Glacier and Ice-Sheet Hydrology

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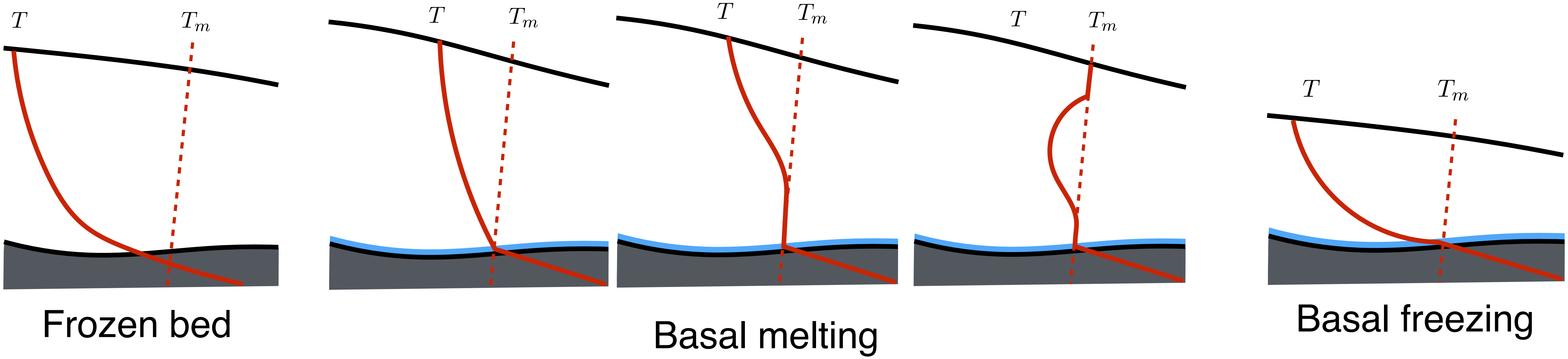
Why is glacier or ice sheet hydrology important?

Where is water produced on a glacier or ice sheet? How much?

What happens to that water?

How does water move at the base of a glacier or ice sheet?

