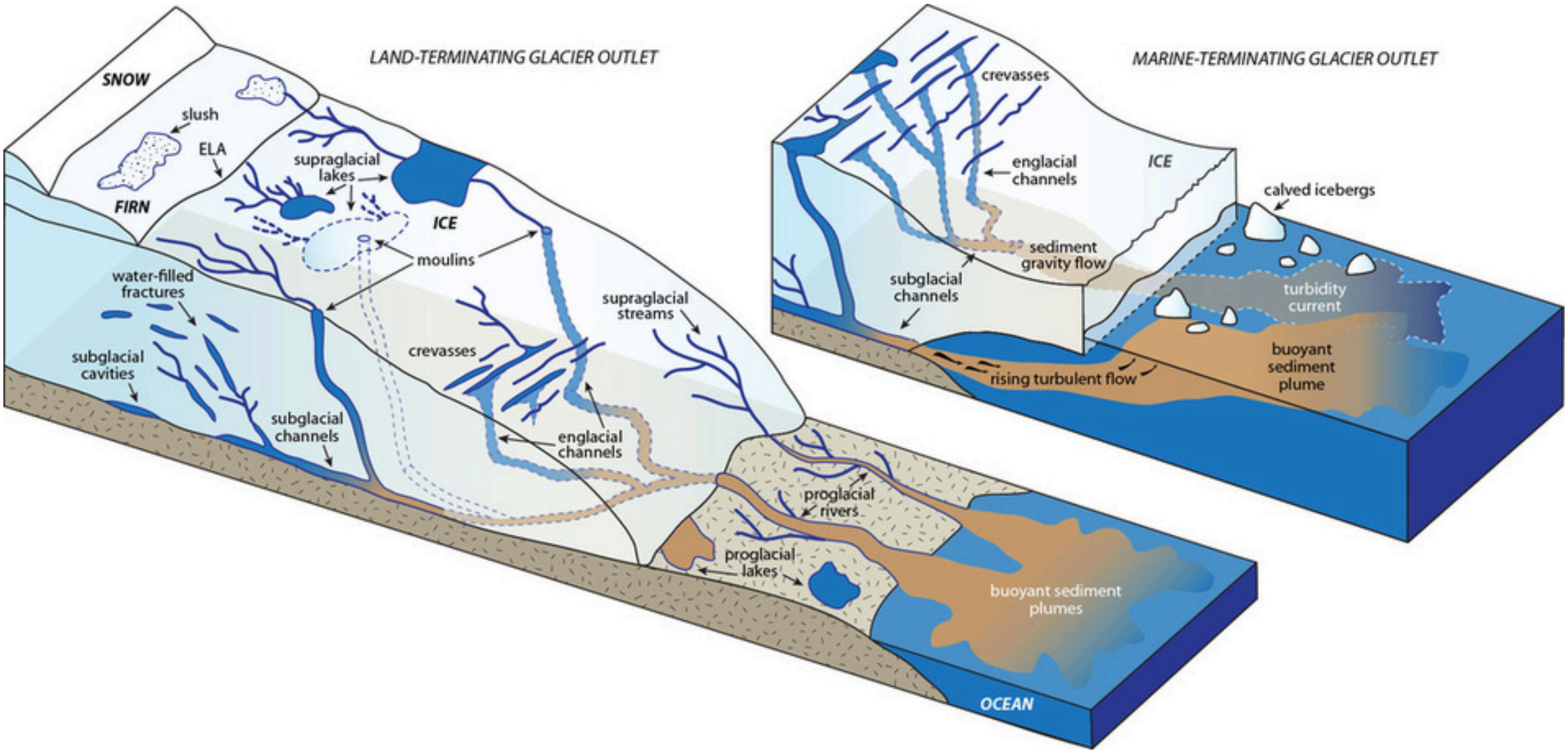
Glacial Hydrology

Where glacial hydrology lives



Why glaciologists care about hydrology

1. Water content of ice has strong influence on ice viscosity (i.e. value of A or E)

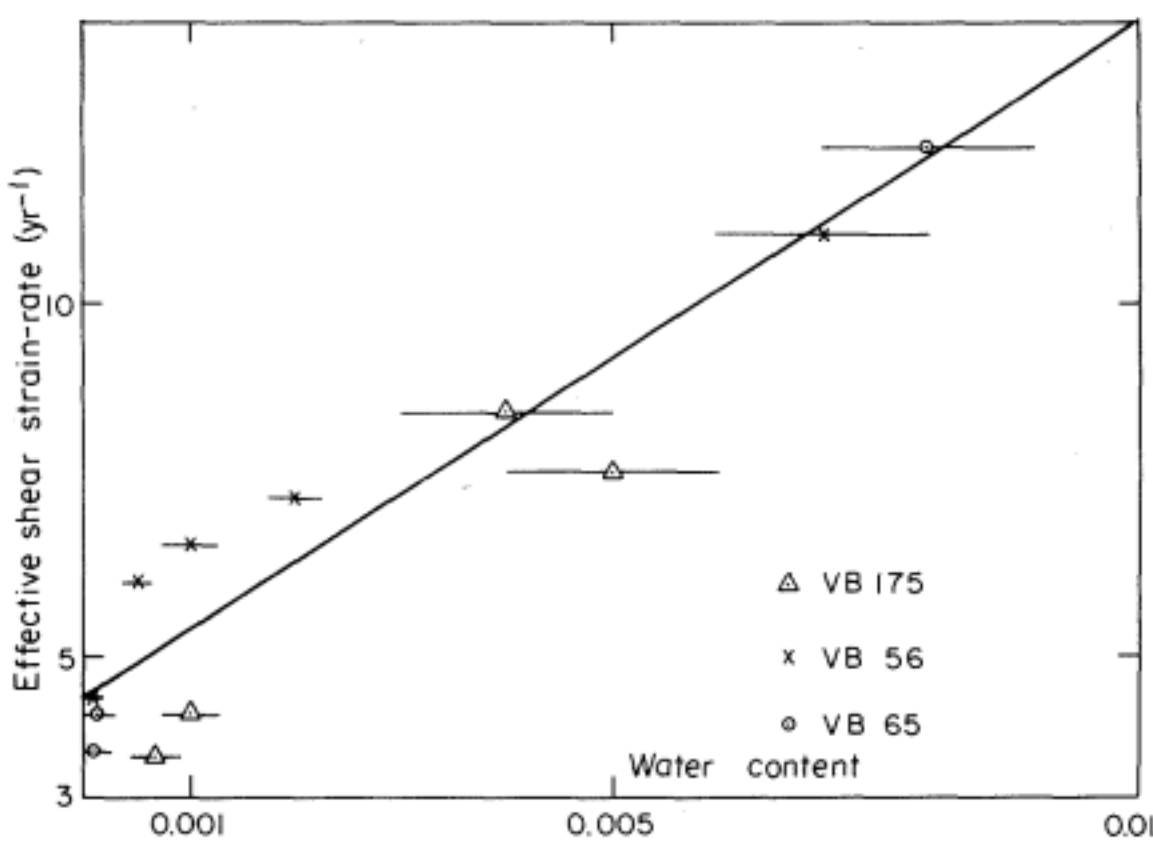


FIGURE 1. Tertiary effective shear strain rate *versus* water content. Effective shear stress τ = 2.90 b.

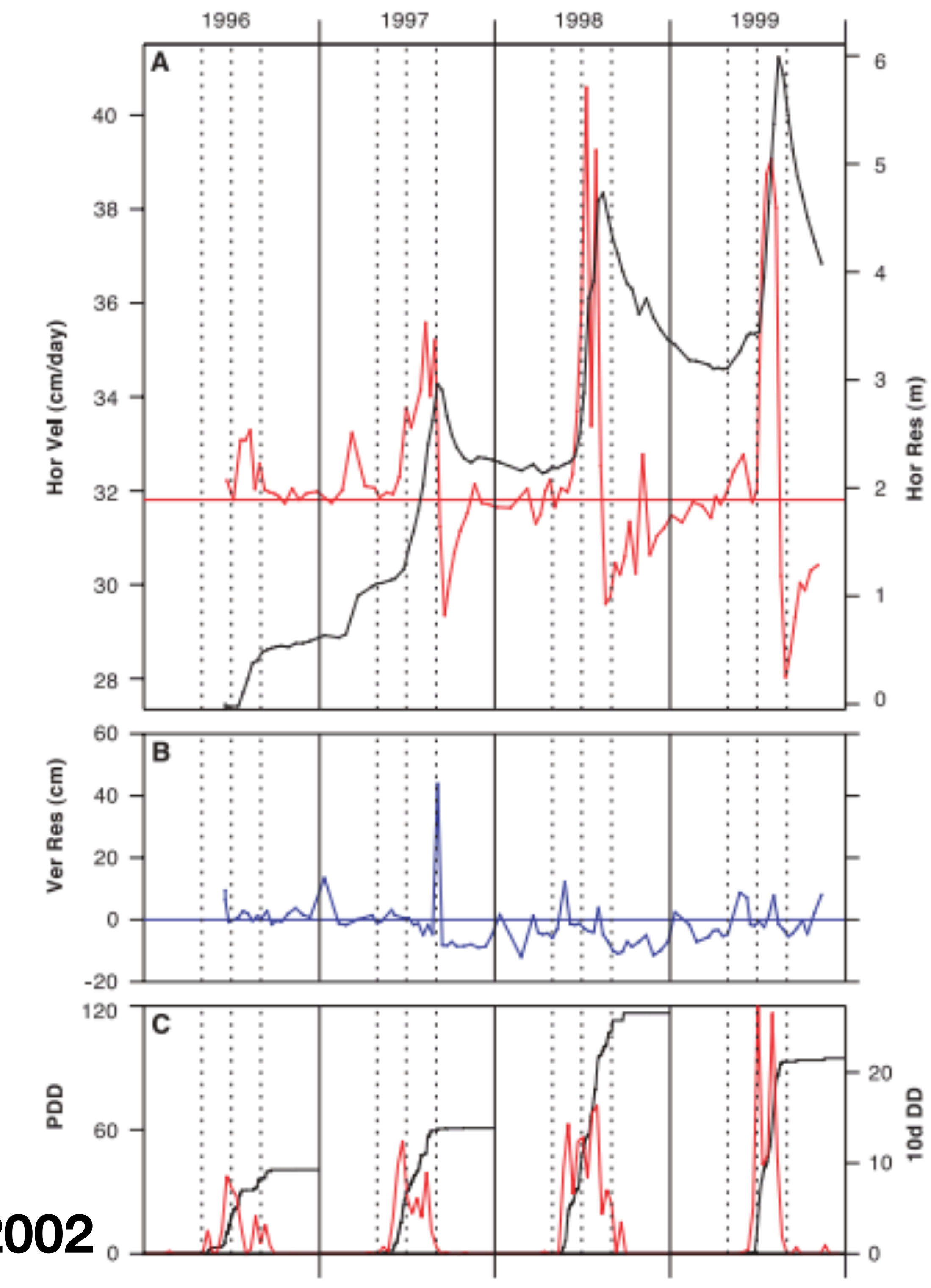
Duval 1977

Why glaciologists care about hydrology

2. Water is an important process that causes subglacial erosion (of ice and rock/sediment)

Why glaciologists care about hydrology

3. Water at the ice-bed interface can influence the rate of sliding or till deformation



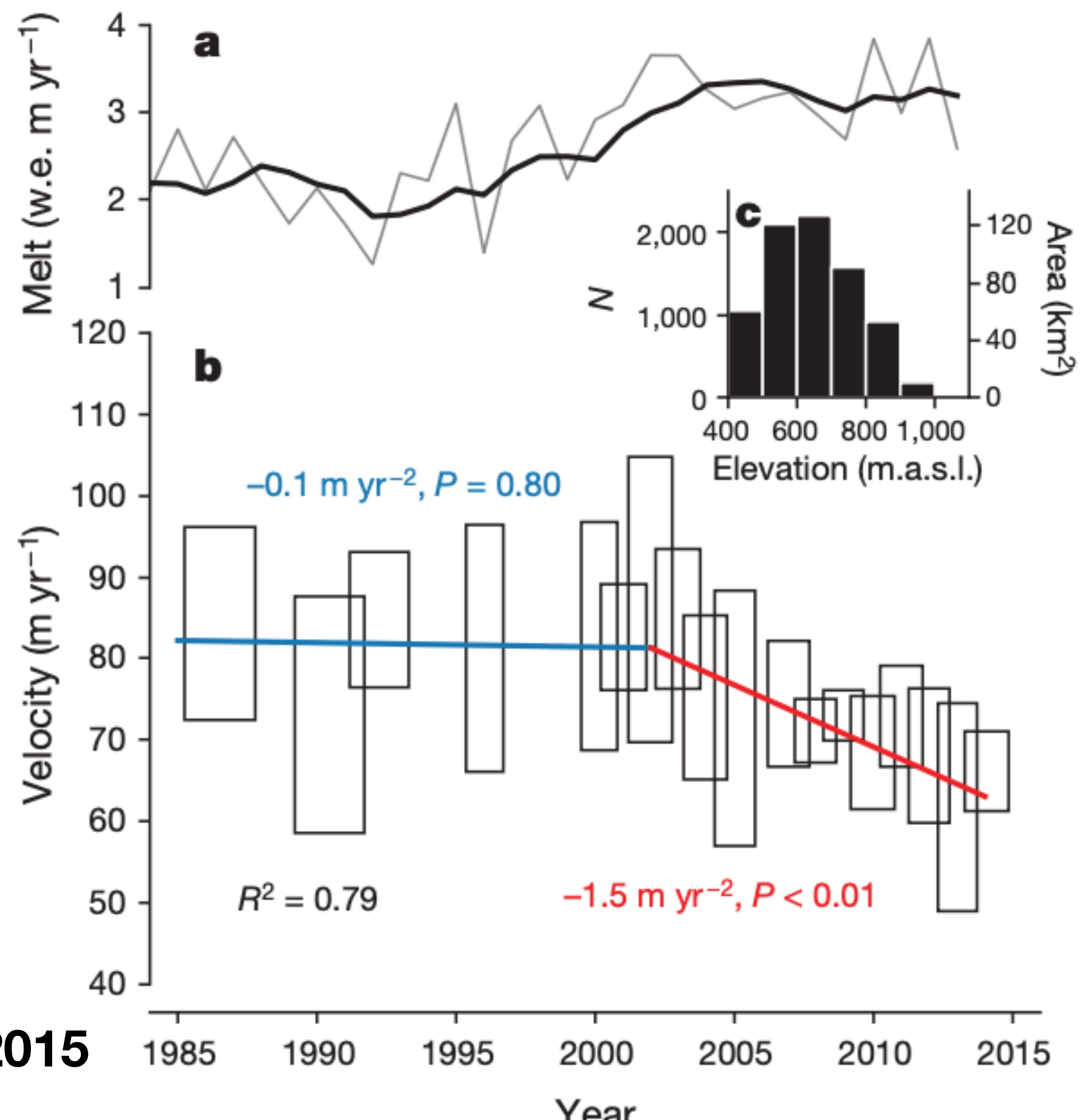
Water lubricates ice flow?

Zwally et al. 2002

Why glaciologists care about hydrology

3. Water at the ice-bed interface can influence the rate of sliding or till deformation

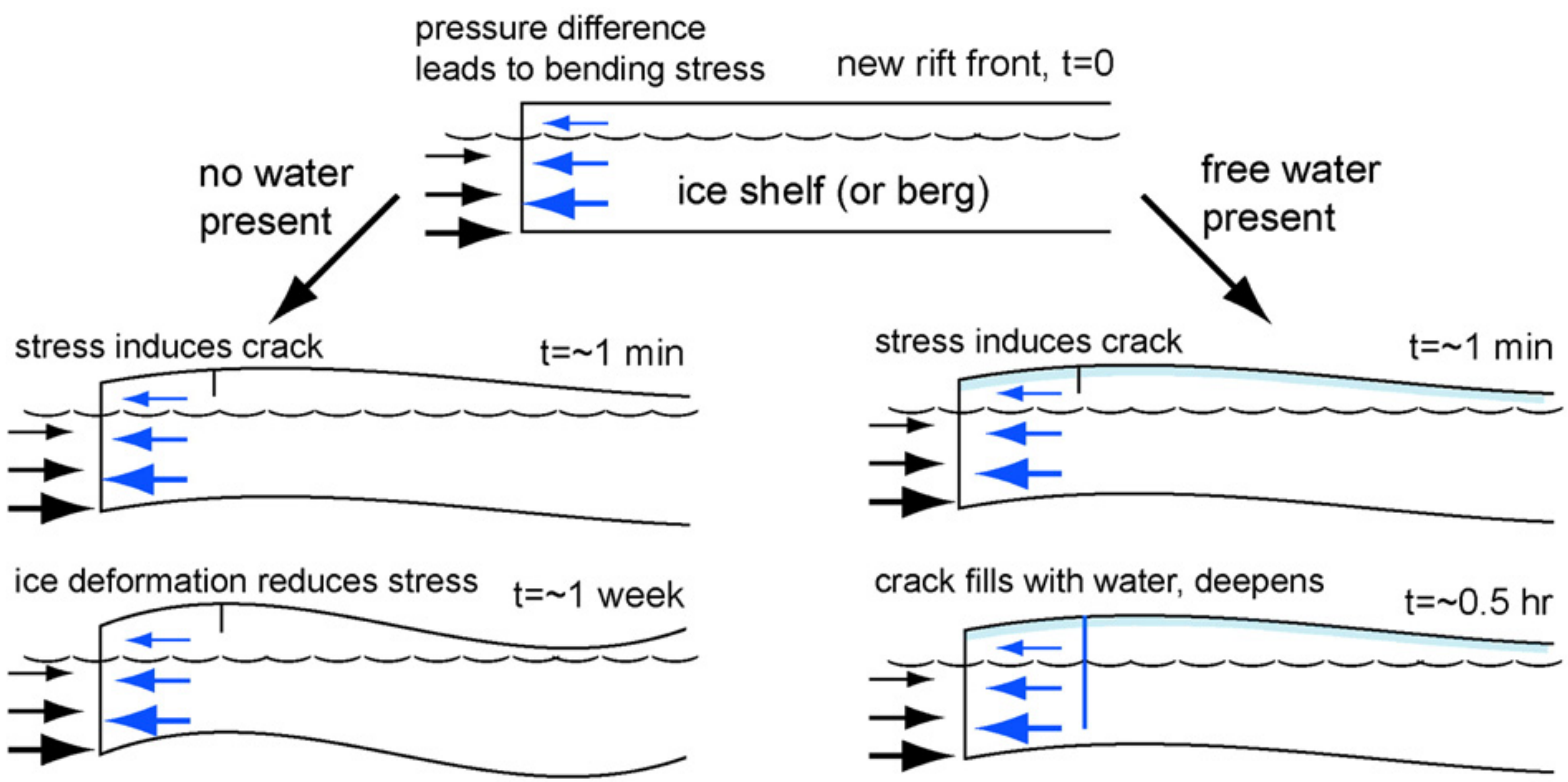
Water organizes drainage, reducing ice flow?



