Glacier hydrology - water in and around glaciers

Motivations

Introduction to glacial hydrology

Emphasis on data, not models

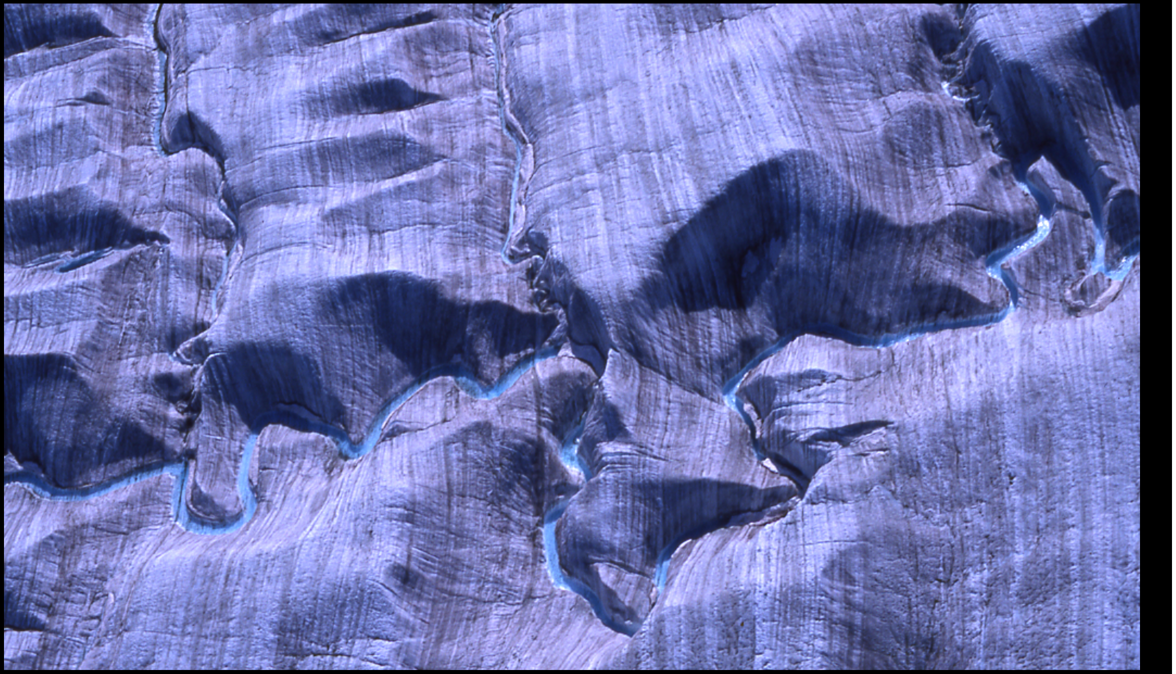
Examples from Alaska
- Bench Glacier
- Kennicott Glacier
- (Greenland…)

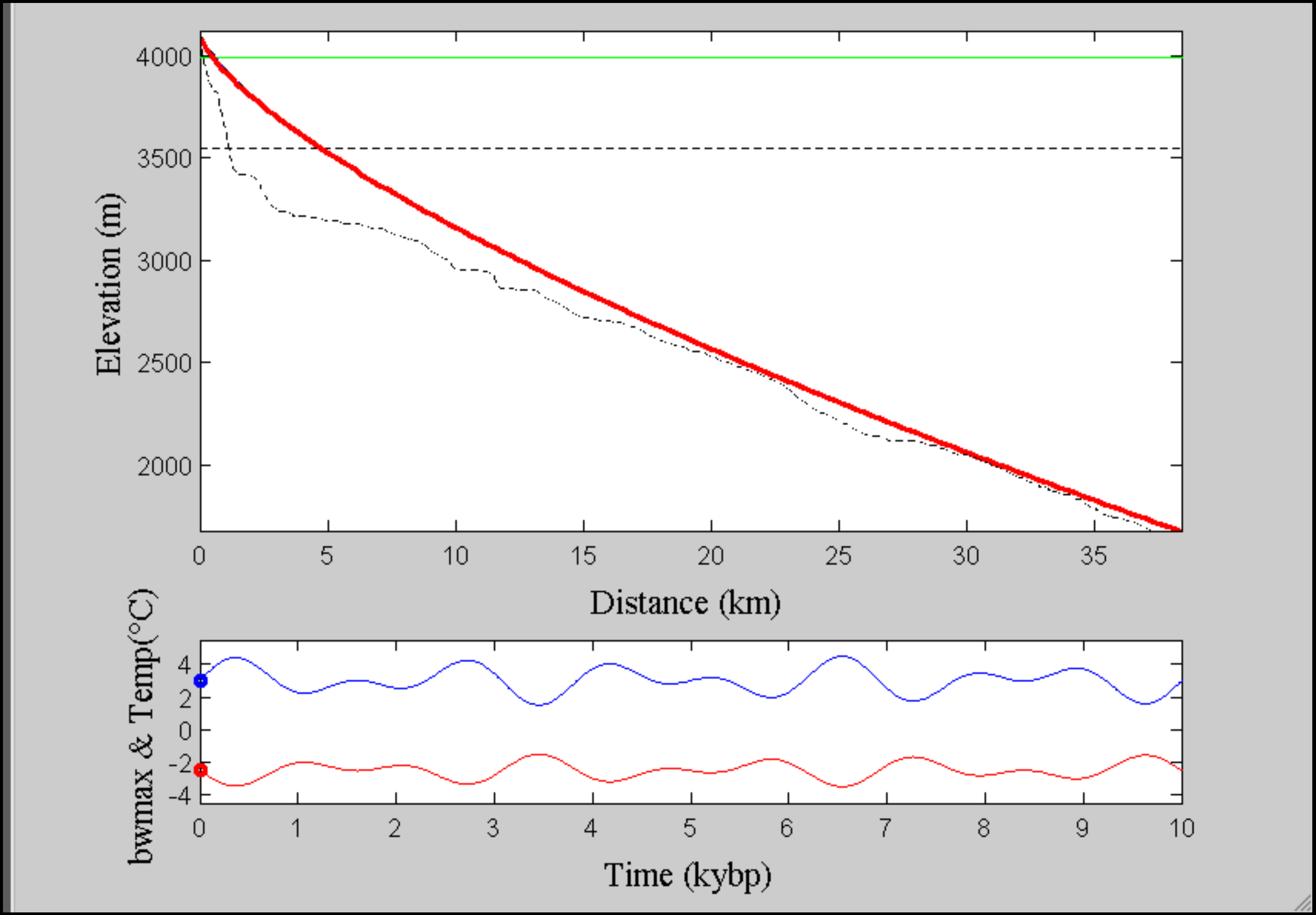
The components
Simple models
Emphasis on the challenges

CSDMS Annual Meeting 2011

Motivations

The glacier hydrograph
Temperature structure
Sliding… hence erosion…hence landscape evolution
Surges
Depositional forms: eskers
Outburst floods from blockage of drainage





Long-term landscape evolution

Start with surface hydrology, then subsurface

Point 1. A distinction with other systems is that the glacial plumbing system collapses and must be re-grown

Point 2. We are finding that the alpine model can indeed be applied to Greenland outlet glaciers

The daily hydrograph… and a surge

Snowmelt input requires models of meteorologically driven snowmelt, infiltration, warming of the snowpack, and vadose-zone behavior.
Note the timescale is <1day

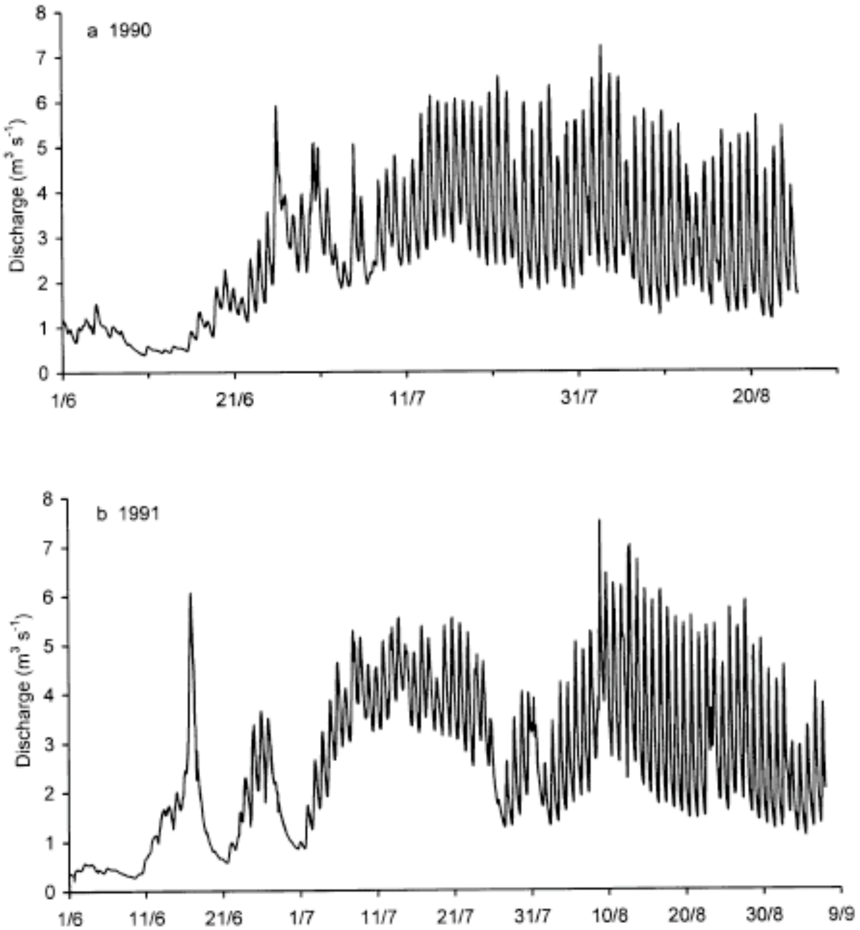
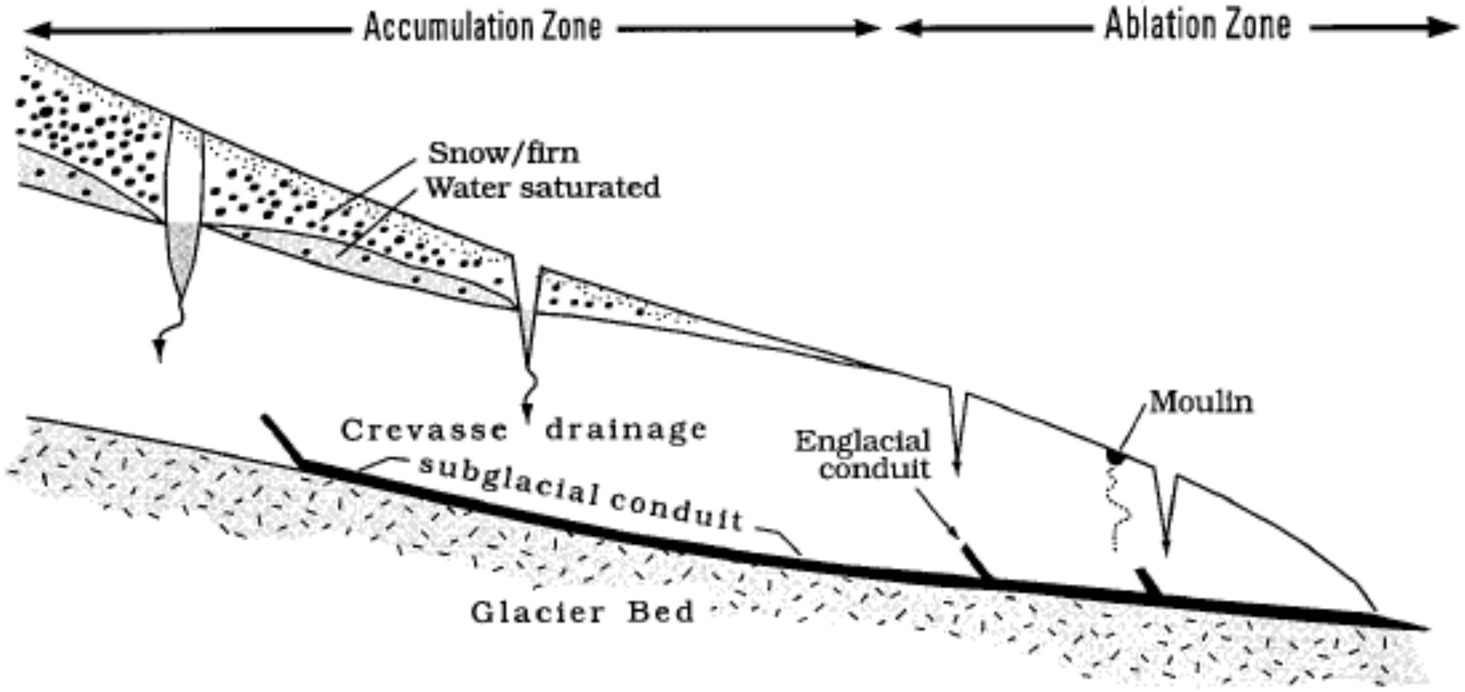


Figure 2. Meltwater discharge records for the Haut Glacier d'Arolla for the summers of (a) 1990 and (b) 1991. Data provided by Grande Dixence SA

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.

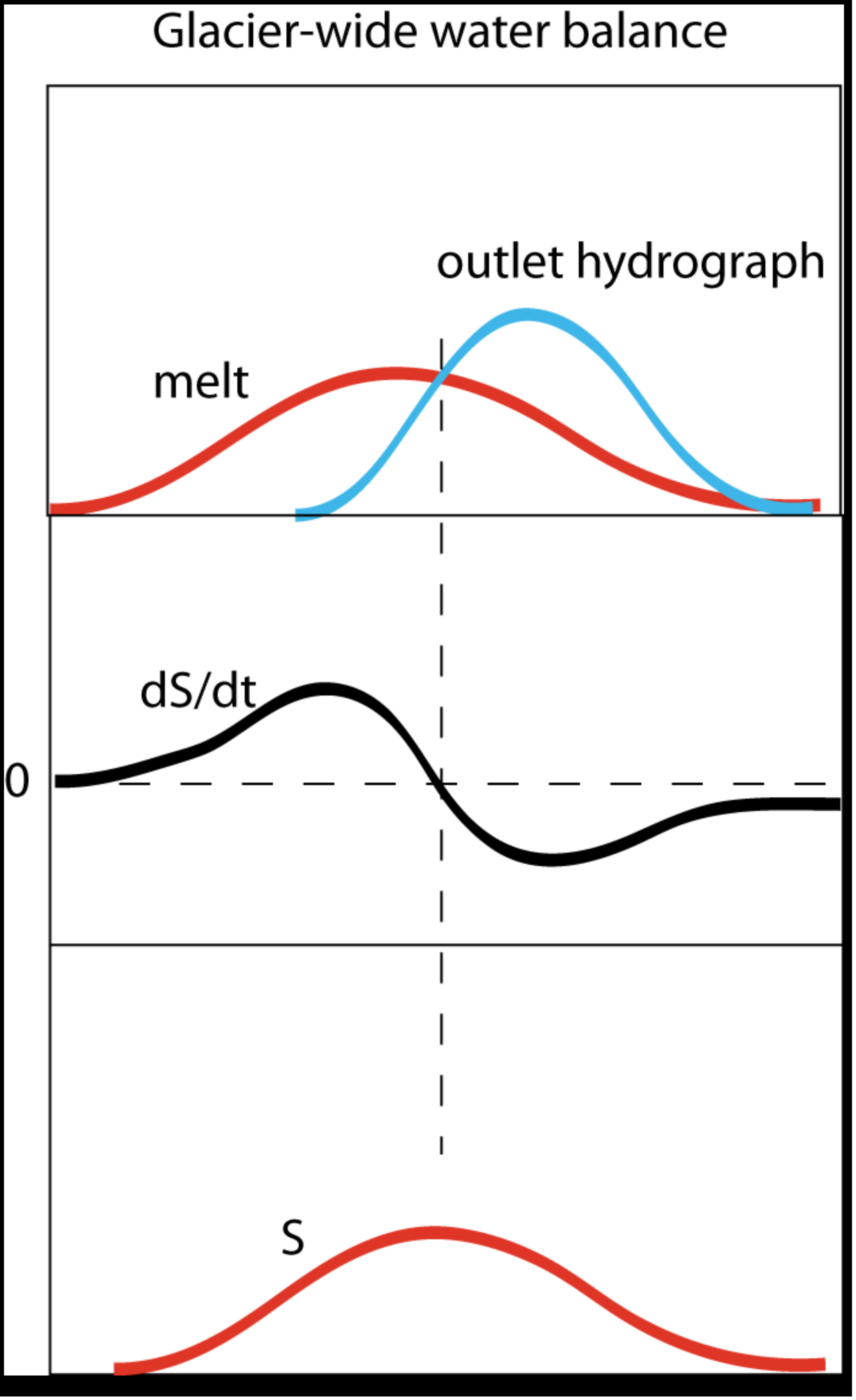


Rothlisberger and Lang 1987

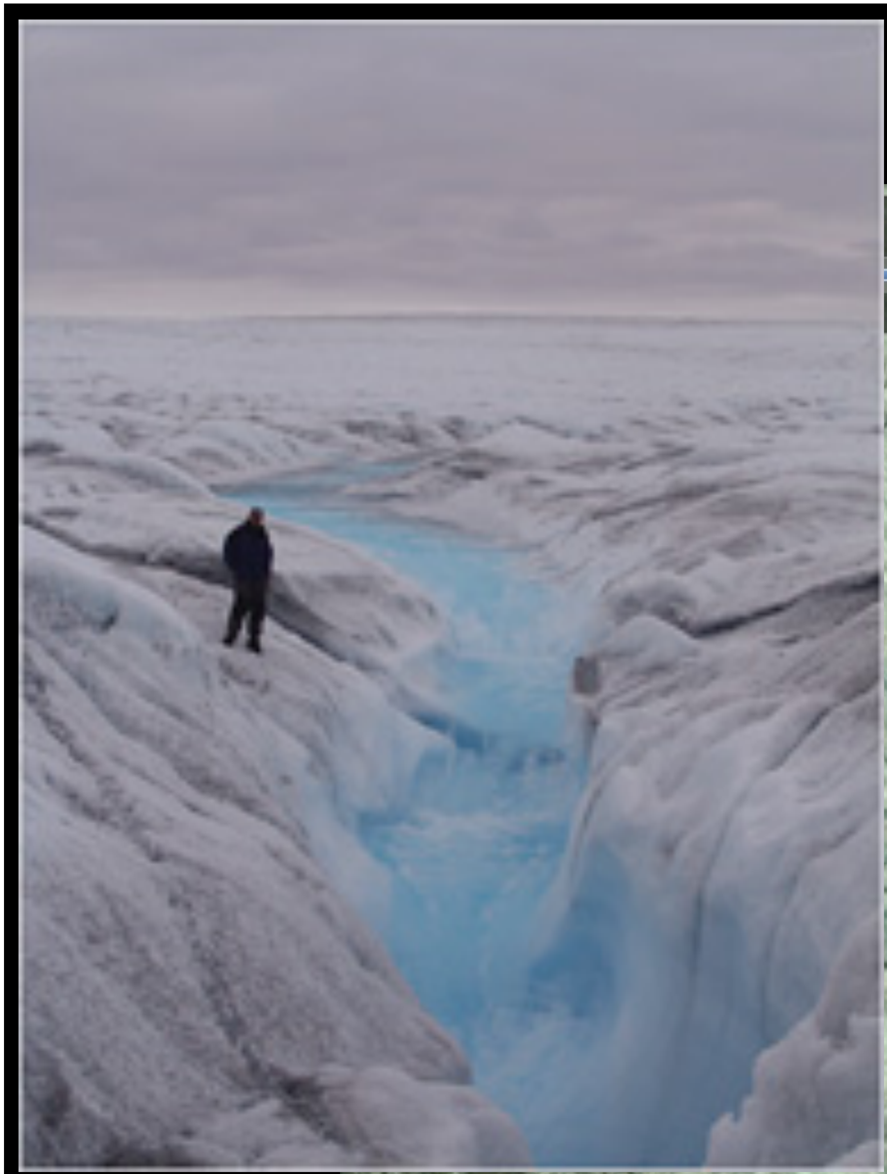
Glacier-wide water balance

$dS/dt = I-O$

Lag of outlet due to:
- Filling of pore space by melt bringing the snowpack to isothermal
- Development of through-going conduits…



Supraglacial streams



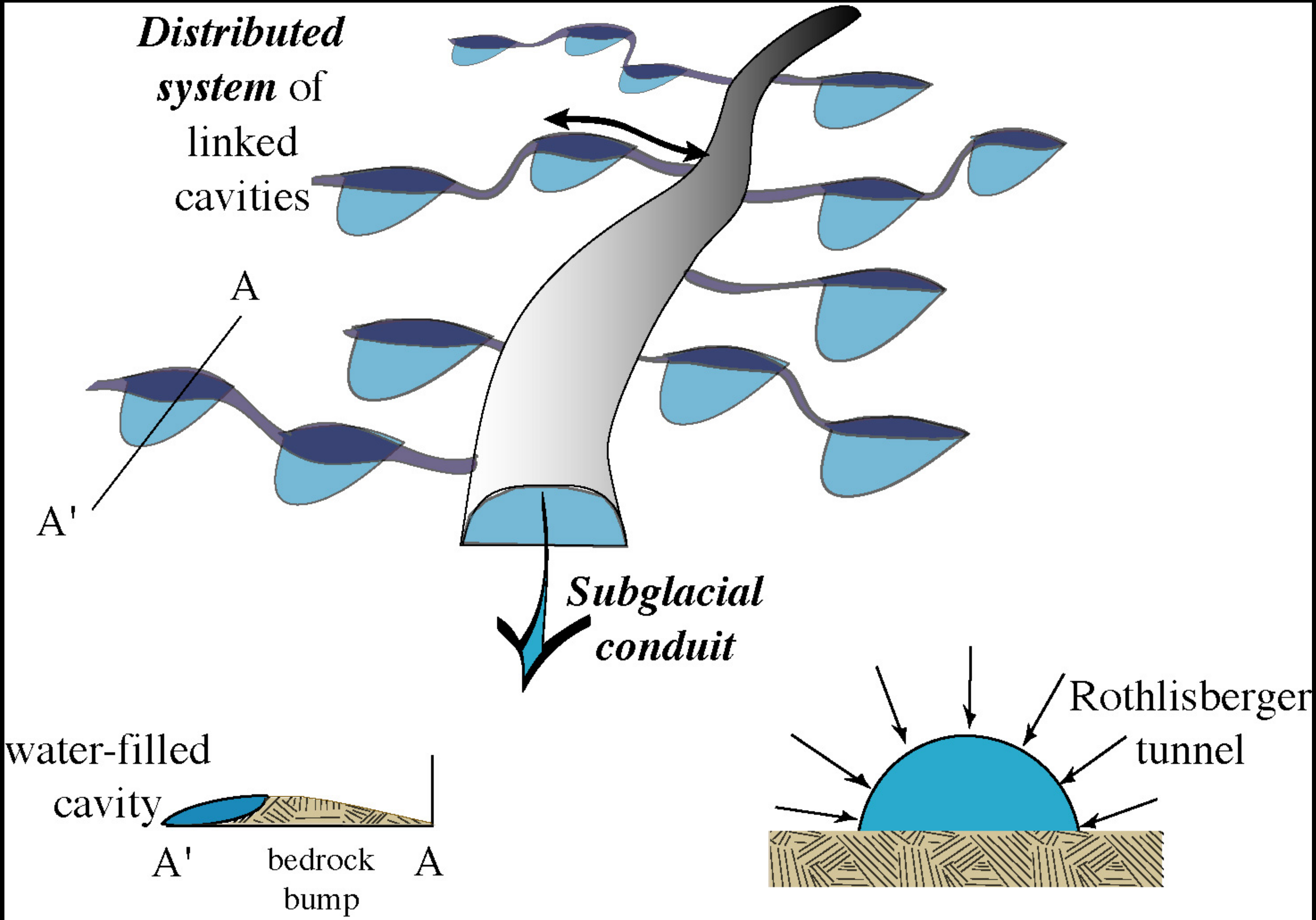
crevasses

These serve to interrupt the supraglacial drainage system, and serve as local reservoirs

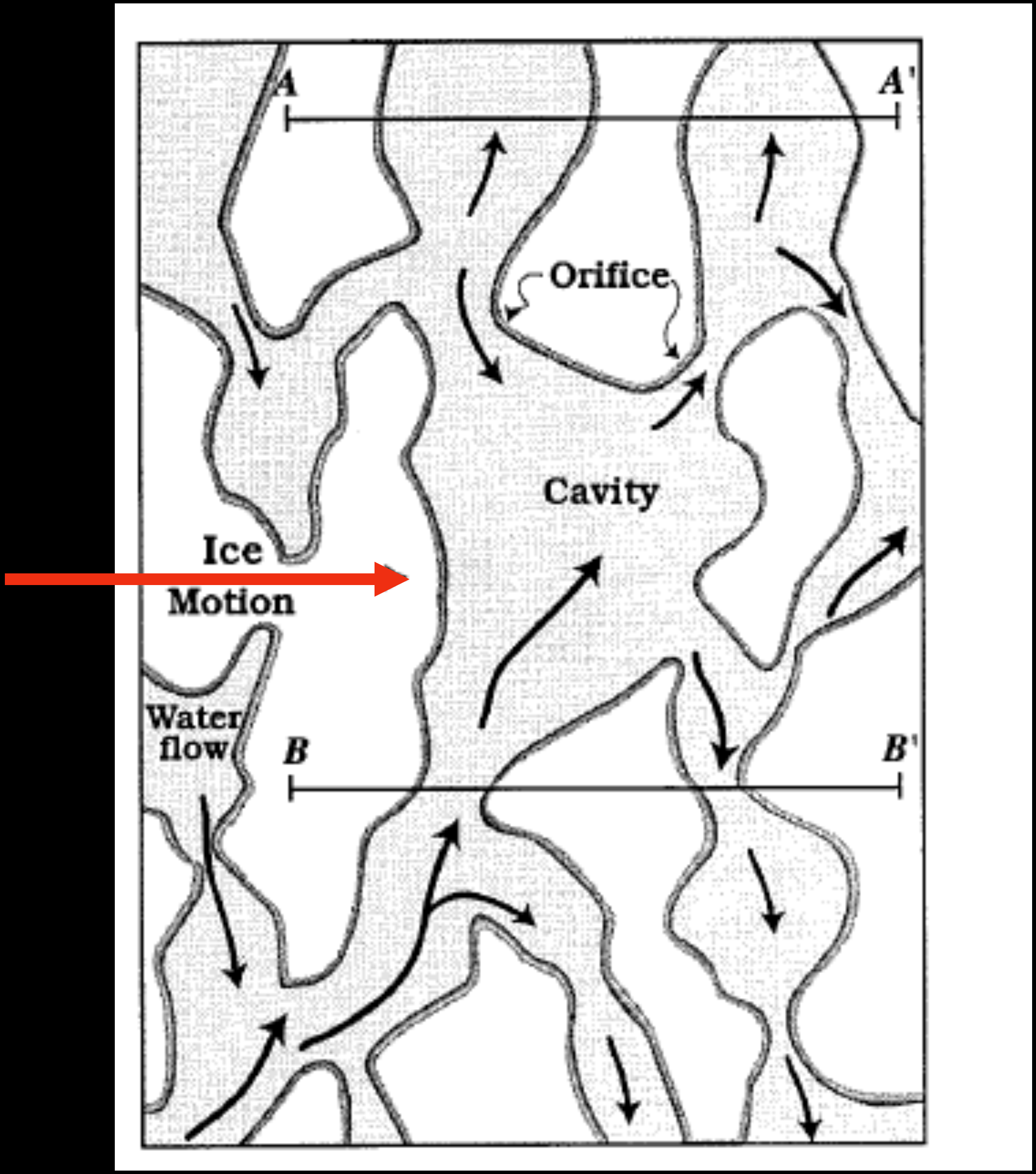
Englacial system

Hard to see.
But basically a low porosity material, perhaps 1-2% voids

Subglacial hydrology

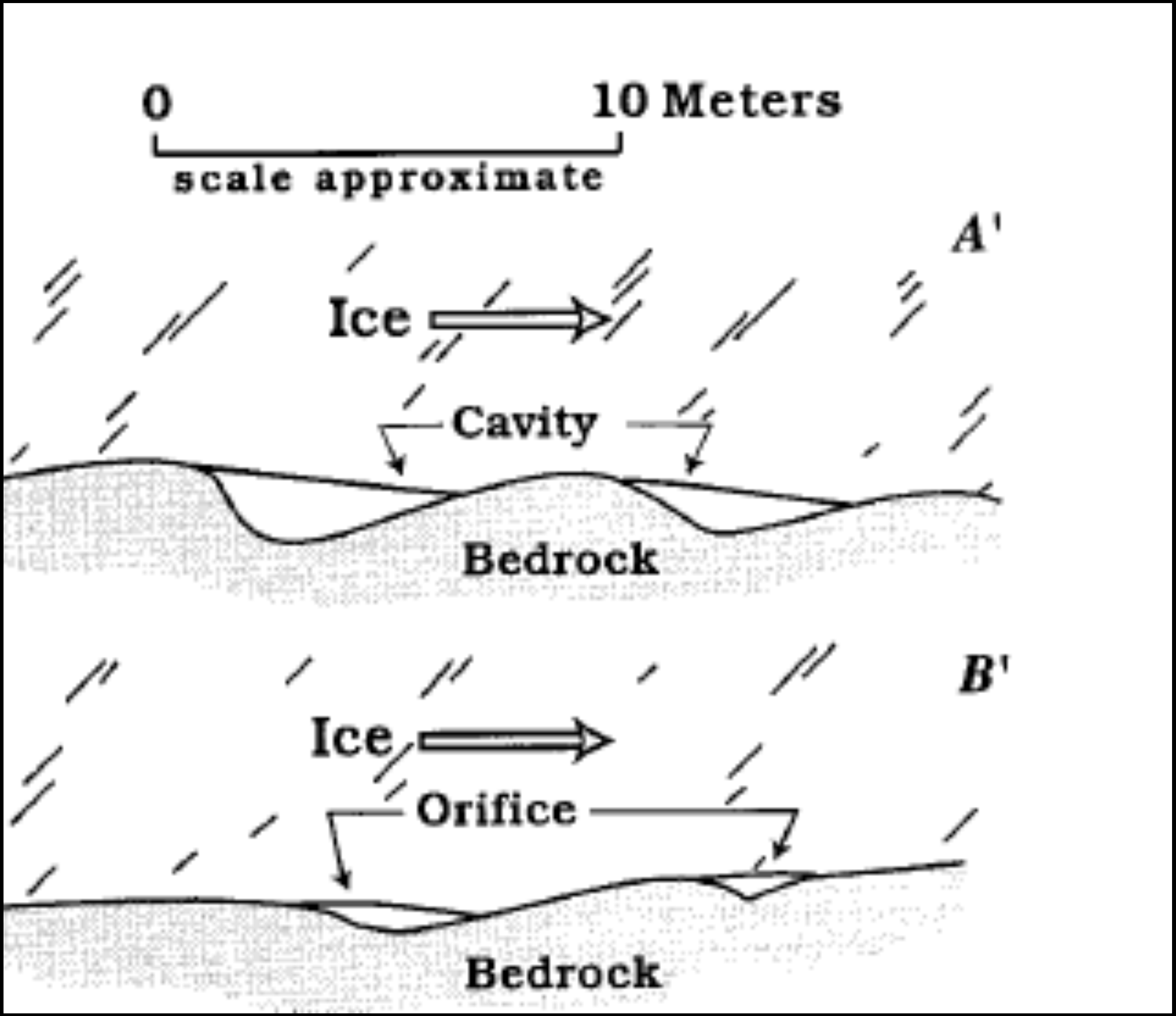


The slow system,
Linked cavities



Note high connectivity
Normal to sliding direction

Fountain & Walder (1998) *Rev. Geophys.* 36:299-328.

