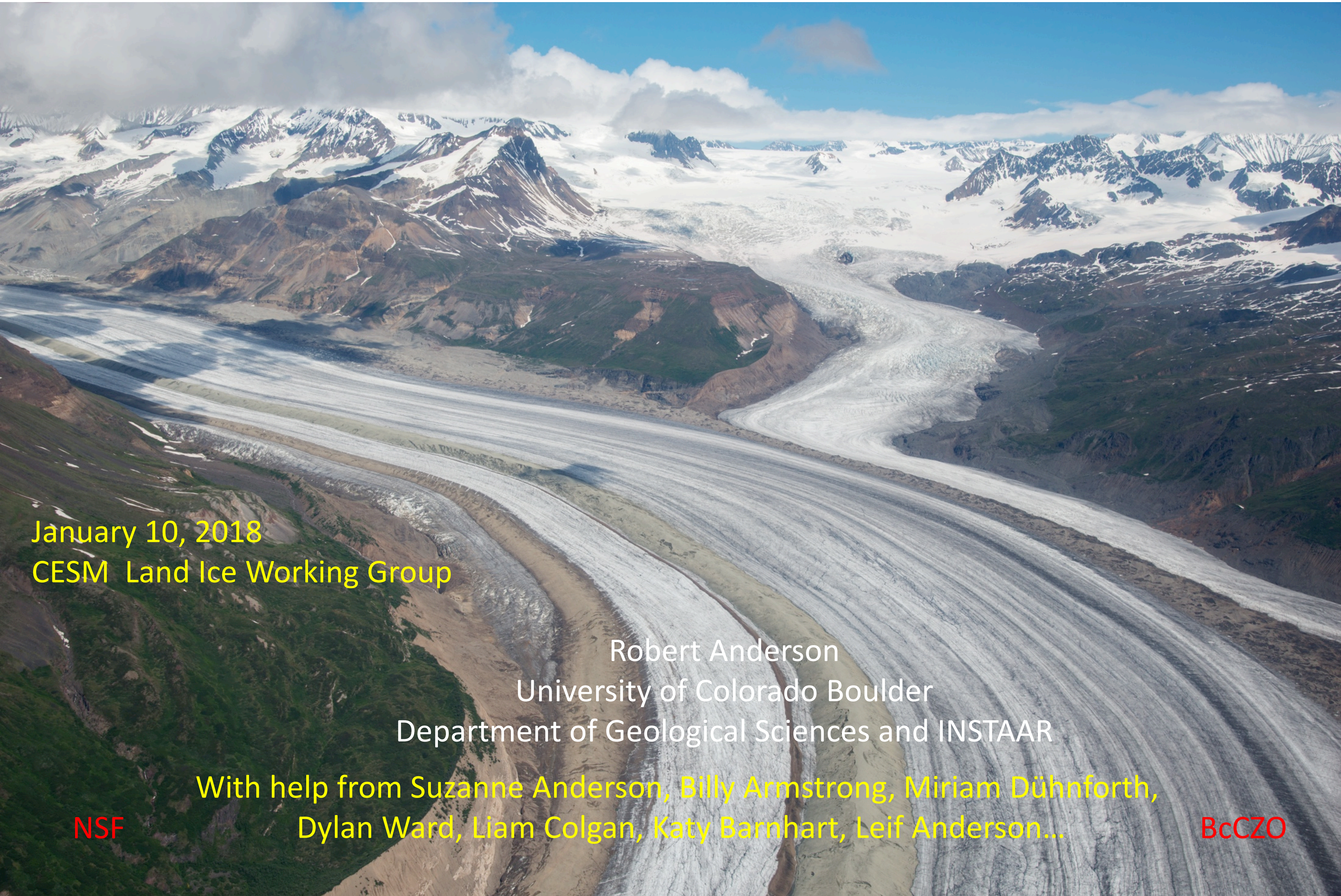
# Of rocks and ice: The glacier-rock glacier cycle



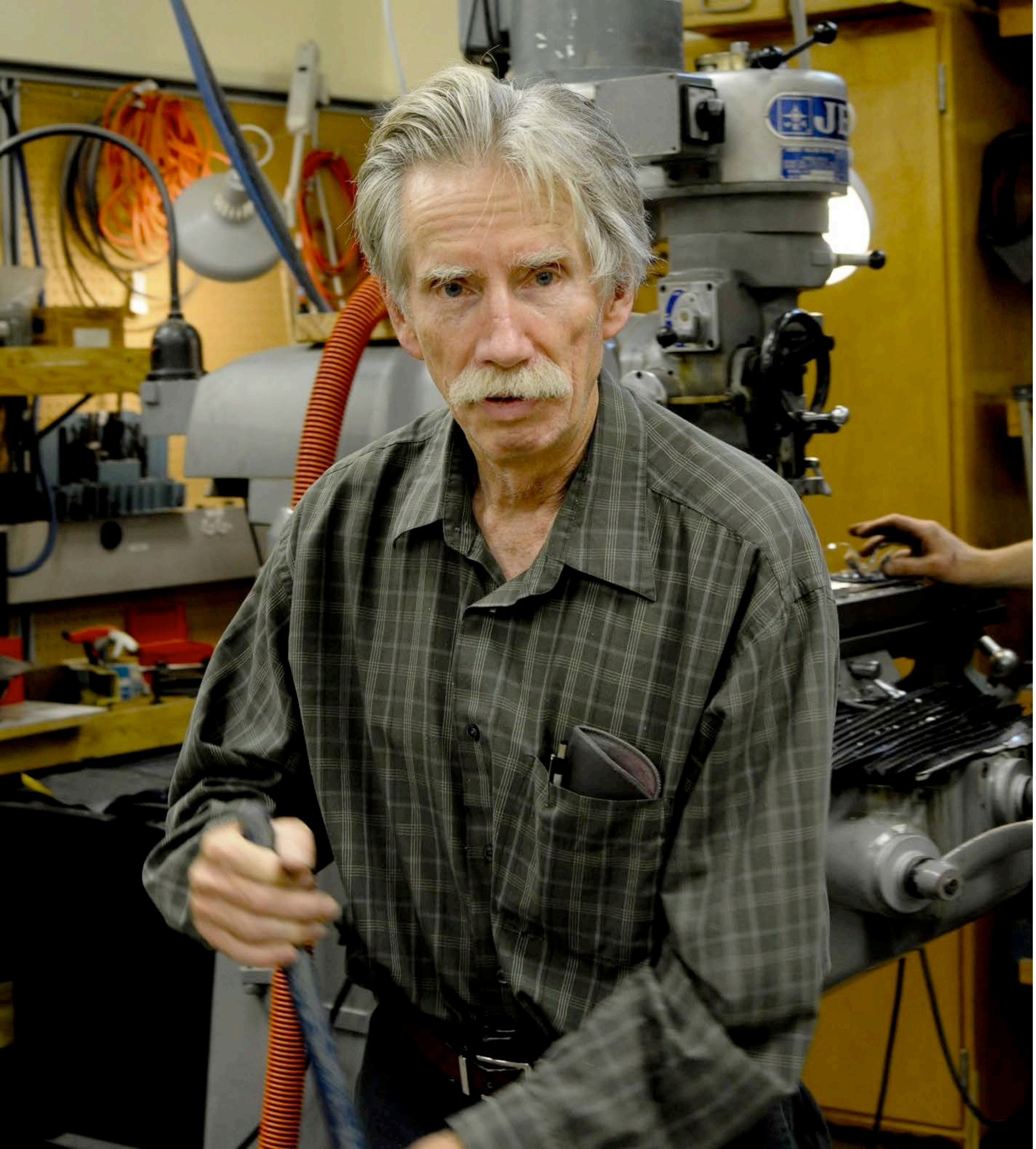
January 10, 2018
CESM  Land Ice Working Group

Robert Anderson
University of Colorado Boulder
Department of Geological Sciences and INSTAAR

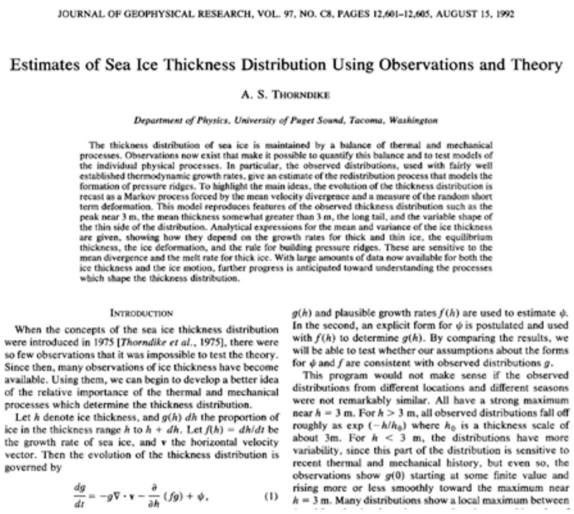
With help from Suzanne Anderson, Billy Armstrong, Miriam Dühnforth,
Dylan Ward, Liam Colgan, Katy Barnhart, Leif Anderson…

NSF

BcCZO



# Alan S. Thorndike



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. C8, PAGES 12,601–12,605, AUGUST 15, 1992

## Estimates of Sea Ice Thickness Distribution Using Observations and Theory

A. S. THORNDIKE

*Department of Physics, University of Puget Sound, Tacoma, Washington*

The thickness distribution of sea ice is maintained by a balance of thermal and mechanical processes. Observations now exist that make it possible to quantify this balance and to test models of the individual physical processes. In particular, the observed distributions, used with fairly well established thermodynamic growth rates, give an estimate of the redistribution process that models the formation of pressure ridges. To highlight the main ideas, the evolution of the thickness distribution is recast as a Markov process forced by the mean velocity divergence and a measure of the random short term deformation. This model reproduces features of the observed thickness distribution such as the peak near 3 m, the mean thickness somewhat greater than 3 m, the long tail, and the variable shape of the thin side of the distribution. Analytical expressions for the mean and variance of the ice thickness are given, showing how they depend on the growth rates for thick and thin ice, the equilibrium thickness, the ice deformation, and the rule for building pressure ridges. These are sensitive to the mean divergence and the melt rate for thick ice. With large amounts of data now available for both the ice thickness and the ice motion, further progress is anticipated toward understanding the processes which shape the thickness distribution.

### INTRODUCTION

When the concepts of the sea ice thickness distribution were introduced in 1975 [*Thorndike et al.*, 1975], there were so few observations that it was impossible to test the theory. Since then, many observations of ice thickness have become available. Using them, we can begin to develop a better idea of the relative importance of the thermal and mechanical processes which determine the thickness distribution.

Let $h$ denote ice thickness, and $g(h)\,dh$ the proportion of ice in the thickness range $h$ to $h + dh$. Let $f(h) = dh/dt$ be the growth rate of sea ice, and $\mathbf{v}$ the horizontal velocity vector. Then the evolution of the thickness distribution is governed by

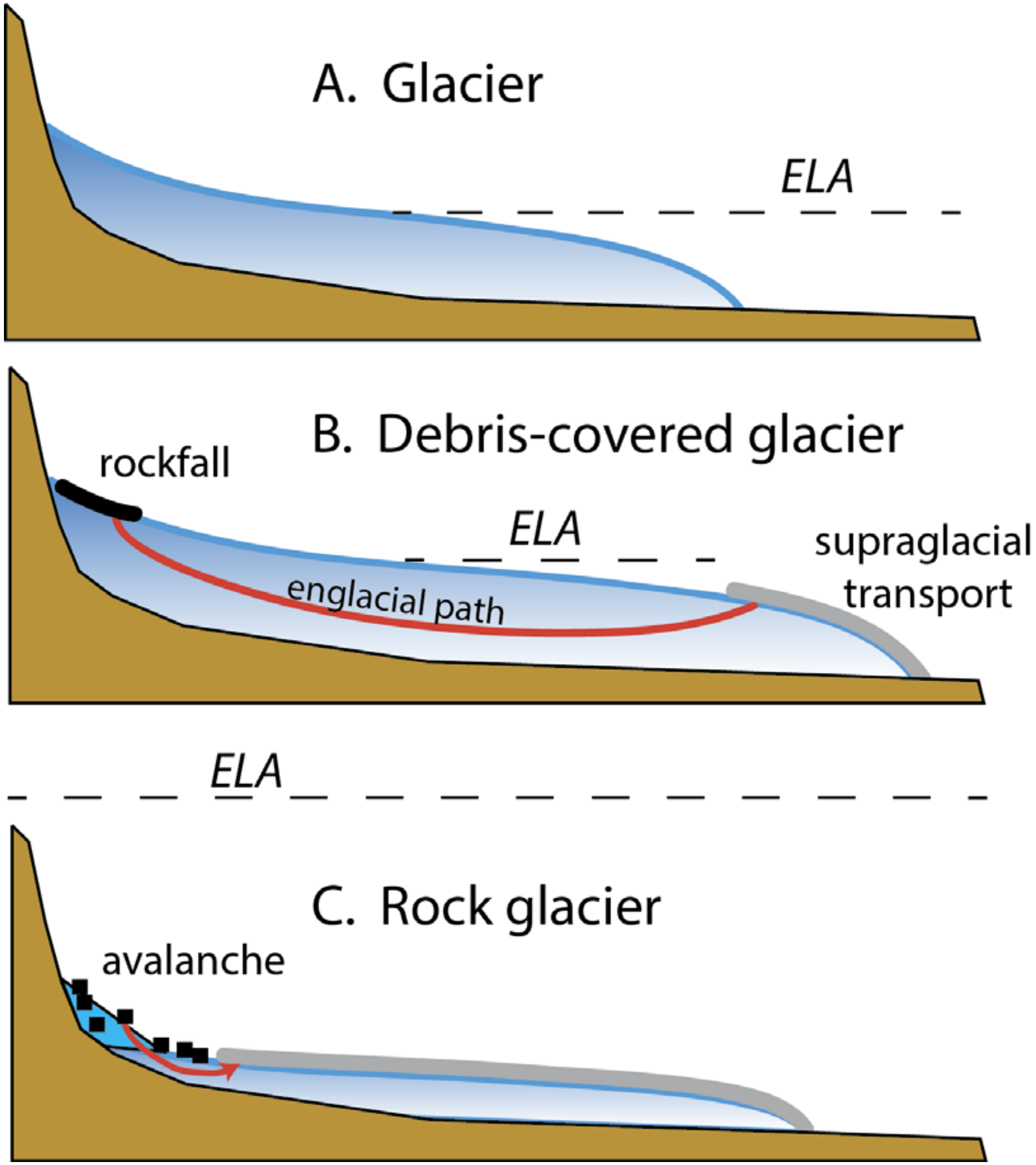
$$\frac{dg}{dt} = -g\nabla \cdot \mathbf{v} - \frac{\partial}{\partial h}(fg) + \psi, \qquad (1)$$

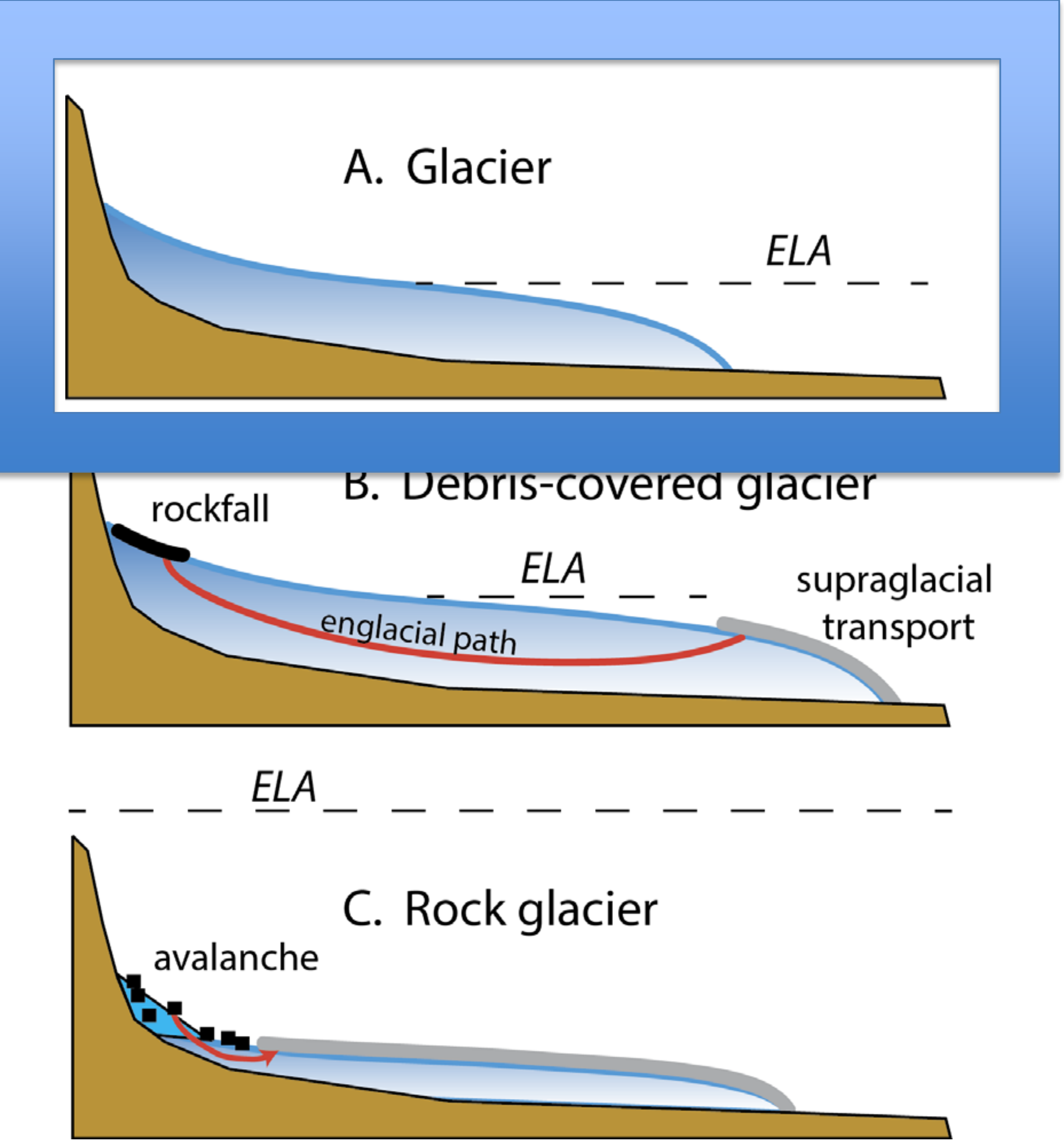
$g(h)$ and plausible growth rates $f(h)$ are used to estimate $\psi$. In the second, an explicit form for $\psi$ is postulated and used with $f(h)$ to determine $g(h)$. By comparing the results, we will be able to test whether our assumptions about the forms for $\psi$ and $f$ are consistent with observed distributions $g$.