Tedstone et al. 2015

Why glaciologists care about hydrology

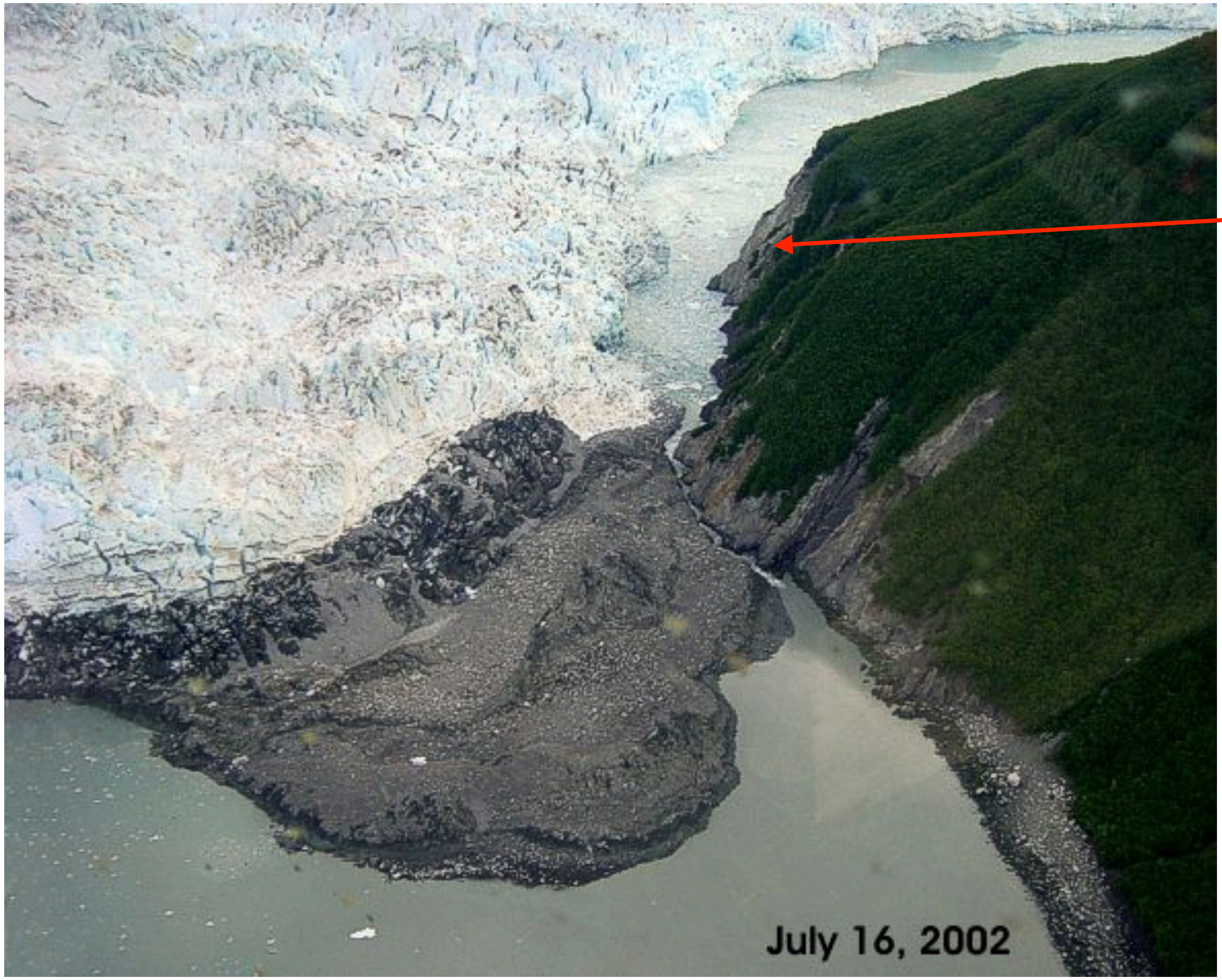
4. Water at surface can influence the rate of fracturing and calving



Scambos et al. 2009

Why everyone cares about glacial hydrology

1. Glacier dammed lakes can burst leading to loss of life and property



Waterway closed off from ocean by advancing glacier, rose 20 meters in 10 weeks

Why everyone cares about glacial hydrology

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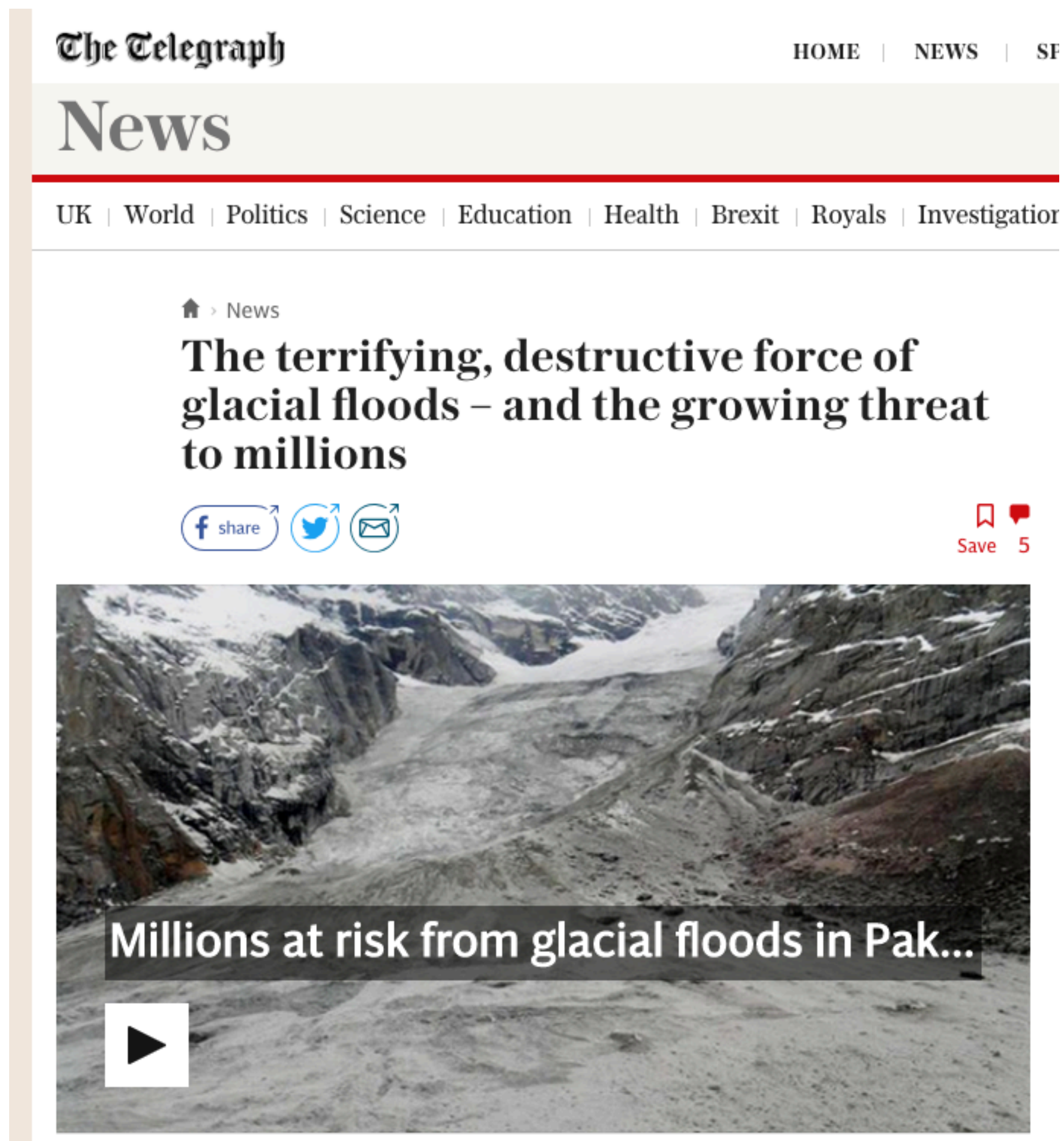

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News

The terrifying, destructive force of glacial floods – and the growing threat to millions

share

Save 5

Why everyone cares about glacial hydrology

2. Hydroelectric power from glacier runoff is important power source for many in Europe and elsewhere

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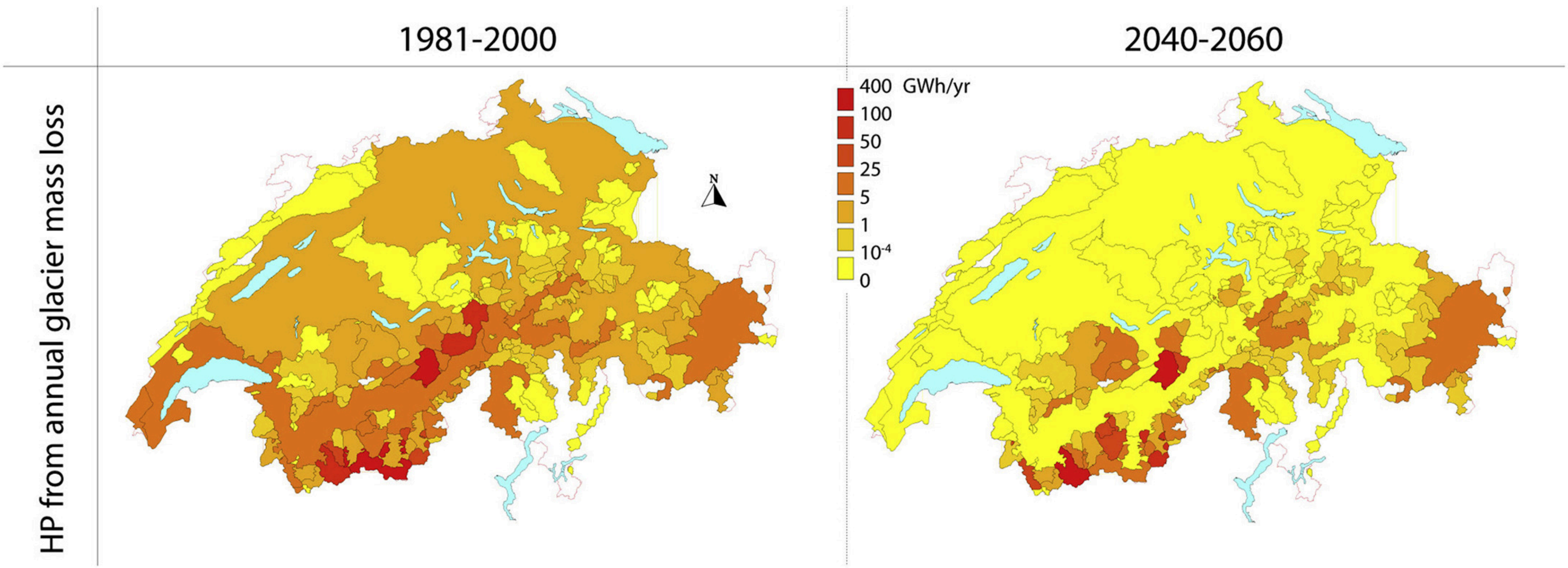
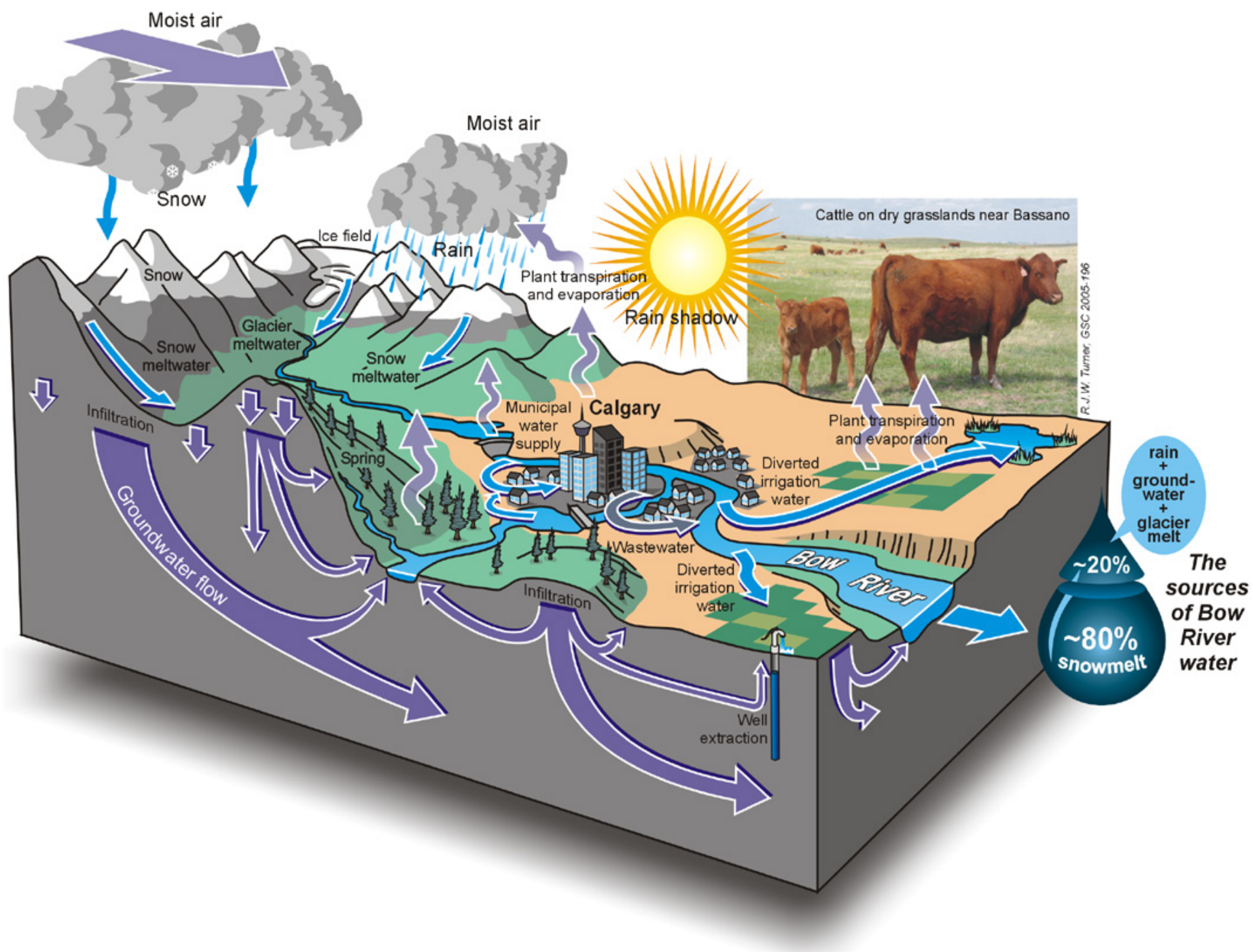


Why everyone cares about glacial hydrology

3. Glacier-fed rivers provide water supply for hundreds of millions of people



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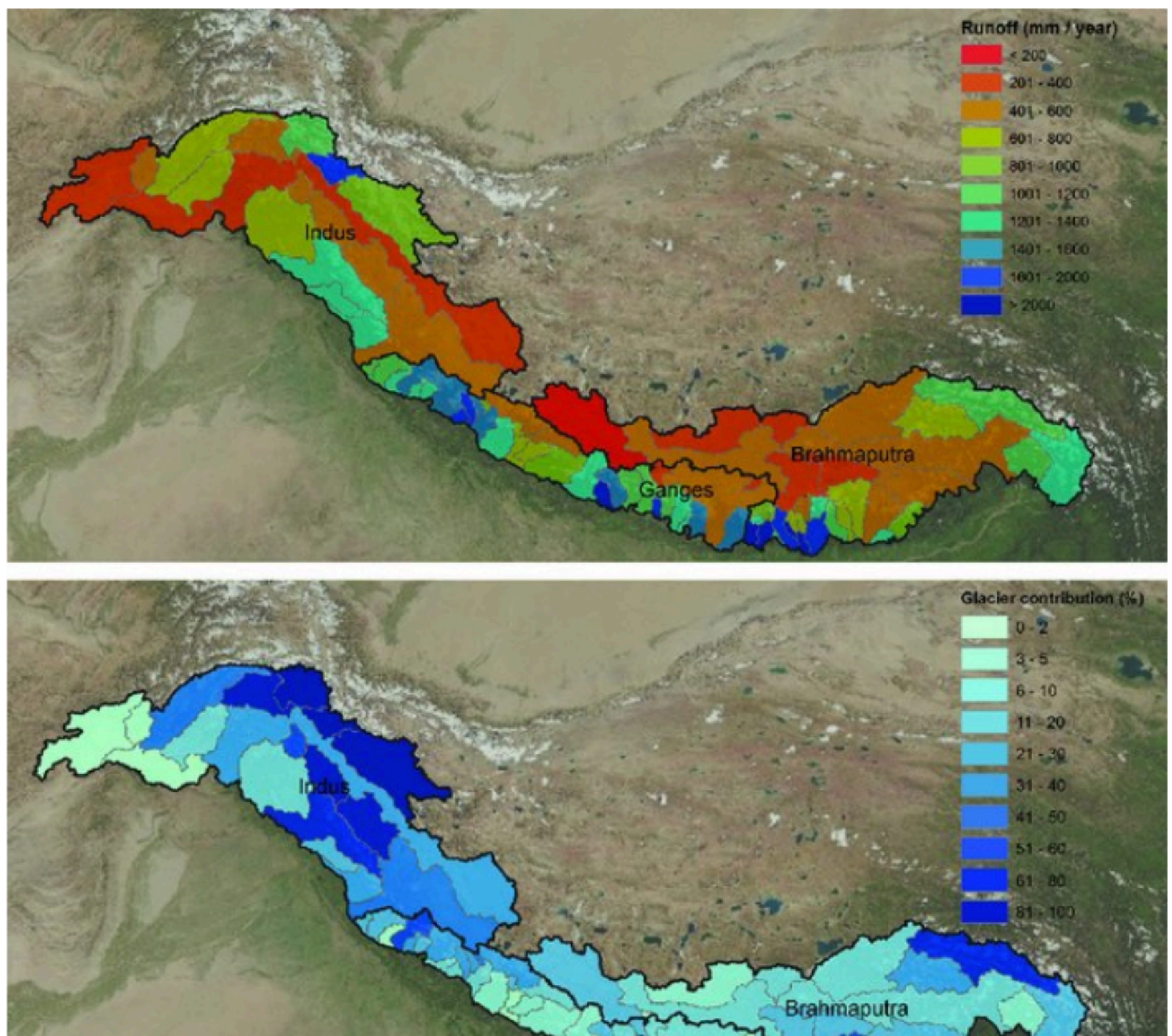

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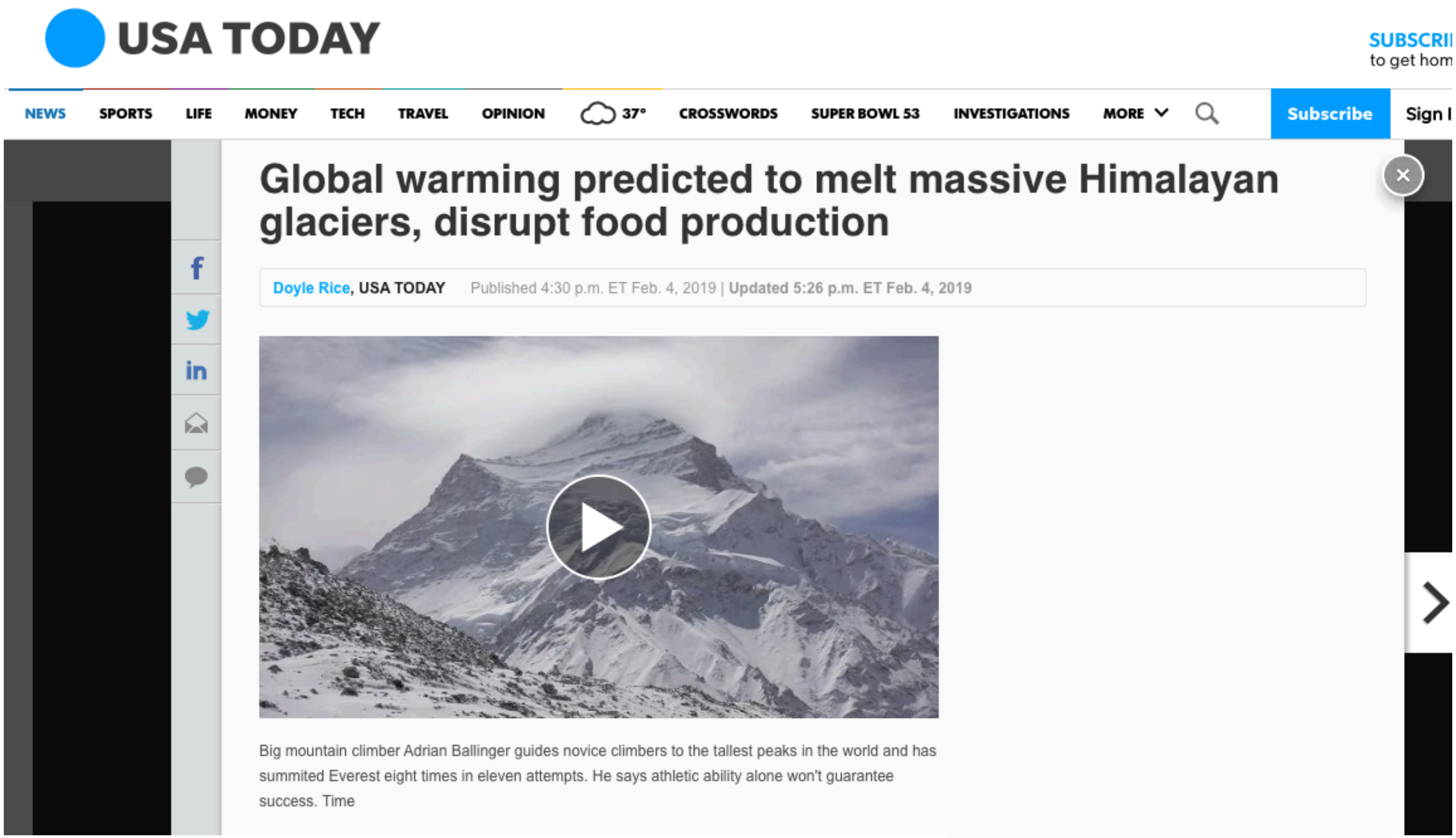

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Global warming predicted to melt massive Himalayan glaciers, disrupt food production

Doyle Rice, USA TODAY Published 4:30 p.m. ET Feb. 4, 2019 | Updated 5:26 p.m. ET Feb. 4, 2019

Big mountain climber Adrian Ballinger guides novice climbers to the tallest peaks in the world and has summited Everest eight times in eleven attempts. He says athletic ability alone won't guarantee success. Time

