Glacier Deformation and Flow

Jean Louis Rodolphe Agassiz (May 28, 1807 – December 14, 1873)


Wikipedia

- **Dilatation Hypothesis** based on Scheuchzer, and by Charpentier, melt water and rain enter the glacier, refreezes, expands, enlarging the glacier down valley.

James David Forbes FRS (20 April 1809 – 31 December 1868)

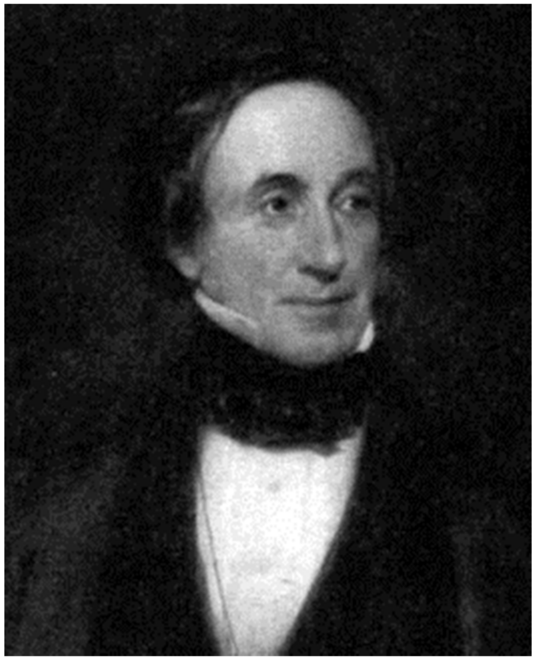
Yours Sincerely
James D. Forbes

Wikipedia

- **Viscous Hypothesis** Measured flow, found it to be continuous, occurring over the entire glacier, variable from day to day, and week to week, fastest the middle and slowest on the sides. Abbe Rendu a cleric coined the theory ‘viscous theory’

William Hopkins **FRS (2 February 1793 – 13 October 1866)**

- **Sliding Hypothesis** Proposed by Agassiz attributed to Gruner and to de Saussure, finally picked up by William Hopkins



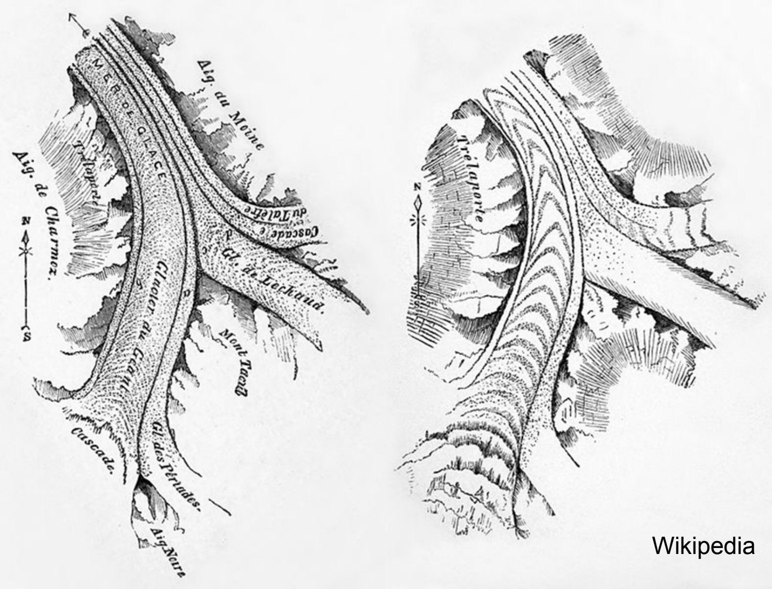
Wikipedia

John Tyndall **Physicist FRS (2 August 1820 – 4 December 1893)**

Tyndall visited the Alps mountains in 1856 for scientific reasons and ended up becoming a pioneering mountain climber. He visited the Alps almost every summer from 1856 onward. He lead of one of the early teams to reach the top of the Matterhorn (1868).

Known for his advocacy of **apparent viscosity and regelation processes** (in dispute with Faraday on regelation)

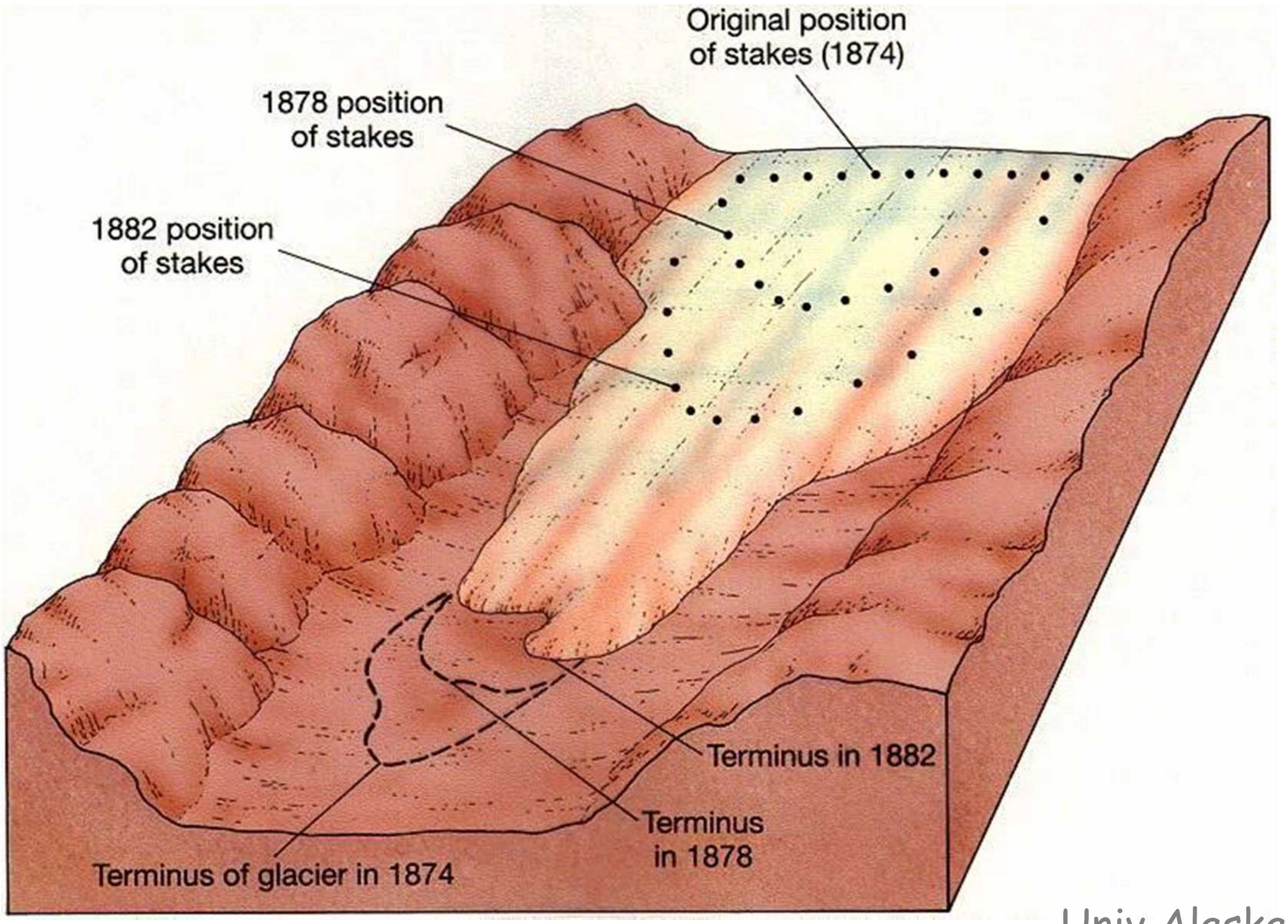
John Tyndall 1850



Wikipedia

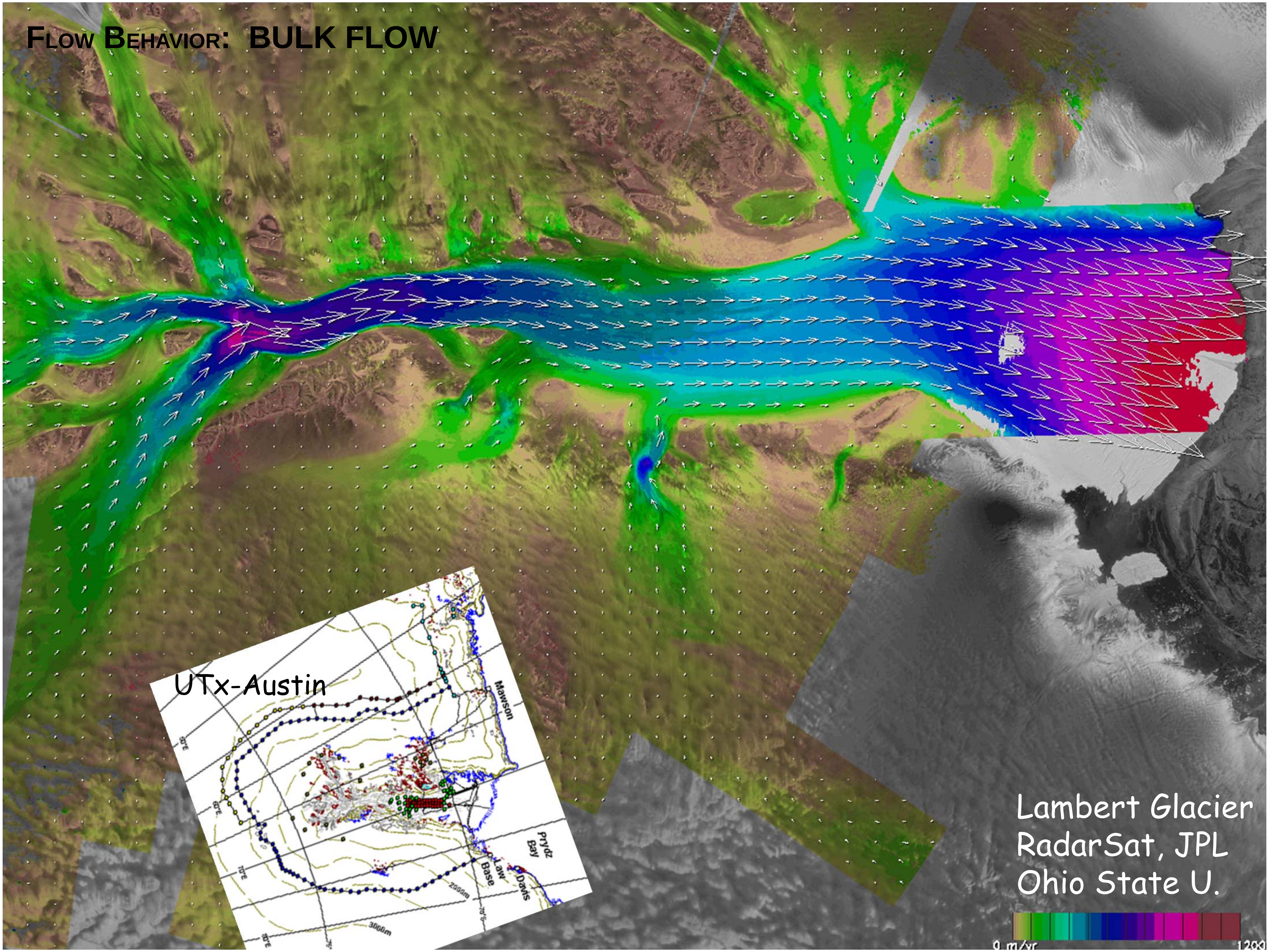
Maps of Mer de Glace in 1957 by Tyndal

FLOW BEHAVIOR: BULK FLOW



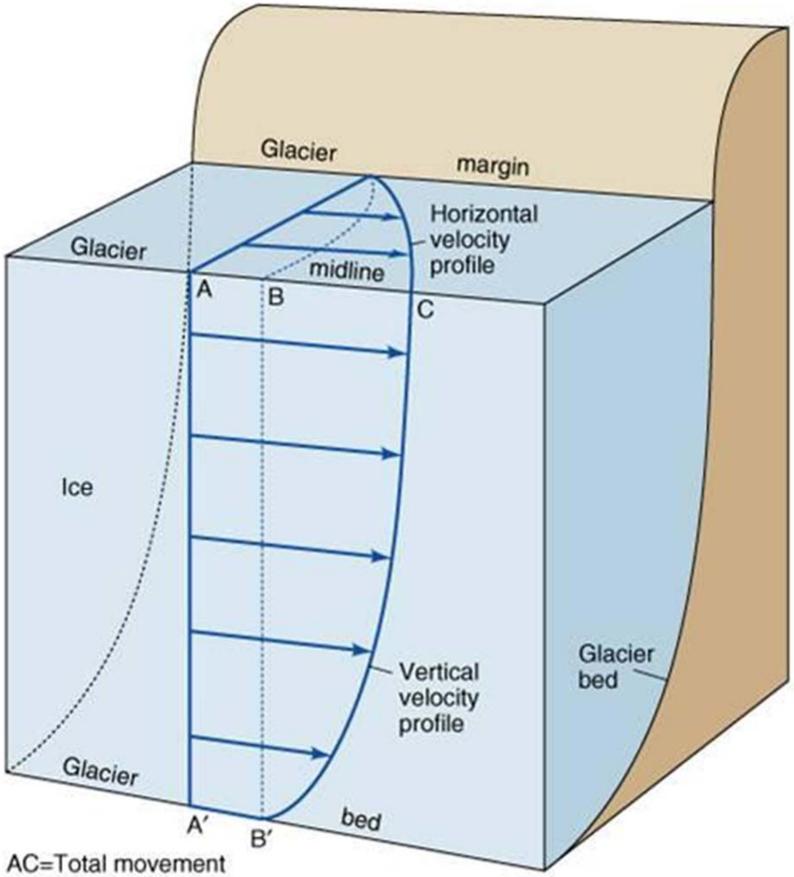
Univ Alaska

FLOW BEHAVIOR: BULK FLOW



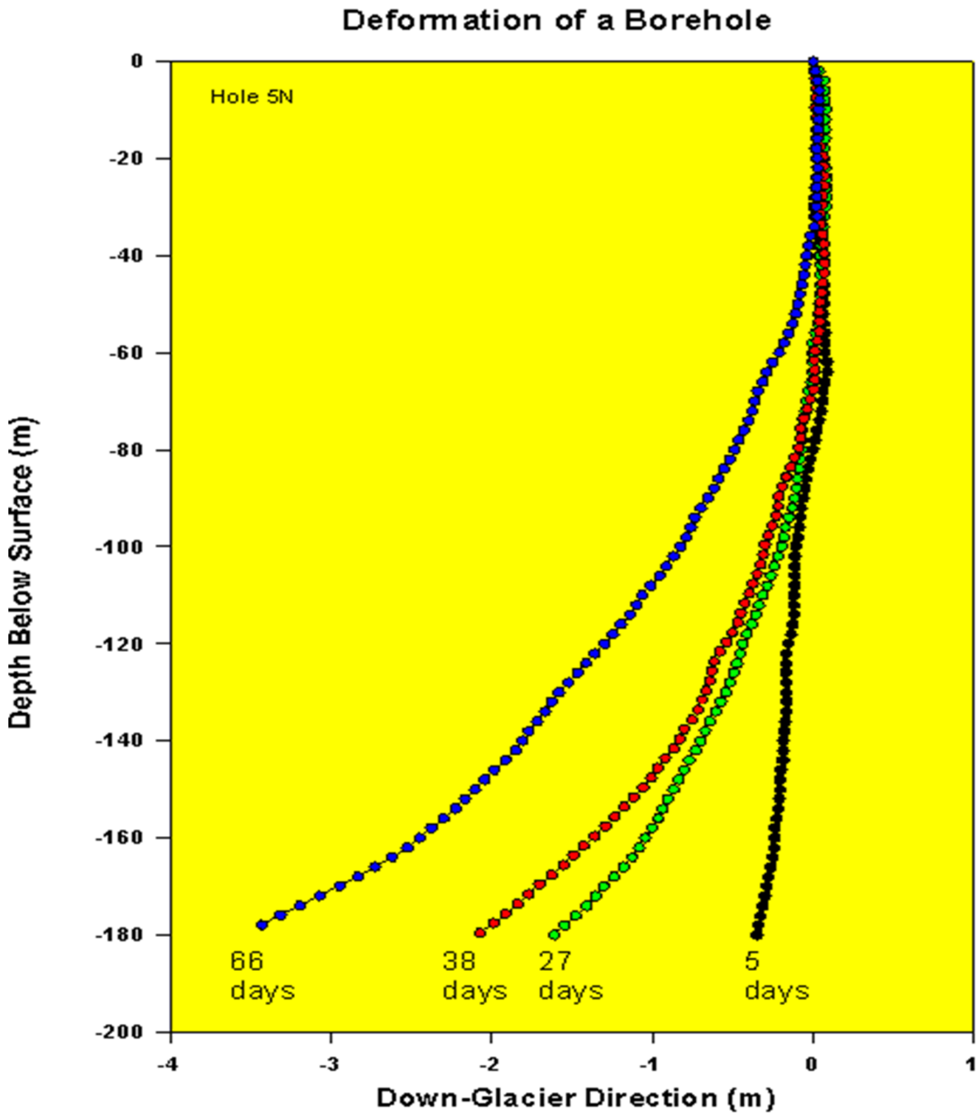
Lambert Glacier
RadarSat, JPL
Ohio State U.