This program would not make sense if the observed distributions from different locations and different seasons were not remarkably similar. All have a strong maximum near $h = 3$ m. For $h > 3$ m, all observed distributions fall off roughly as exp $(-h/h_0)$ where $h_0$ is a thickness scale of about 3m. For $h < 3$ m, the distributions have more variability, since this part of the distribution is sensitive to recent thermal and mechanical history, but even so, the observations show $g(0)$ starting at some finite value and rising more or less smoothly toward the maximum near $h = 3$ m. Many distributions show a local maximum between

Lyell and Maclure glaciers, Yosemite NP

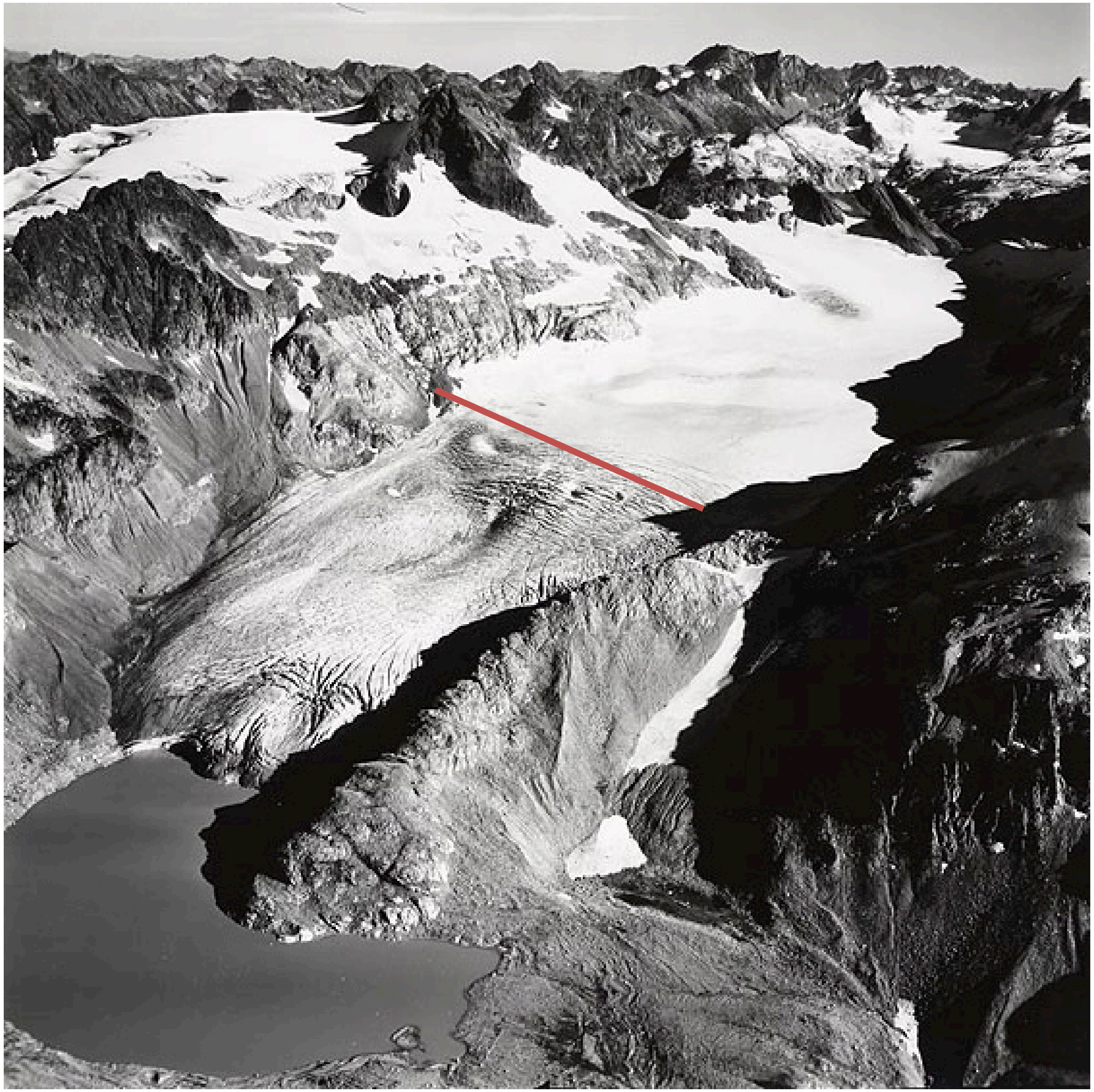
National Creek Rock Glacier, Kennicott Alaska


A. Glacier
ELA
B. Debris-covered glacier
rockfall
ELA
supraglacial
transport
englacial path
ELA
C. Rock glacier
avalanche



Pure ice
End-member

South Cascade Glacier, Washington

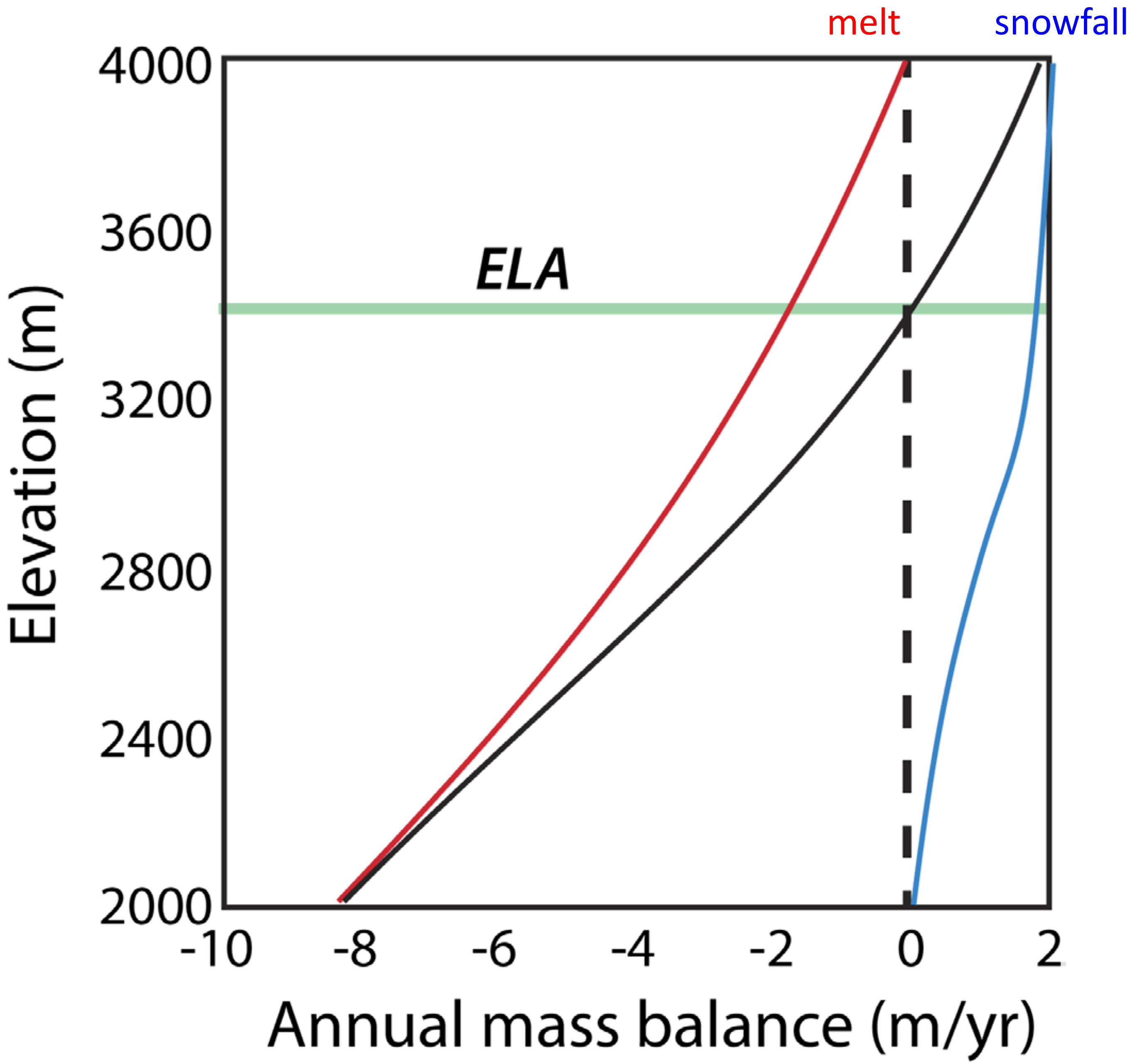


Accumulation zone

Equilibrium line

Ablation zone

Basic architecture of a glacier

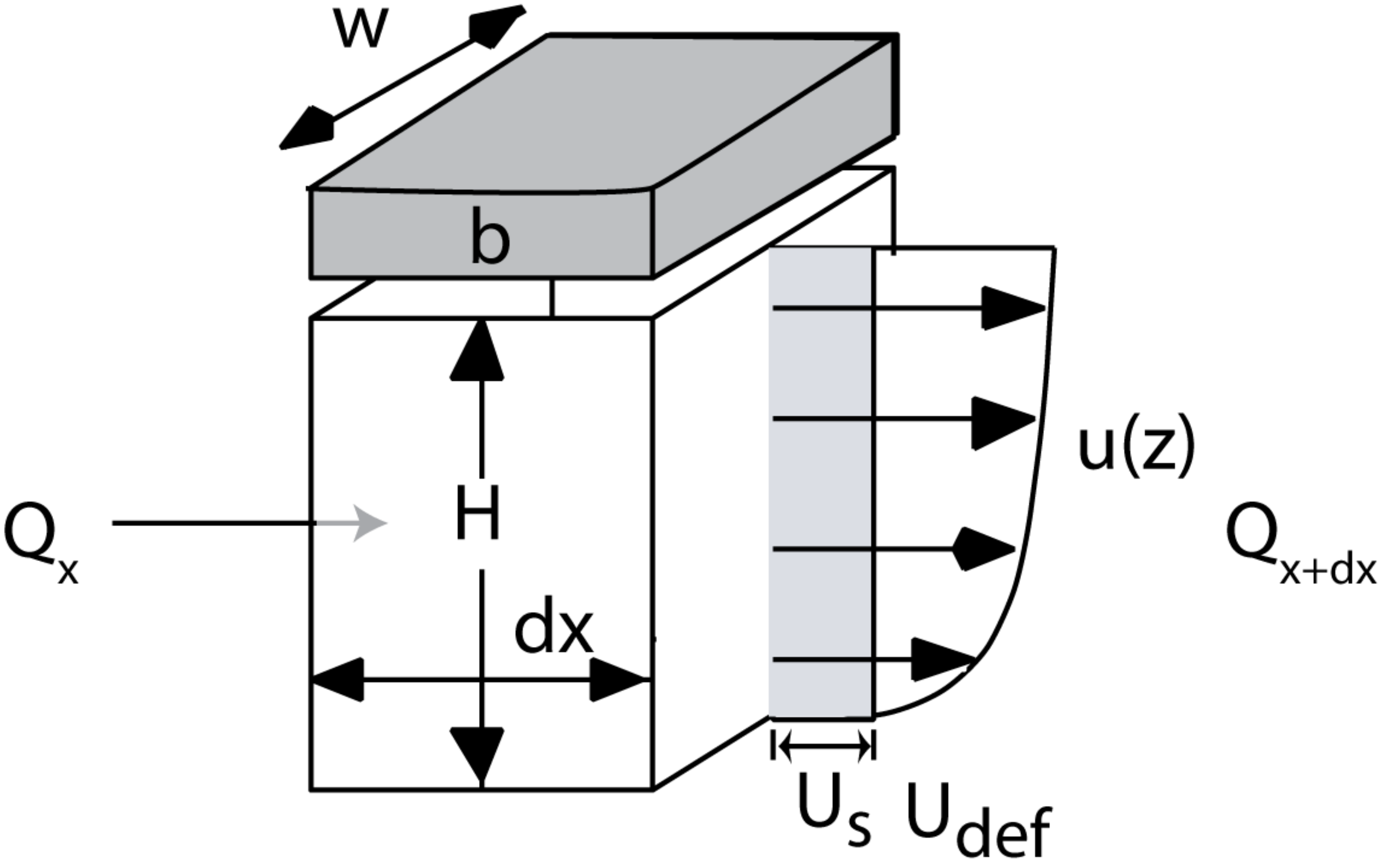


Red = summer

Black = net balance

Blue = winter

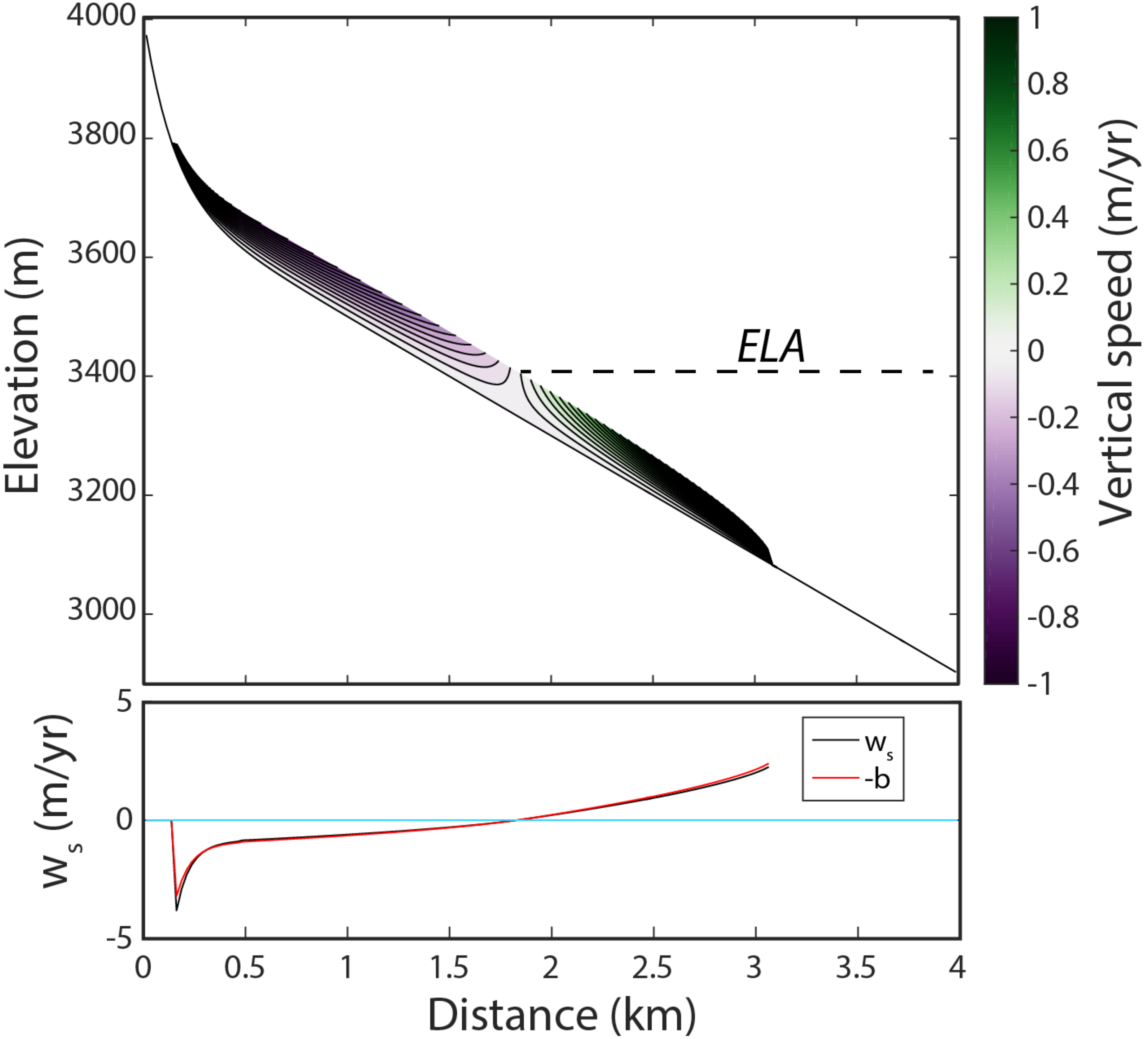
# Conservation of ice volume in a column

