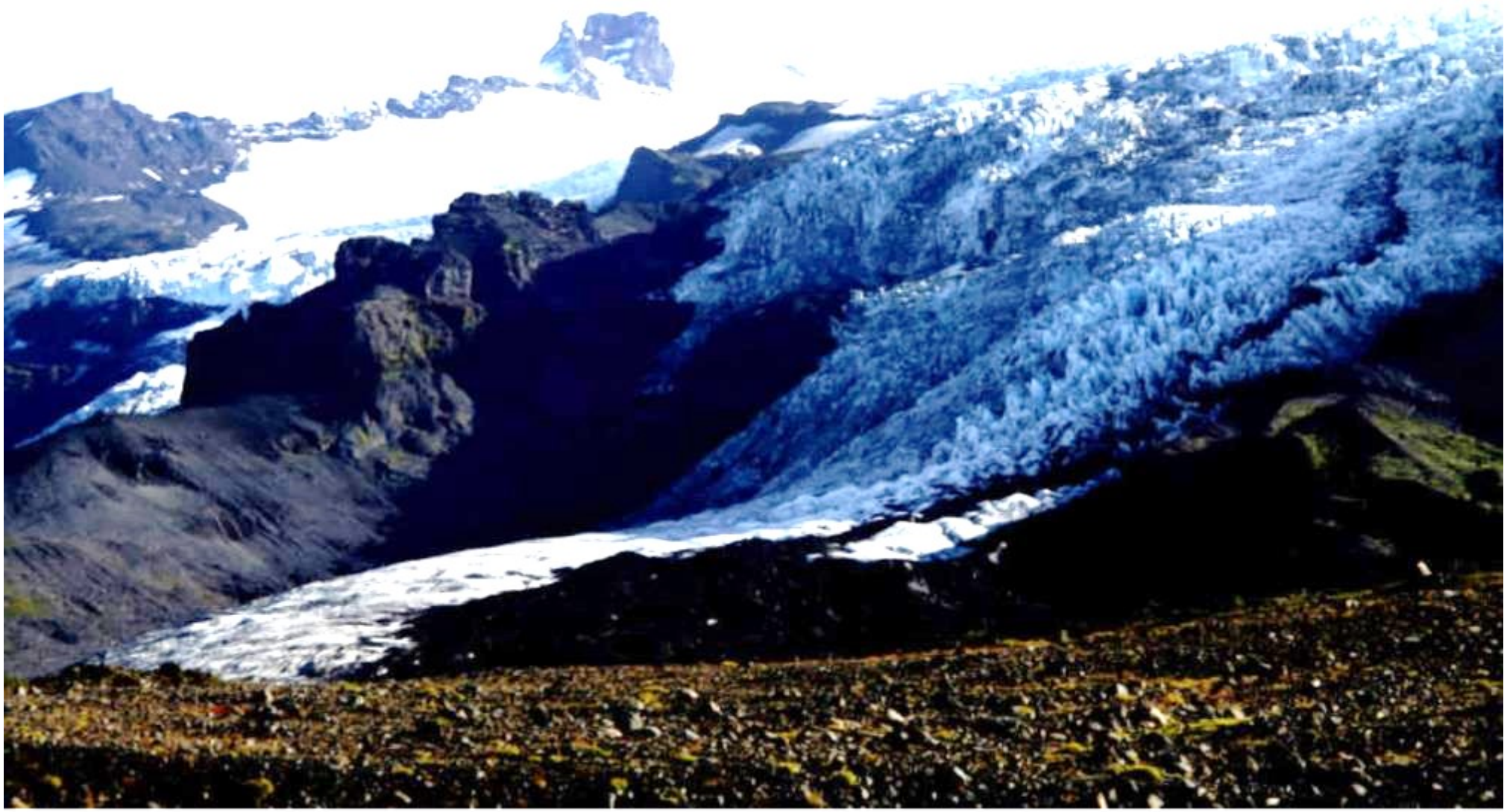
Glacial Movements

Lecture 02

Skaftafelljokull (glacier)

Glacier: Flowing mass of ice



Fjallsjokull (glacier)

Glacier: Flowing mass of ice

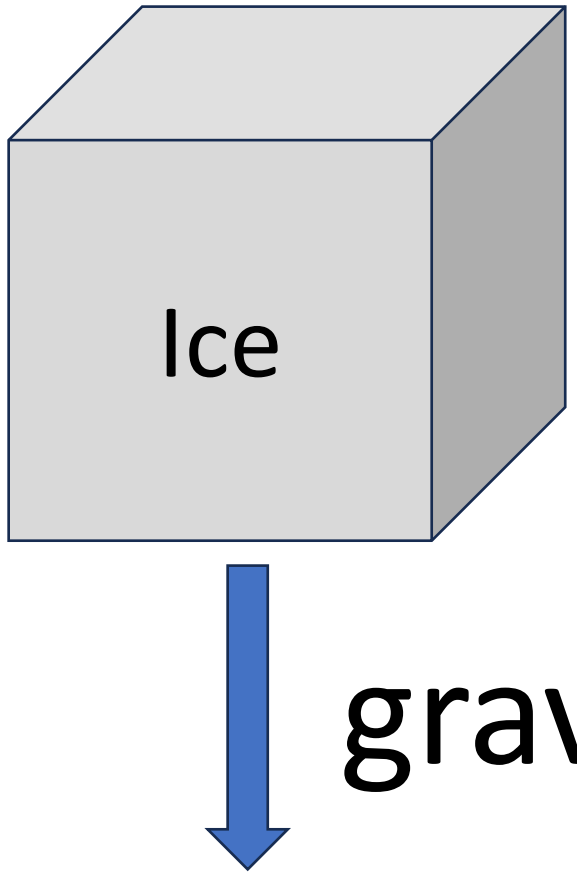
Fjallsjokull (glacier)

What force drives the flow?

Fjallsjokull (glacier)