Why everyone cares about glacial hydrology

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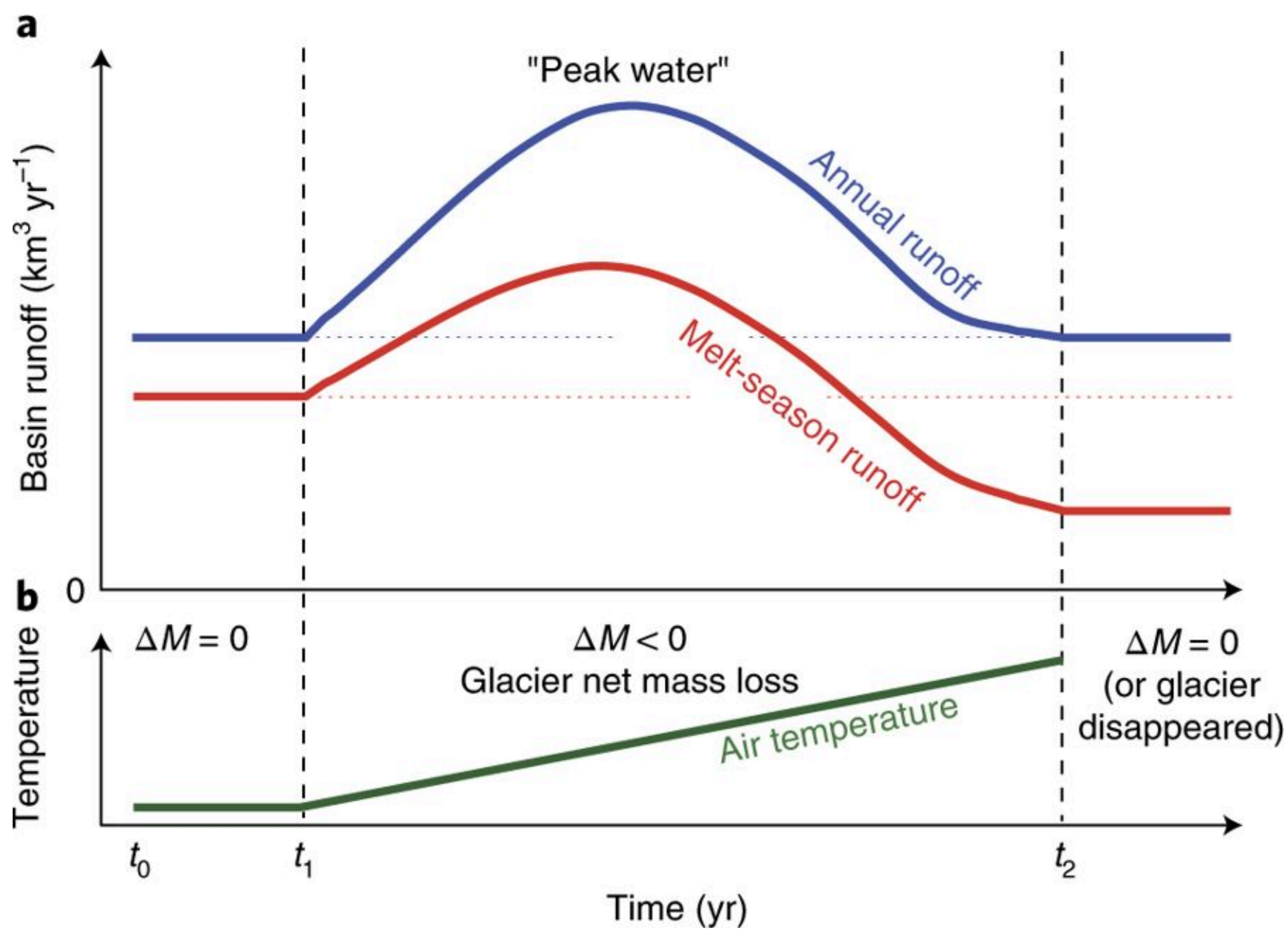

Huss & Hock 2018

Why everyone cares about glacial hydrology

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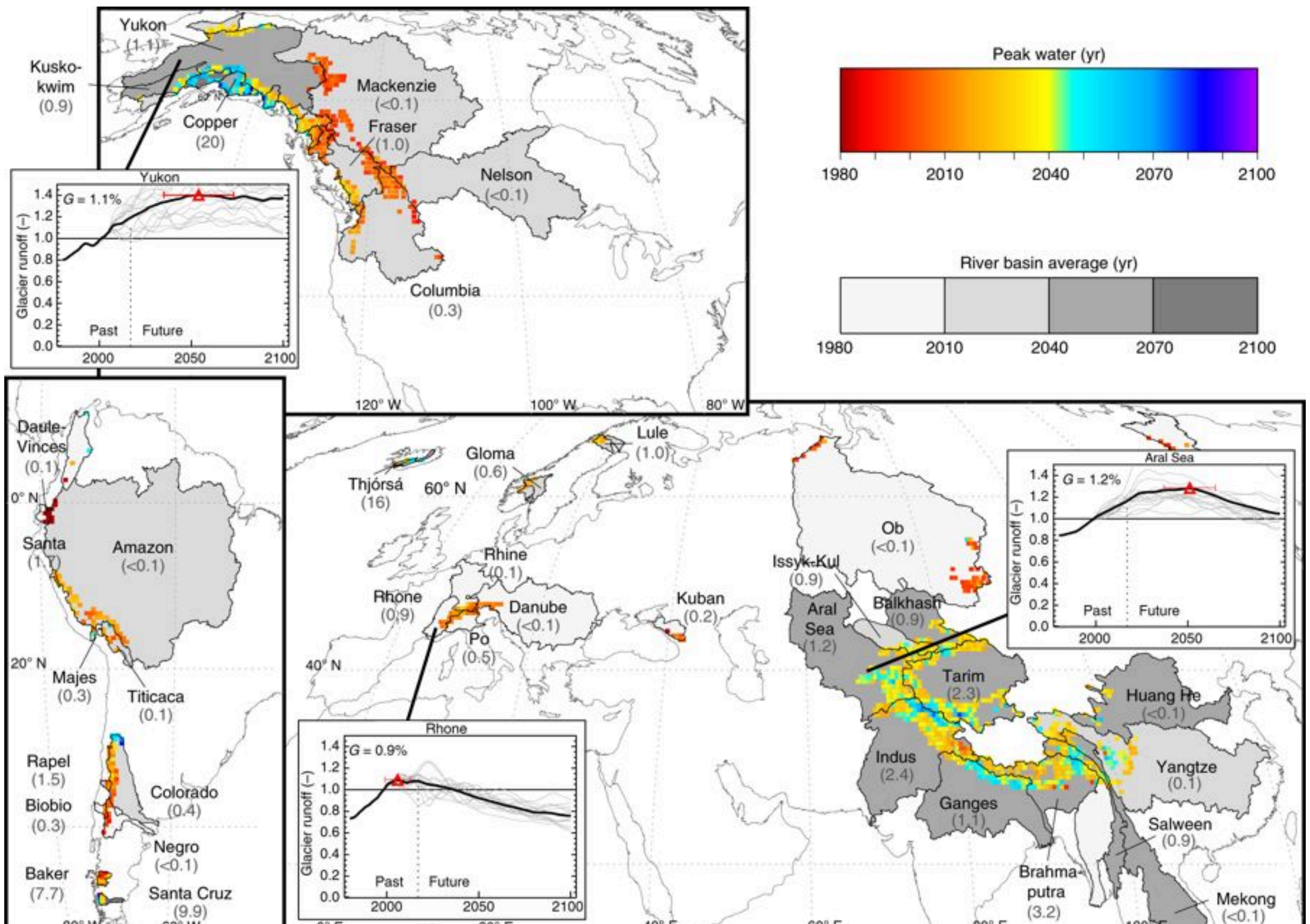
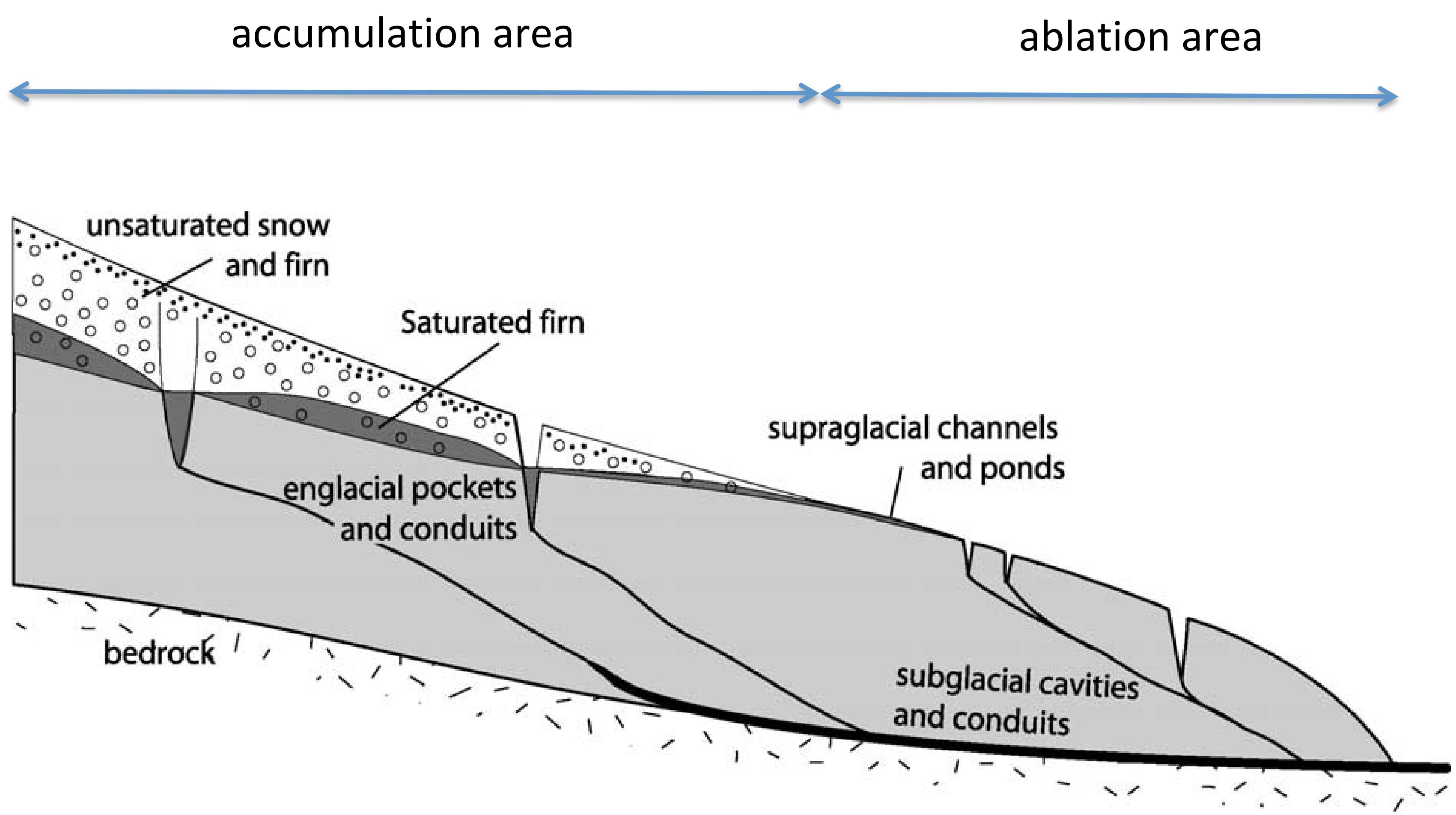


Huss & Hock 2018

Start at the glacier surface



Snow melts (where there is snow) and percolates down through the snowpack. It either:

(a) Stays in the snowpack and potentially refreezes at a later, colder time (wherein it forms an ice lens), or

(b) Reaches some ice surface (either the bottom of the firn layer or a previously-frozen ice lens) and then runs off horizontally

(c) Finds a fracture or moulin to move down into the glacier

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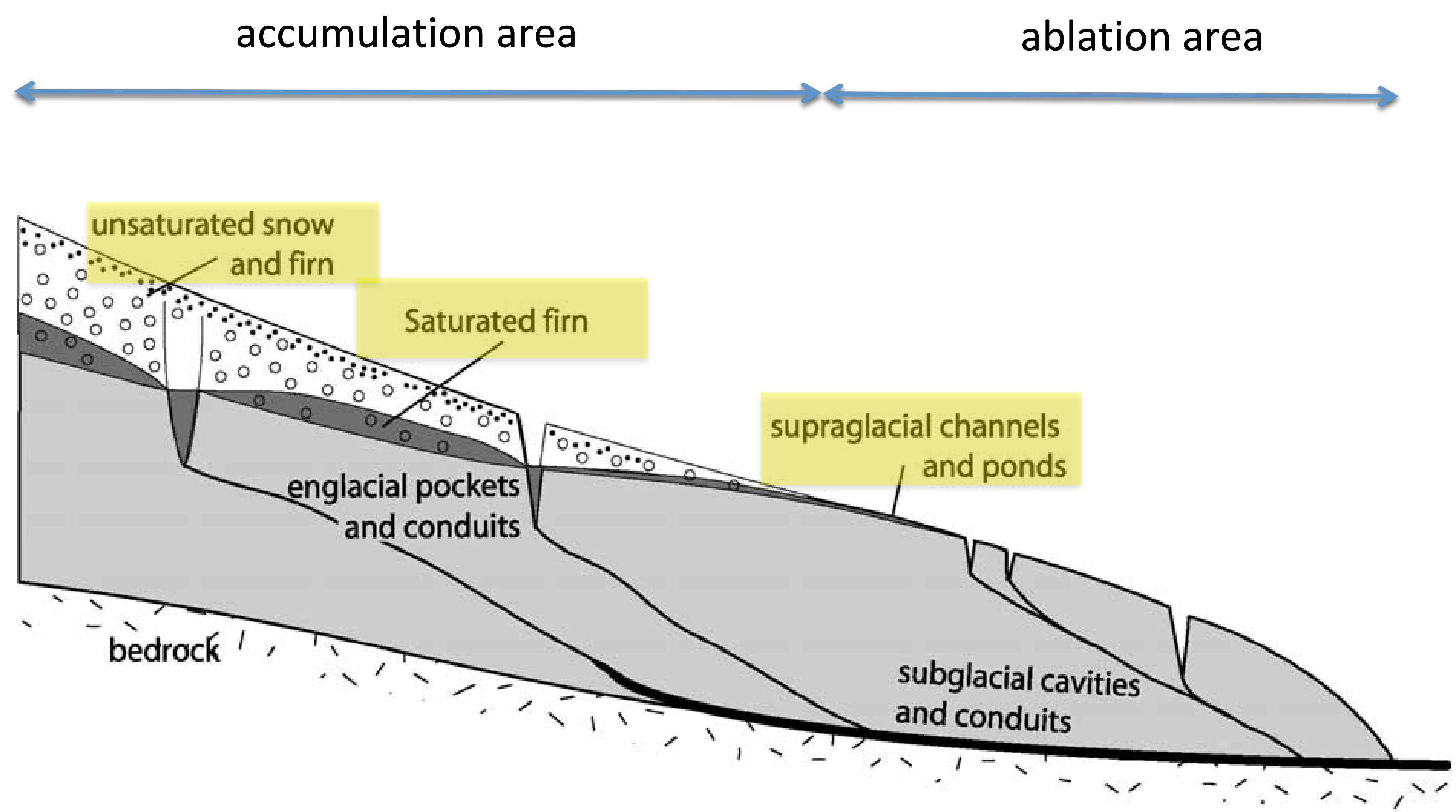

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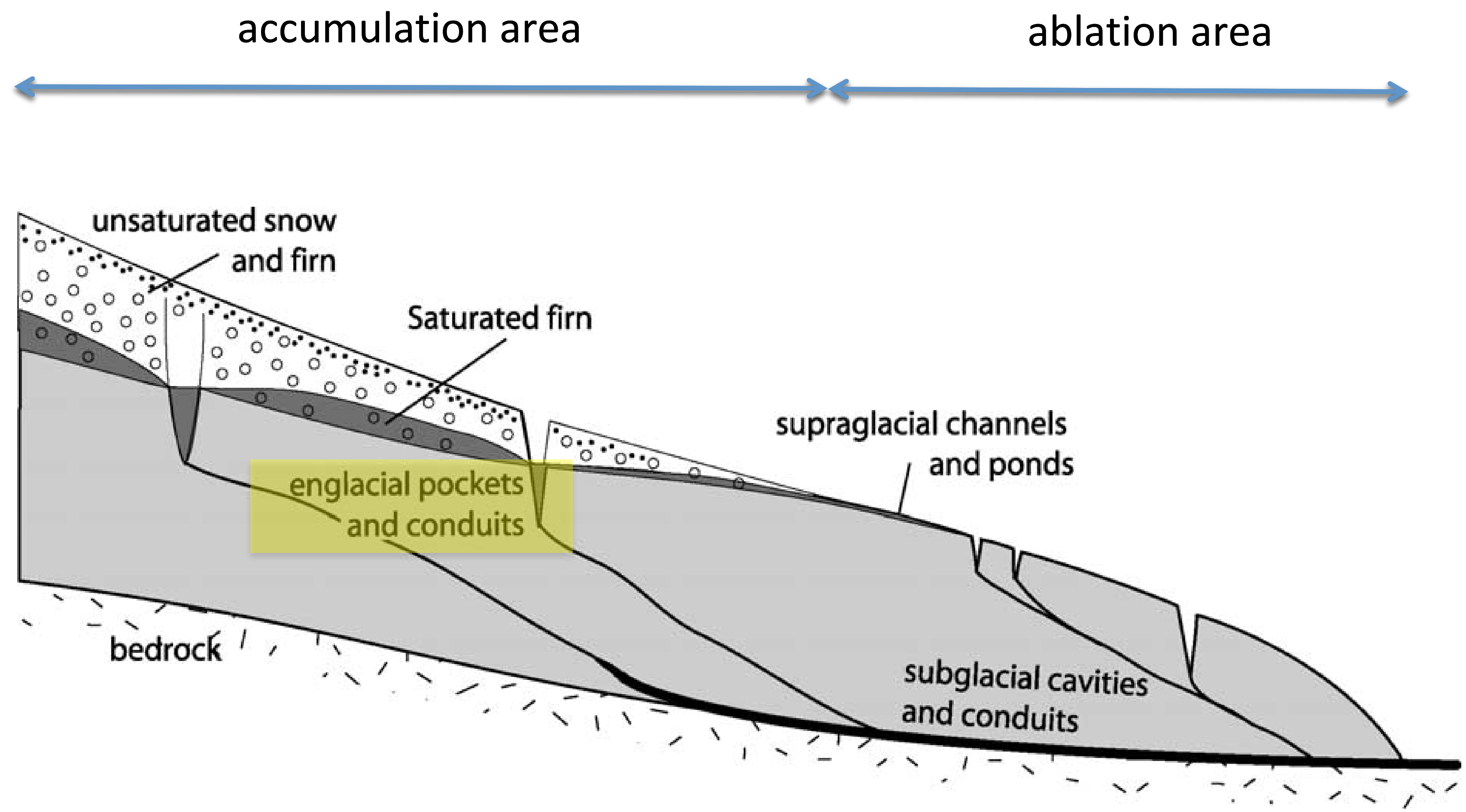

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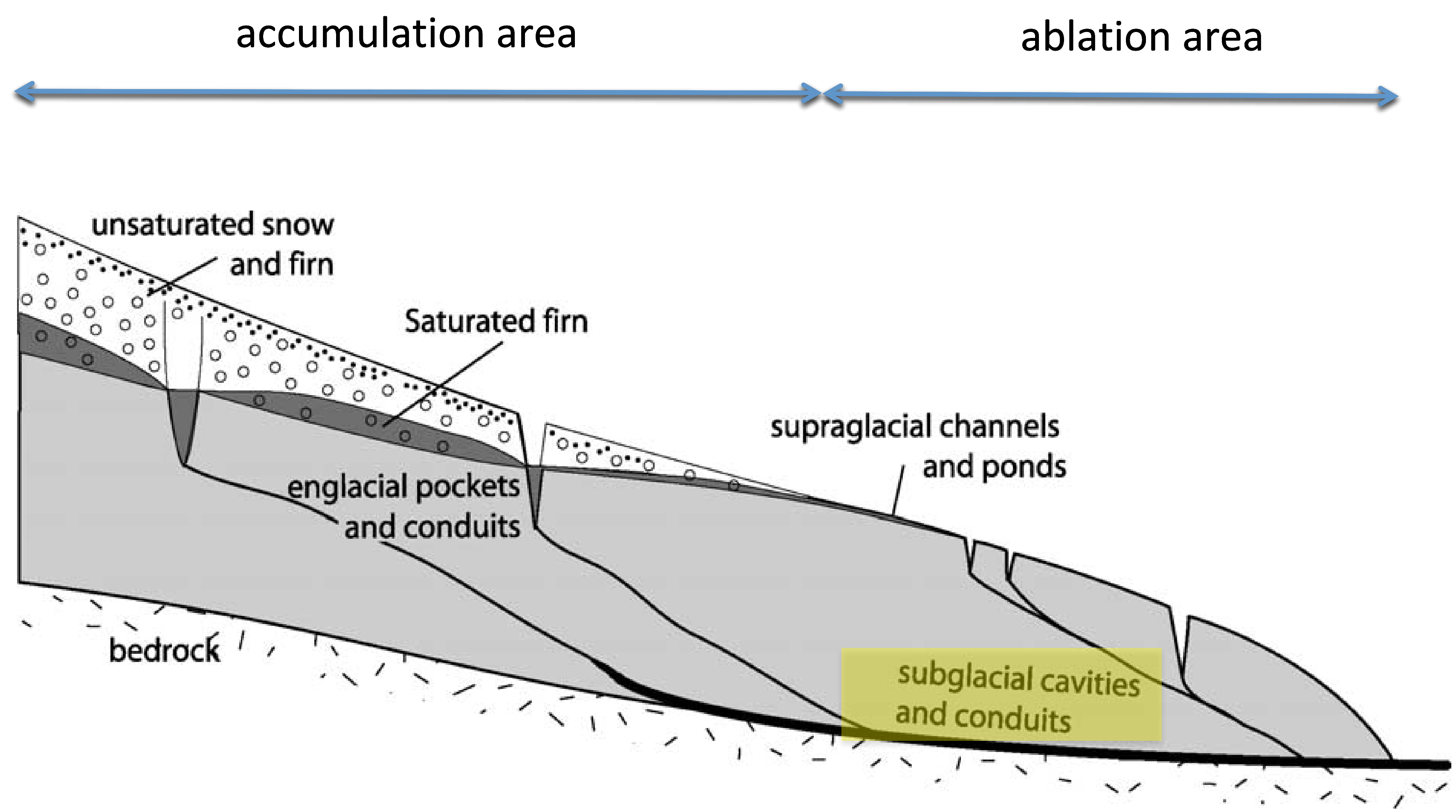