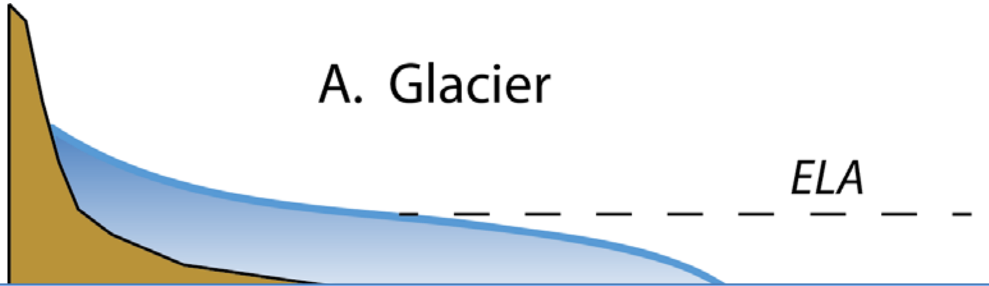


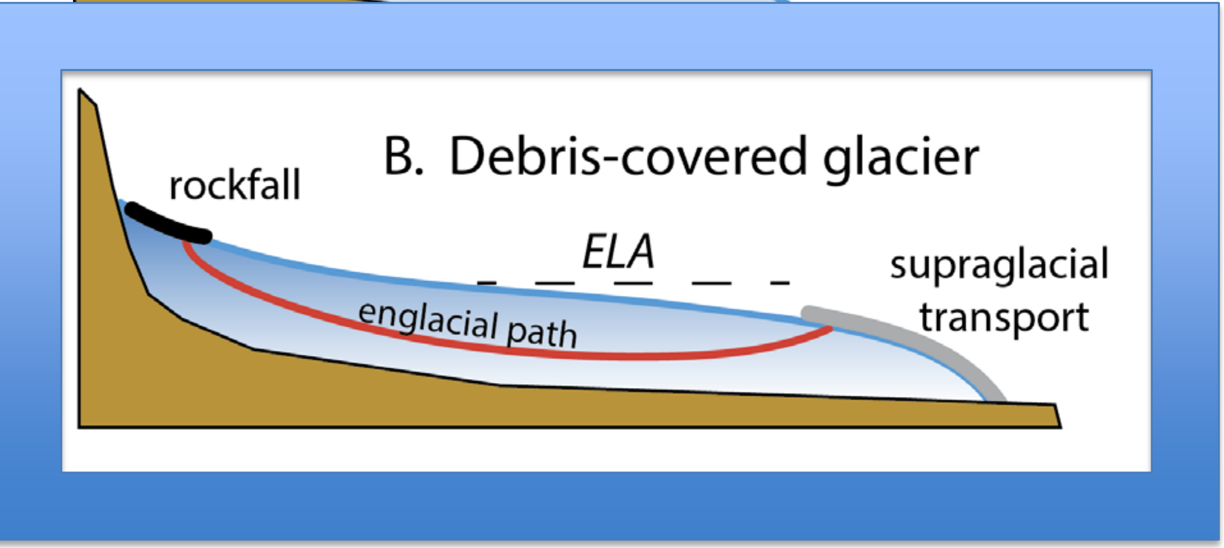
$$\boxed{\frac{\partial H}{\partial t} = b - \frac{\partial Q}{\partial x}}$$

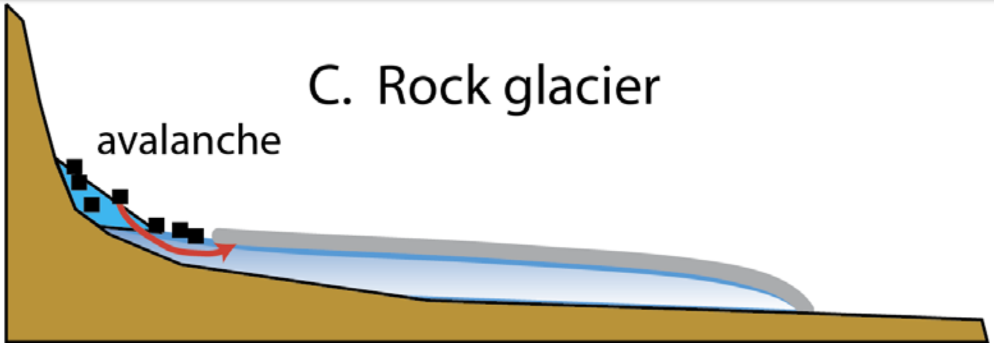
Conservation of ice

# Approach to steady state for a simple pure ice case


Elevation (m)
4000
3800
3600
3400
3200
3000
ELA
Vertical speed (m/yr)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
$w_s$ (m/yr)
5
0
-5
$w_s$
-b
0
0.5
1
1.5
2
2.5
3
3.5
4
Distance (km)


A. Glacier
ELA

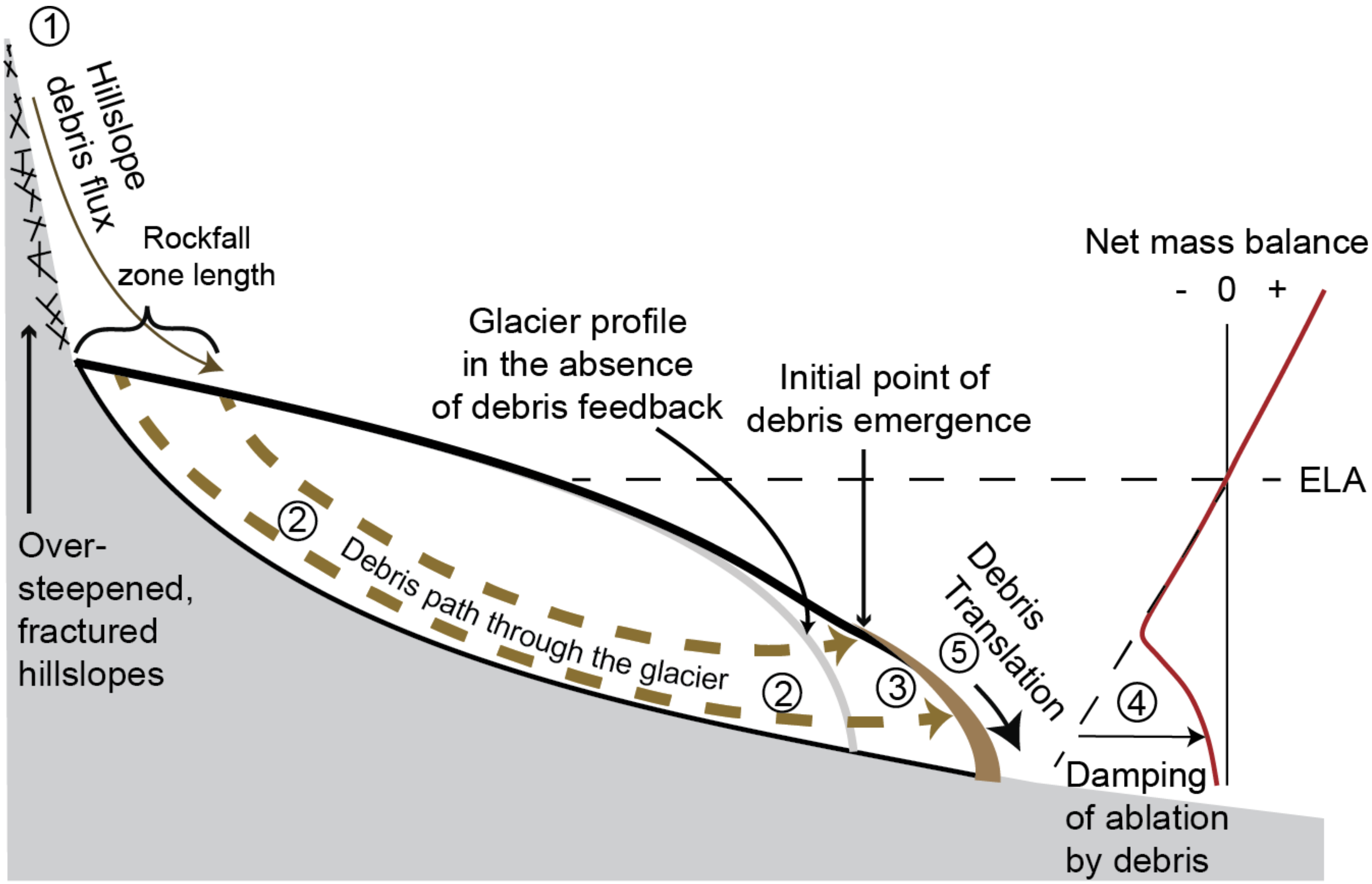

B. Debris-covered glacier
rockfall
ELA
supraglacial transport
englacial path


C. Rock glacier
avalanche

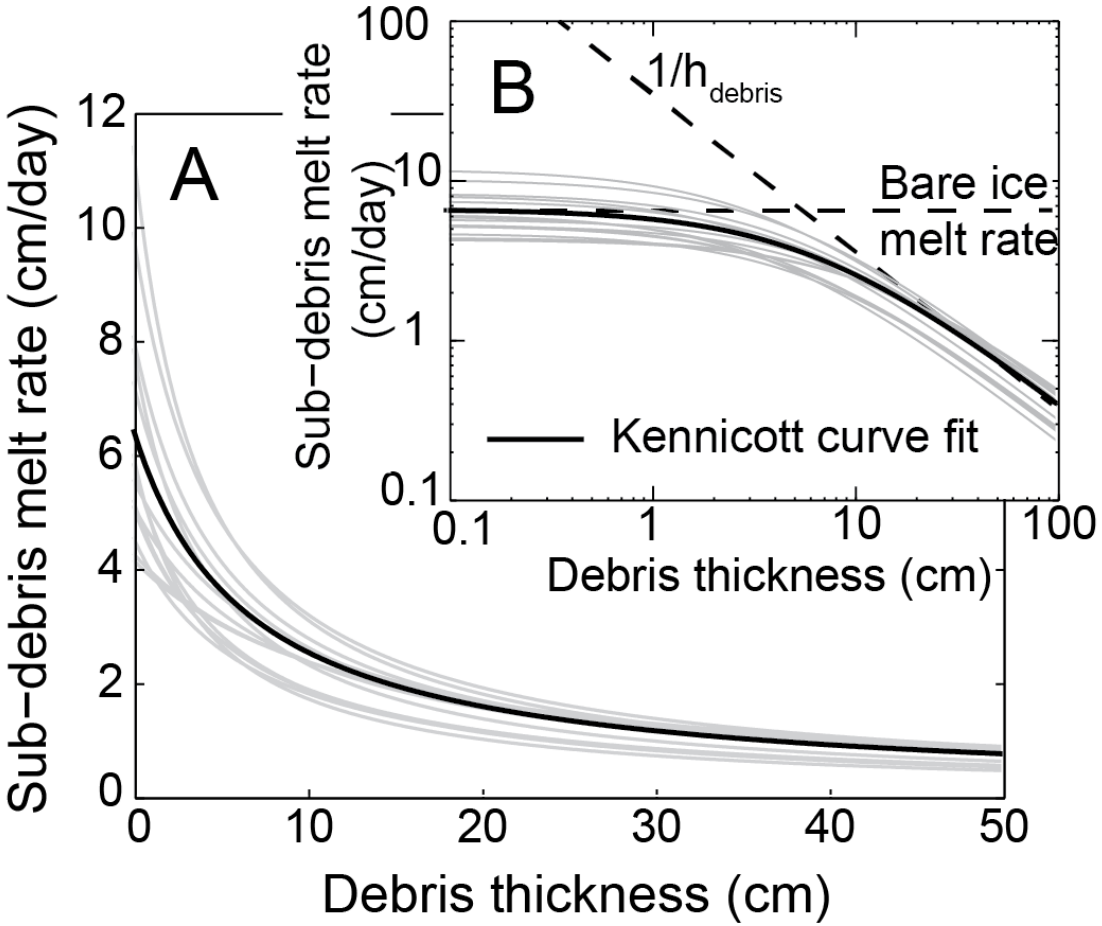
British Columbia Coast Range

The dirty snout of Kennicott Glacier

# Key elements of the debris-covered glacier



# How does the presence of debris reduce sub-debris ice melt?

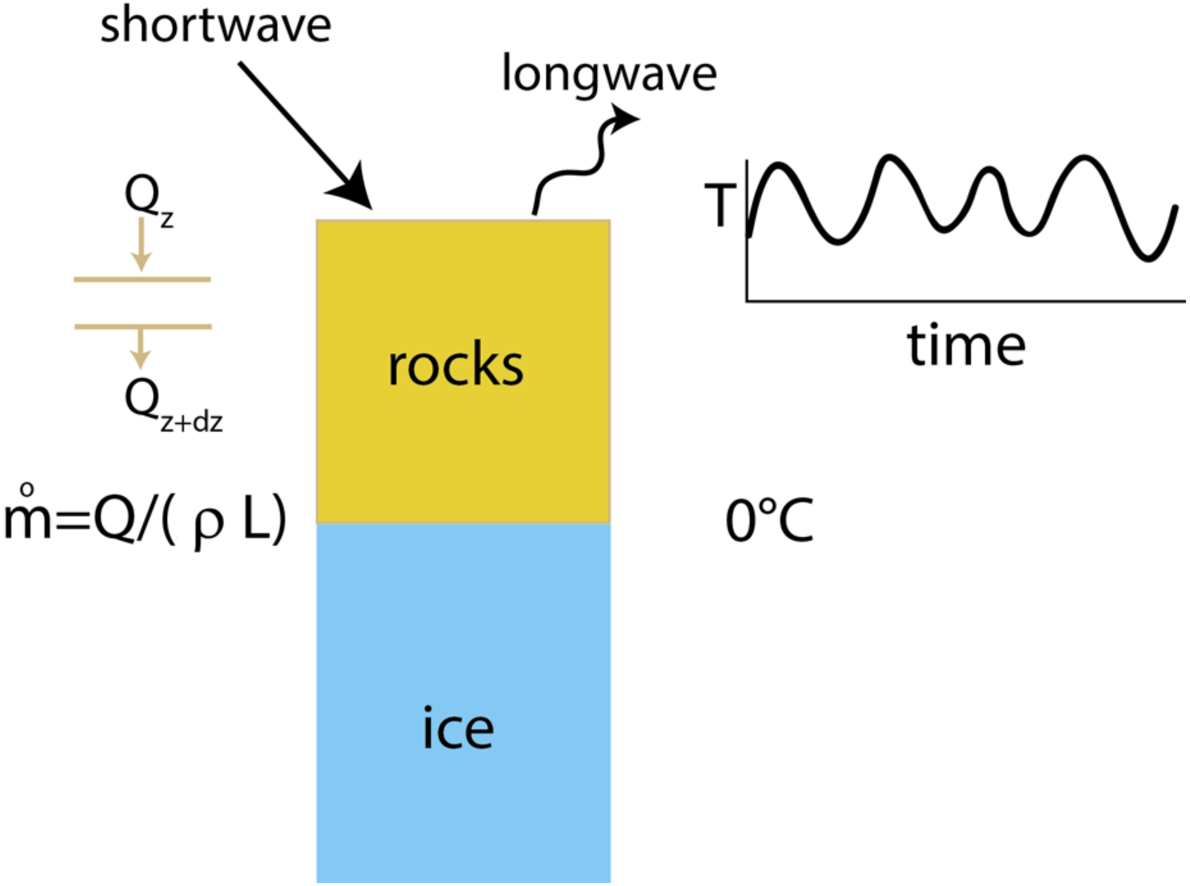


Leif Anderson

Dependence of melt rate on debris thickness is well described by a hyperbolic (1/h) function.