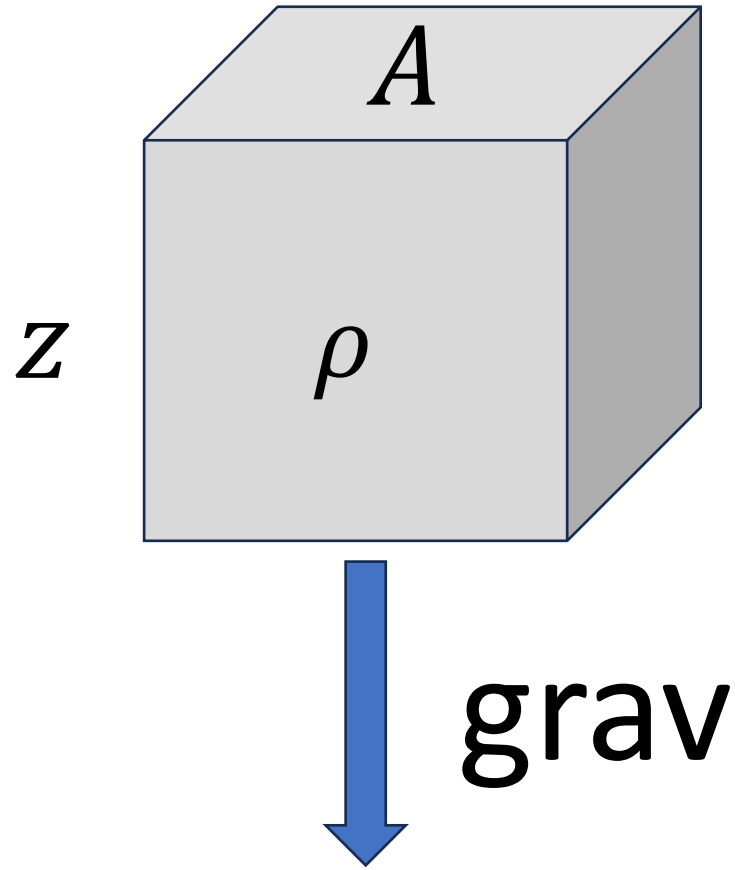
Gravity

Force of Gravity



Force = density x
acceleration of gravity x
height x area

Force of Gravity

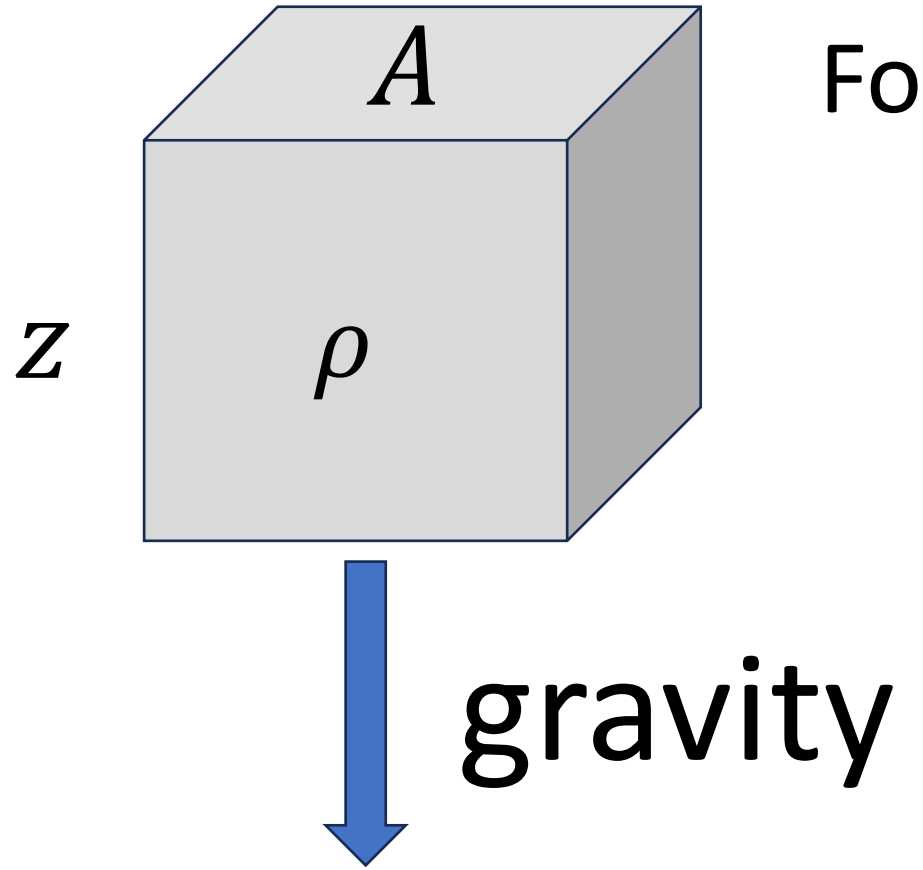


force = density x
acceleration of gravity x
height x area

$$f = \rho g z A$$

Stress of Gravity

stress = force per unit area

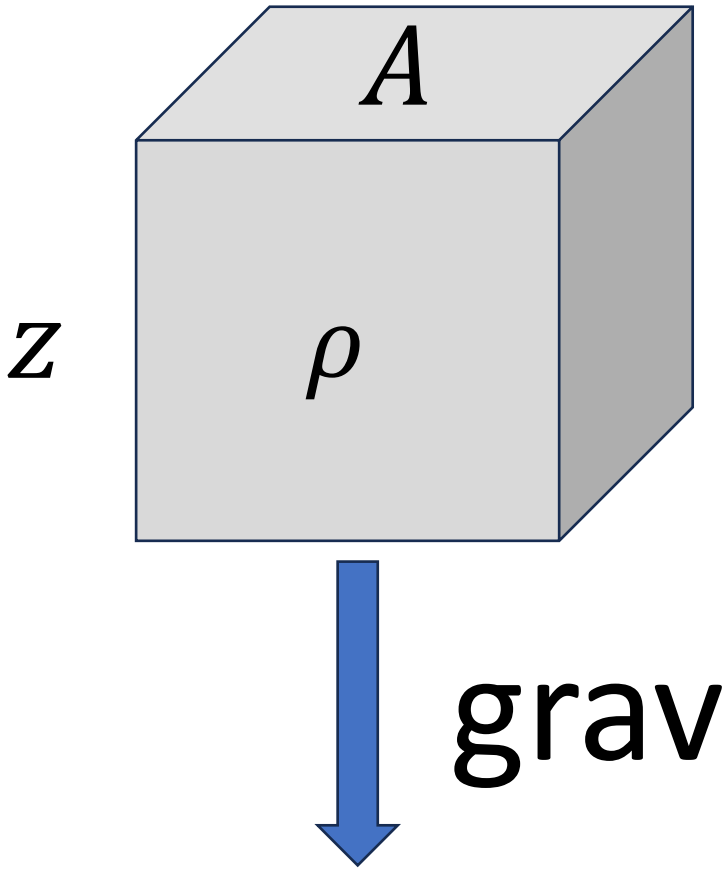


Force = density x
acceleration of gravity x
height x area

$$\frac{f}{A} = \rho g z$$

Stress of Gravity

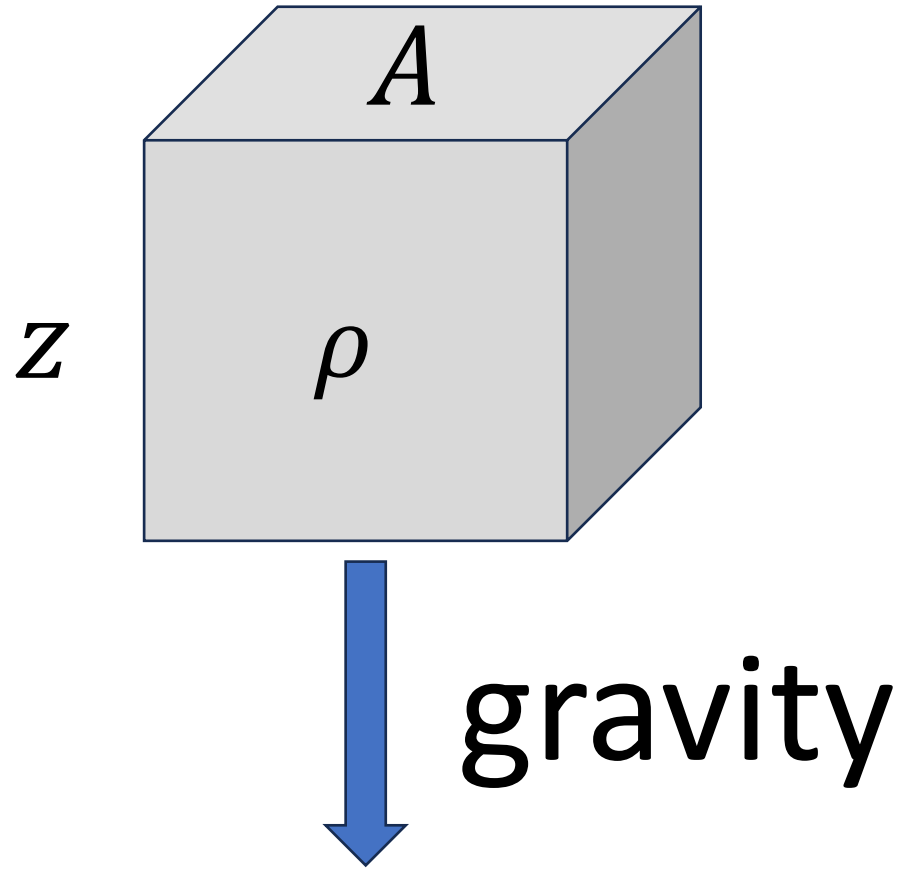
stress = σ = force per unit are



Force = density x
acceleration of gravity x
height x area

$$\sigma = \frac{f}{A} = \rho g z$$

Stress of Gravity



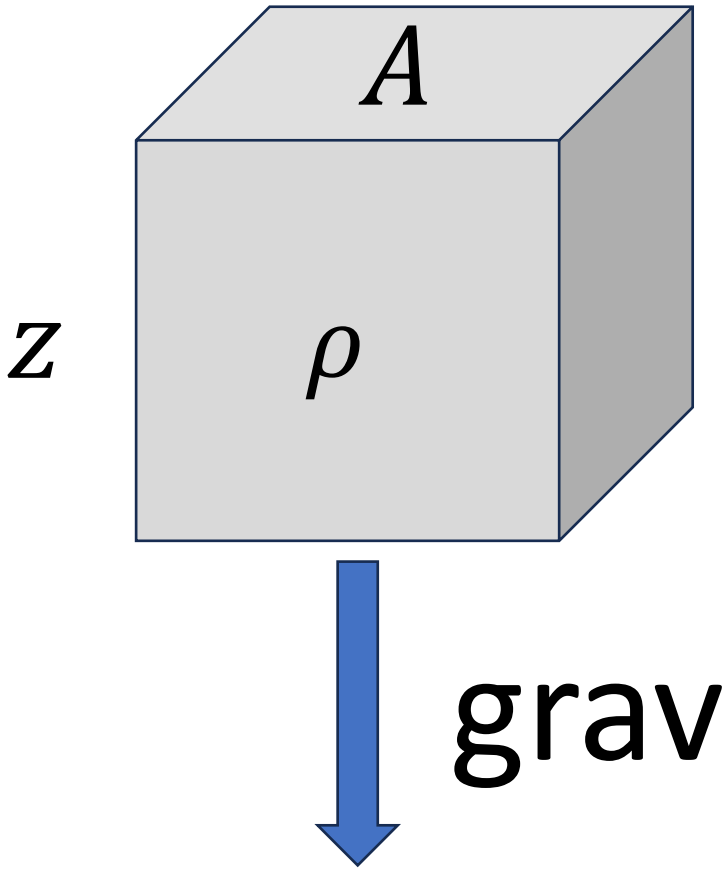
$$\frac{\sigma}{z} = \rho g$$

$$\rho = 917\ \mathrm{kg/m^3}$$

$$\mathrm{g} = 9.81\ \mathrm{m/s^2}$$

$$\frac{\sigma}{z} \approx 9000\ pascal/m$$

Stress of Gravity



$$\frac{\sigma}{z} = \rho g$$

$$\frac{\sigma}{z} \approx 9 \text{ kpa/m}$$

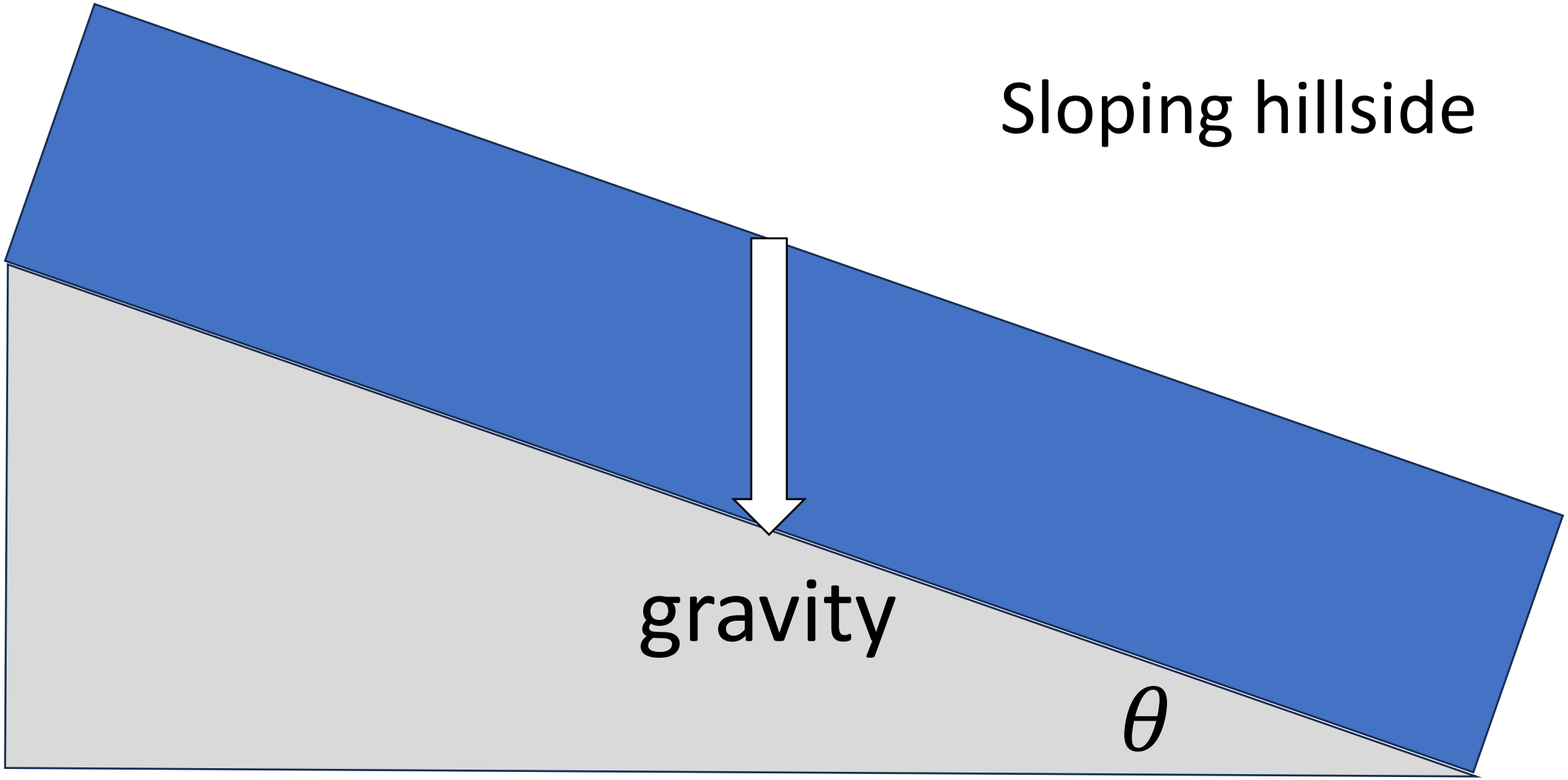
frozen water bottle

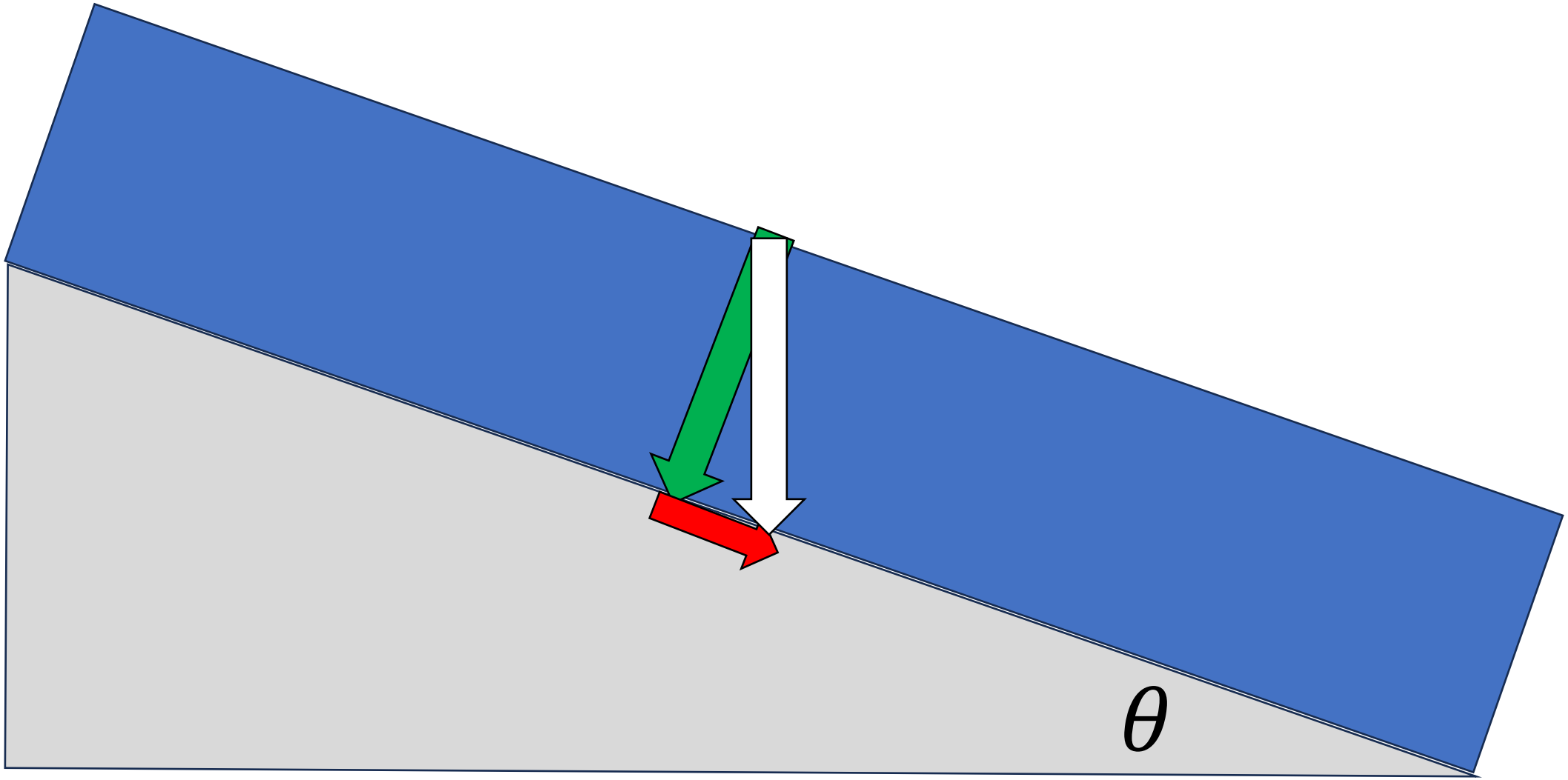
$$z = 0.2\ \mathrm{m}$$

$$\sigma \approx 9\ \times 0.2\ \mathrm{kpa} \approx 2\ \mathrm{kpa}$$

What else besides gravity do you need for flow?