FLOW BEHAVIOR: BULK FLOW



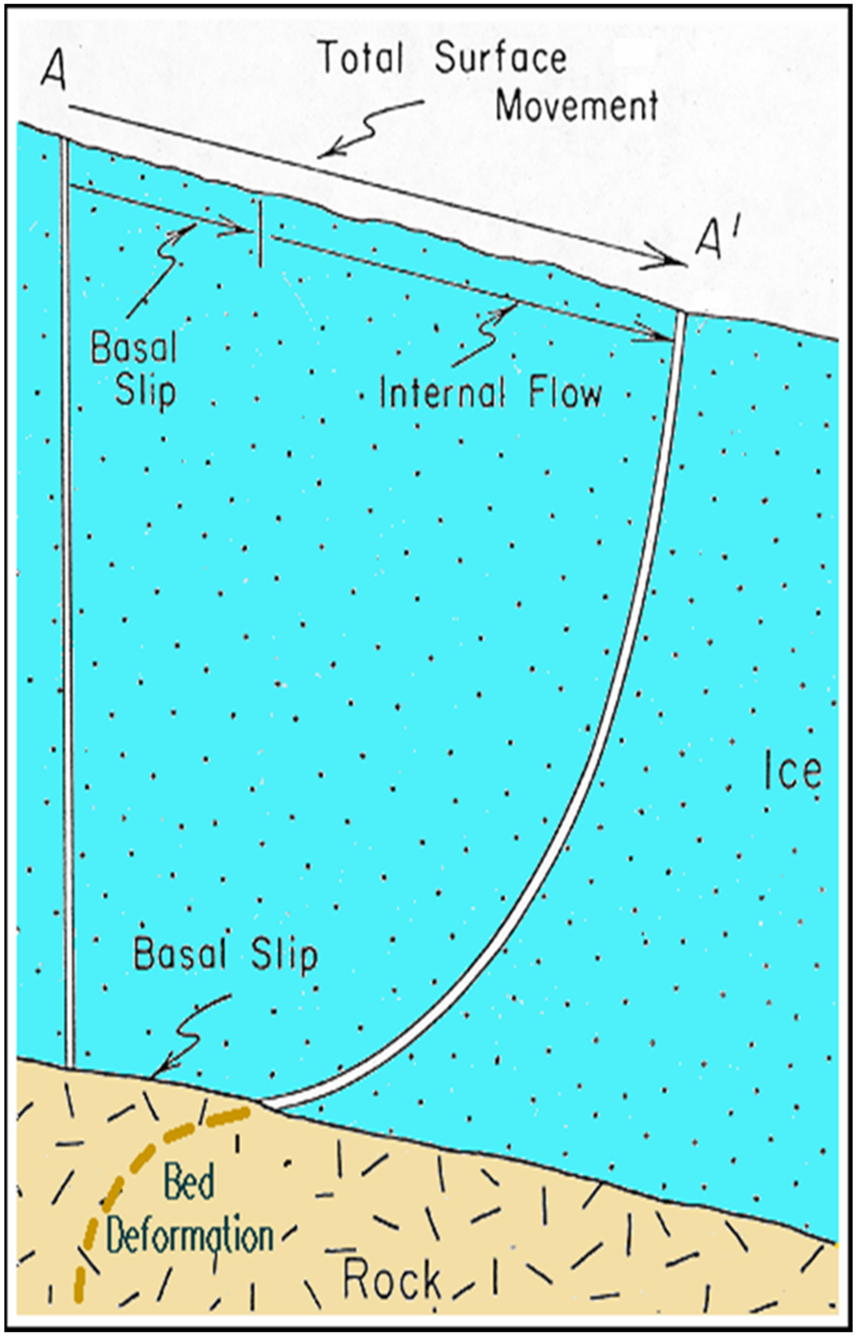
AC=Total movement
AB=A′B′=Sliding on bed
BC=Internal flow

FLOW BEHAVIOR: BULK FLOW



Deformation of a Borehole

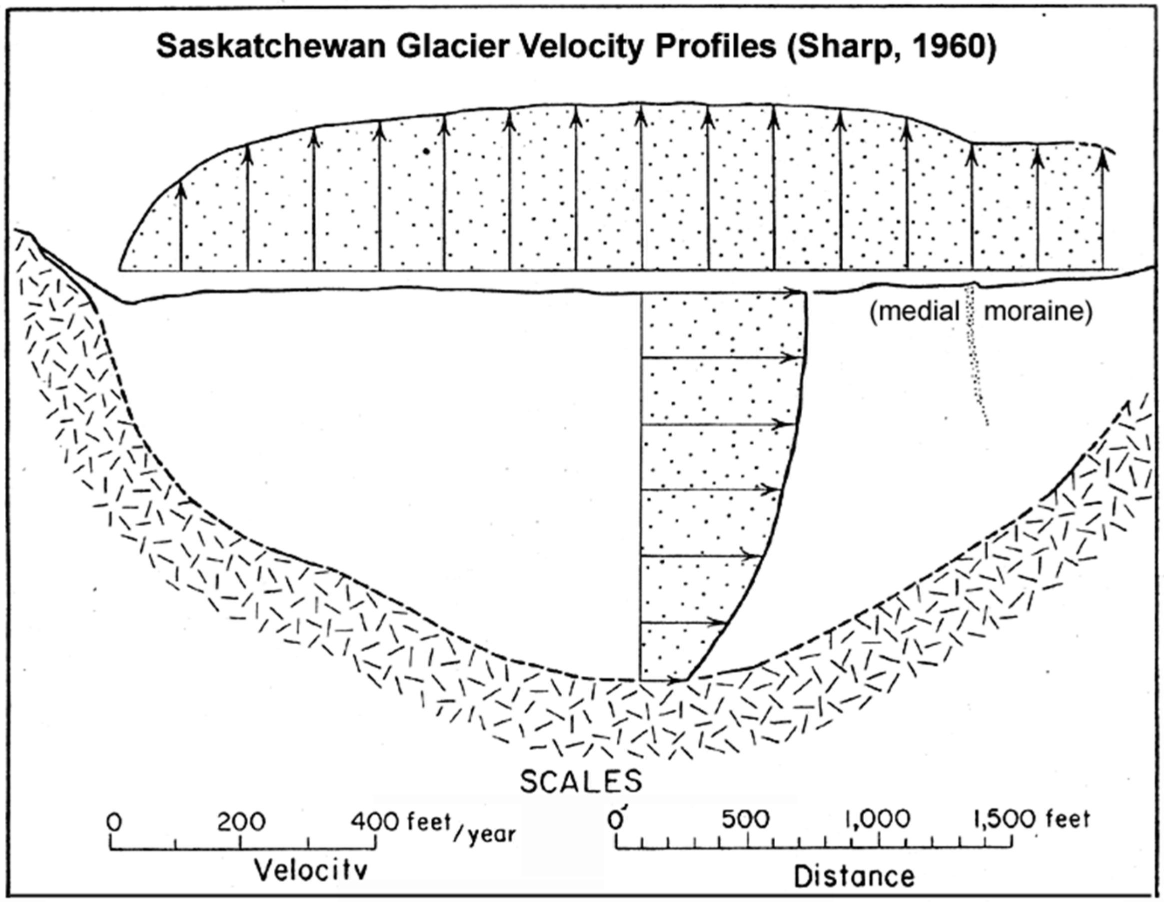
Worthington Glacier
UWyo, UC-Boulder



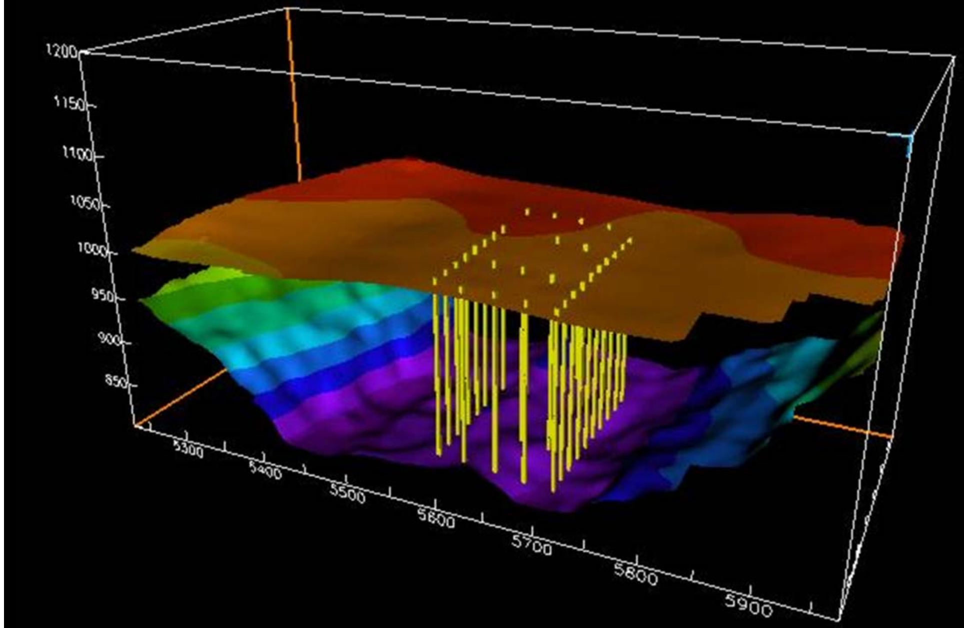
Textbook Diagram

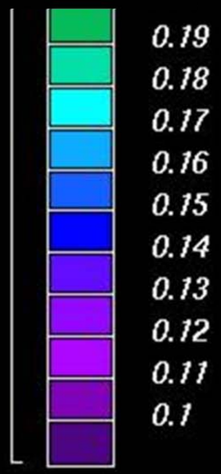
Observed flow: Plan and profile

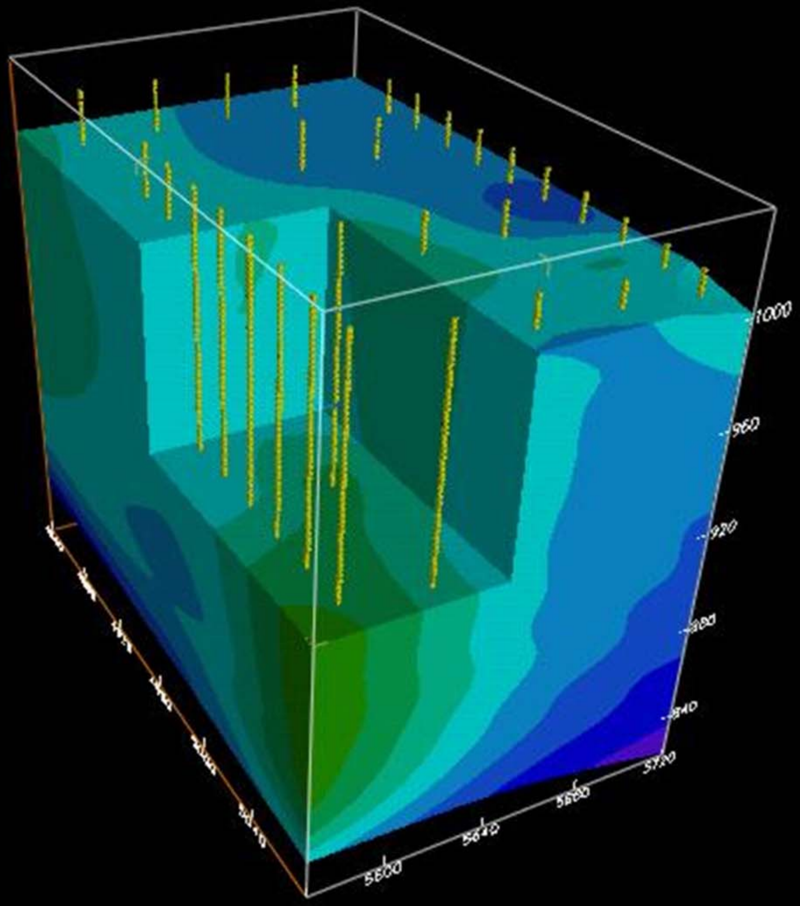
- Plan View
  - parabolic
- Vertical Profile
  - exponential
  - non-zero at the bed



FLOW BEHAVIOR: BULK FLOW



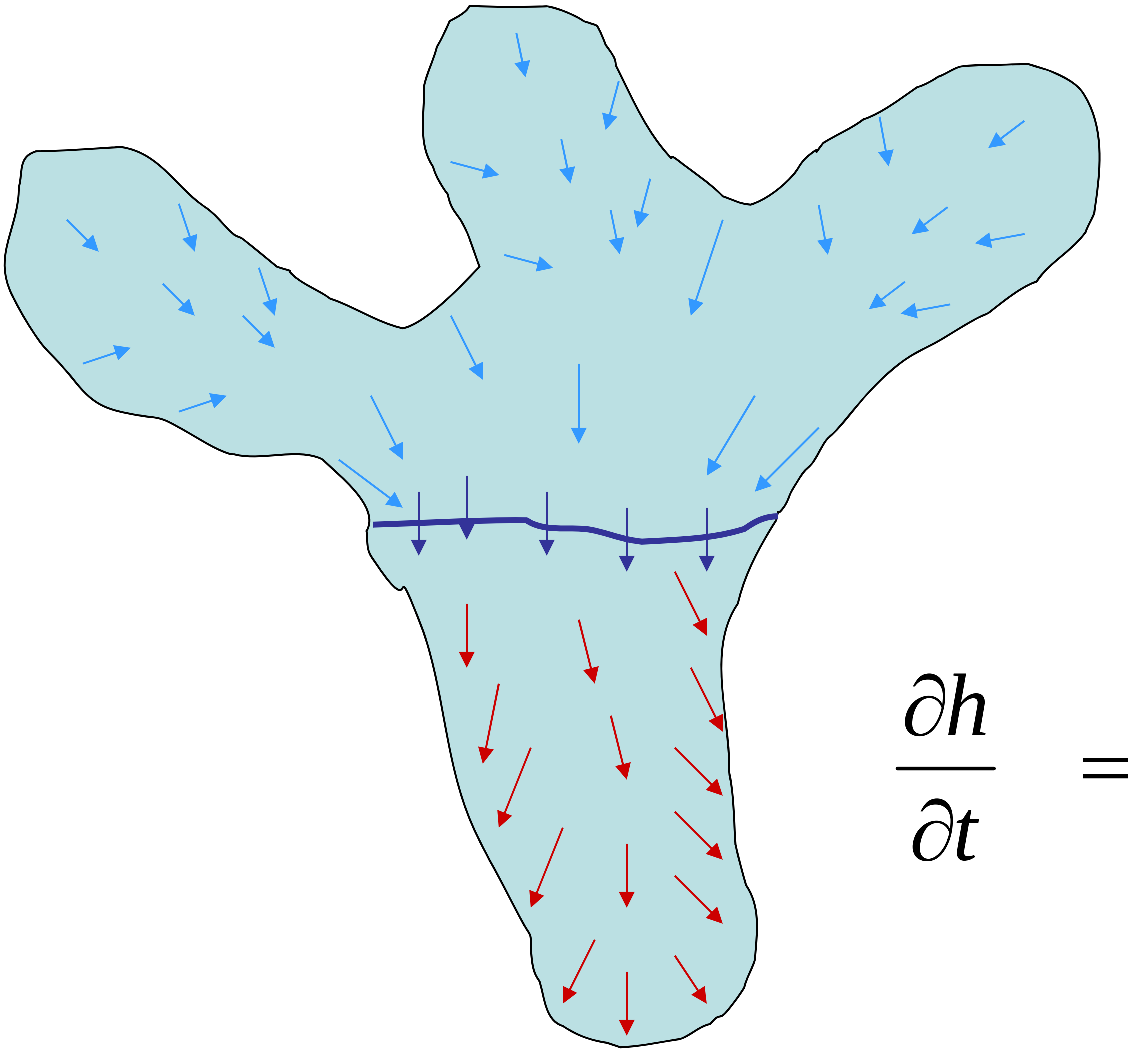




Worthington Glacier
UWyo, UC-Boulder

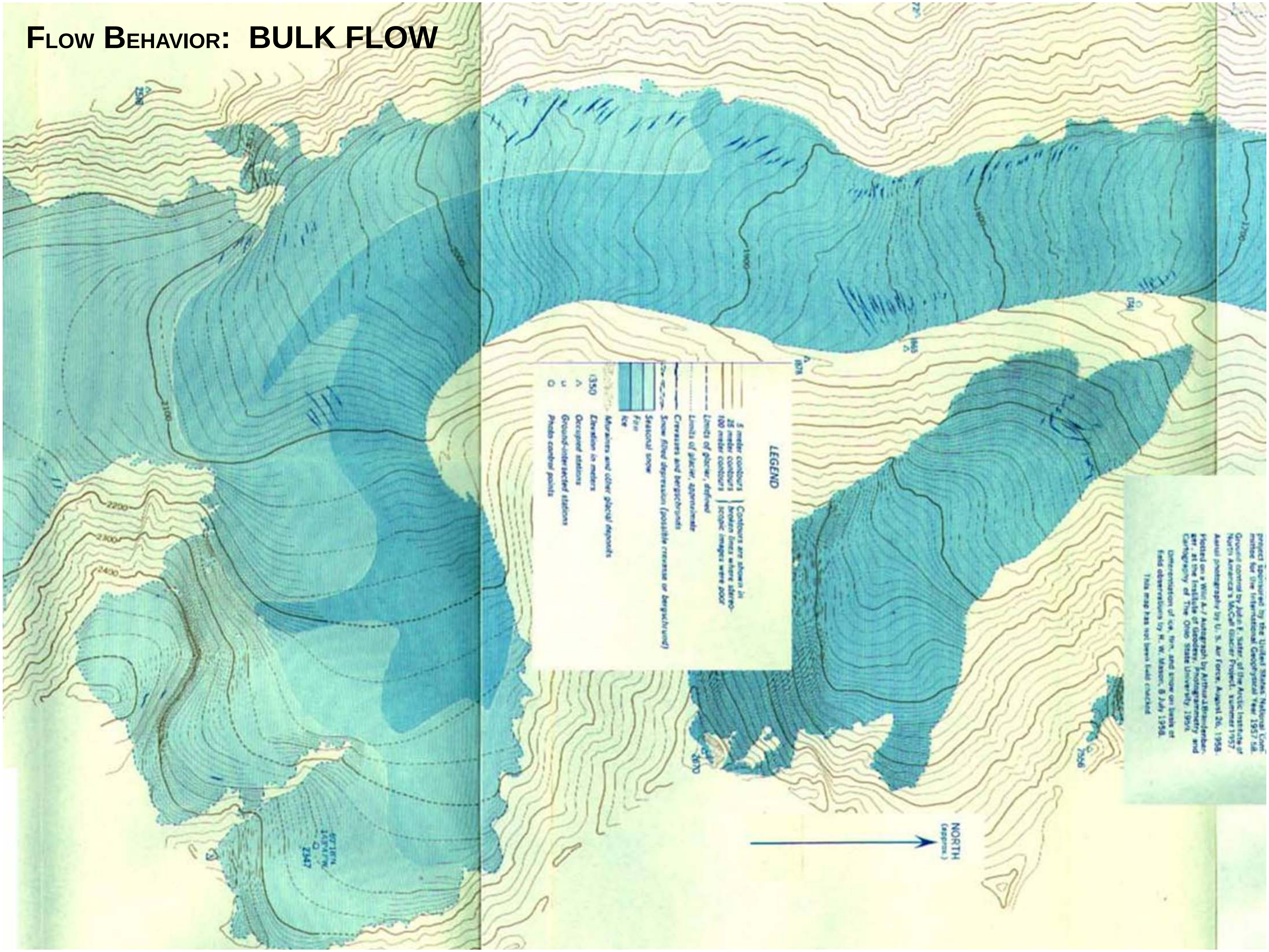
Flow Behavior: BULK FLOW

Surface Flow Direction



$$\frac{\partial h}{\partial t} = \dot{b} + \nabla q$$

FLOW BEHAVIOR: BULK FLOW



project sponsored by the United States National Committee for the International Geophysical Year 1957-58.