Why? It is to 1st order a conduction problem

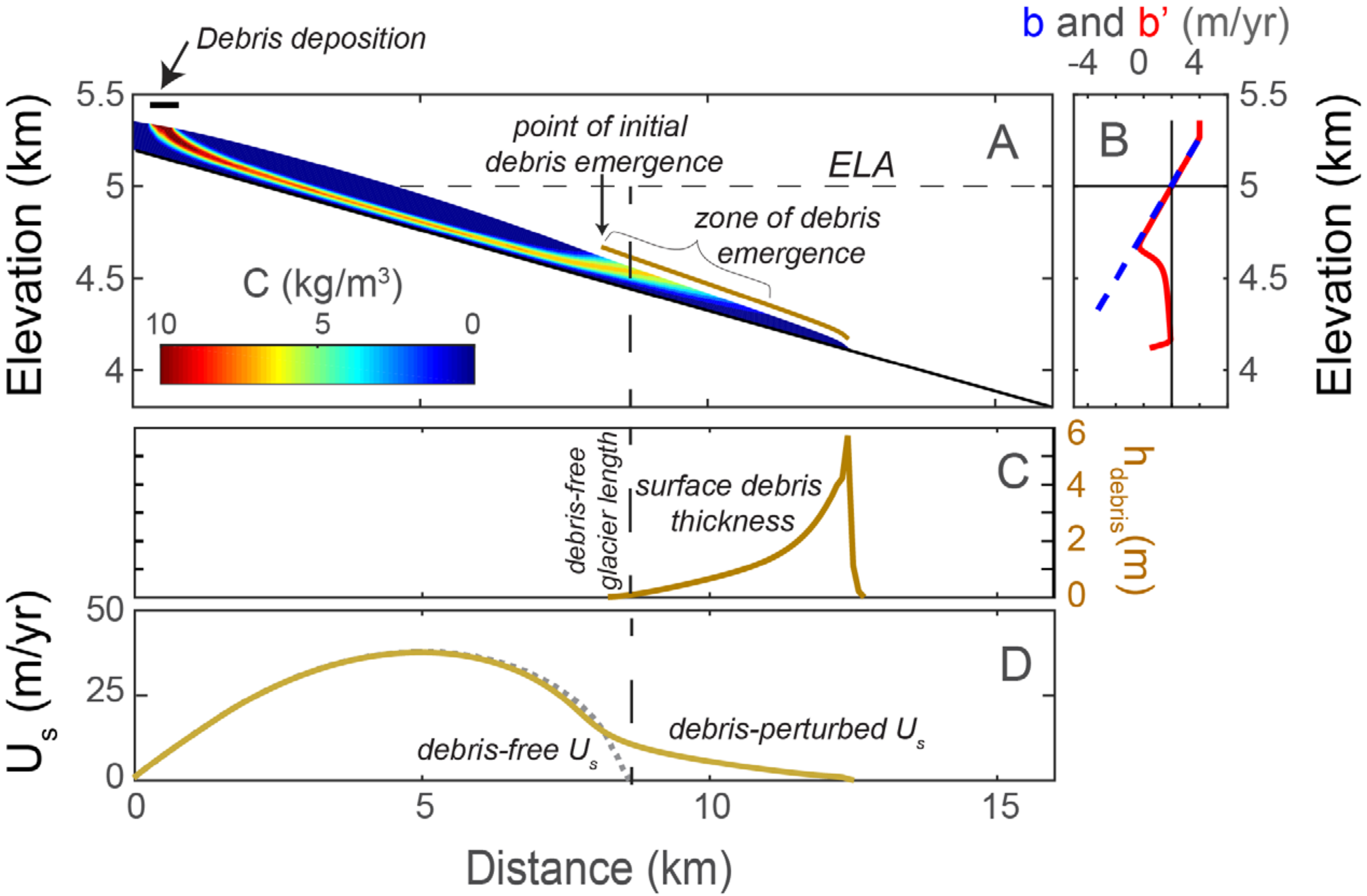
# The rocky umbrella



▶

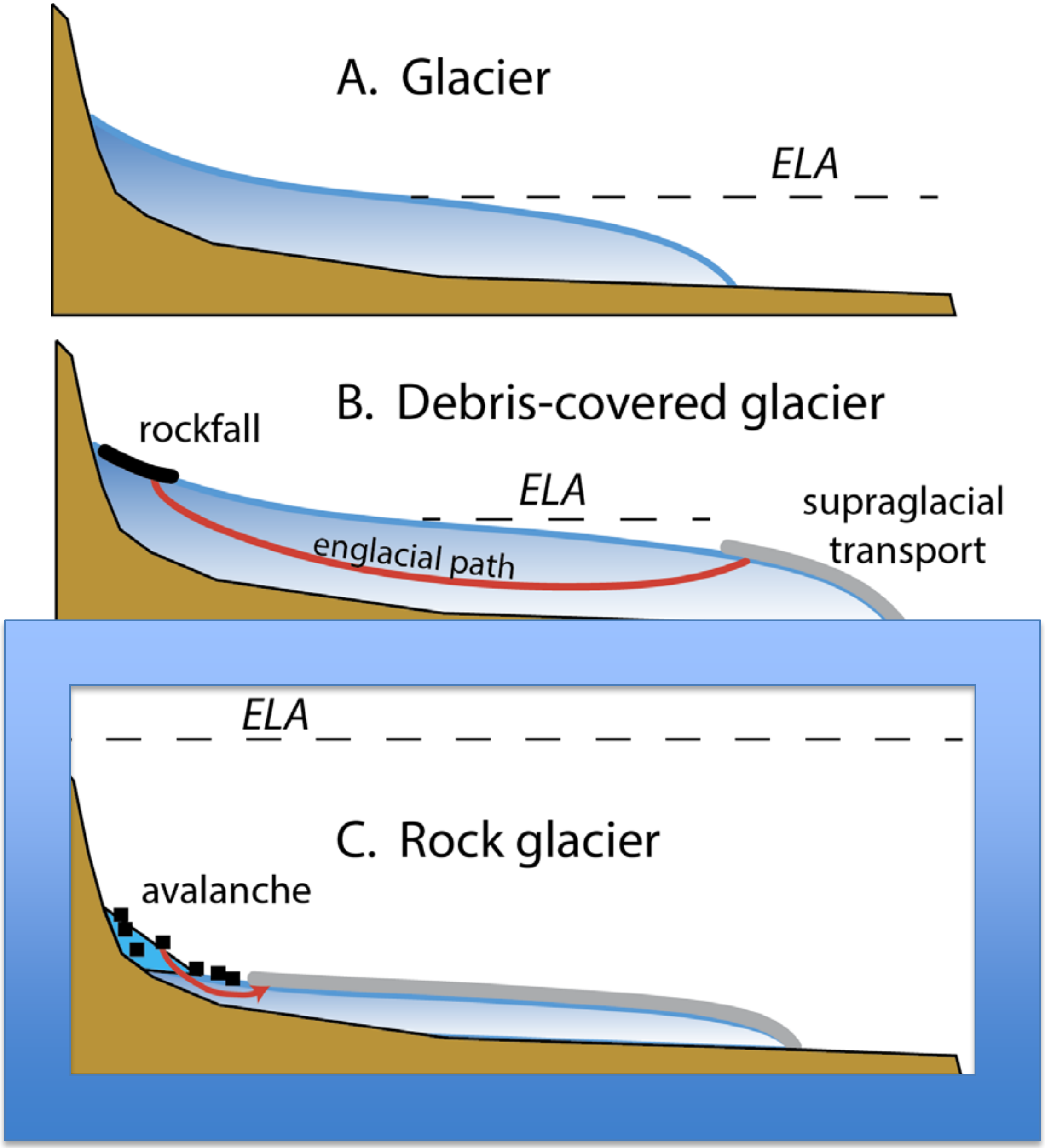
Effects of debris cover include glacier extension

Leif Anderson



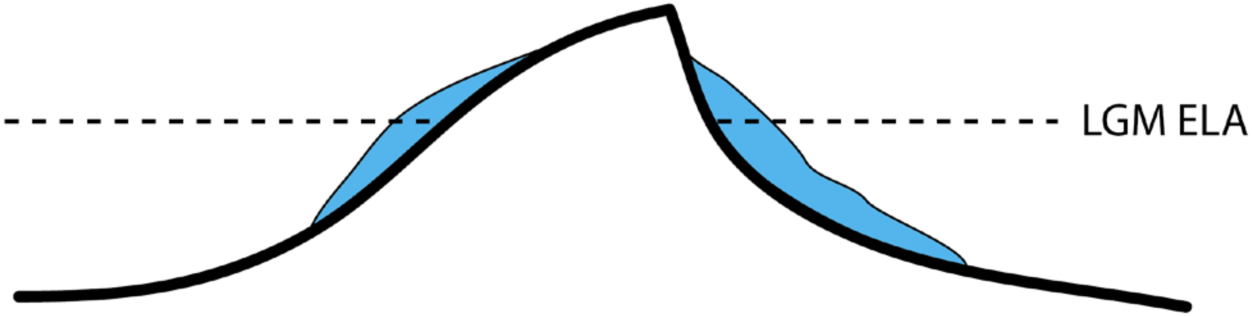
Bottom line: debris-covered glaciers can be way longer than their debris-free cousins

Leif Anderson

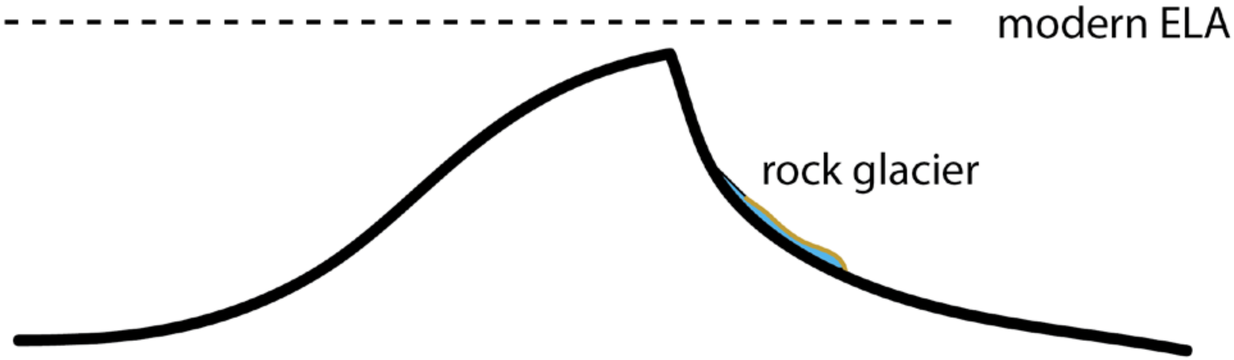


The rock glacier
end-member

Glacial
state



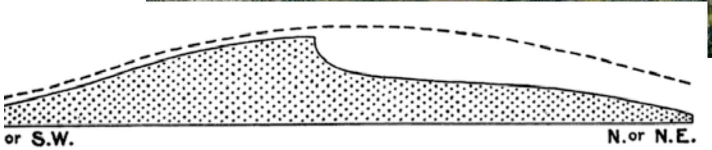
Interglacial
state



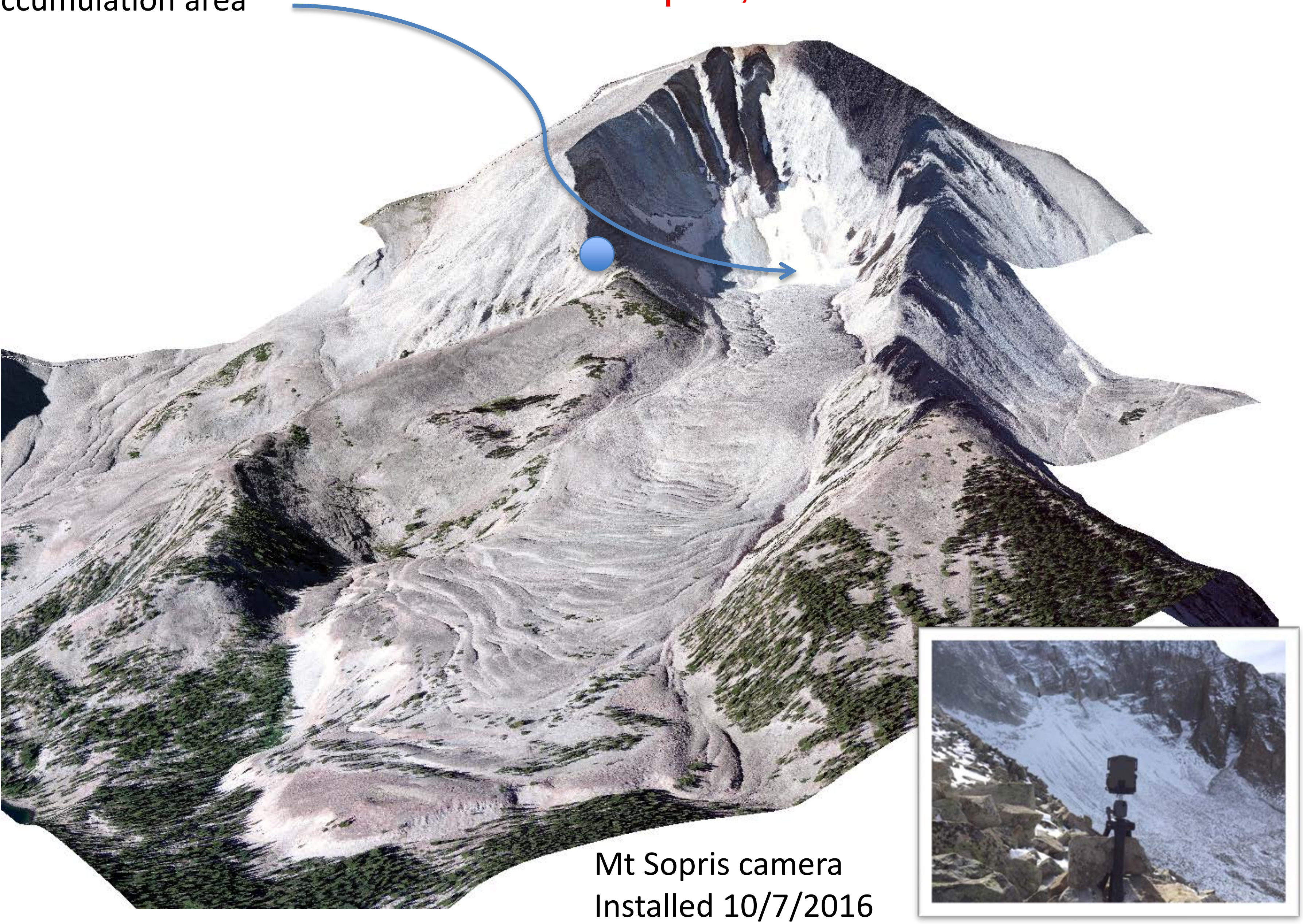
National Creek Rock Glacier, Kennicott Alaska

Sourdough rock glacier, Alaska

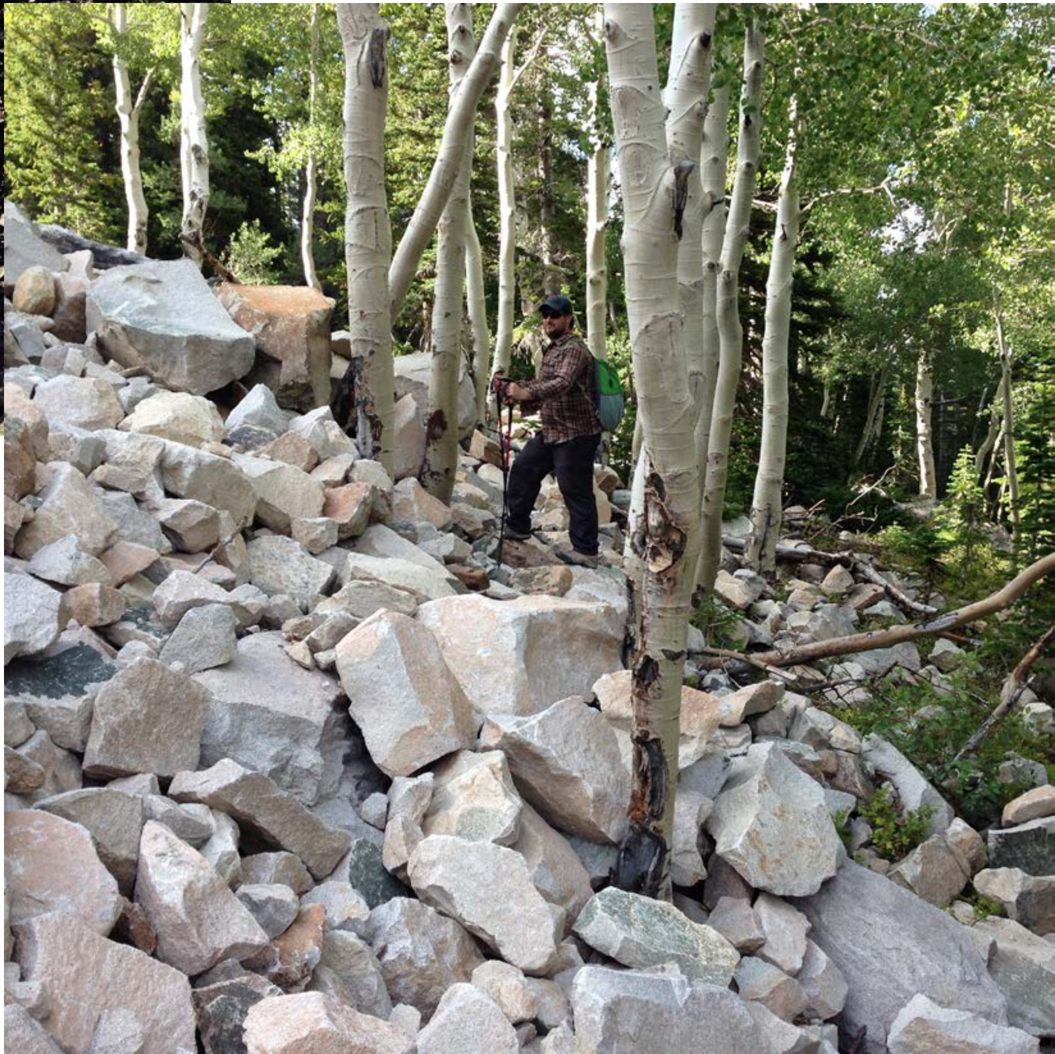
# Note the strong asymmetry



# Mt Sopris, Colorado

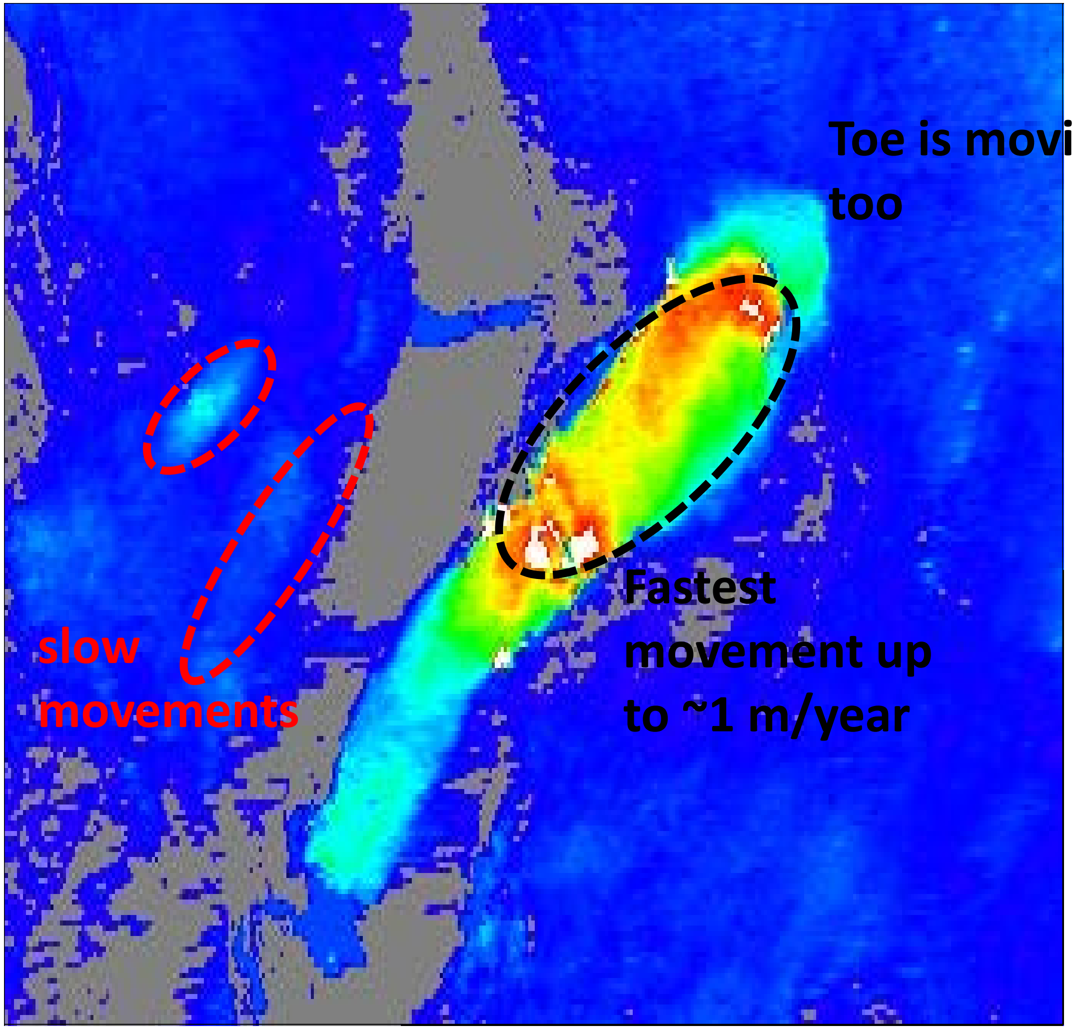


Mt Sopris camera
Installed 10/7/2016
at blue dot by Brett Oliver



They are cruising into the trees!