Thermal setting



Geothermal heating $G \sim 0.06 \text{ W m}^{-2}$

Frictional heating $\tau_b \sim 100 \text{ kPa}$

$u_b \sim 30 \text{ m y}^{-1}$

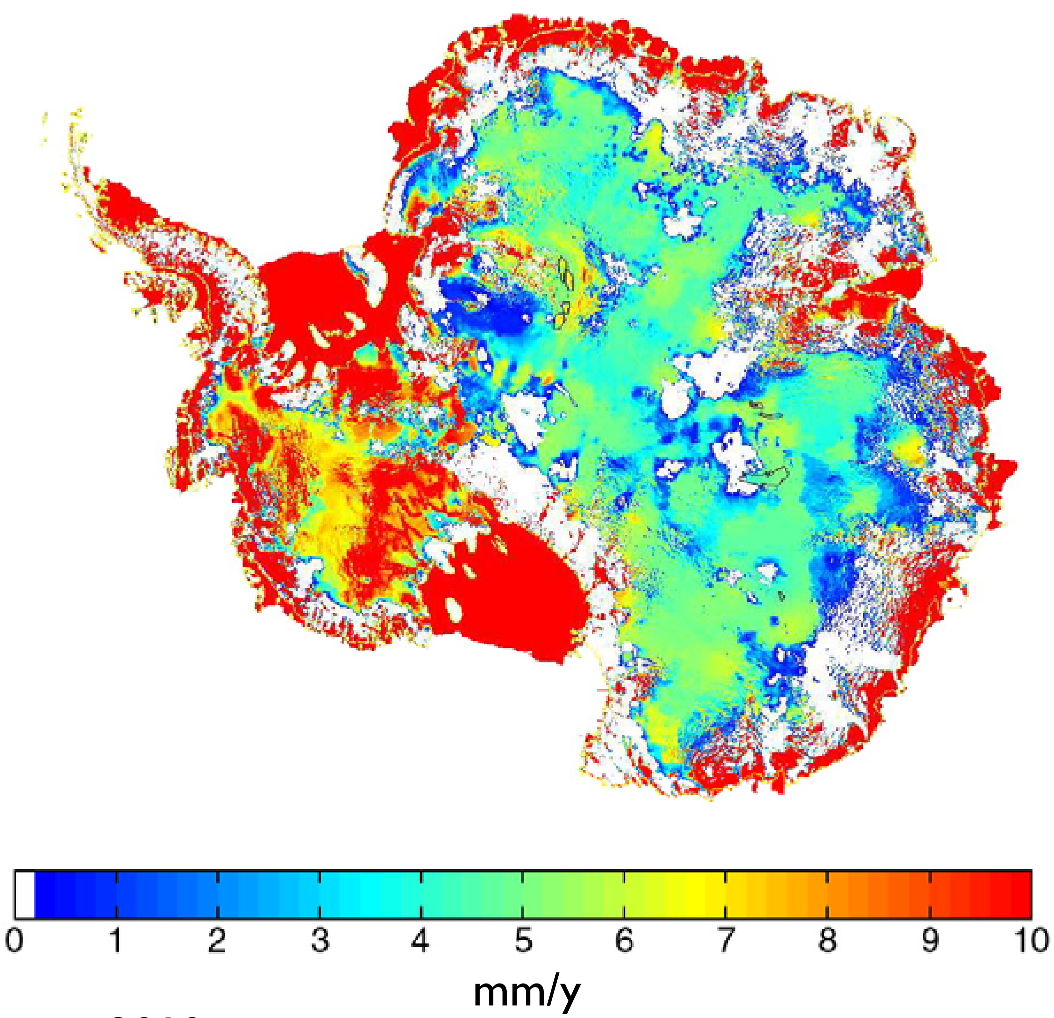
$\tau_b u_b \sim 0.1 \text{ W m}^{-2}$

→ Basal melting

$m \sim 10 \text{ mm y}^{-1}$

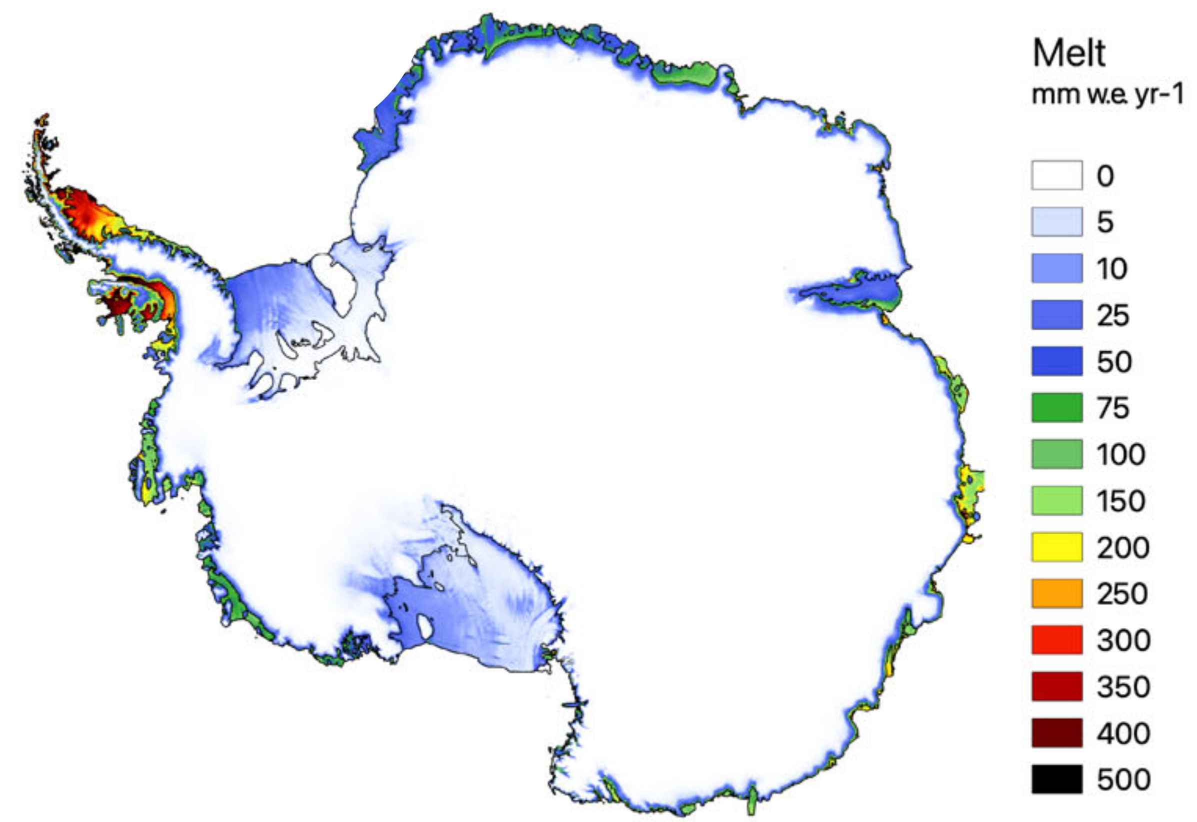
Water sources in Antarctica

Basal melting ~ 10 mm/y



Pattyn 2010

Surface melting ~ 10 cm/y

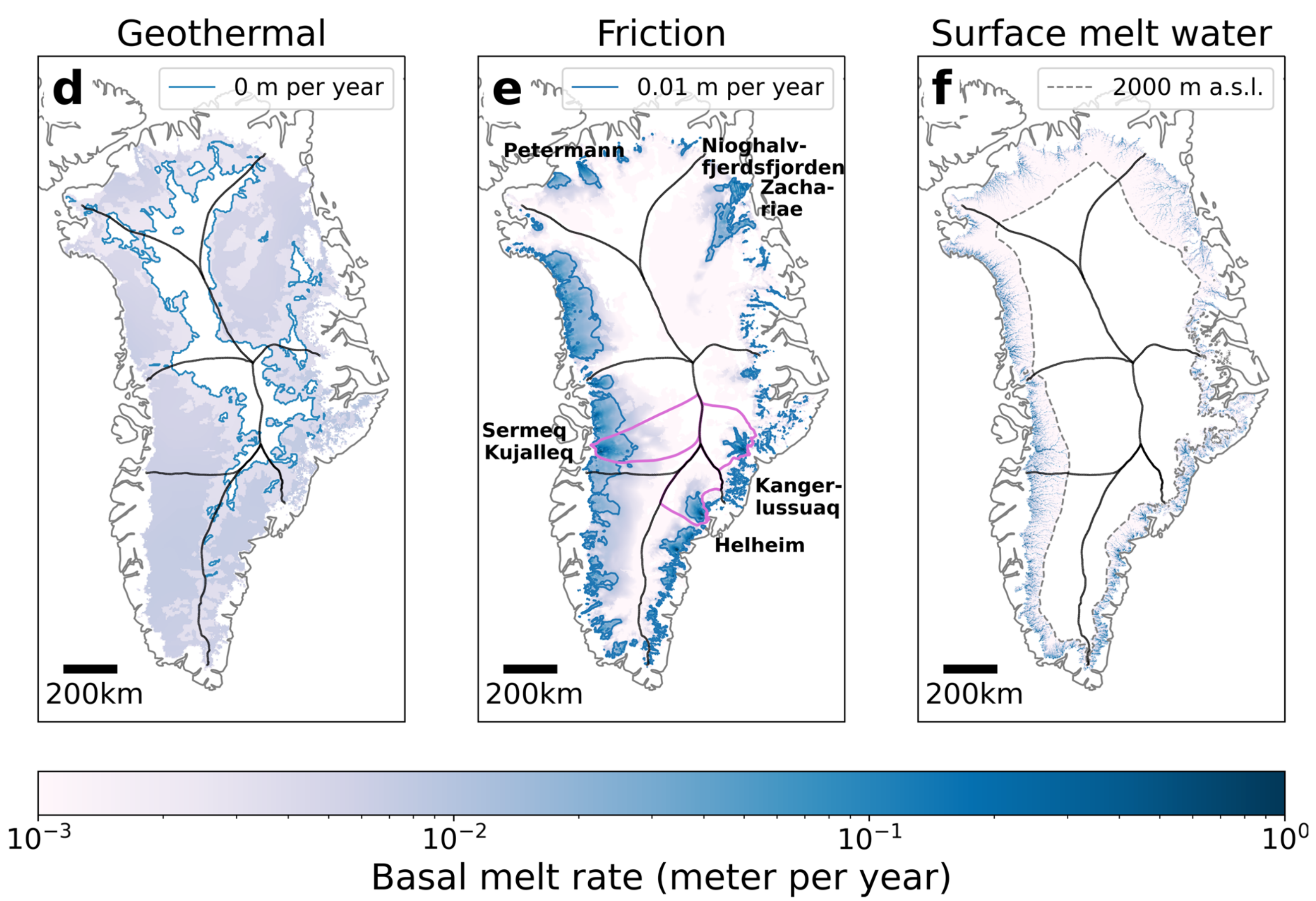


Noël et al 2023

⇨ Basal melting (grounded ice) ~ 65 Gt/y   Surface melting ~ 150 Gt/y

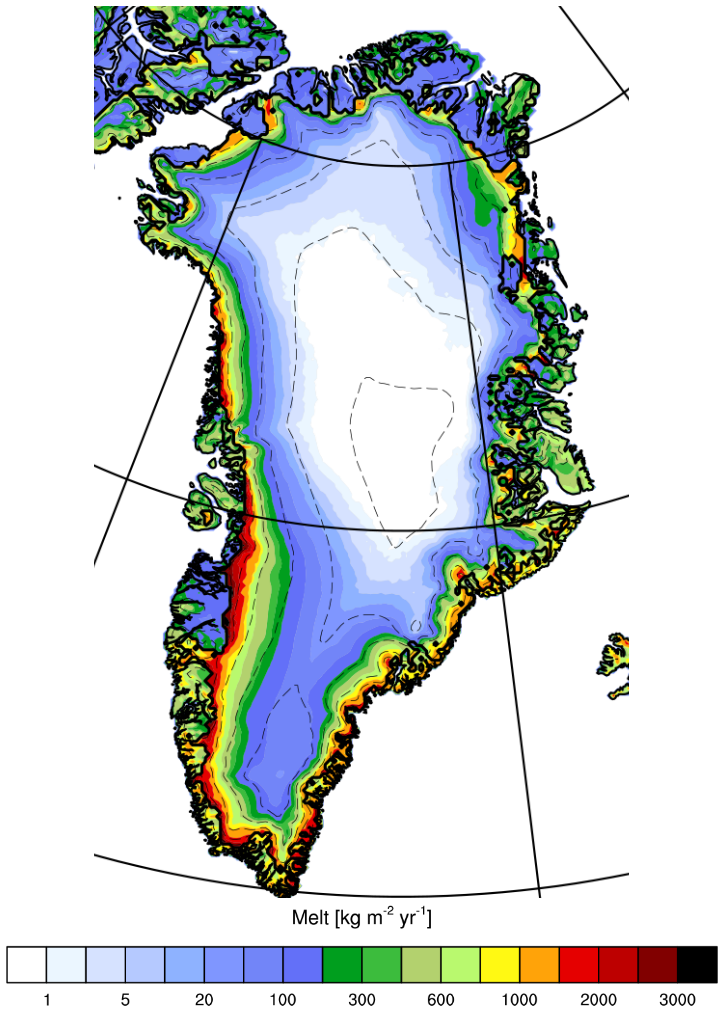
Water sources in Greenland

Basal melting ~ 10 mm/y



Karlsson et al 2021

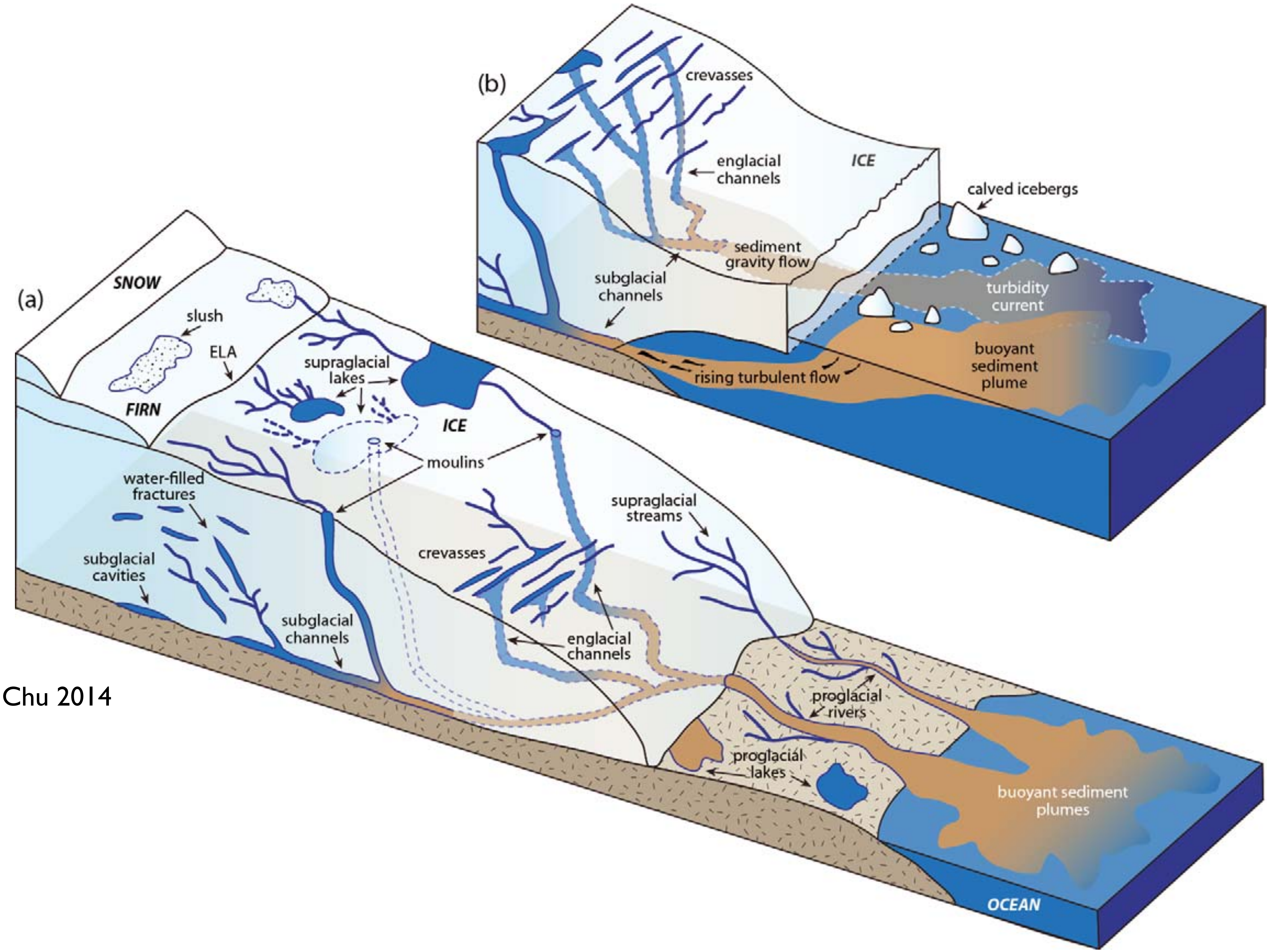
Surface melting ~ 1 m/y



Van den Broeke et al 2016

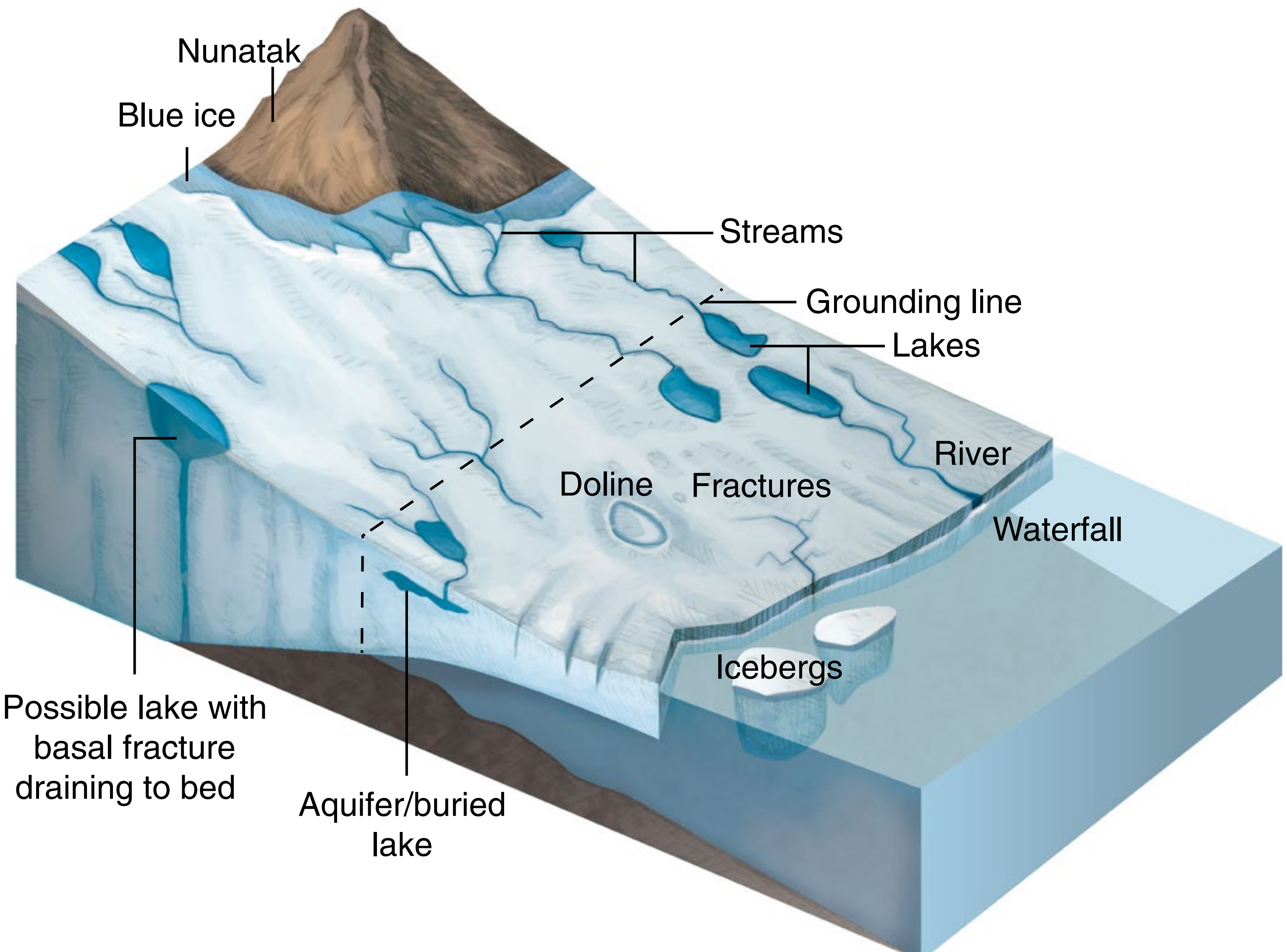
⇨ Basal melting ~ 20 Gt/y   Surface melting ~ 400 Gt/y