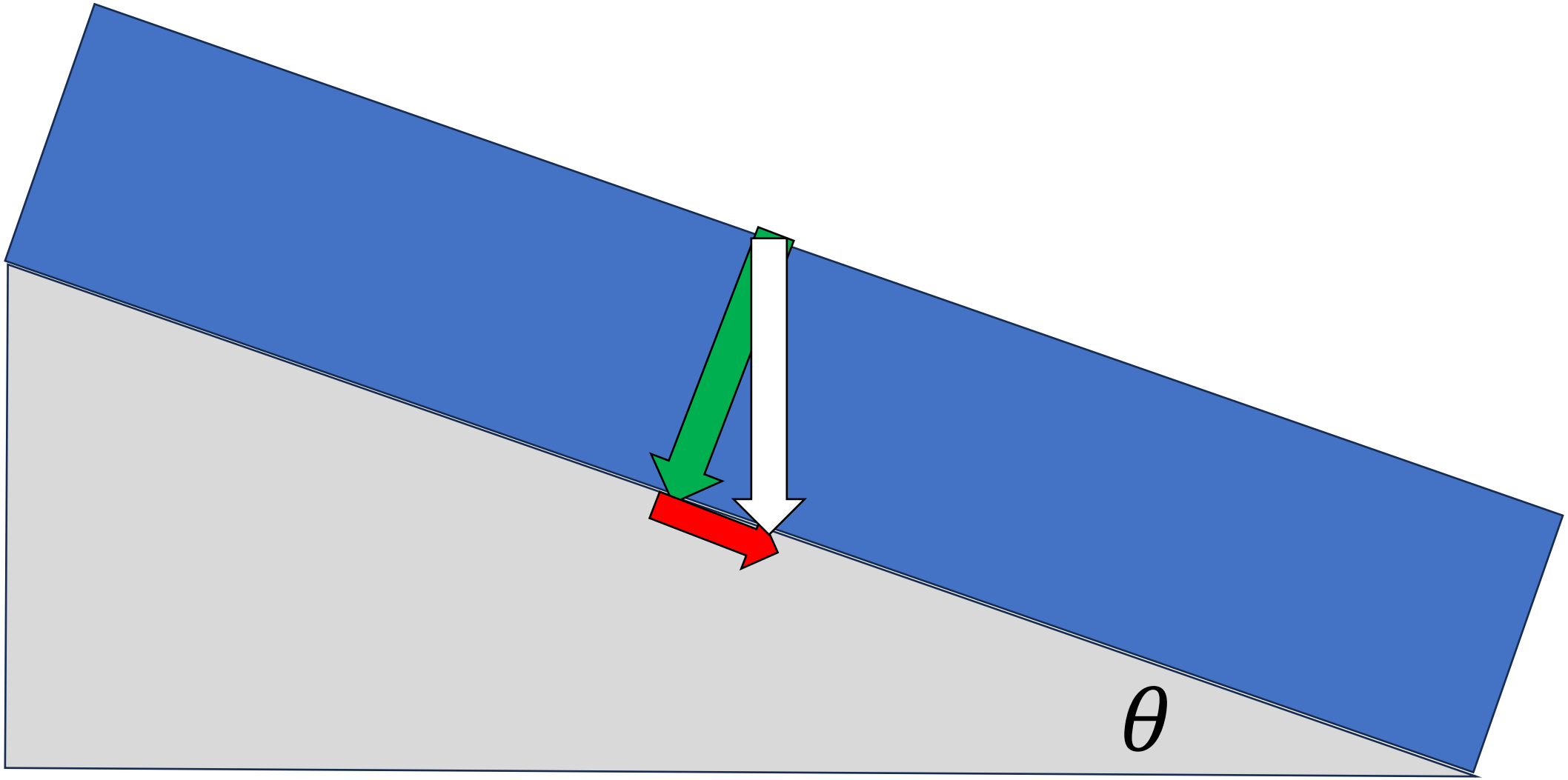
Fjallsjokull (glacier)