Ground control by John E. Sater, of the Arctic Institute of North America's McCall Glacier Project, summer 1957.

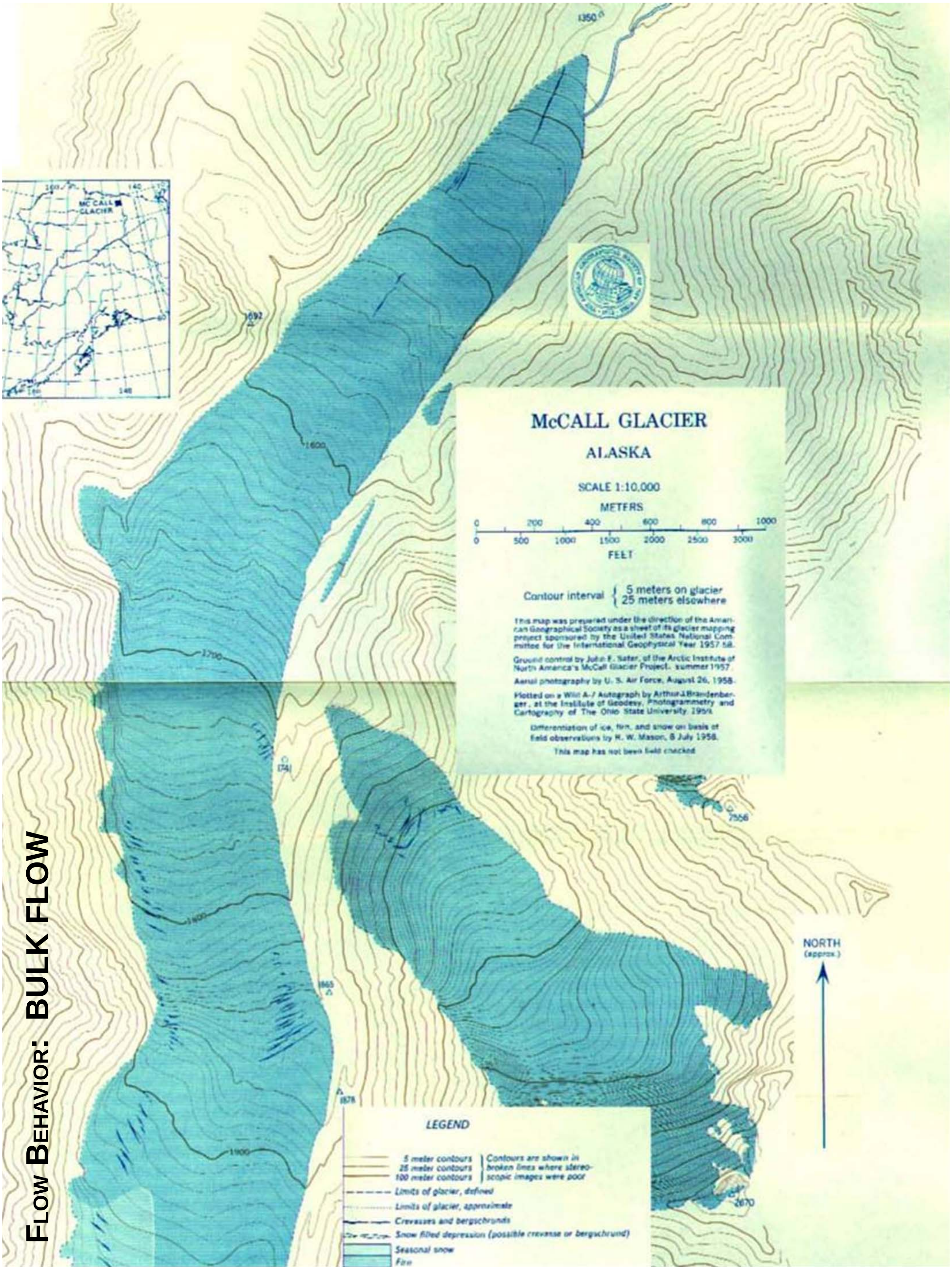
Aerial photography by U. S. Air Force, August 26, 1958.

Plotted on a Wild A-7 Autograph by Arthur J. Brandenberger, at the Institute of Geodesy, Photogrammetry and Cartography of The Ohio State University, 1959.

Differentiation of ice, firn, and snow on basis of field observations by R. W. Mason, 8 July 1958.

This map has not been field checked

FLOW BEHAVIOR: BULK FLOW



McCALL GLACIER

ALASKA

SCALE 1:10,000

Contour interval { 5 meters on glacier / 25 meters elsewhere

This map was prepared under the direction of the American Geographical Society as a sheet of its glacier mapping project sponsored by the United States National Committee for the International Geophysical Year 1957-58.

Ground control by John F. Sater, of the Arctic Institute of North America's McCall Glacier Project, summer 1957.

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Balance velocity and discharge

- Discharge thru each cross-section:

  $Q\ (x) = \Sigma\ (\ w_x\ b_x\ )$

- Balance (avg) velocity:

  $v\ (x) = Q\ (x)\ /\ A\ (x)$

- (wedge diagram)
  - steeper mass balance gradient → more mass transfer → higher Q and v

FLOW BEHAVIOR: BULK FLOW

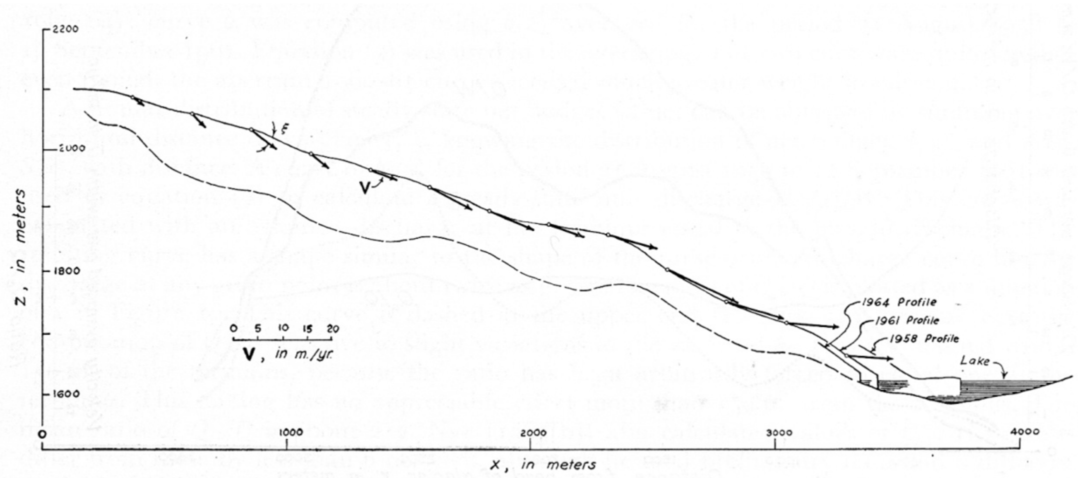


Fig. 9. Longitudinal profile showing surface velocity vectors and calculated bedrock profile. Vertical distances are exaggerated 2·5 times. Bedrock profile is calculated on the assumption that $\bar{\bar{u}} = \bar{u}$. *Surface and bedrock profiles and surface velocity vectors represent averages taken over the width of the glacier*

Submergence and emergence velocity

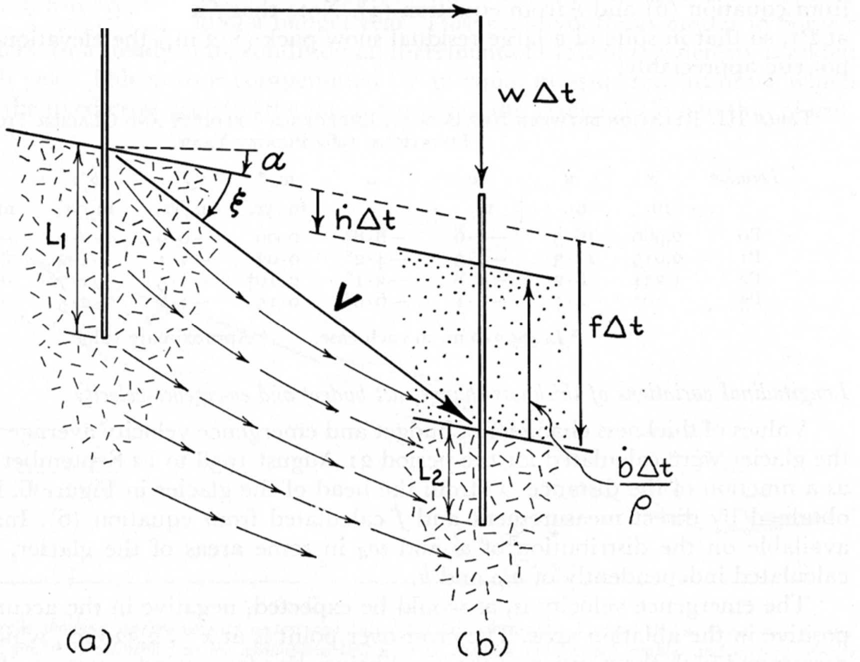
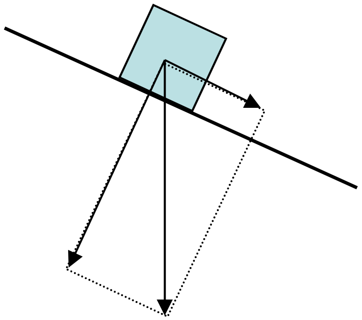


Fig. 8. Diagrammatic longitudinal section at glacier surface showing one stake at beginning (a) and end (b) of one budget year Δt, *and several velocity components. Curving arrows in the firn (random dashes) show approximate paths of flow in time and space, but are neither stream lines nor streak lines. Snow added during budget year is indicated by dotted area*

Meier and Tangborn, 1965

How do glaciers move?

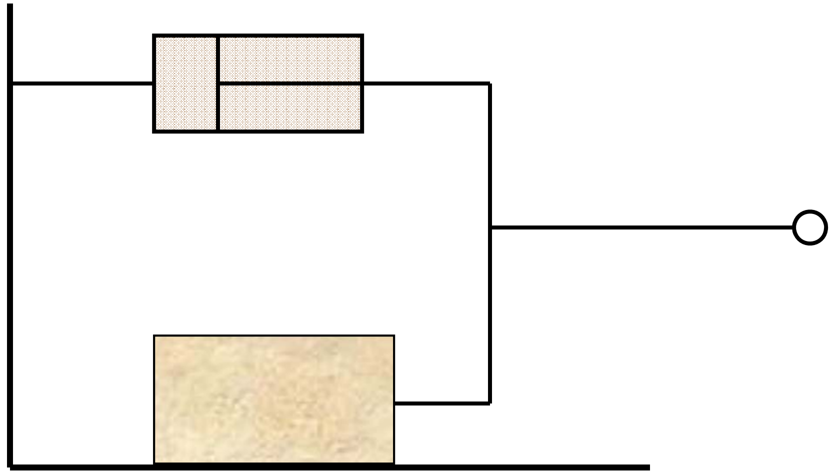
Driving Force: $\tau_b = \rho g h \sin\alpha$



Response:

1. Deformation
2. Sliding
3. Substrate deformation

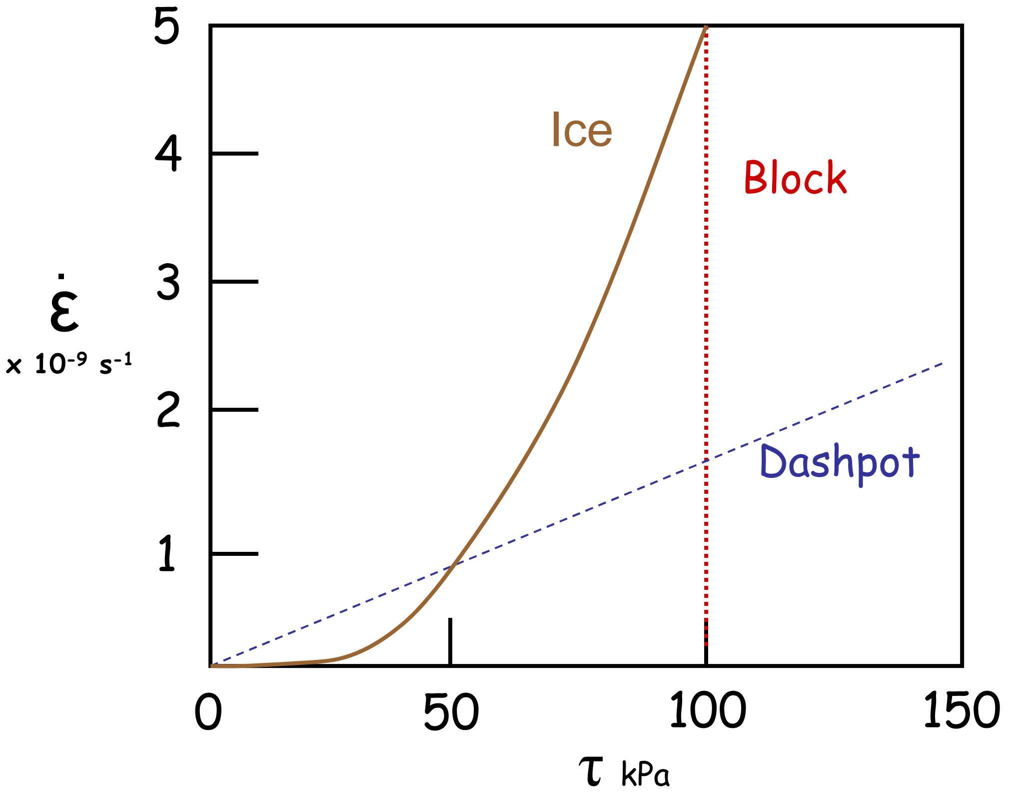
Deformation: Ice is a visco-plastic



$$\dot{\varepsilon} = A\tau^{n}$$

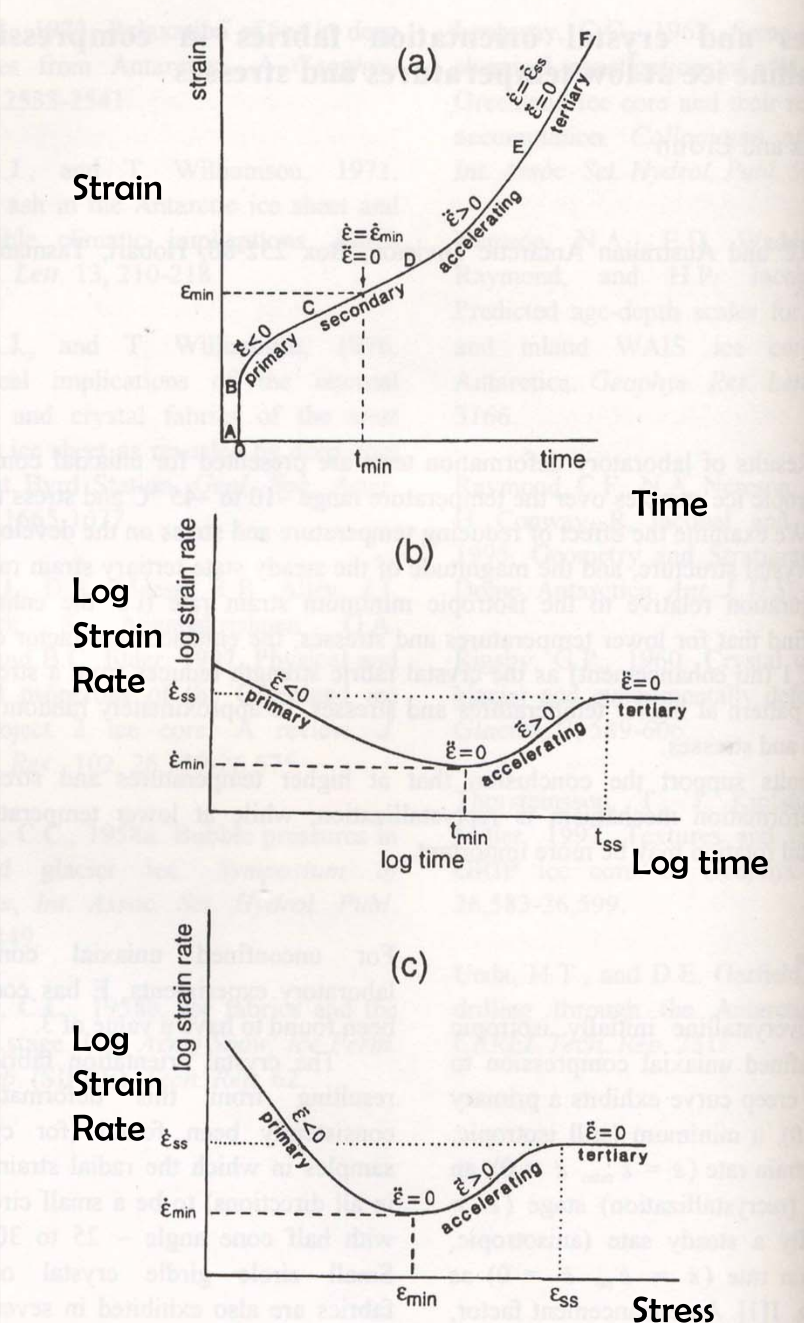
$A \sim 10^{-16}\ s^{-1}\ kPa^{-3}$

$n = 3$



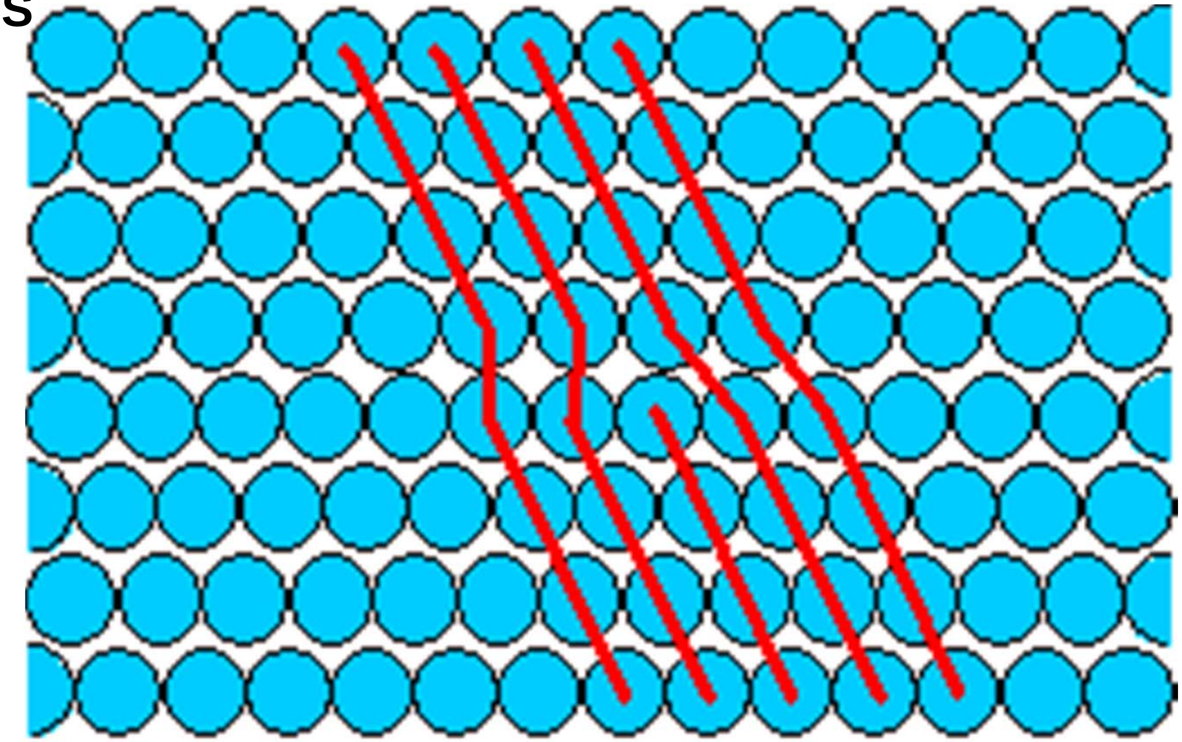
FLOW BEHAVIOR: MICROPHYSICS

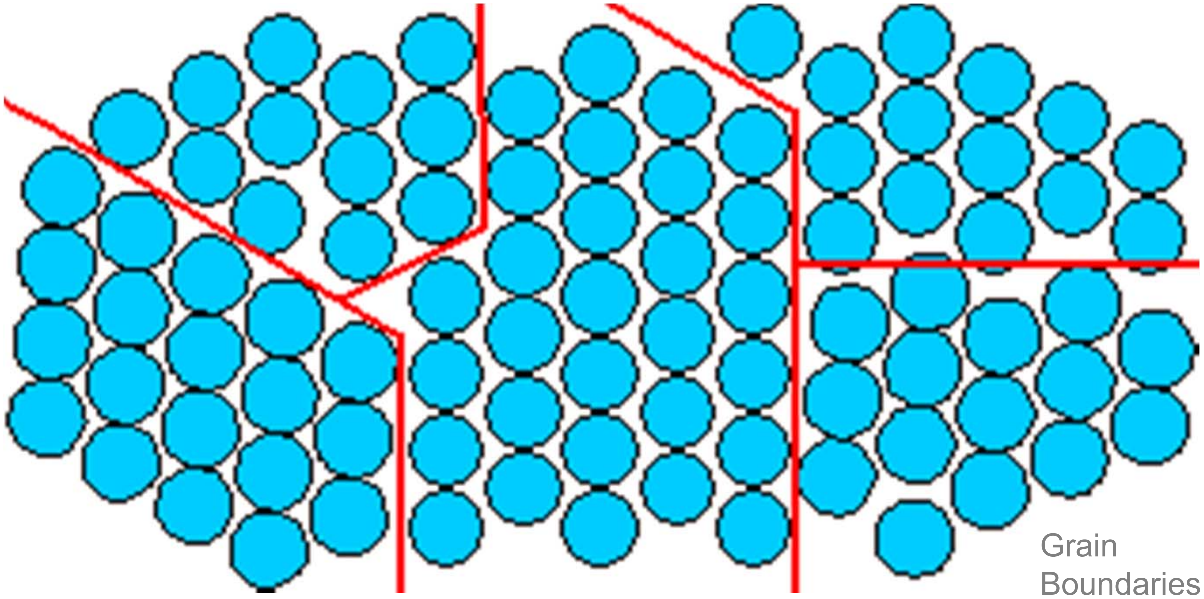
Initial Deformation Processes



FLOW BEHAVIOR: MICROPHYSICS

Deformation Through Dislocations



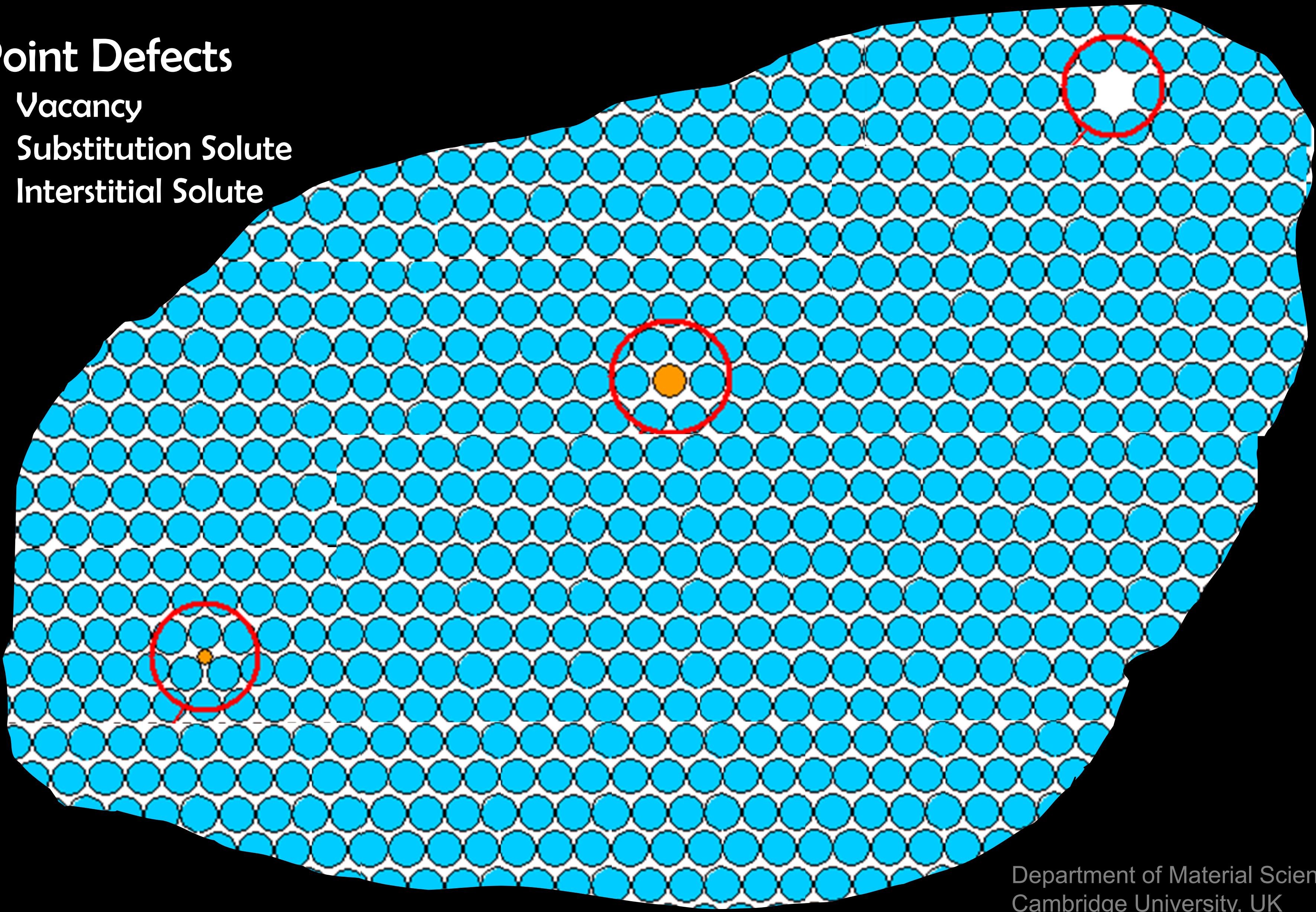


Grain Boundaries

Department of Material Science
Cambridge University, UK

Point Defects

- Vacancy
- Substitution Solute
- Interstitial Solute



Department of Material Science
Cambridge University, UK

FLOW BEHAVIOR: MICROPHYSICS

Video Examples of Motion

http://www.msm.cam.ac.uk/doitpoms/tlplib/dislocations/index.php

Dislocation glide
Dislocation motion

Effects on rheology

Dust

Soluble impurities

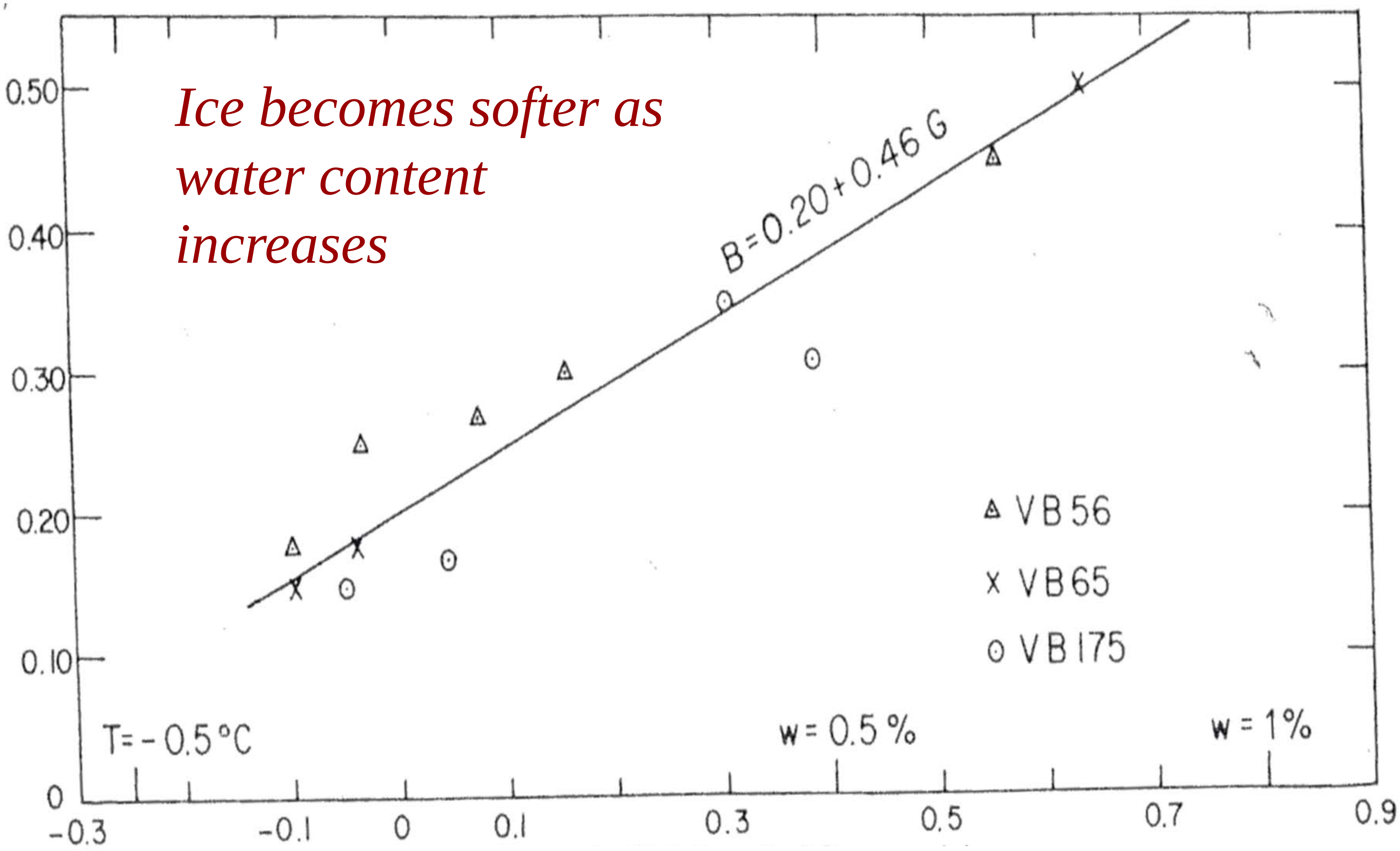
Crystal size

Crystal orientation

Temperature

	A
0 °C	6.8×10^{-15}
-45 °C	7.3×10^{-18}

Effect of water content on rheology



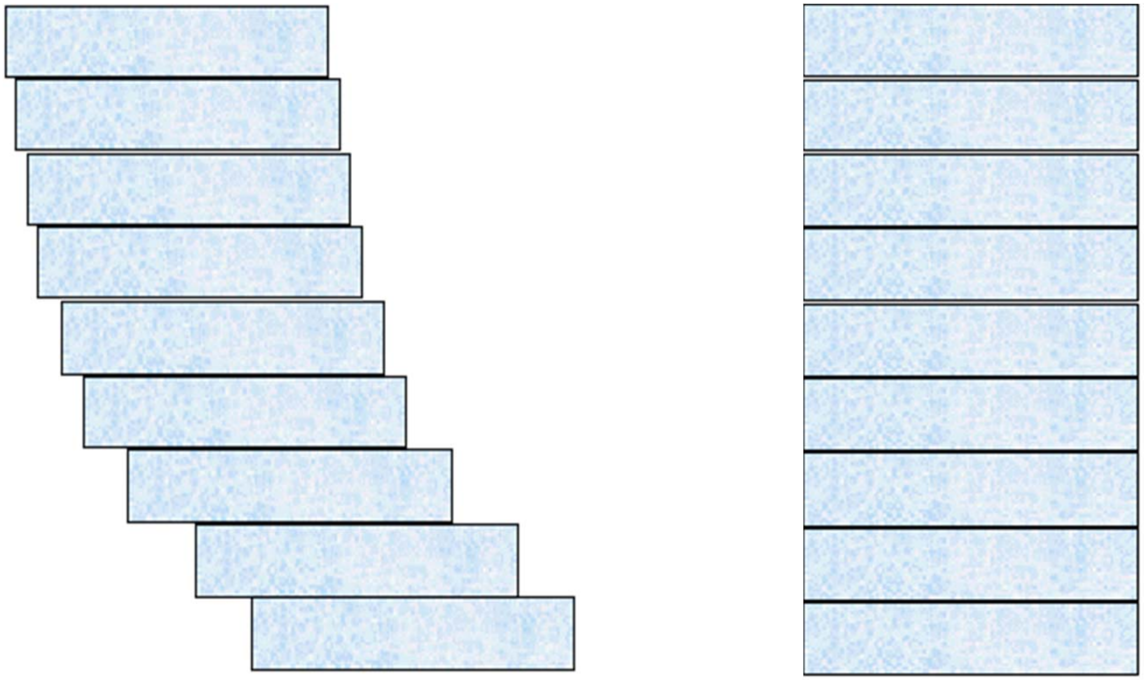
Ice becomes softer as water content increases

softness

Water content

FLOW BEHAVIOR: MACROSCALE

Ice Deformation



Univ Aber.