Greenland hydrology



Chu 2014

Antarctic hydrology



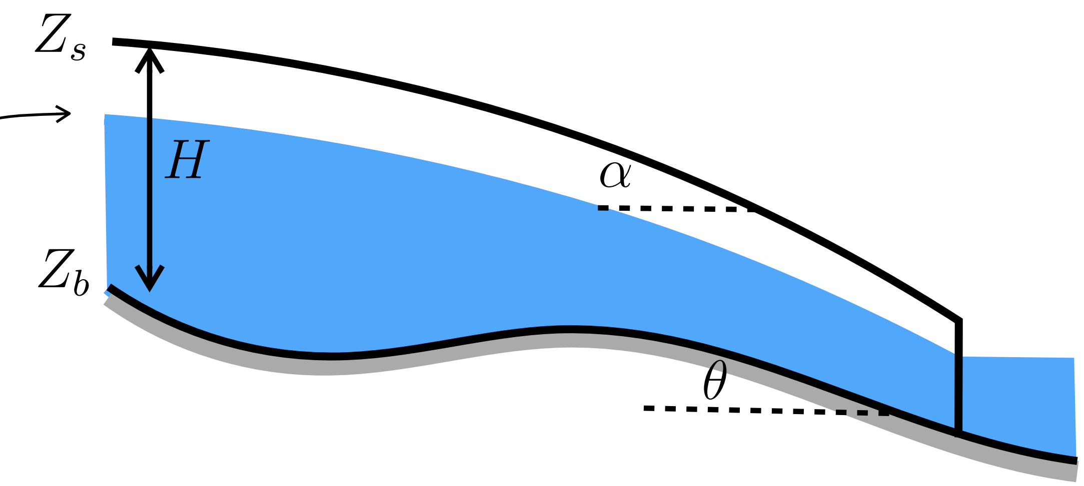
Bell et al 2018


Laura Stevens
Greenland


Adam Scott / Frozen Planet
Greenland

Pressurised subglacial water

Hydraulic head $\frac{\phi}{\rho_w g}$



Hydraulic potential

$$\phi = \rho_w g Z_b + p_w$$

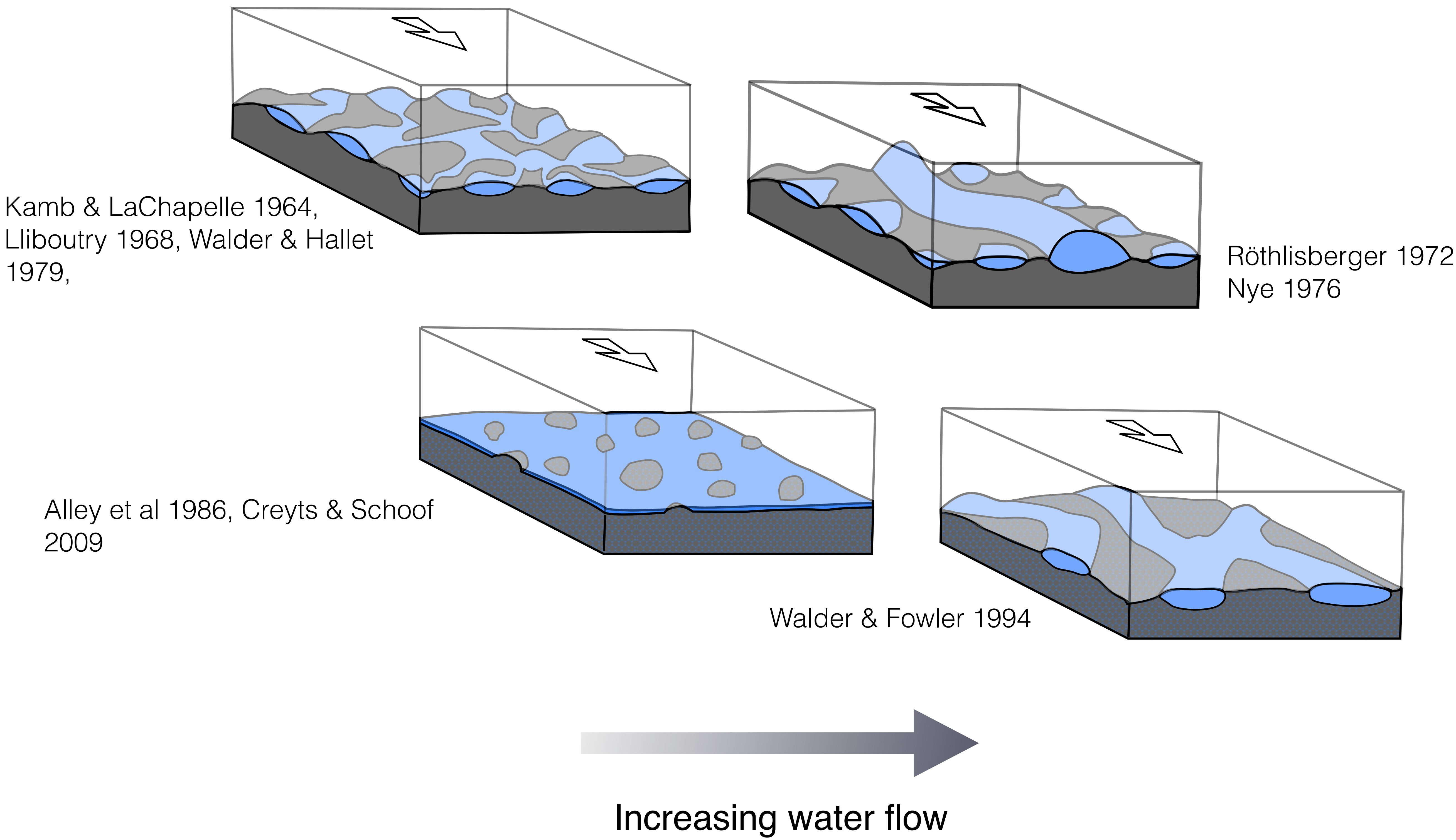
$$= \rho_w g Z_b + \rho_i g (Z_s - Z_b) - N$$ in terms of **effective pressure** $N = p_i - p_w$

Potential gradient $-\nabla\phi = \Psi + \nabla N$ $\quad \Psi = \rho_i g \tan\alpha + (\rho_w - \rho_i) g \tan\theta$

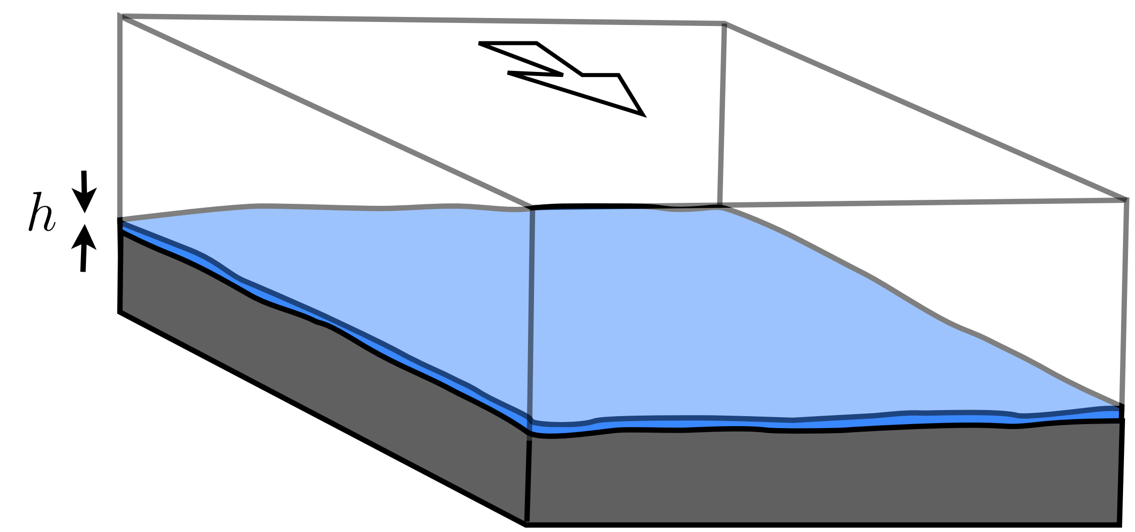
Potential gradient if basal water pressure were equal to ice pressure

⇨ Predominant control on water flow direction comes from **ice surface slope**

Subglacial drainage systems



Weertman film Weertman 1972, Walder 1982



Weertman suggested water could flow as a **film**

Poiseuille flux $Q = \frac{h^3}{12\eta}(\Psi + \nabla N)$

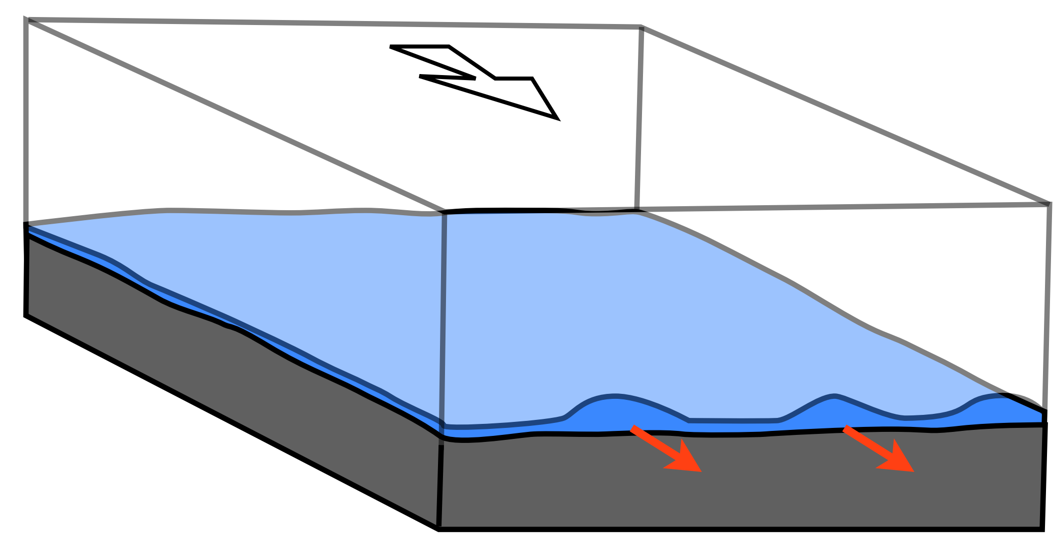
Water flow dissipates energy through heating