# InSAR Displacement Map, zoomed over the rock glacier, scaled from displacements over 46 days to annual rate in cm/year



Toe is moving too

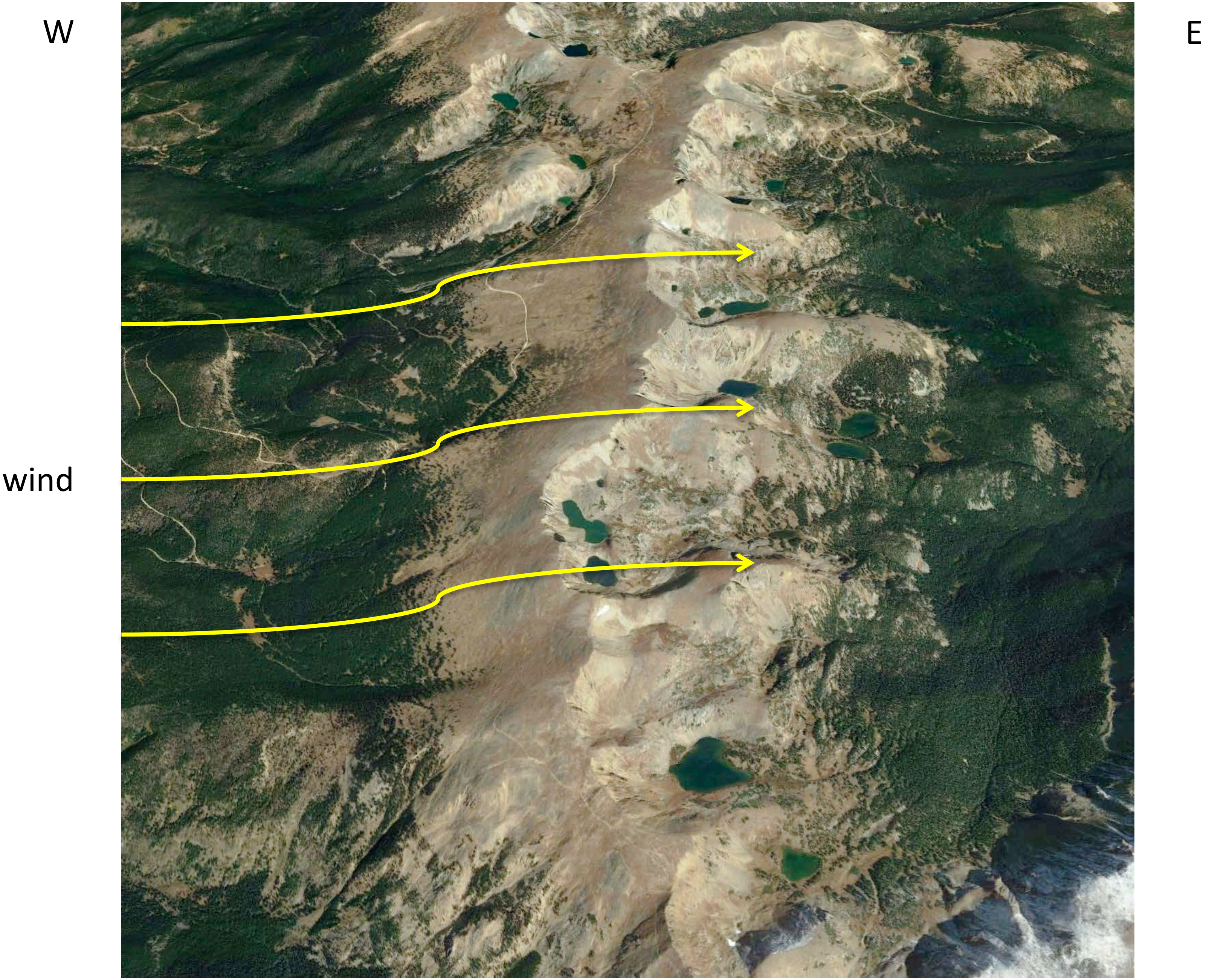
slow movements

Fastest movement up to ~1 m/year

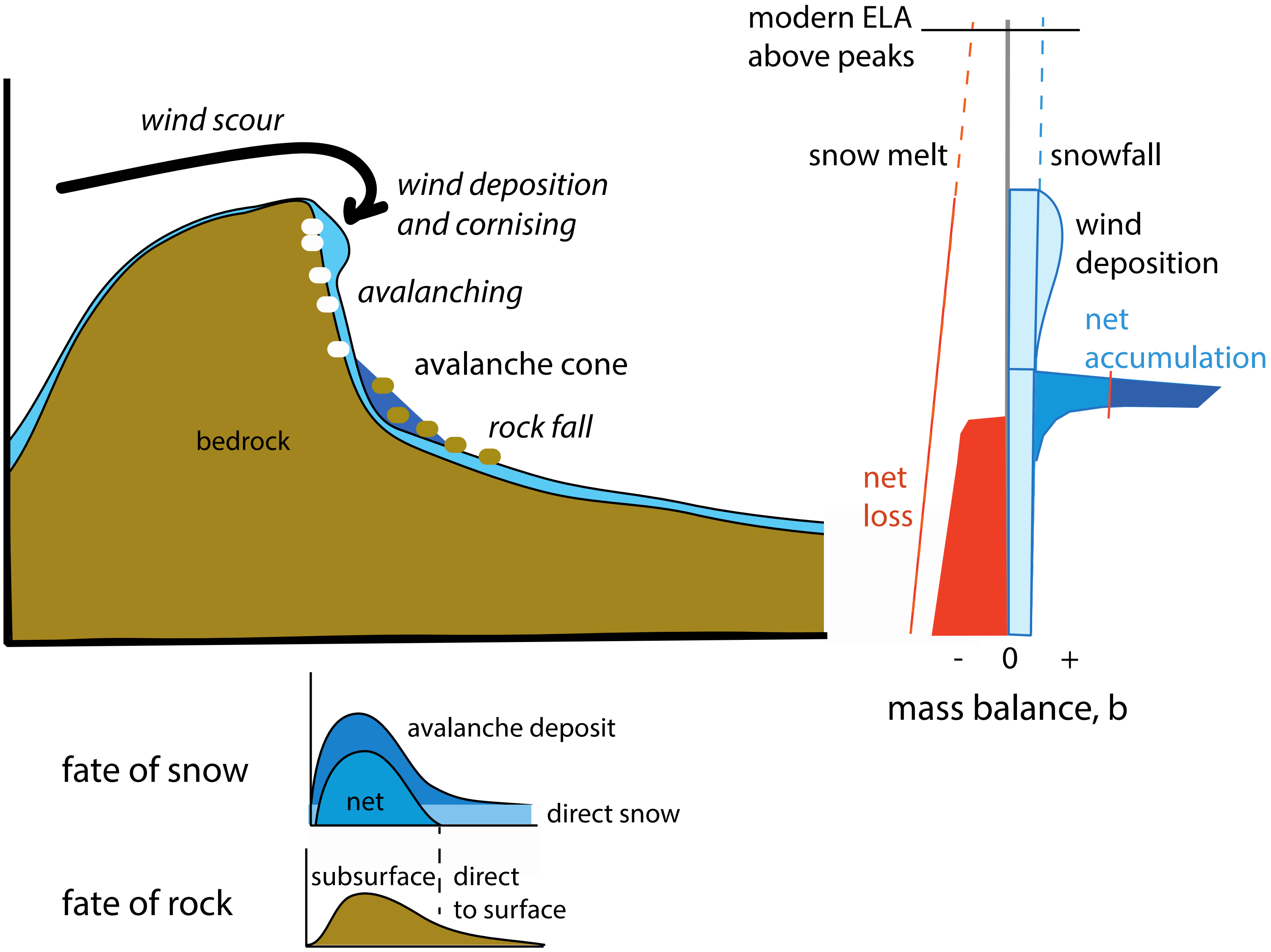
Courtesy of Lin Liu

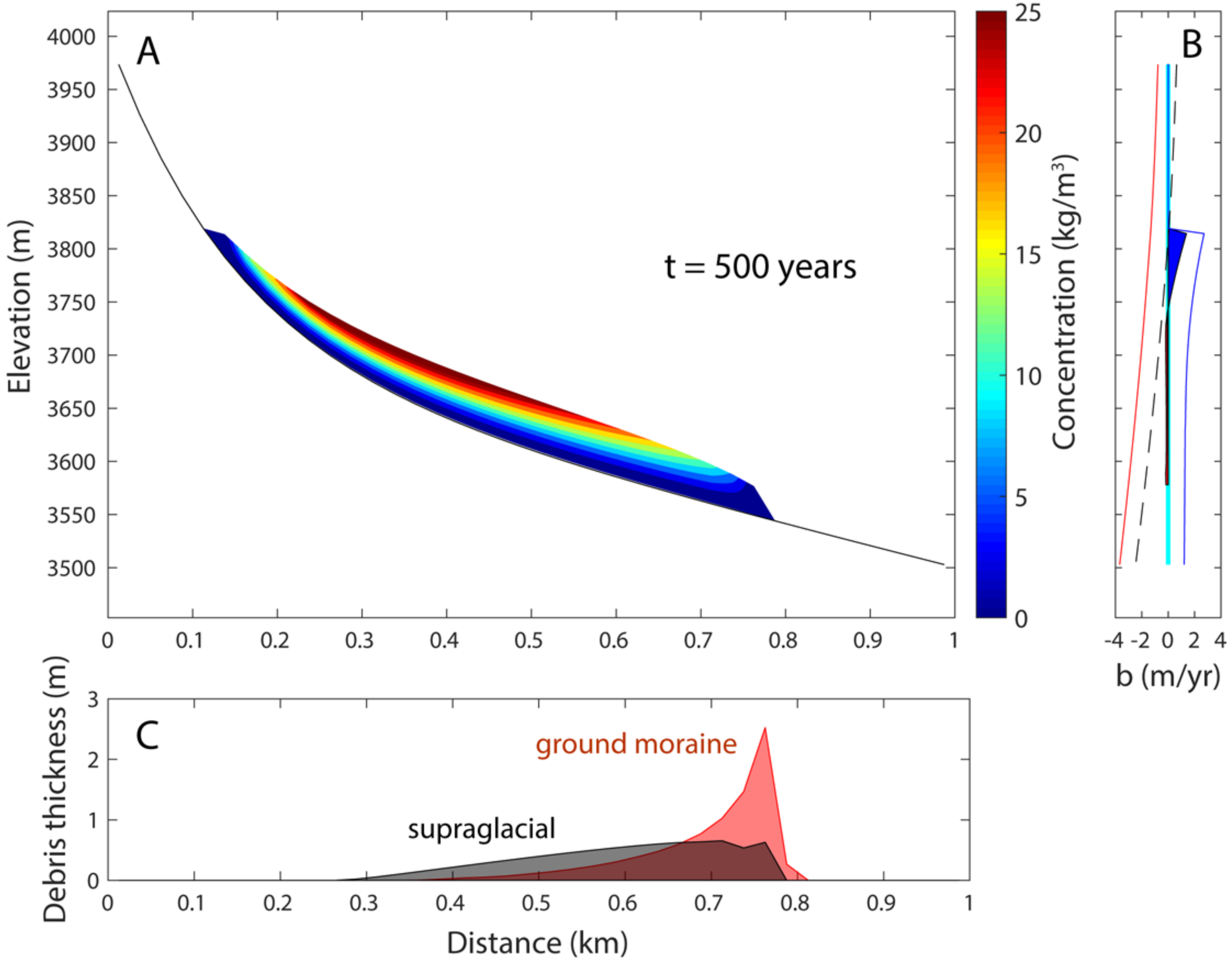
Rate (cm/year)

# Front Range, Colorado



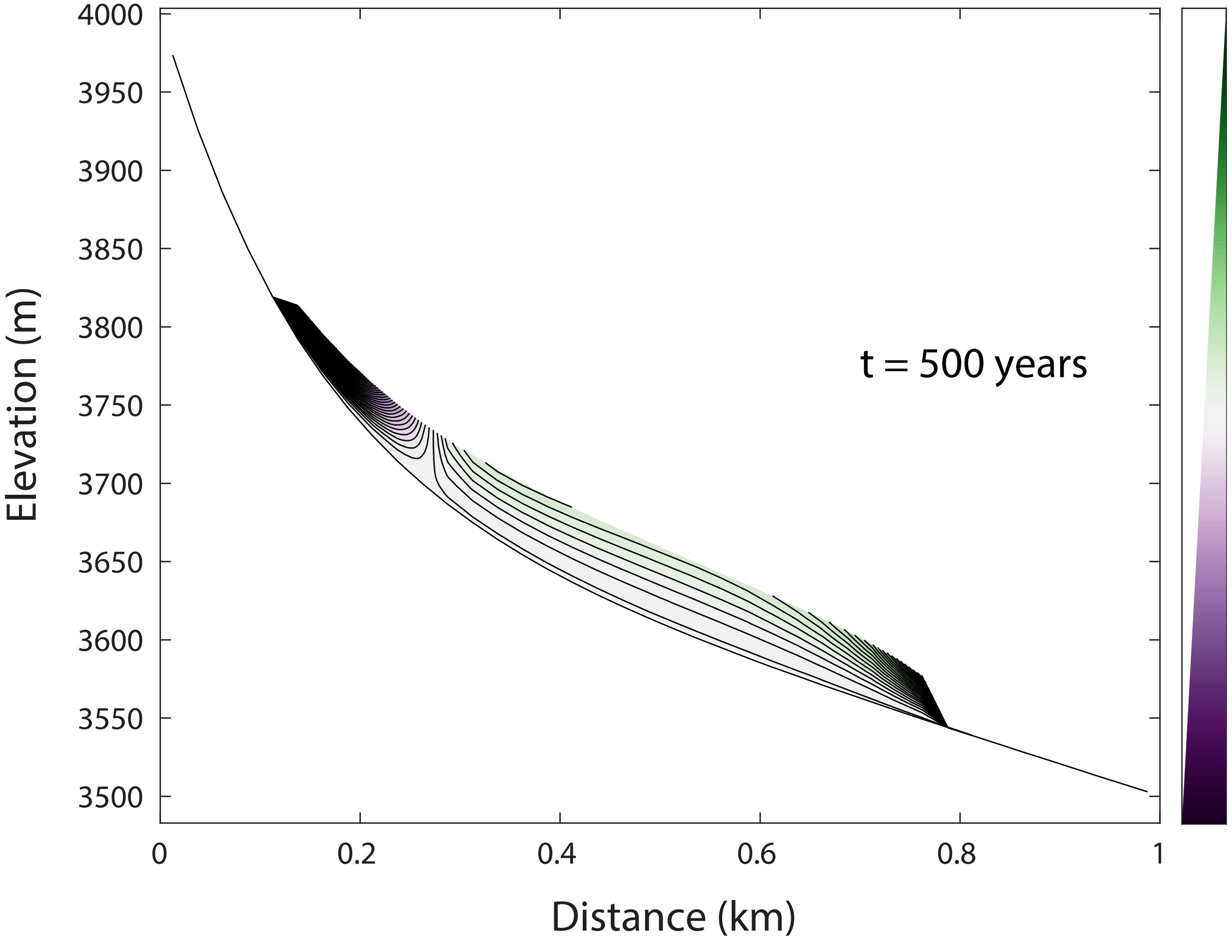
# Mass balance pattern on a rock glacier