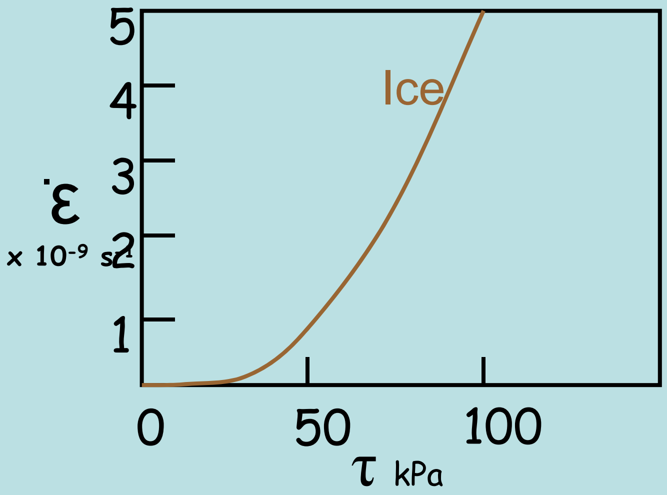
FLOW BEHAVIOR: MACROSCALE MODEL

$$\dot{\varepsilon} = A\tau^{n}$$

$$\tau = \rho g h \sin\alpha$$

$$\dot{\varepsilon} = A\tau^{3}$$

$A \sim 10^{-16}\ s^{-1}\ kPa^{-3}$



$$\dot{\varepsilon} = \frac{1}{2}\frac{du}{dz}$$

Horizontal velocity

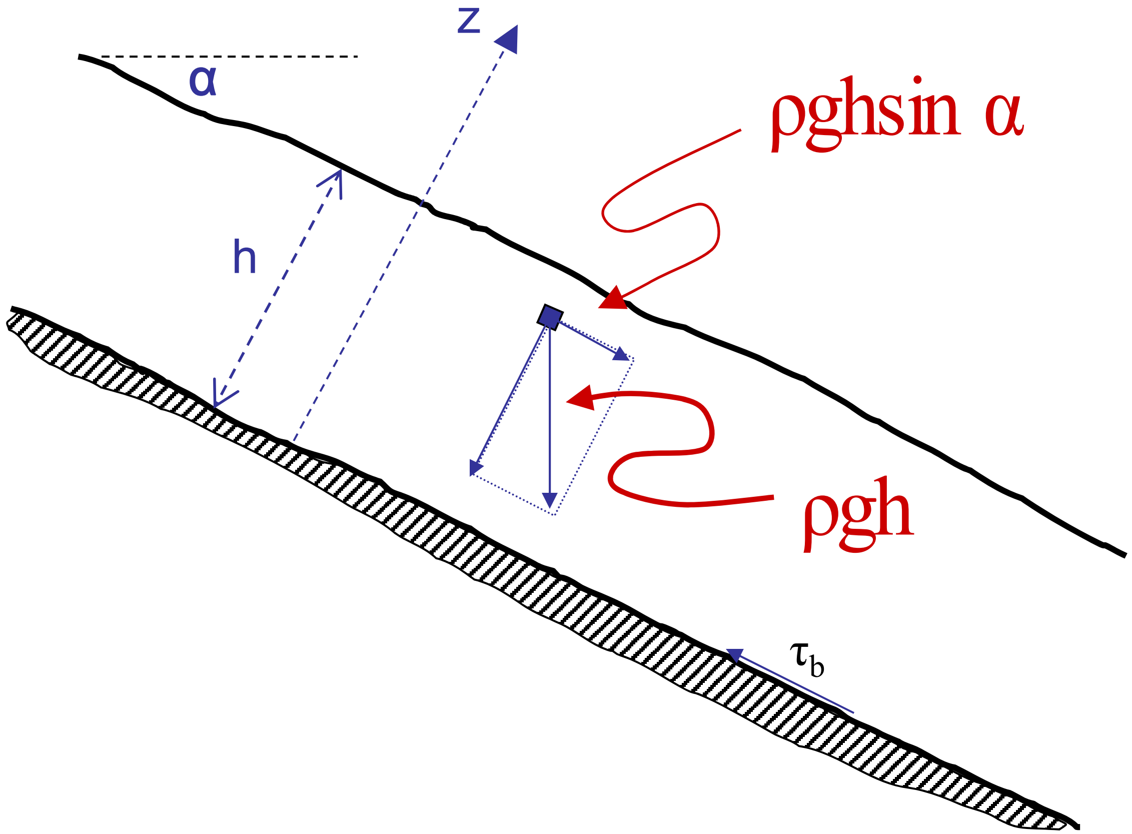
Vertical Coordinate

FLOW BEHAVIOR: MACROSCALE MODEL

Steady Flow of a Glacier

$$\frac{1}{2}\frac{du}{dz} = A\left[\rho g h \sin\alpha\right]^3$$

(h–z)

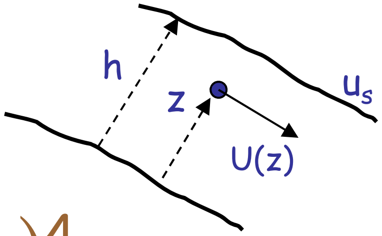


From Paterson, 1994

Flow Behavior: MACROSCALE MODEL

$$\frac{1}{2}\frac{du}{dz} = A\left[\rho g(h-z)\sin\alpha\right]^3$$

Integrate from z to h, therefore from u(z) to u_s

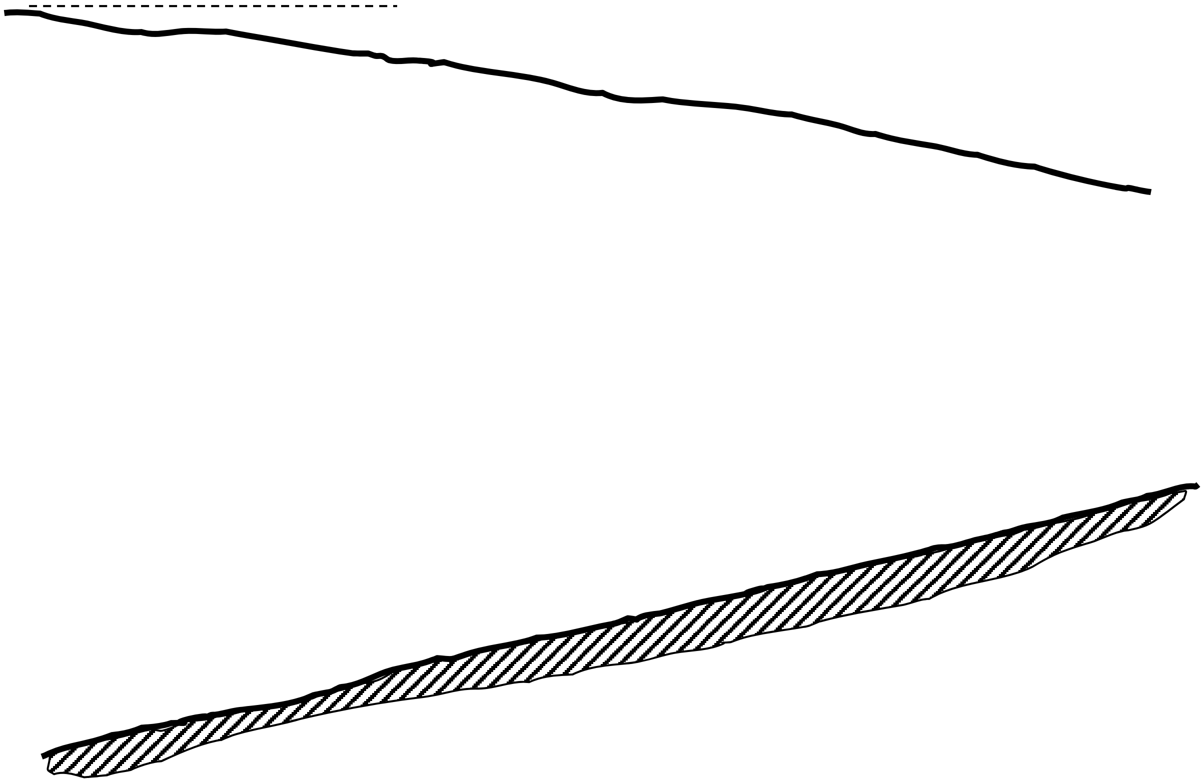


$$u_s - u(z) = \frac{2A}{4}(\rho g\sin\alpha)^3(h-z)^4$$

$$u_s - u_b = \frac{A}{2}(\rho g\sin\alpha)^3 h^4$$

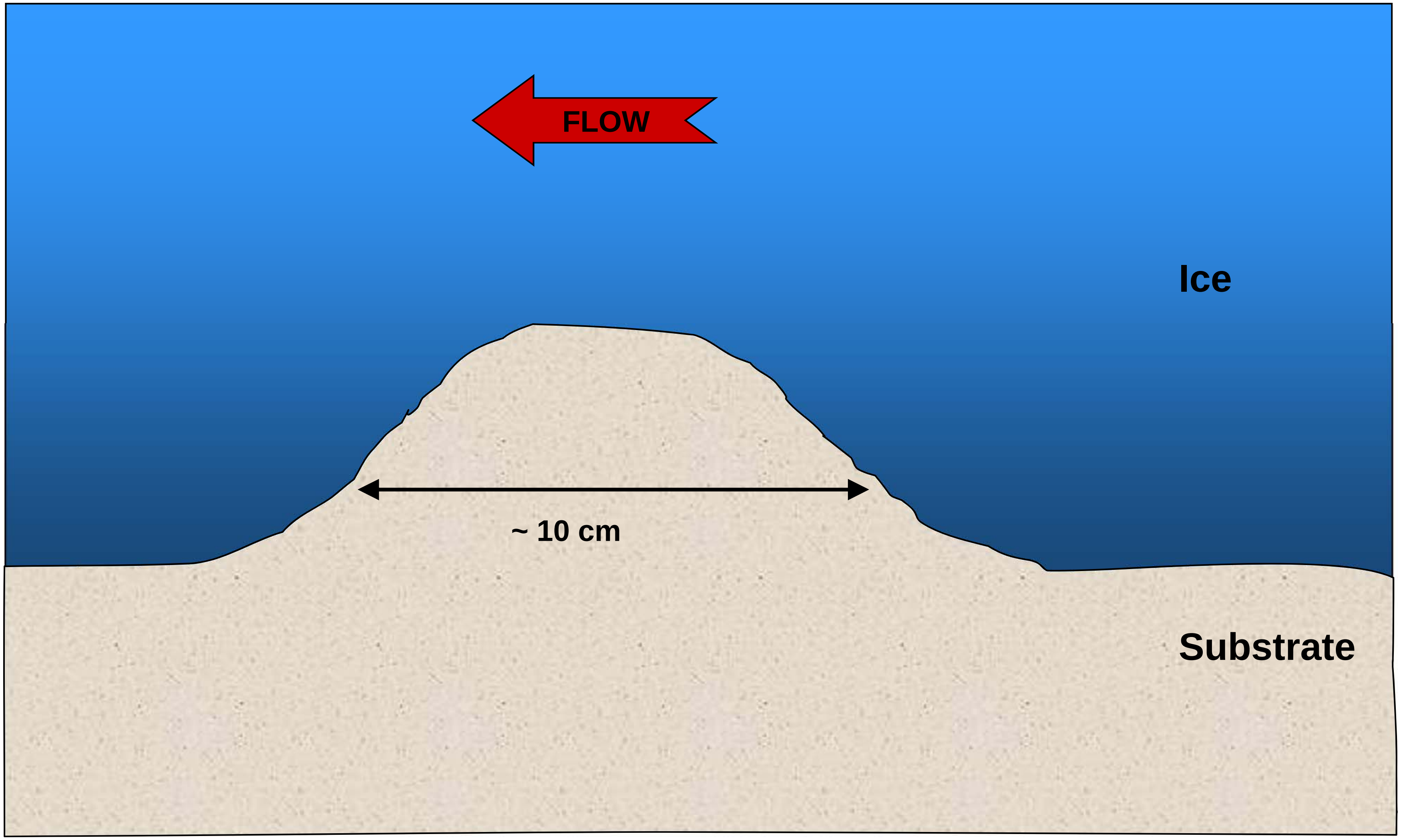
$$u_s = \underbrace{\frac{A}{2}(\rho g\sin\alpha)^3 h^4}_{\text{Deformation}} + \underbrace{u_b}_{\text{Sliding and/or bed deformation}}$$