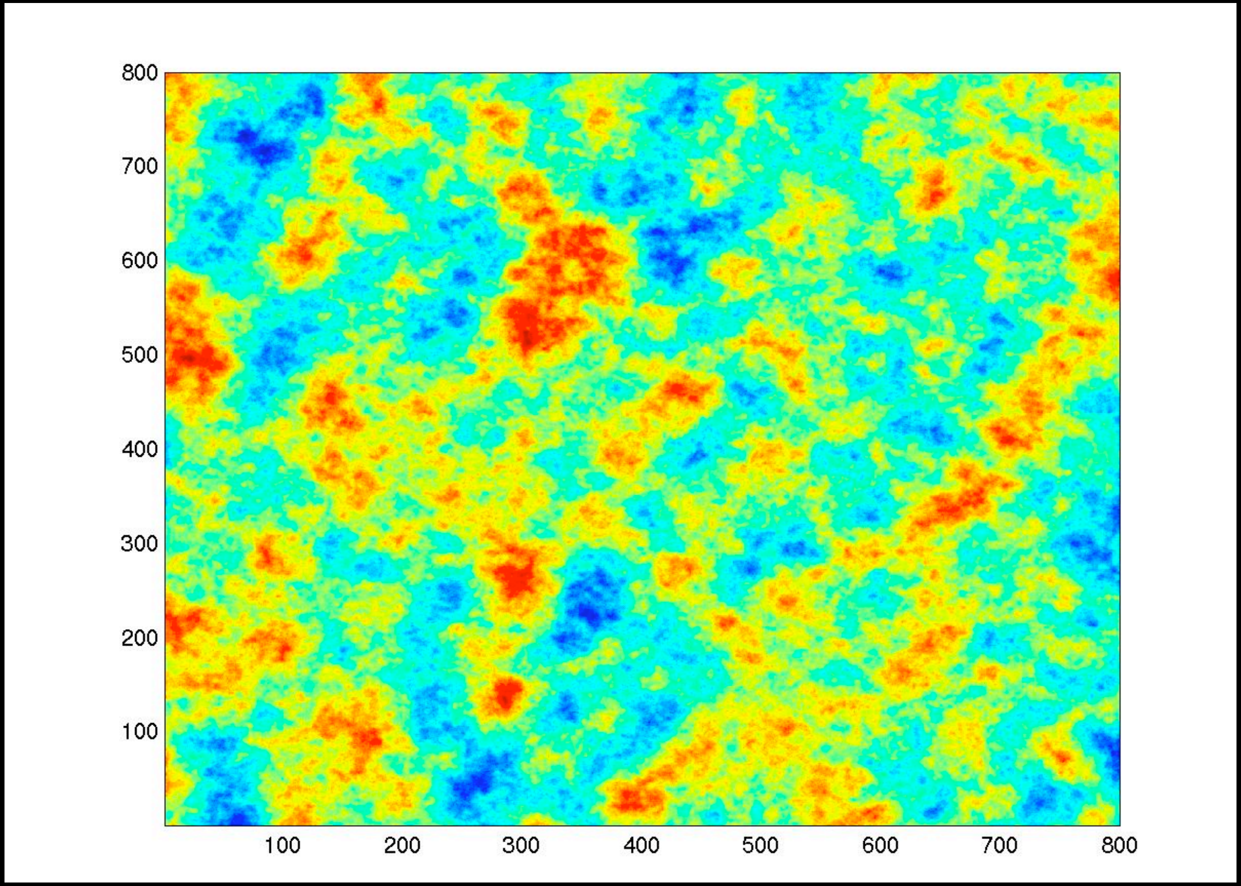

0
10 Meters
scale approximate
A'
Ice
Cavity
Bedrock
B'
Ice
Orifice
Bedrock

After Kamb

View of the bed as a fault - between rock and ice

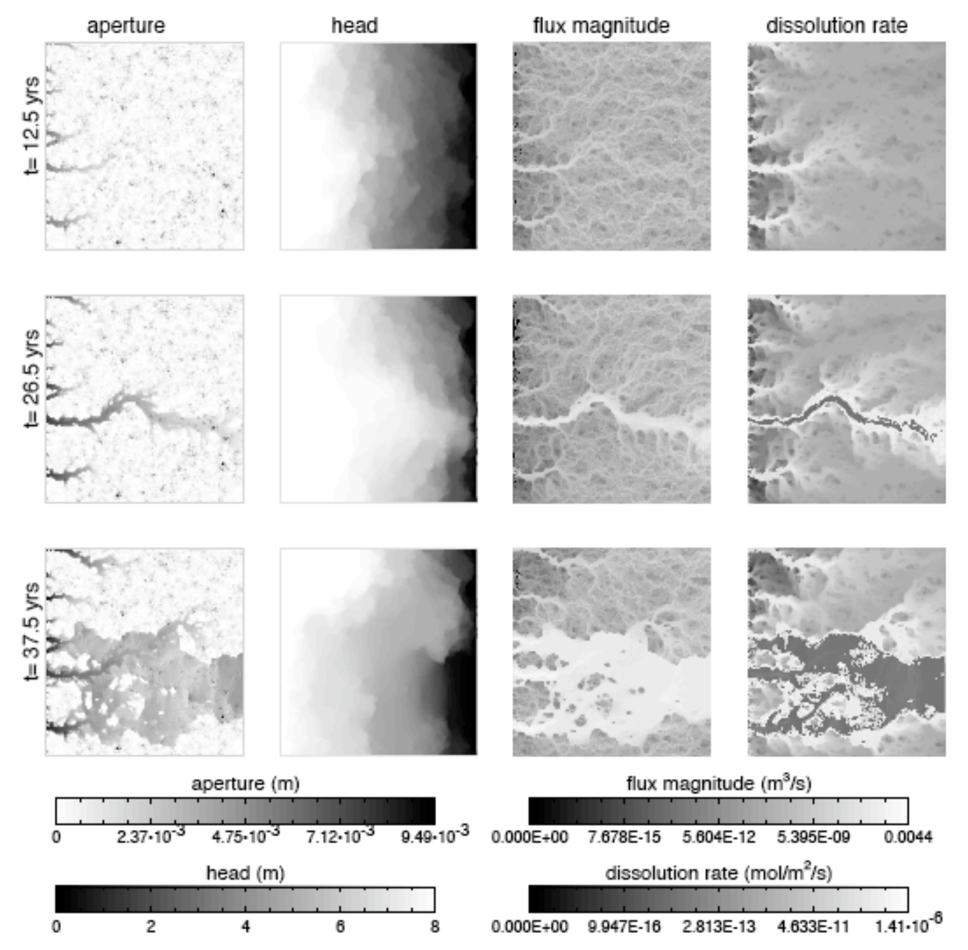
Sliding of initial fracture surface results in anisotropic topographic/hydraulic connectivity

sliding →



after Hari Rajaram

Also analogous to karst systems:
Pipes grow in size and hence efficiency
But the glacial system can collapse…
and operates on much shorter timescales



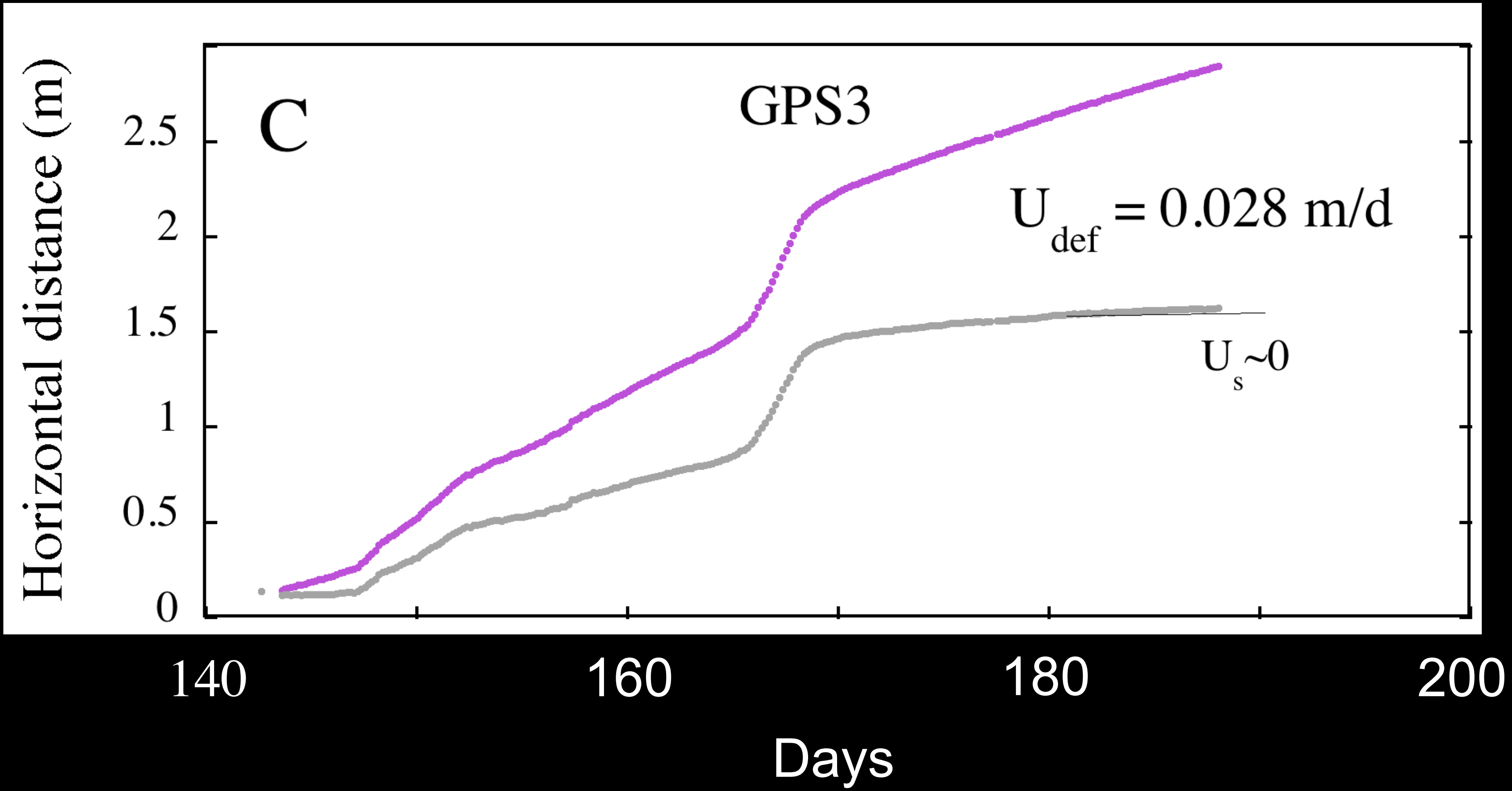
Hari Rajaram karst models

..but all this stuff happens beneath tens to hundreds of meters of opaque substance…

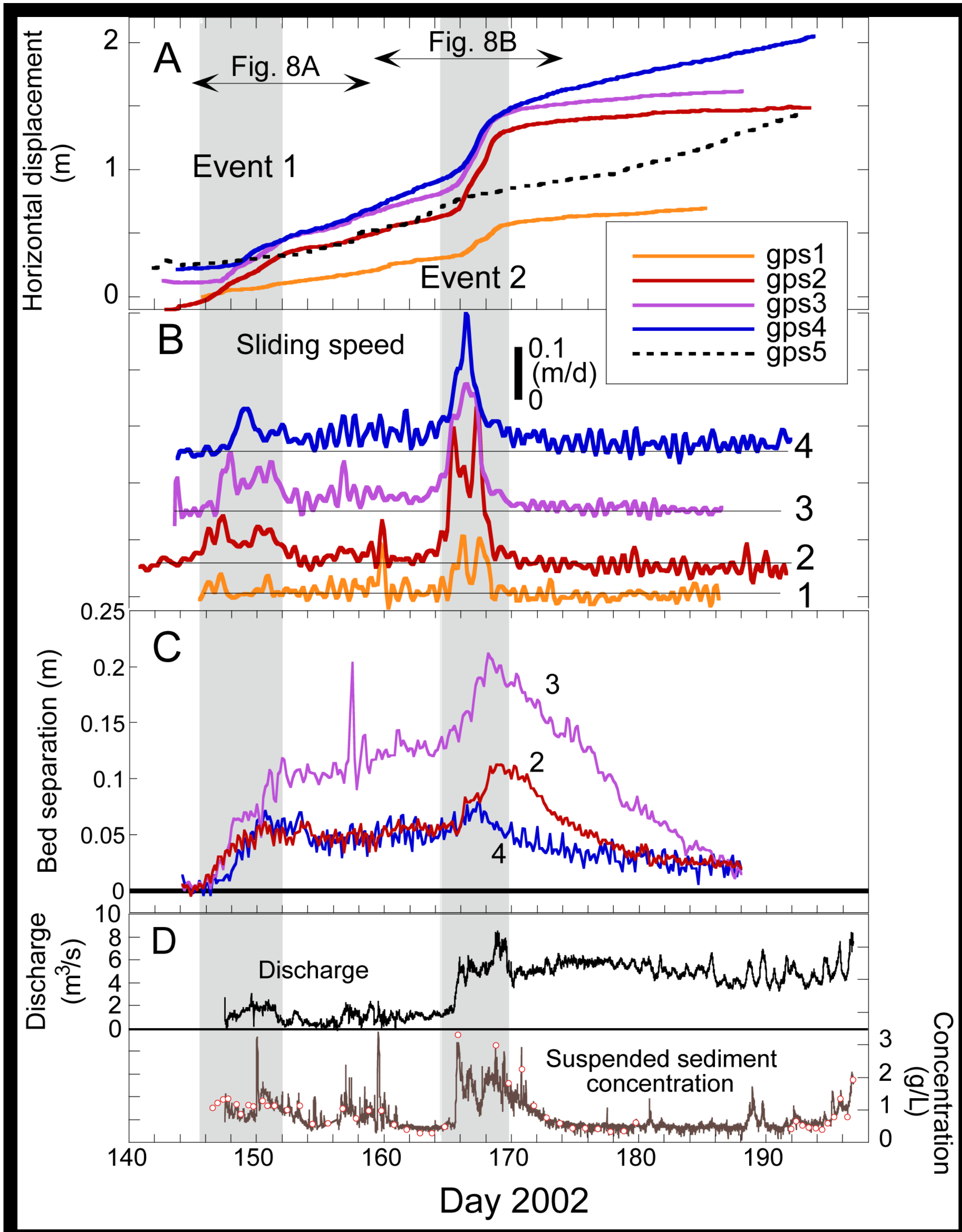
What can we tell from observations at the surface of a glacier?

Sliding results in surface uplift…

Bench Glacier, Alaska



GPS to the rescue!

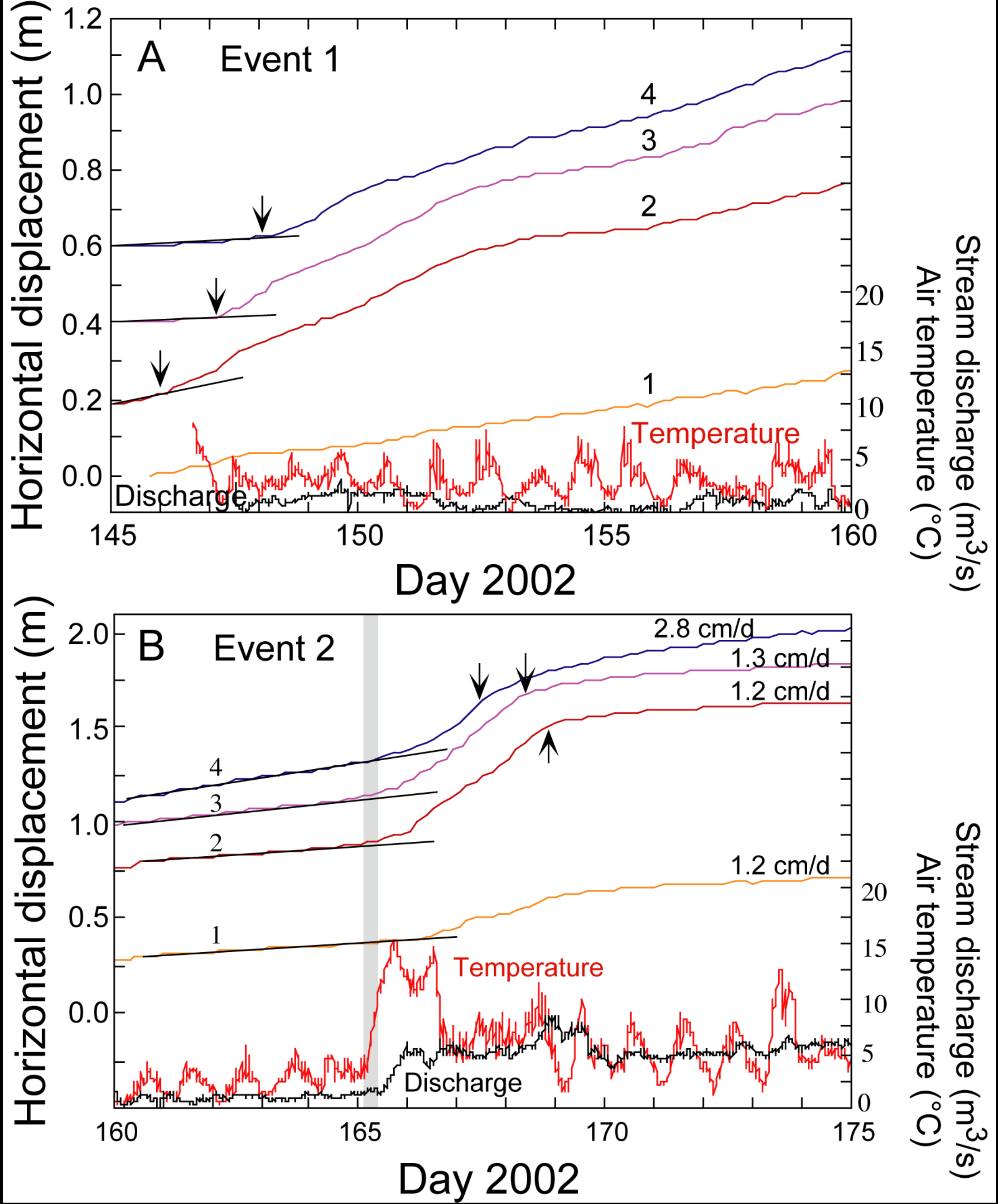


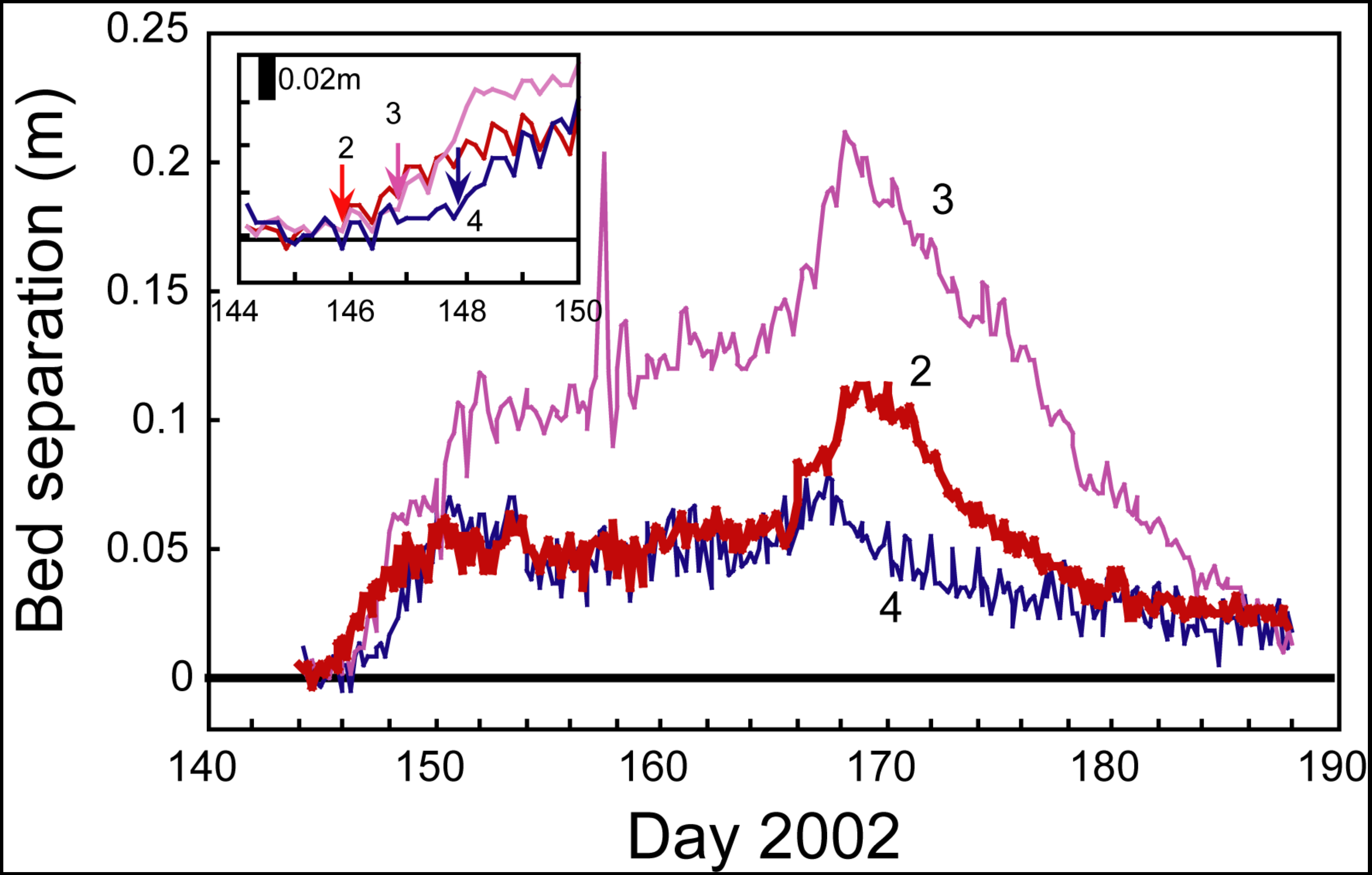
Bench Glacier

The Spring event
on an alpine glacier

Note timescale of collapse

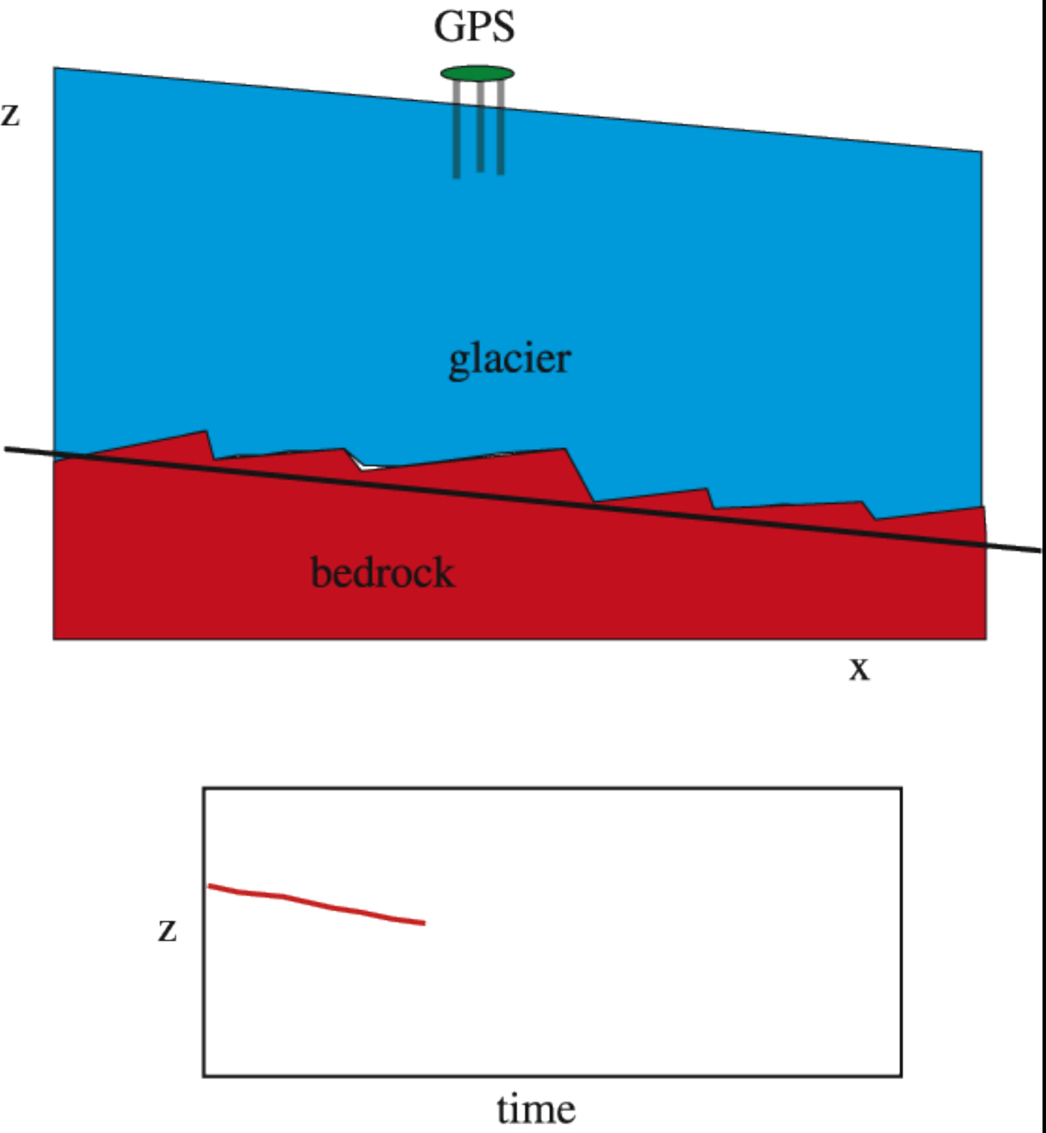
Note abrupt onset of high Q

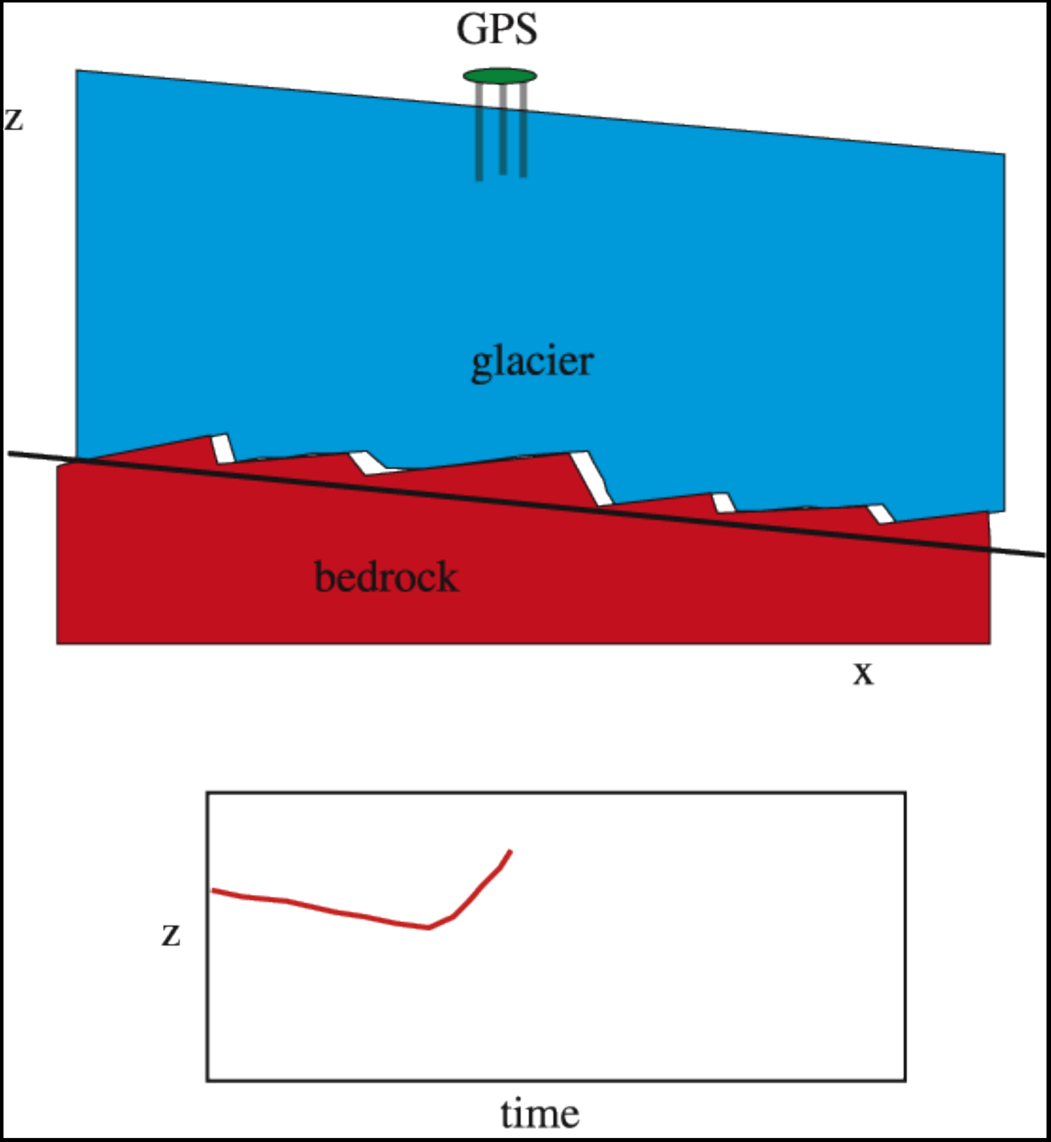

A
Event 1
Horizontal displacement (m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
4
3
2
1
Temperature
Discharge
145
150
155
160
Day 2002
20
15
10
5
0
Stream discharge (m^3/s)
Air temperature (°C)
B
Event 2
Horizontal displacement (m)
2.0
1.5
1.0
0.5
0.0
2.8 cm/d
1.3 cm/d
1.2 cm/d
1.2 cm/d
4
3
2
1
Temperature
Discharge
160
165
170
175
Day 2002
20
15
10
5
0
Stream discharge (m^3/s)
Air temperature (°C)