Sloping hillside
gravity
θ



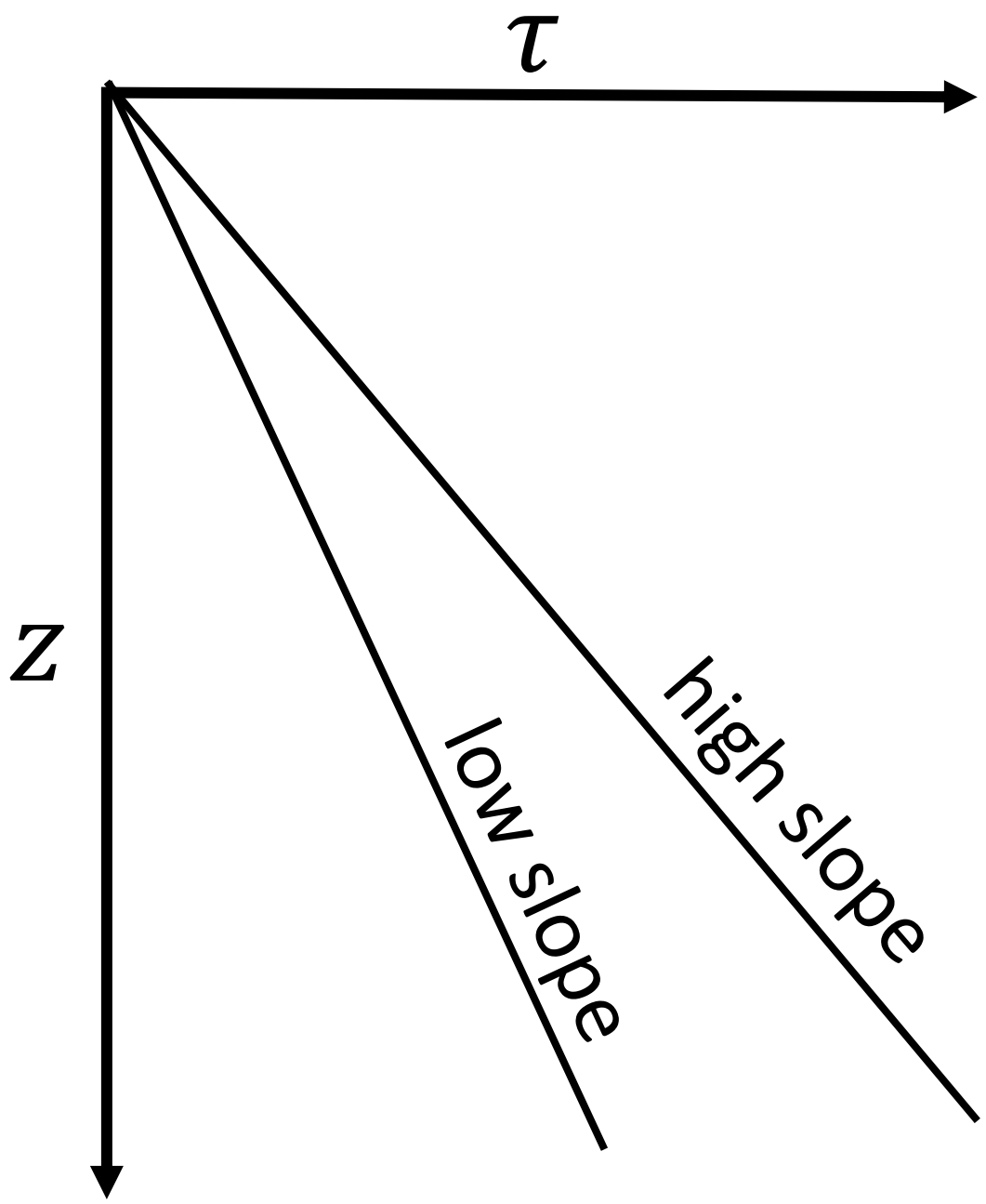
compressive stress of gravity

shear stress of gravity



$p = \rho g z \cos\theta$

$\tau = \rho g z \sin\theta$ drives flow



shear stress increases
with depth in the glacier

steeper the slope
the faster the increase

shear stress
causes the ice to flow

flow

ice is moving

ice has a velocity

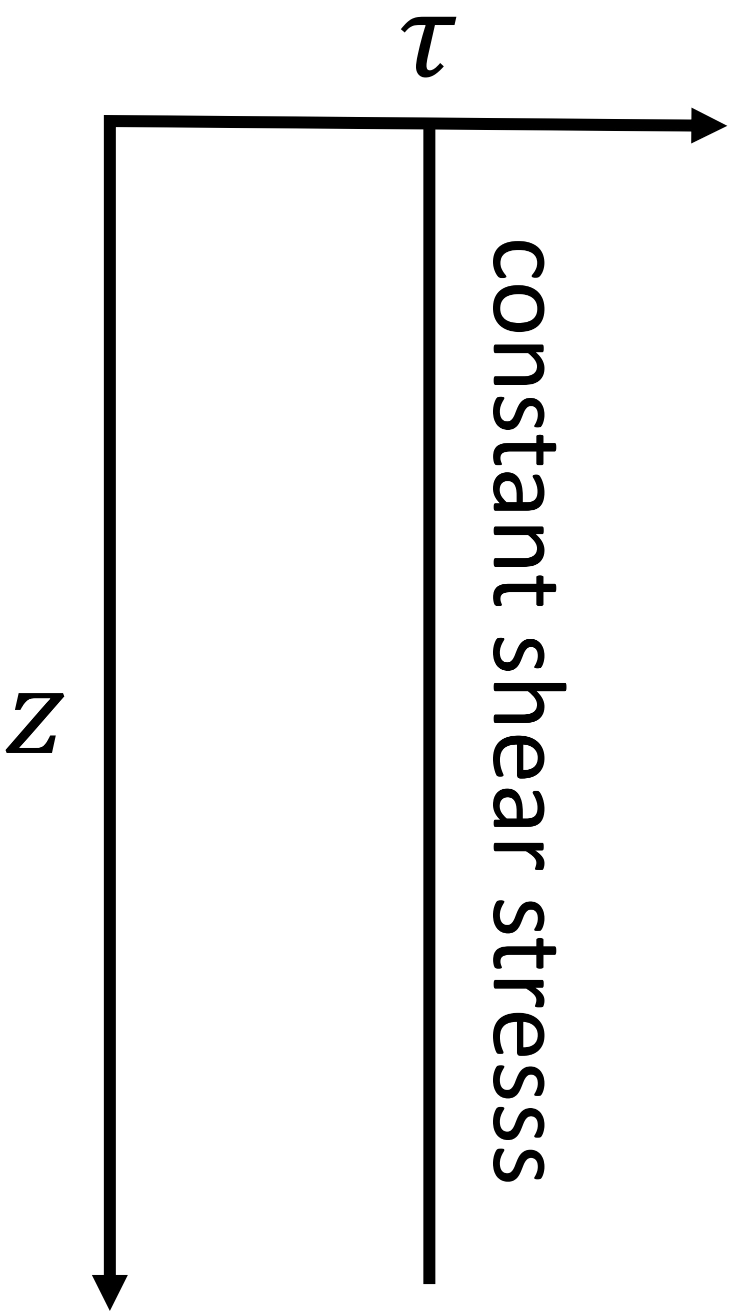
v

measured in m/s

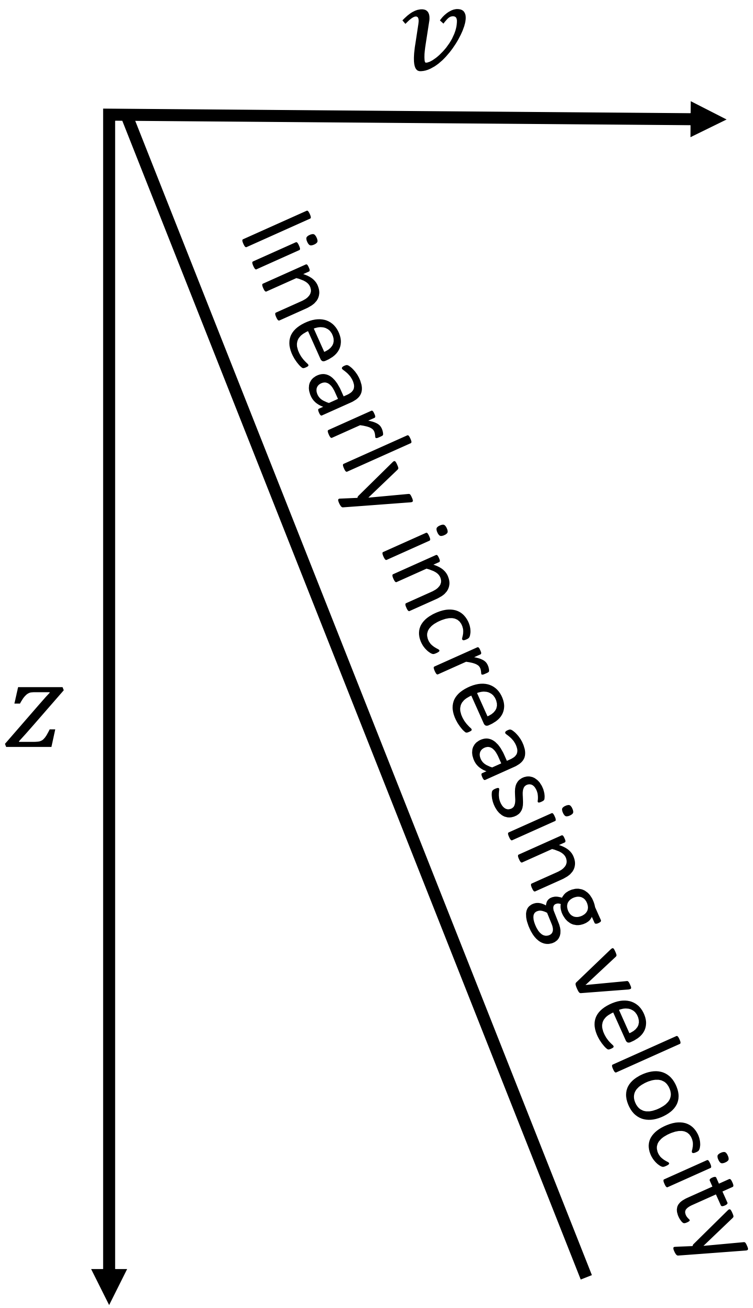
Lab experiments

Glen flow law

shear stress
causes the ice to flow



τ
z
constant shear stresss



v
z
linearly increasing velocity

Lab experiments

Glen flow law

$$\frac{dv}{dz} = A\tau^3$$

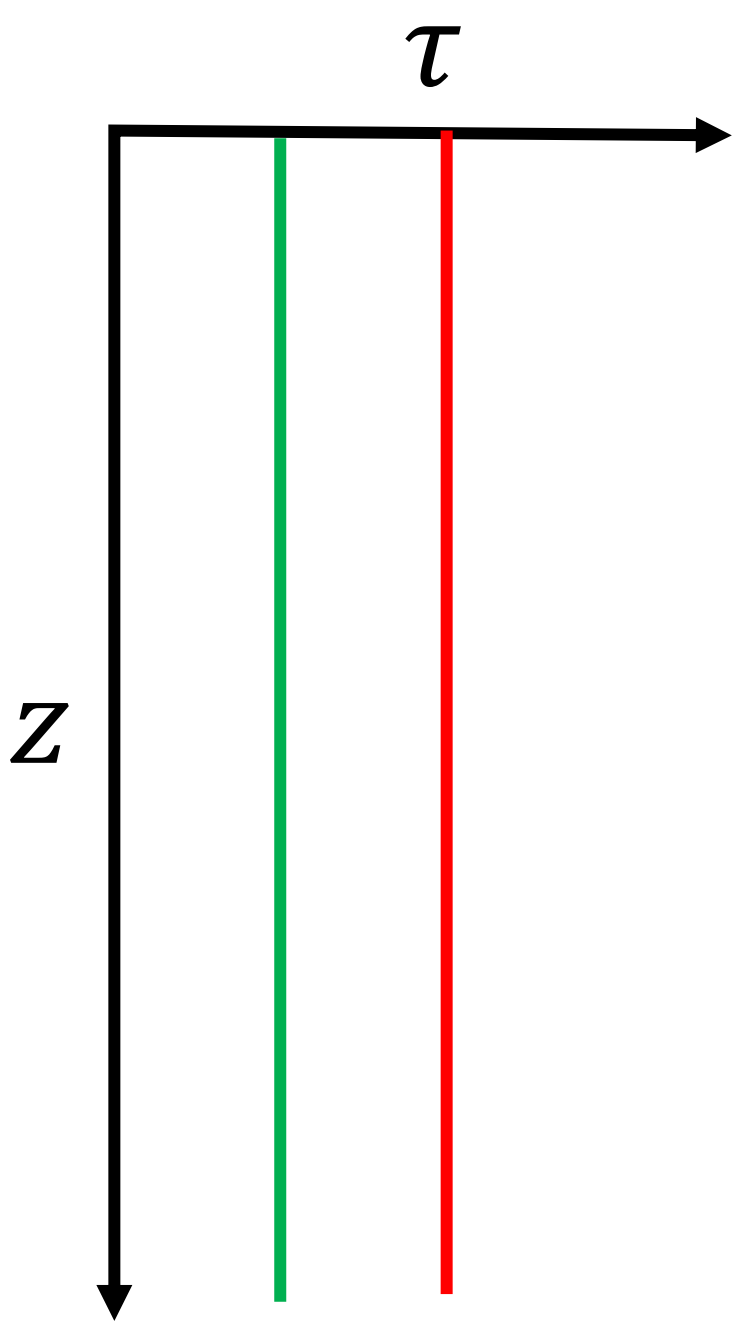
Lab experiments

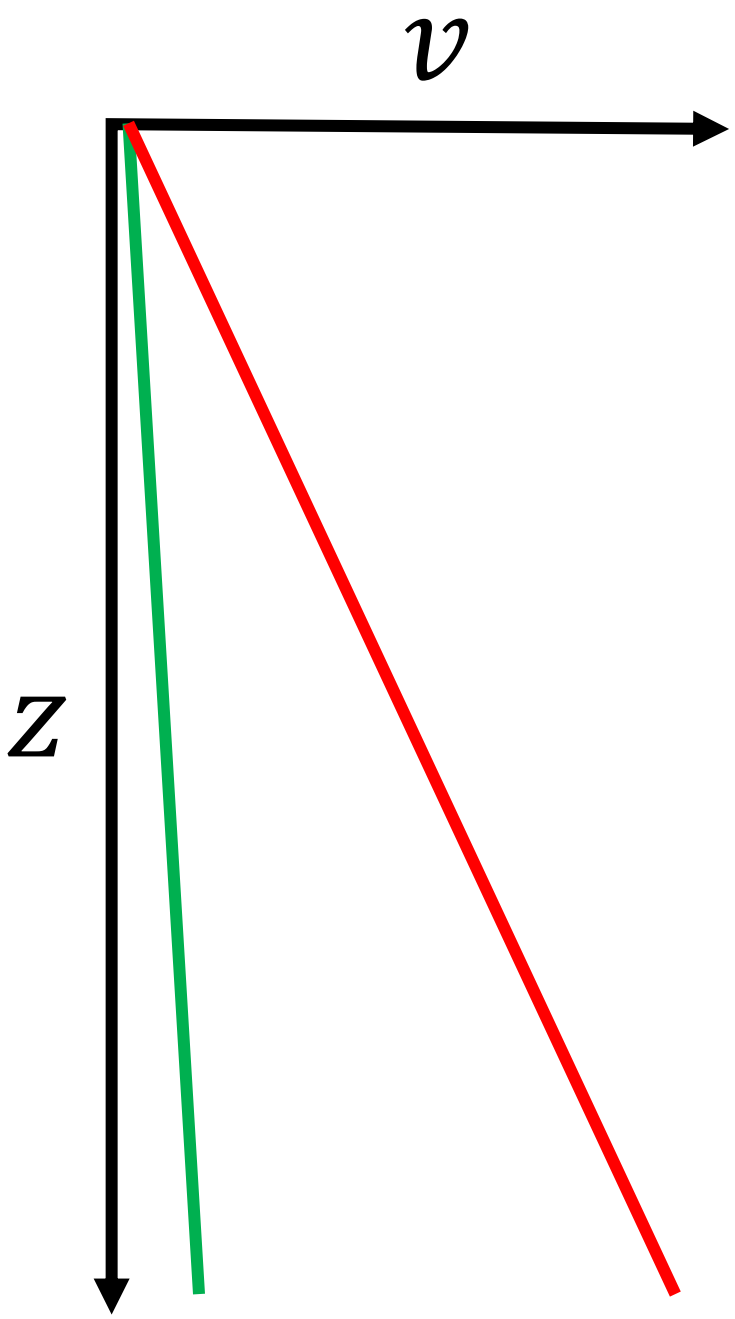
Glen flow law

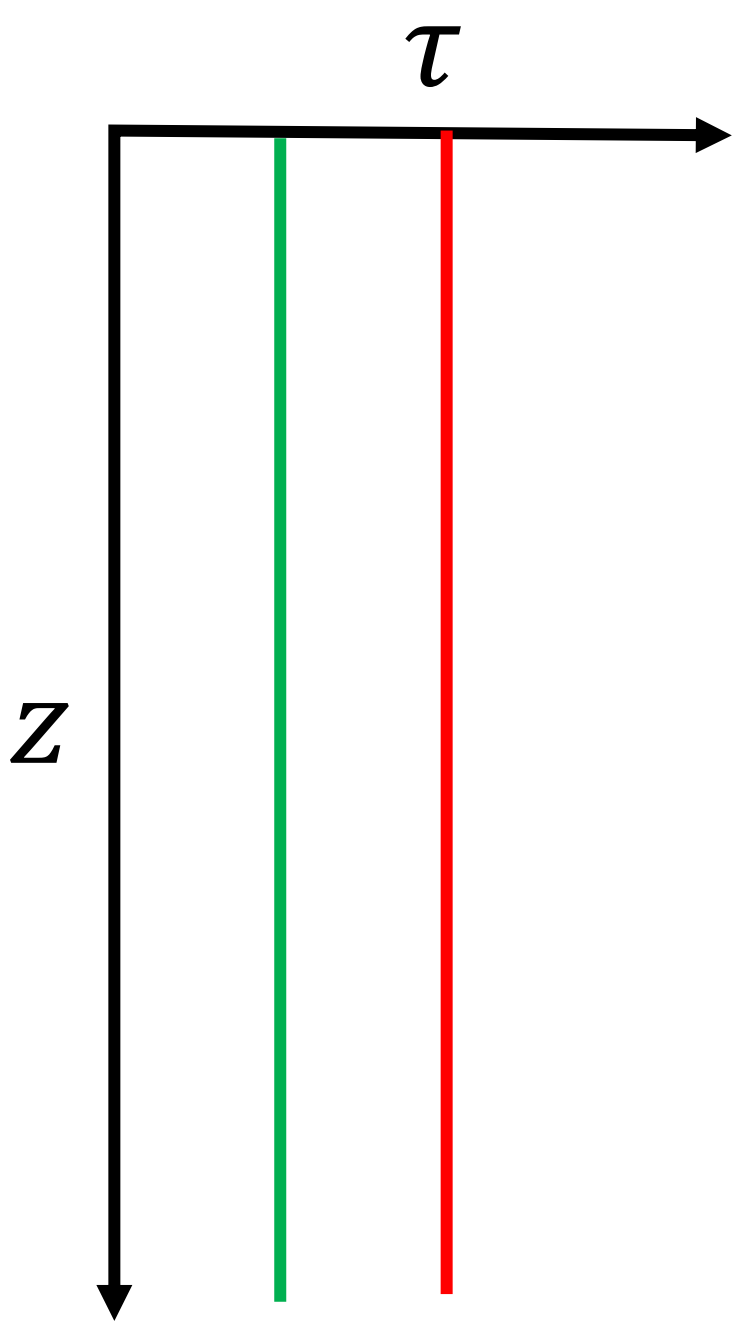
$$\frac{dv}{dz} = A\tau^{3}$$

double the stress

velocity increase is eight times bigger


τ
z


v
z



glaciers flow much faster on steep hill than shallow sloped

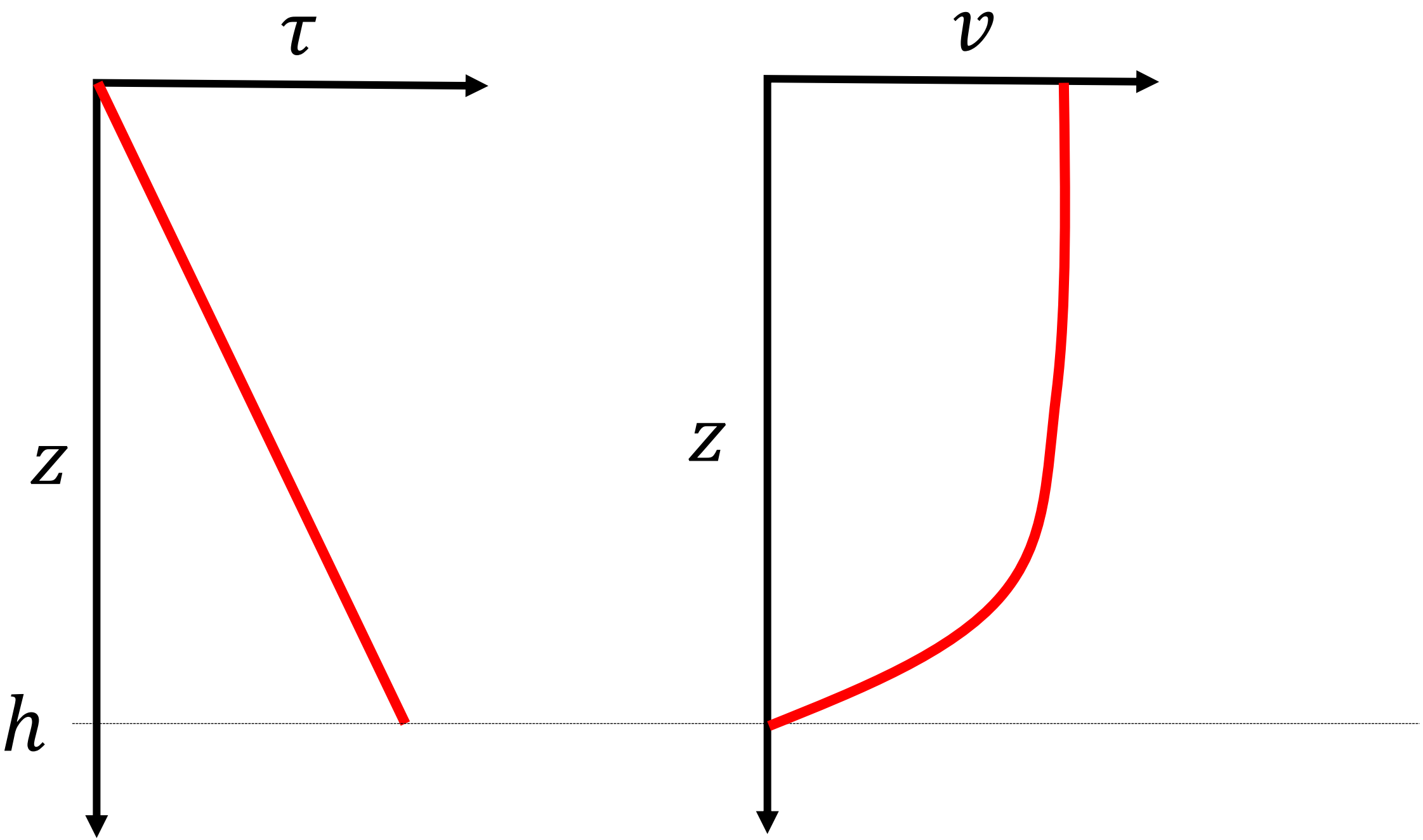
very idealized glacier of constant thickness h