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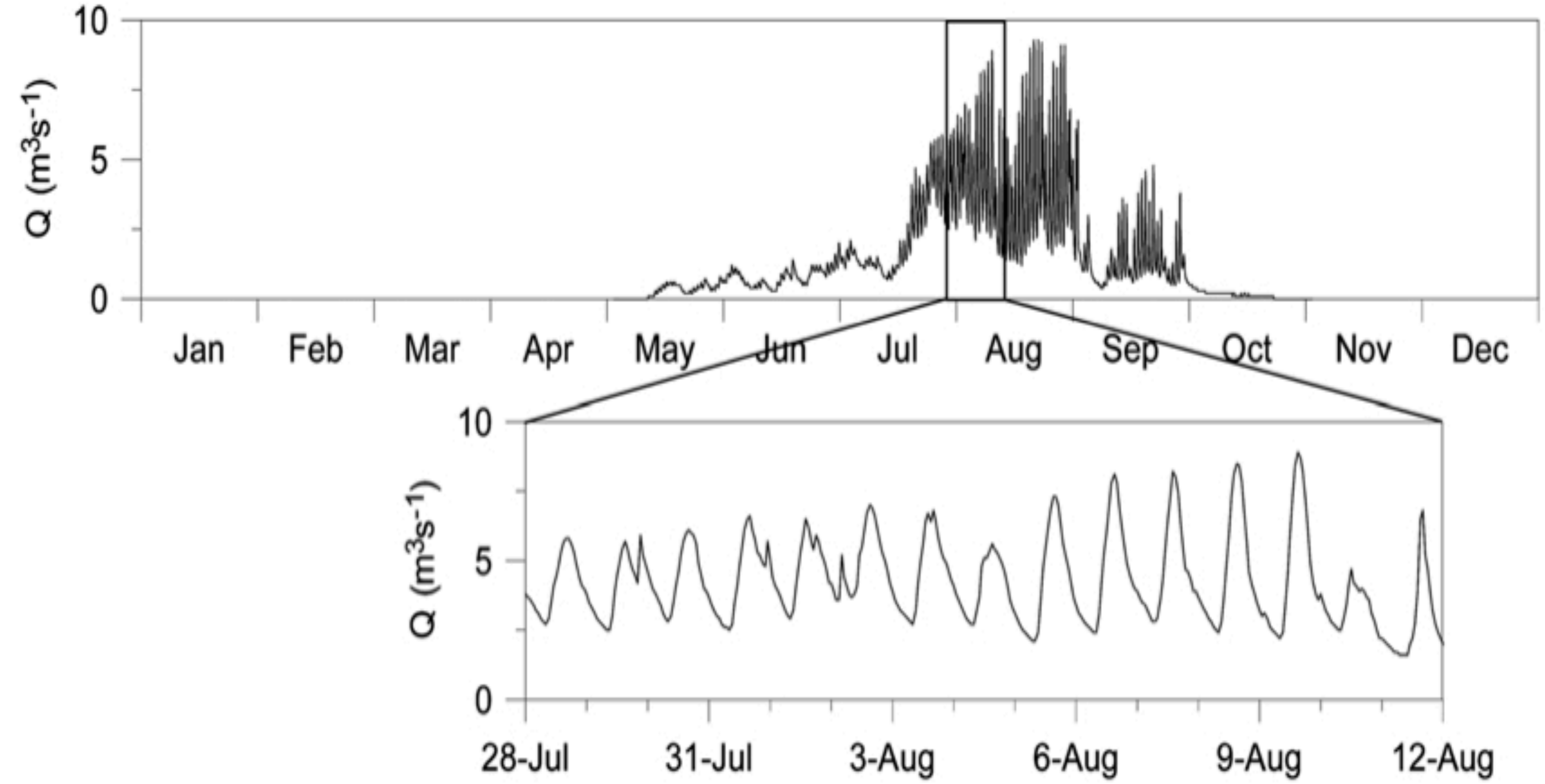
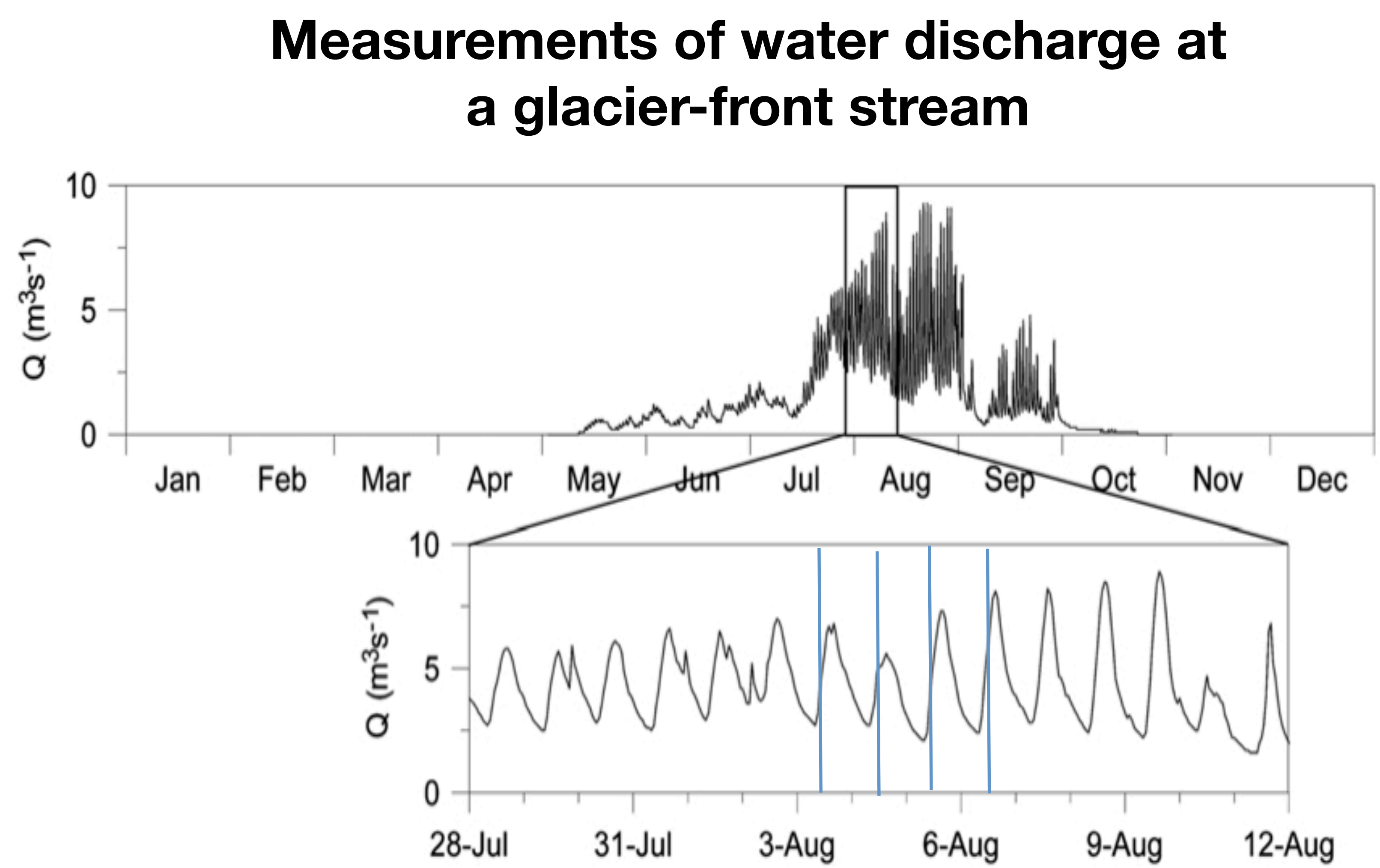
The journey of water to the glacier front

Measurements of water discharge at a glacier-front stream



The journey of water to the glacier front



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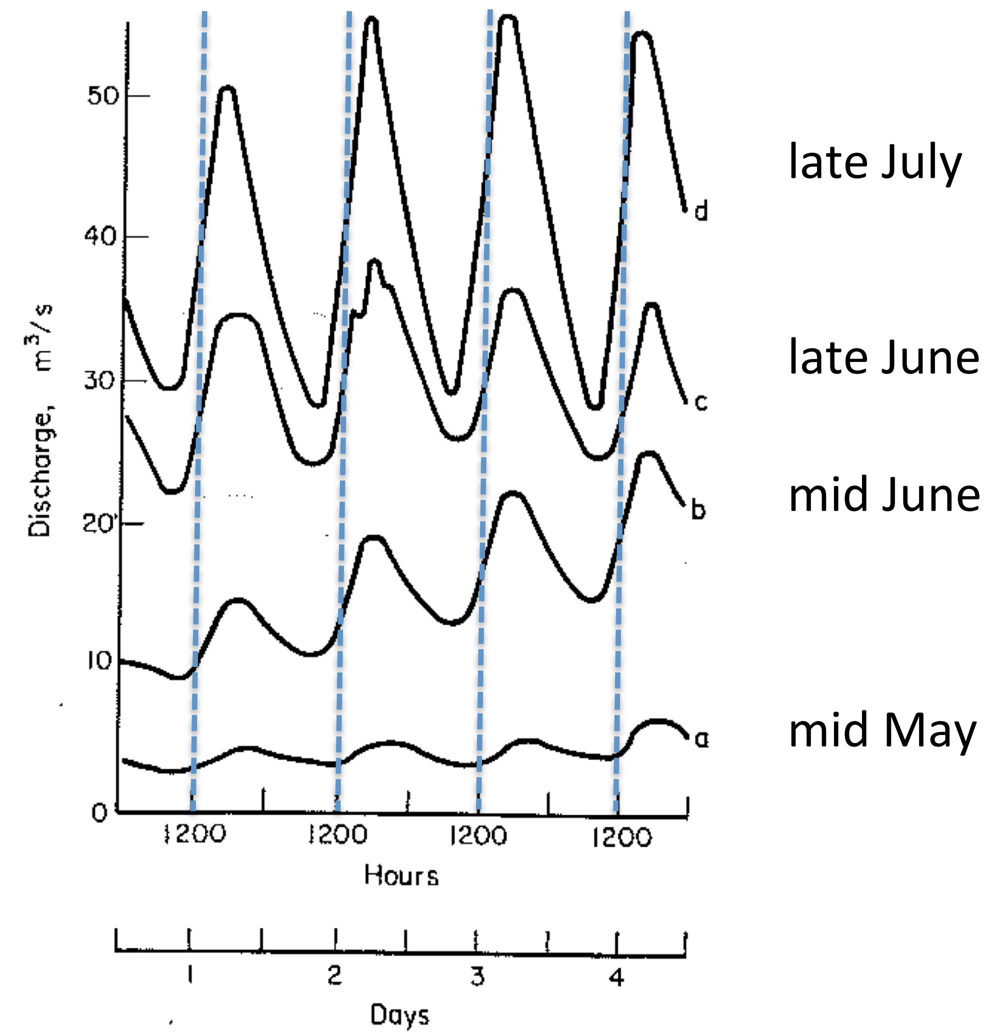


Why is there a delay between peak melt (at noon) at peak discharge? Why does it change over the course of the melt season?

The journey of water to the glacier front

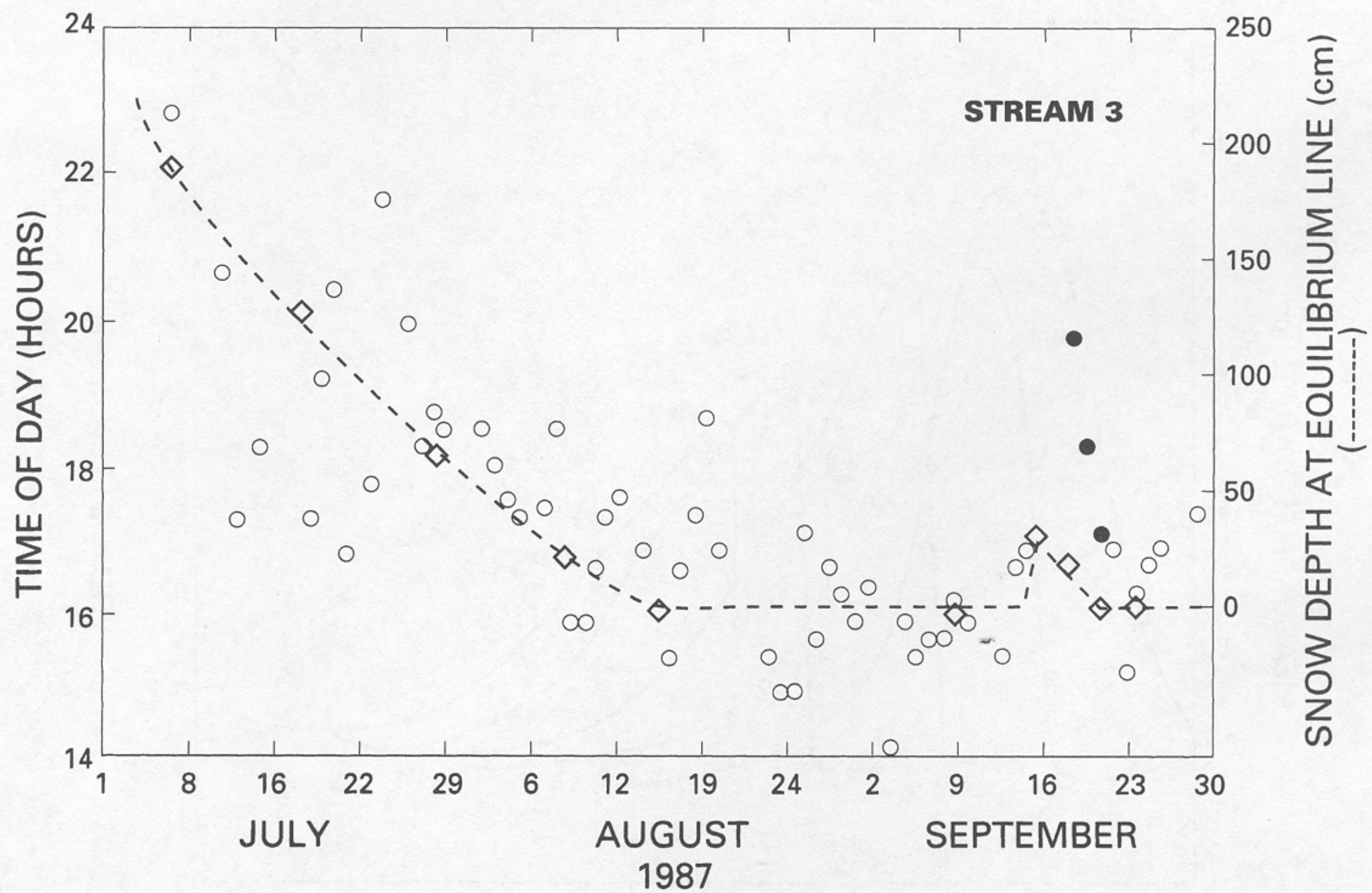
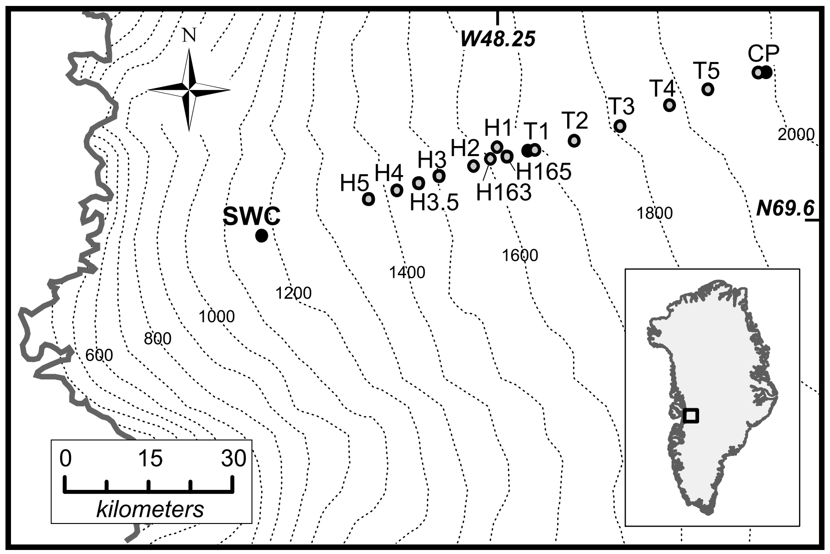
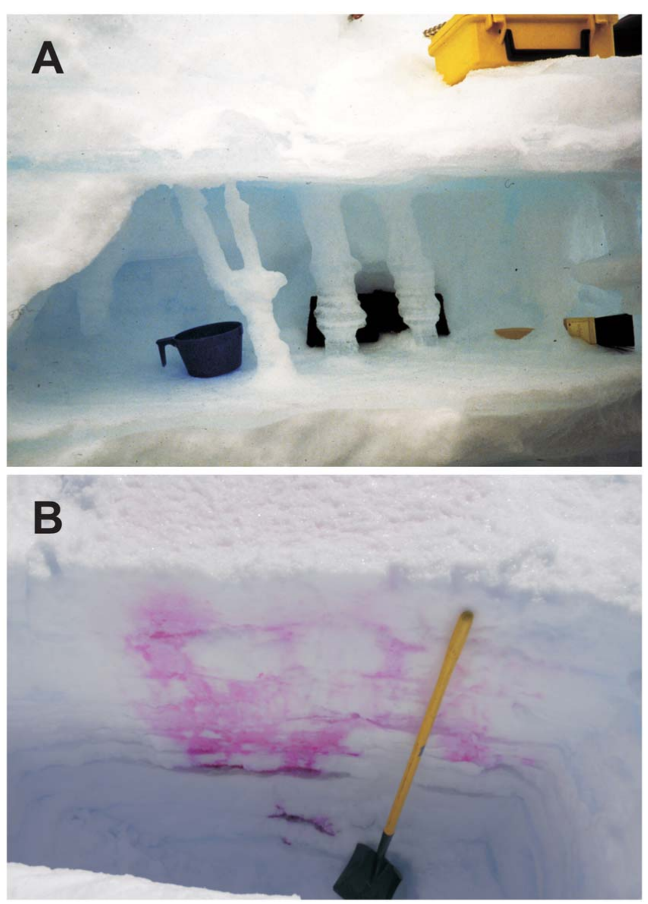


Figure 3. Time of daily peak water discharge for stream 3 at South Cascade Glacier, Washington, USA. The broken line is the interpolated snow depth at the equilibrium line; open diamonds indicate measured thickness; closed circles are times of peak daily discharge following a snowfall (adapted from Fountain, 1992b). Reproduced courtesy of the International Glaciological Society from the *Journal of Glaciology*, 1992, **38** (128), 191, figure 2

As snowpack melts, buffer between melt and water entry in hydrologic system is delayed! Glacier/snow hydrology is interesting between the aquifer medium is the solid phase of the liquid being stored.