Flow up an Adverse Slope



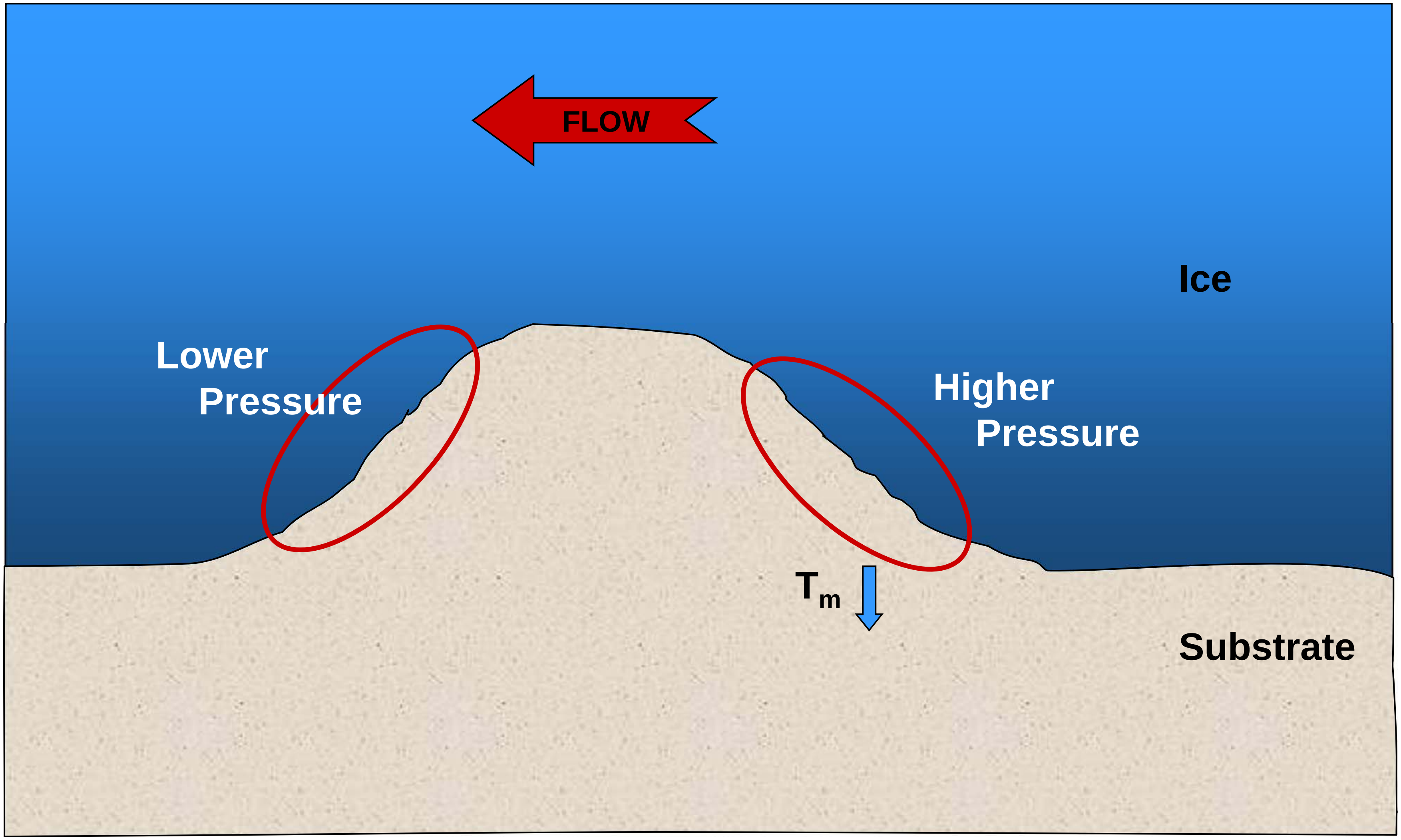
FLOW BEHAVIOR: **BASAL SLIDING**

Regelation : requires a film of water

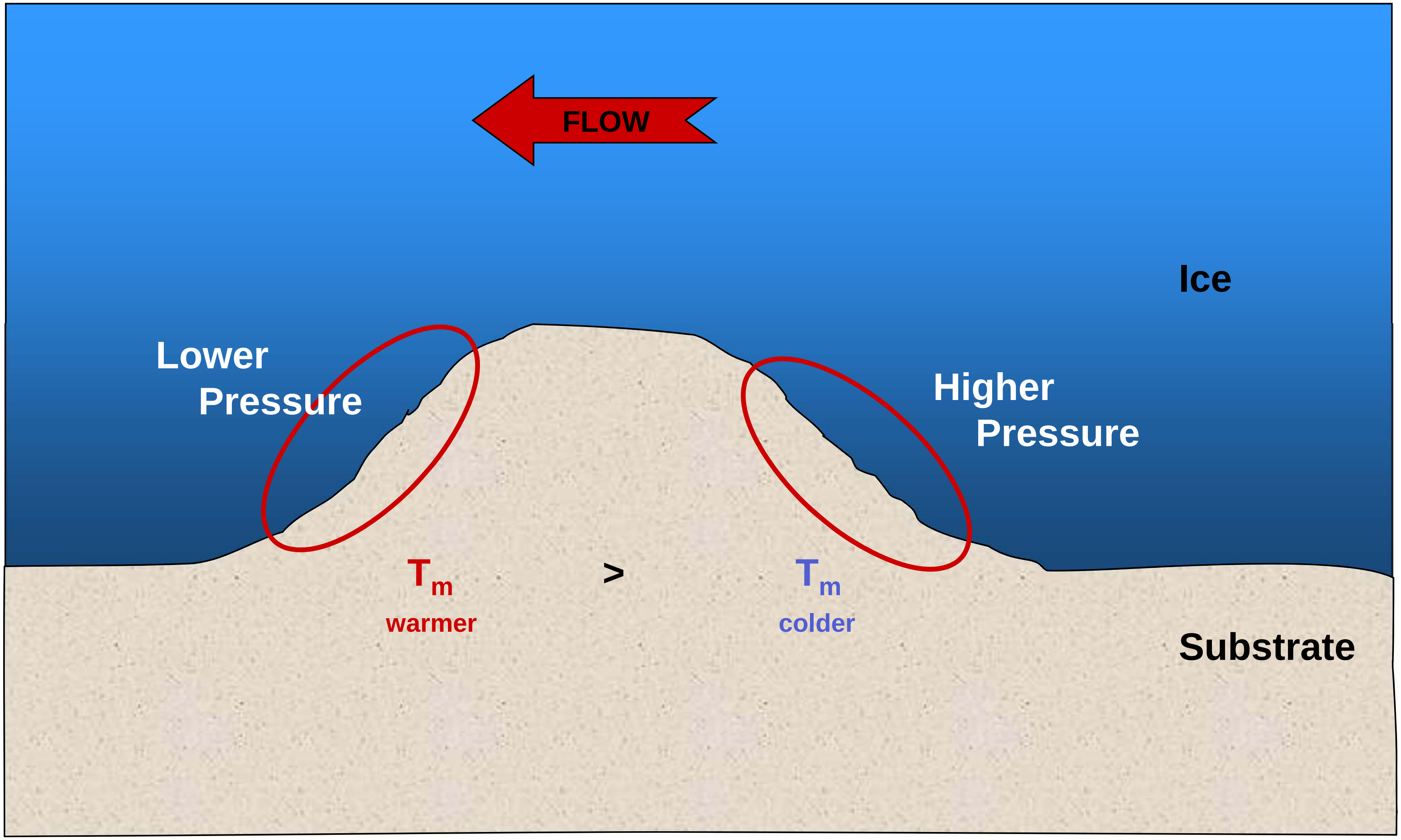


FLOW BEHAVIOR: BASAL SLIDING

Regelation : requires a film of water

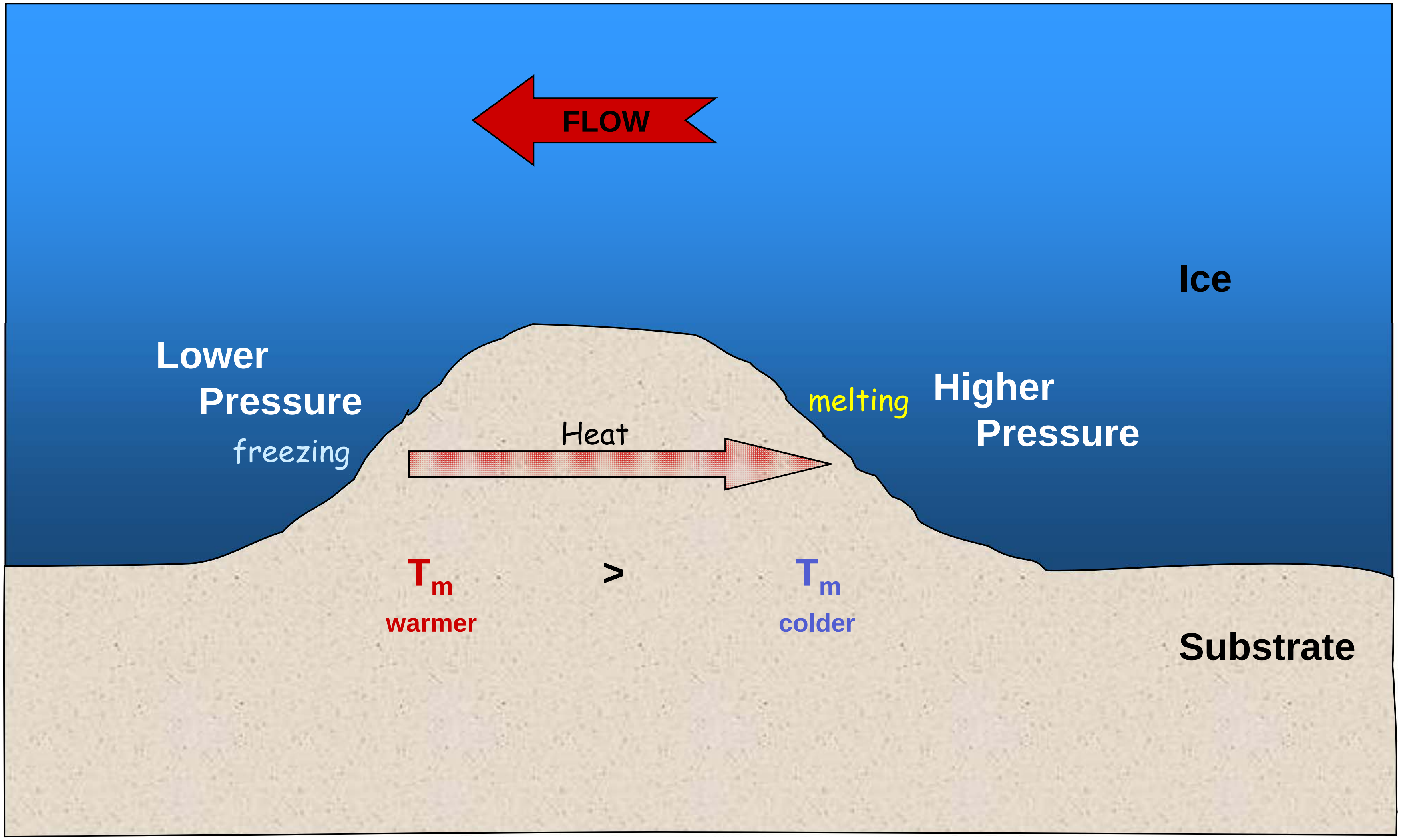


Regelation : requires a film of water

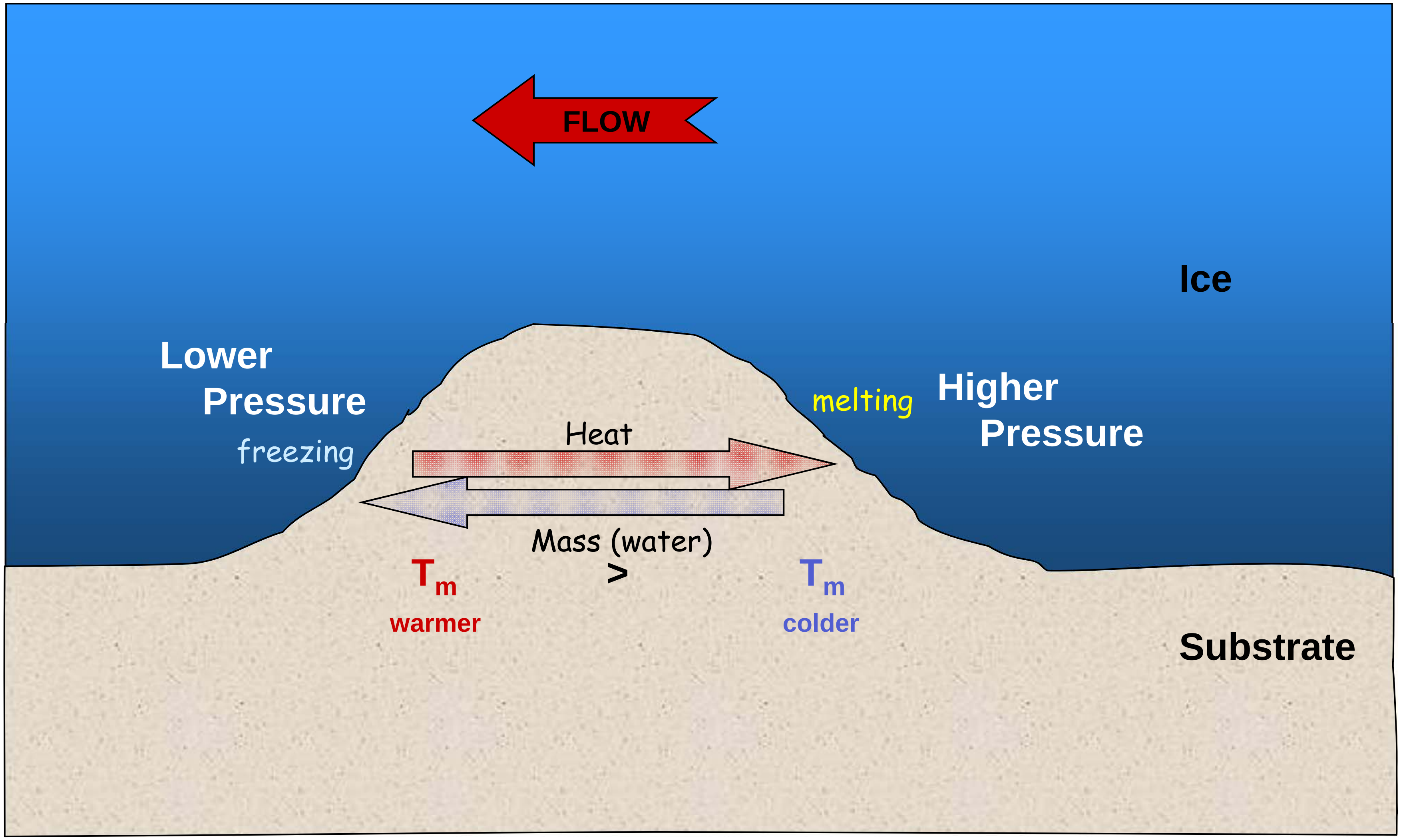


Basal Sliding

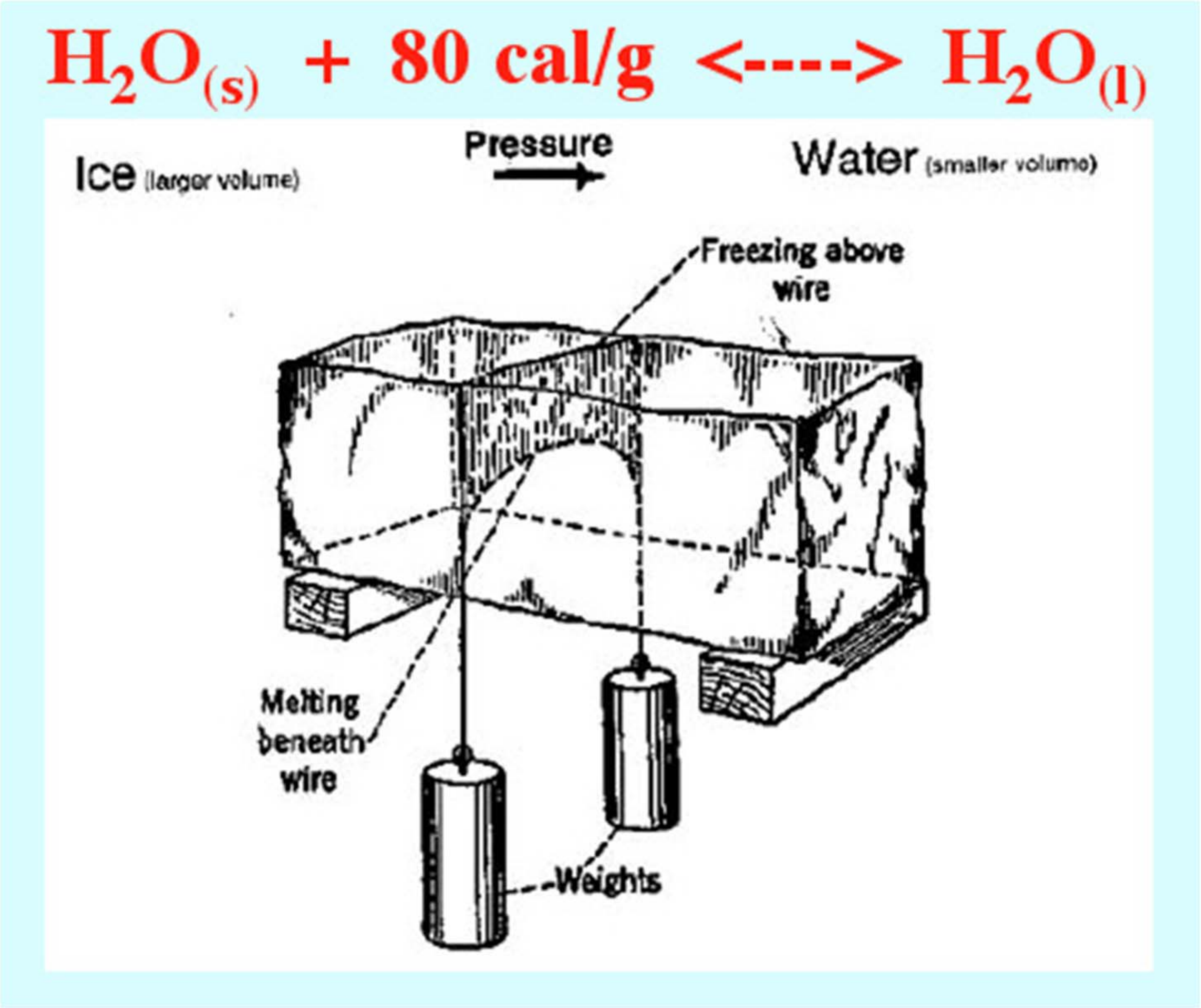
Regelation : requires a film of water



Regelation : requires a film of water



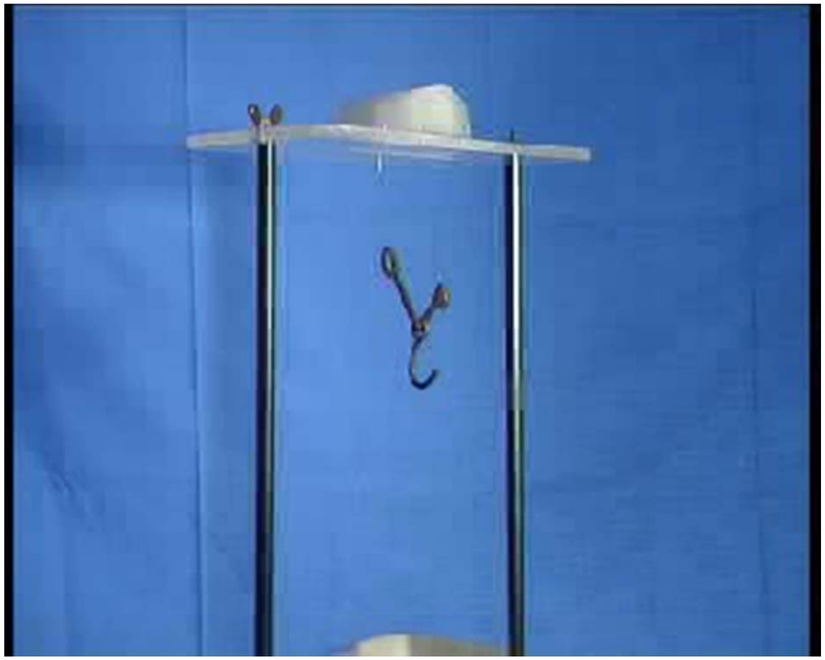
FLOW BEHAVIOR: **REGELATON PROCESS**



$$H_2O_{(s)} + 80\ \text{cal/g} \longleftrightarrow H_2O_{(l)}$$

FLOW BEHAVIOR: REGELATON PROCESS

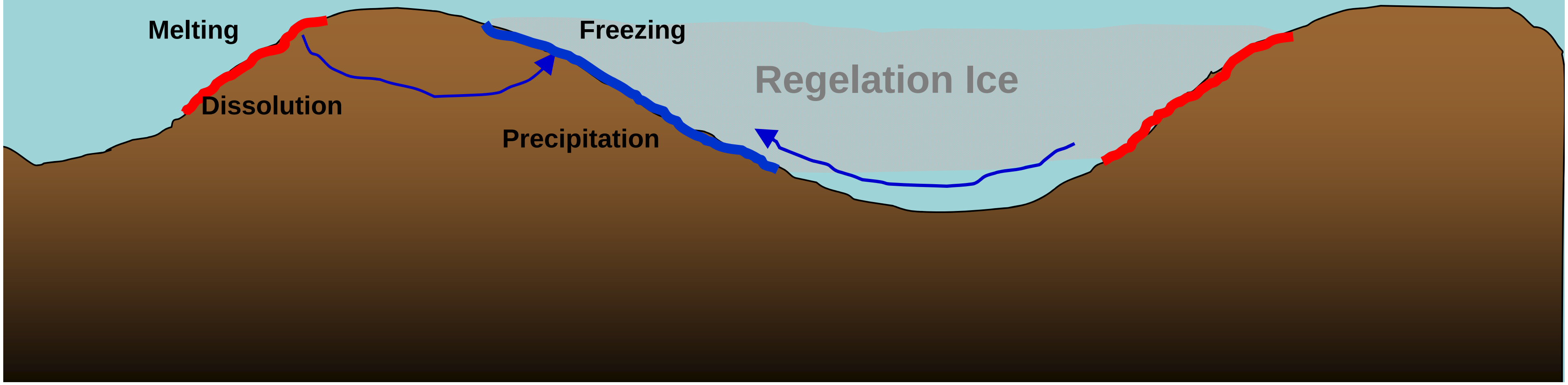
Regelation Experiment ……in GERMAN!