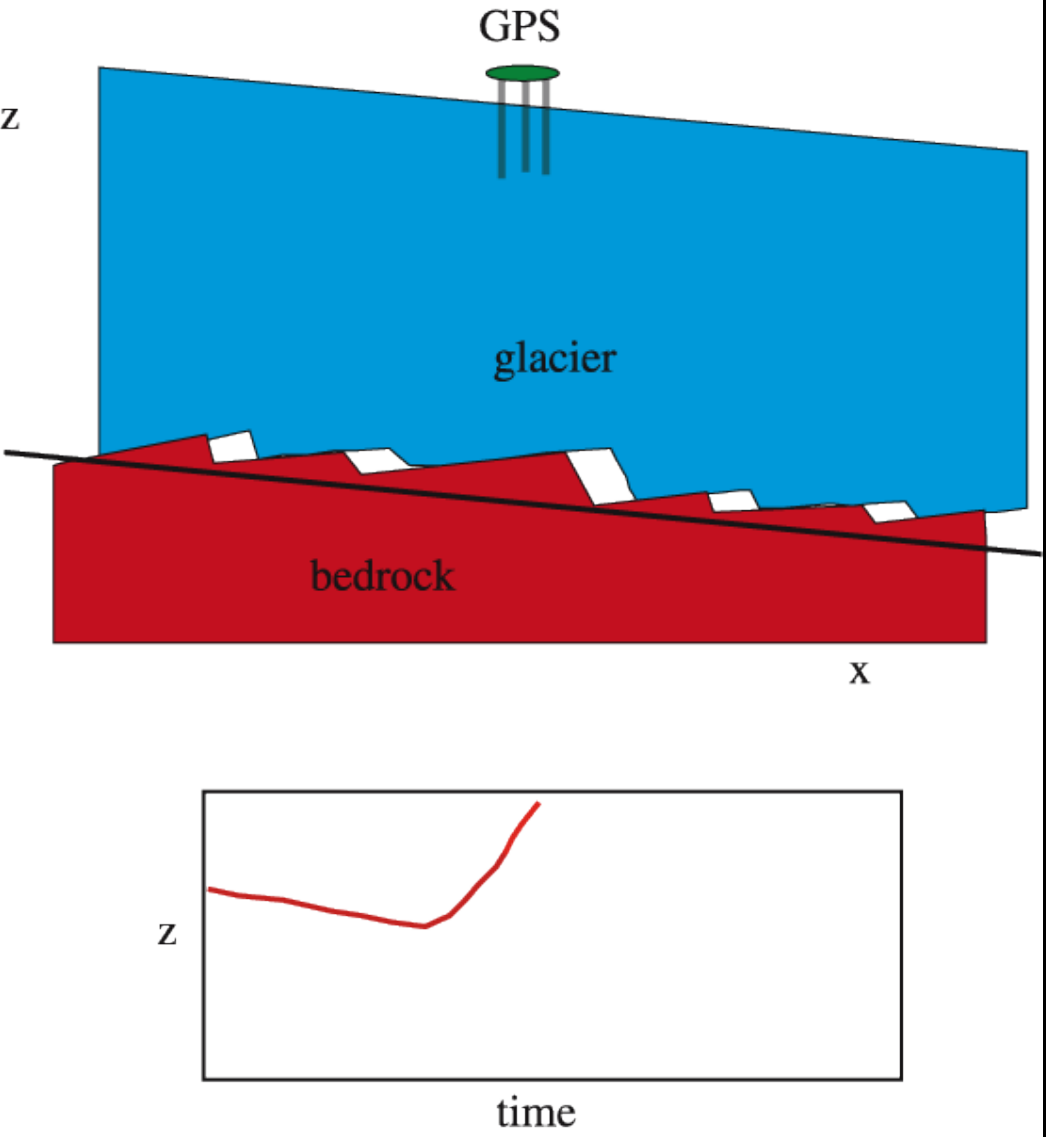


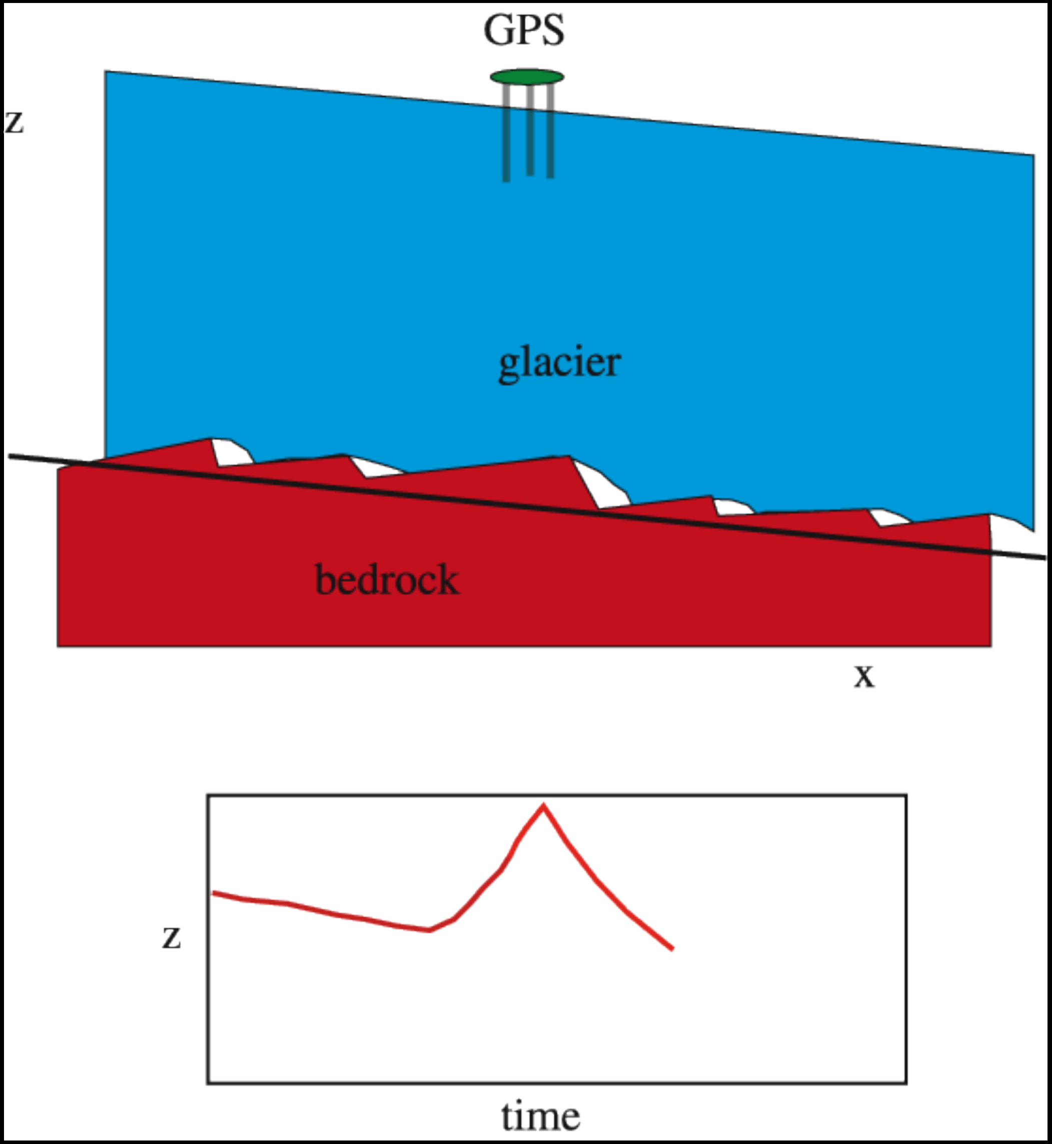
Note 8-day decay time

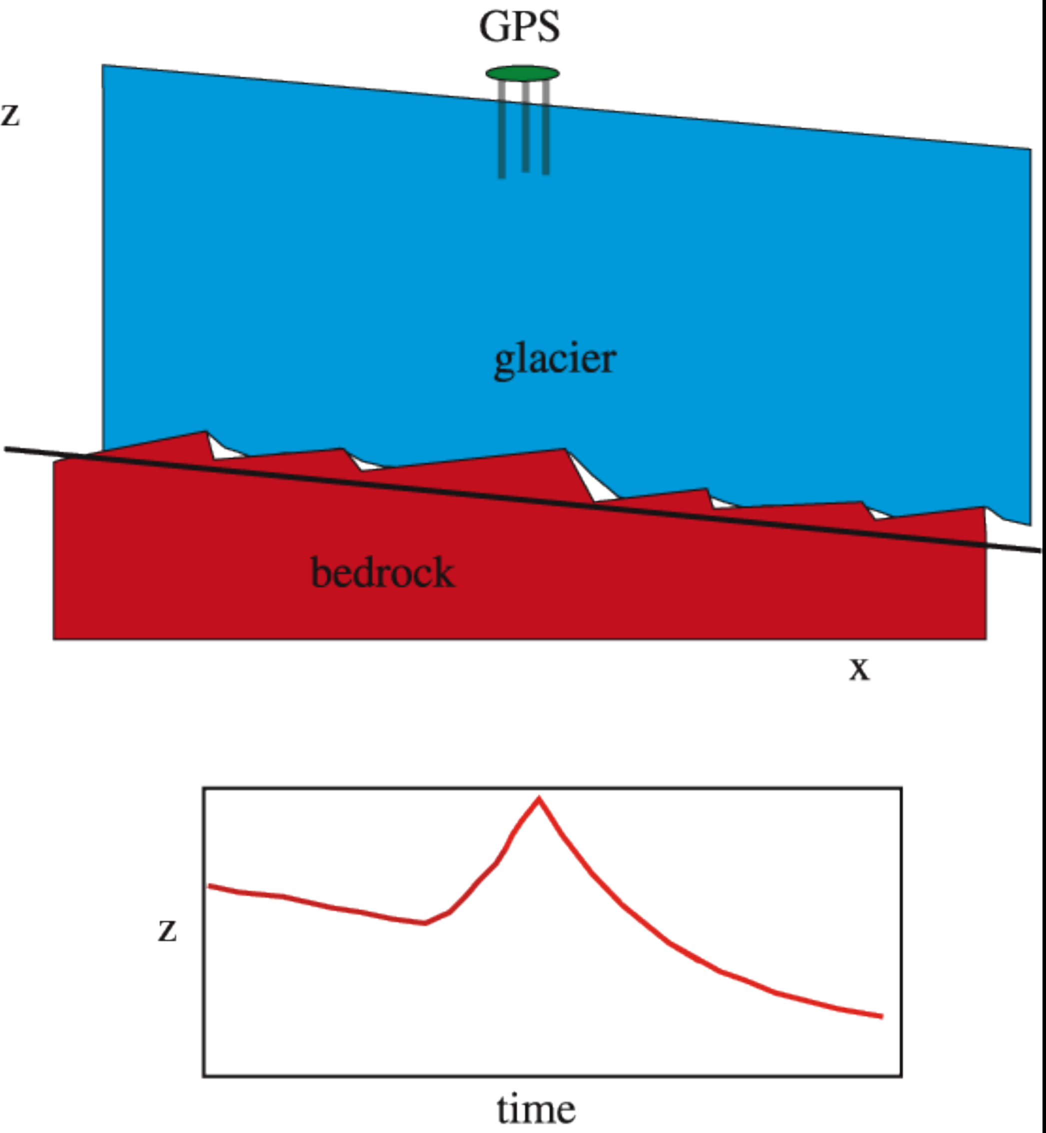
…so the vertical GPS records cavity size through time…


GPS
z
glacier
bedrock
x
z
time


GPS
z
glacier
bedrock
x
z
time


GPS
z
glacier
bedrock
x
z
time


GPS
z
glacier
bedrock
x
z
time


GPS
z
glacier
bedrock
x
z
time

Rate of change of area of cavities
= growth rates - collapse rates

Growth by sliding
Growth by melting
Collapse by creep

n=3
Nonlinear rheology

Crudely…

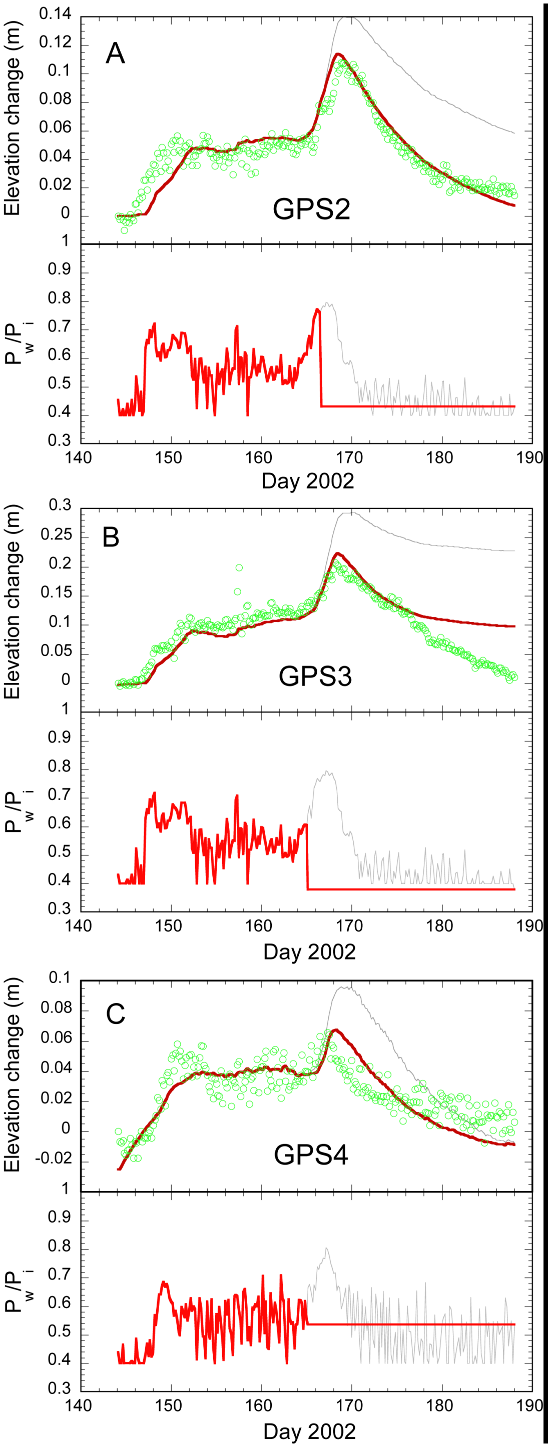
$$\frac{dS}{dt} = U_s h + \dot{m}\lambda - 2A\left[\frac{P_i - P_w}{n}\right]^n S$$

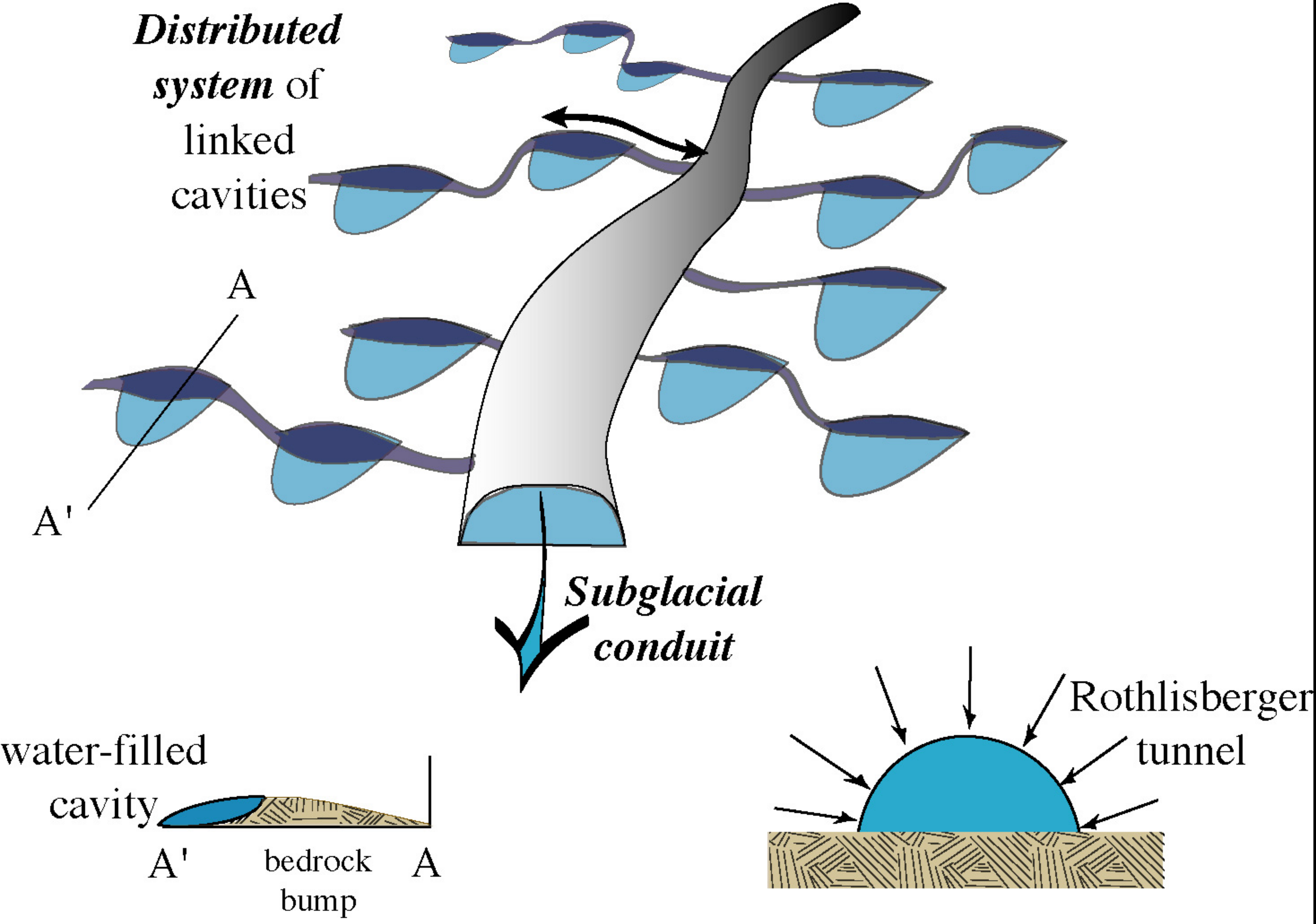
S = cross section of the cavity

But Us ~ Pw or really as 1/(Pi-Pw)

Modeling the bed separation record

Assumes that sliding is proportional to local shear stress and inversely proportional to the effective stress:
$N = (P_i - P_w)$,
so that as P_w increases, sliding increases.
Also, roof collapse goes as N^3, so increases as P_w decreases.




Distributed system of linked cavities
A
A'
Subglacial conduit
water-filled cavity
A'
bedrock bump
A
Rothlisberger tunnel

The pipe system

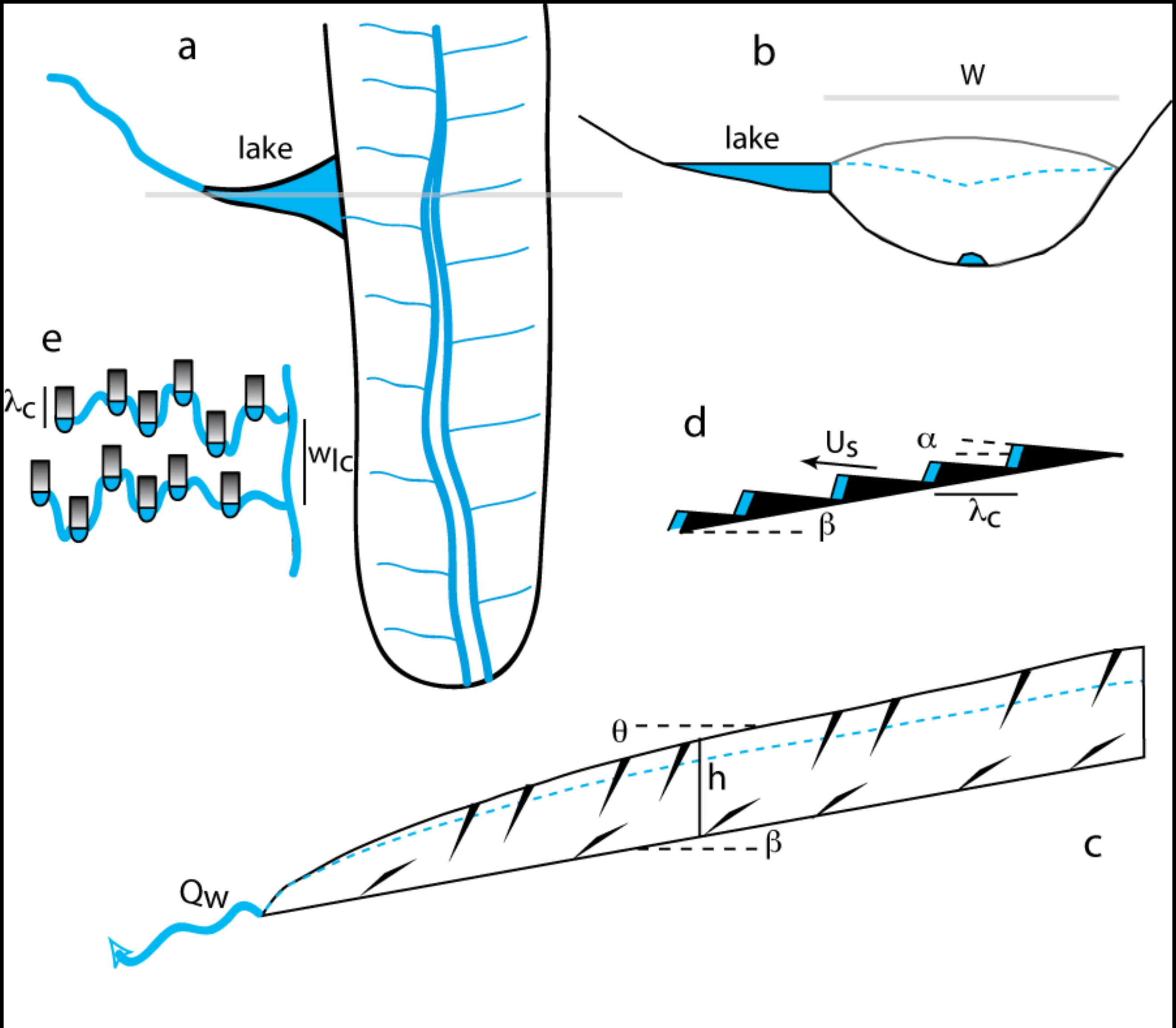
Again a competition between growth and decay of a cross section

$$\frac{dS}{dt} = \dot{m}L - 2A\left[\frac{P_i - P_w}{n}\right]^n S$$

L=circumference
A = flow law parameter
m ~ Q

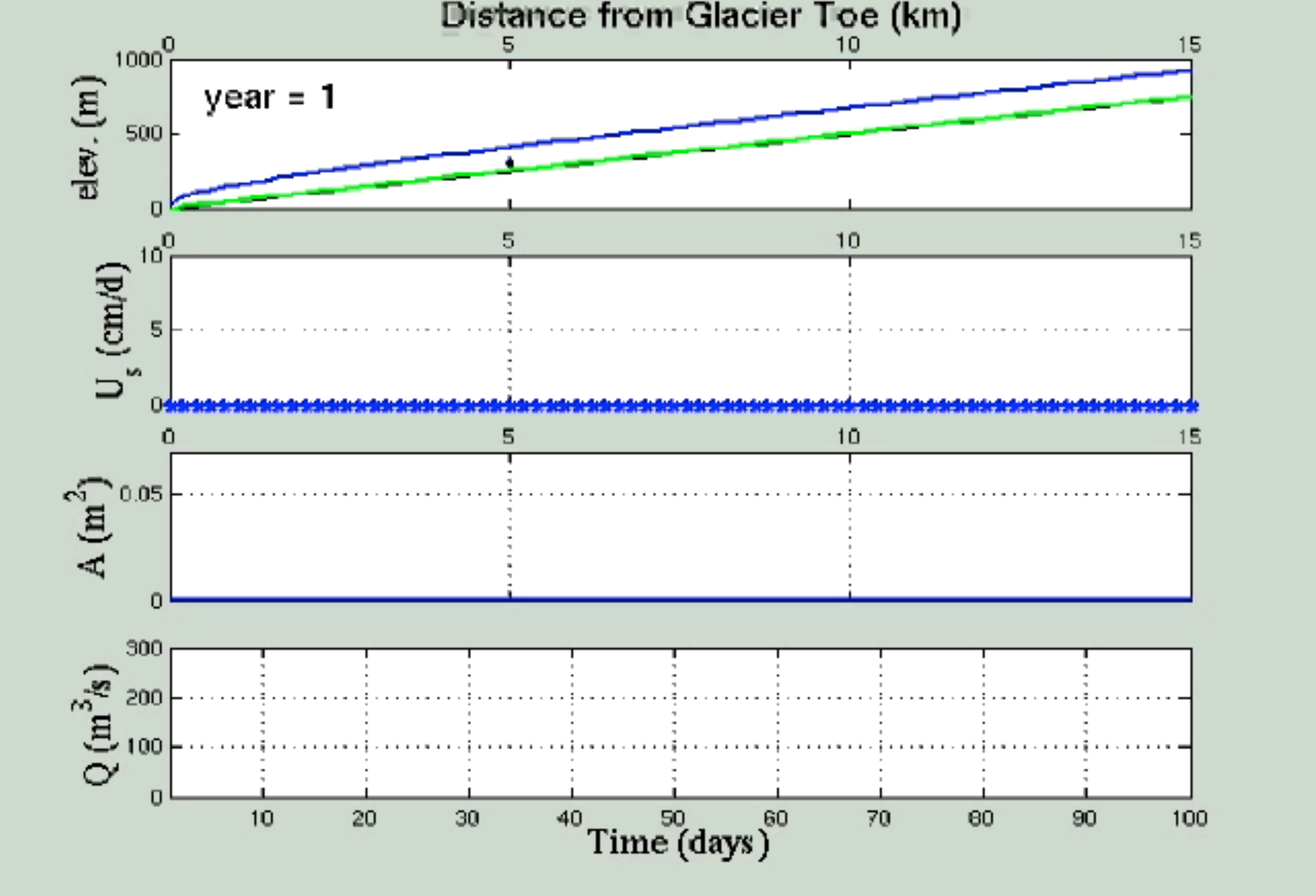
Melt rate ~ Q
As melt rate->0, S declines… exponentially

Linking them all together



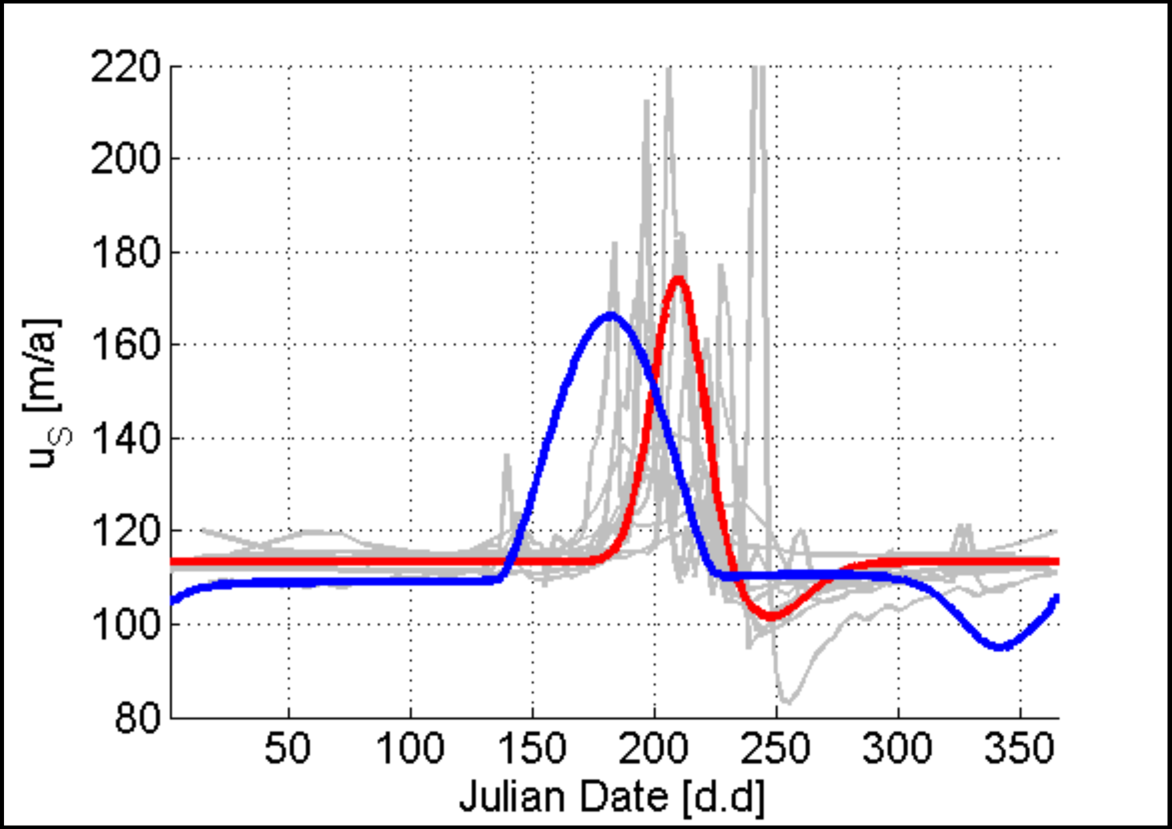
Kessler and Anderson GRL 2005

Inspired by Clarke’s lumped element model



Rug-flap sliding & outburst flood

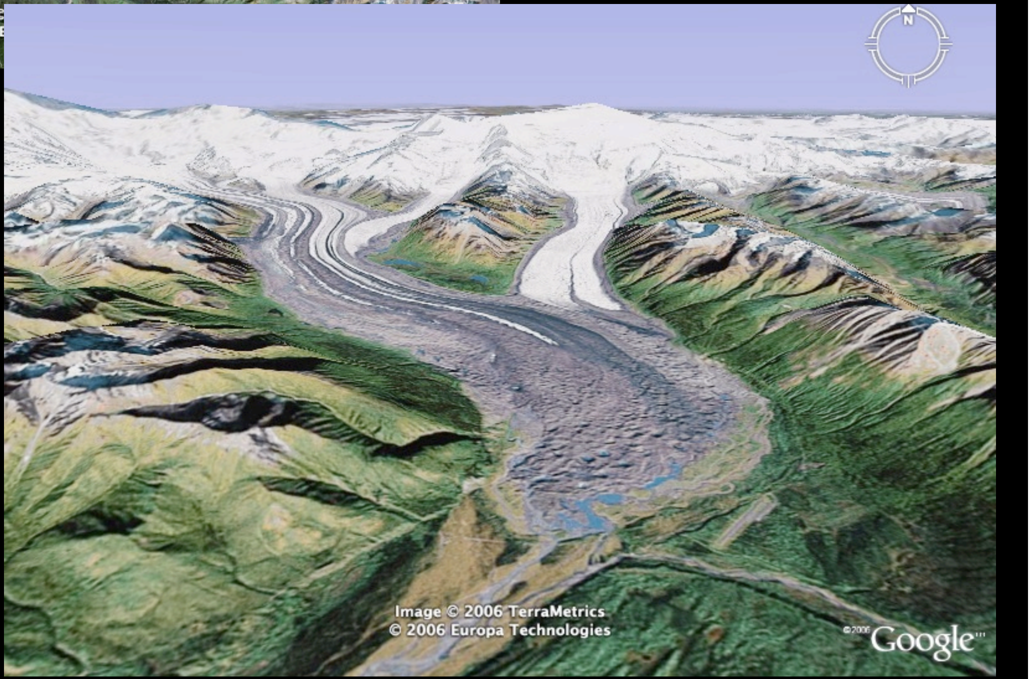
Kessler and Anderson GRL



Greenland outlet glaciers show the same annual cycle of sliding

How should the time scale depend upon
Ice thickness?
How quickly is pipe size reset to “small”
Under what ice thicknesses might
we expect pipes to persist overwinter…