⇨ Leads to an instability

Larger sheet thickness

→ Larger flux

→ Melting of ice roof

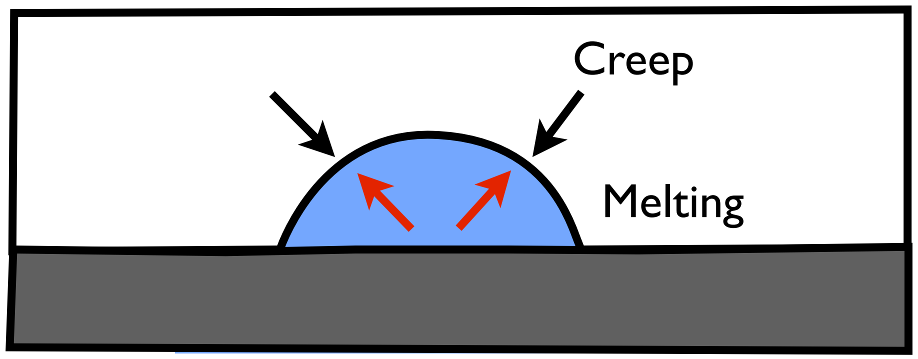


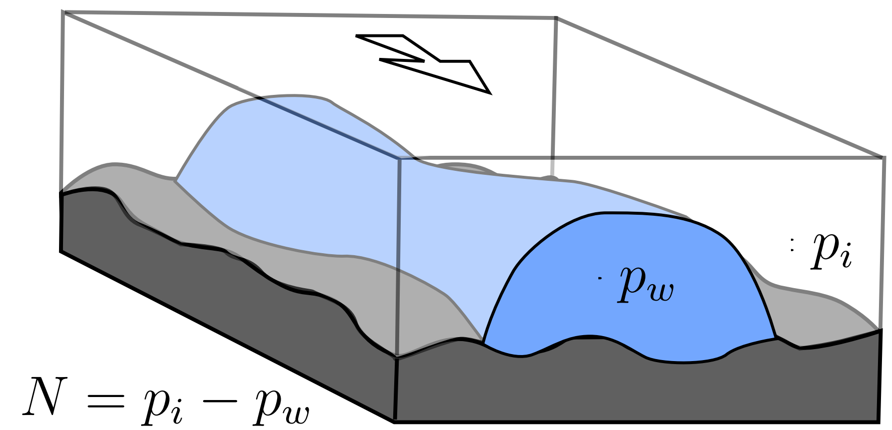
⇨ Flow wants to concentrate in **localized channels / tunnels**

Röthlisberger channels

Röthlisberger 1972, Nye 1976

Ice wall **melting** is counteracted by **viscous creep**





Röthlisberger/Nye theory (ignoring pressure dependence of melting temperature)

$$\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = \frac{m}{\rho_w} + M$$

water mass conservation

$$\frac{\partial S}{\partial t} = \frac{m}{\rho_i} - \tilde{A} S N^n$$

wall evolution

$$mL = Q\left(\Psi + \frac{\partial N}{\partial x}\right)$$

local energy conservation

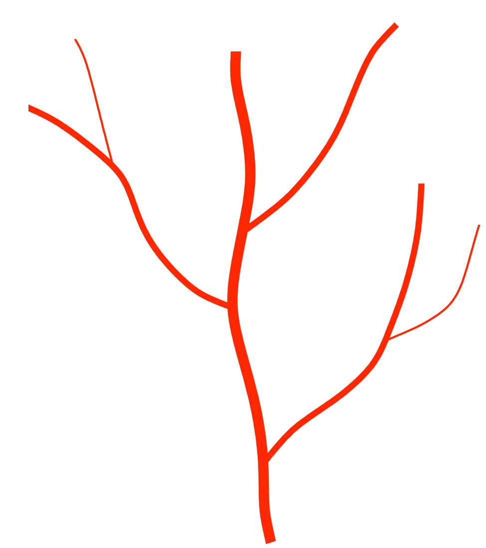
$$Q = K_c S^{4/3}\left(\Psi + \frac{\partial N}{\partial x}\right)^{1/2}$$

momentum conservation
(turbulent flow parameterization)

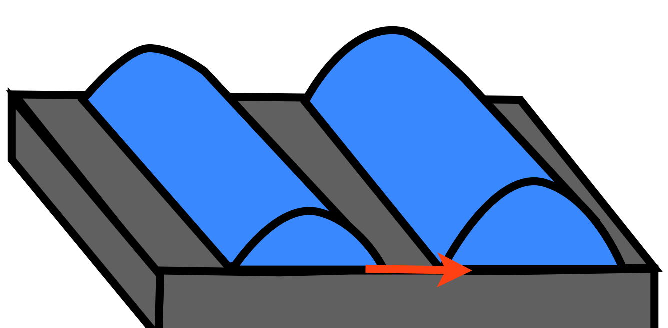
Steady state ⇨

$$N \approx \left(\frac{K_c^{3/4}}{\rho_i L \tilde{A}}\right)^{1/n} \Psi^{11/8n}\, Q^{1/4n}$$

Effective pressure INCREASES with discharge

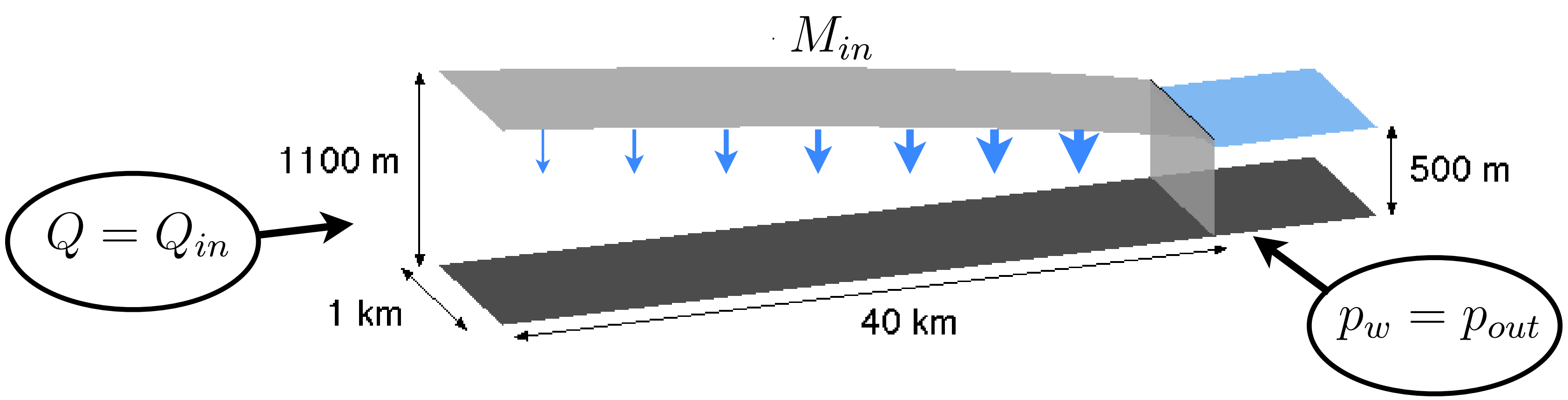


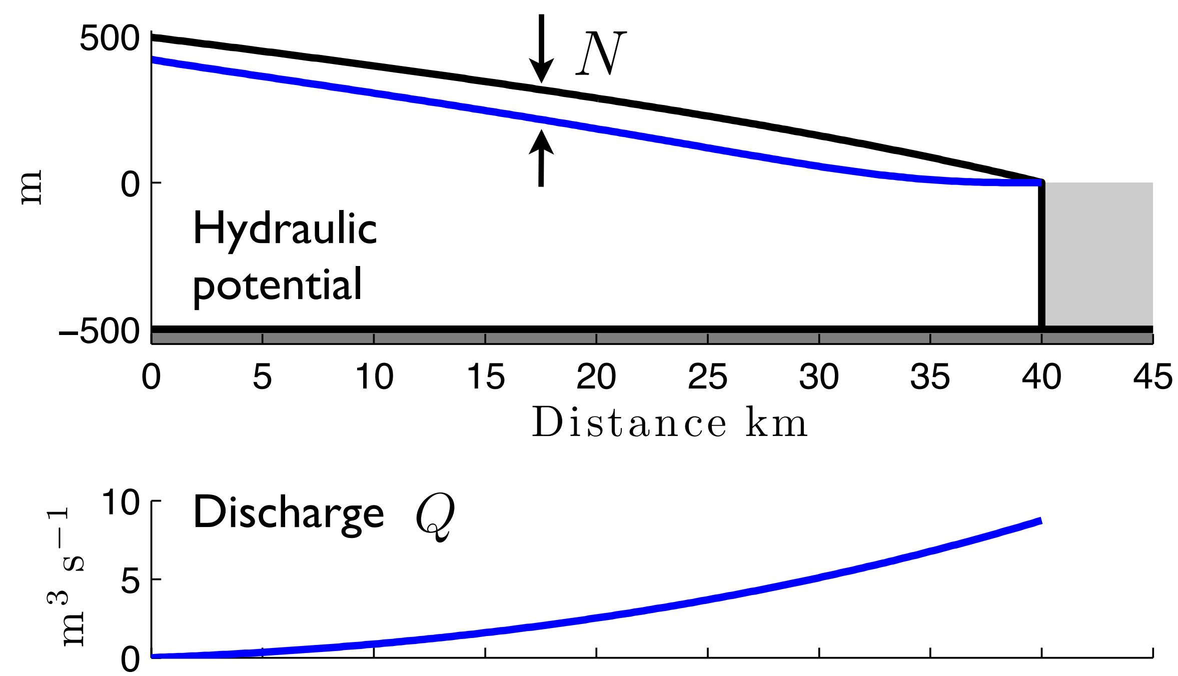
Neighbouring channels compete with one another



⇨ leads to an arterial network

Röthlisberger channels





Jökulhlaups (Glacial Lake Outburst Floods)