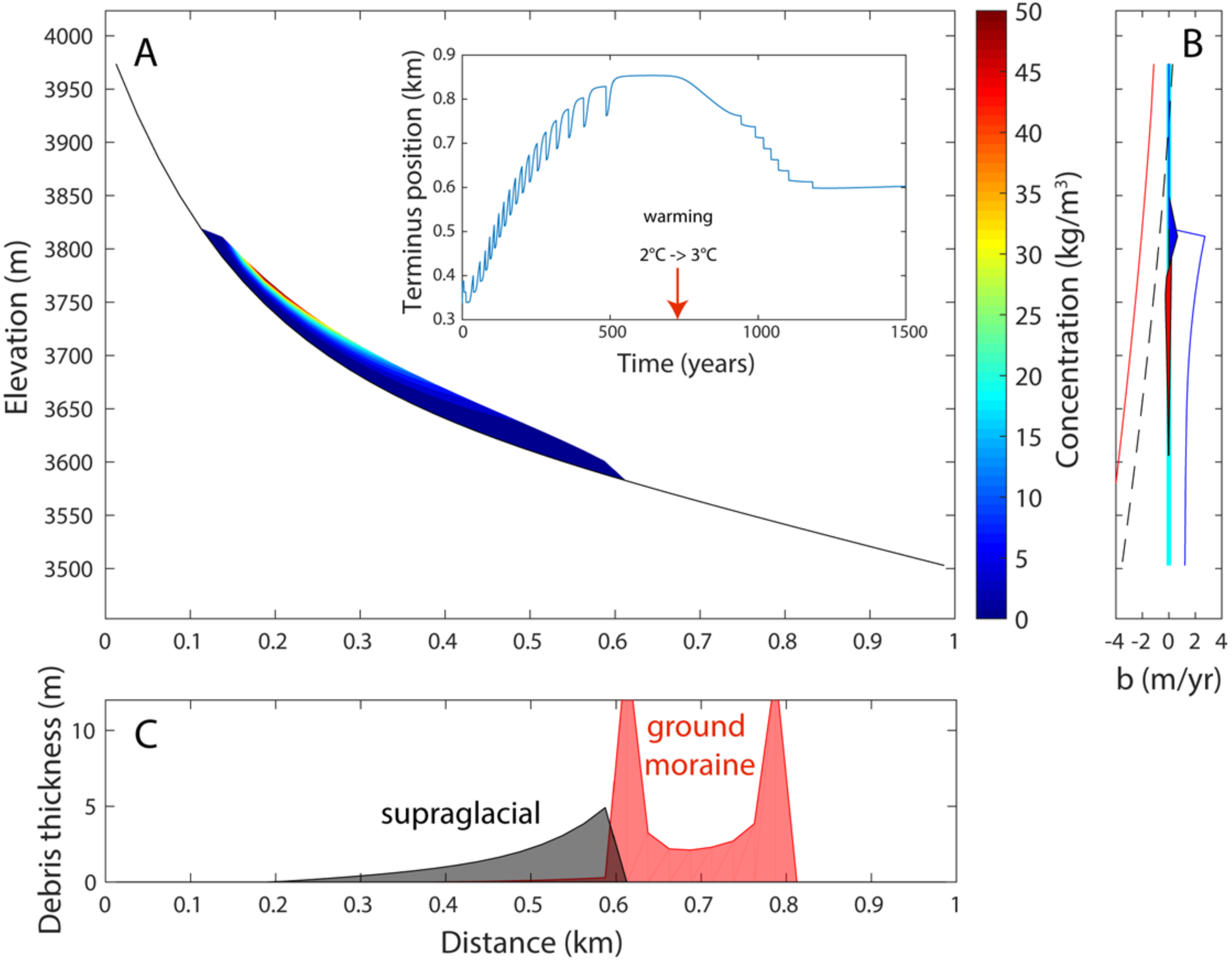
Some debris outruns avalanche

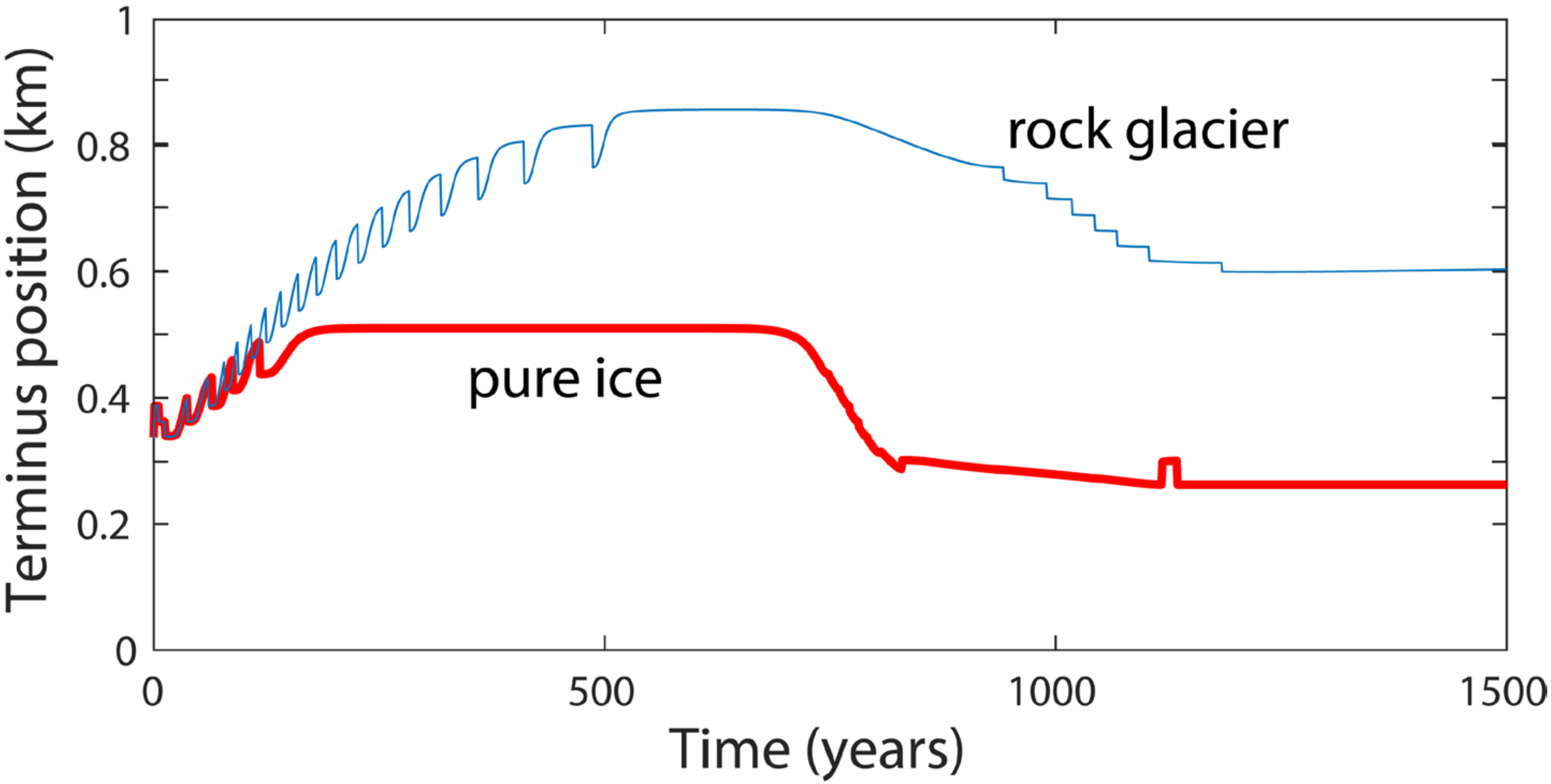
# Vertical speed structure in a rock glacier



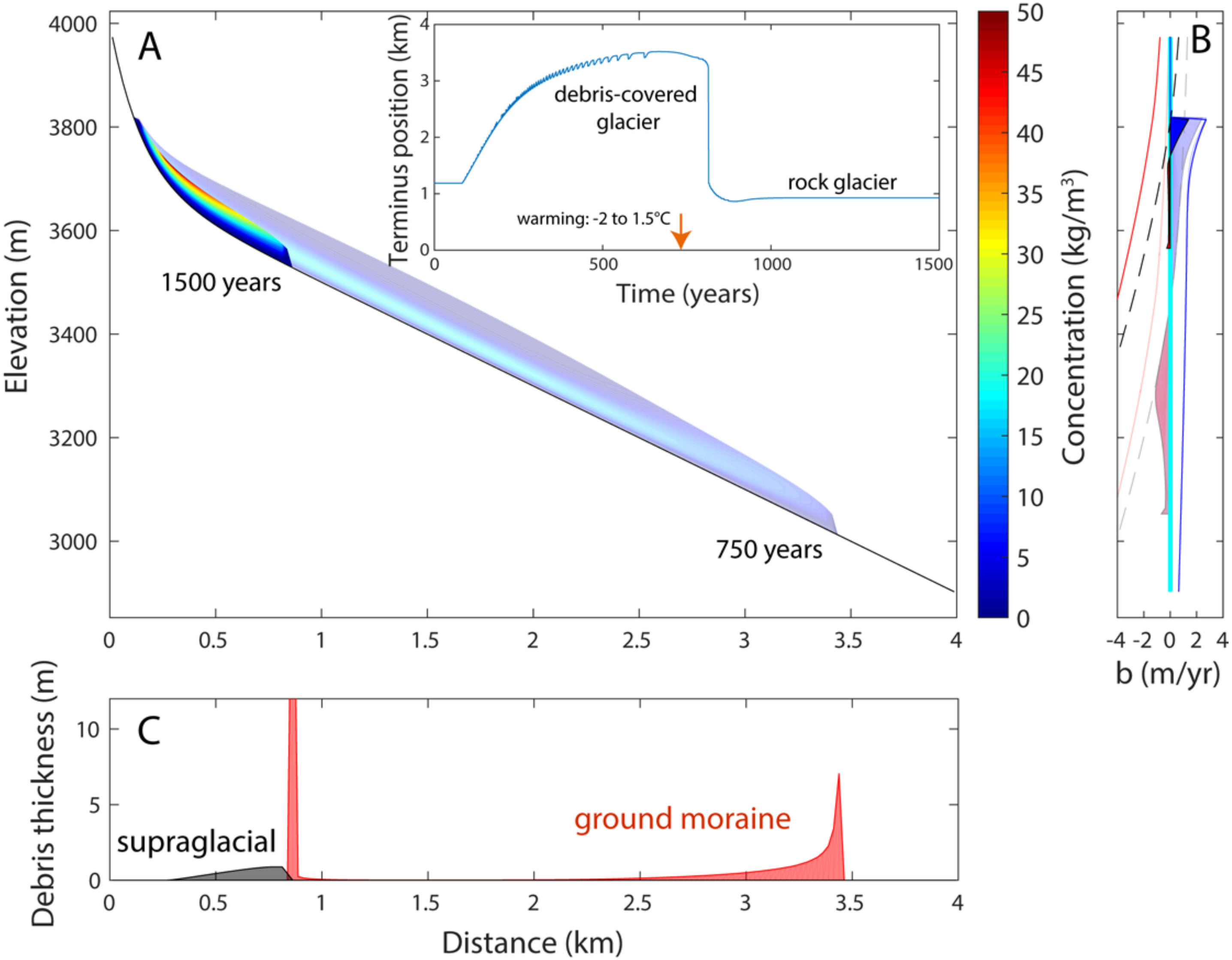
▶

Response to slight climate warming of 1°C

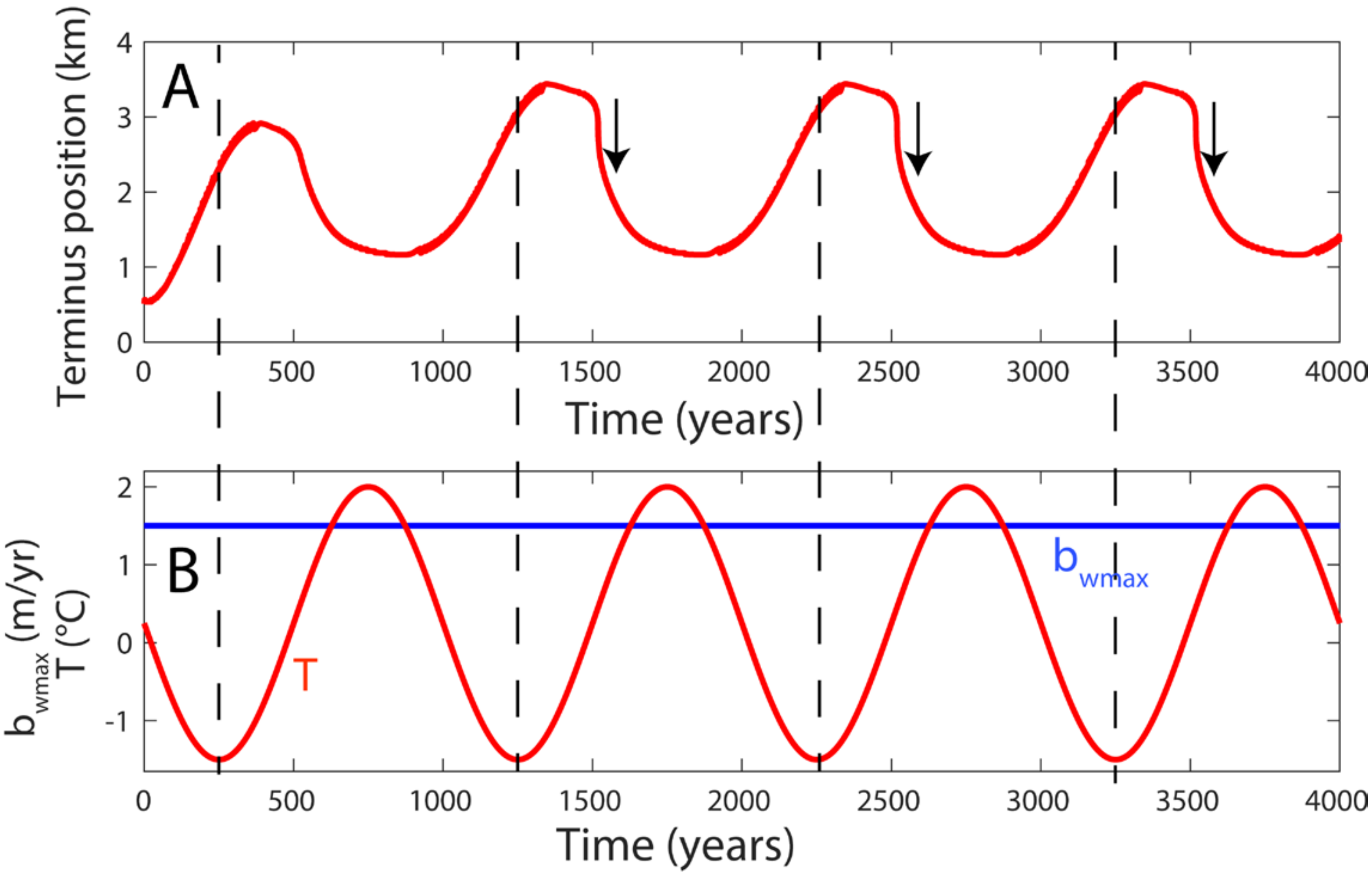

A
Elevation (m)
4000
3950
3900
3850
3800
3750
3700
3650
3600
3550
3500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Terminus position (km)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
500
1000
1500
Time (years)
warming
2°C -> 3°C
Concentration (kg/m³)
50
45
40
35
30
25
20
15
10
5
0
B
-4
-2
0
2
4
b (m/yr)
C
Debris thickness (m)
10
5
0
supraglacial
ground moraine
Distance (km)



Rock glaciers are survivors


A
B
C
Elevation (m)
4000
3800
3600
3400
3200
3000
1500 years
750 years
Terminus position (km)
Time (years)
debris-covered glacier
rock glacier
warming: -2 to 1.5°C
0
500
1000
1500
Concentration (kg/m³)
0
5
10
15
20
25
30
35
40
45
50
b (m/yr)
-4
-2
0
2
4
Debris thickness (m)
supraglacial
ground moraine
Distance (km)
0
0.5
1
1.5
2
2.5
3
3.5
4
10
5
0

# Sinusoidal climate: debris-covered to rock-glacier cycling



Debris-covered glacier

Rock glacier

# Stripes from Space: medial moraines

Rhone Glacier, Wrangells-St Elias National Park, Alaska

Barnard Glacier, Alaska
Medial moraine

# The Medial Moraine

What the glacier provides:

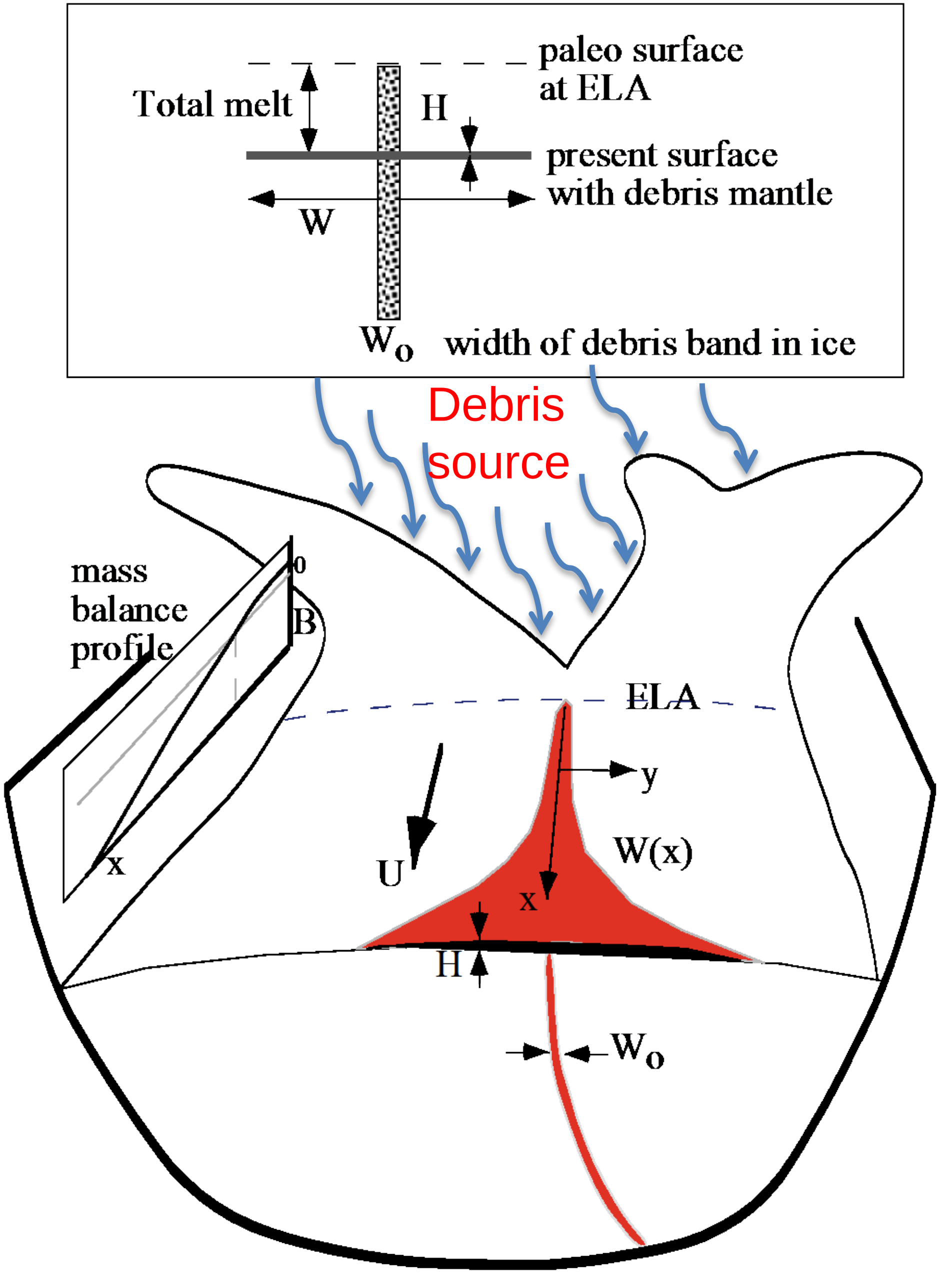
- debris-rich septum
- motion down-valley

What the climate provides:

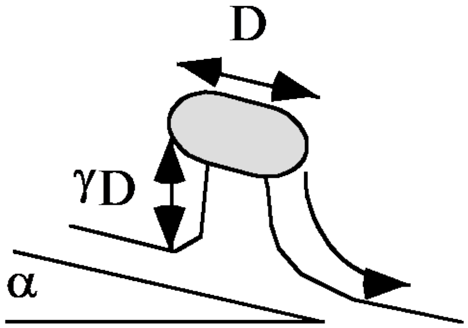
- a pattern of down-valley Increasing melt rates