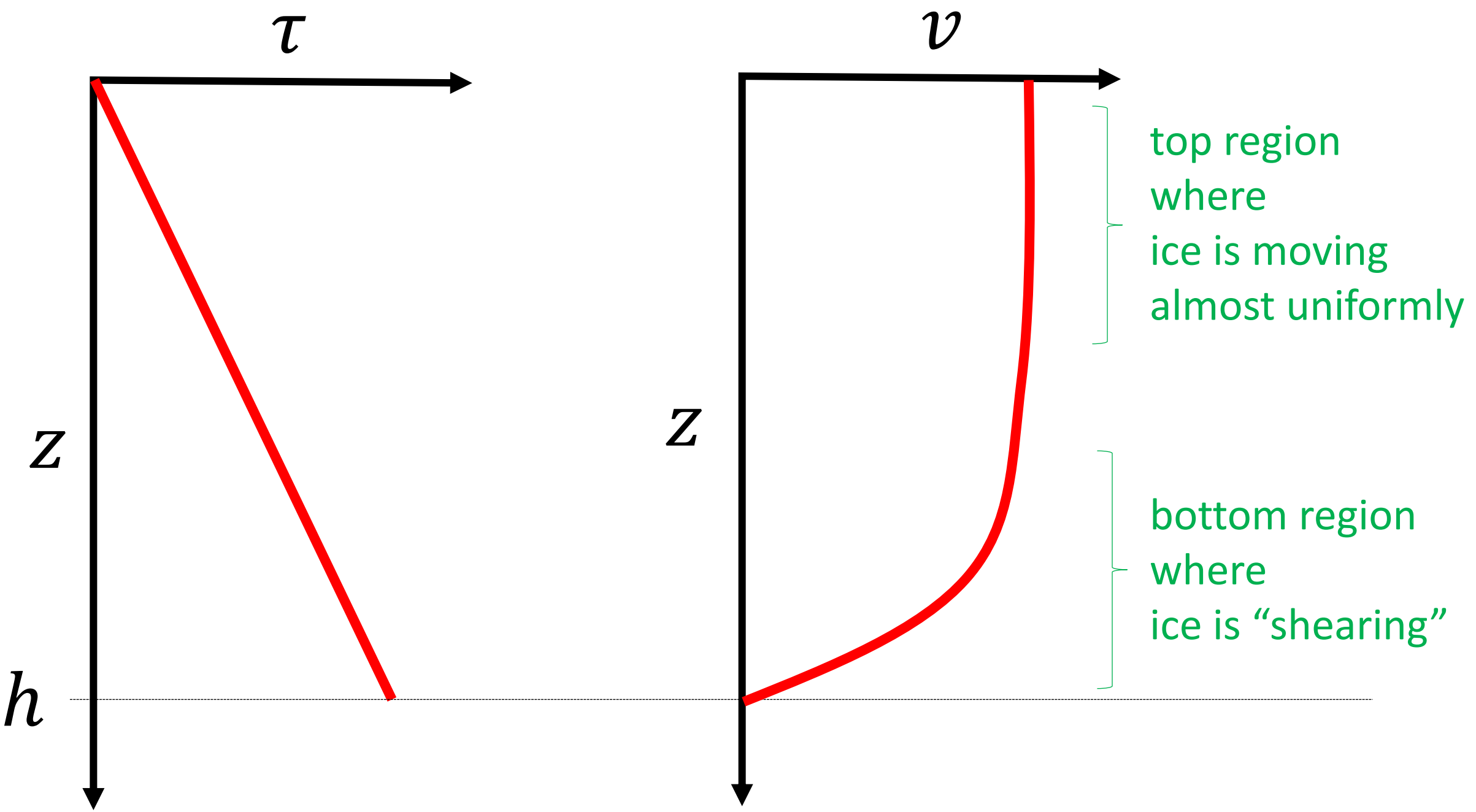
very wide, so edges of glacial valley unimportant

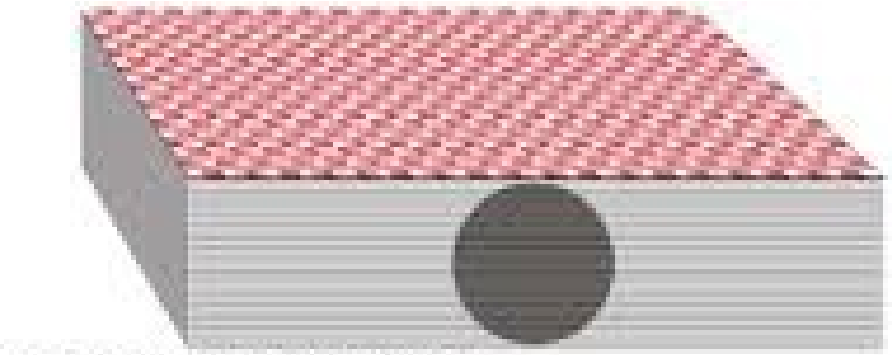
on hill of constant slope

top has zero shear stress

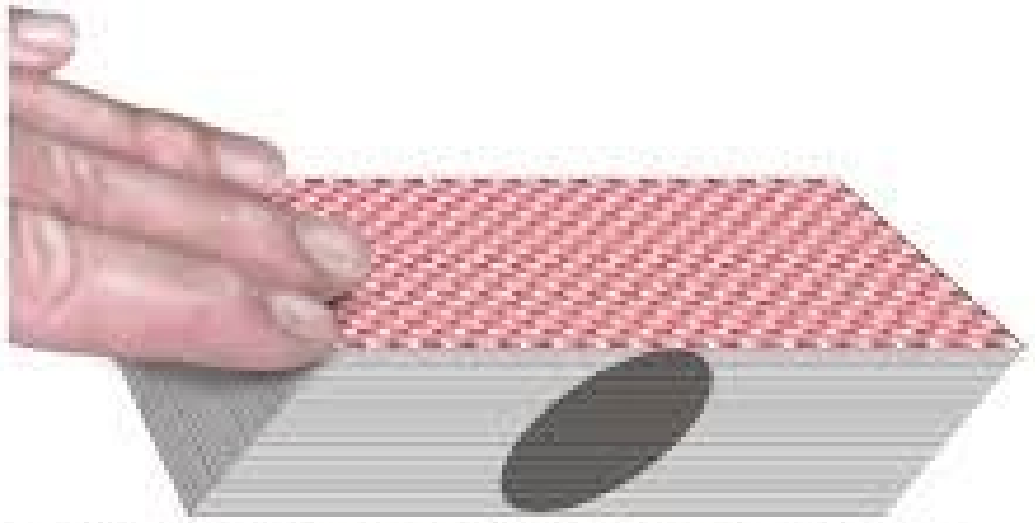
bottom frozen to bed, so velocity is zero


τ
z
h
v
z

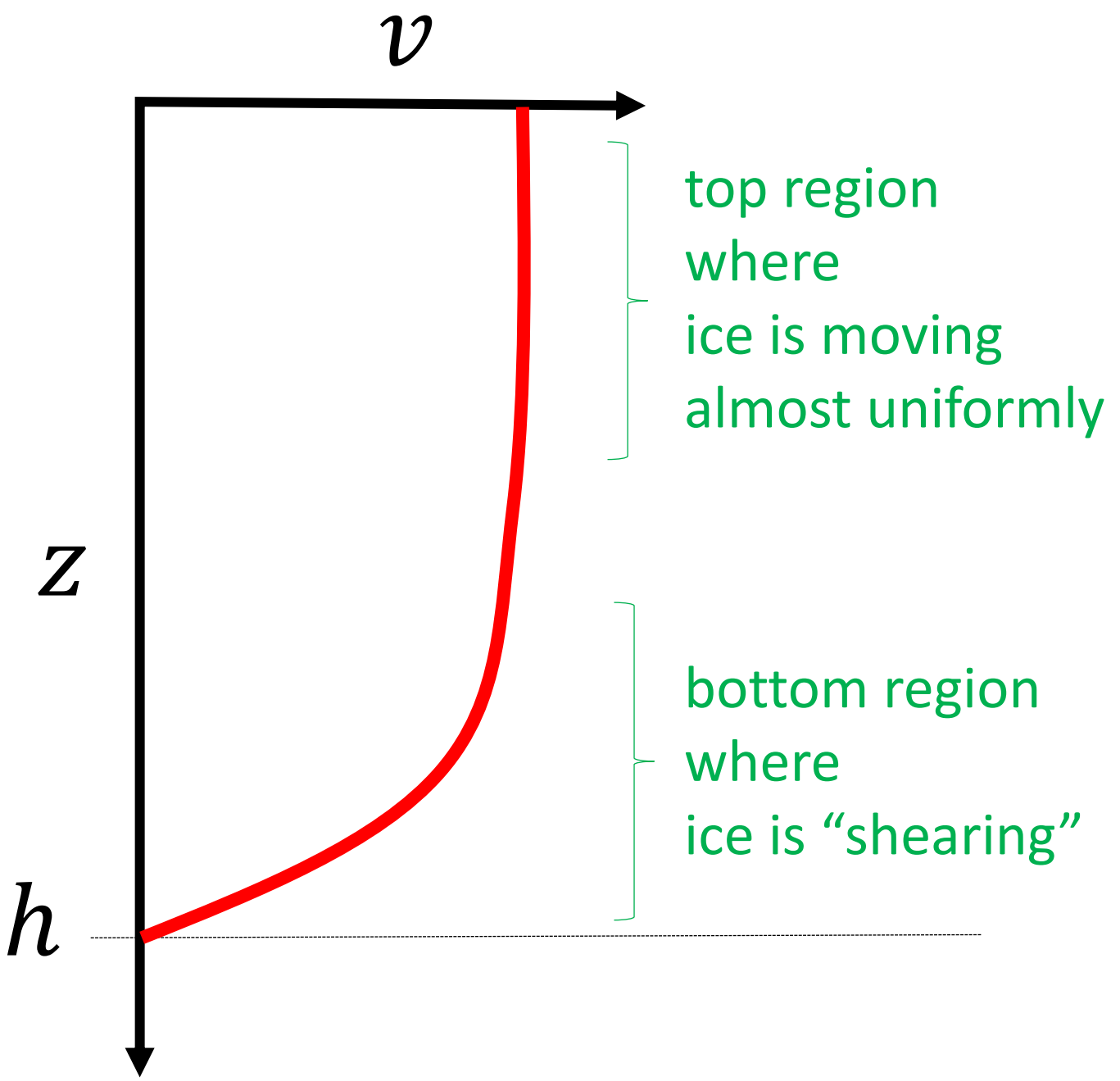

τ
z
h
v
z
top region
where
ice is moving
almost uniformly
bottom region
where
ice is “shearing”



A. Deck of playing cards



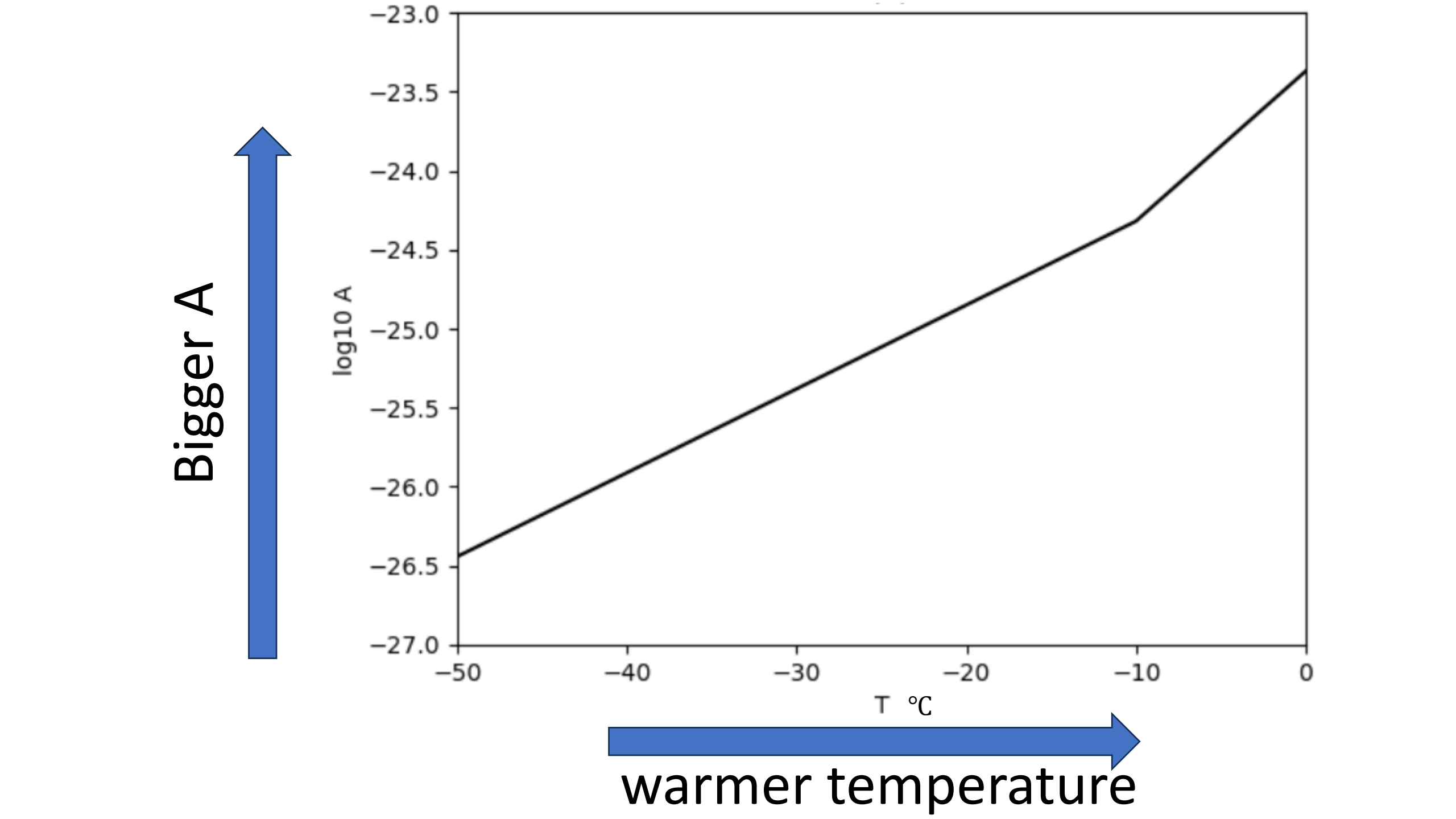
B. Shearing occurs when hand pushes top of deck