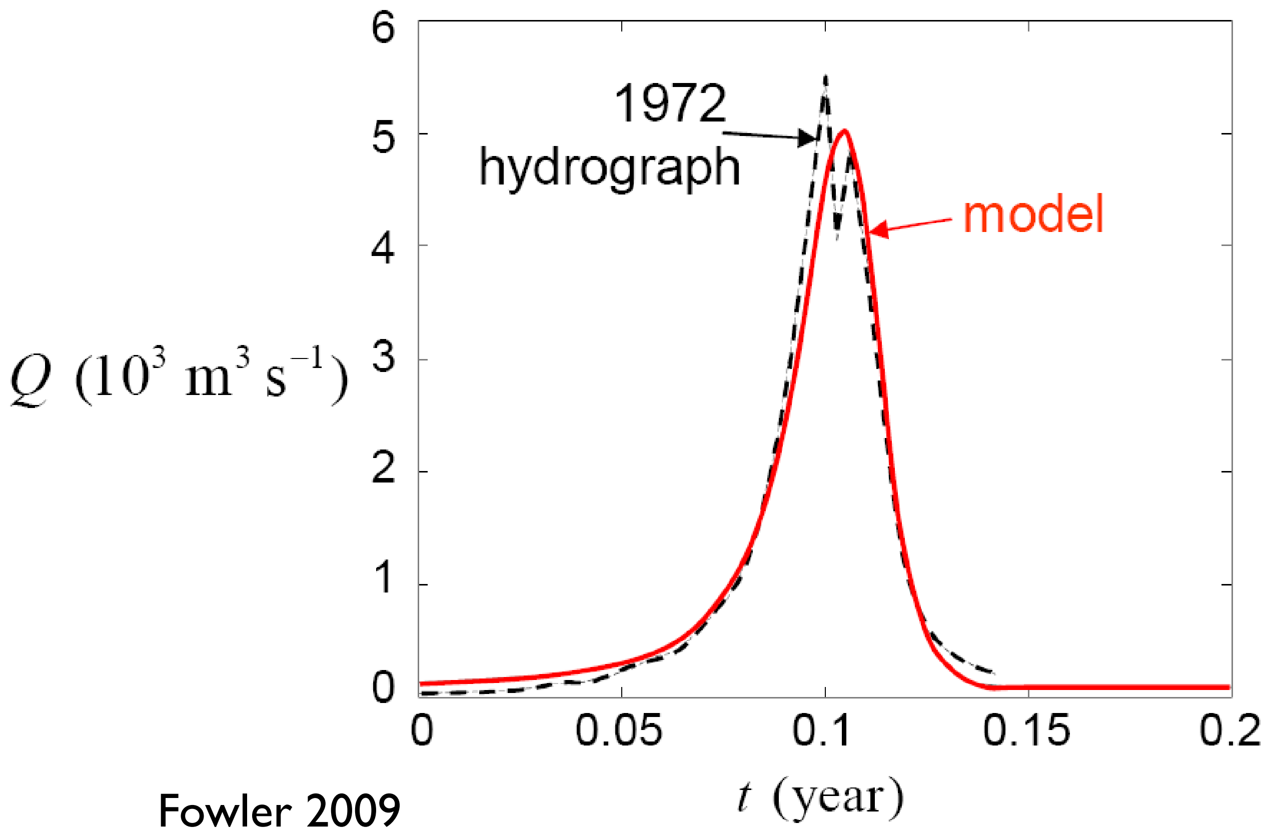
Skeidarársandur, Iceland 1996

Jökulhlaups Nye 1976, Spring & Hutter 1981, Clarke 2003

A significant success of the channel theory is the application to **floods from ice-dammed lakes**

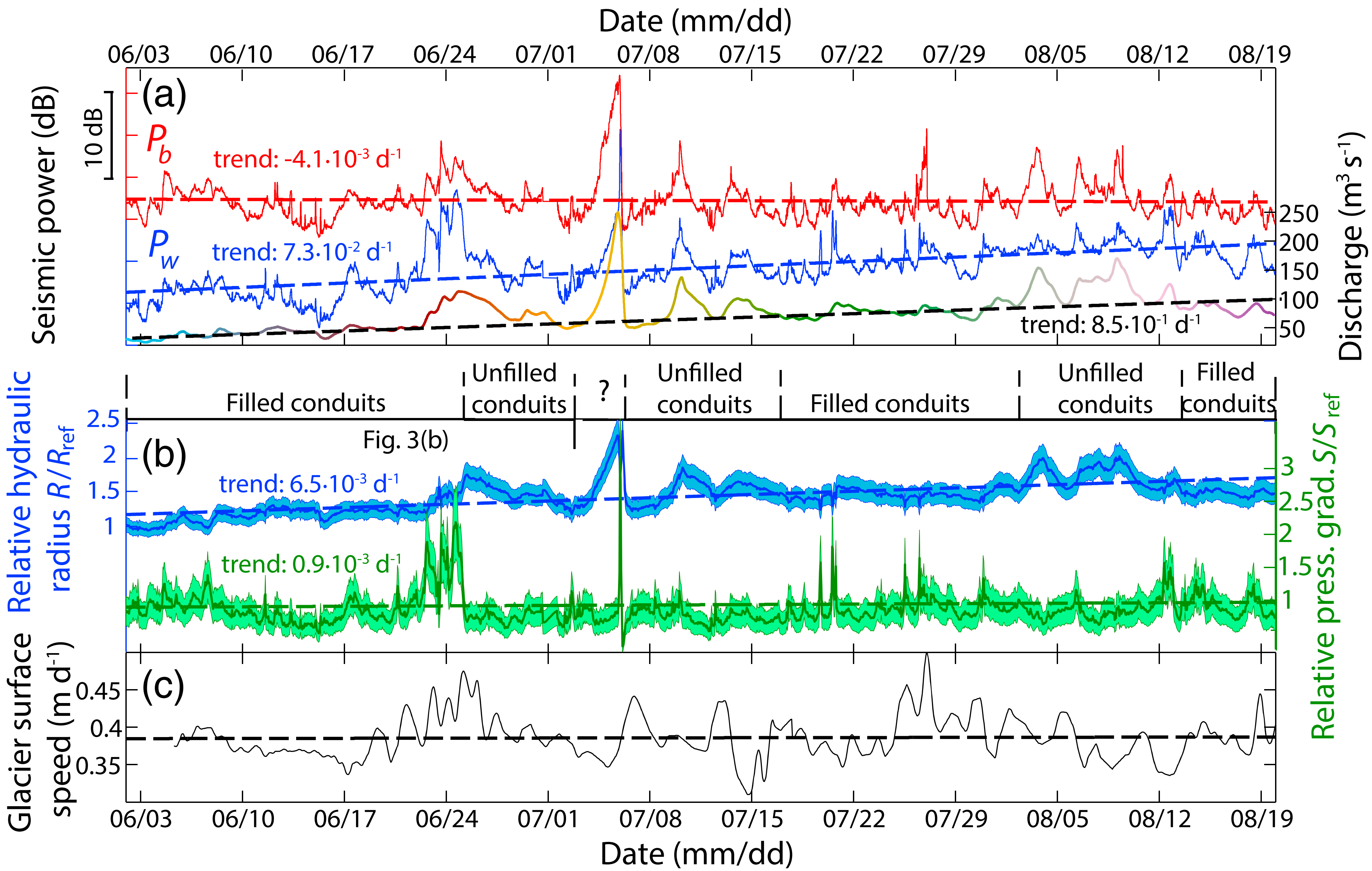
Combine **channel evolution** equation $$\frac{\partial S}{\partial t} = \frac{S^{4/3}\Psi^{3/2}}{\rho_i L} - \tilde{A} S N^n$$

with a **lake filling** equation $$-\frac{A_L}{\rho_w g}\frac{\partial N}{\partial t} = m_L - Q$$



Fowler 2009

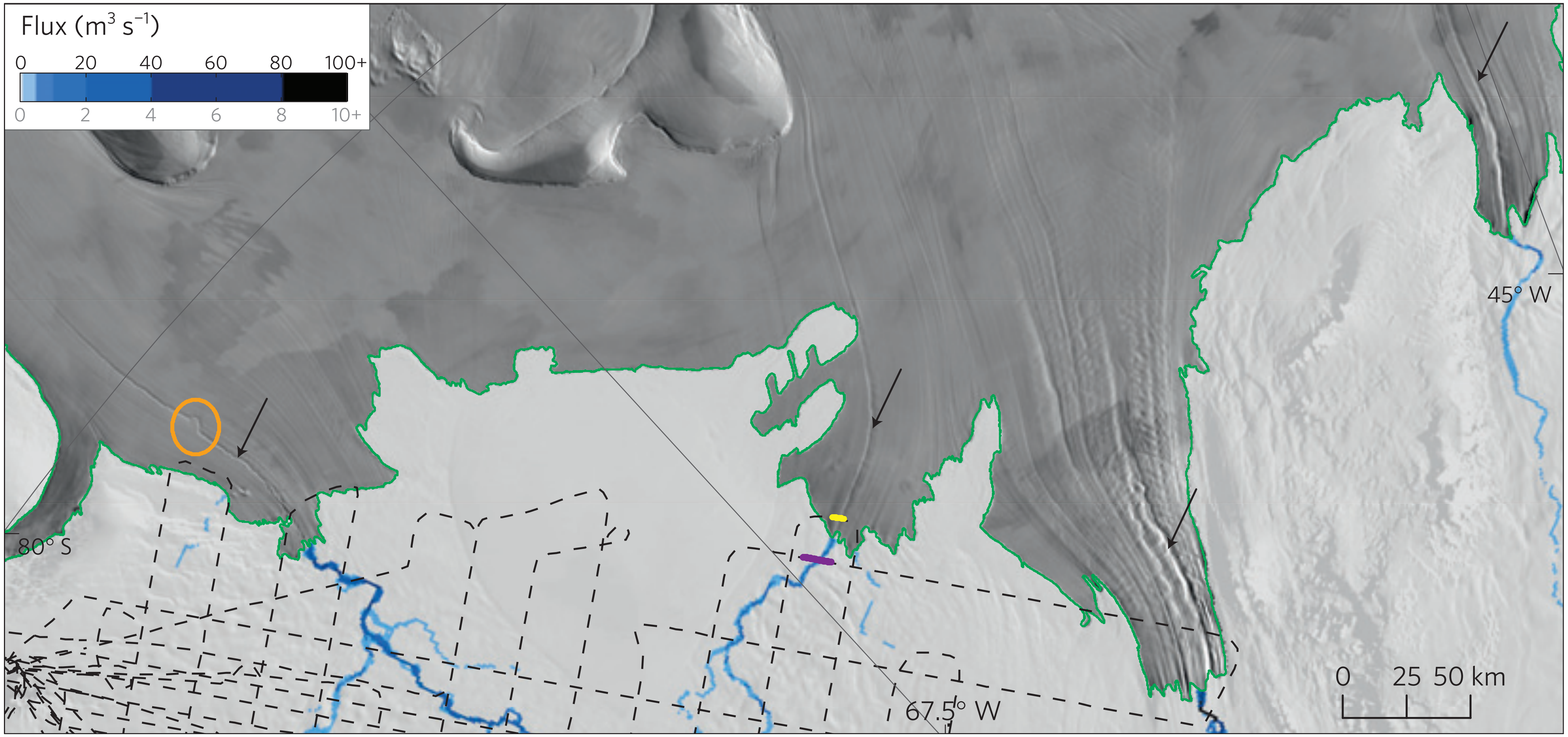
Seismic detection of Röthlisberger channels