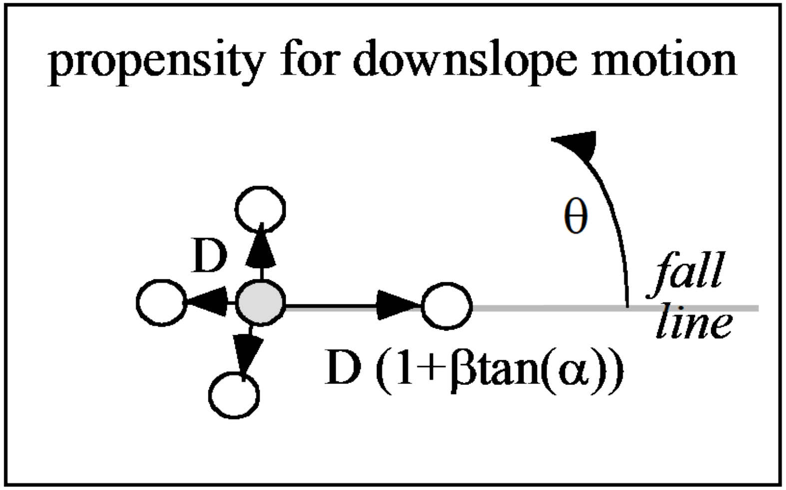
The pieces of the problem

- ablation rate altered
- slope generated
- debris moves downslope



# The topple-walk mechanism




propensity for downslope motion

Emergence of medial moraines below the ELA

Medial moraine collision leads to complete debris cover

# Summary

- A model that includes both ice and rock dynamics can explain the continuum of glacier types

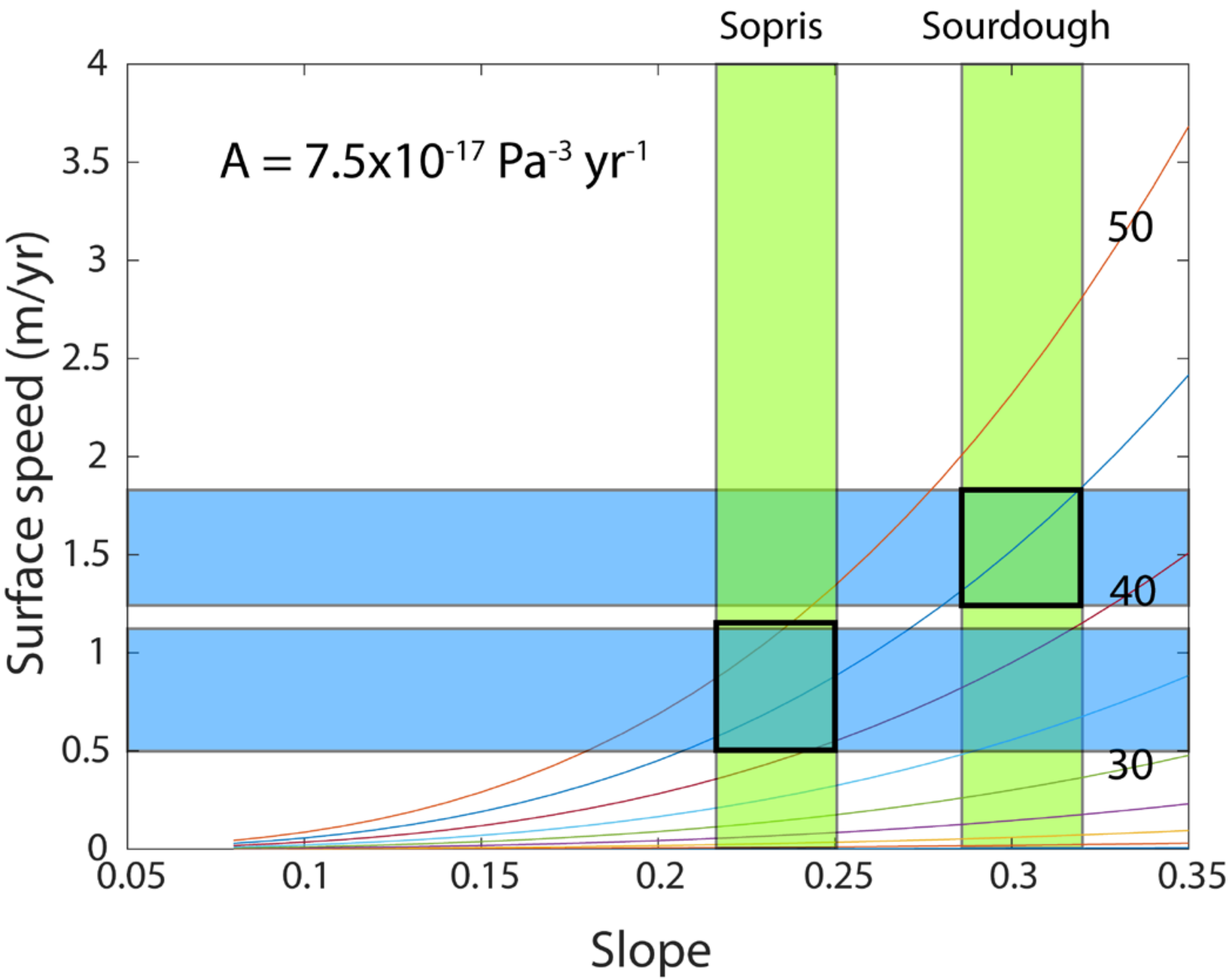
- Debris-covered glaciers can be significantly longer than debris-free counterparts

- Rock glaciers require both an avalanche source of snow and a headwall source of rock

- In complex terrain debris cover is dominated by medial moraines and their collisions

The End

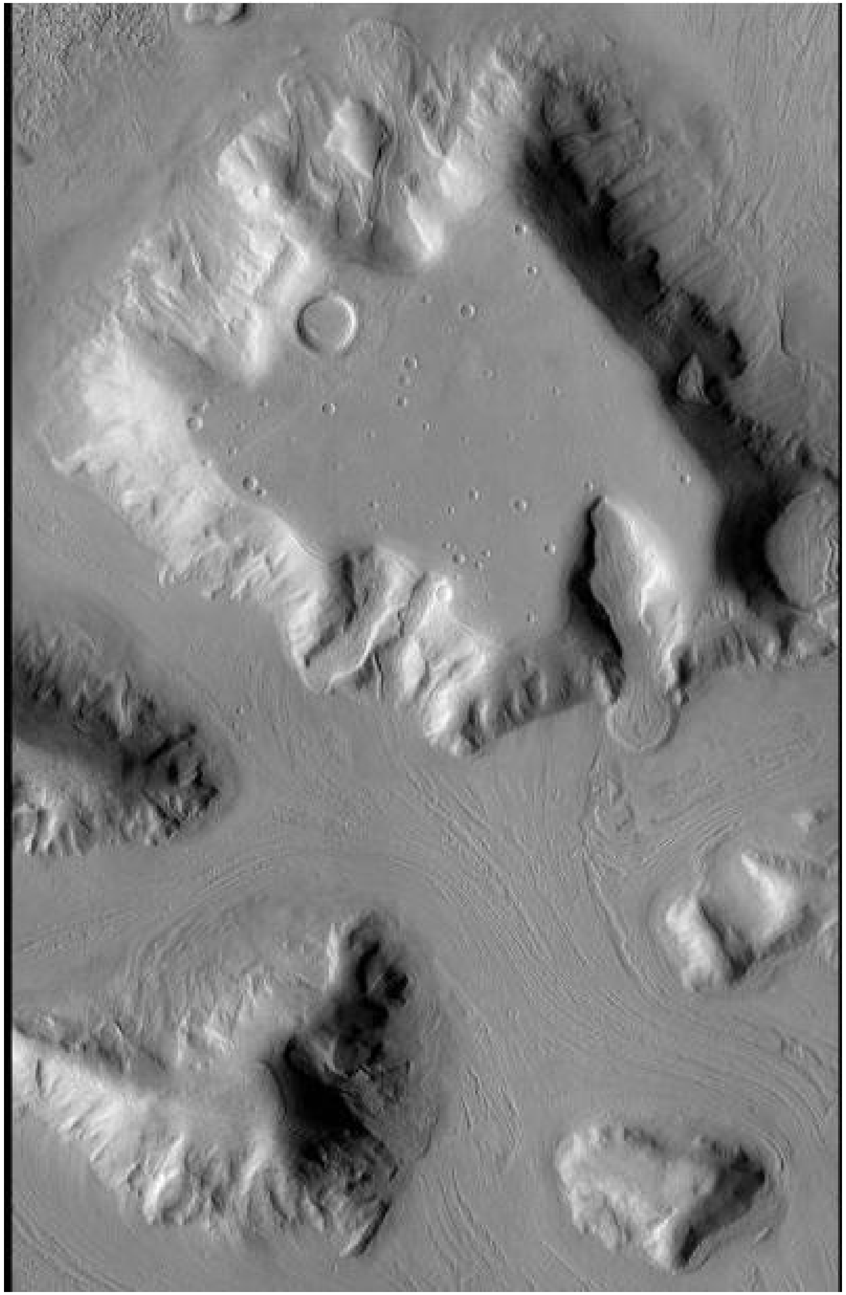
# A model in which glacier is pure ice with only a thin rocky cap succeeds



Surface speeds expected on measured slopes for a range of possible thicknesses
Assuming pure ice, deformation only

# Mars


ESP_047193_1440_RED
500 meters
NASA/JPL/University of Arizona
MRO/HiRISE

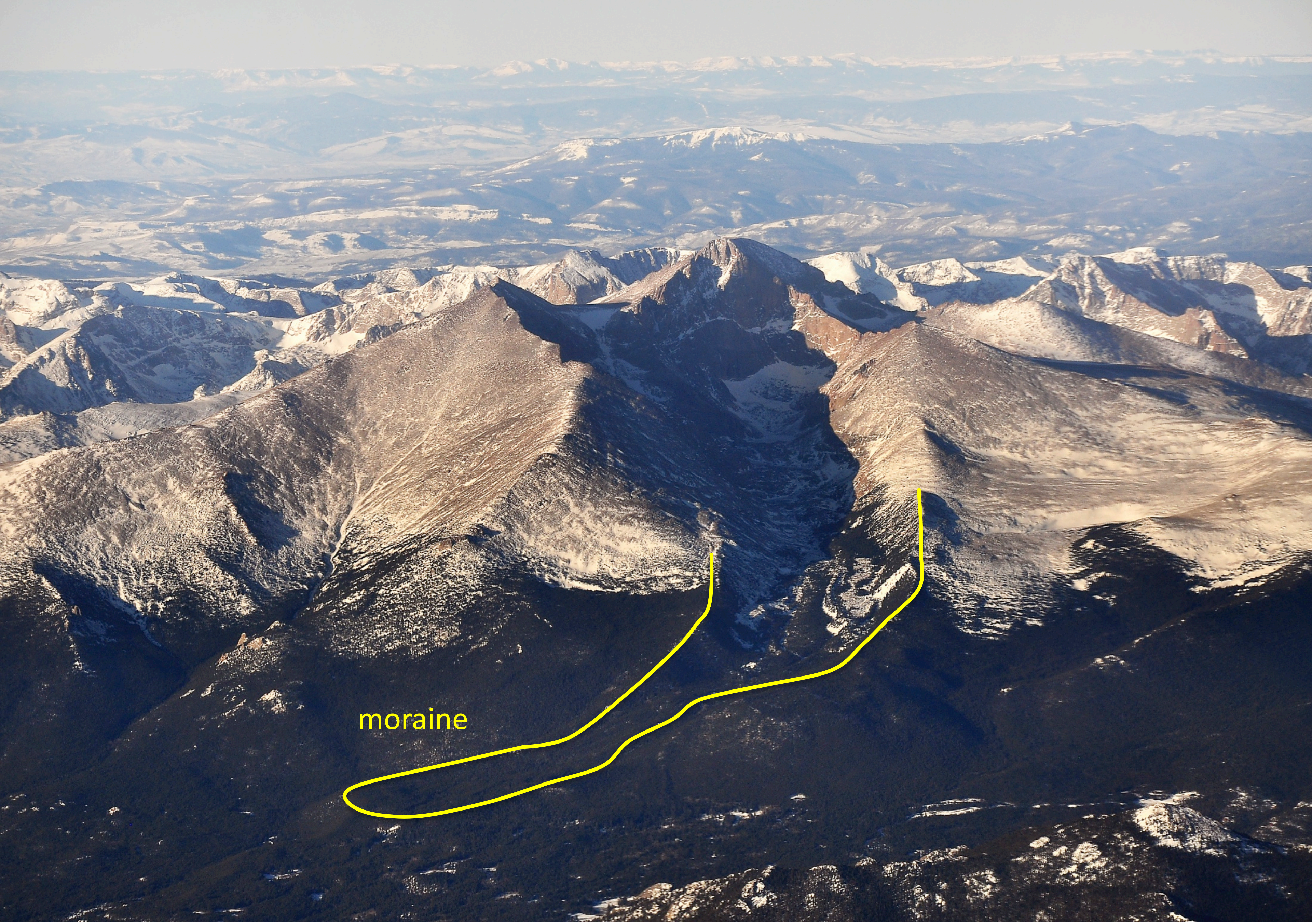


Martian glacial features

By Jim Secosky modified NASA image

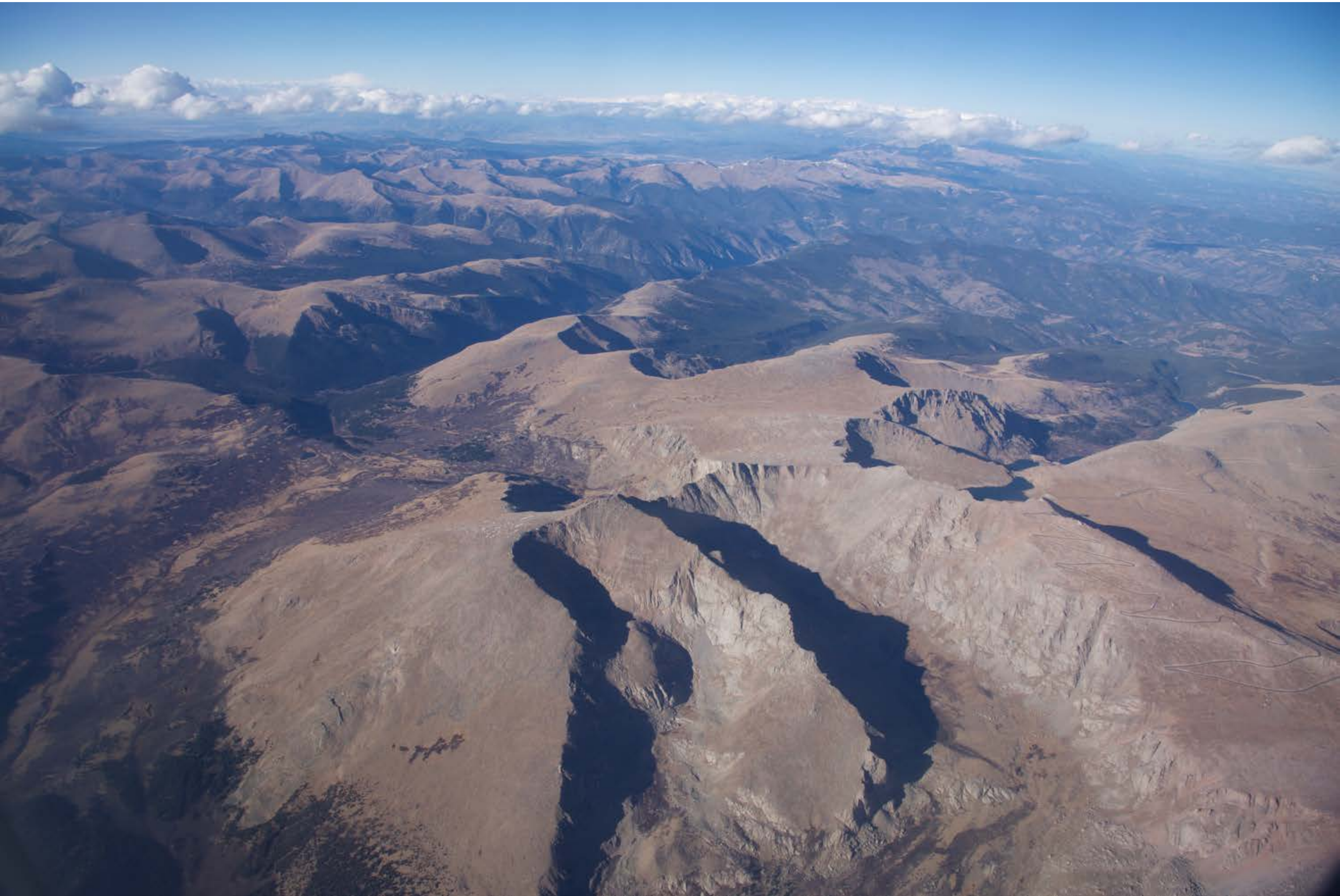
# Glacial signature in alpine landscapes