Migration of water through snowpack





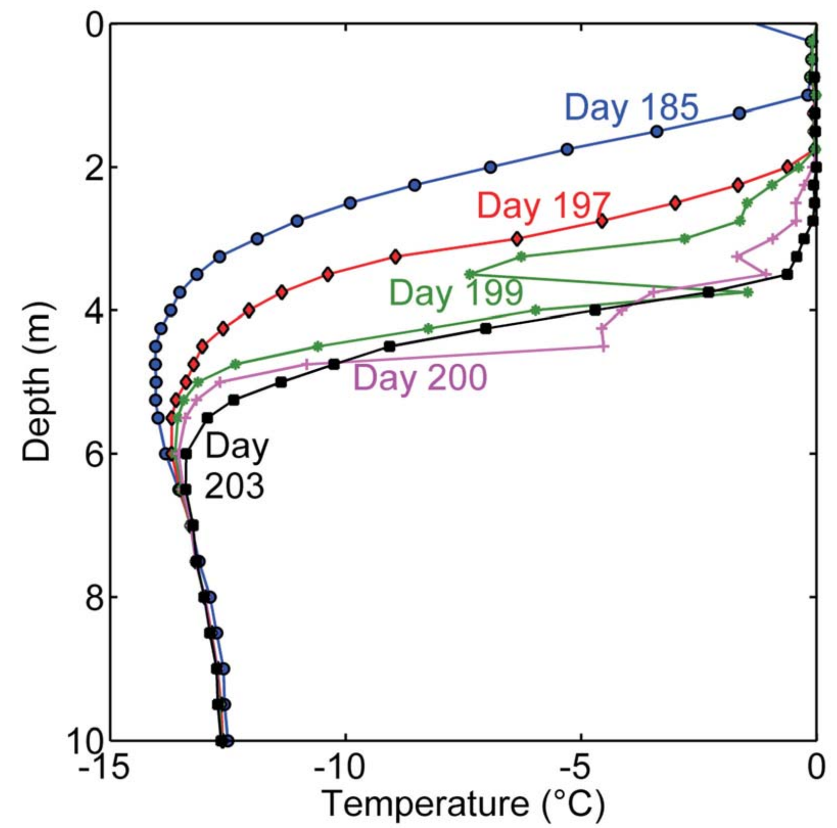
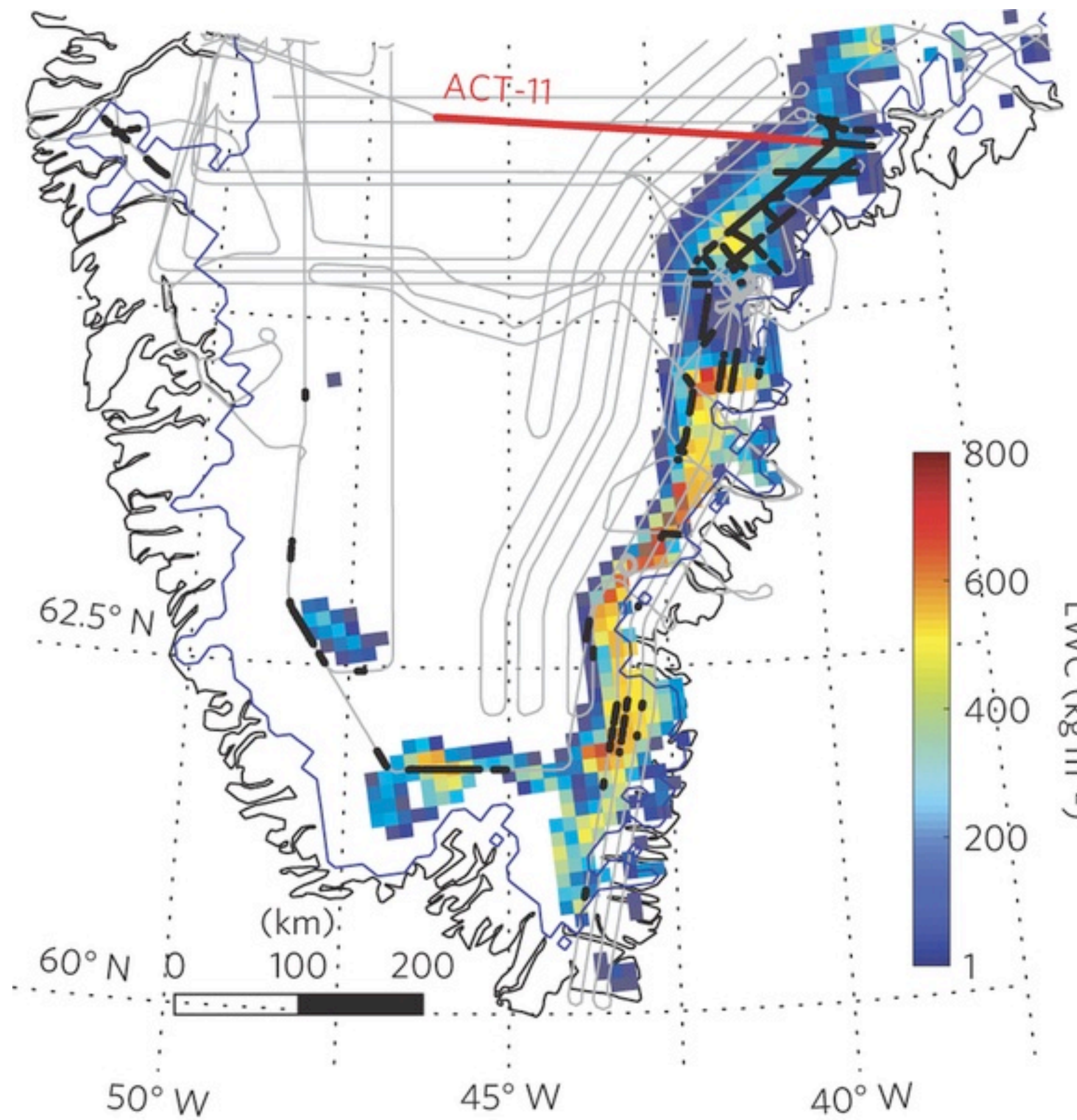


Figure 7. Five time slices of temperature versus depth during the summer of 2007 at site T2 showing wetting front migration. On day 185 (5 July) the upper 1 m of the firn column was wetted and at 0°C. Slow downward motion of the wetting front moved the 0°C isotherm to more than 2 m depth by day 197. Significant piping events at depths > 4.5 m on days 197 and 199 are shown. These events warmed firn below the maximum depth of the wetting front. The wetting front halted downward progress at 3.75 m depth on day 200 (July 22).

Firn Aquifer



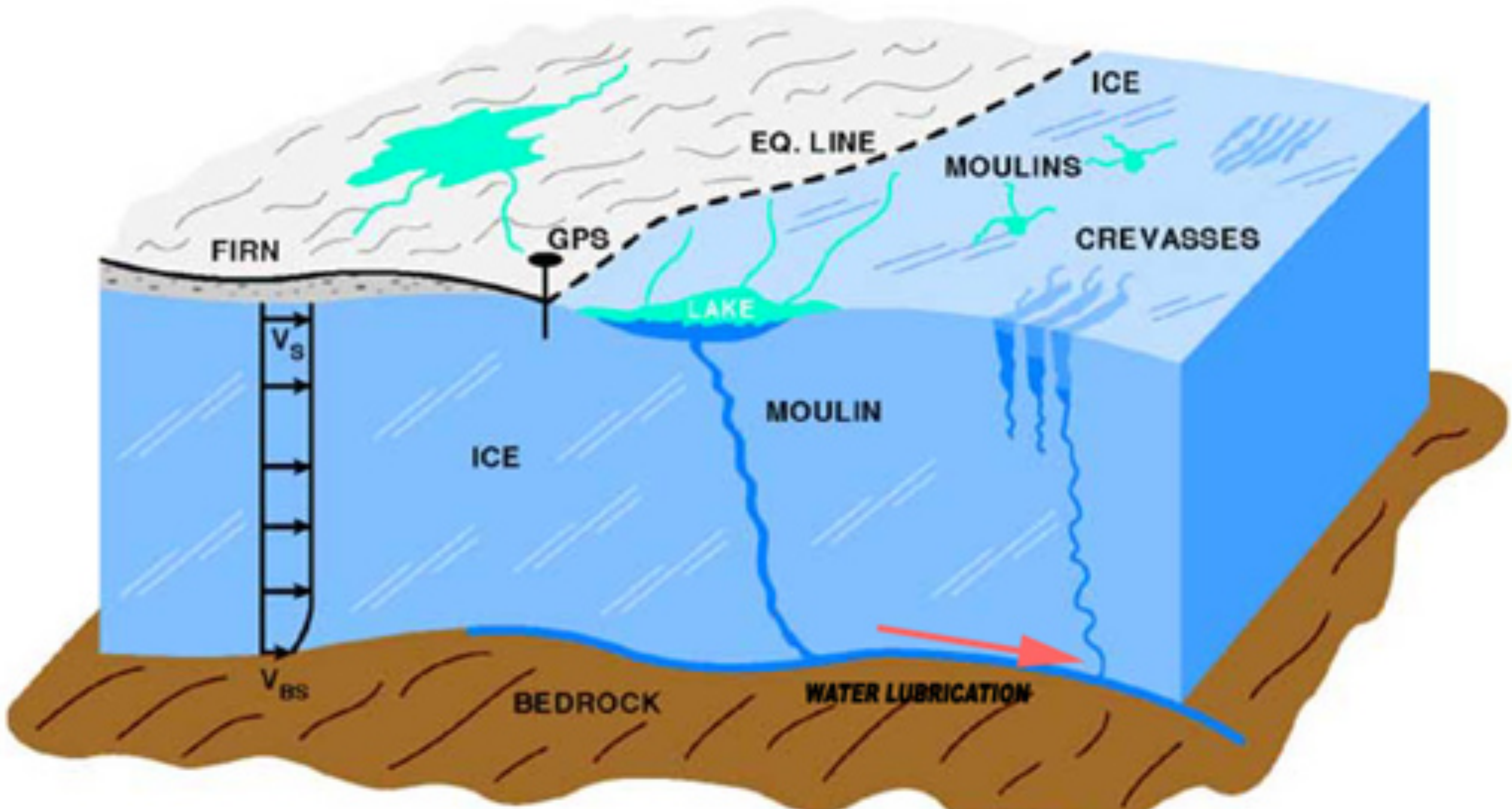
Firn aquifer can be quite extensive!

Supraglacial lakes

Where there is bare ice and a depression in the ice, lakes (up to many kms in diameter) can form. This is especially prominent in Greenland, though this also happens at the edges of some mountain glaciers

Supraglacial lake drainage

Moulin is an englacial pathway though which surface meltwater (from a lake or stream) can drain to the bed



GLACIOLOGICAL FEATURES OF A MOULIN

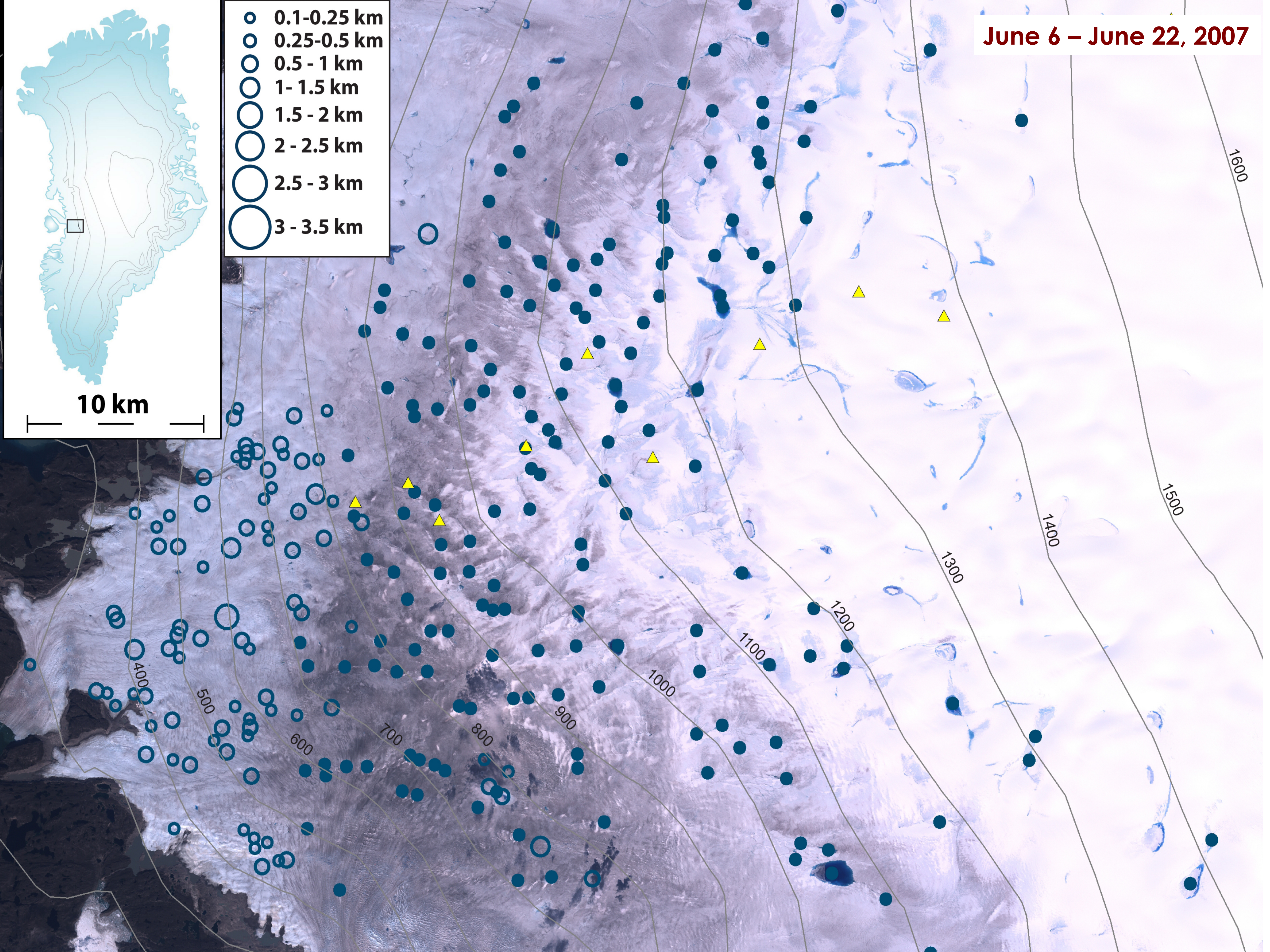
Supraglacial lake drainage

Movie 3

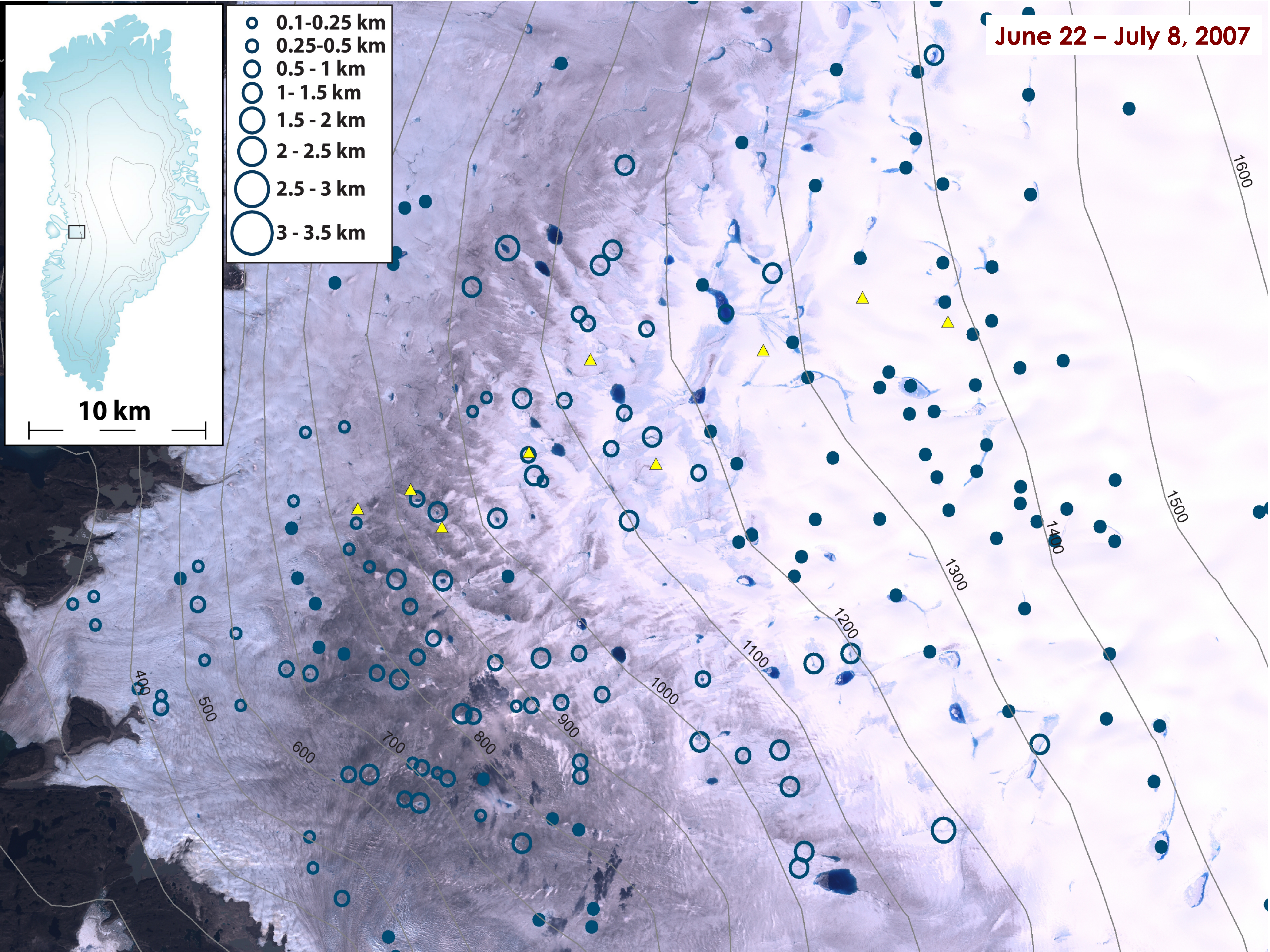
Network Inversion Filter results for the 2013 North Lake rapid drainage

(Stevens et al., 2015)

Crack forming top-down or down-top? (Stevens et al. 2015)



June 6 – June 22, 2007
0.1-0.25 km
0.25-0.5 km
0.5 - 1 km
1- 1.5 km
1.5 - 2 km
2 - 2.5 km
2.5 - 3 km
3 - 3.5 km
10 km
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
1600



June 22 – July 8, 2007
0.1-0.25 km
0.25-0.5 km
0.5 - 1 km
1- 1.5 km
1.5 - 2 km
2 - 2.5 km
2.5 - 3 km
3 - 3.5 km
10 km
400
500
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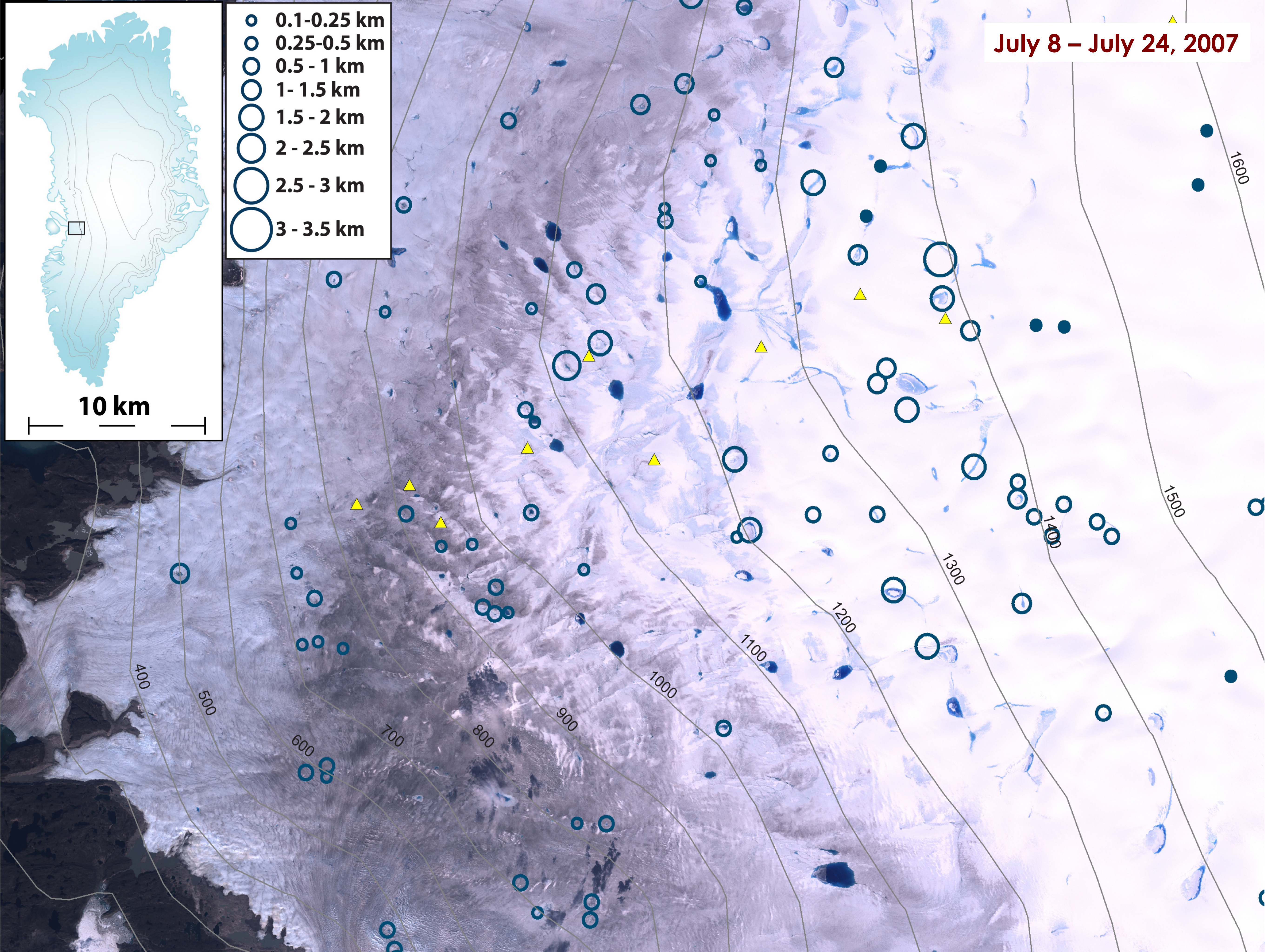