Gimbert et al 2016 - Mendenhall Glacier, Alaska

Evidence for channelised water flow beneath grounding lines

a



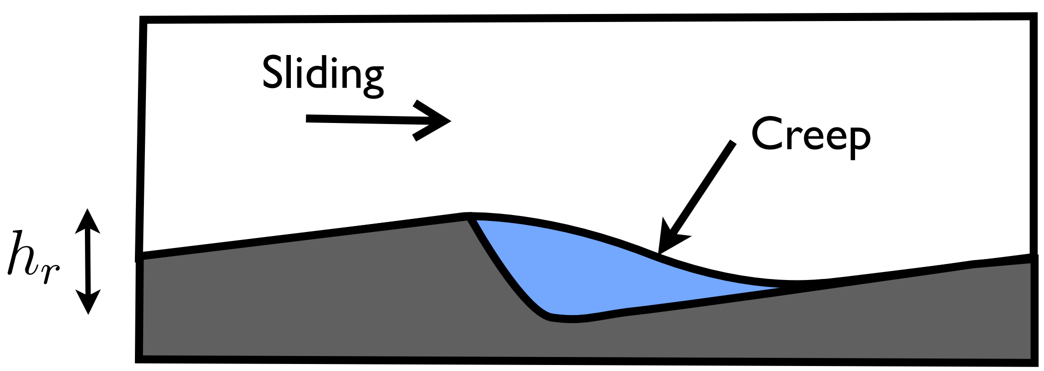
Le Brocq et al 2013

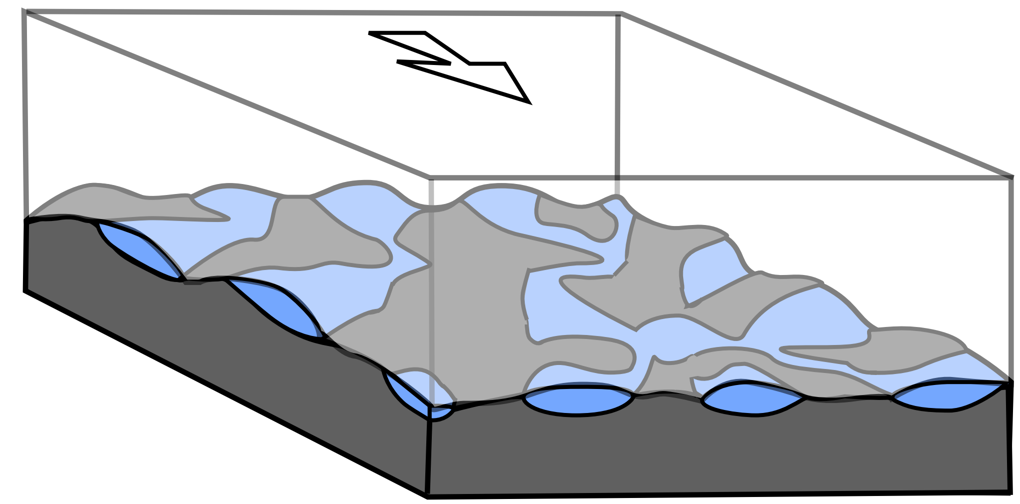
Localised subglacial out flow initiates plumes and ice-shelf channels


2 m

Linked cavities Walder 1986, Kamb 1987

Cavities grow through sliding over bedrock





Model

$$\frac{\partial \hat{S}}{\partial t} = U_b h_r - \tilde{A}\hat{S}N^n$$

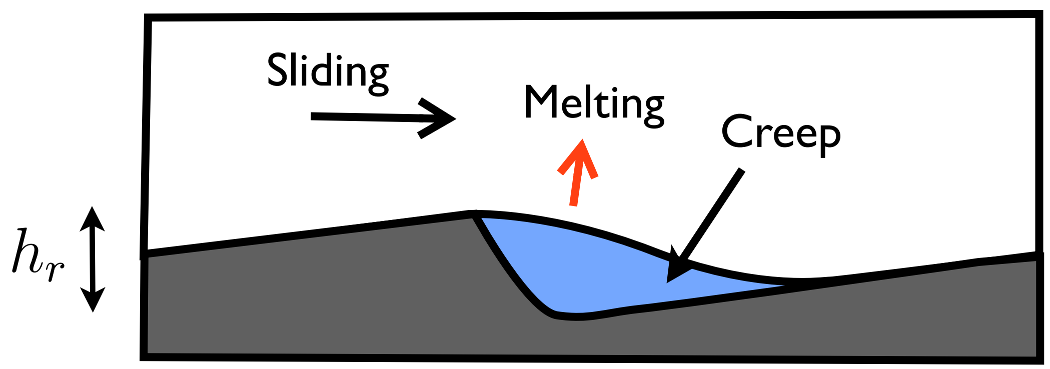
Approximate steady-state relationship

⇨ $N(Q) \quad \frac{\partial N}{\partial Q} < 0$ ⇨ Effective pressure DECREASES with discharge ⇨ Flow is distributed

Cavity size is controlled by parameter $\Lambda = \frac{U_b}{N^n}$ i.e. depends on effective pressure **and** sliding speed

Drainage system stability

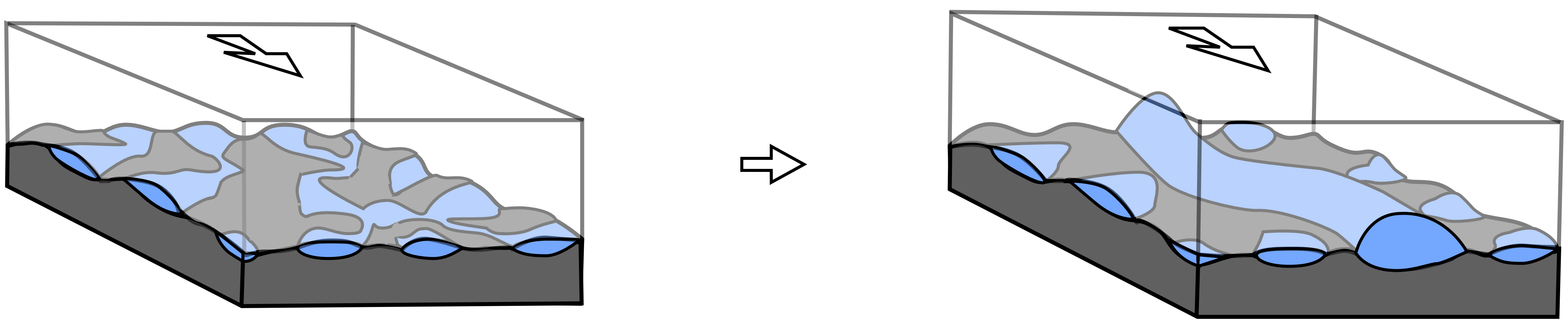
Energy is still dissipated by water flow



$$\frac{\partial S}{\partial t} = \frac{m}{\rho_i} + U_b h_r - \tilde{A} S N^n$$

A linked cavity system can become unstable to produce **channels**

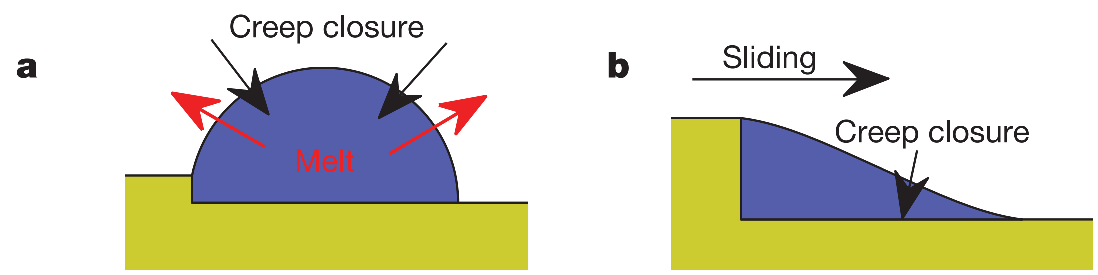
eg. if discharge becomes sufficiently large, or sliding speed sufficiently low



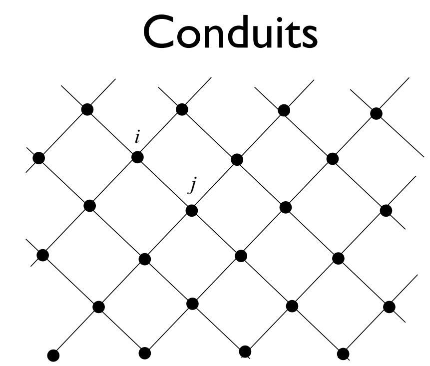
Conversely, a channel can become unstable to **cavities**