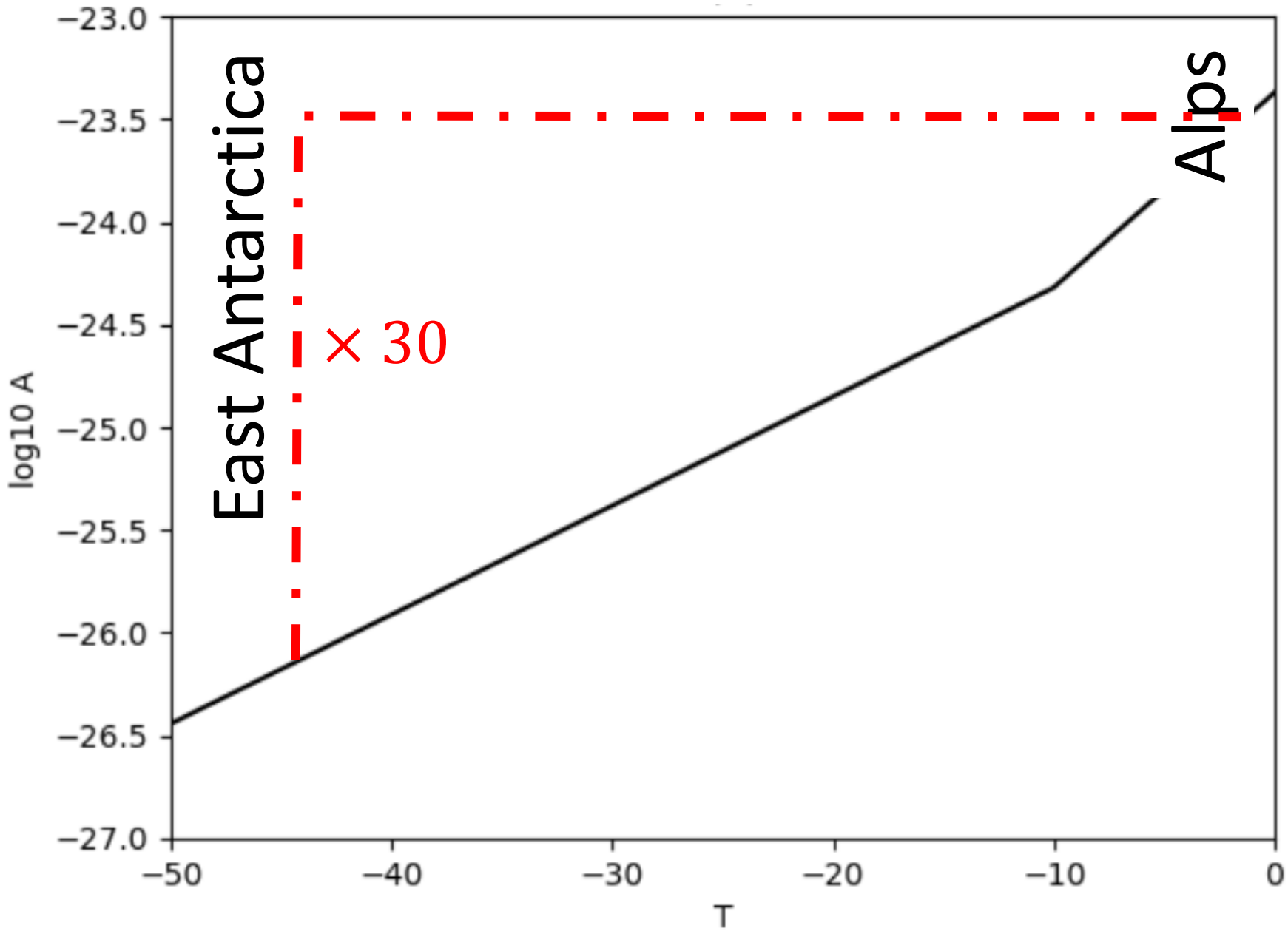
Glen flow law

$$\frac{dv}{dz} = A\tau^3$$

warm ice has an A that is orders of magnitude bigger than cold ice

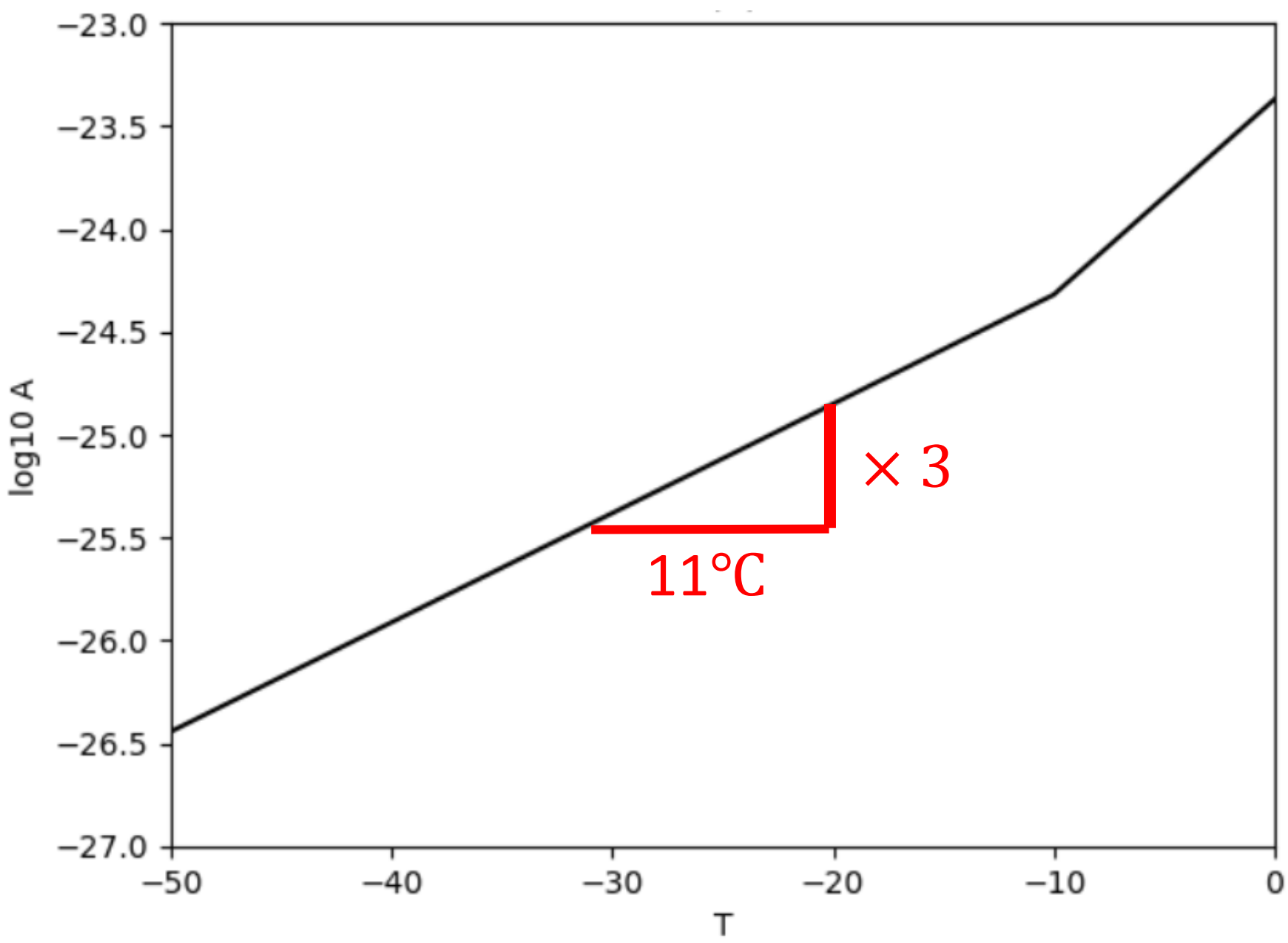

Bigger A
log10 A
−23.0
−23.5
−24.0
−24.5
−25.0
−25.5
−26.0
−26.5
−27.0
−50
−40
−30
−20
−10
0
T ℃
warmer temperature

Glaciers behave differently in different climates



Glaciers behaves differently during the Ice Age (when it was 11°C colder)