July 8 – July 24, 2007
0.1-0.25 km
0.25-0.5 km
0.5 - 1 km
1- 1.5 km
1.5 - 2 km
2 - 2.5 km
2.5 - 3 km
3 - 3.5 km
10 km
400
500
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700
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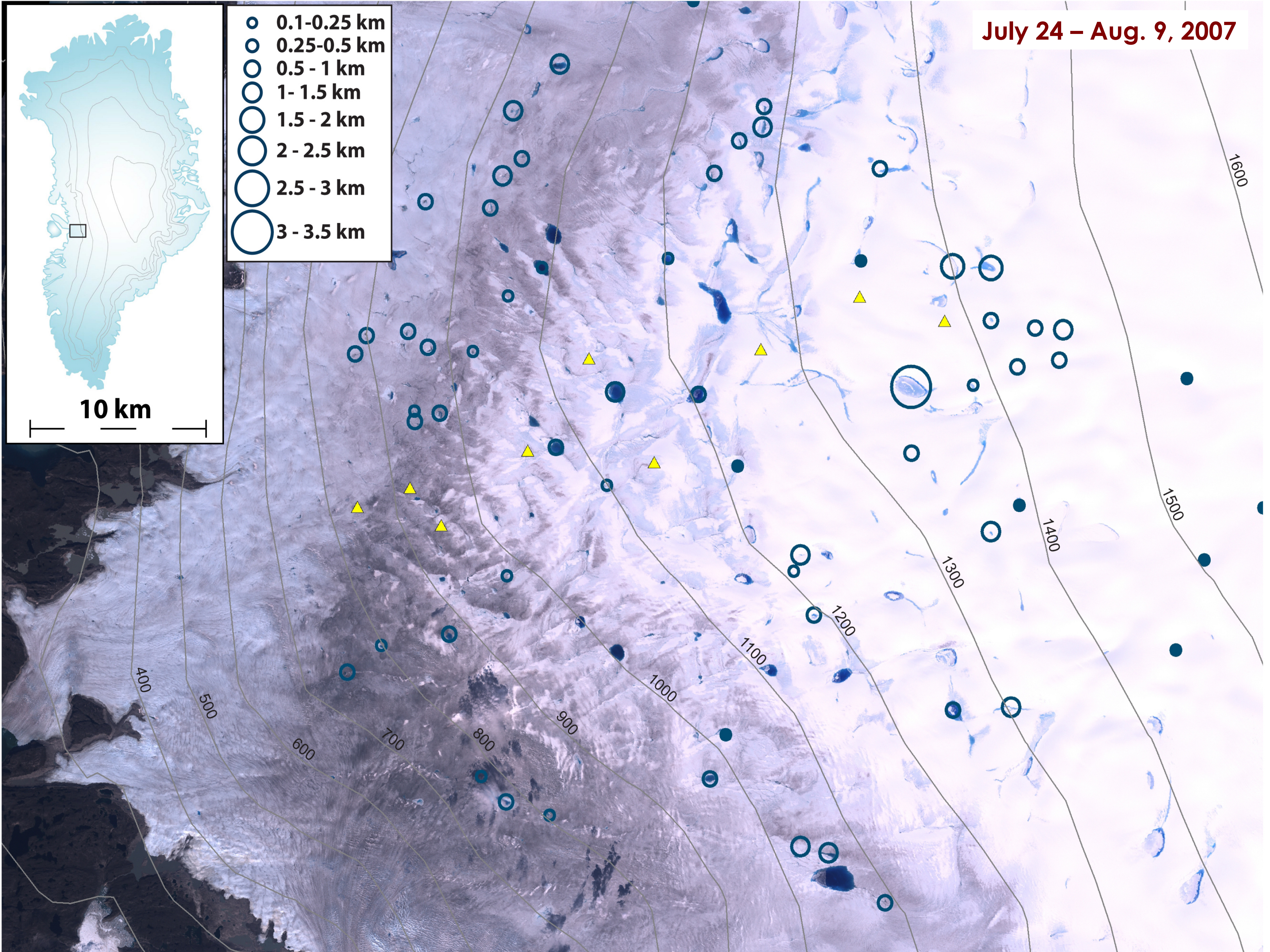

July 24 – Aug. 9, 2007
0.1-0.25 km
0.25-0.5 km
0.5 - 1 km
1- 1.5 km
1.5 - 2 km
2 - 2.5 km
2.5 - 3 km
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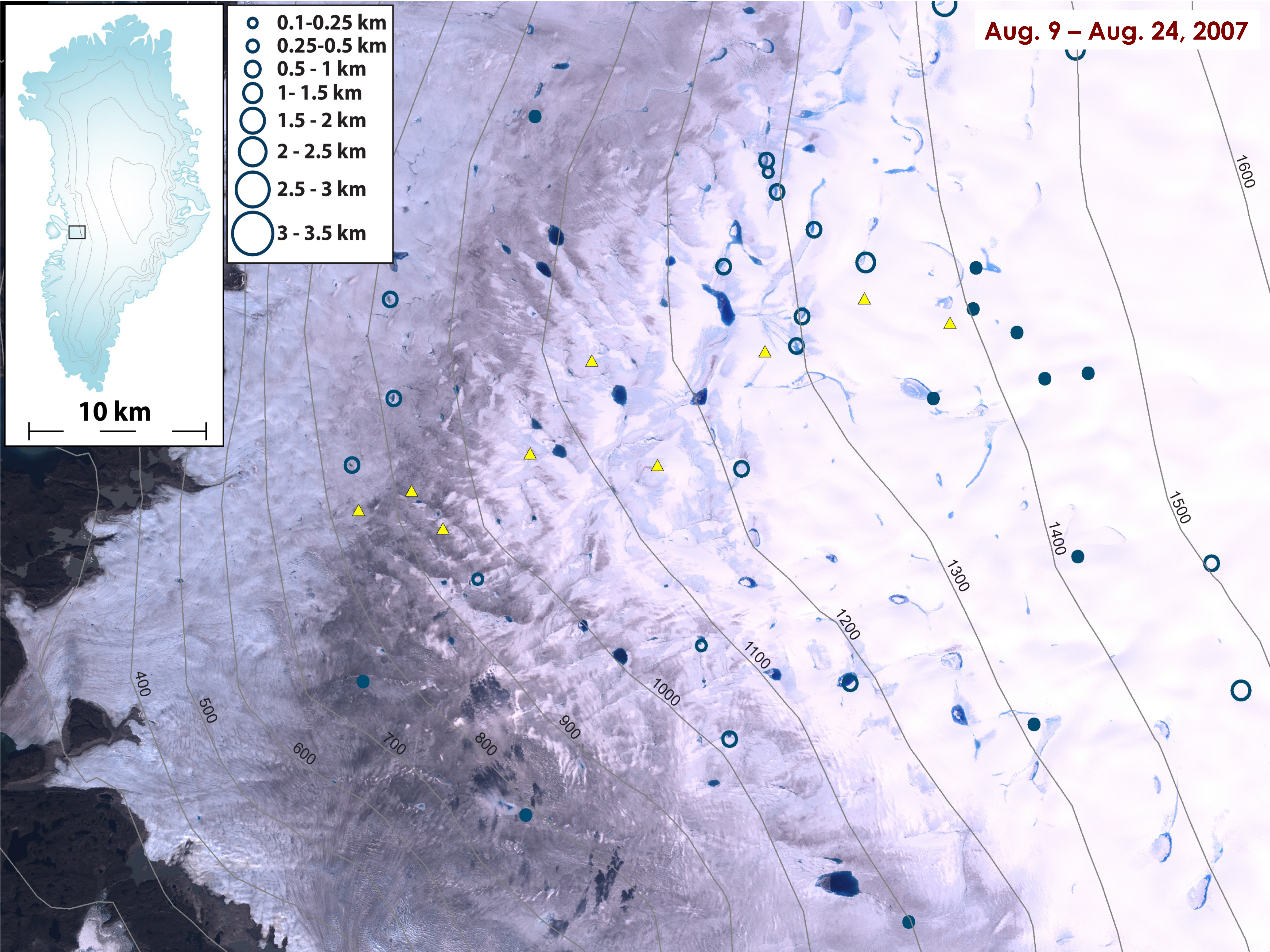

Aug. 9 – Aug. 24, 2007
0.1-0.25 km
0.25-0.5 km
0.5 - 1 km
1- 1.5 km
1.5 - 2 km
2 - 2.5 km
2.5 - 3 km
3 - 3.5 km
10 km
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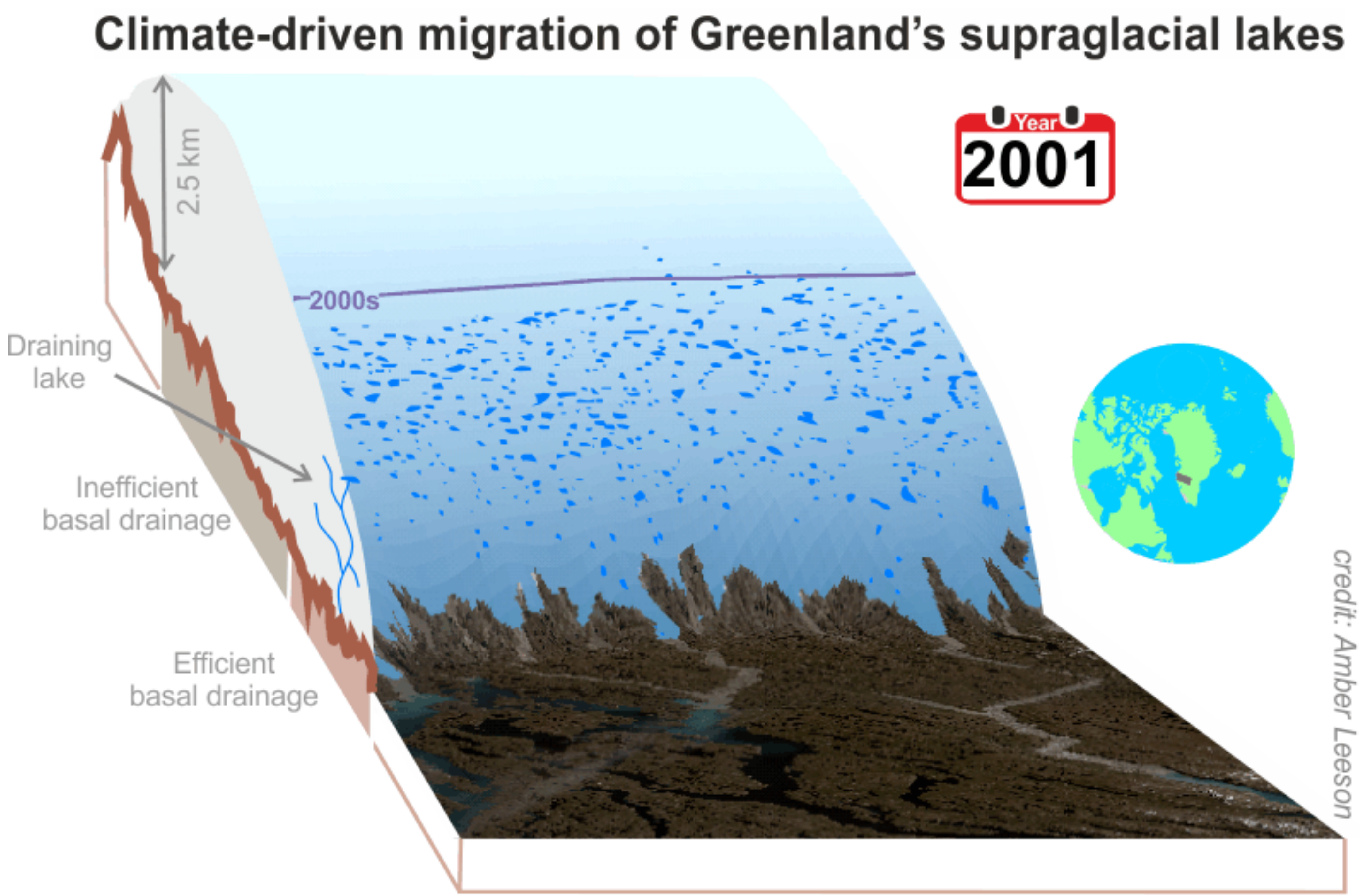
Supraglacial lakes



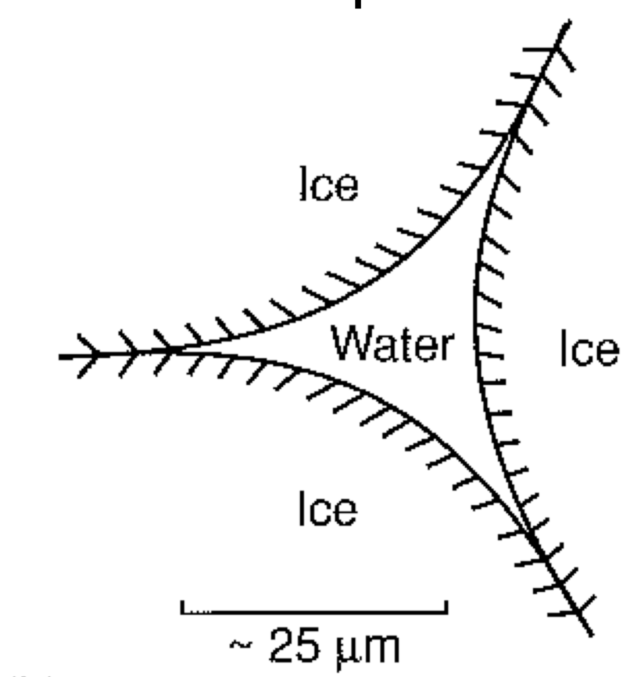
Lakes will migrate up the glacier slope with warming

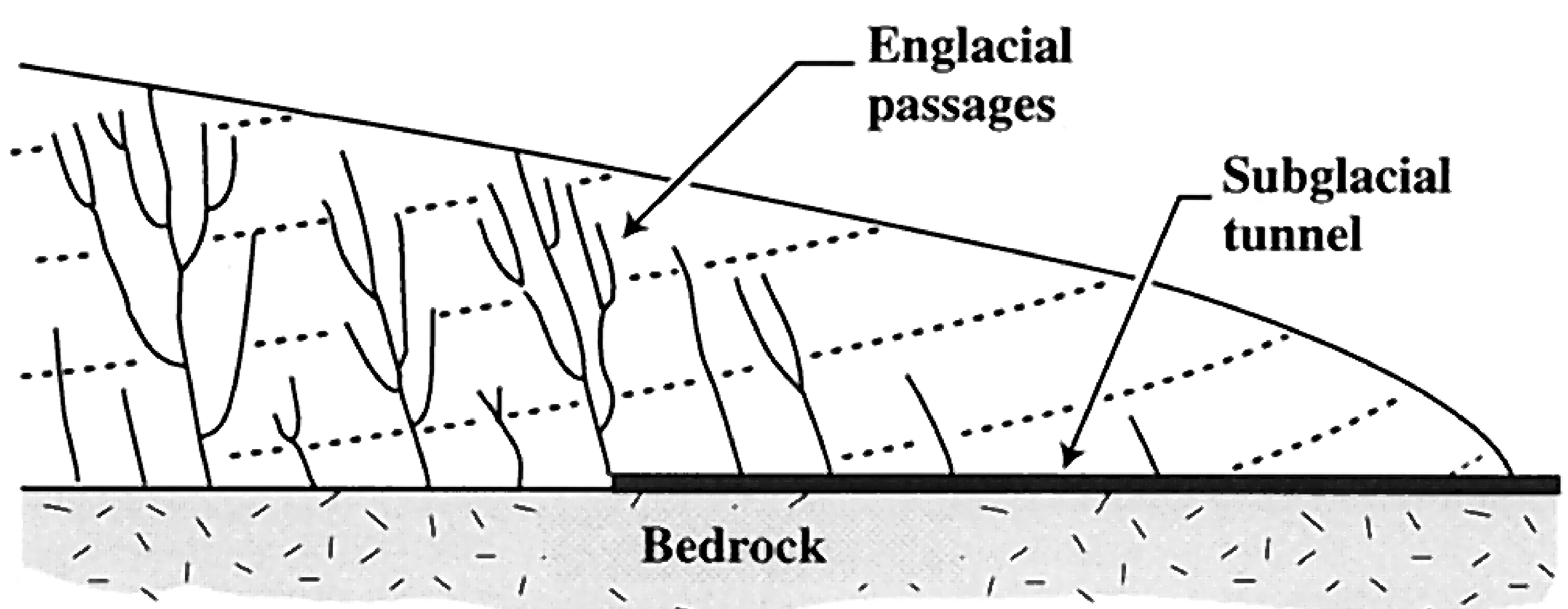
Shreve's Englacial Water Flow

- Shreve (1972) contributed the dominant conceptual model for how water flows through glaciers

- The primary idea: ice is a porous medium. The pores in ice are the voids between grains of ice, which form tiny conduits for water flow that can expand and contract with changing water pressure and ice temperature.

- With sufficiently large water flux, tiny conduits will grow to form large veins that span the whole glacier thickness (as large conduits outcompete smaller ones)

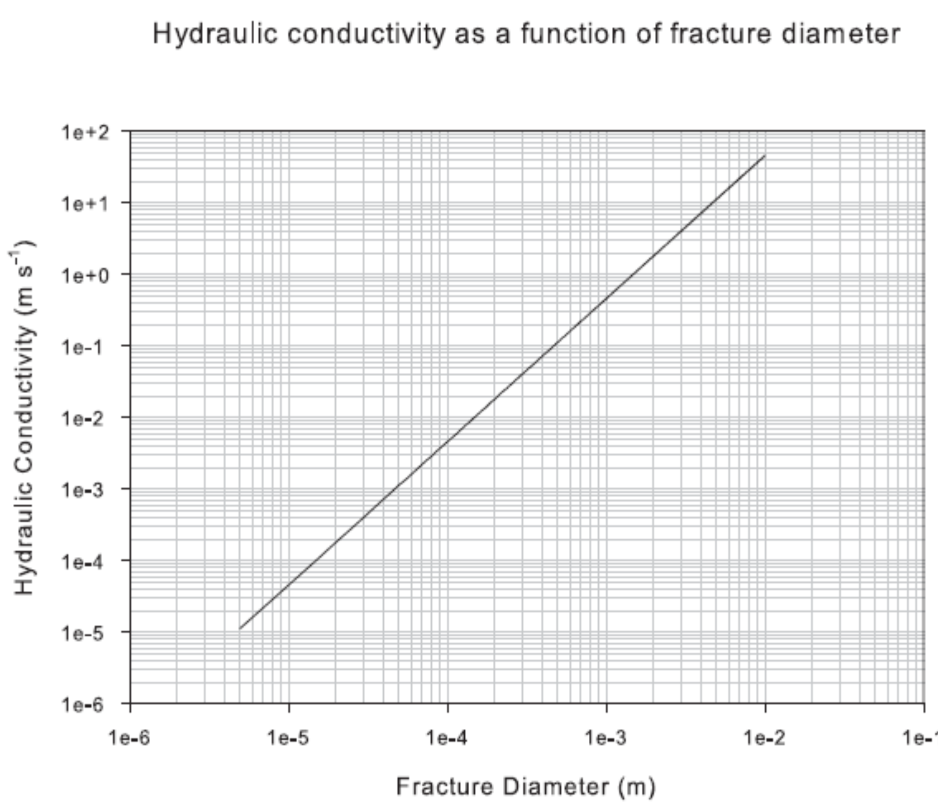




Reality: englacial storage and drainage happens through fractures and moulins

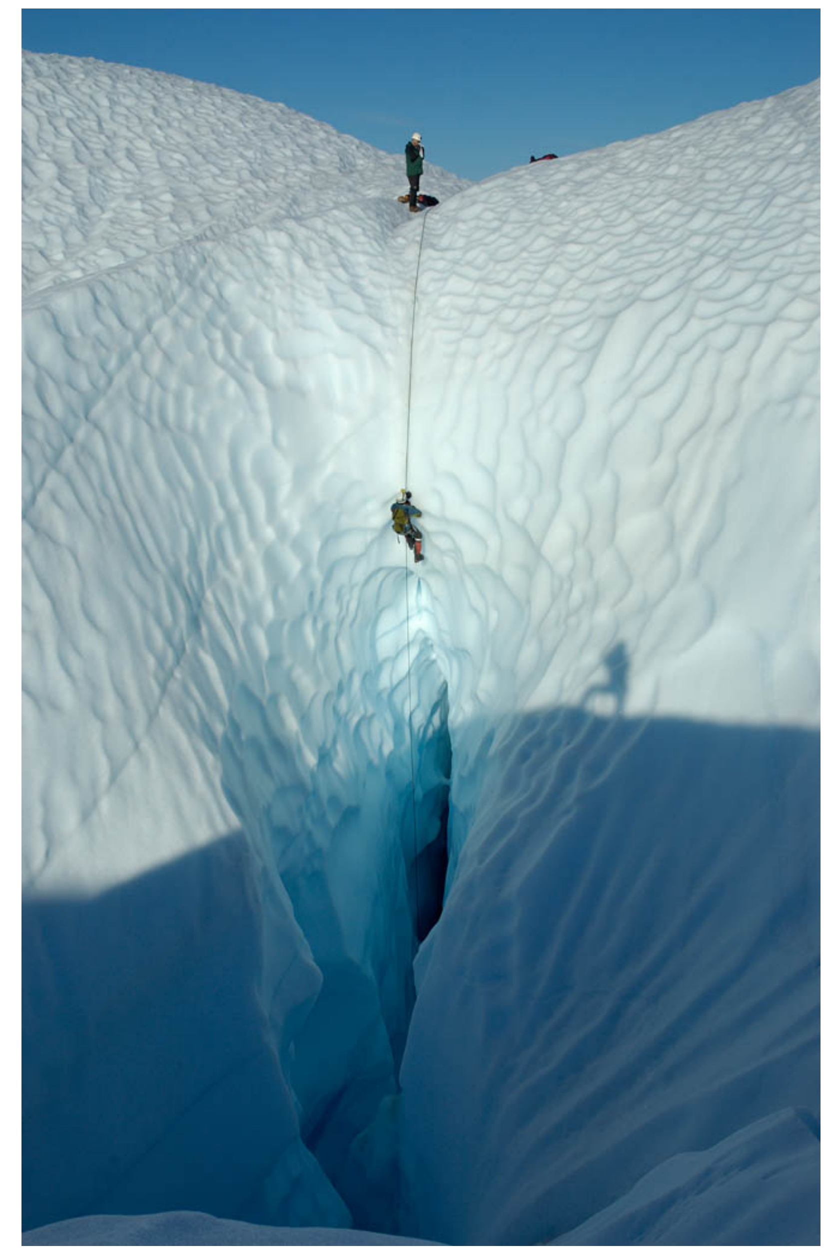
- The problem with Shreve's theory: the hydraulic conductivity of ice is in practice 10^{-11} m/s - why stable lakes can form on top of glaciers
- Observations later showed that water content of firn is highly variables, and is much lower in places close to crevasses (fractures in ice)
- Hydraulic conductivity for fractures is much higher!