Let’s go to another, bigger glacier…

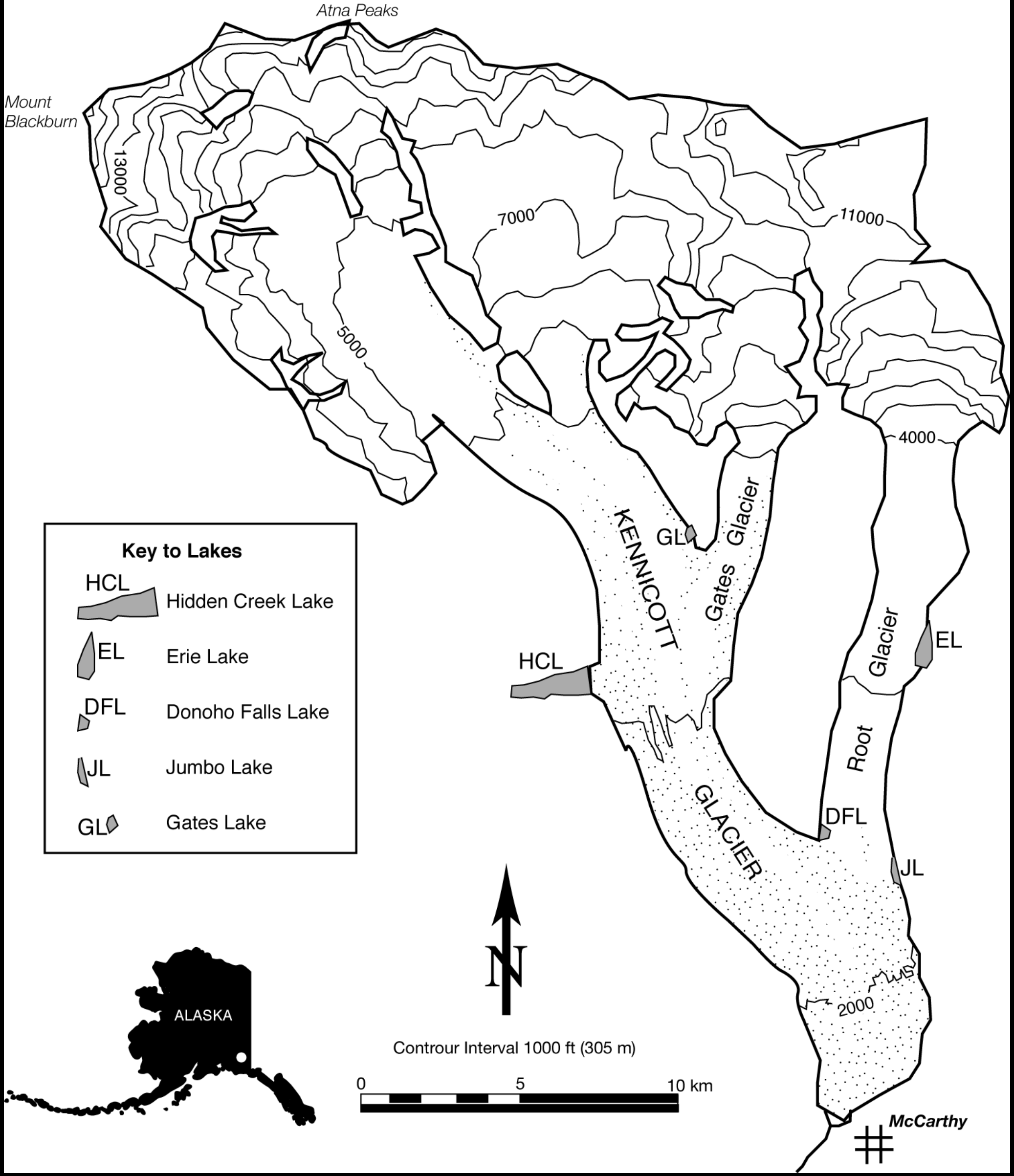


Kennicott Glacer, Wrangell Mountains

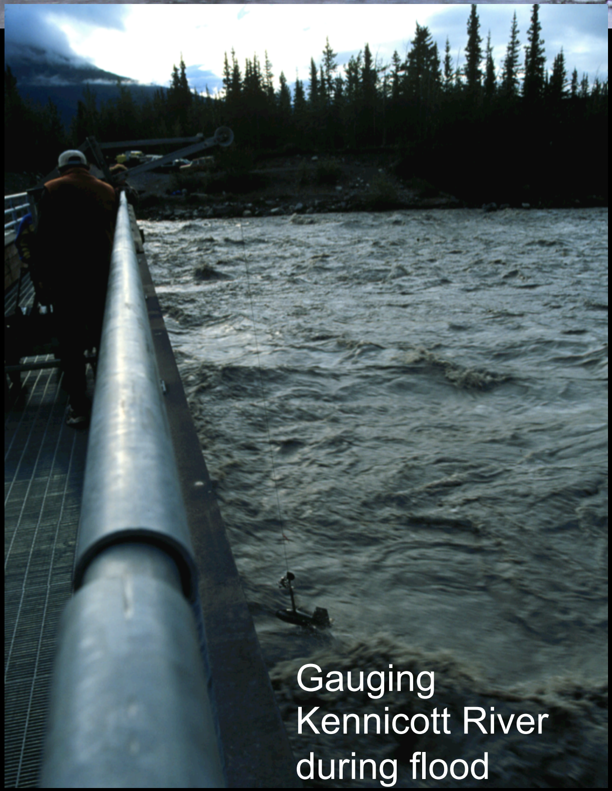
40 km long, ~400 m thick

Annual jökulhlaups from Hidden Creek Lake

1999 & 2000 jökulhlaup studies




Sounding Hidden Creek Lake


Gauging Kennicott River during flood

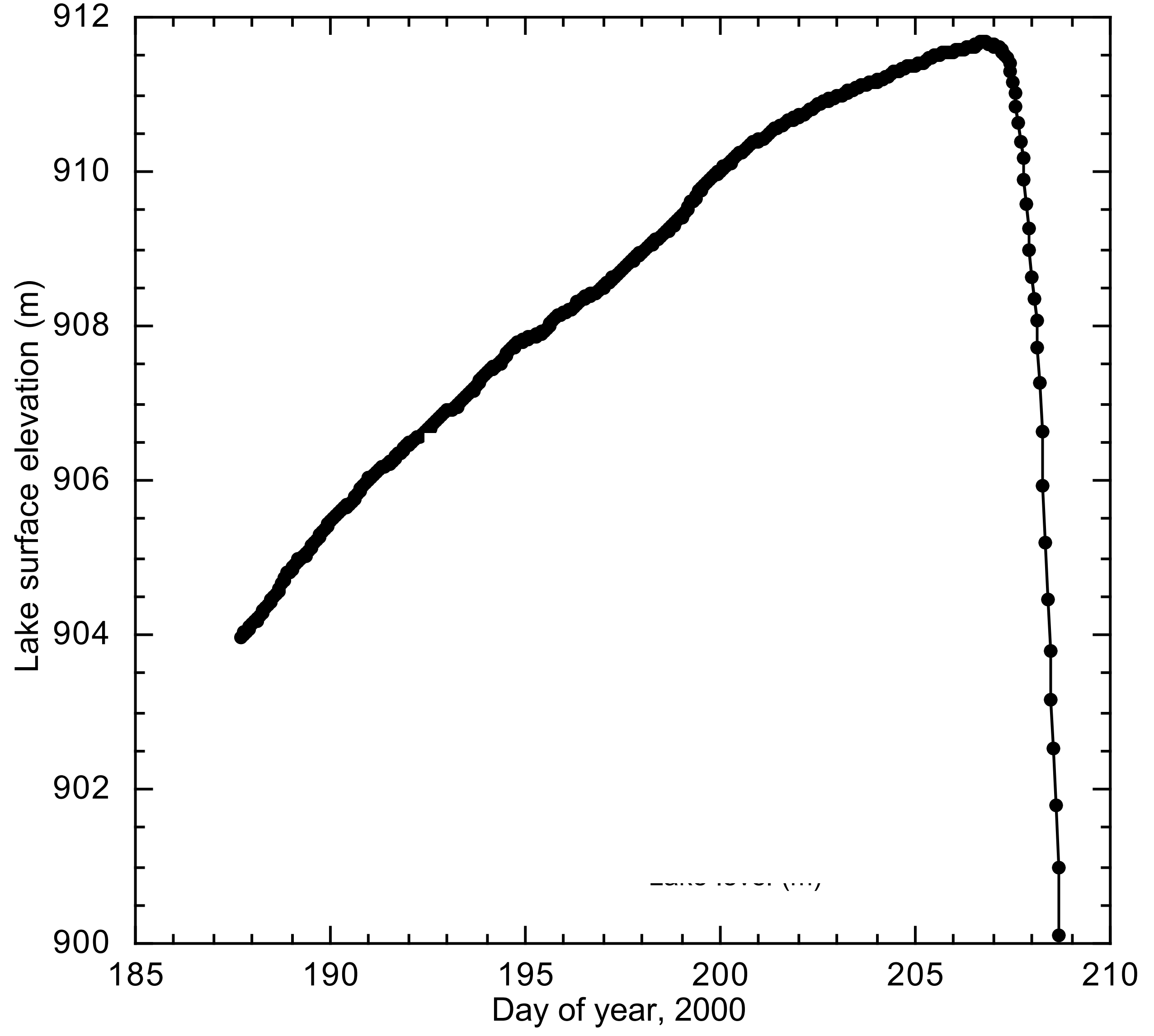
Donoho Falls Lake

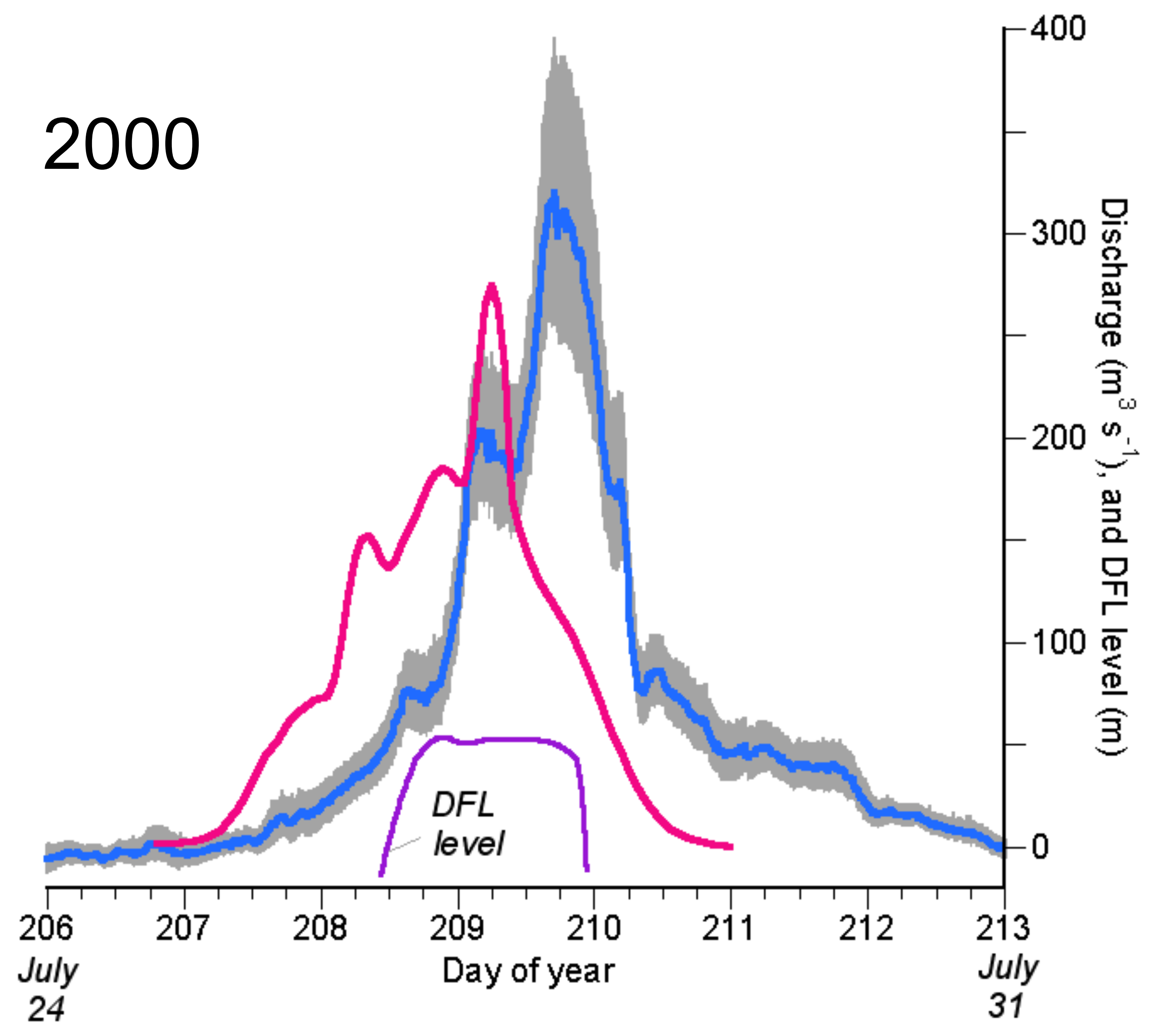
Photo by Christy Swindling

Hidden Creek Lake…before

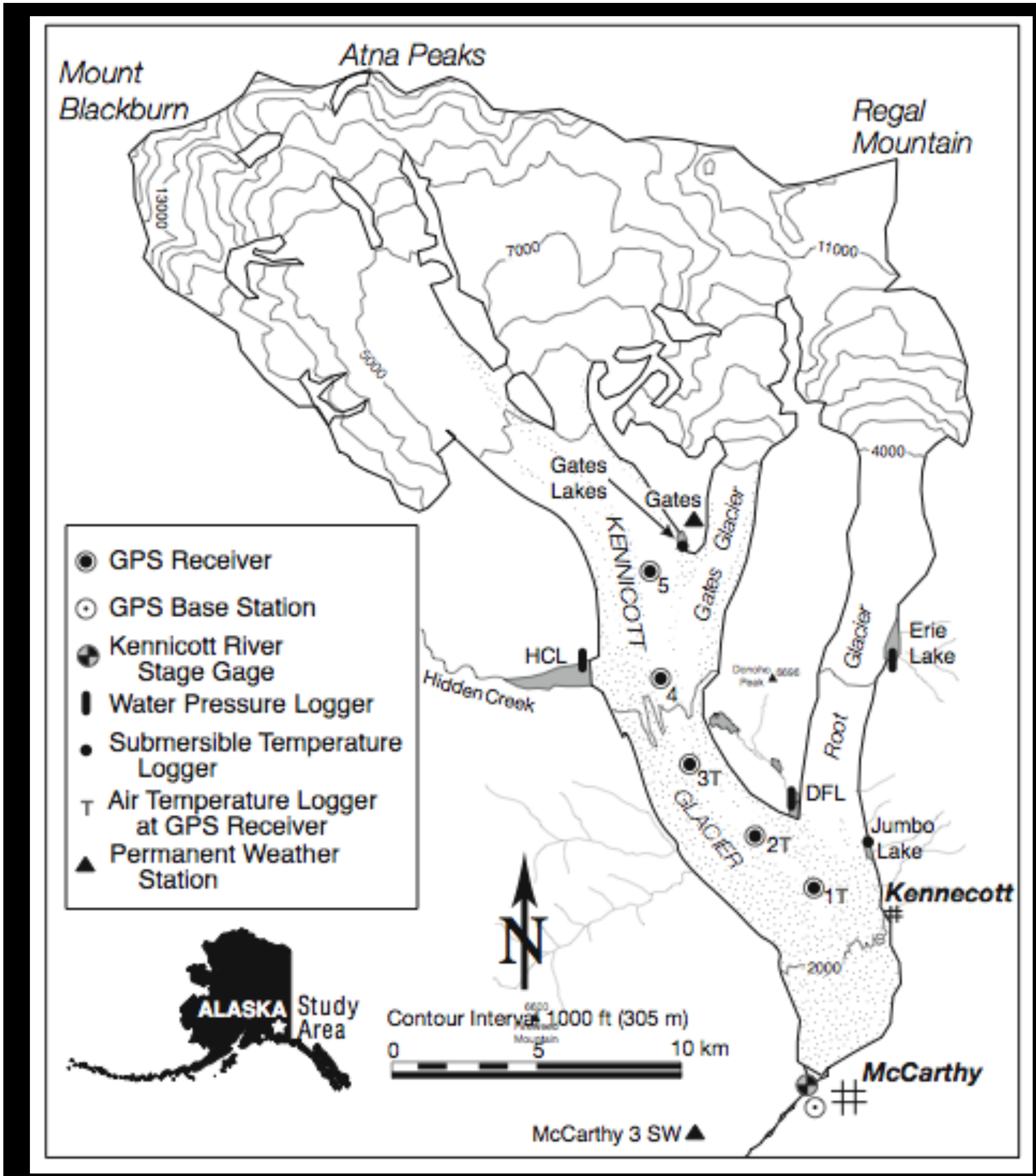
after

Lake stage record- first step toward lake volume history

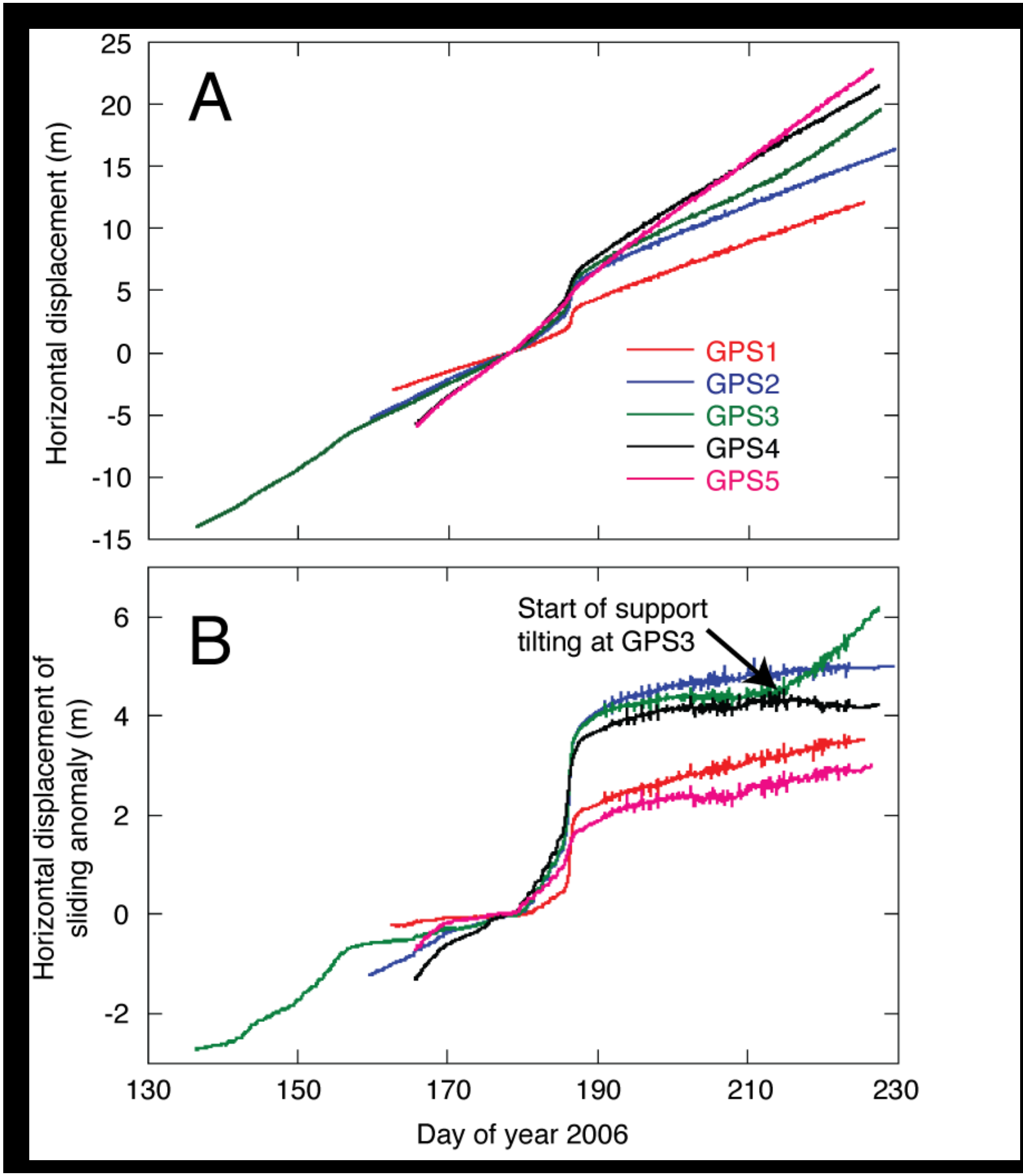




DFL serves as a manometer



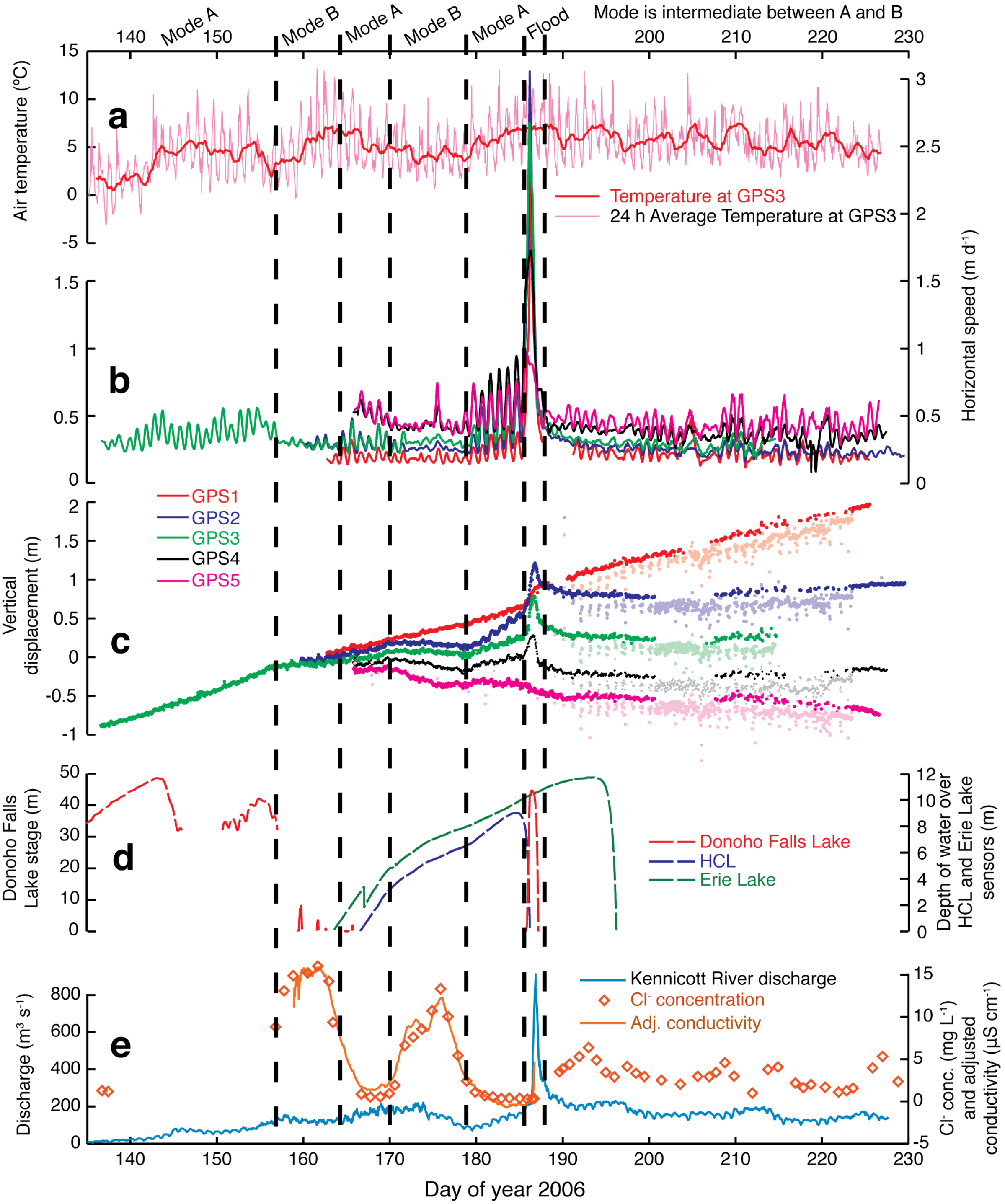
2006 field season



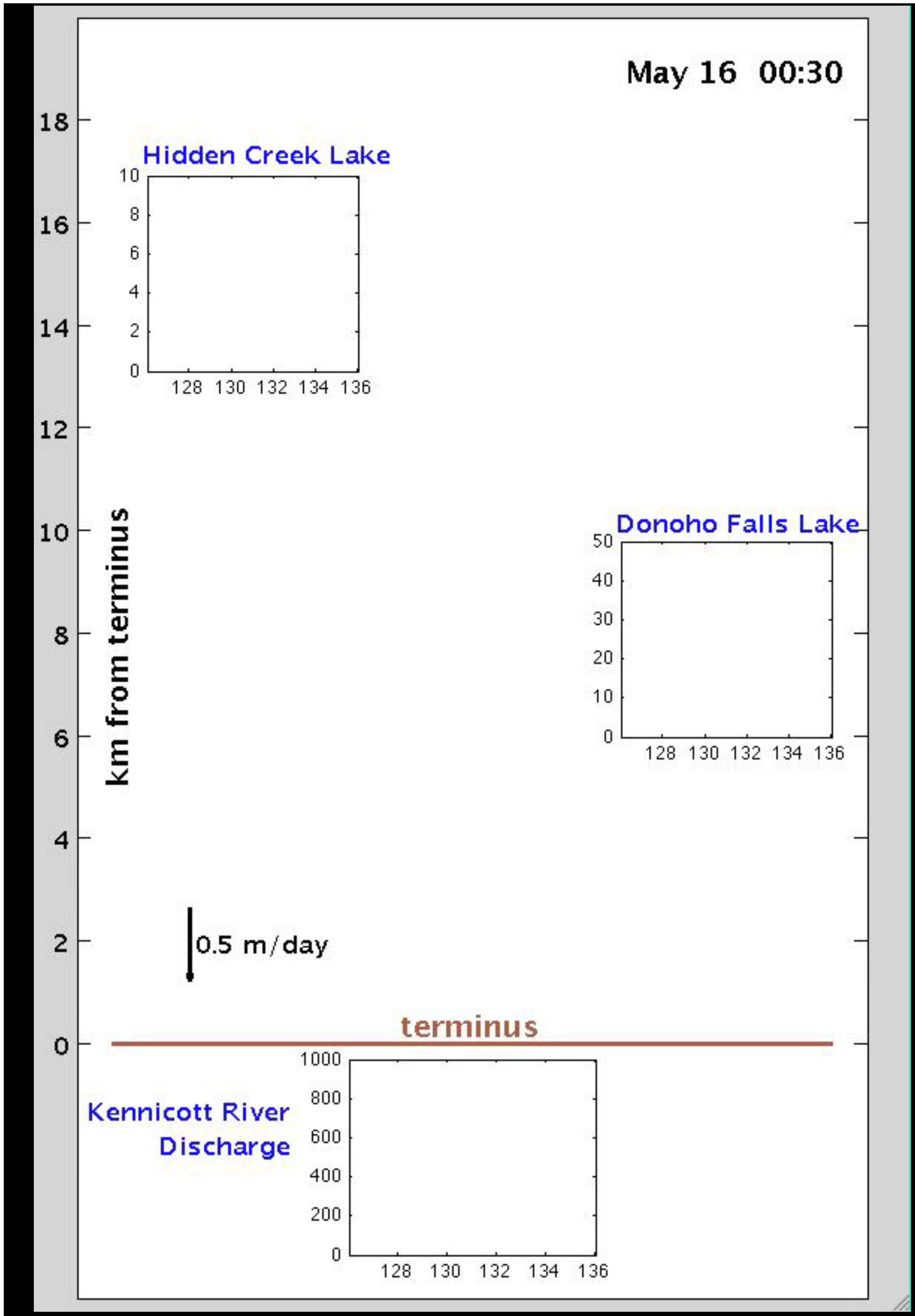
GPS records

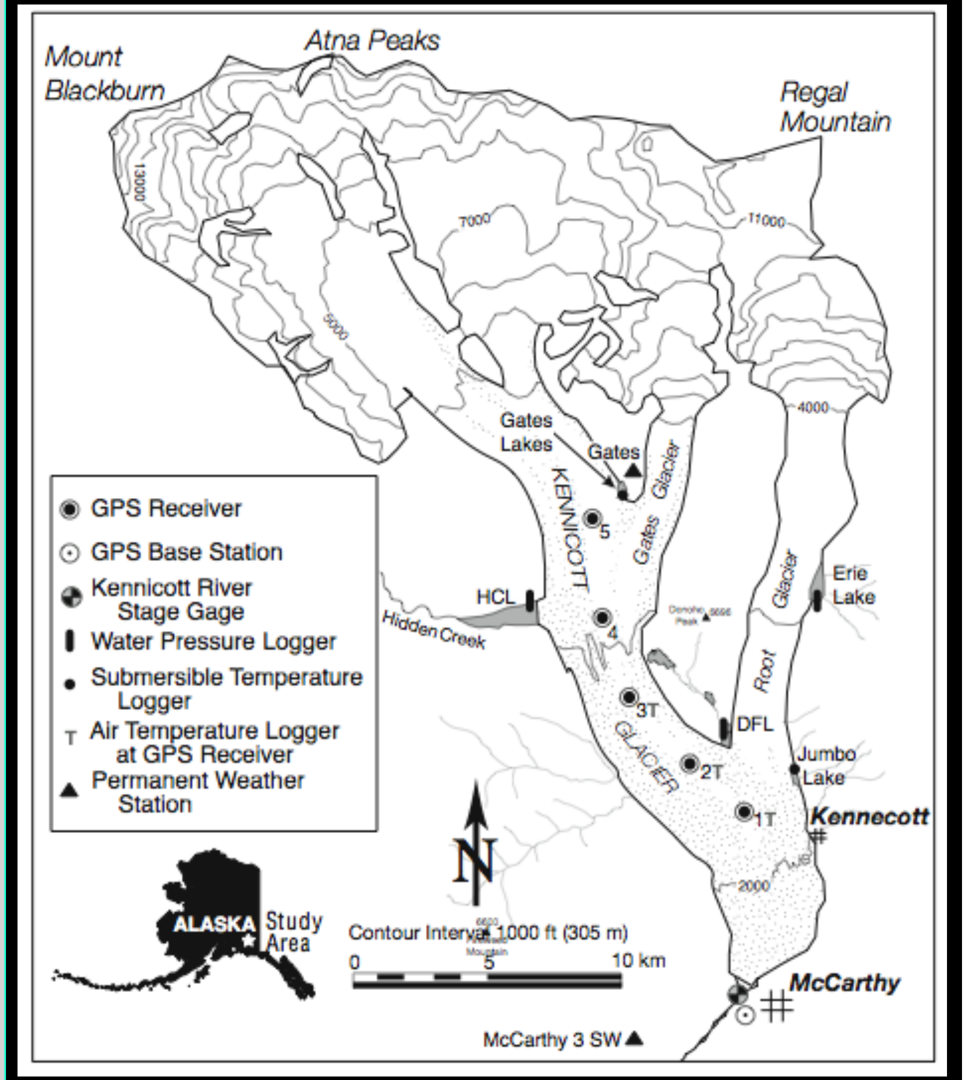
Raw

Sliding only

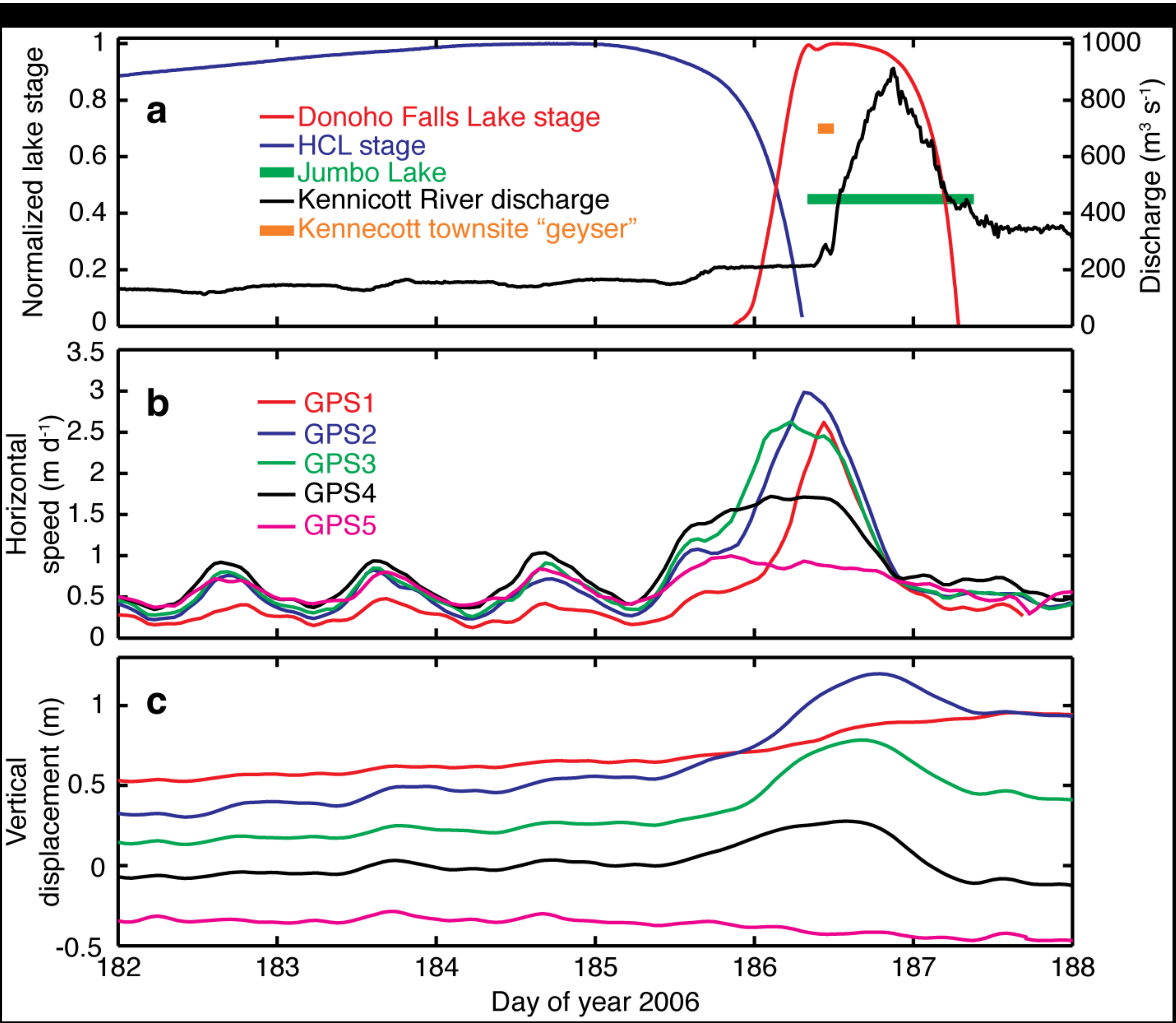


Mode A
Mode B
Mode A
Mode B
Mode A
Flood
Mode is intermediate between A and B
140
150
200
210
220
230
a
Air temperature (ºC)
15
10
5
0
-5
Temperature at GPS3
24 h Average Temperature at GPS3
Horizontal speed (m d^{-1})
3
2.5
2
1.5
1
0.5
0
b
1.5
1
0.5
0
GPS1
GPS2
GPS3
GPS4
GPS5
c
Vertical displacement (m)
2
1.5
1
0.5
0
-0.5
-1
d
Donoho Falls Lake stage (m)
50
40
30
20
10
0
Donoho Falls Lake
HCL
Erie Lake
Depth of water over HCL and Erie Lake sensors (m)
12
10
8
6
4
2
0
e
Discharge (m^3 s^{-1})
800
600
400
200
0
Kennicott River discharge
Cl$^-$ conc.
Adj. conductivity
Cl$^-$ conc. (mg L^{-1}) and adjusted conductivity (µS cm^{-1})
15
10
5
0
-5
140
150
160
170
180
190
200
210
220
230
Day of year 2006