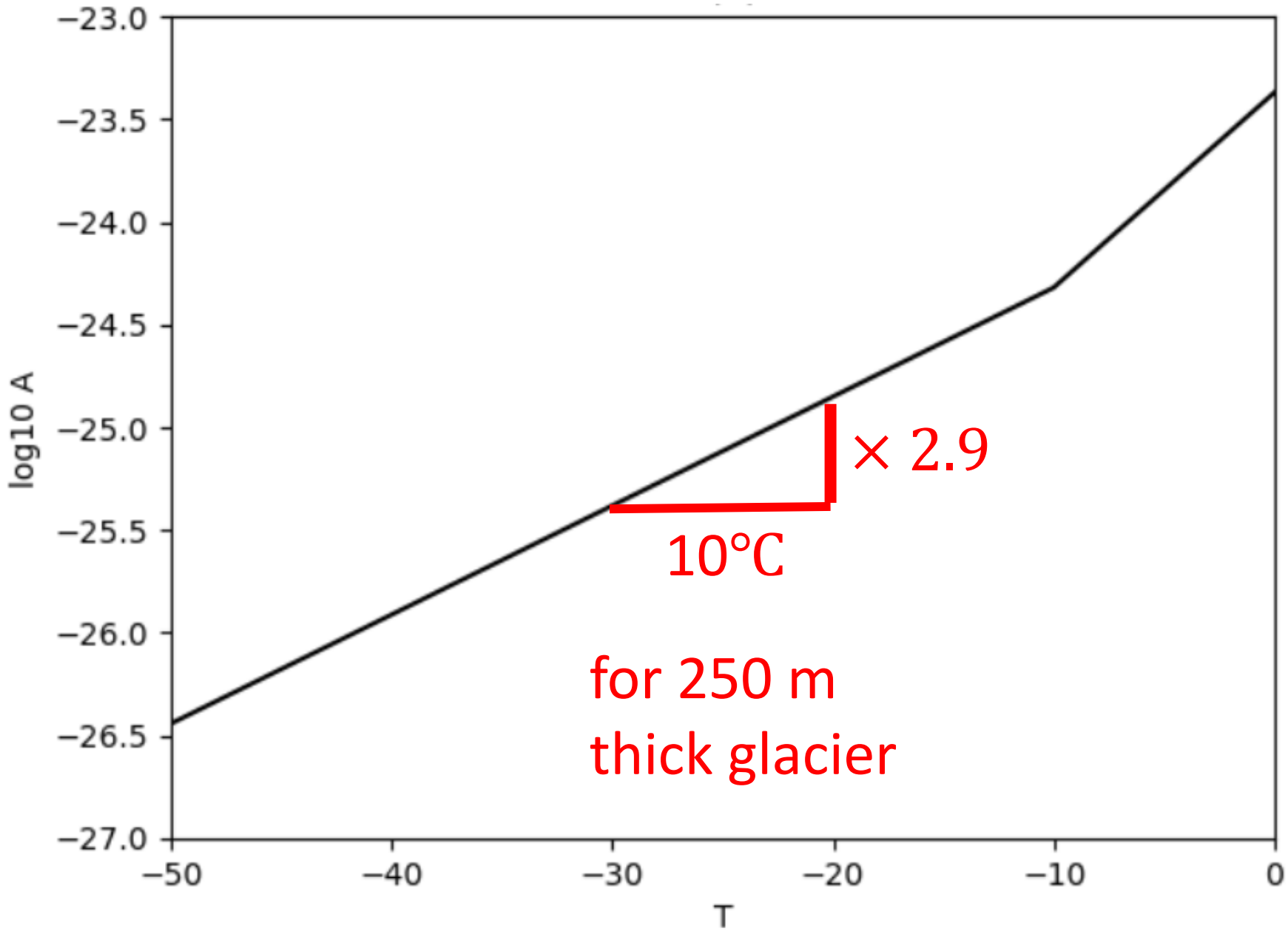
A was about three times smaller



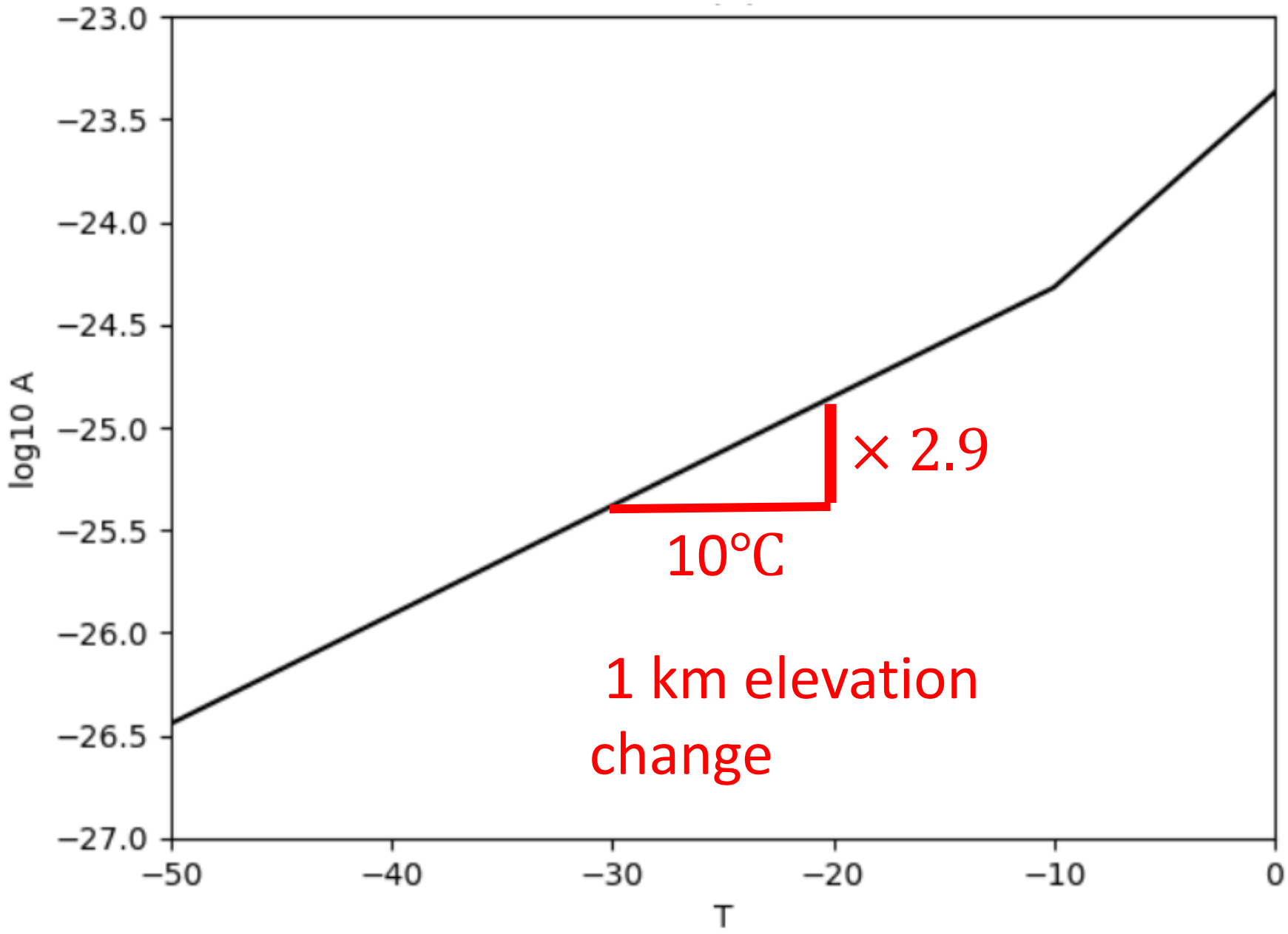
The geothermal gradient

global average 40°C/km

affects ice velocity



Atmospheric lapse rate important



very idealized glacier of constant thickness h

very wide, so edges of glacial valley unimportant

on hill of constant slope

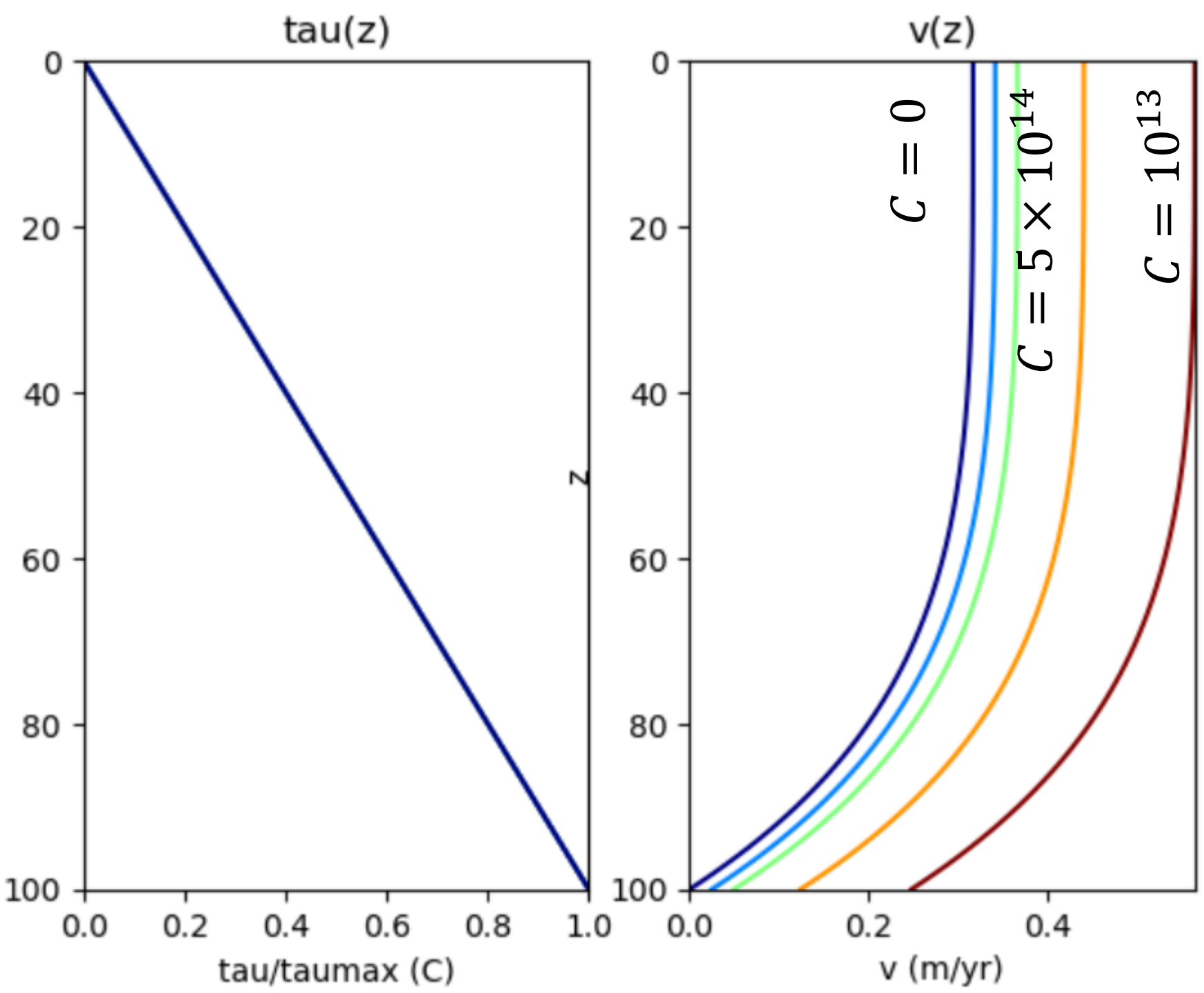
top has zero shear stress

bottom ~~frozen to~~ slides on bed bed, so velocity is not zero

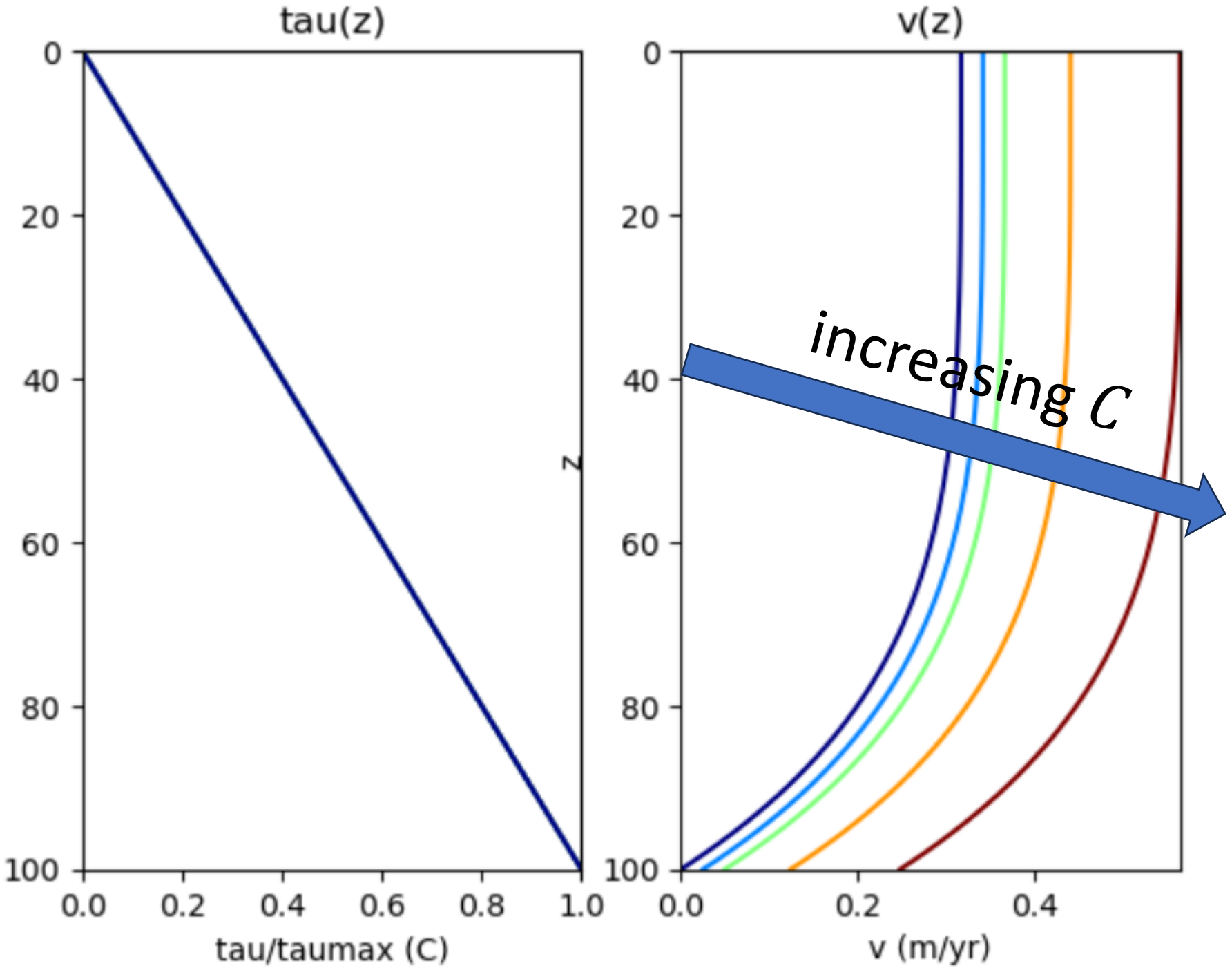
basal sliding law not so well known

one simple law is the linear law

$$v_{basal} = C\tau$$


tau(z)
0
20
40
60
80
100
0.0
0.2
0.4
0.6
0.8
1.0
tau/taumax (C)
z
v(z)
0
20
40
60
80
100
0.0
0.2
0.4
v (m/yr)
$C = 0$
$C = 5 \times 10^{14}$
$C = 10^{13}$

Basal sliding shifts the velocities higher



Sliding is a frictional process
that generates heat
and can lead to melting at the base
of the glacier

Basal Thermal Regime

How close is the base of the glacier to melting?