Largest crevasses and moulins (large hole that may have started as a fracture) are responsible for most englacial water flow



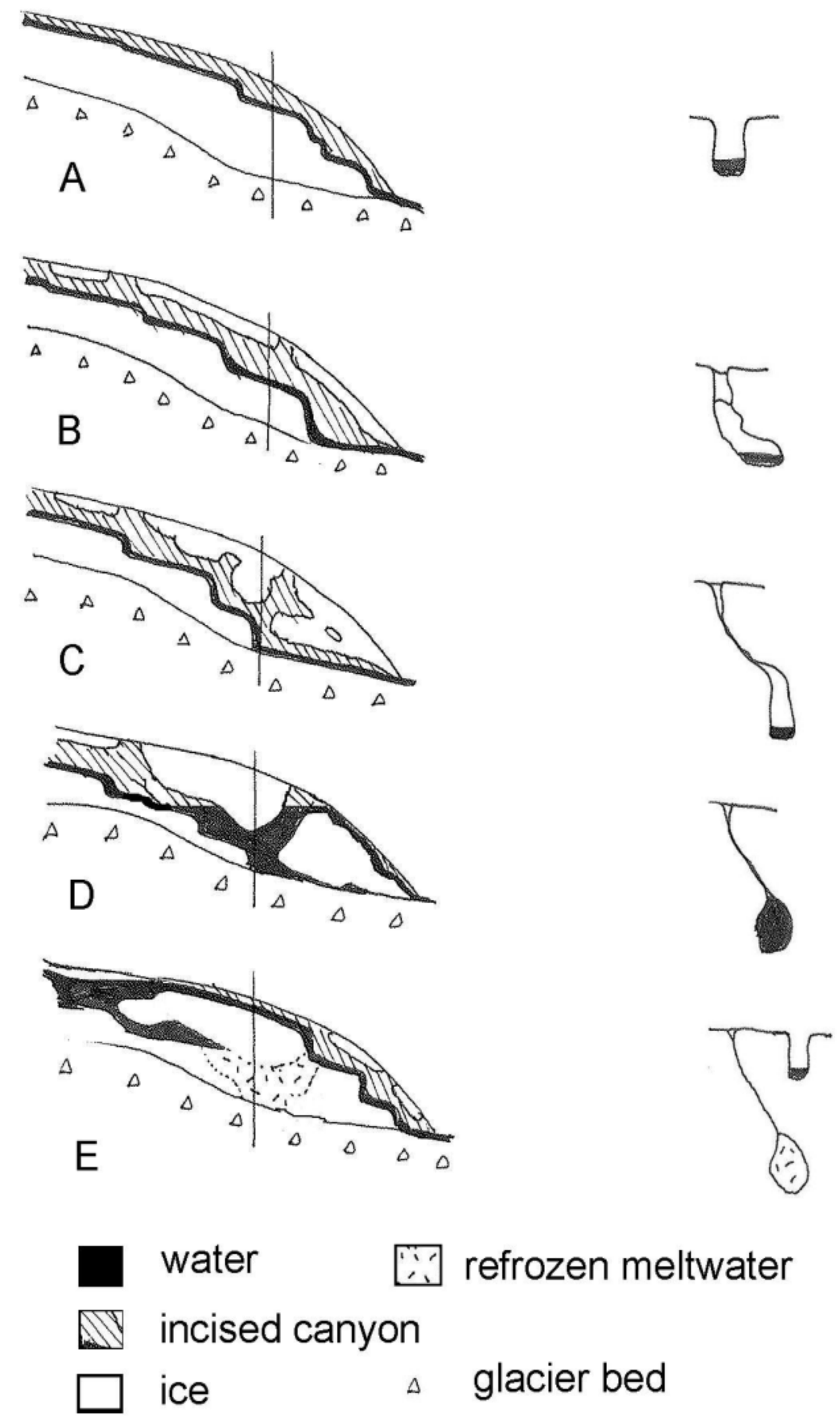
Crevasses are everywhere!
(why field glaciology is dangerous)

Crevasses are everywhere!
(why field glaciology is dangerous)



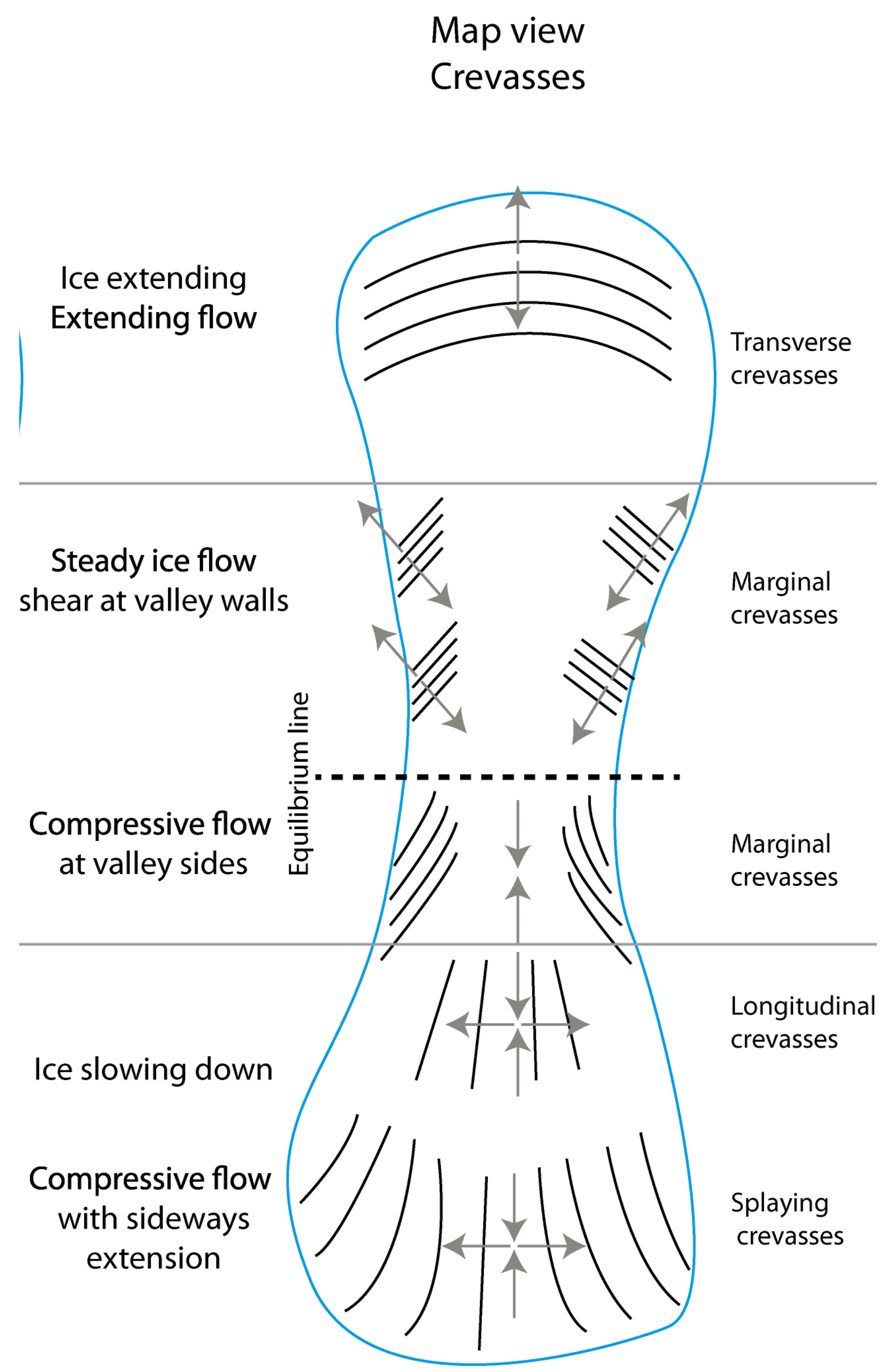
Englacial conduit formation

- **Cut-and-closure:** common where fractures are rare and meltwater is abundant - supraglacial stream erodes surface down and is then covered by subsequent snowfall/ice in winter season

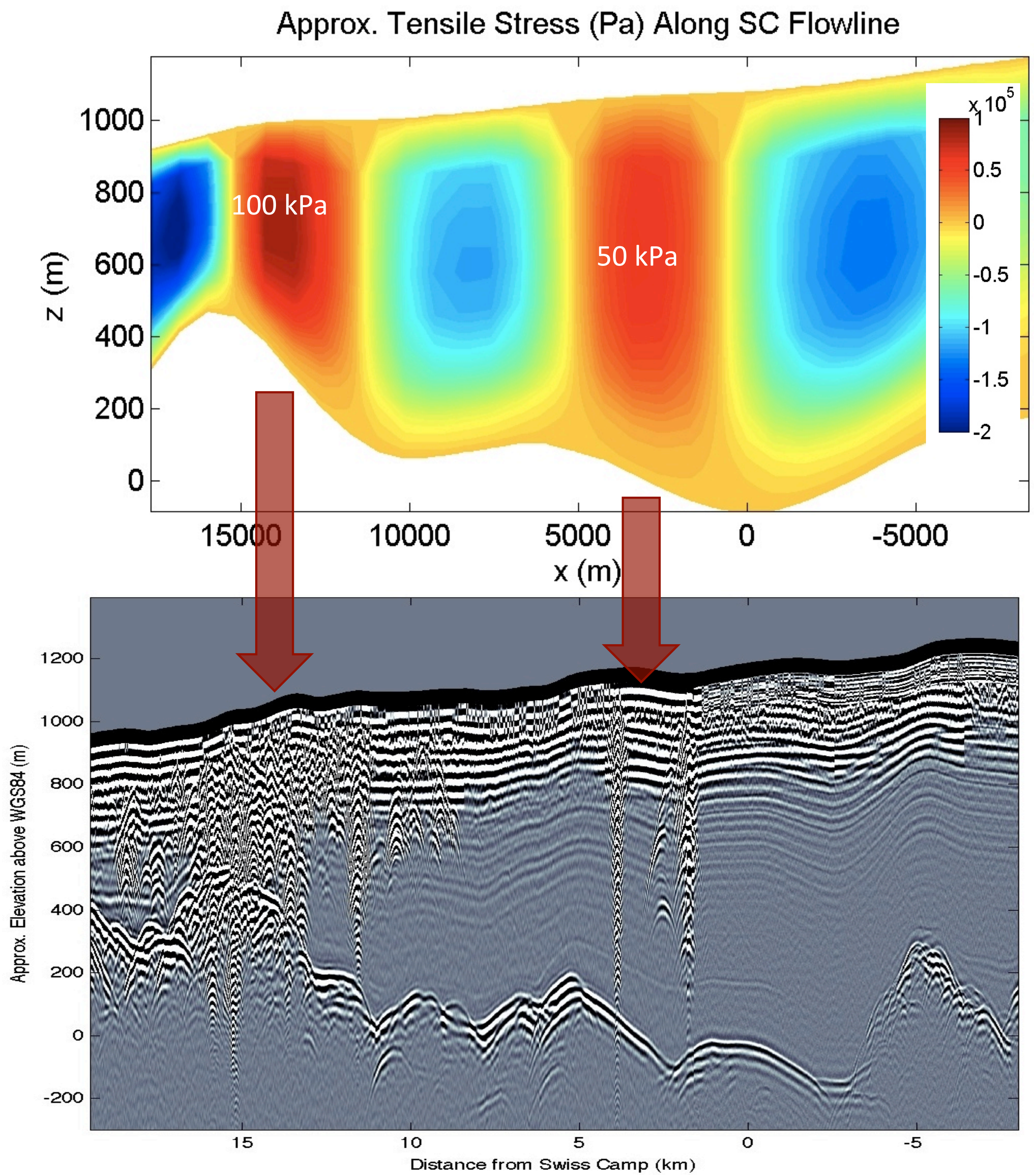


Englacial conduit formation

- **Existing permeability structures:** large tension or shear in ice flow may exceed the strength of ice and open crevasses at the surface. The way in which crevasses are created in most fast-flowing glaciers (or where obstacles cause rapid change in ice flow direction)



Englacial conduit formation



Critical tensile stress required for crevassing
~100 kPa

(Nath & Vaughan, 2001)

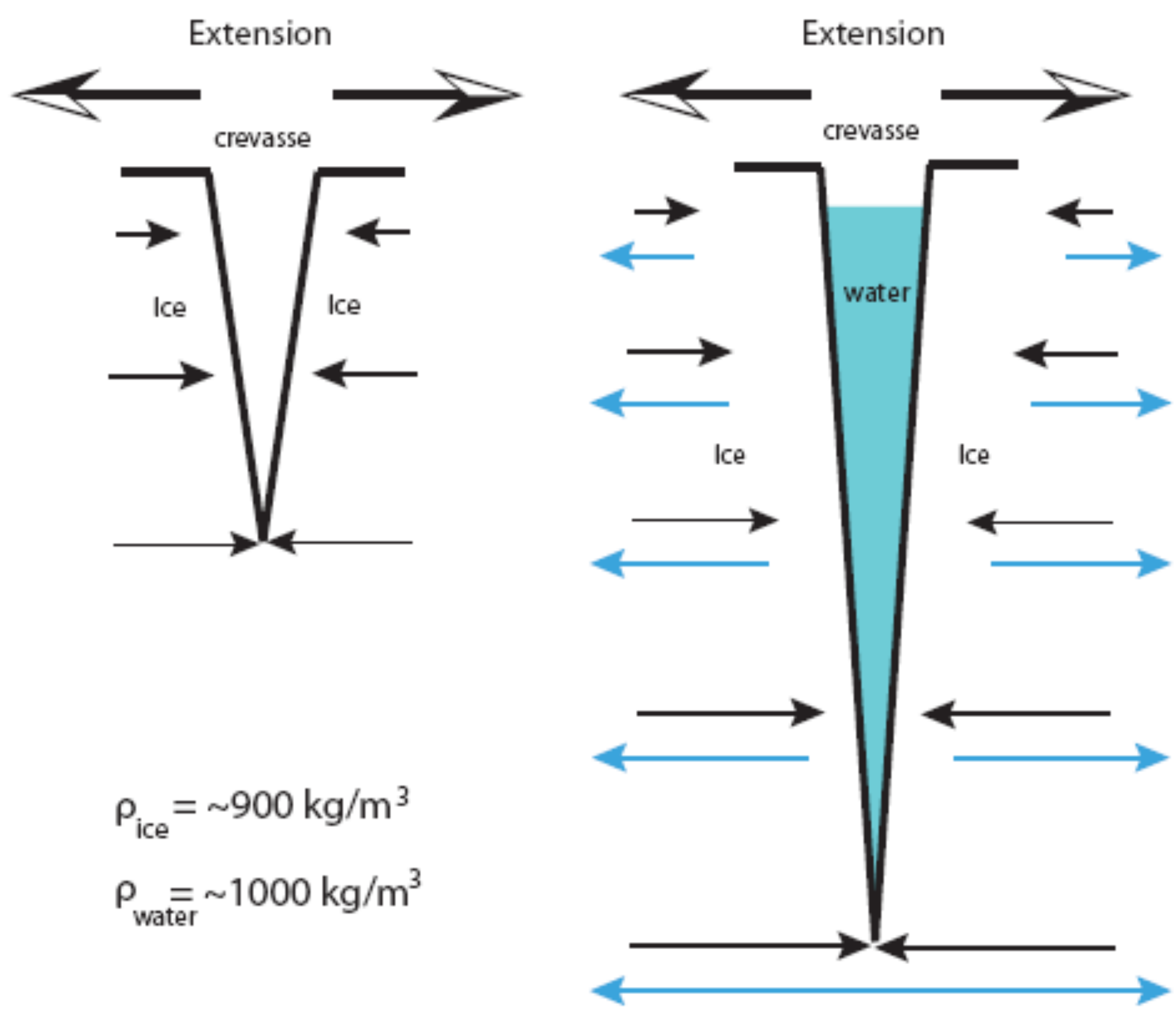
Origin of moulins

- occur in tensile regions from crevasses
- more likely near margin: thin ice, more melt

Englacial conduit formation

- **Hydrofracture:** water enters a crevasse and overcomes glaciostatic stress, causing further penetration into glacier

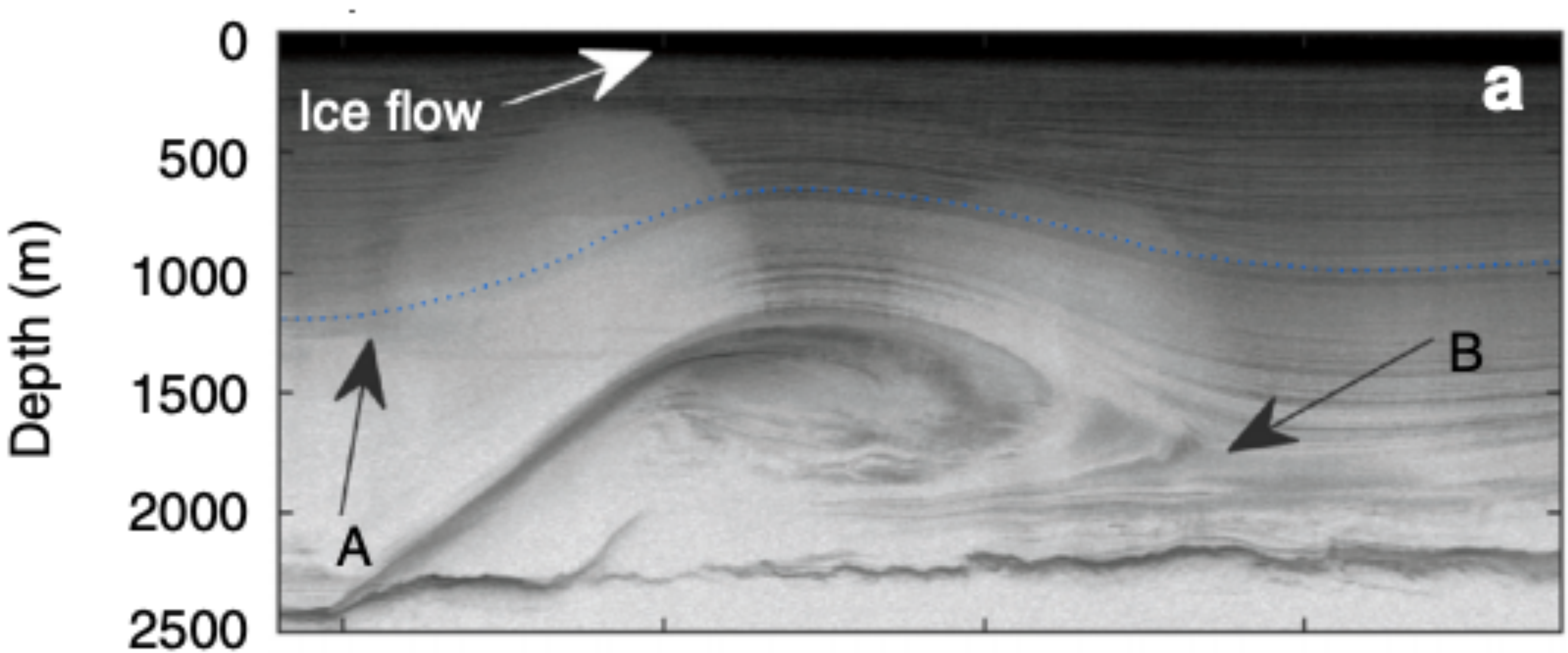
To the board!