eg. if discharge low, or sliding speed sufficiently high

Seasonal evolution of drainage system

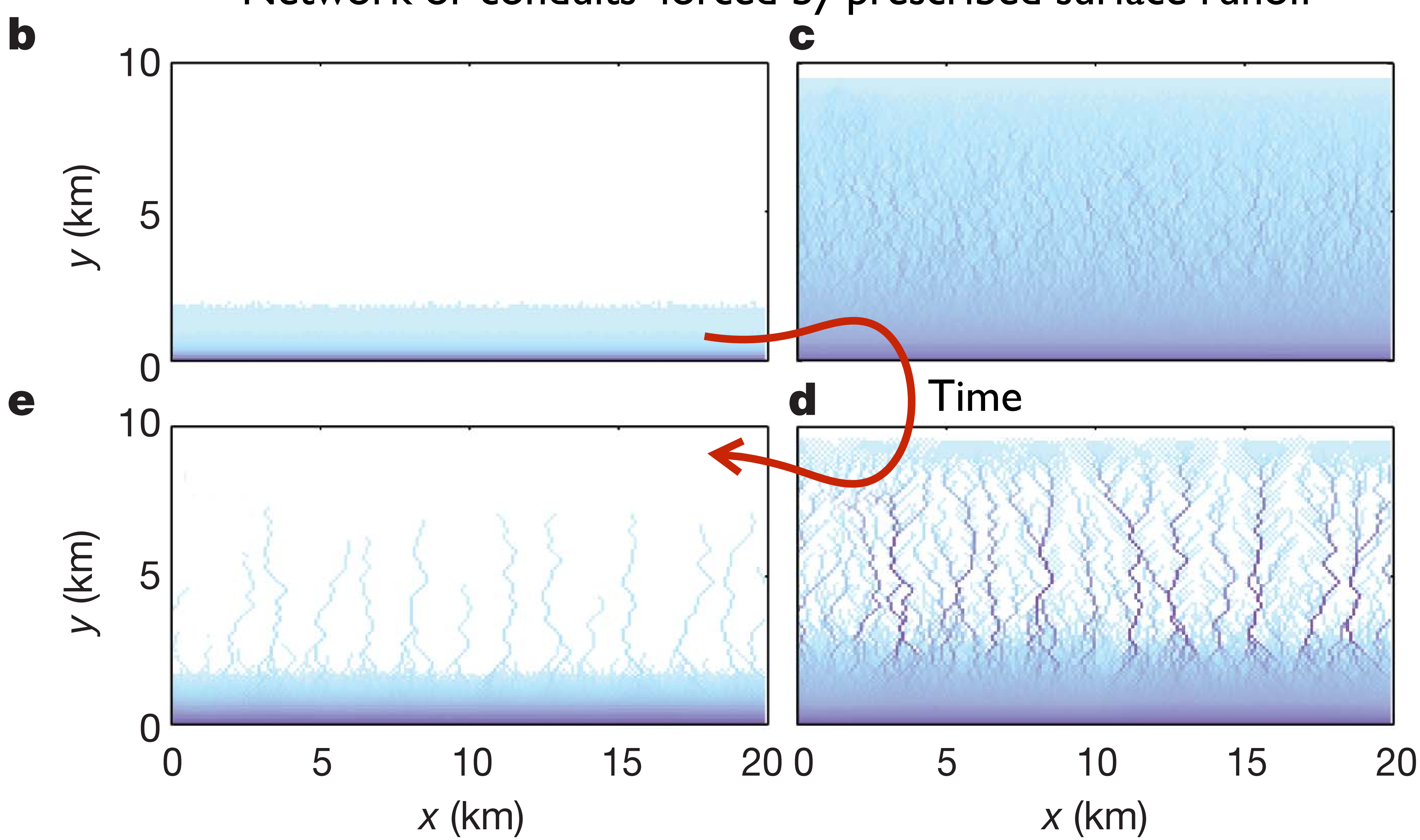


Schoof 2010

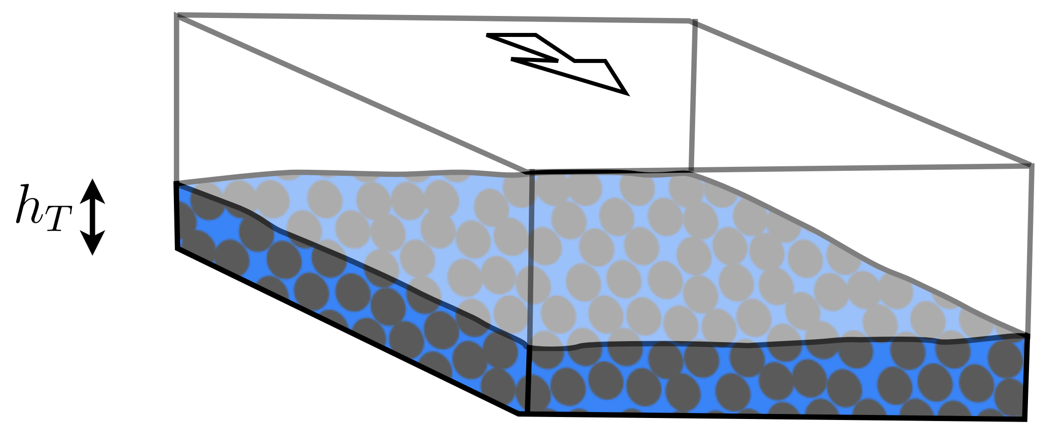


Network of ‘conduits’ forced by prescribed surface runoff

Ice flow



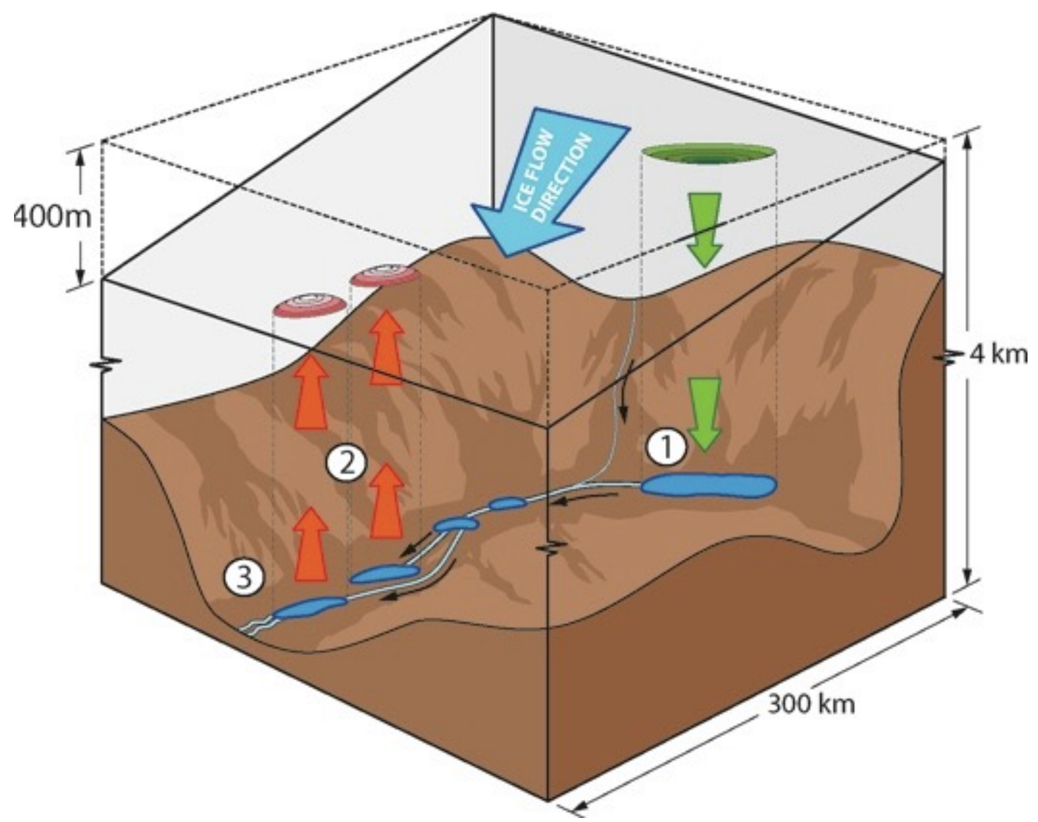
Drainage through sediments

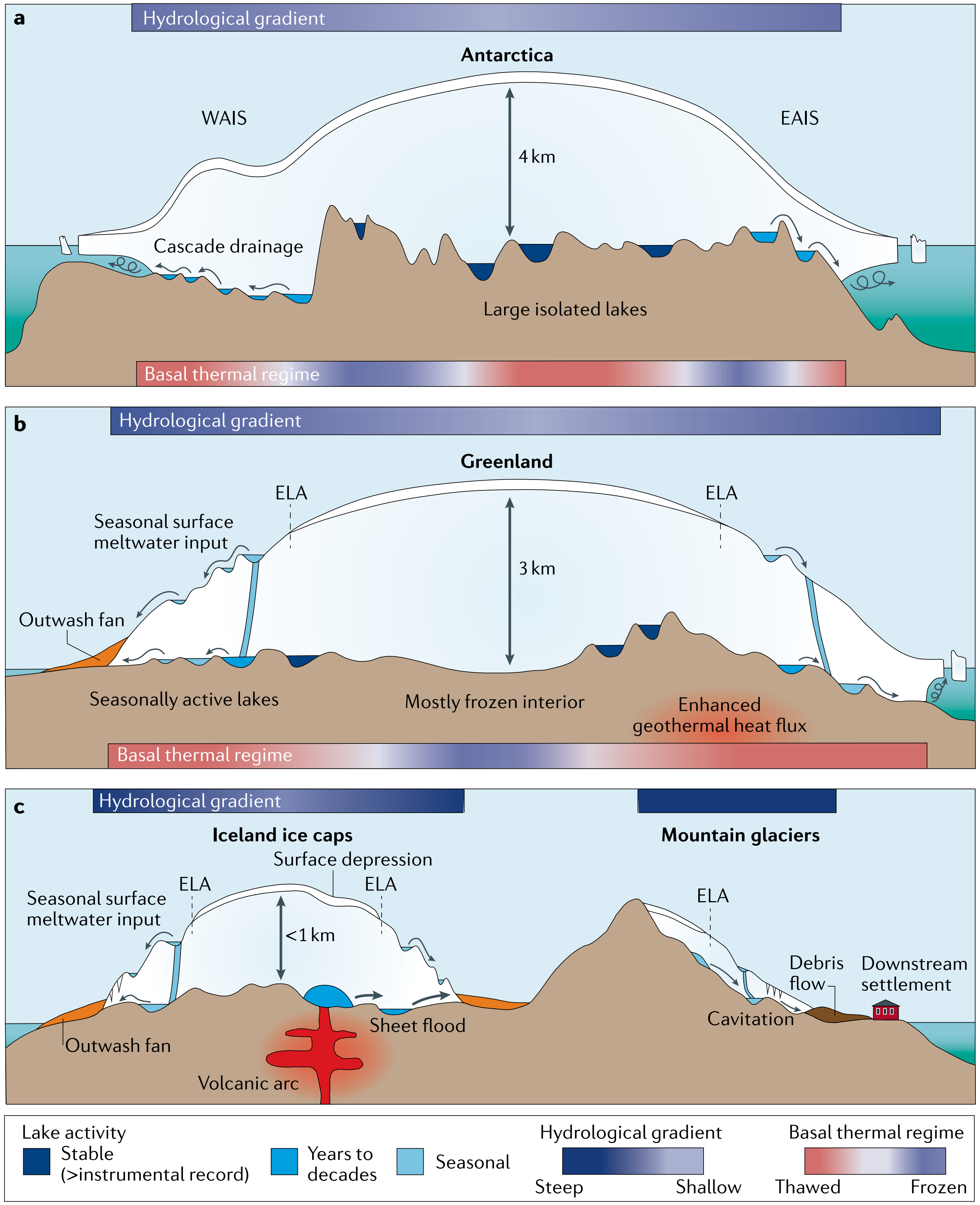


Subglacial lakes

Hundreds of lakes have been detected using radar and satellite observations.

At least some 'active' lakes seem to grow and drain periodically - jökulhlaup-like behaviour?





Livingstone et al 2022

Hydrology in ice-sheet models

See Flowers 2015 review.

On a large scale, distributed systems are described as a 'sheet' flow

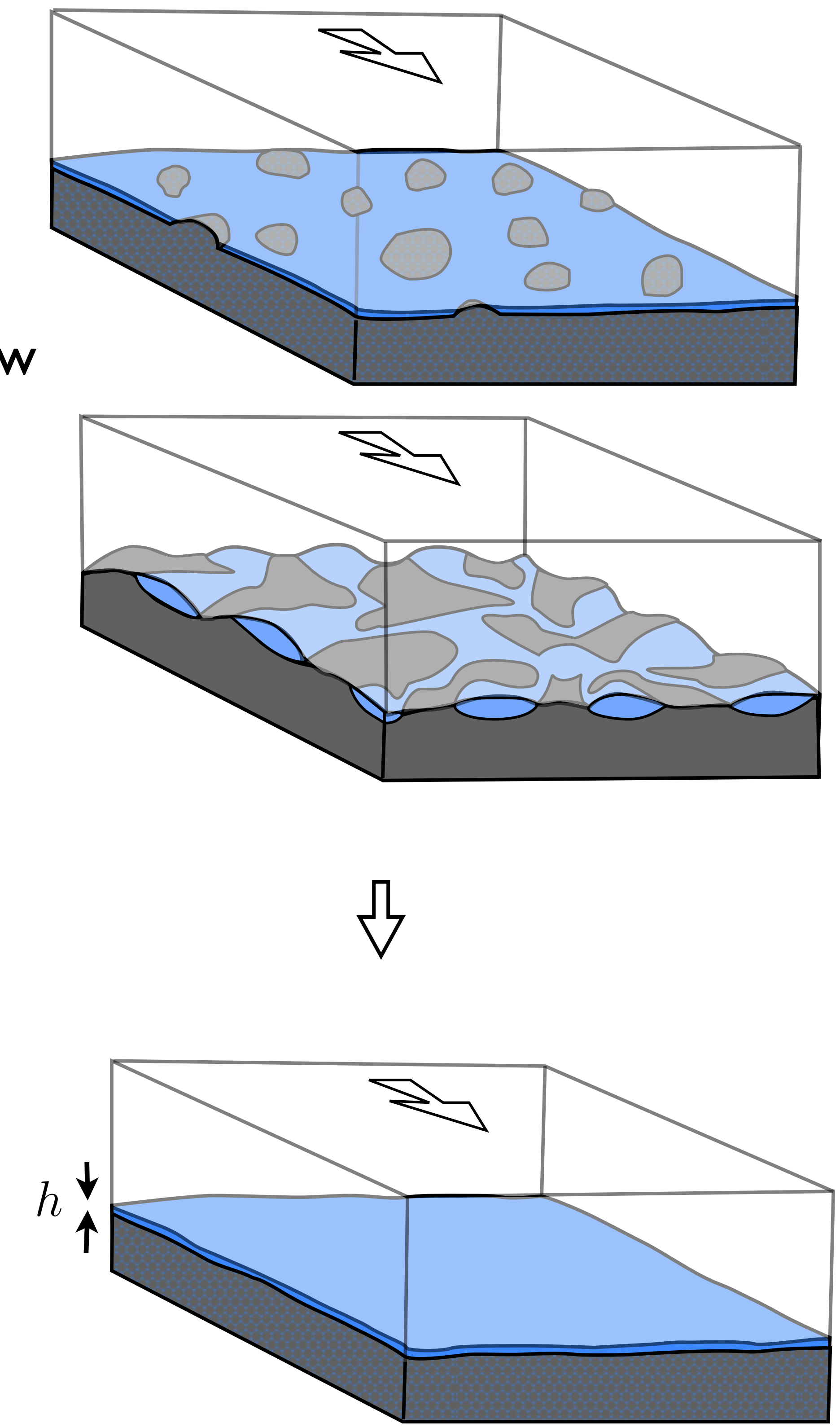
Average water depth h Average water pressure p_w