Regelation film

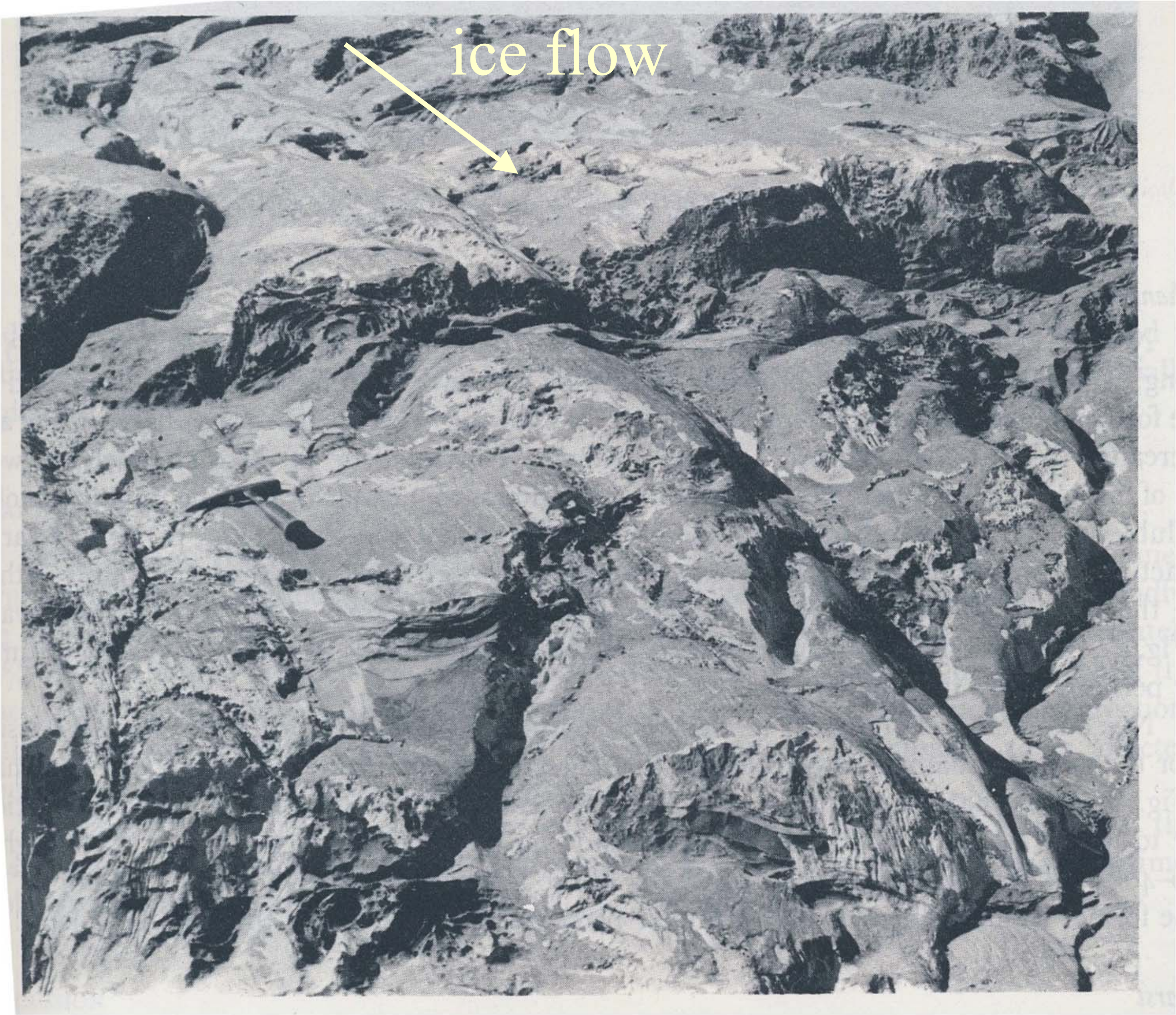
Sliding at the
bed involves
a film of water,
which may
contain solutes.

Glacier Flow



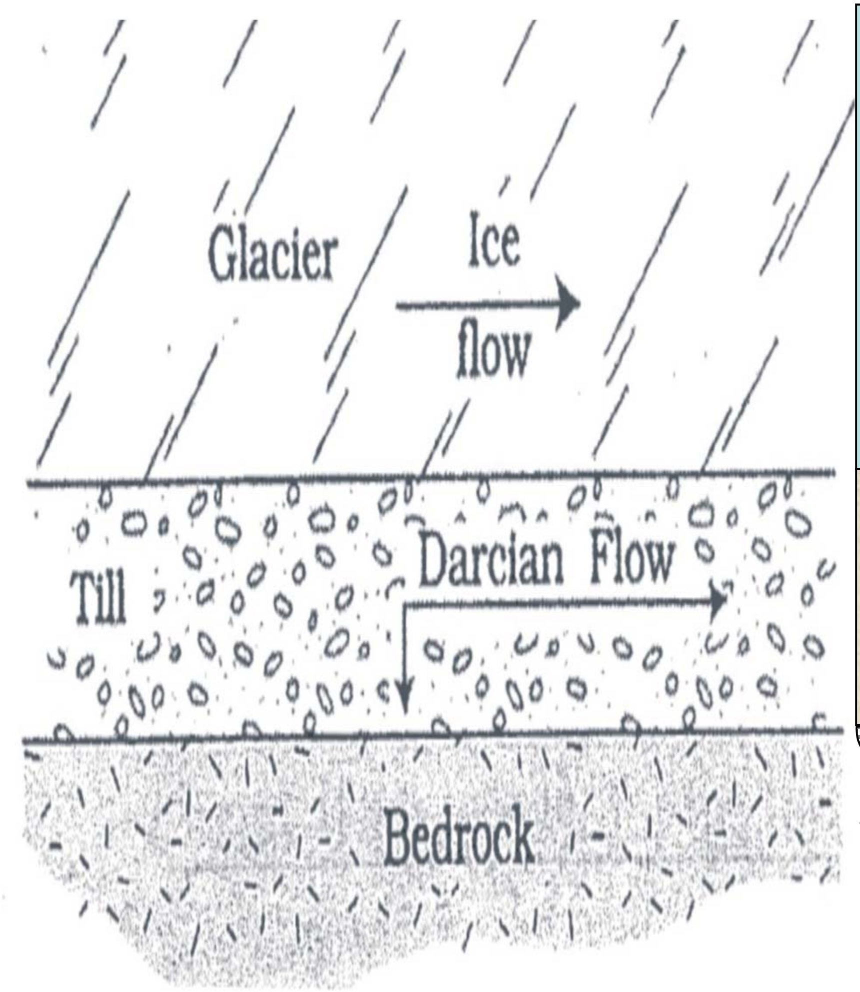
Insight from geomorphology

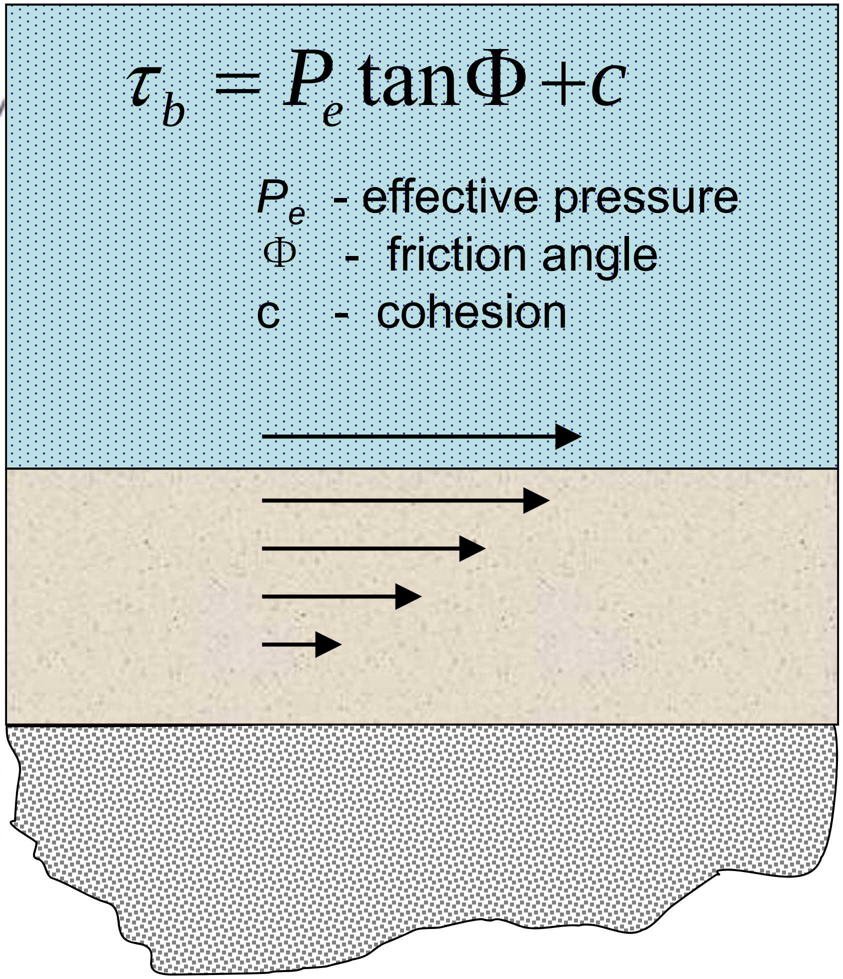
Features exposed on recently deglaciated carbonate bedrock provide insights into geometry of subglacial drainage network.



FLOW BEHAVIOR: SUBGLACIAL TILL

Substrate Deformation   Subglacial Till





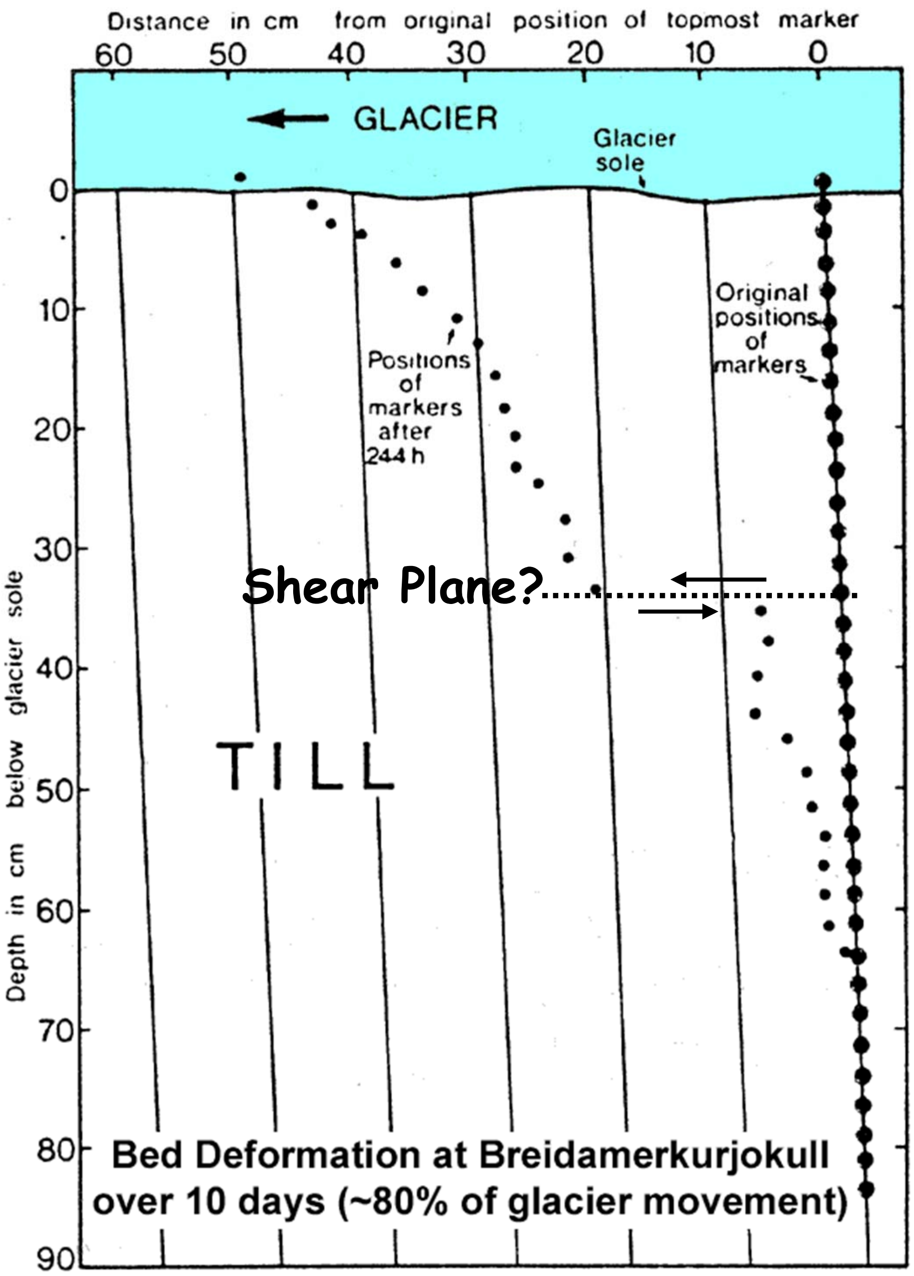
$$\tau_b = P_e \tan\Phi + c$$

P_e - effective pressure
Φ - friction angle
c - cohesion

FLOW BEHAVIOR: **SUBGLACIAL TILL**

Observed bed deformation

- Inferred from structures in till
- Measured from markers emplaced in basal sediment and recovered



Bed Deformation at Breidamerkurjokull over 10 days (~80% of glacier movement)

Boulton et al

$$u_s = \underbrace{\frac{A}{2}(\rho g \sin\alpha)^3 h^4}_{\text{Deformation}} + \underbrace{u_b}_{\text{Sliding and/or bed deformation}}$$

Sliding

$$u_b = \frac{k\tau_b}{(\rho g h - P_w)^q}$$

P_w is the subglacial water pressure

Deformation of subglacial till

$$\tau_c = P_e \tan\Phi + c$$

P_e - effective pressure ($\rho gh-P_w$)

Φ - friction angle

c - cohesion

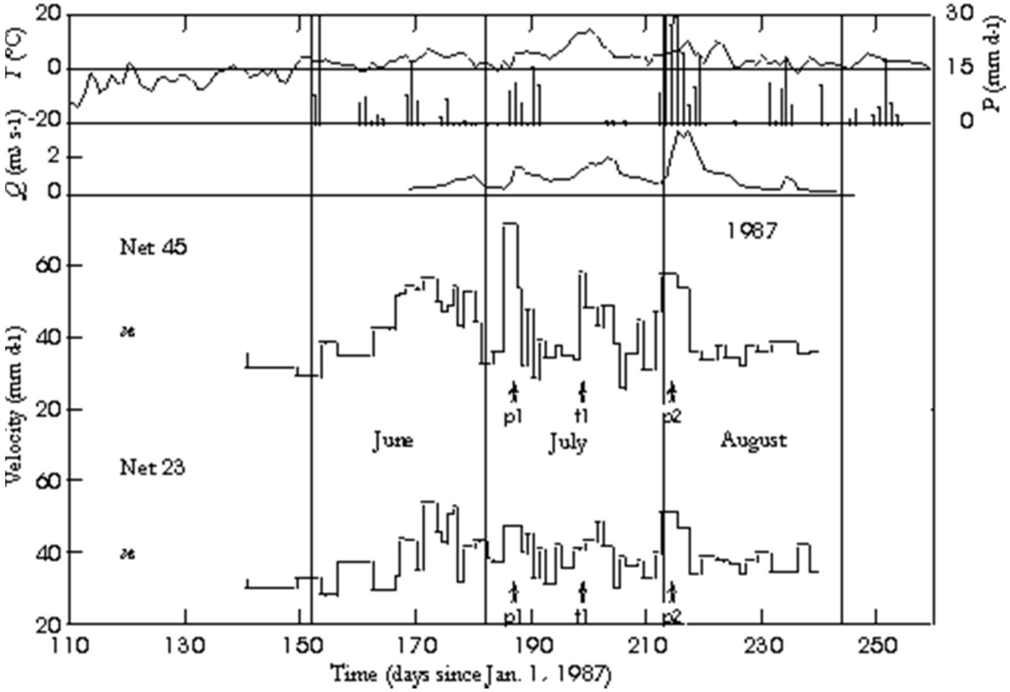
$$\dot{\varepsilon} = \frac{B(\tau_b - \tau_c)^a}{P_e}$$