Hydraulic potential

- Derive from Bernoulli’s equation on the board (quick)
- Show breakdown between surface, bed slope
- Show an example on the board

Subglacial water can flow uphill (and then interesting stuff happens)



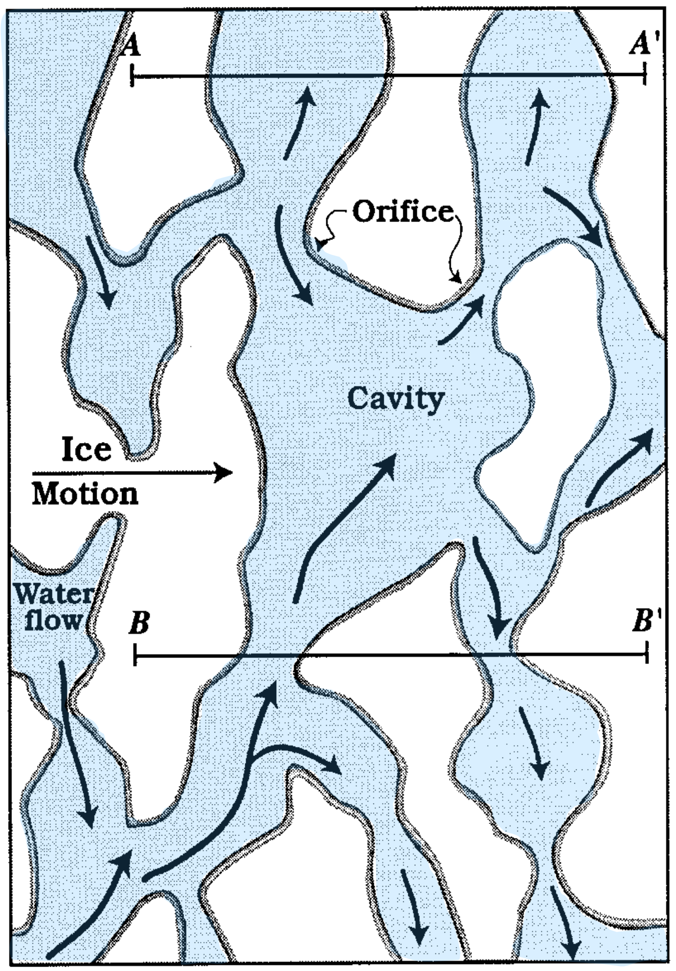
Leysinger-Vieli 2018

What do we want from subglacial hydrology?

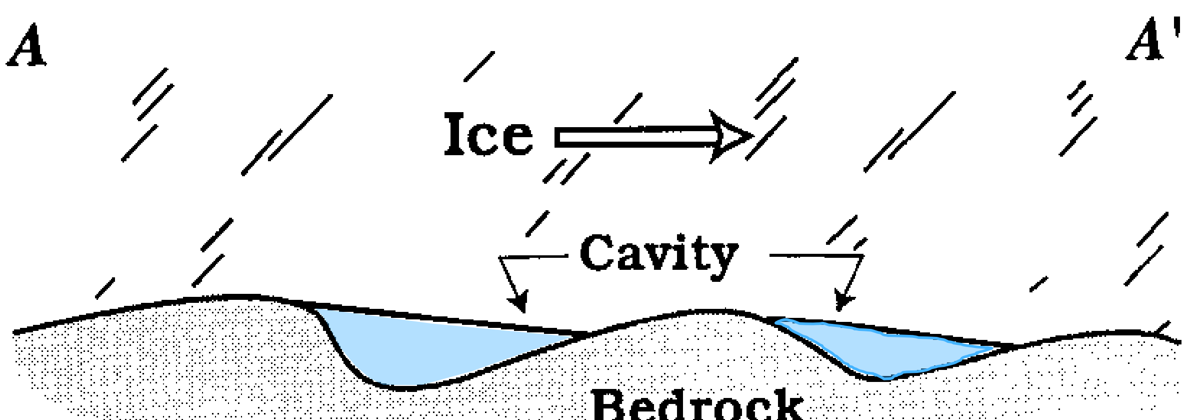
- Subglacial water pressure P_w as a function of water supply Q
- Remember: $u_s = C\tau_b^p N^{-q}$ and $N = \rho g H - P_w$
- Subglacial hydrology exerts a first order control on sliding speed.
- In practice, P_w is the only thing that changes on short time scales because hydrology can be strongly variable on time scales as short as minutes.
- So…what controls P_w?

How is water organized at the ice-bed interface?

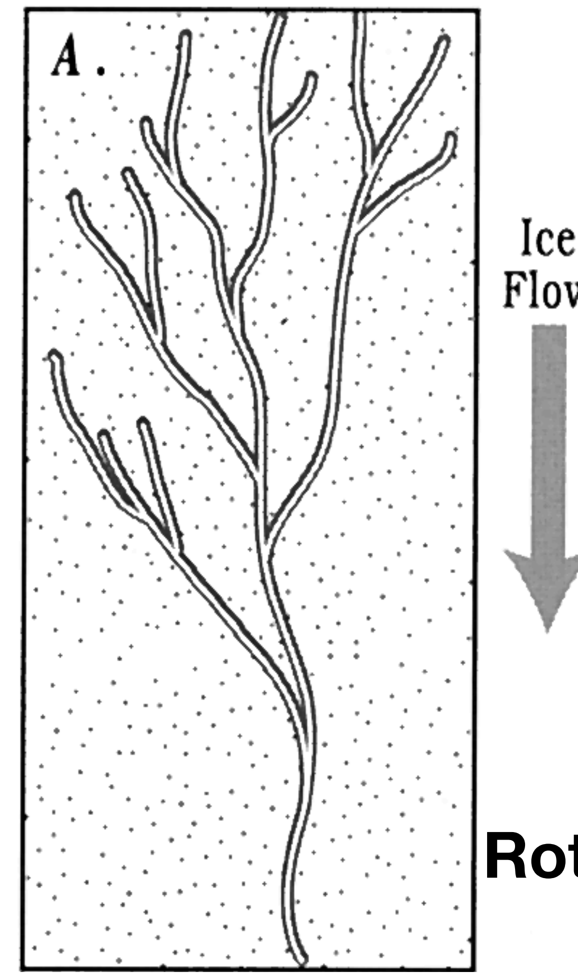
Linked Cavities



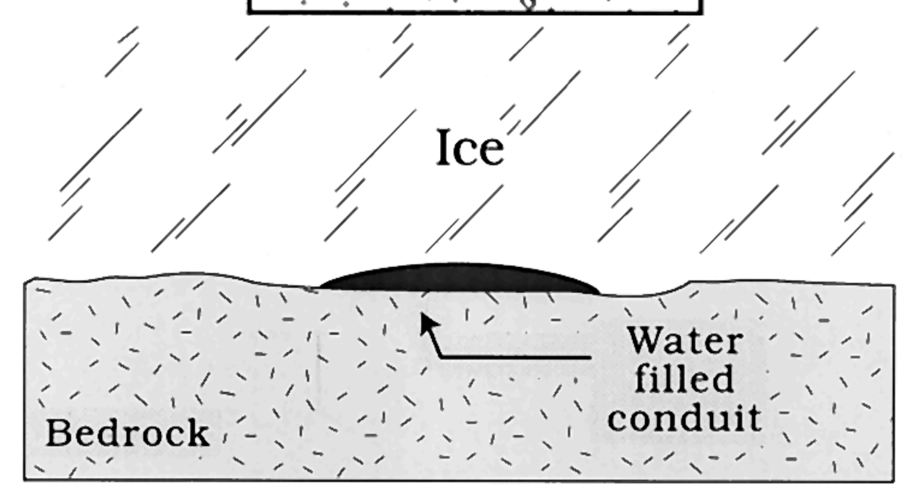
Walder and Fowler 1994



Subglacial Channels



Rothlisberger 1972

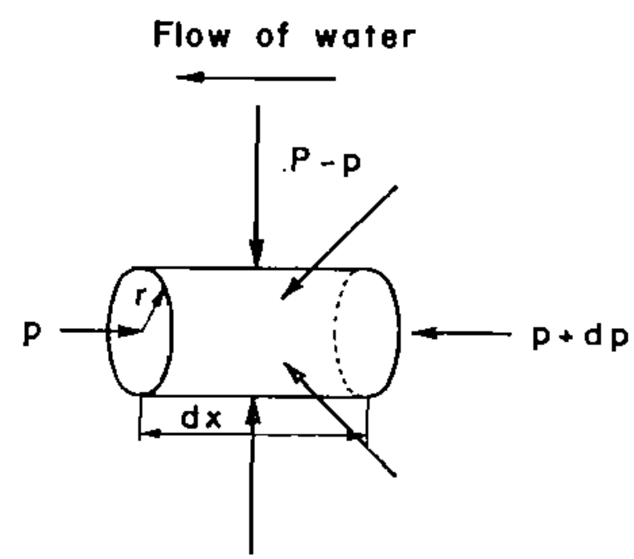


Rothlisberger Channels

Journal of Glaciology, Vol. 11, No. 62, 1972

WATER PRESSURE IN INTRA- AND SUBGLACIAL CHANNELS*

By HANS RÖTHLISBERGER
(Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie an der Eidgenössischen Technischen Hochschule, Zürich, Switzerland)



a. Horizontal conduit

Rothlisberger Channels

Rothlisberger Channels

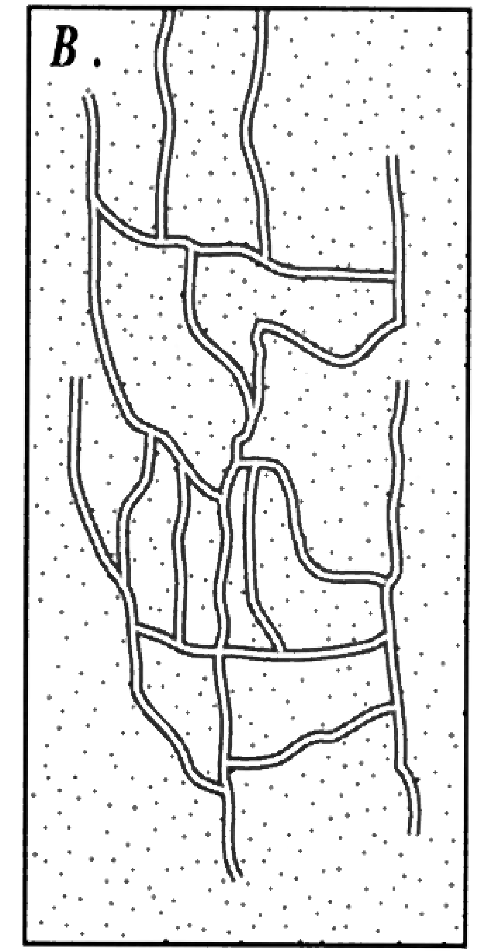
Local sediment plumes are often taken as evidence of submerged exits of R-Channels

Nye Channels or “Canals”

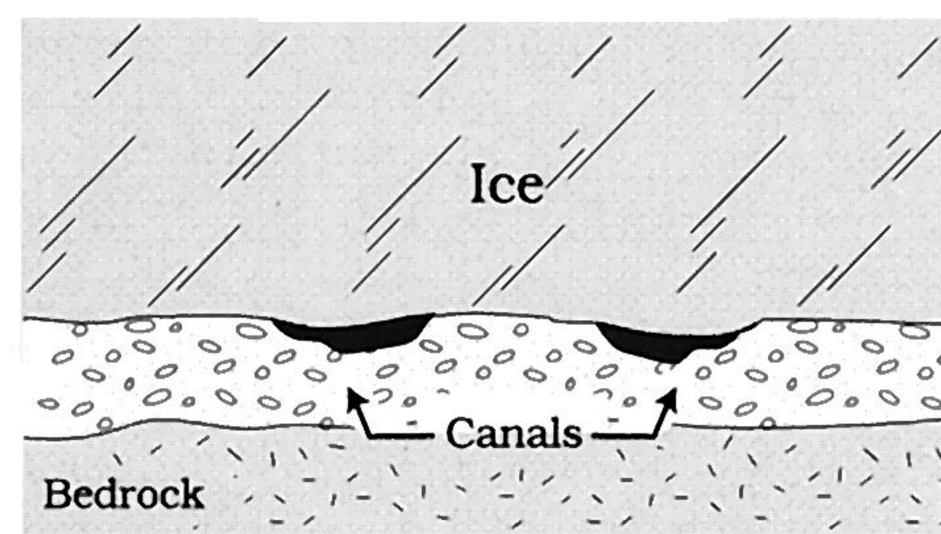
Nye Channels (or N-Channels) eroded into bedrock

Example from previously glaciated bedrock terrain in Indiana

Canals eroded into sediment



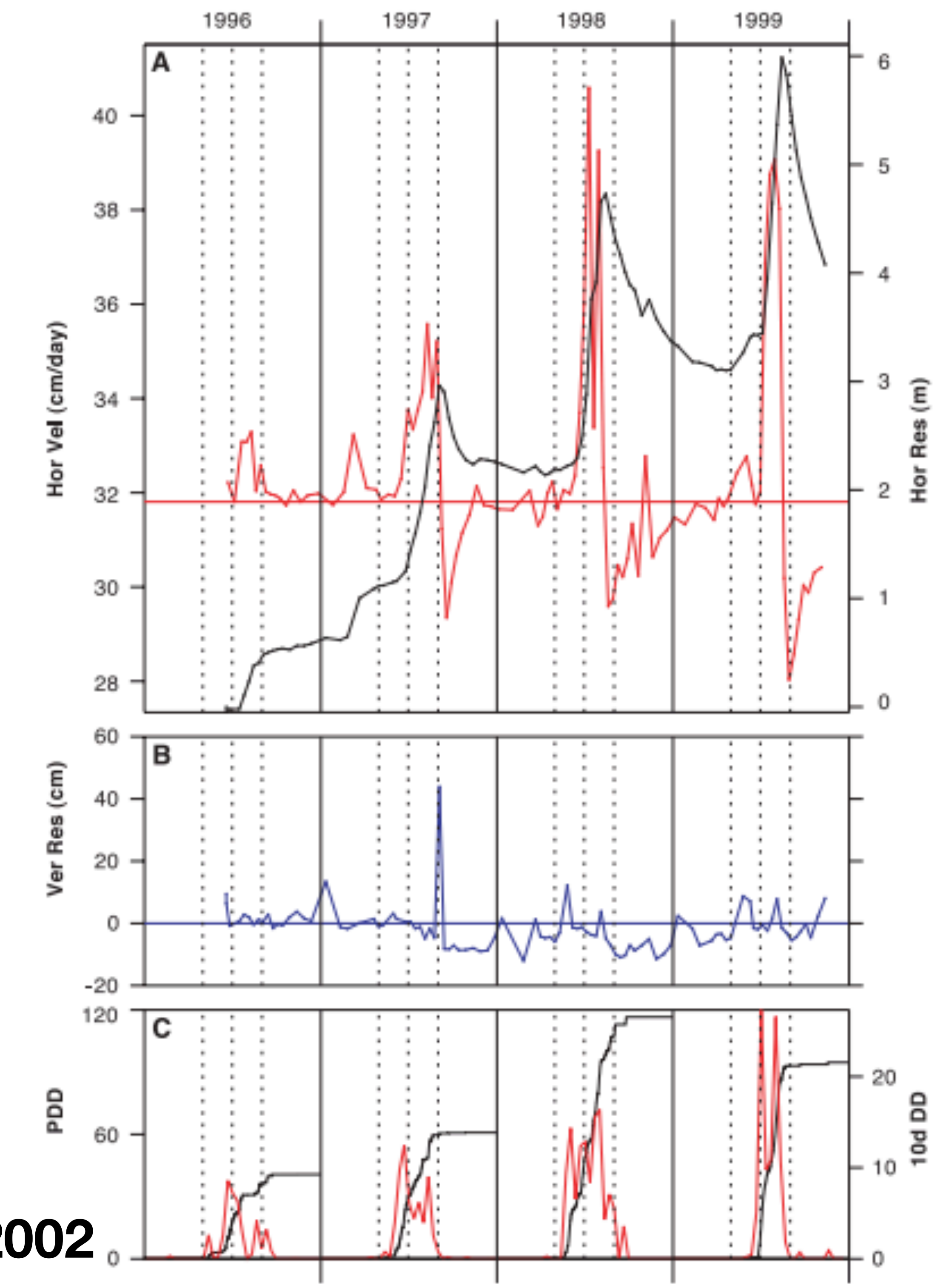
Less efficient water movement than R-Channels



The balance between channel melting, cavity opening and creep closure

- To the board!

Does velocity go up or down with increased water supply?

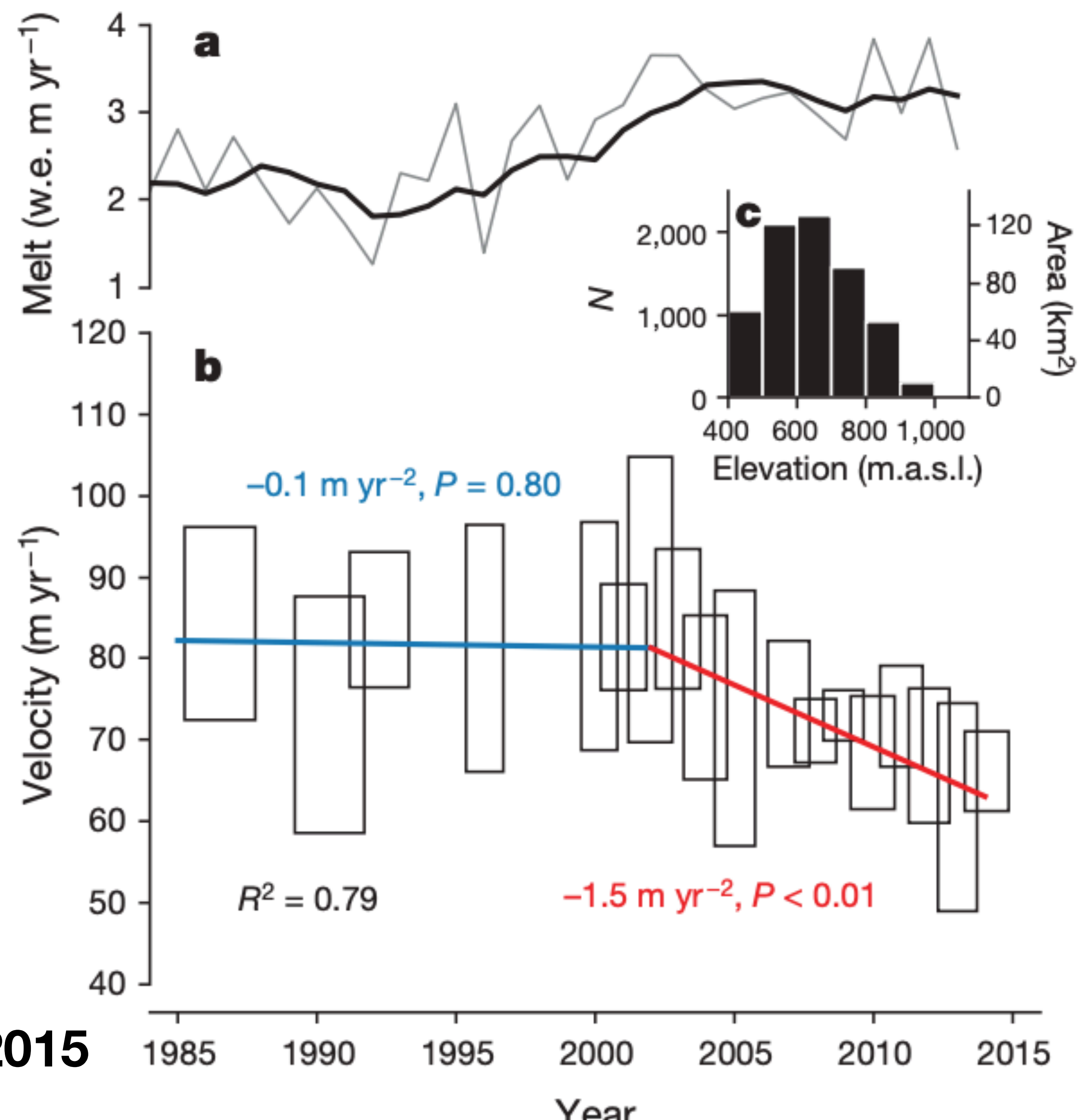


Water lubricates ice flow?

Zwally et al. 2002

Does velocity go up or down with increased water supply?

Water organizes drainage, reducing ice flow?



Tedstone et al. 2015