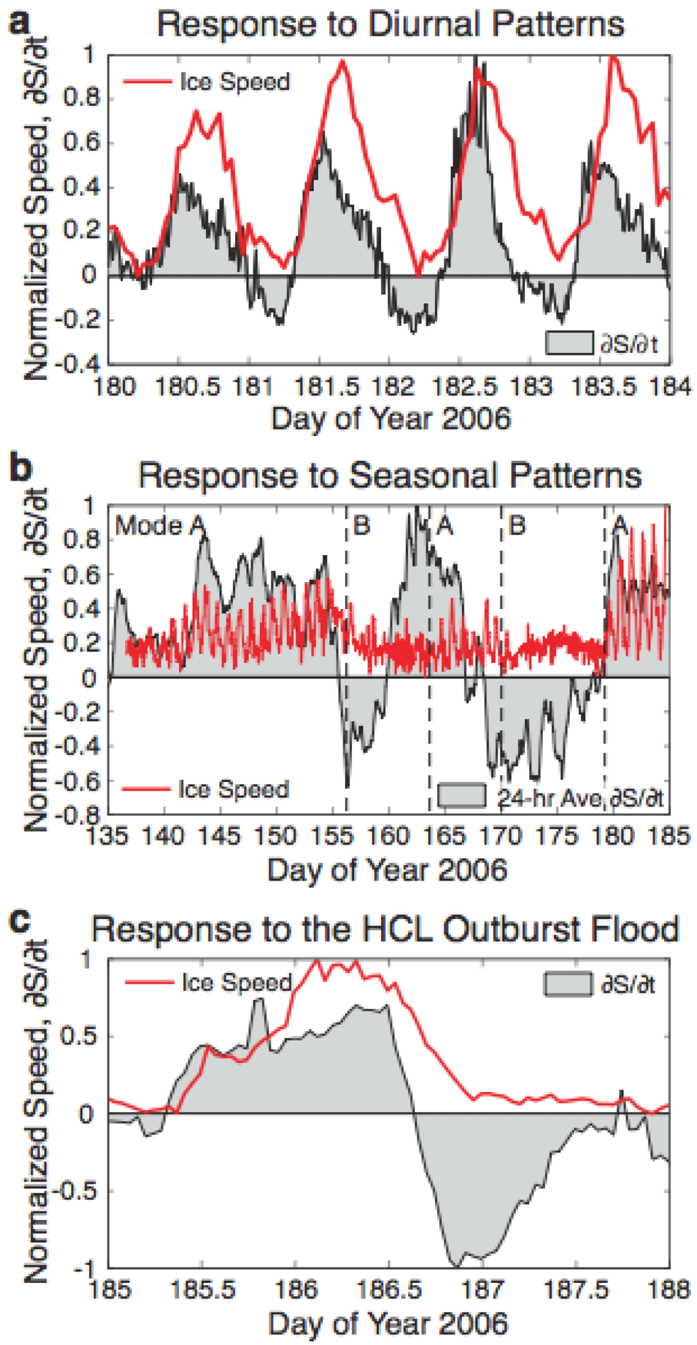


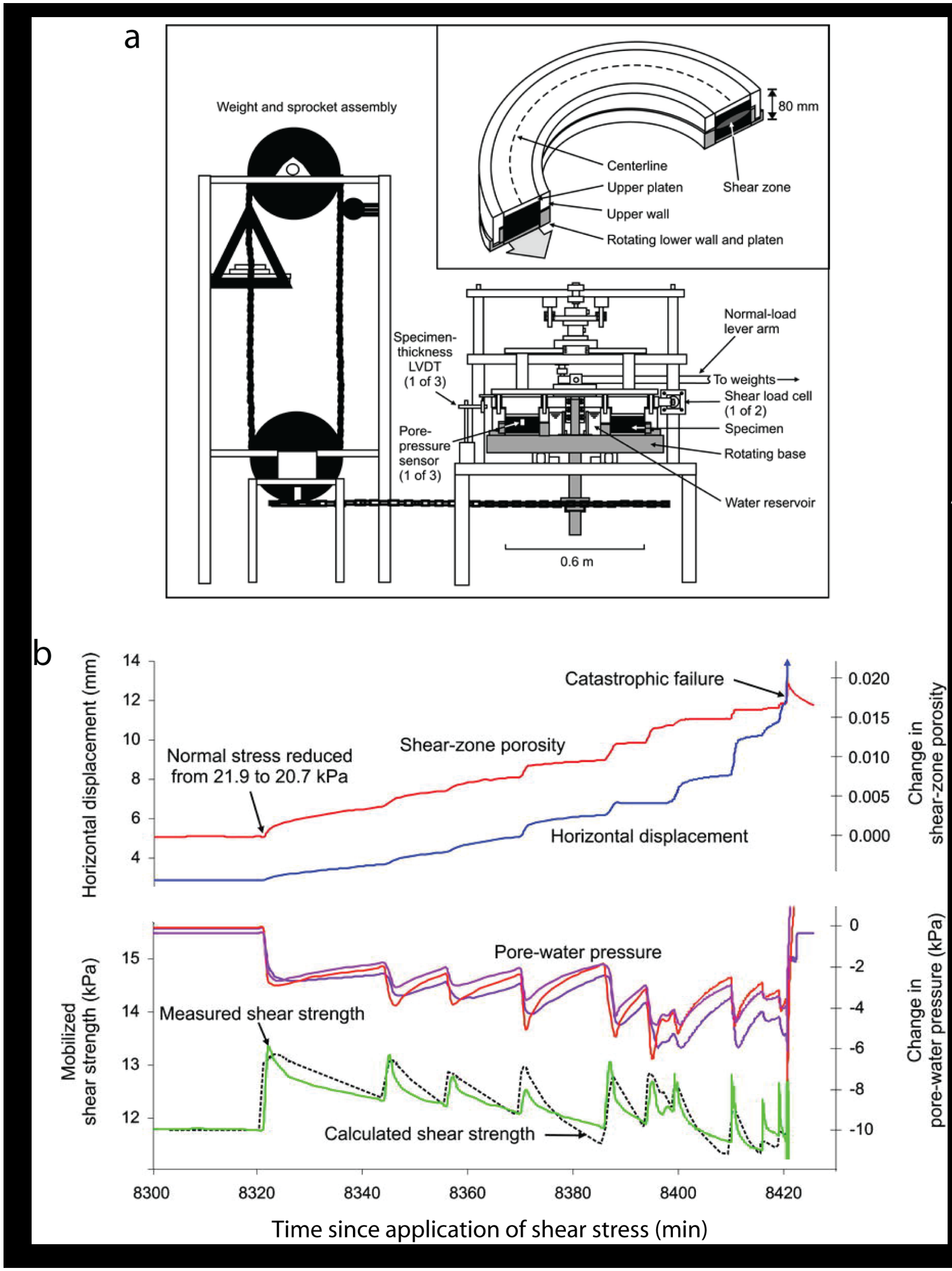
Animation of 2006 data set
by Tim Bartholomaus, 2011



The period leading up to the flood

Bottom line:
Sliding occurs whenever the subglacial plumbing system is overwhelmed by inputs, i.e. whenever dS/dt >0



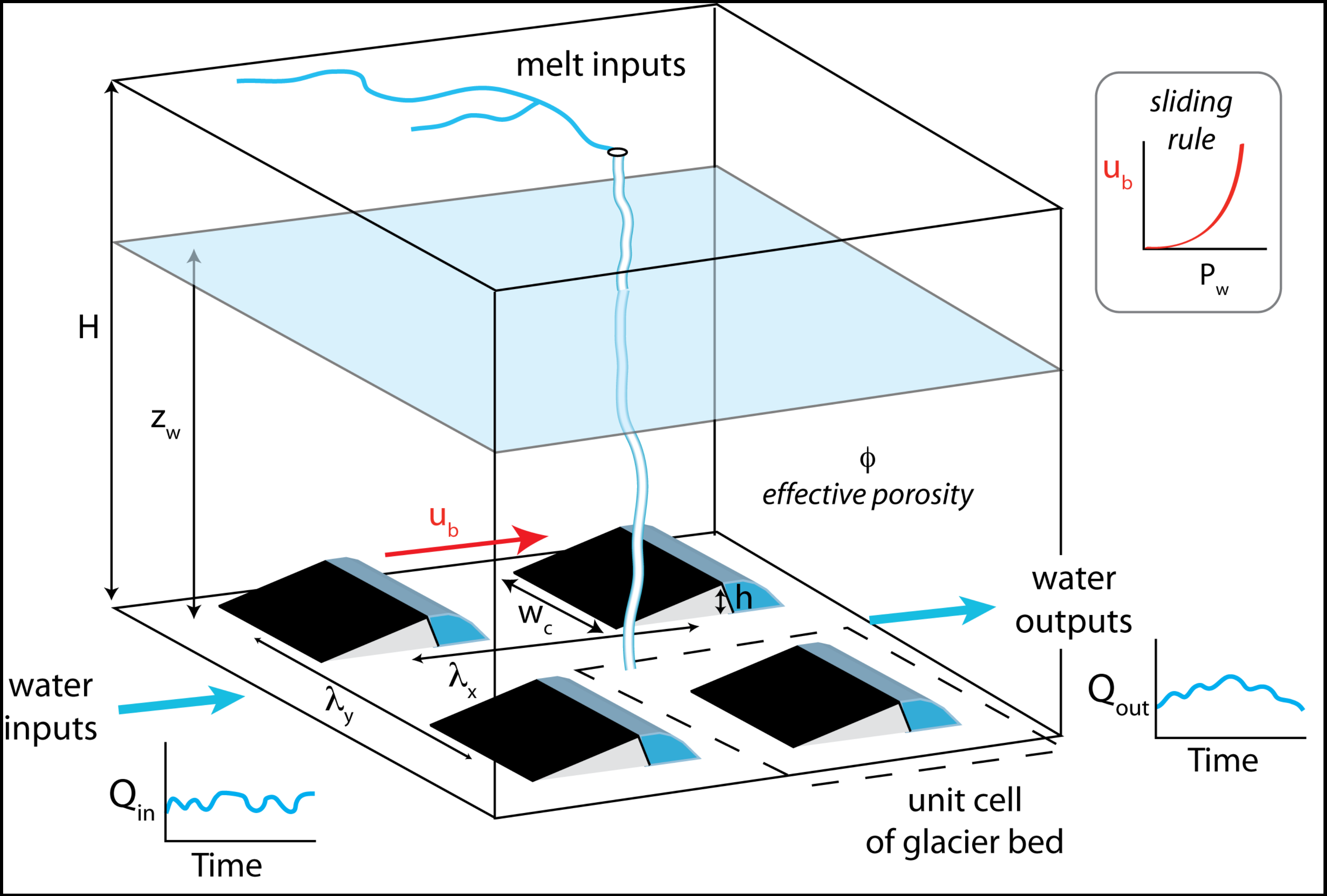


…How to explain
the daily sliding cycle…

Analogy with shearing
of porous granular materials

Moore and Iverson, Geology

In the subglacial system
cavities serve as the dynamic
porosity element

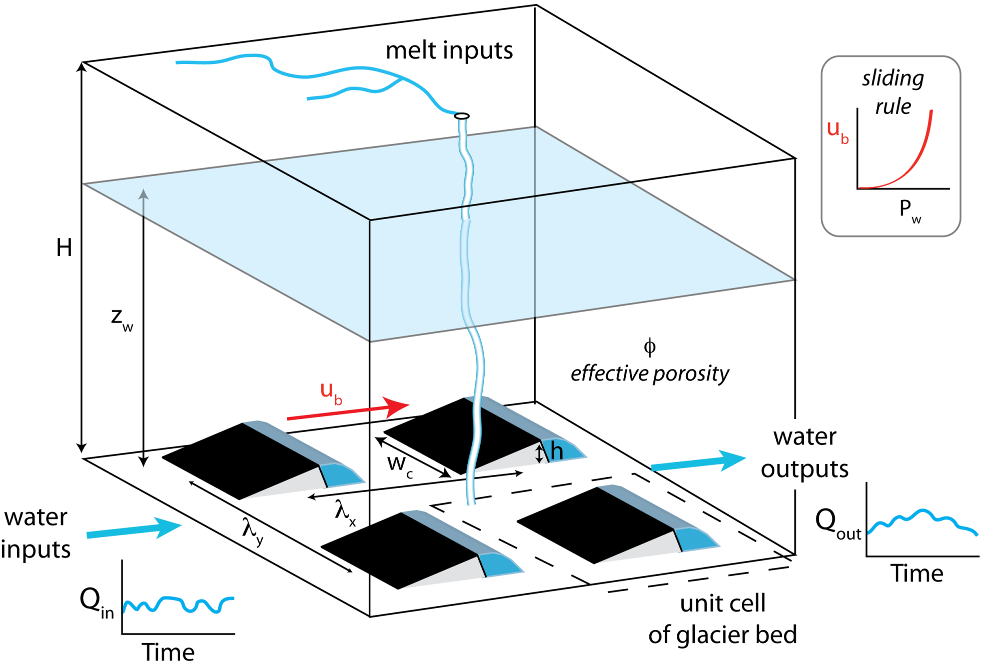

melt inputs
sliding rule
u_b
P_w
H
z_w
ϕ
effective porosity
u_b
w_c
h
λ_x
λ_y
water inputs
water outputs
Q_{in}
Time
Q_{out}
Time
unit cell of glacier bed

$$\boxed{\phi \frac{dz_w}{dt} = \dot{m} - \frac{ds}{dt}}$$

Water table change

$$\boxed{\frac{ds}{dt} = \frac{hw_c}{\lambda_x \lambda_y} u_b = f u_b}$$

Growth of cavity (porosity)



$$\boxed{\frac{dP_w}{dt} = \rho_w g \frac{dz_w}{dt} = \frac{\rho_w g}{\phi}\left(\dot{m} - \frac{ds}{dt}\right) = \frac{\rho_w g}{\phi}\left(\dot{m} - \frac{hw_c u_b}{\lambda_x \lambda_y}\right) = \frac{\rho_w g}{\phi}\left(\dot{m} - f u_b\right)}$$

$$\boxed{\frac{du_b}{dt} = \frac{du_b}{dP_w}\frac{dP_w}{dt}}$$

Response of sliding to water pressure

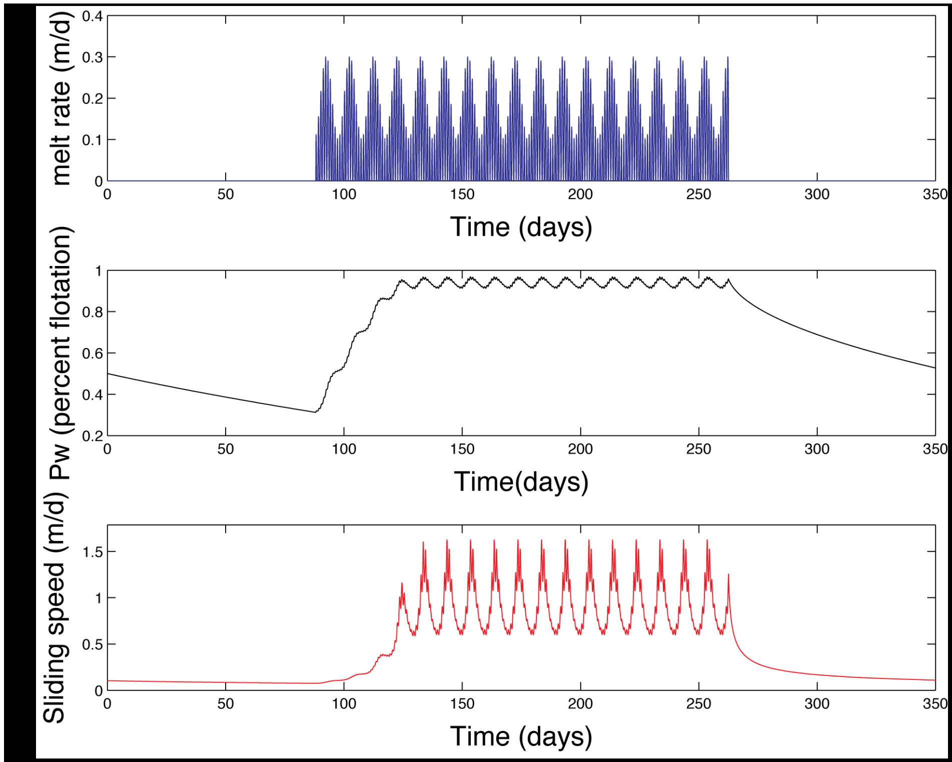
$$\frac{du_b}{dt} = -\left(\frac{\gamma k \rho_w g h w_c}{\phi \lambda_x \lambda_y N^{\gamma+1}}\right) u_b$$

The negative feedback

$$\tau = \frac{\phi \lambda_x \lambda_y N^{\gamma+1}}{\rho_w g \gamma k h w_c} = \left(\frac{1}{\rho_w g}\right)\left(\frac{\phi}{f}\right)\left(\frac{N^{\gamma+1}}{\gamma k}\right)$$

Time scale of response

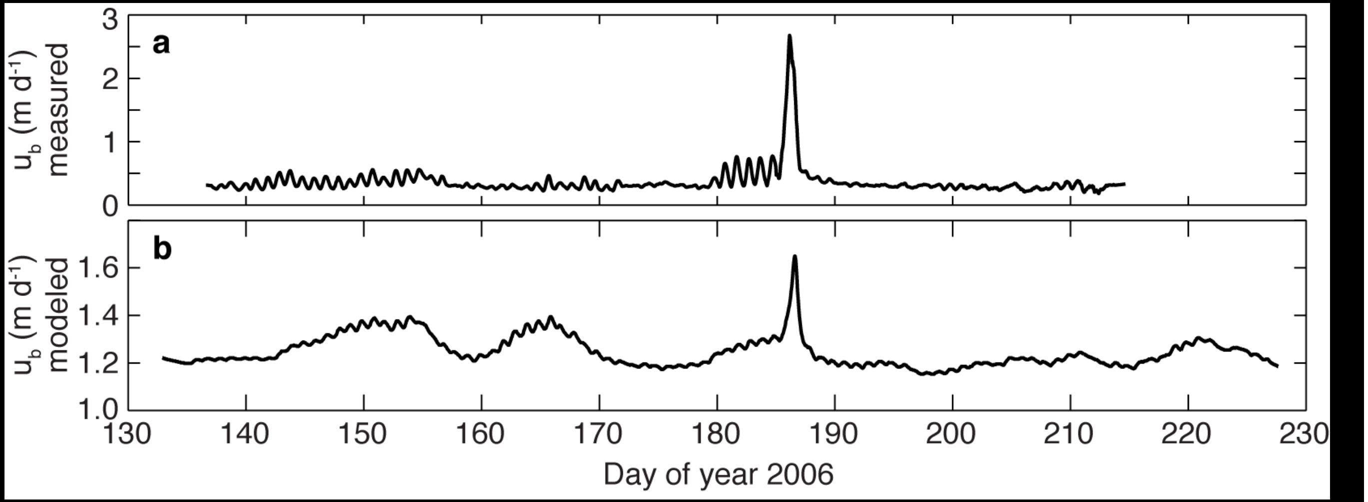
The shorter the time scale the stronger the feedback



Generic run

data

model



There is much left to do:

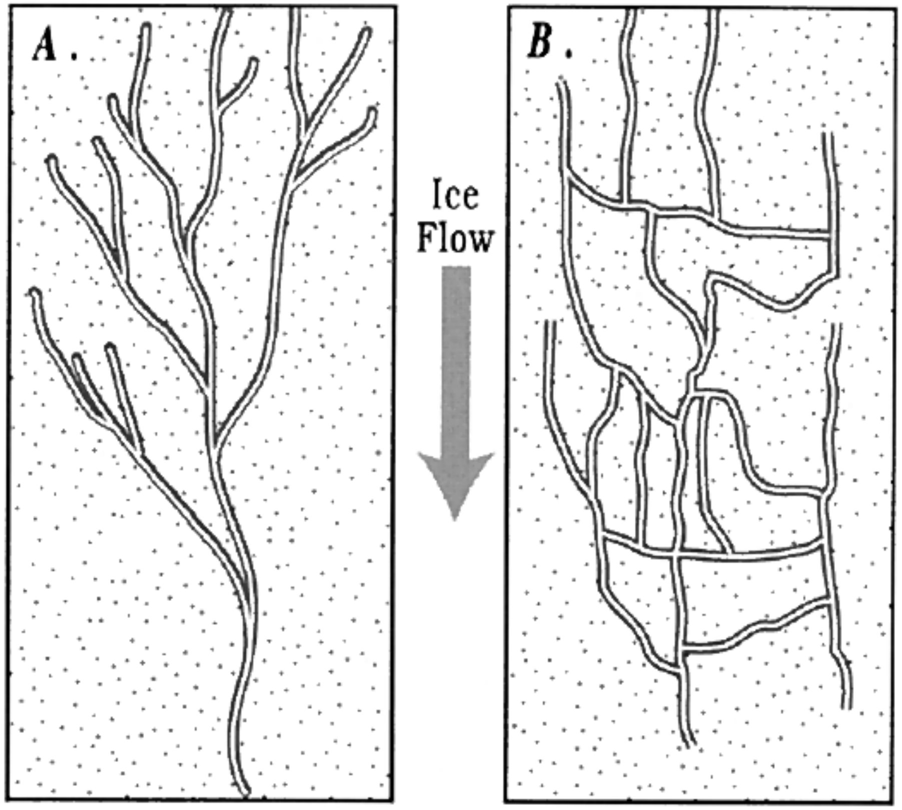
- weather forcing of system
- point-wise inputs of water to the subglacial system
- proper characterization of sliding vs water pressure
- challenge of crossing from sub-daily to many-ka timescales

….

The End

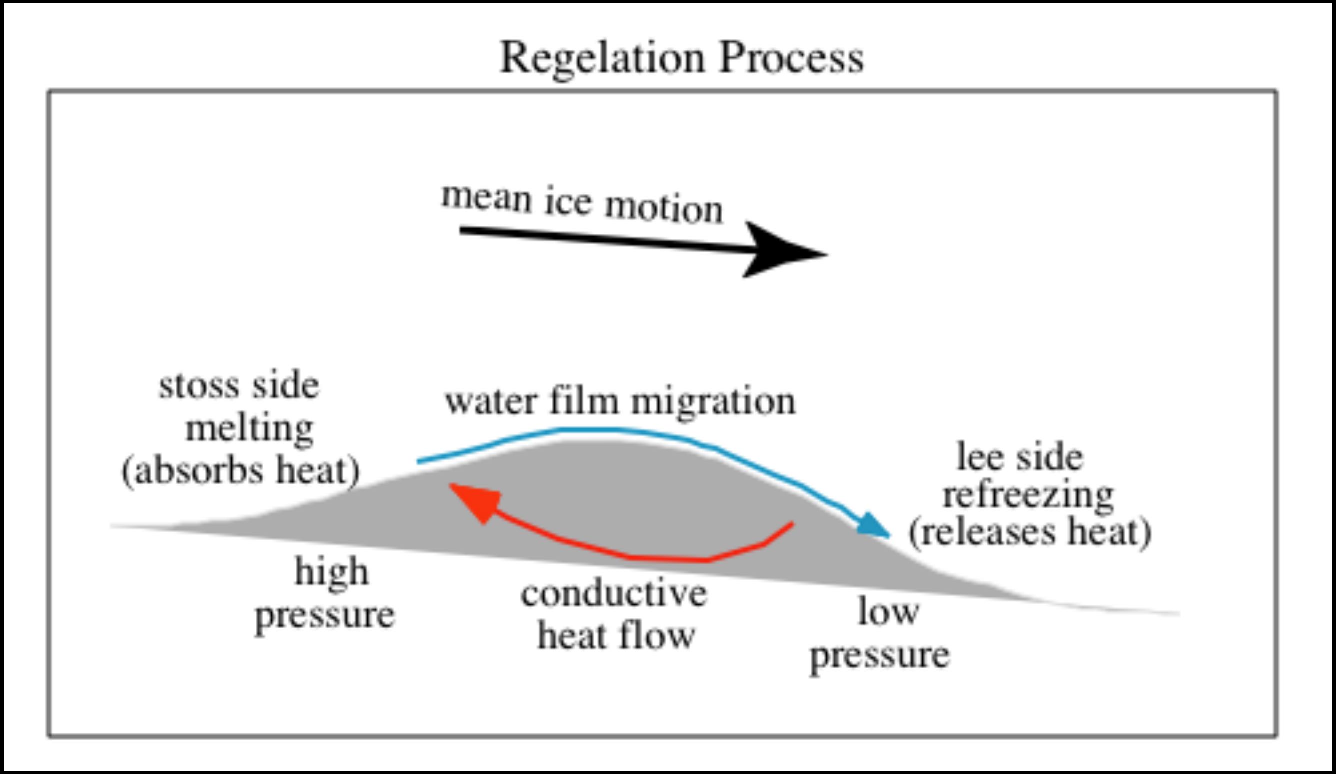
Measuring the Kennicott River discharge

fast slow



Fountain & Walder (1998) *Rev. Geophys.* 36:299-328.