(A) Net basal heating: ice melts at base
(B) Equilibrium
(C) Net basal cooling: water freezes at base

Mass Balance

New snow added everywhere, but

Net addition of ice at high elevations
because cold temperatures suppress melting

Net loss of ice at low elevations
because warm temperatures facilitate melting

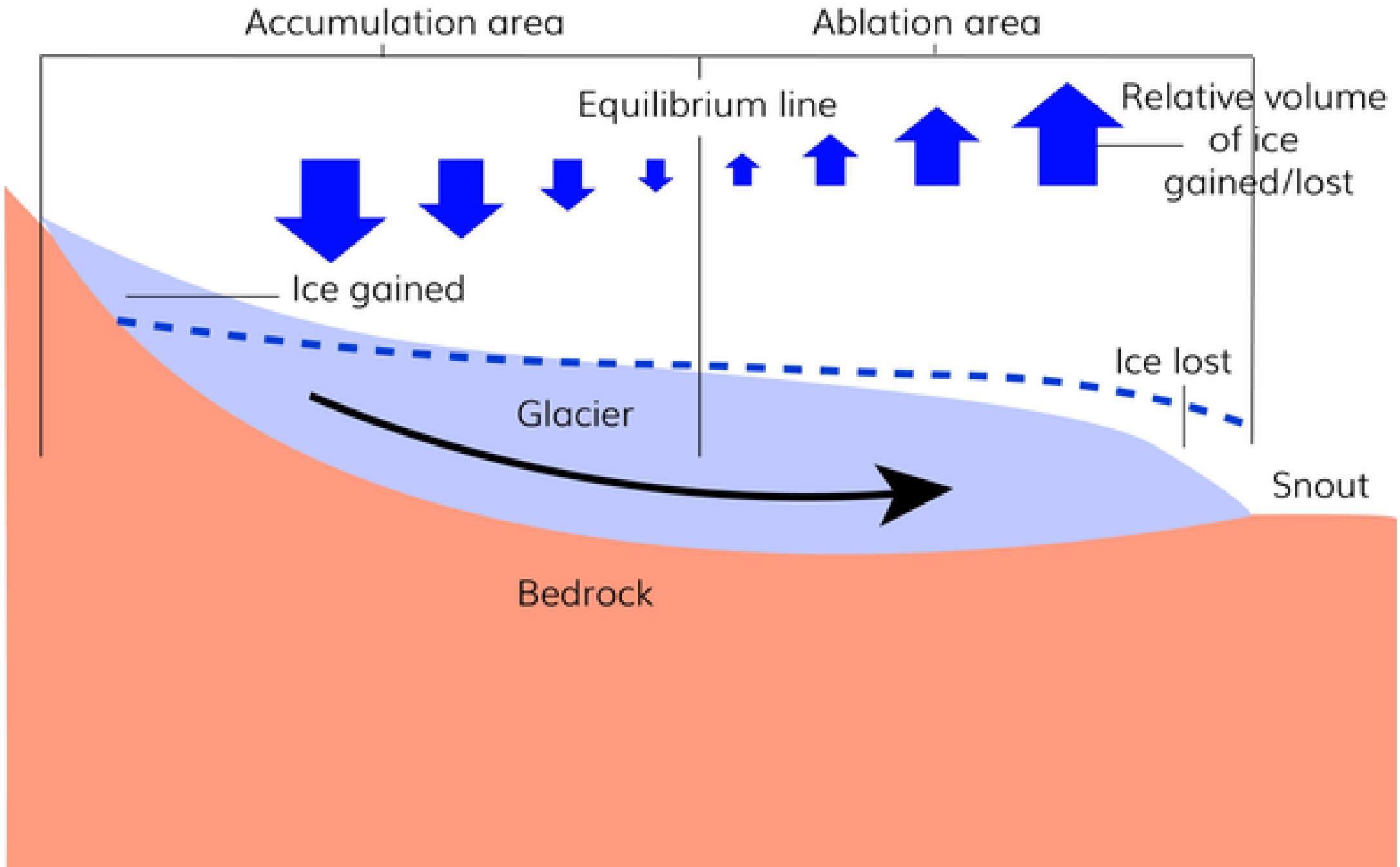
At equilibrium,

a glacier maintains a constant shape

because flow from higher to lower elevations is

is balanced

by addition of snow at higher elevations
and melting at lower elevations


Accumulation area
Ablation area
Equilibrium line
Relative volume of ice gained/lost
Ice gained
Ice lost
Glacier
Snout
Bedrock

equilibrium is only an idealization

because

in reality many glaciers are either

advancing or retreating


Crevasse: tension crack in surface of glacier

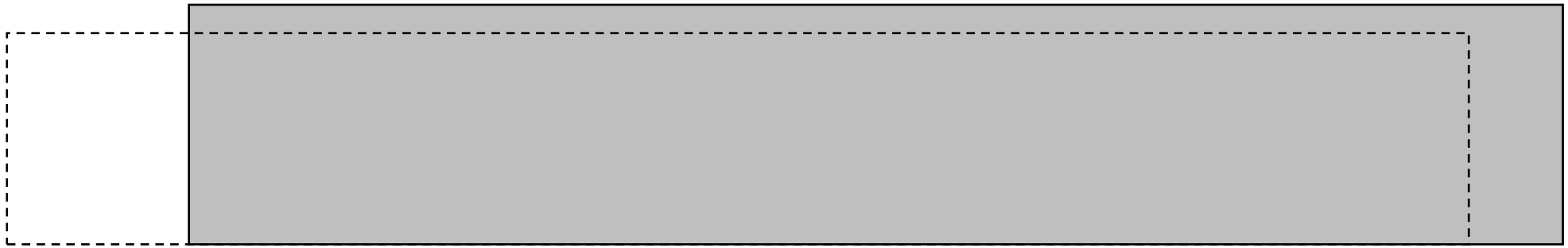
bad to fall into

bad to drive into

need extensional horizontal stress to open crevasse

case 1: Compressing glacier

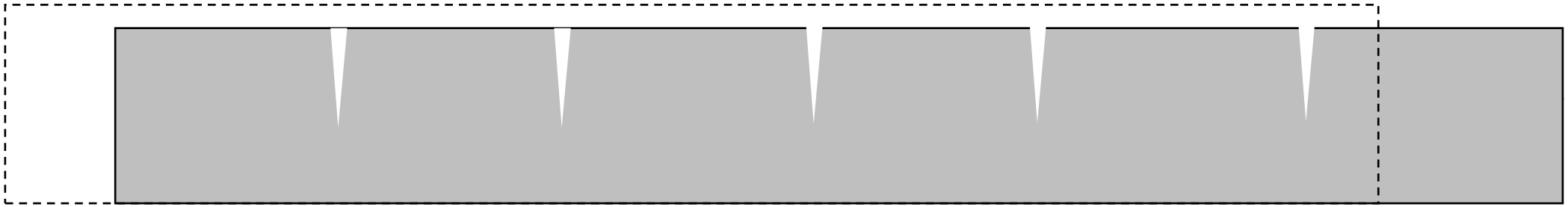
case 1: Glacier thickens

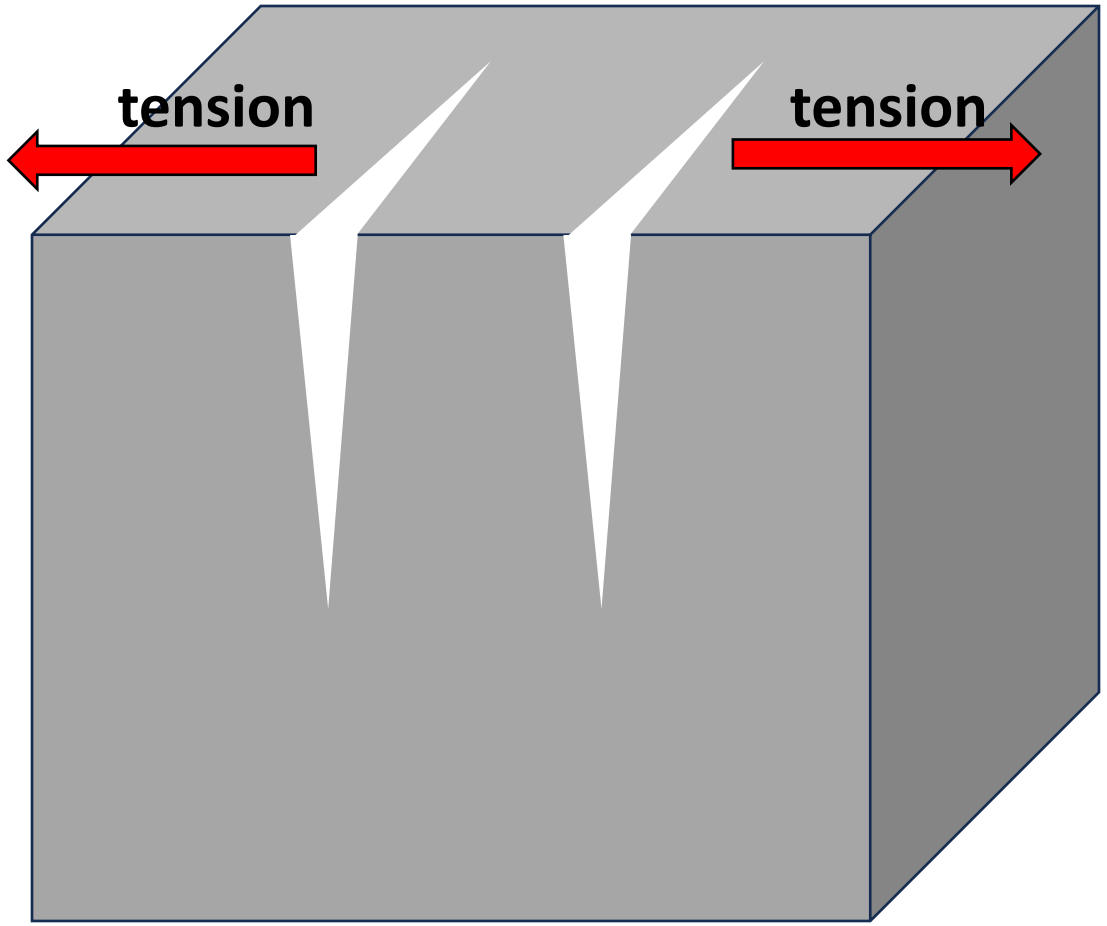


case 2: Extending glacier

case 2: Extending glacier

Crevasses form



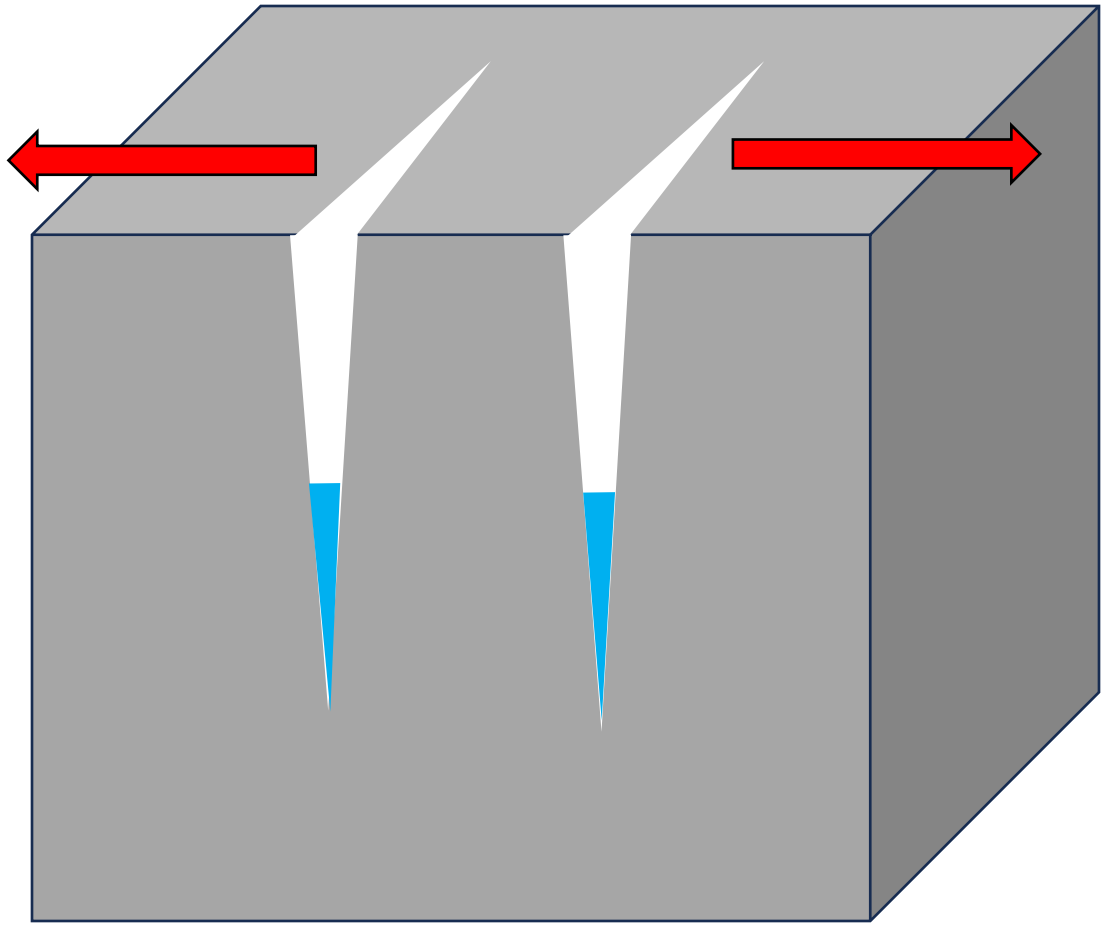


form when horizontal stress is tensional

(but their dynamics are not a subject of this class)

But for an analysis, see

https://www.ldeo.columbia.edu/~menke/www_users_menke/SED23/SED23_Lec26.pdf



meltwater can deepen them