B - constant

a - constant

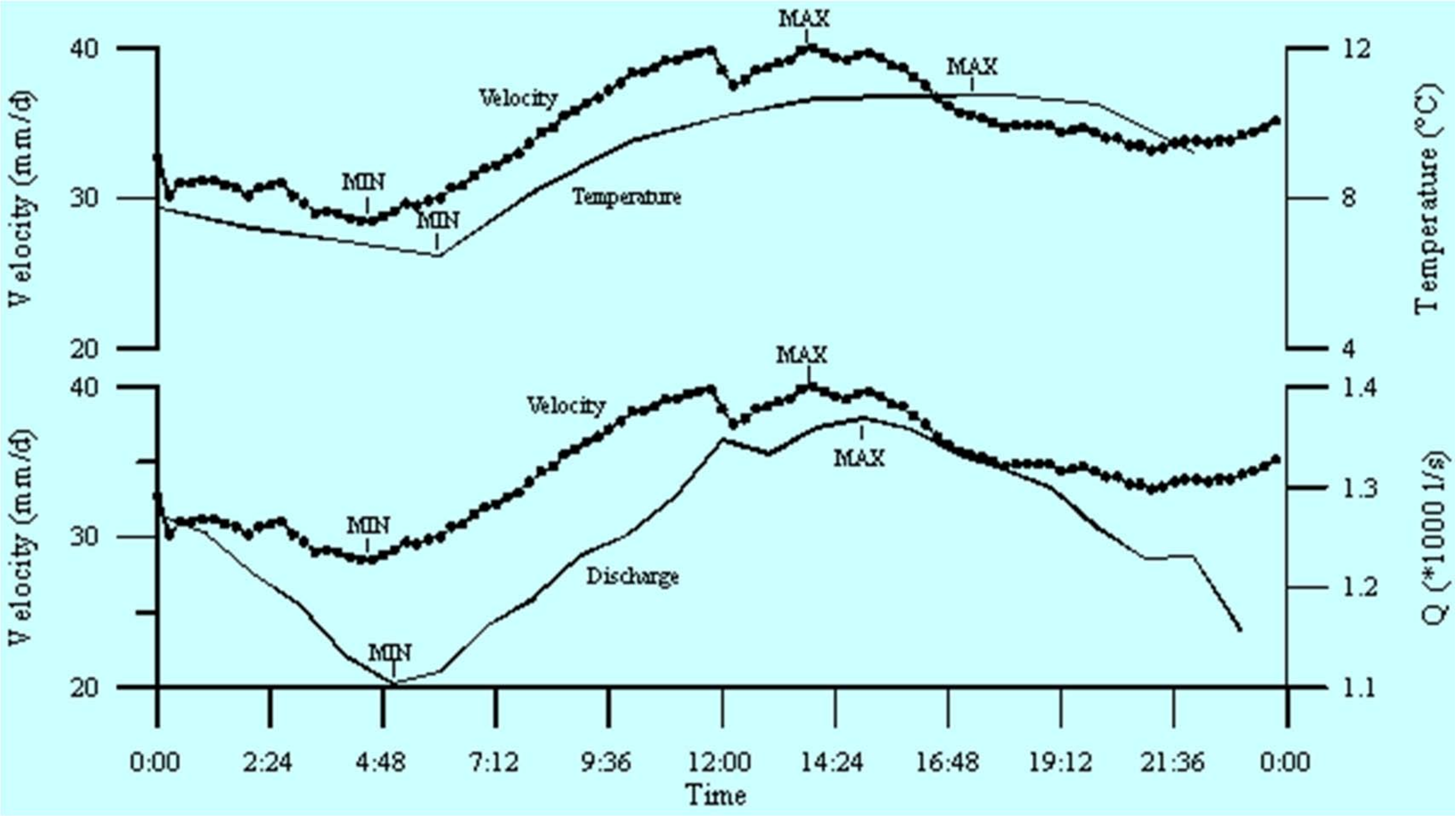
UNSTEADY FLOW: Seasonal Velocity Change

Storglaciären, Sweden



Peter Jansson
Stockholm University

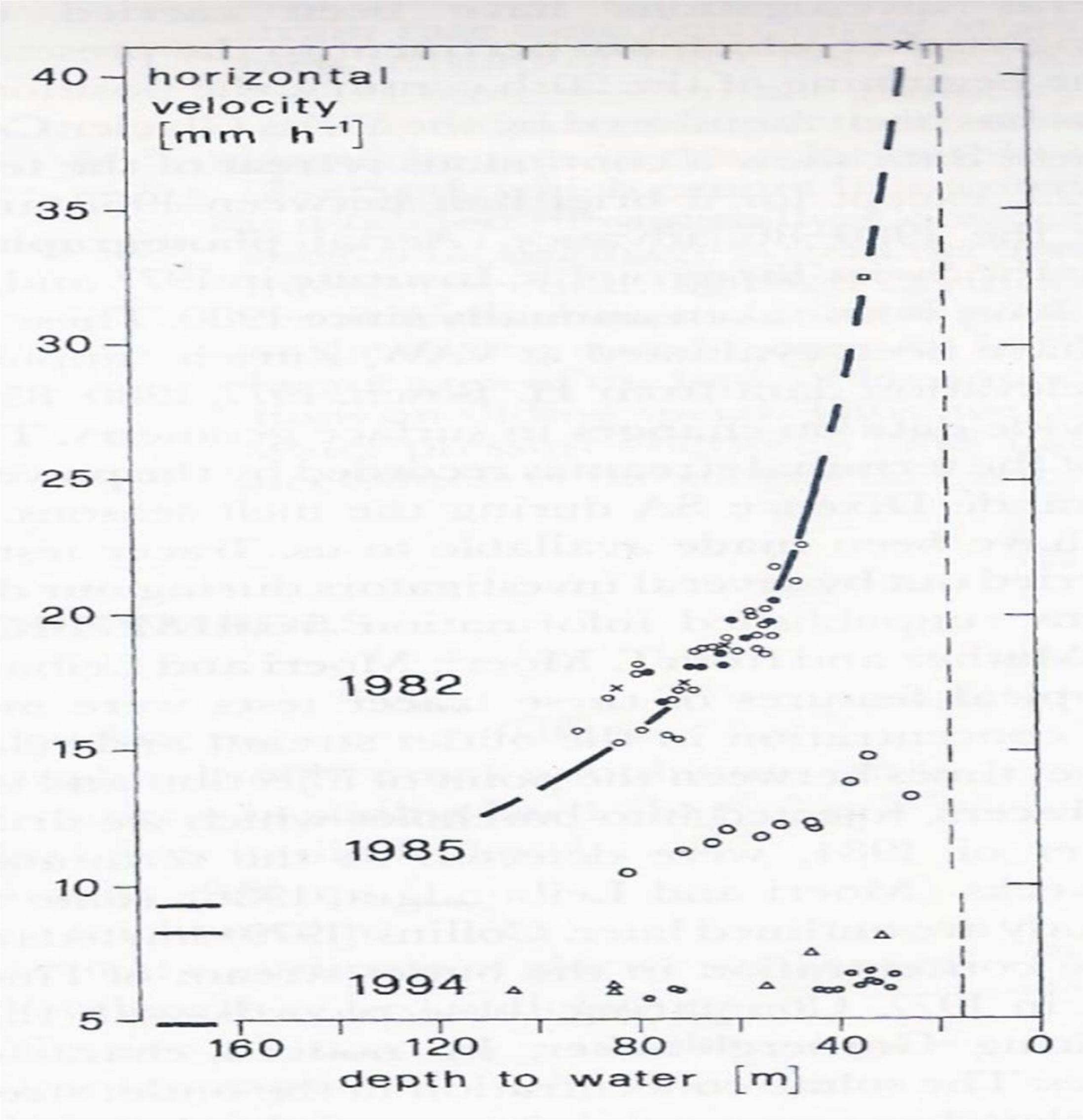
UNSTEADY FLOW: Daily Velocity Change



Storglaciären
Fredin, U. Stockholm

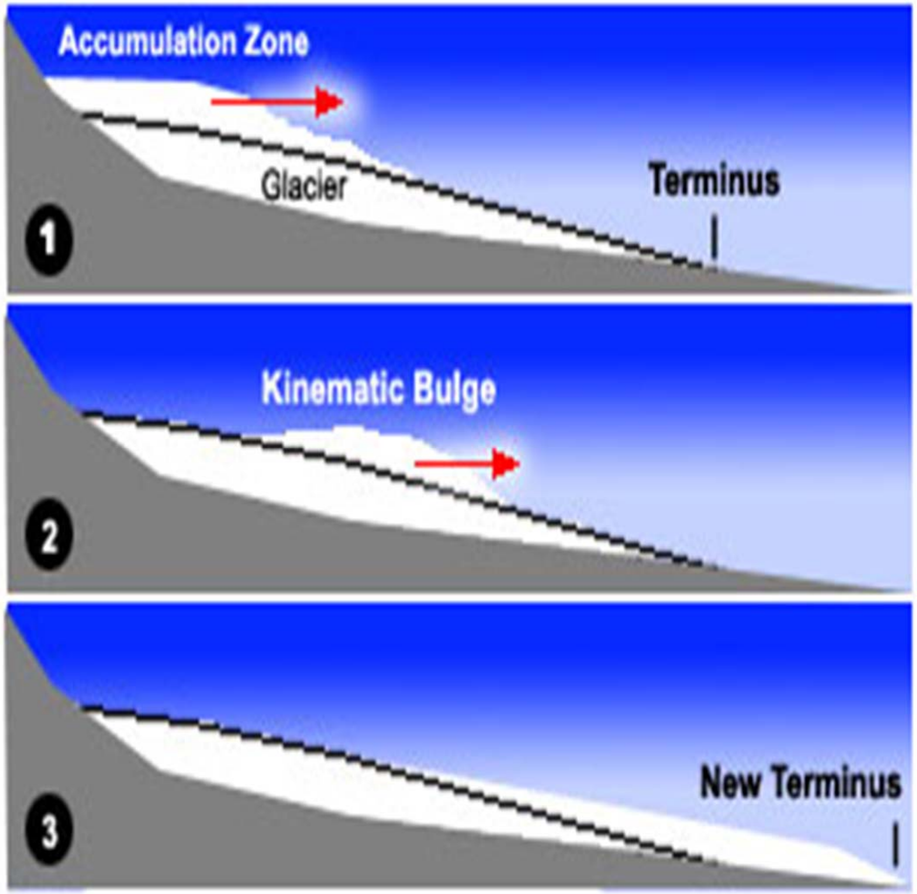
FLOW BEHAVIOR: **UNSTEADY FLOW**

Effects of water pressure on sliding



Kinematic Waves

- Thickening increases depth linearly
- Depth increases stress linearly
- Stress increases strain (flow) exponentially
- Therefore, a pulse propagates through the glacier

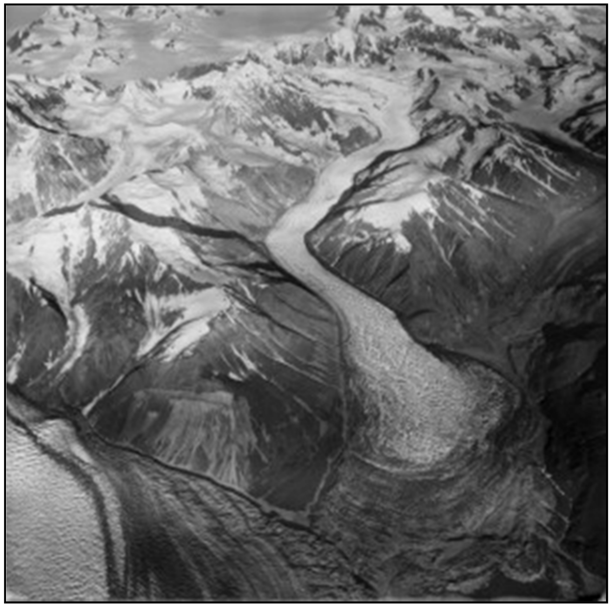


FLOW BEHAVIOR: UNSTEADY FLOW

Surging

VARIEGATED GLACIER

1963(?)

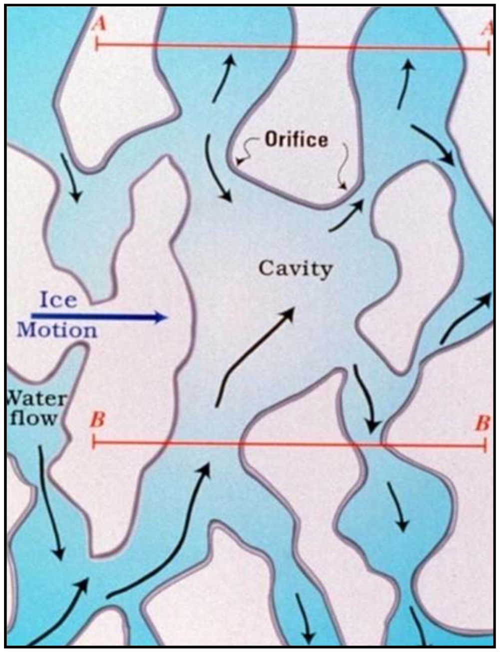


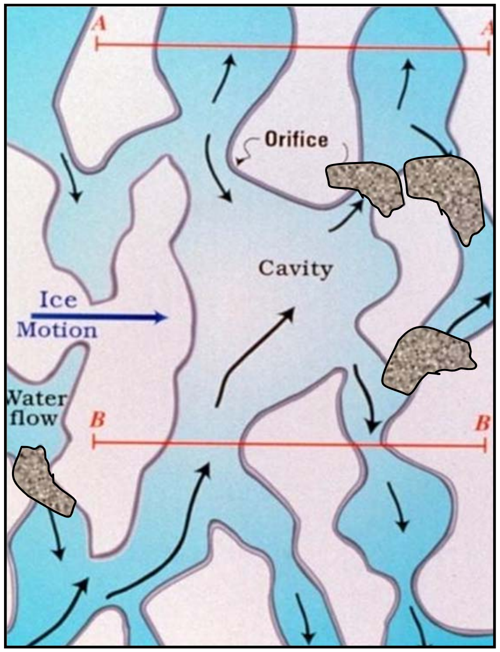
1965

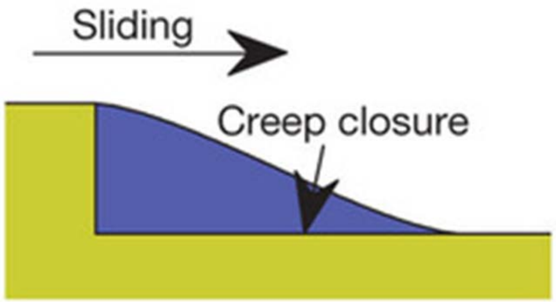
Austin Post

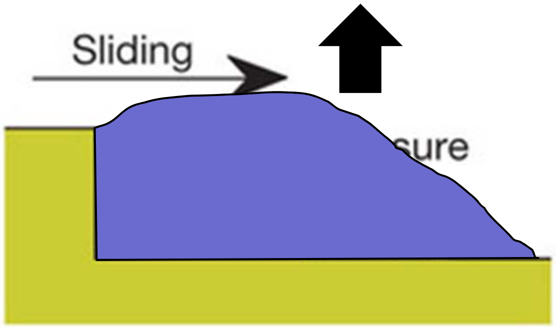
http://www.youtube.com/watch?v=HZaknW8m6tI

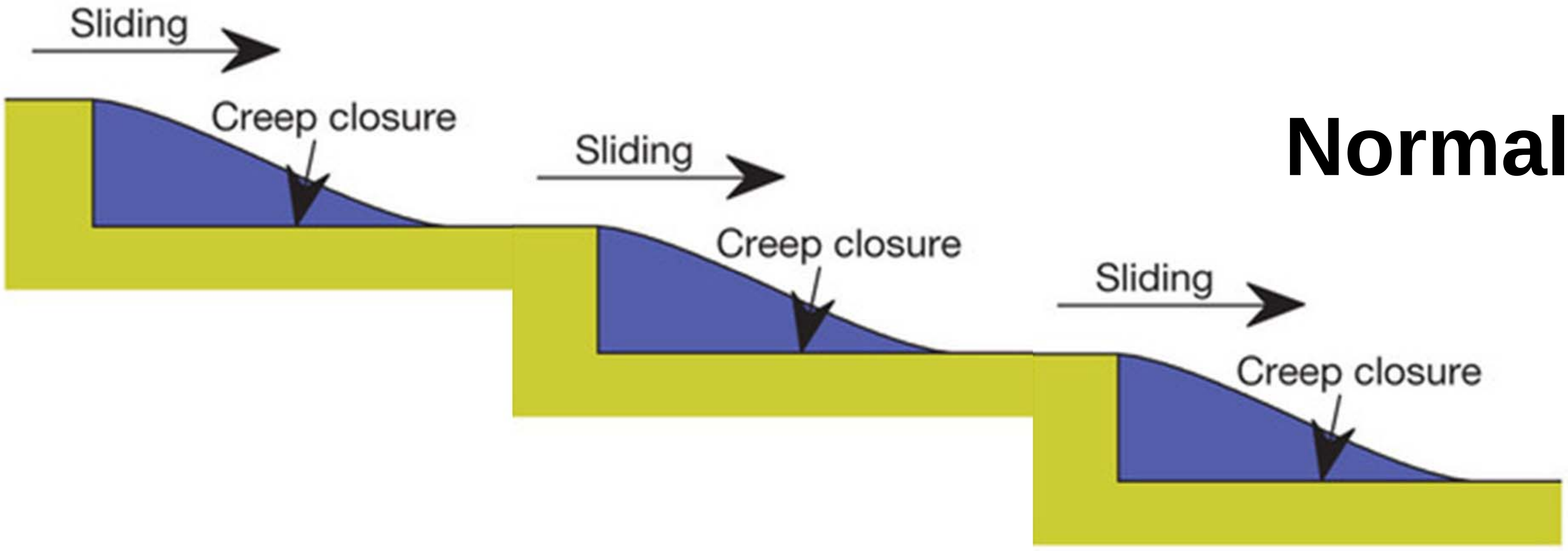
FLOW BEHAVIOR: UNSTEADY FLOW



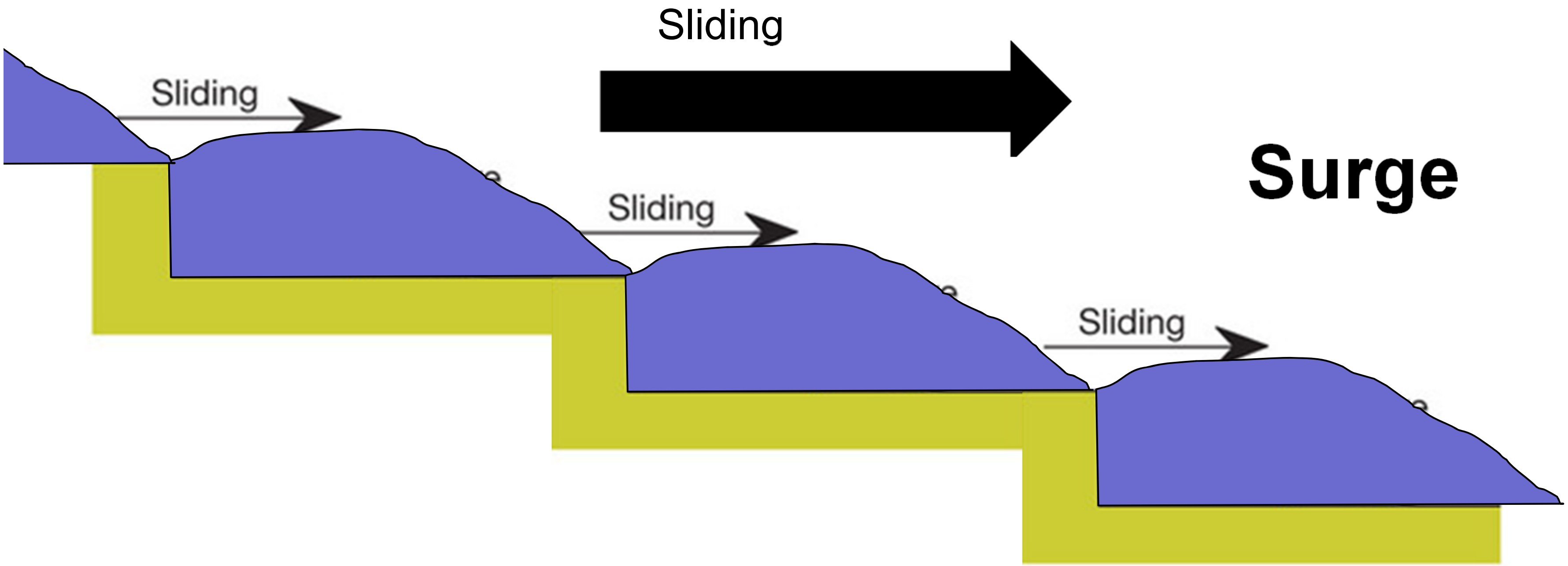








Normal



Surge

57. *Looped medial moraine resulting from periodic surges, Black Rapids Glacier, Alaska Range*

The most famous set of contorted medial moraines in Alaska is that of the Susitna Glacier (Fig. 59). The 1941 photograph by Bradford Washburn (Fig. 59a) has been widely published. Figure 59b, taken twenty-five years later, shows the

59a. The generation of looped and folded moraine patterns by periodic surges of a valley glacier with steady-state tributary, Susitna Glacier, Alaska Range, 1941


END