Average water flux $\mathbf{q} = -Kh^{\alpha}\nabla\phi$

Mass conservation $\frac{\partial h}{\partial t} + \nabla \cdot \mathbf{q} = \frac{m}{\rho_w} + M$

Basal melting

Englacial/supraglacial source



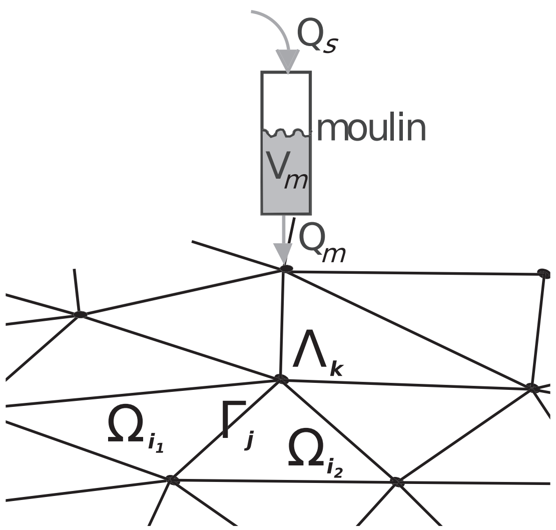
+ some additional ingredient to determine water pressure

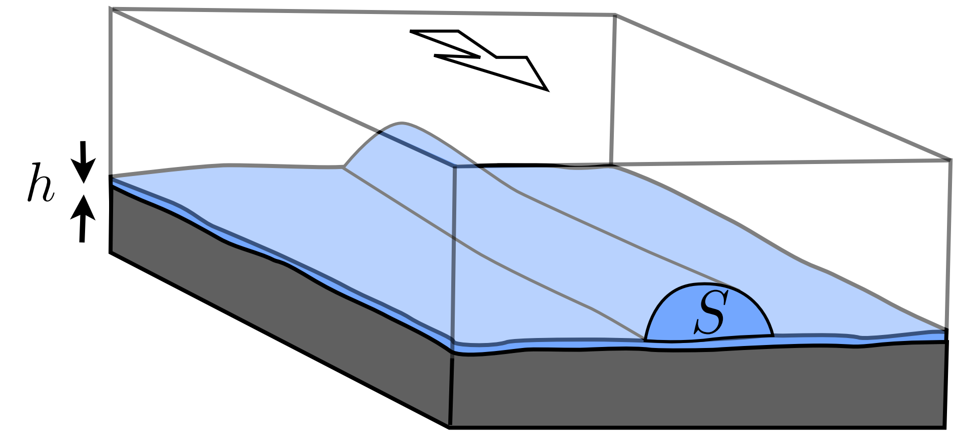
eg. water pressure = ice pressure ('routing model'),
or an equation for the evolution of the sheet permeability

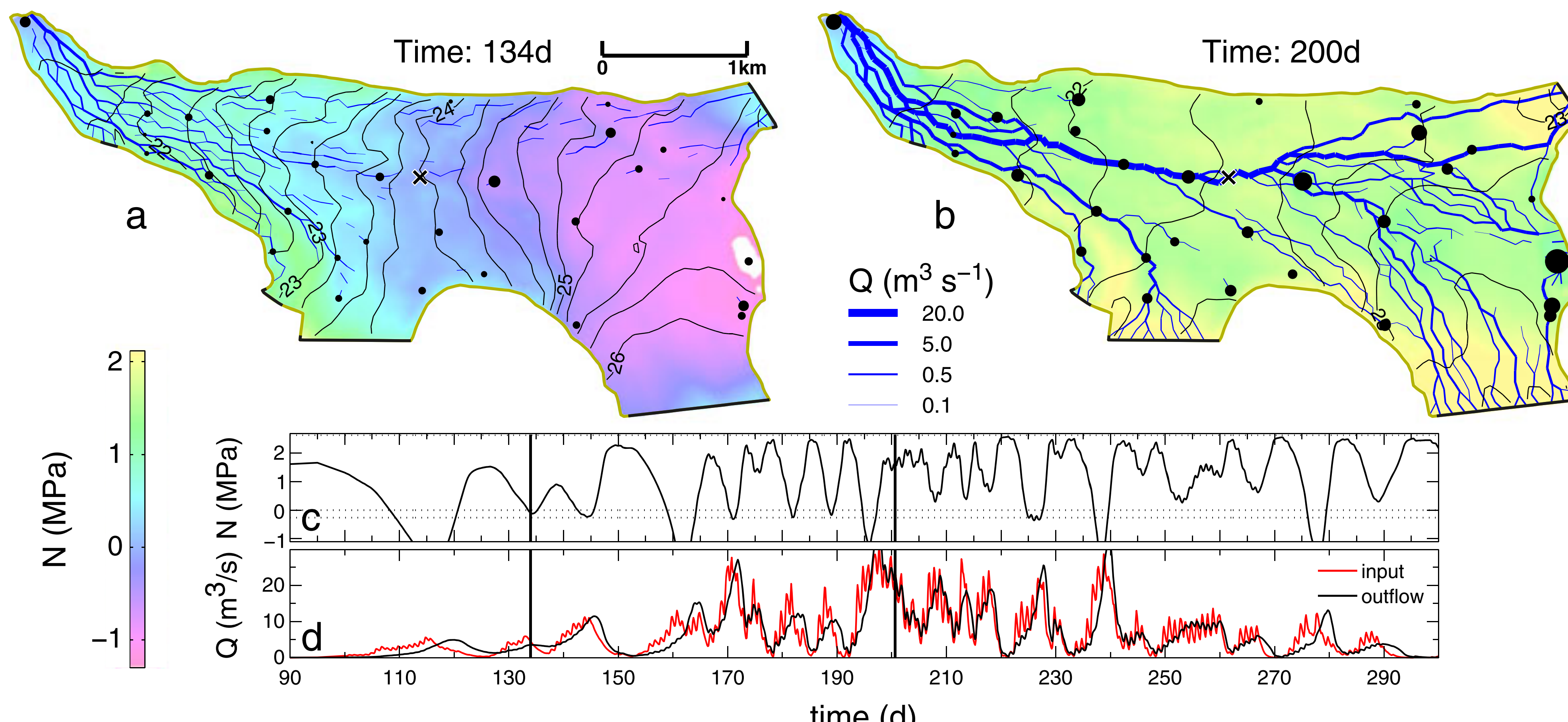
+ potential to couple to sliding law

Hydrology in ice-sheet models

Some models couple a distributed ‘sheet’ with discrete conduits (eg. GLaDS)



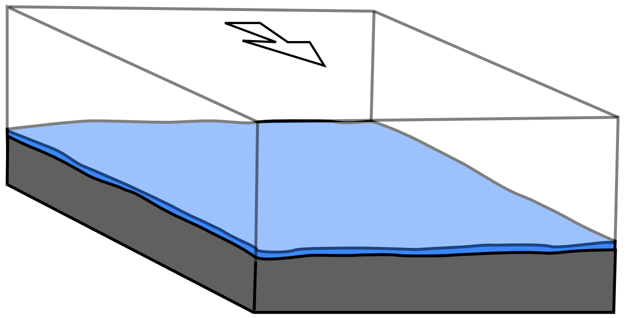




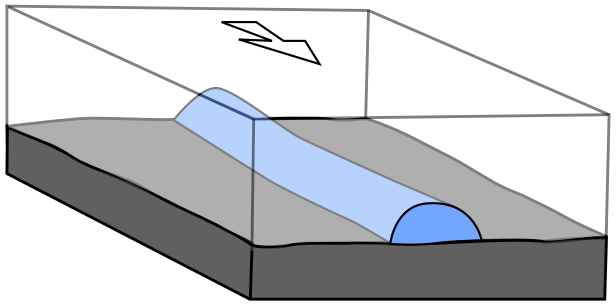
Werder et al 2013

Summary

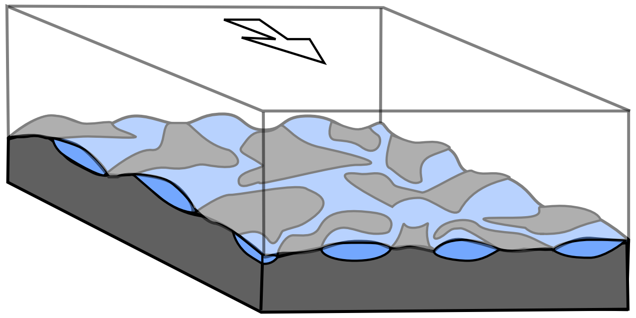
Uniform water film is **unstable**.



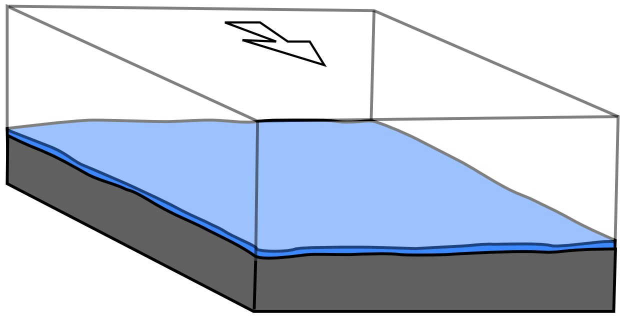
Röthlisberger channels form arterial networks.



Distributed flow in **linked cavities** or **sediments** is possible.



On a large scale, the drainage system can be modelled as a **water layer** with variable thickness and permeability.



Evolution of the drainage system has important consequences for ice dynamics

(seasonal/diurnal velocity changes, surges, ice streams, grounding line dynamics)