Our own Longs Peak



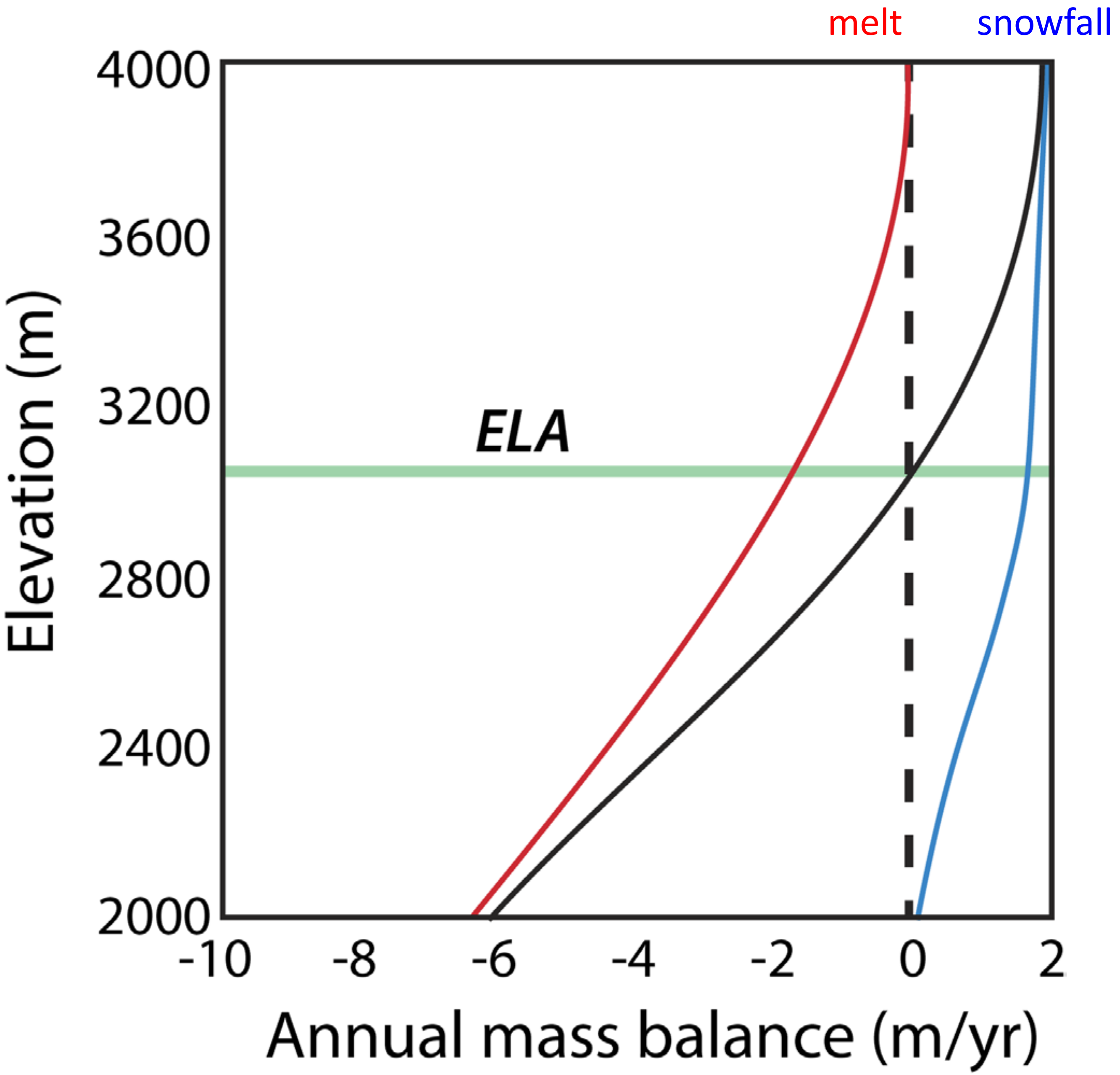
Our own Longs Peak

# Asymmetry of divides - Mt Evans



The Tenmile Range, Colorado

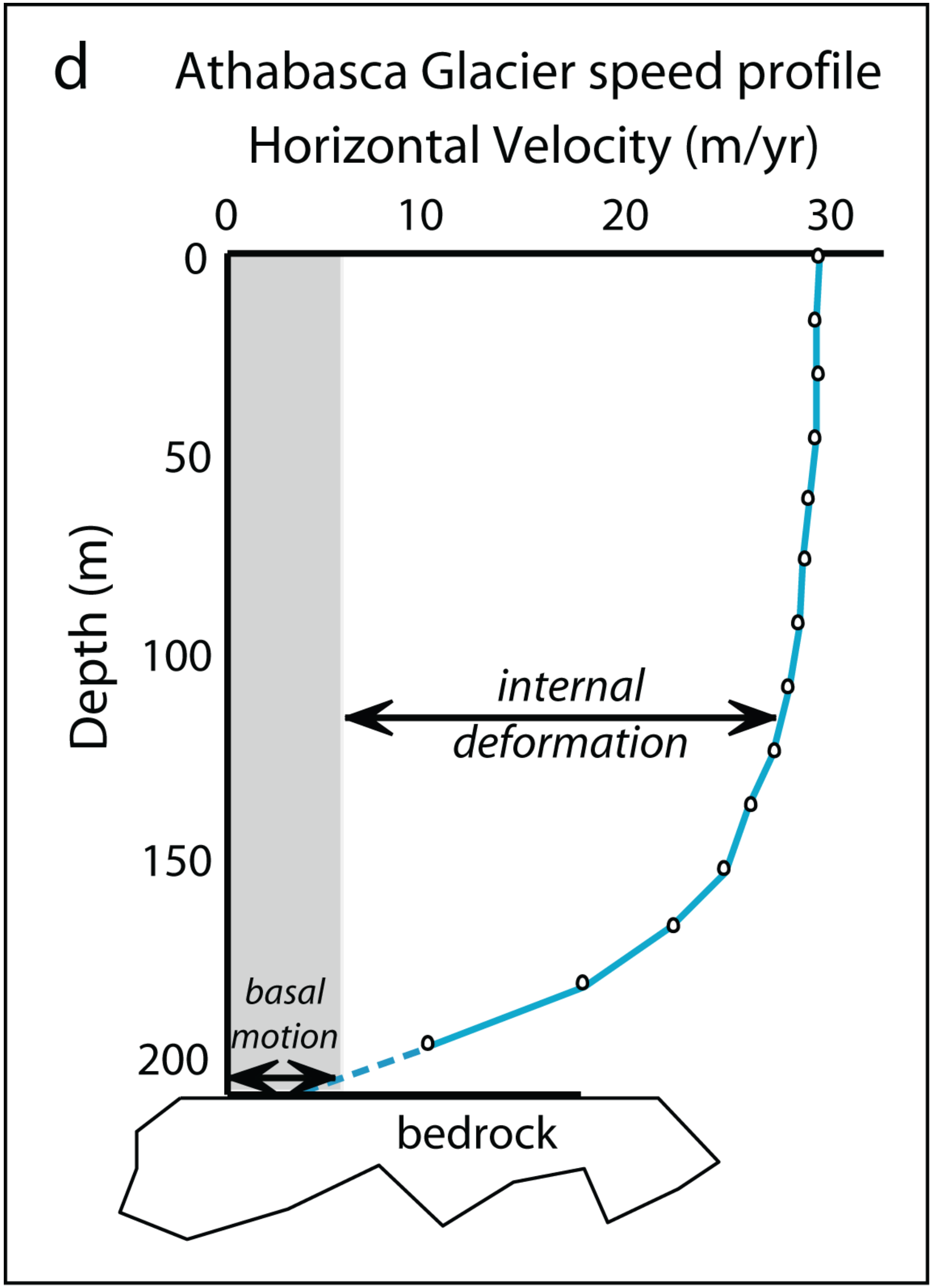
Moving on to longer time scales:
How has climate changed over the last
couple million years?



Melt less, snow more -> lower ELA

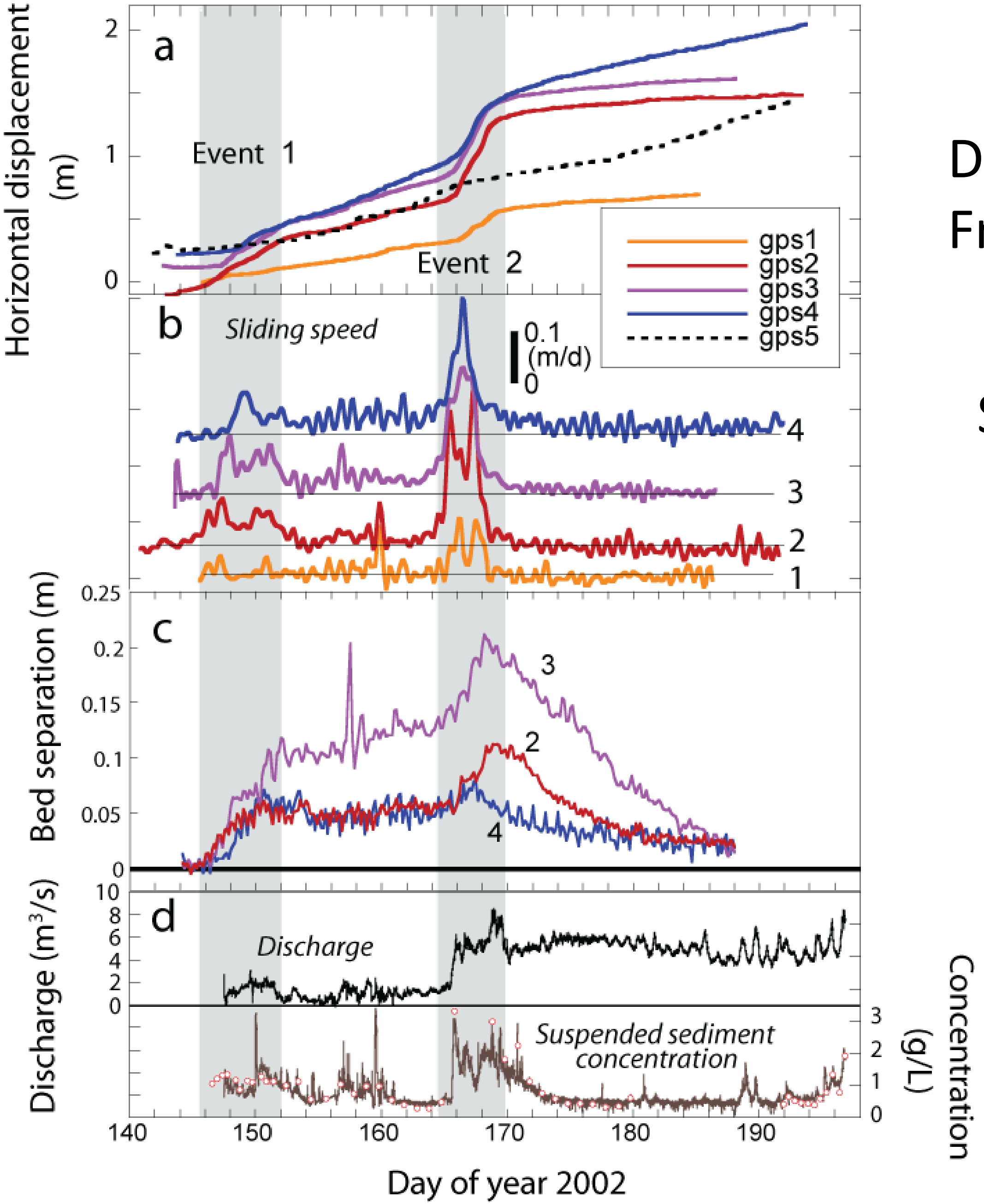
# Ice transfer:
# How does ice move?

Deformation
plus
sliding



# Front Range, Colorado

The annual cycle of glacier motion



Displacement history
From GPS monuments

Sliding speed

Bench glacier, Alaska

Photo: Neil Humphrey


late summer cornise
rock glacier

InSAR also shows slow movement

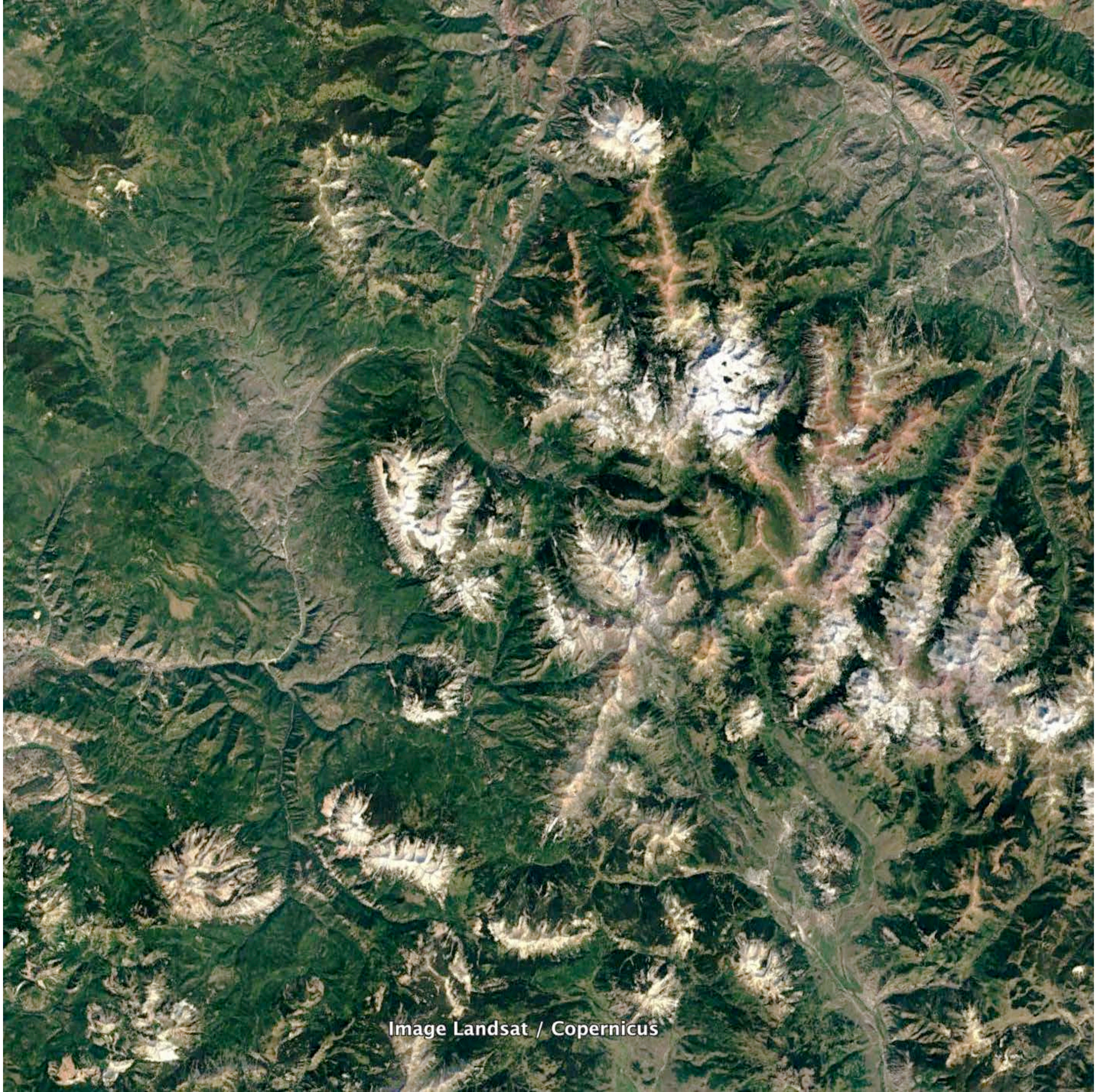
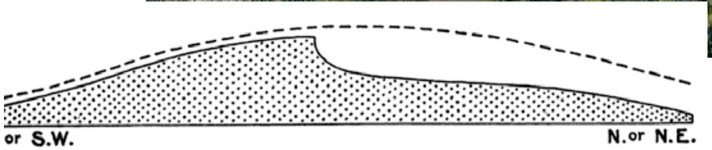


Image Landsat / Copernicus

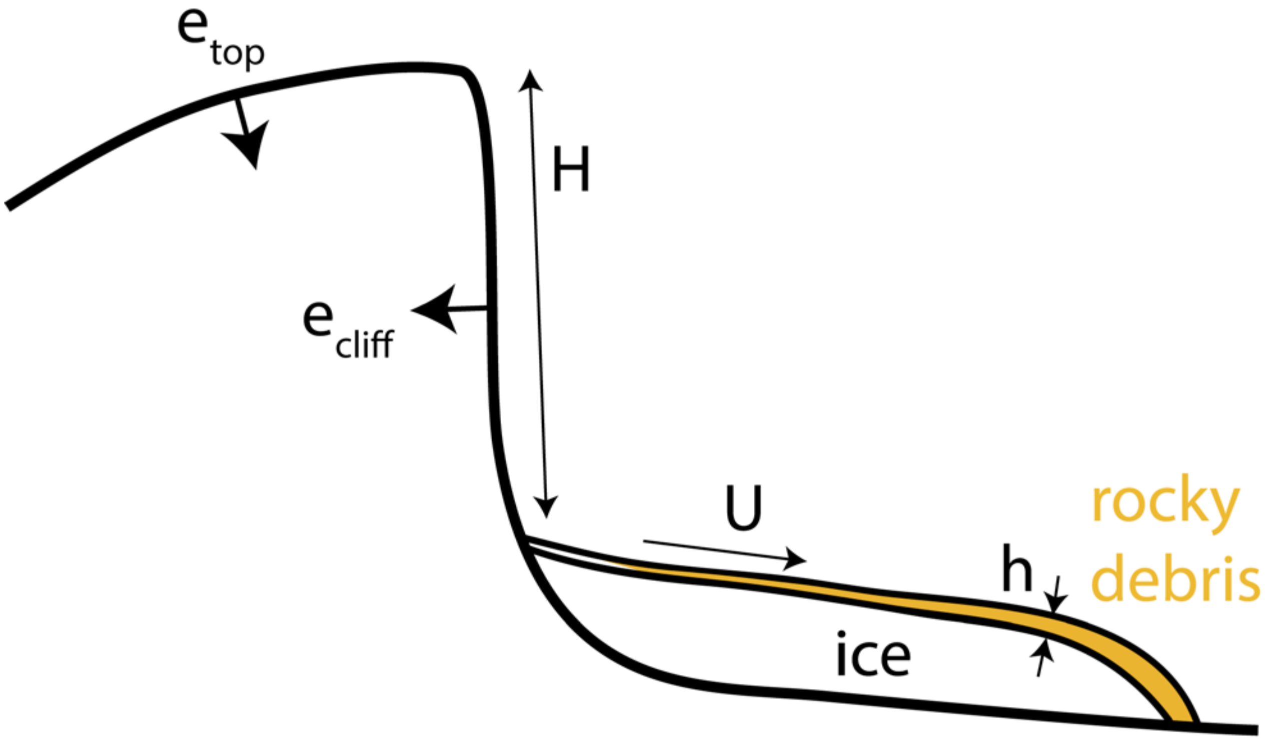
~30 Ma granite
Blobs embedded
in sedimentary
rock

West Elks
Central Colorado

# Note the strong asymmetry



# The importance of edges: they migrate...



***conservation of debris requires***:

$e_{cliff}H = Uh$

$e_{cliff} = U(h/H)$

if $U = 1$ m/yr, $h = 1$ m, $H = 300$ m

$e_{cliff} = 3.3$ mm/yr $>> e_{top} = 0.01\text{-}0.03$ mm/yr