But first, a little on films…



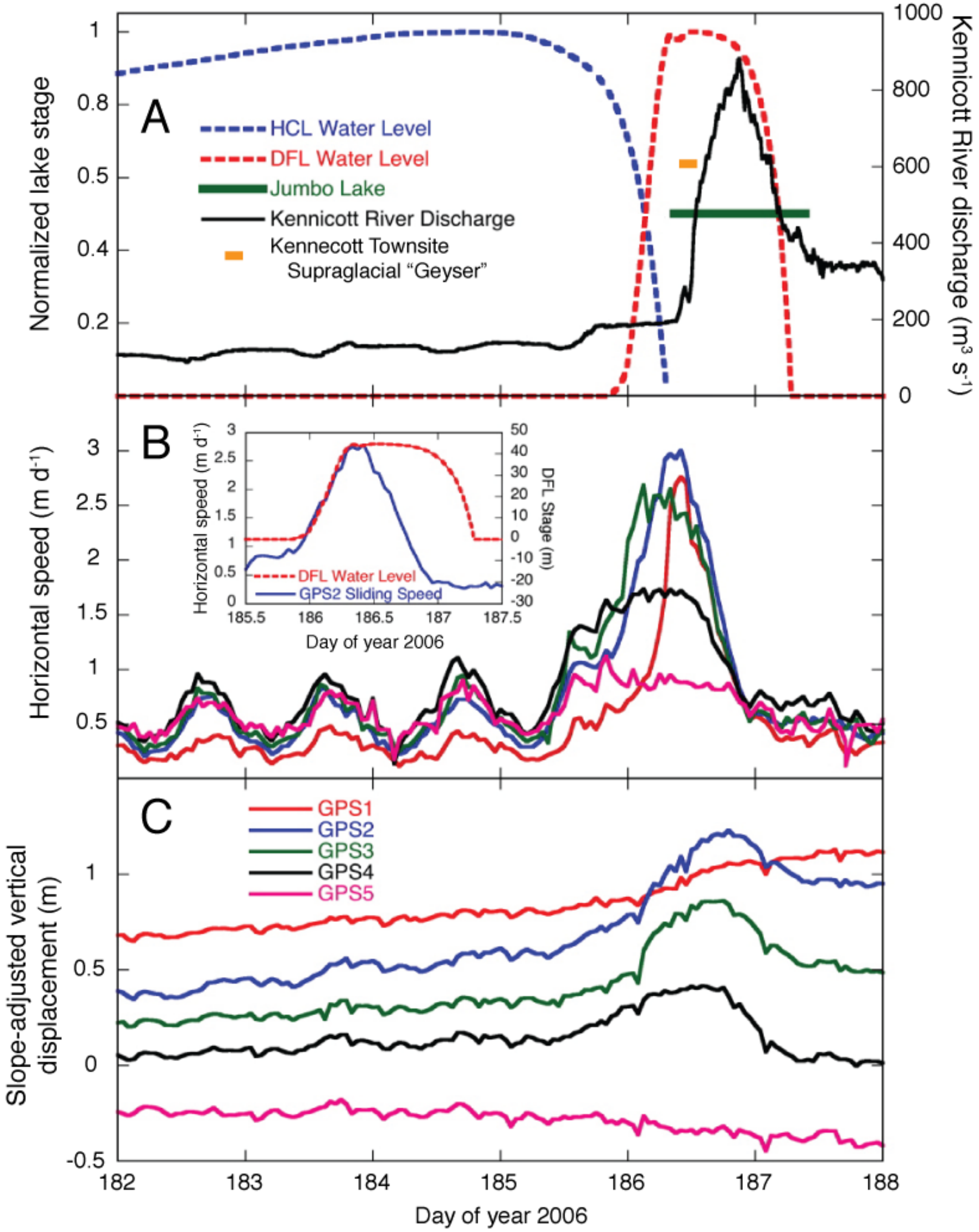
Regelation requires pressure-melting, transfer of water around the bump, and transfer of heat through it

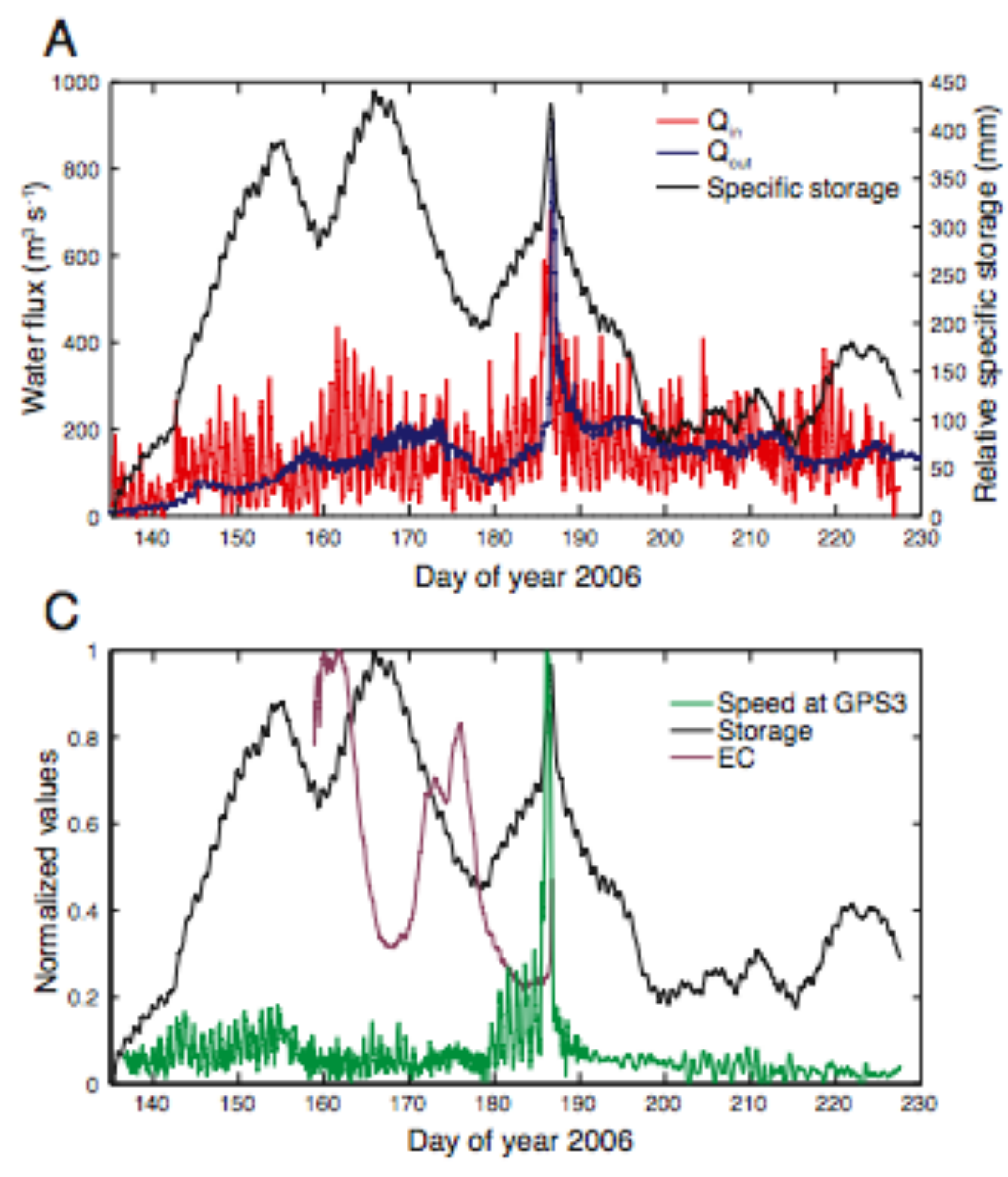
Foreland of Blackfoot Glacier
Glacier National Park

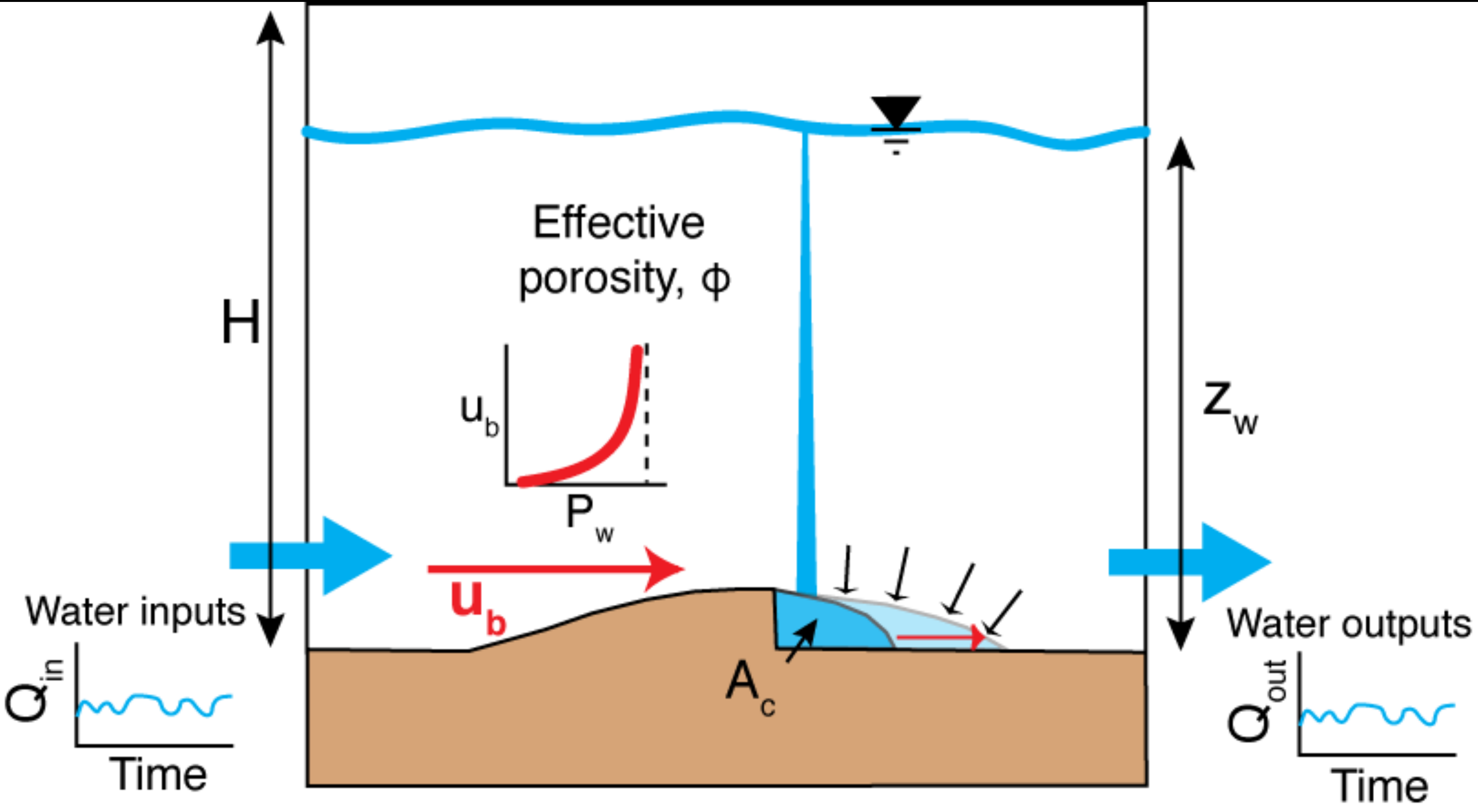
The Kennicott Hidden Creek Lake floods

Why Kennicott? It happens every year…

And this sets up the 2006 experiment
to explore the glacial response to the outburst


A
HCL Water Level
DFL Water Level
Jumbo Lake
Kennicott River Discharge
Kennecott Townsite
Supraglacial "Geyser"
Normalized lake stage
1
0.8
0.5
0.4
0.2
Kennicott River discharge ($m^3 s^{-1}$)
1000
800
600
400
200
0
B
Horizontal speed ($m d^{-1}$)
3
2.5
2
1.5
1
0.5
DFL Water Level
GPS2 Sliding Speed
Horizontal speed ($m d^{-1}$)
DFL Stage (m)
50
40
30
20
10
0
-10
-20
-30
185.5
186
186.5
187
187.5
Day of year 2006
C
GPS1
GPS2
GPS3
GPS4
GPS5
Slope-adjusted vertical displacement (m)
1
0.5
0
-0.5
182
183
184
185
186
187
188
Day of year 2006


A
Water flux ($m^3 s^{-1}$)
Relative specific storage (mm)
Q_{in}
Q_{out}
Specific storage
0
200
400
600
800
1000
0
50
100
150
200
250
300
350
400
450
140
150
160
170
180
190
200
210
220
230
Day of year 2006
C
Normalized values
Speed at GPS3
Storage
EC
0
0.2
0.4
0.6
0.8
1
140
150
160
170
180
190
200
210
220
230
Day of year 2006



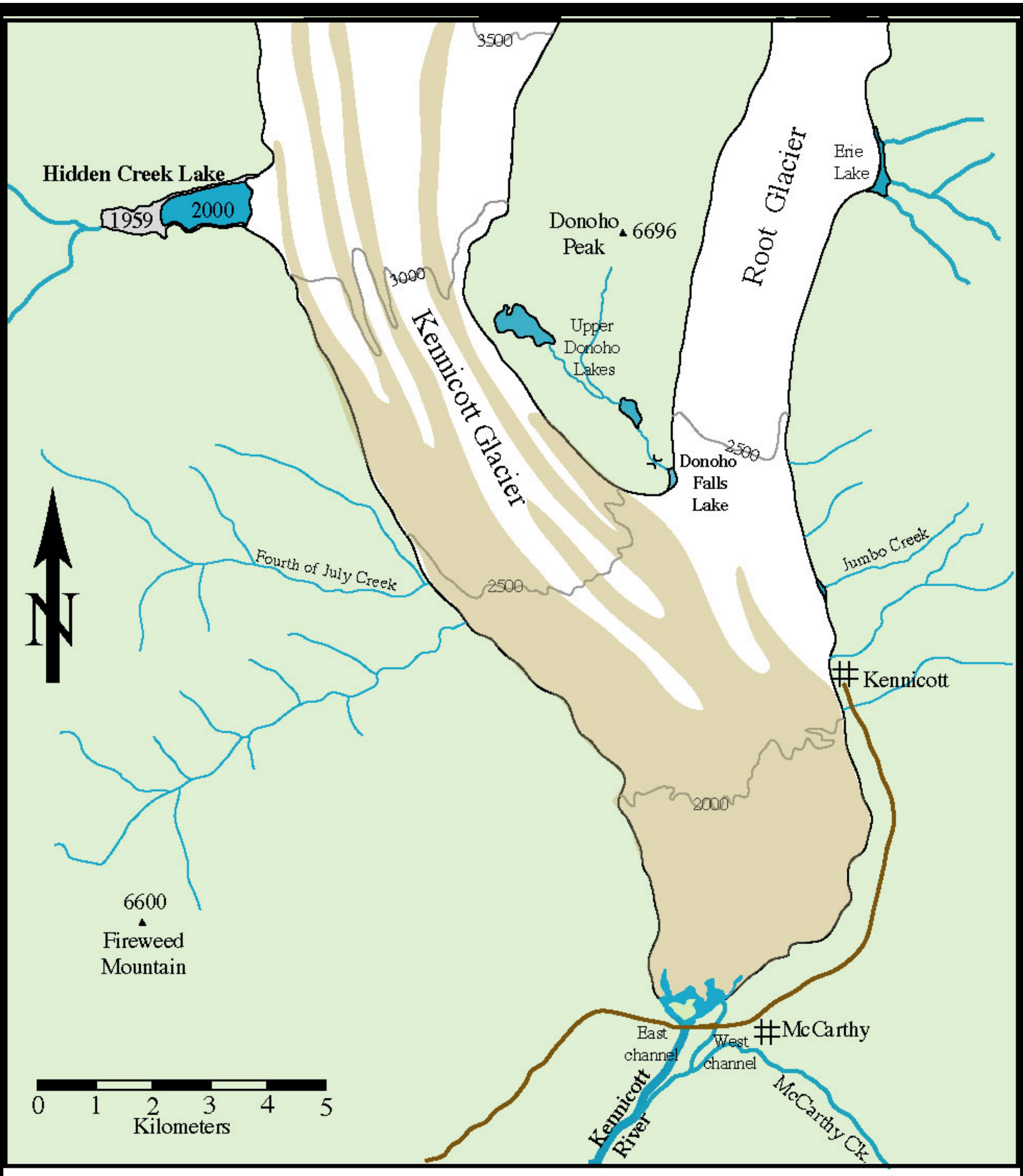
$$S = (n_{cavs})(w_c)(A_c) + (\phi)(z_w)(W \times L)$$

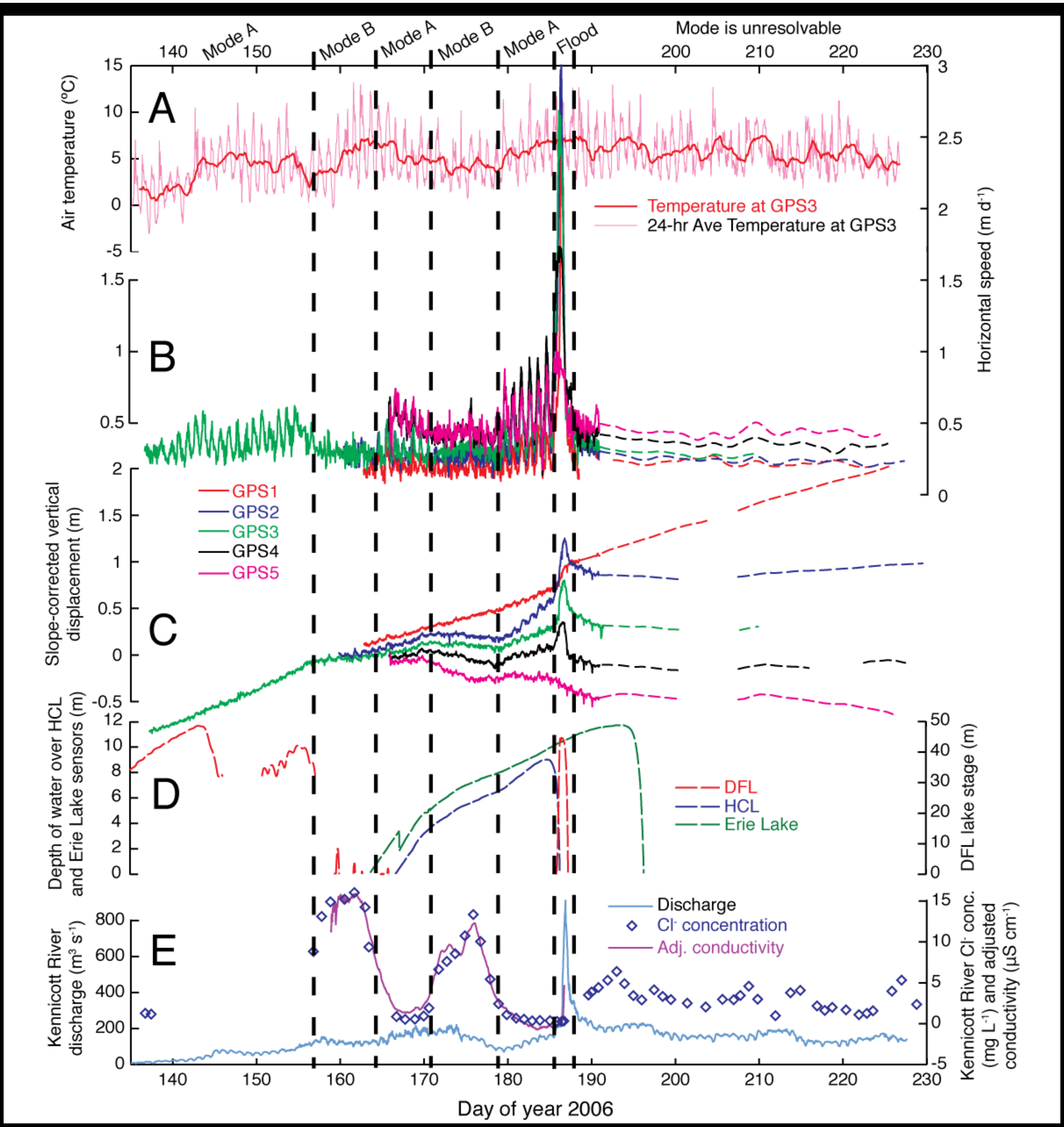
Fieldwork:

1) Hidden Creek Lake monitoring

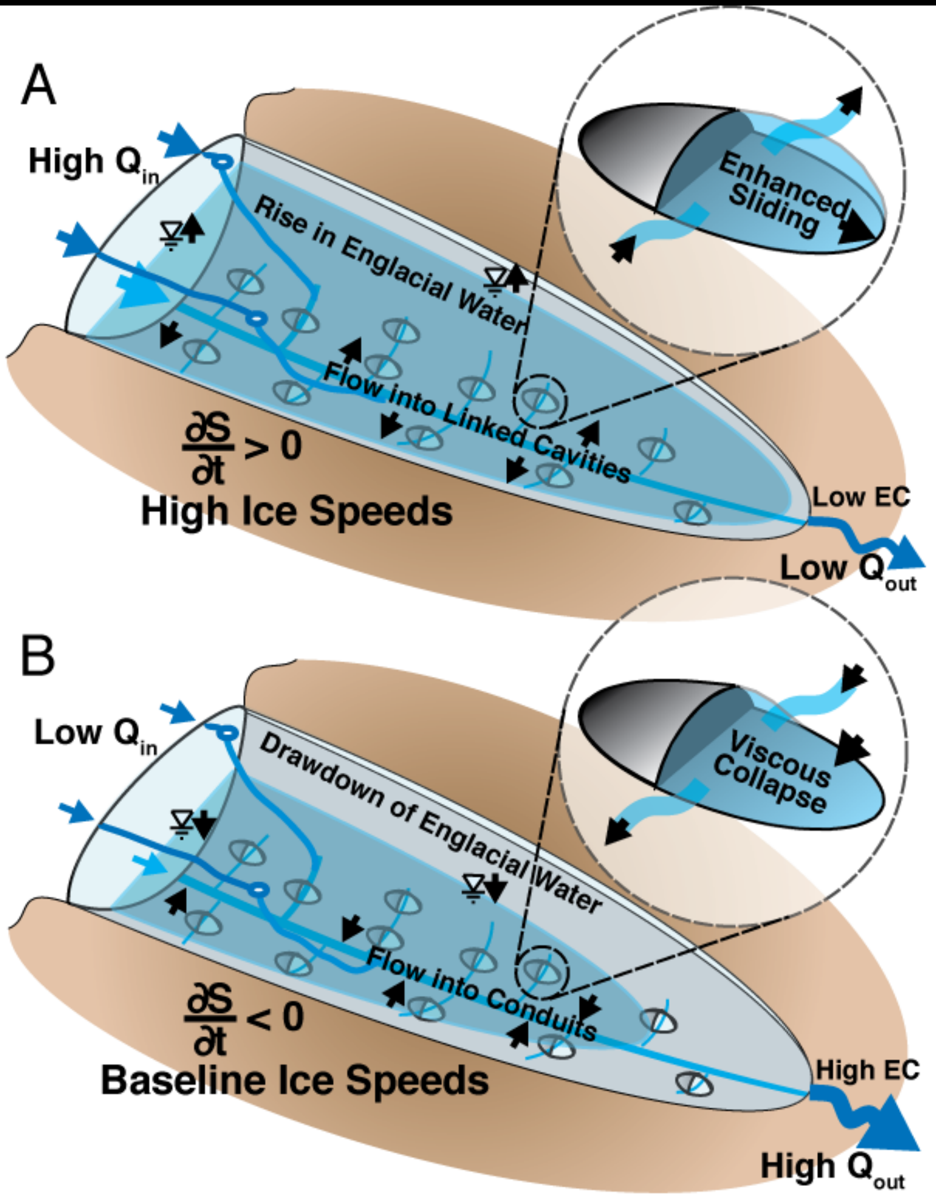
2) Kennicott River monitoring

3) Donoho Falls Lake level observations

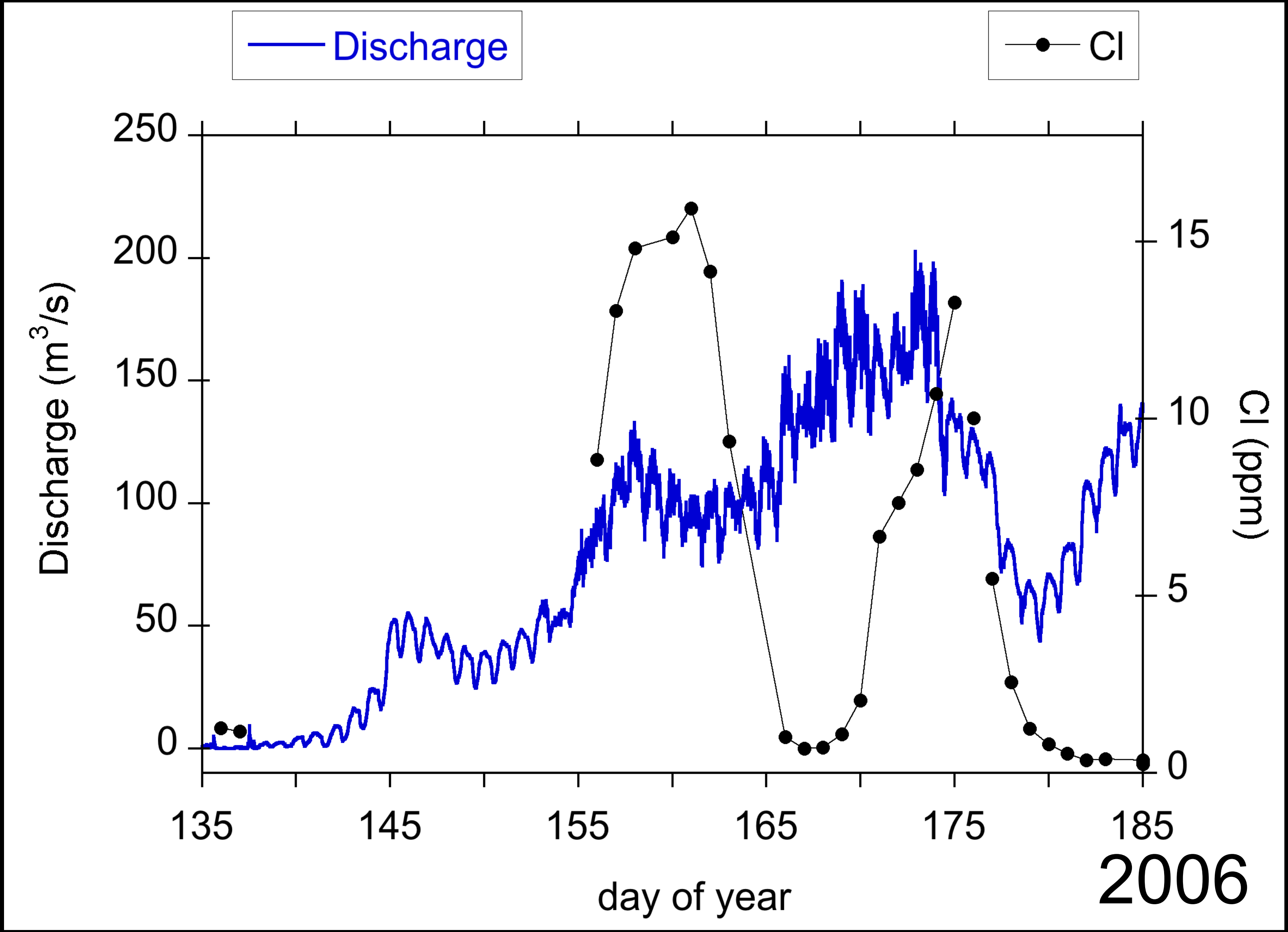


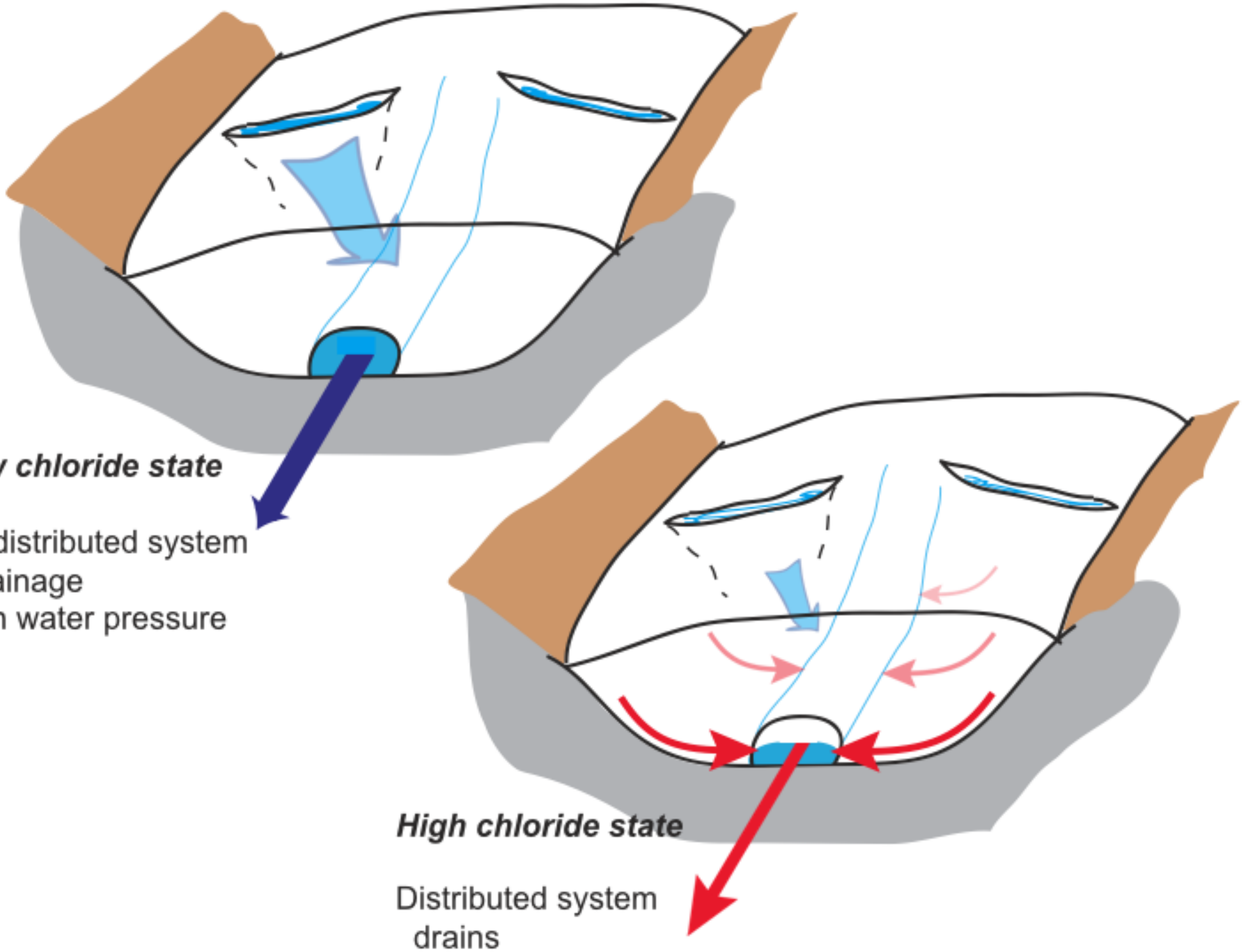

Mode A
Mode B
Mode A
Mode B
Mode A
Flood
Mode is unresolvable
140
150
200
210
220
230
A
Air temperature (ºC)
15
10
5
0
-5
Temperature at GPS3
24-hr Ave Temperature at GPS3
B
1.5
1
0.5
Horizontal speed (m d^{-1})
3
2.5
2
1.5
1
0.5
0
C
Slope-corrected vertical displacement (m)
2
1.5
1
0.5
0
-0.5
GPS1
GPS2
GPS3
GPS4
GPS5
D
Depth of water over HCL and Erie Lake sensors (m)
12
10
8
6
4
2
0
DFL lake stage (m)
50
40
30
20
10
0
DFL
HCL
Erie Lake
E
Kennicott River discharge (m^3 s^{-1})
800
600
400
200
0
Discharge
Cl$^-$ concentration
Adj. conductivity
Kennicott River Cl$^-$ conc. (mg L^{-1}) and adjusted conductivity (µS cm^{-1})
15
10
5
0
-5
140
150
160
170
180
190
200
210
220
230
Day of year 2006

V=30 Mm^3


A
High Q_{in}
Rise in Englacial Water
Flow into Linked Cavities
Enhanced Sliding
$\frac{\partial S}{\partial t} > 0$
High Ice Speeds
Low EC
Low Q_{out}
B
Low Q_{in}
Drawdown of Englacial Water
Flow into Conduits
Viscous Collapse
$\frac{\partial S}{\partial t} < 0$
Baseline Ice Speeds
High EC
High Q_{out}

2006 River flow and chemistry



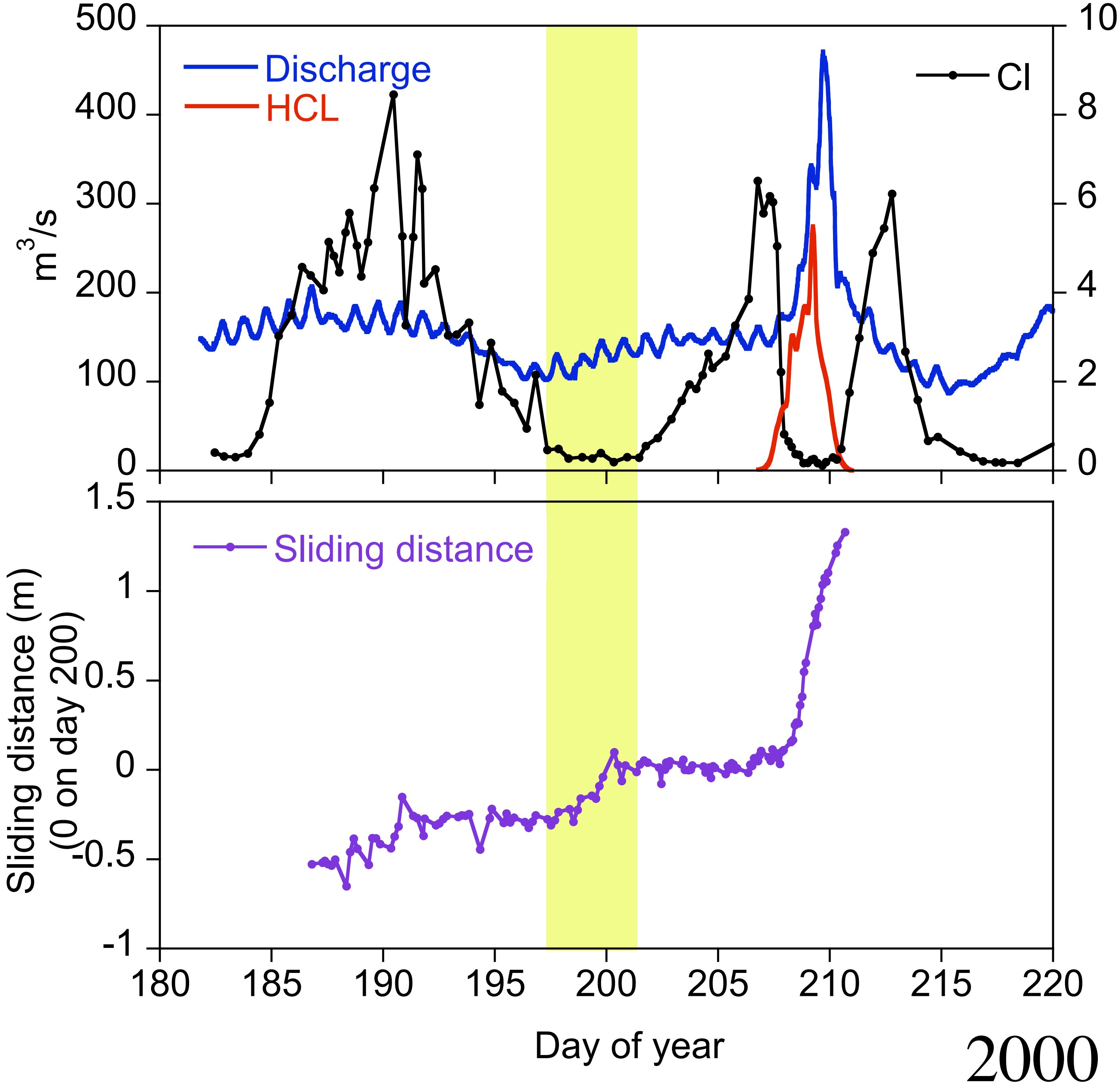


Low chloride state

No distributed system
drainage
High water pressure

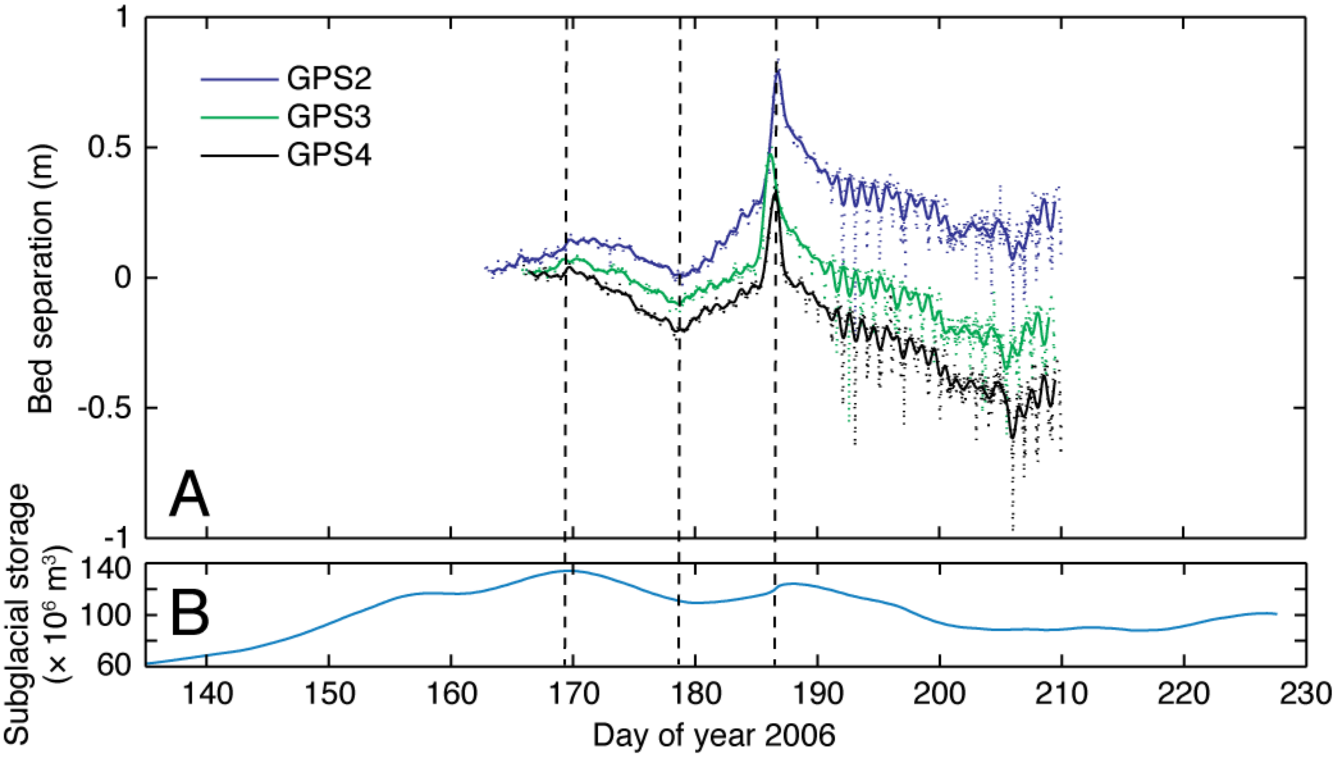
High chloride state

Distributed system
drains
Low water pressure



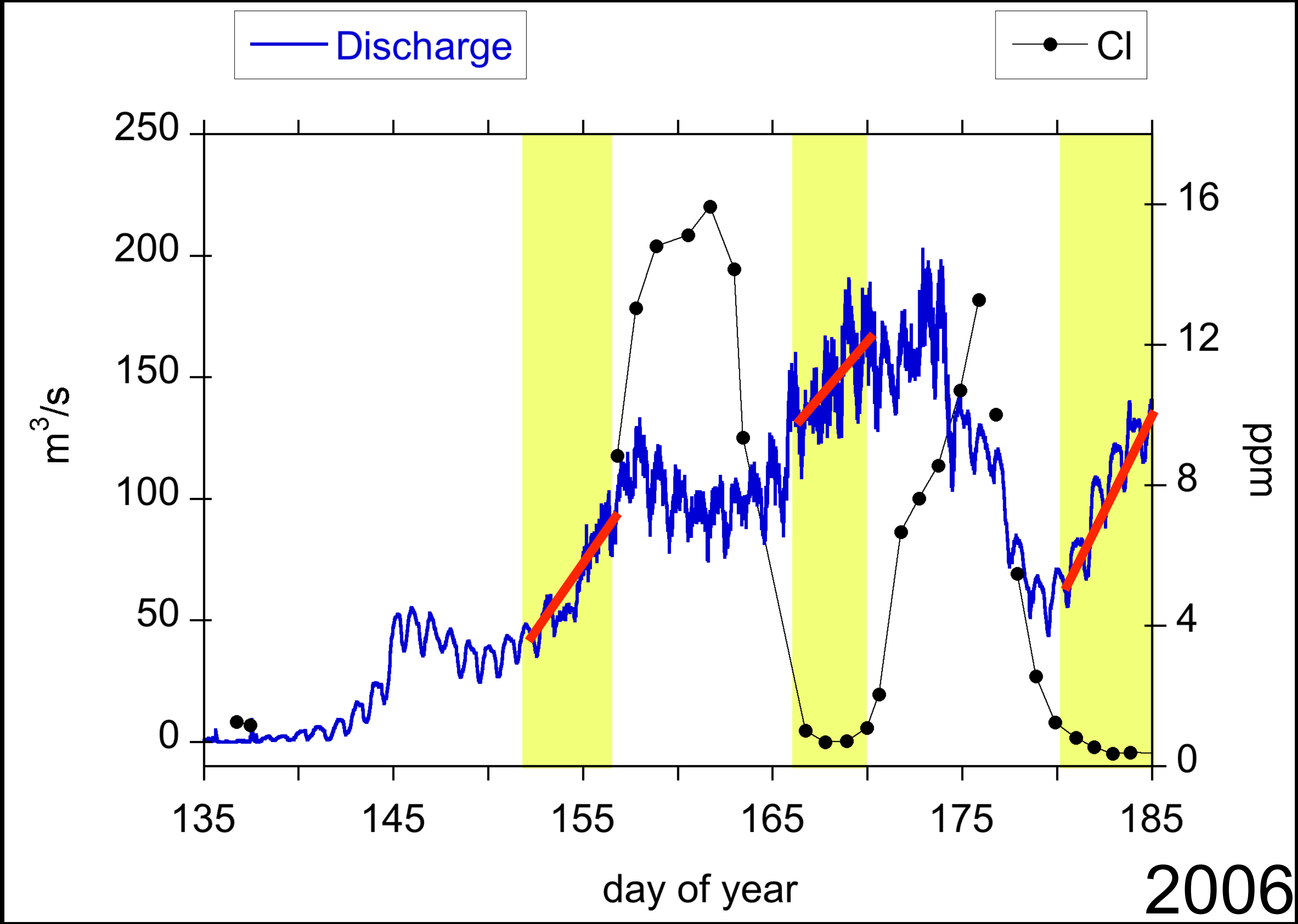
500
400
300
200
100
0
m^3/s
10
8
6
4
2
0
ppm
Discharge
HCL
Cl
1.5
1
0.5
0
-0.5
-1
Sliding distance (m)
(0 on day 200)
Sliding distance
180
185
190
195
200
205
210
215
220
Day of year

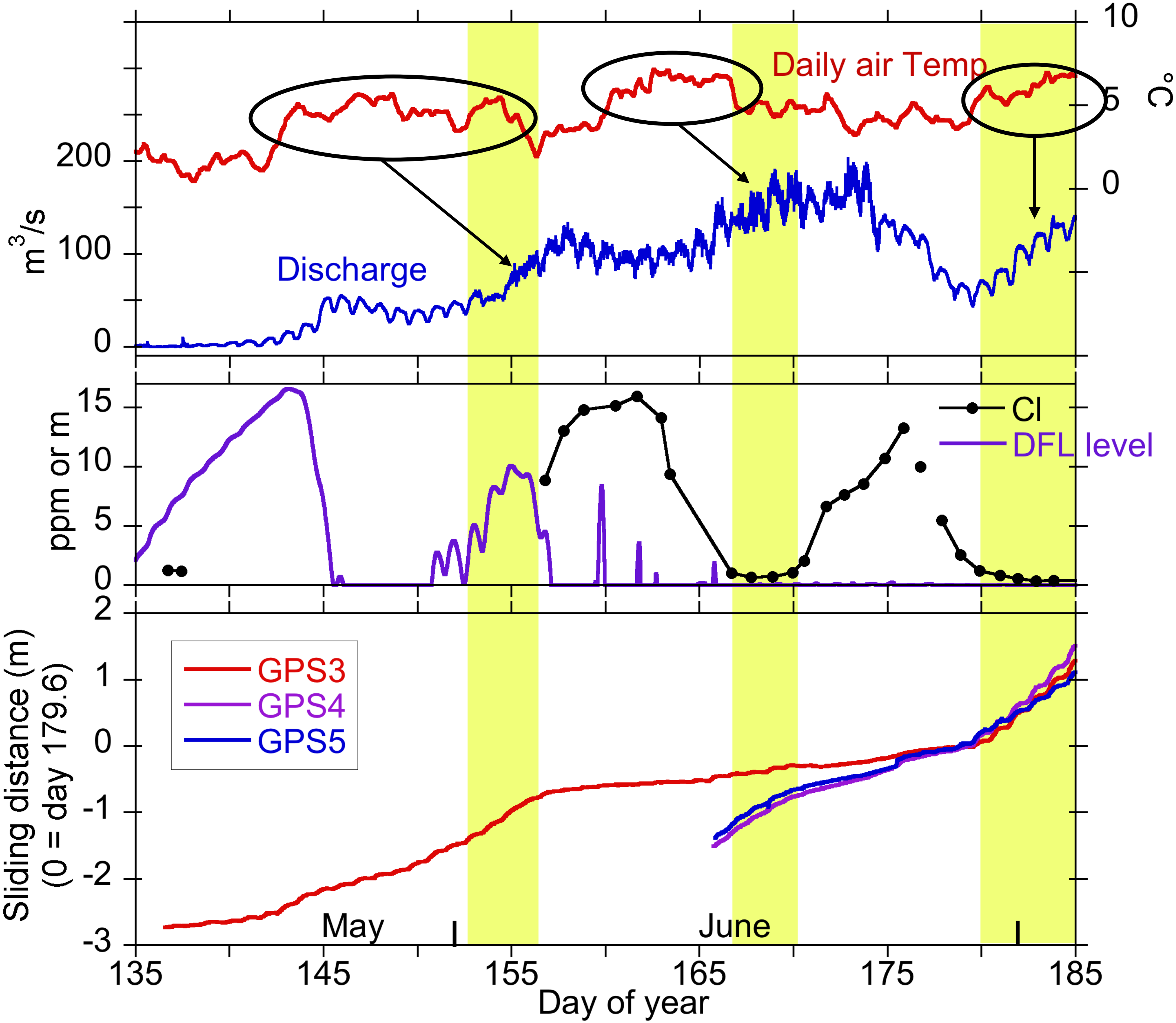
2000



Bed separation

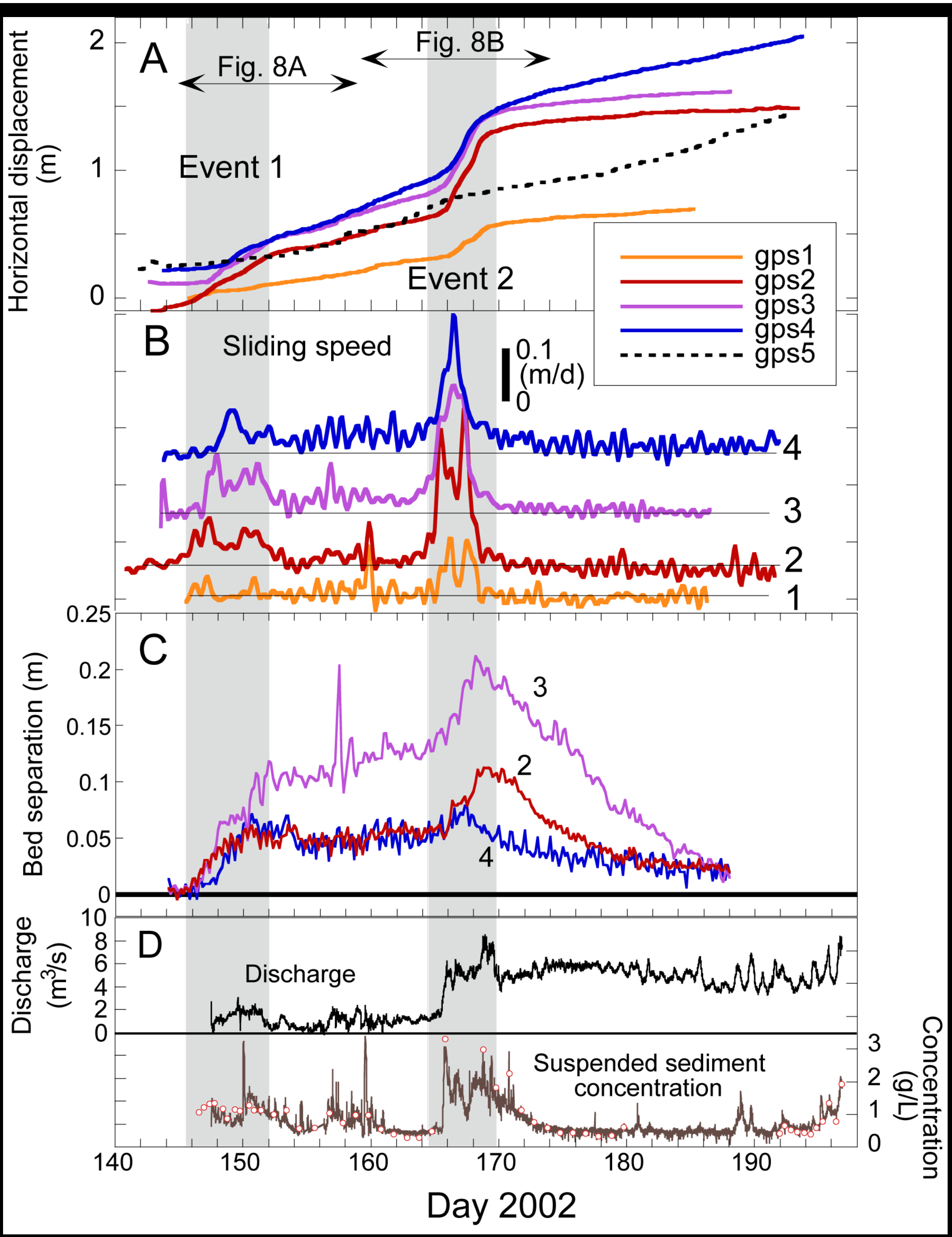
Low Cl during rising discharge



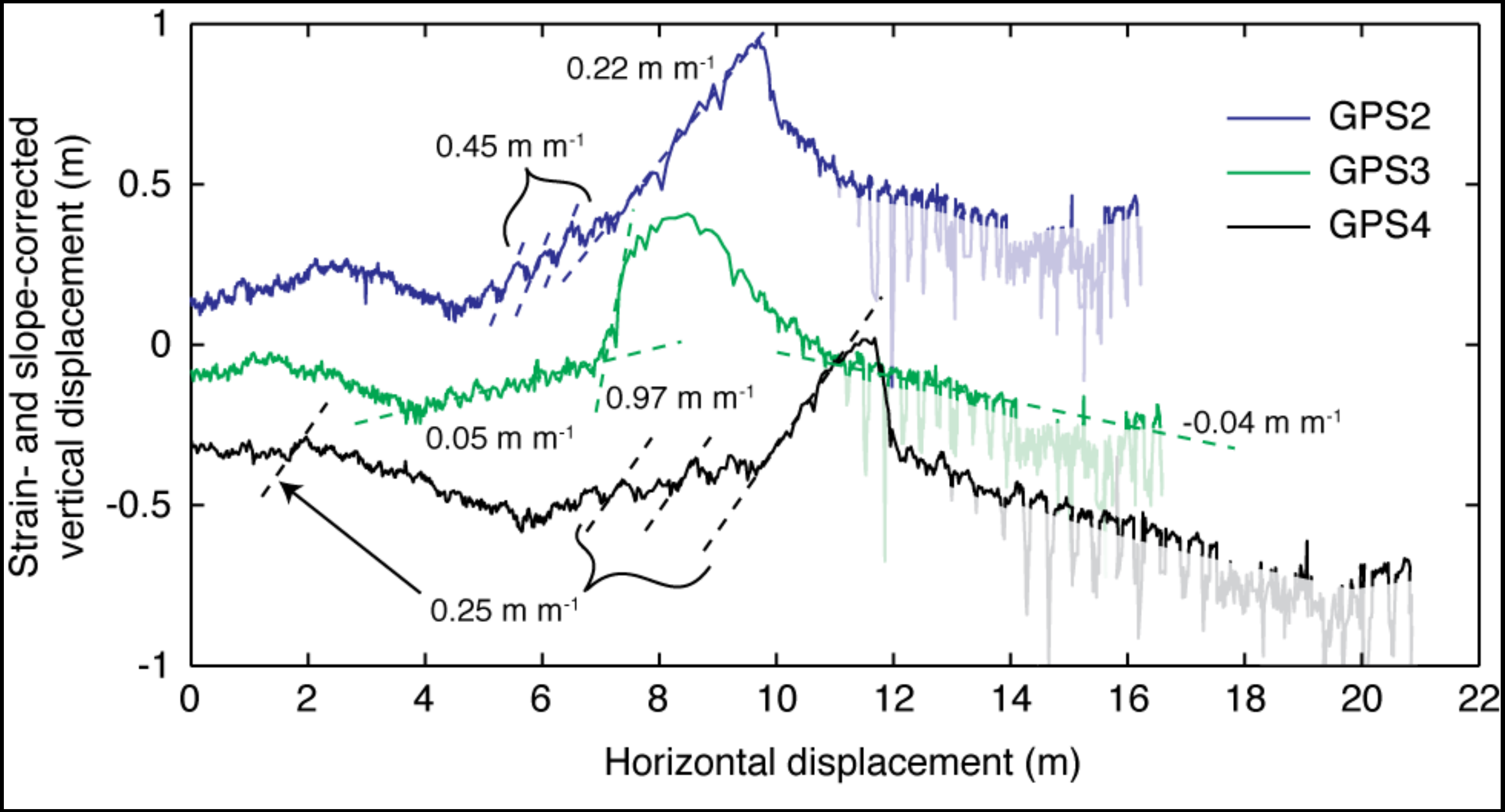


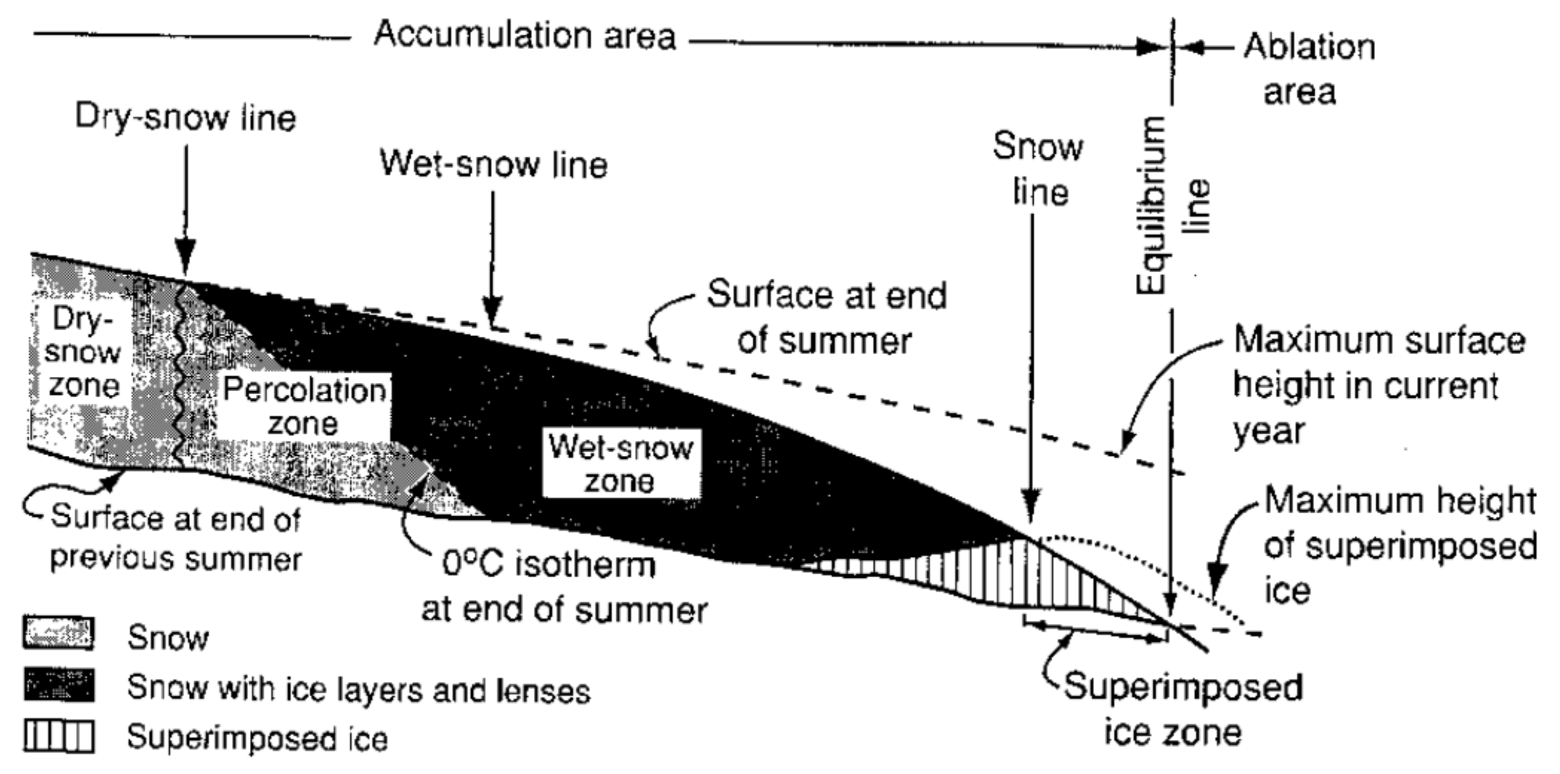
High melt water inputs ➔ high P ➔ low Cl *and* rapid sliding

Low melt or conduit fm ➔ low P ➔ high Cl *and* no sliding


A
Fig. 8A
Fig. 8B
Event 1
Event 2
Horizontal displacement (m)
0
1
2
gps1
gps2
gps3
gps4
gps5
B
Sliding speed
0.1 (m/d)
0
4
3
2
1
C
Bed separation (m)
0.25
0.2
0.15
0.1
0.05
0
3
2
4
D
Discharge
Discharge (m^3/s)
10
8
6
4
2
0
Suspended sediment concentration
Concentration (g/L)
3
2
1
0
140
150
160
170
180
190
Day 2002

Ice trajectory during sliding ..note the consistent slopes




Accumulation area
Ablation area
Dry-snow line
Wet-snow line
Snow line
Equilibrium line
Surface at end of summer
Maximum surface height in current year
Dry-snow zone
Percolation zone
Wet-snow zone
Maximum height of superimposed ice
Surface at end of previous summer
0°C isotherm at end of summer
Superimposed ice zone
Snow
Snow with ice layers and lenses
Superimposed ice

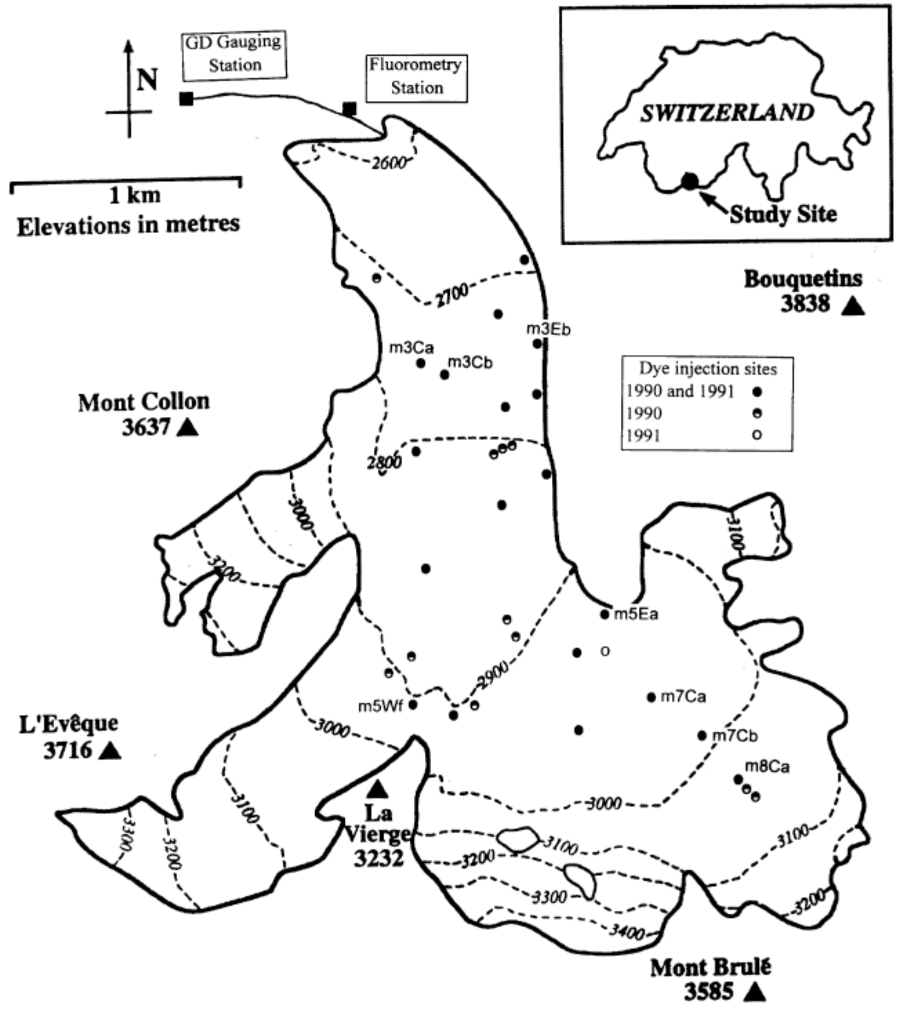
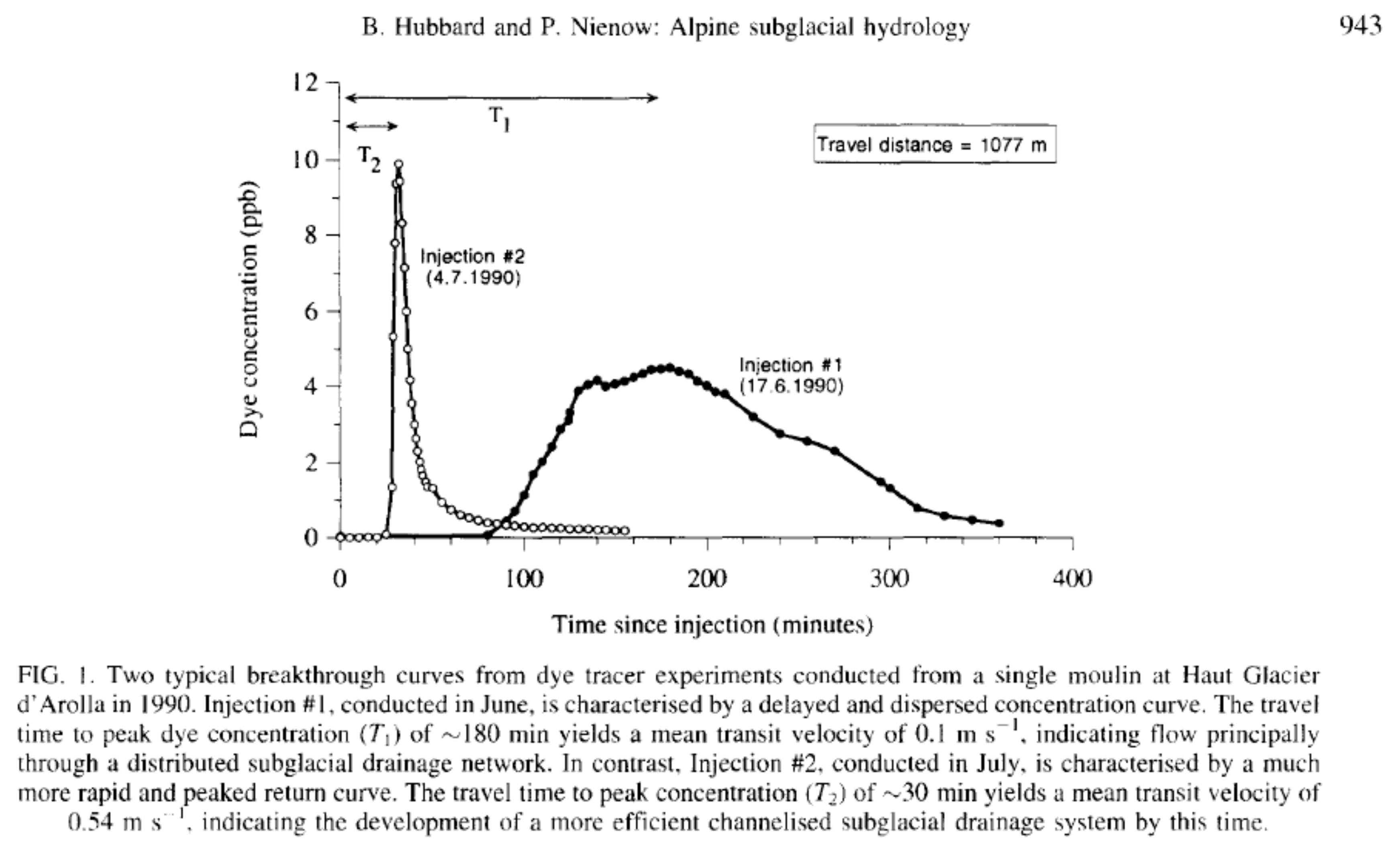


Figure 1. Map of Haut Glacier d'Arolla, showing the location of dye injection sites used during the summers of 1990 and 1991, the fluorometry station and the Grand Dixence gauging station. The labelled moulins are referred to in the text. A four-digit code is used to classify sites as either moulins (m) or extraglacial streams (s), to show their longitudinal (1–8 in 500 m long segments, with 1 being the segment closest to the glacier snout) and transverse (E, C. W) position on the glacier, and their relative proximity to the glacier snout in a given segment (a to z, with a being closest to the snout)

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.



B. Hubbard and P. Nienow: Alpine subglacial hydrology 943

FIG. 1. Two typical breakthrough curves from dye tracer experiments conducted from a single moulin at Haut Glacier d'Arolla in 1990. Injection #1, conducted in June, is characterised by a delayed and dispersed concentration curve. The travel time to peak dye concentration (T_1) of ~180 min yields a mean transit velocity of 0.1 m s^{-1}, indicating flow principally through a distributed subglacial drainage network. In contrast, Injection #2, conducted in July, is characterised by a much more rapid and peaked return curve. The travel time to peak concentration (T_2) of ~30 min yields a mean transit velocity of 0.54 m s^{-1}, indicating the development of a more efficient channelised subglacial drainage system by this time.

Hubbard & Nienow (1997) *Quat. Sci. Rev.* 16: 939-955.

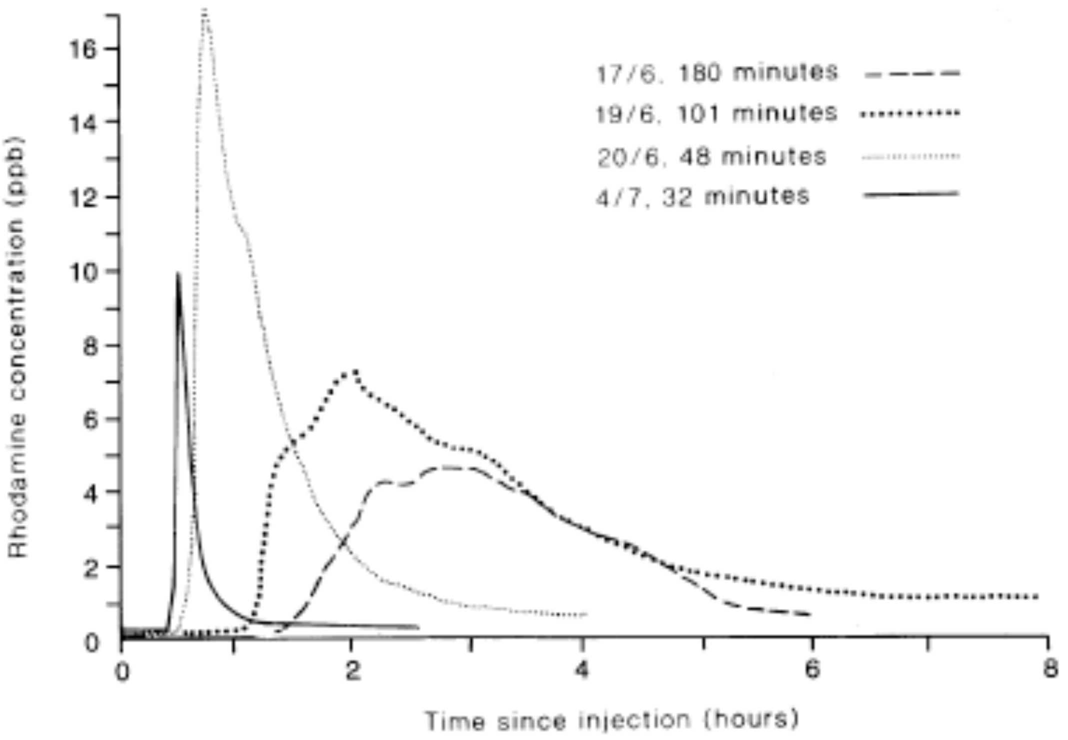


Figure 4. Sequence of four return curves derived from injections made at moulin m3Ca between 17 June and 4 July 1990

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.

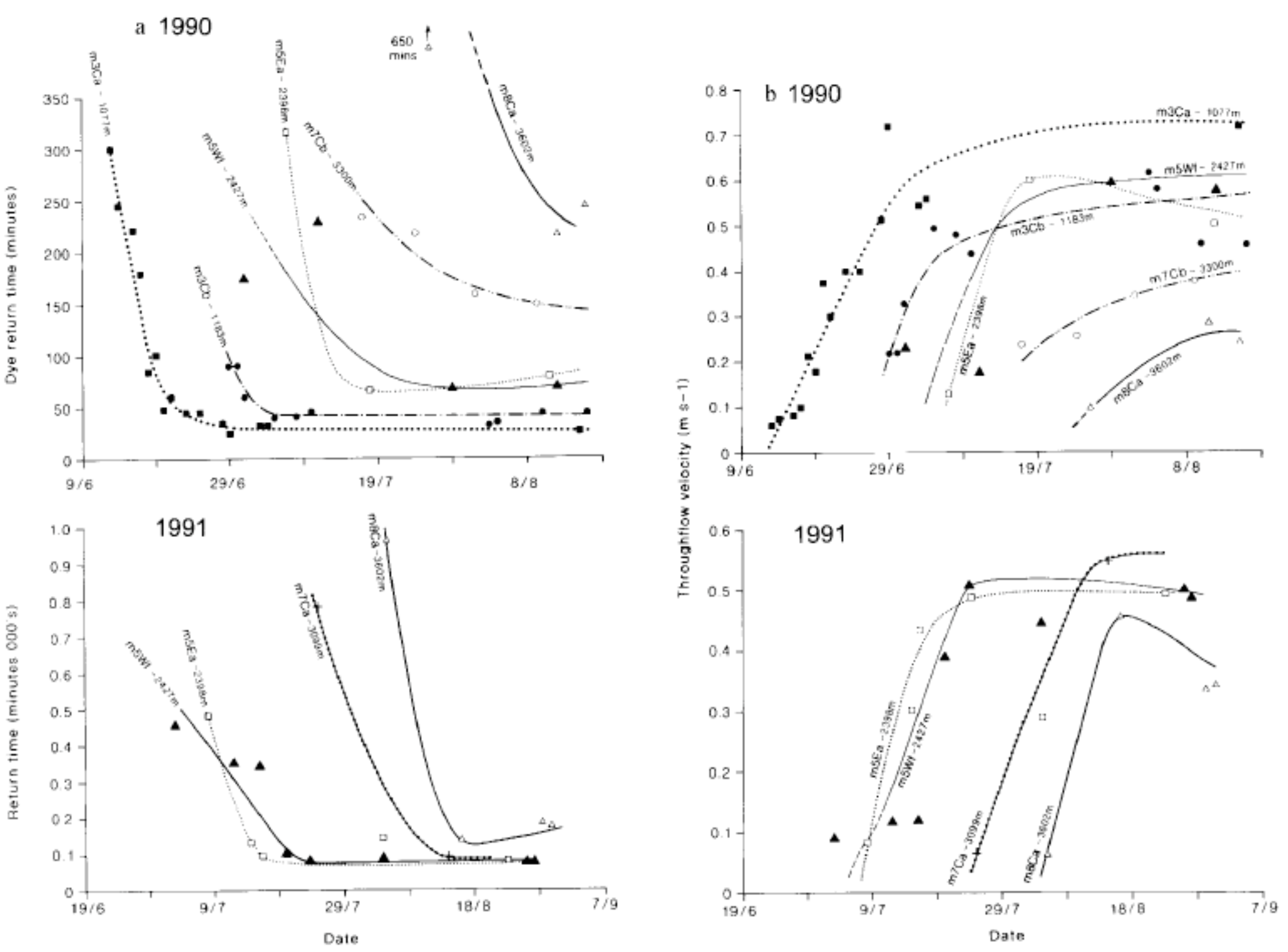


Figure 3. Plots of (a) dye return time and (b) flow velocity as a function of date of injection for selected moulins during the summers of 1990 and 1991. For days on which more than one injection was made at a given site, the shortest return time/highest velocity is plotted. Lines added by hand to aid interpretation

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.

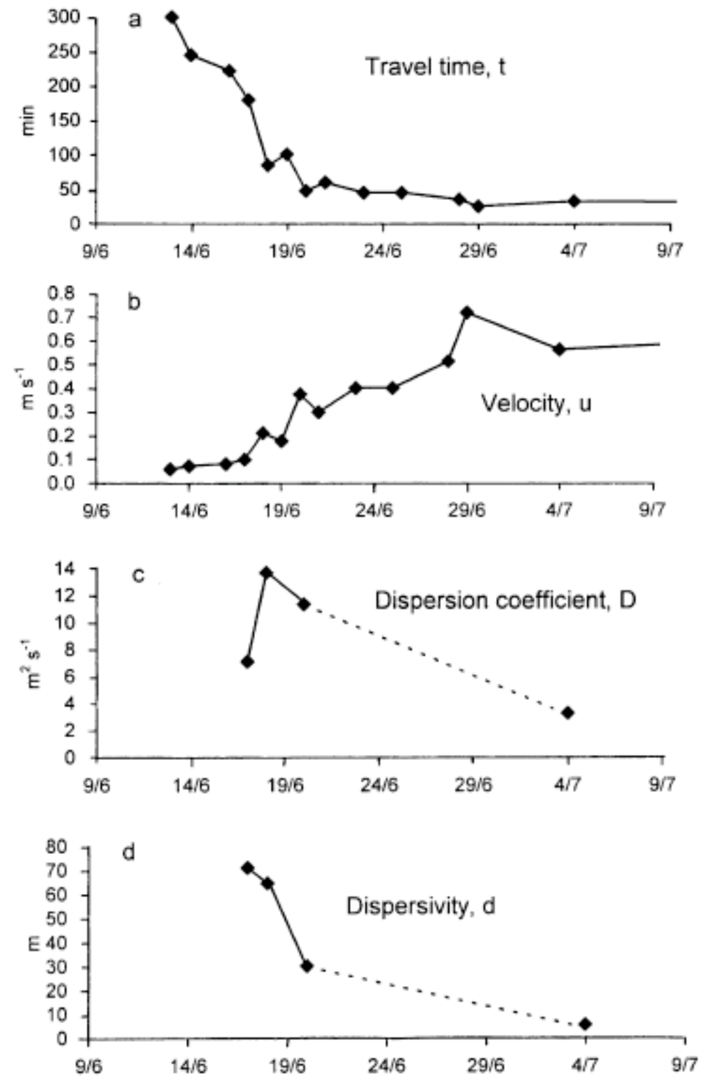
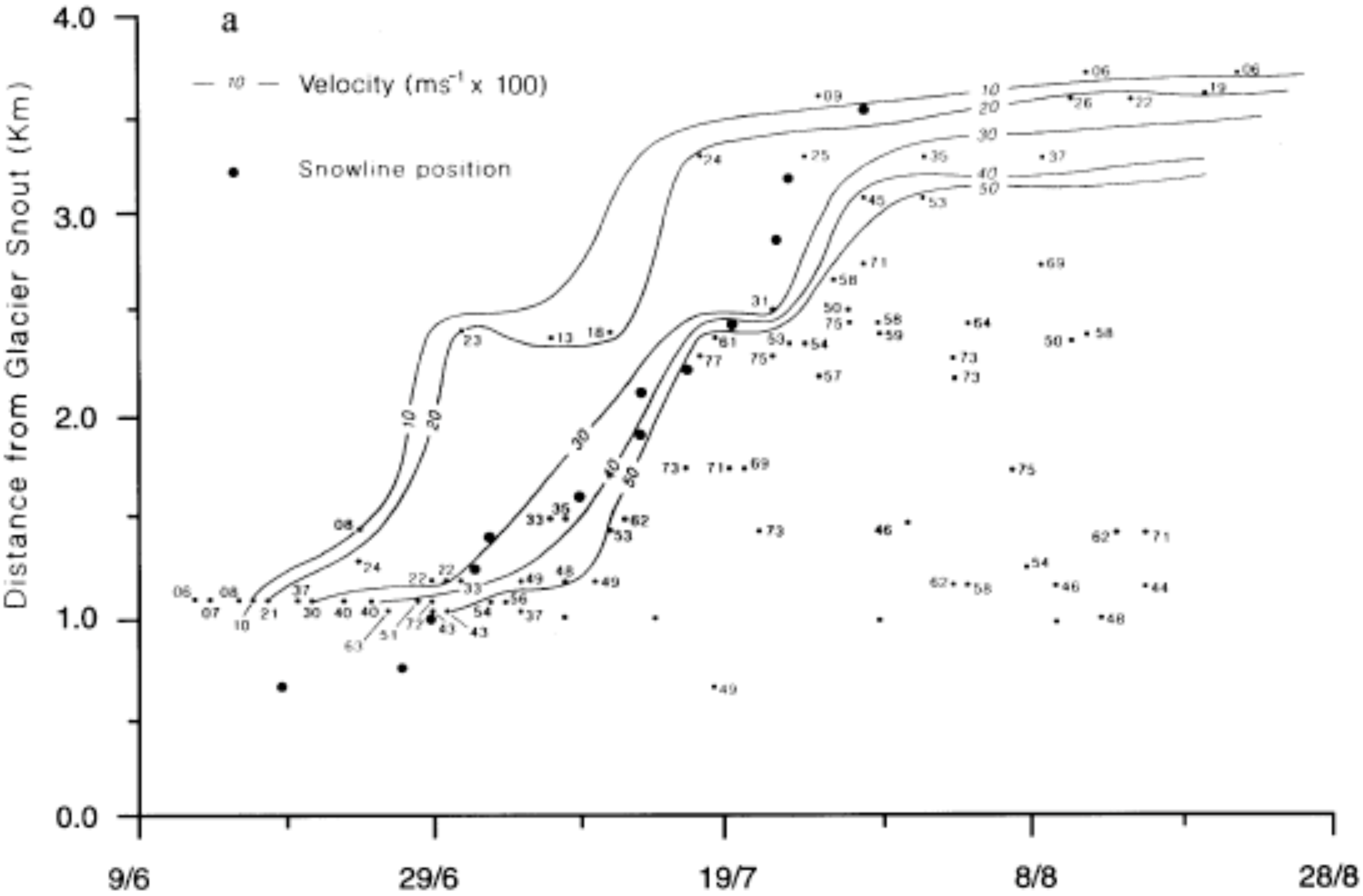
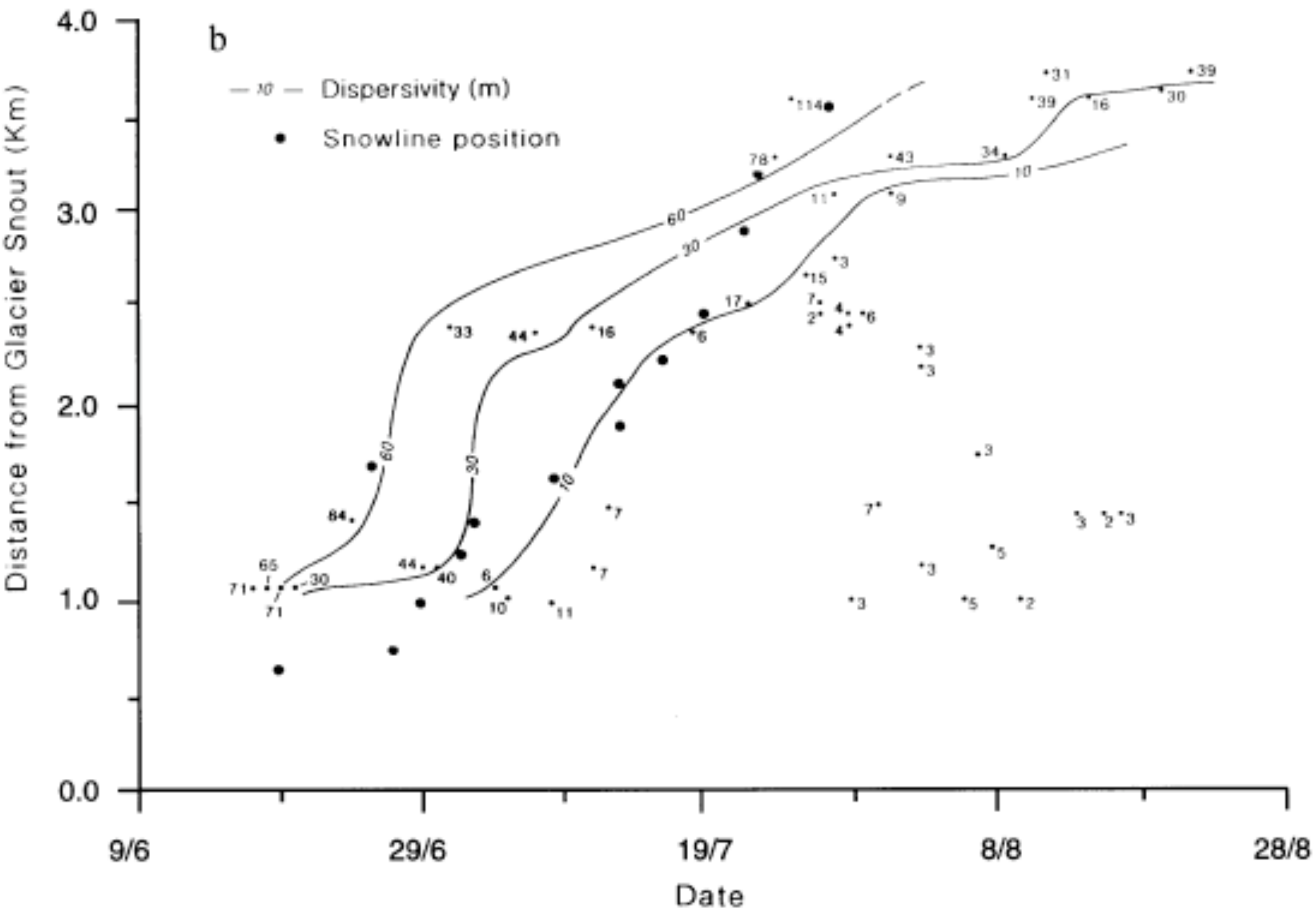


Figure 5. Plots of (a) dye return time, (b) flow velocity, (c) dispersion coefficient, and (d) dispersivity as a function of date of injection for moulin m3Ca during summer 1990. The poor record of dispersion coefficient results from problems involved in analysing breakthrough curves derived from fluorescein tracer tests (see Methods)

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.



Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.



e 8. Contoured plots of (a) flow velocity, and (b) dispersivity as a function of location and date of injection for the 1990 melt season. Large dots indicate the position of the snowline at the glacier centreline

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-845.

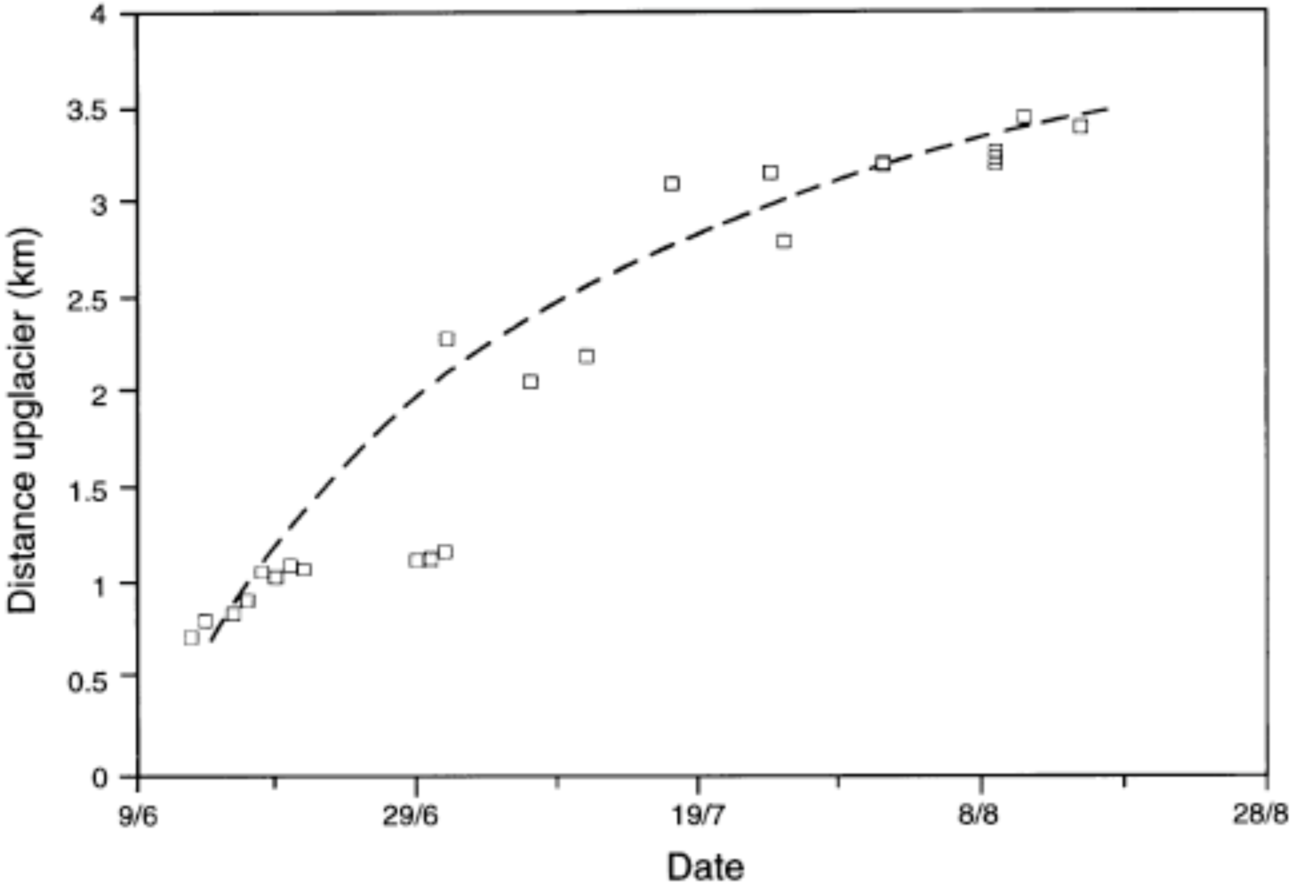


Figure 9. Position of the head of the channelised component of the drainage system during the 1990 melt season, as determined from observed dye return times and the assumption that water flowed through a two-component drainage system. Velocity in the distributed system=0·025 m s^{-1}, velocity in the channel system is between 0·3 and 0·5 m s^{-1} depending upon meltwater discharge (see text for details)

Nienow, Sharp & Willis (1998) *Earth Surf. Process. and Landforms* 23: 825-843.

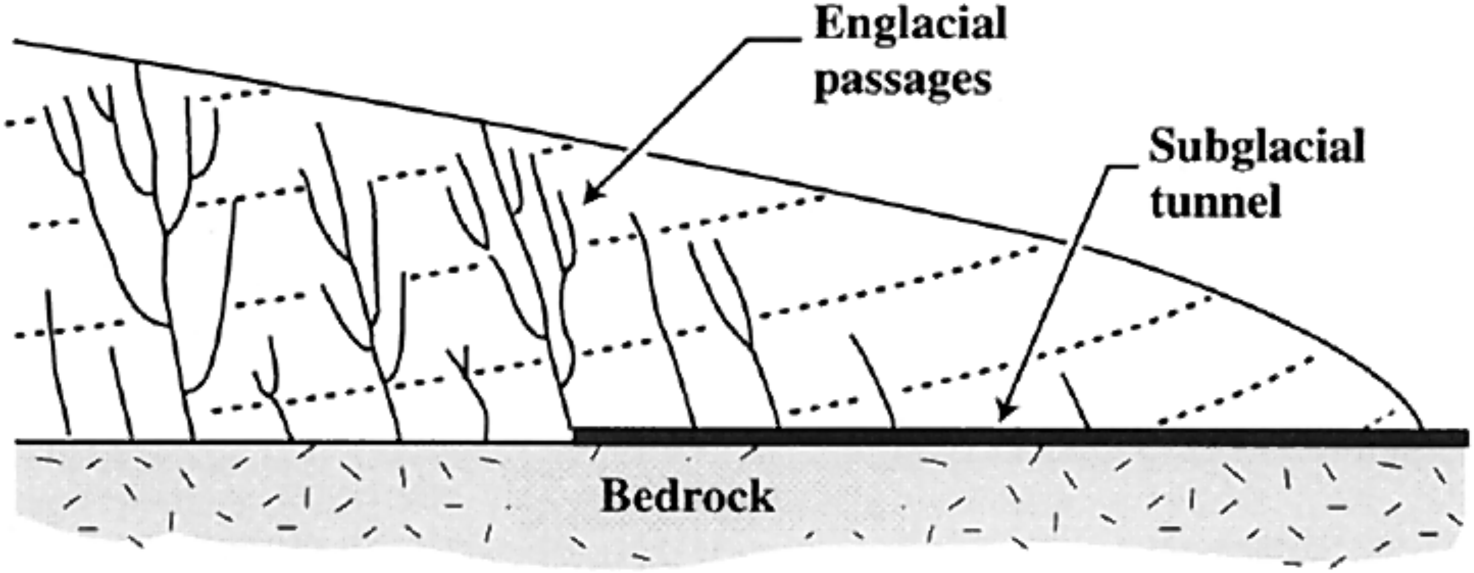


Figure 4. Fluid equipotentials (dotted curves) and a hypothetical network of arborescent englacial channels [after *Shreve*, 1985]. Reproduced with permission of the publisher, the Geological Society of America, Boulder, Colorado USA. Copyright @ 1985 Geological Society of America.

Fountain & Walder (1998) *Rev. Geophys.* 36:299-328.

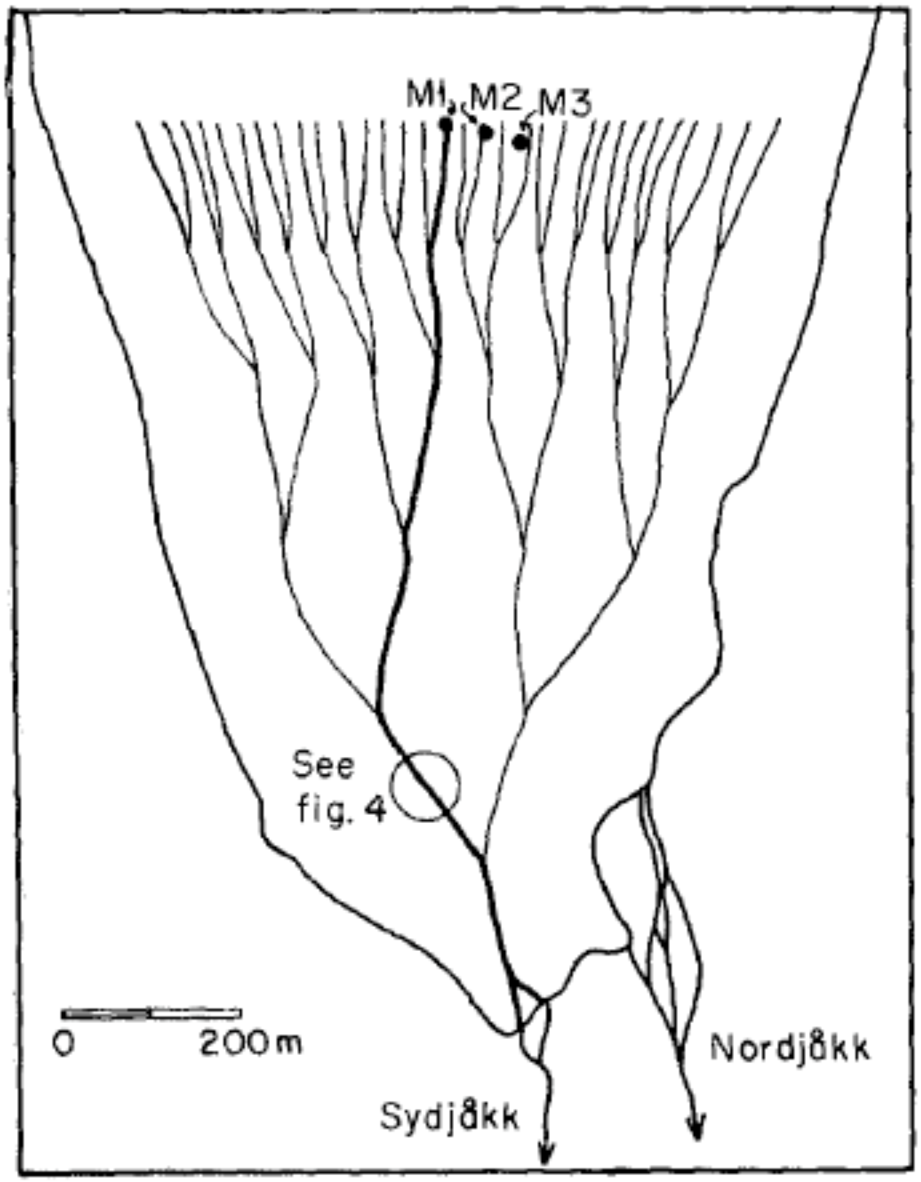


Figure 6. Schematic sketch illustrating the type of arborescent conduit system we envisage. Each individual conduit is considered to be braided as shown in Figure 4. Moulins M1, M2, and M3 are in their true positions, but are shown for reference only. Possible path from M1 to terminus is shown by heavy line. Locations of conduits and bifurcations is totally hypothetical; the essential point is that there are probably many bifurcations.

Hock and Hooke (1993) *Geol. Soc. Am. Bull.* 105: 537-546.

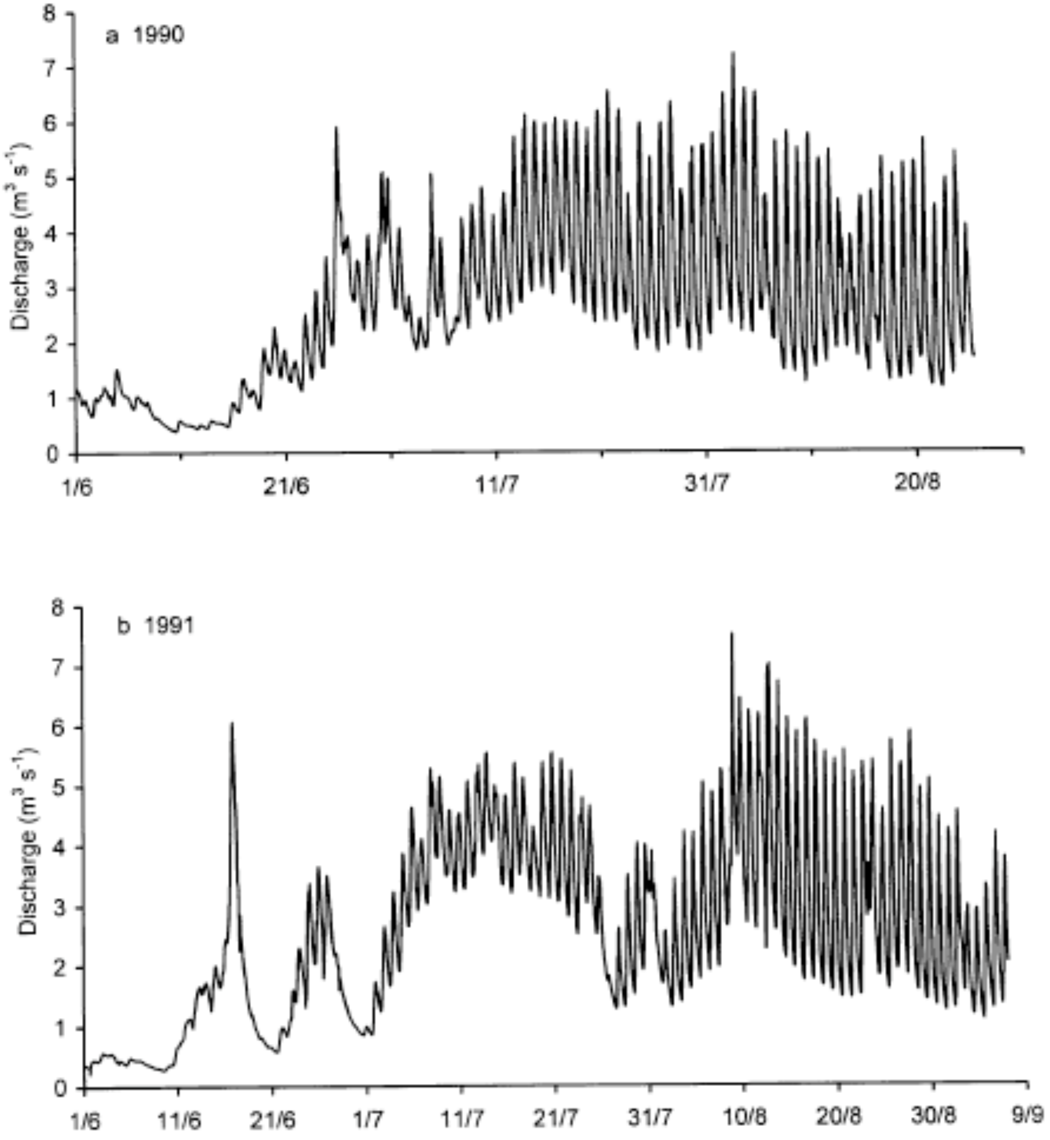


Figure 2. Meltwater discharge records for the Haut Glacier d'Arolla for the summers of (a) 1990 and (b) 1991. Data provided by Grande Dixence SA

The sink(s). Outlet rivers

How do we measure the discharge?
What do you expect a rating curve to look like?
Law of the wall, Mannings, Darcy-Weisbach formulations
What if a braided river? – Larry Smith method from satellites

Delay during passage through the snowpack

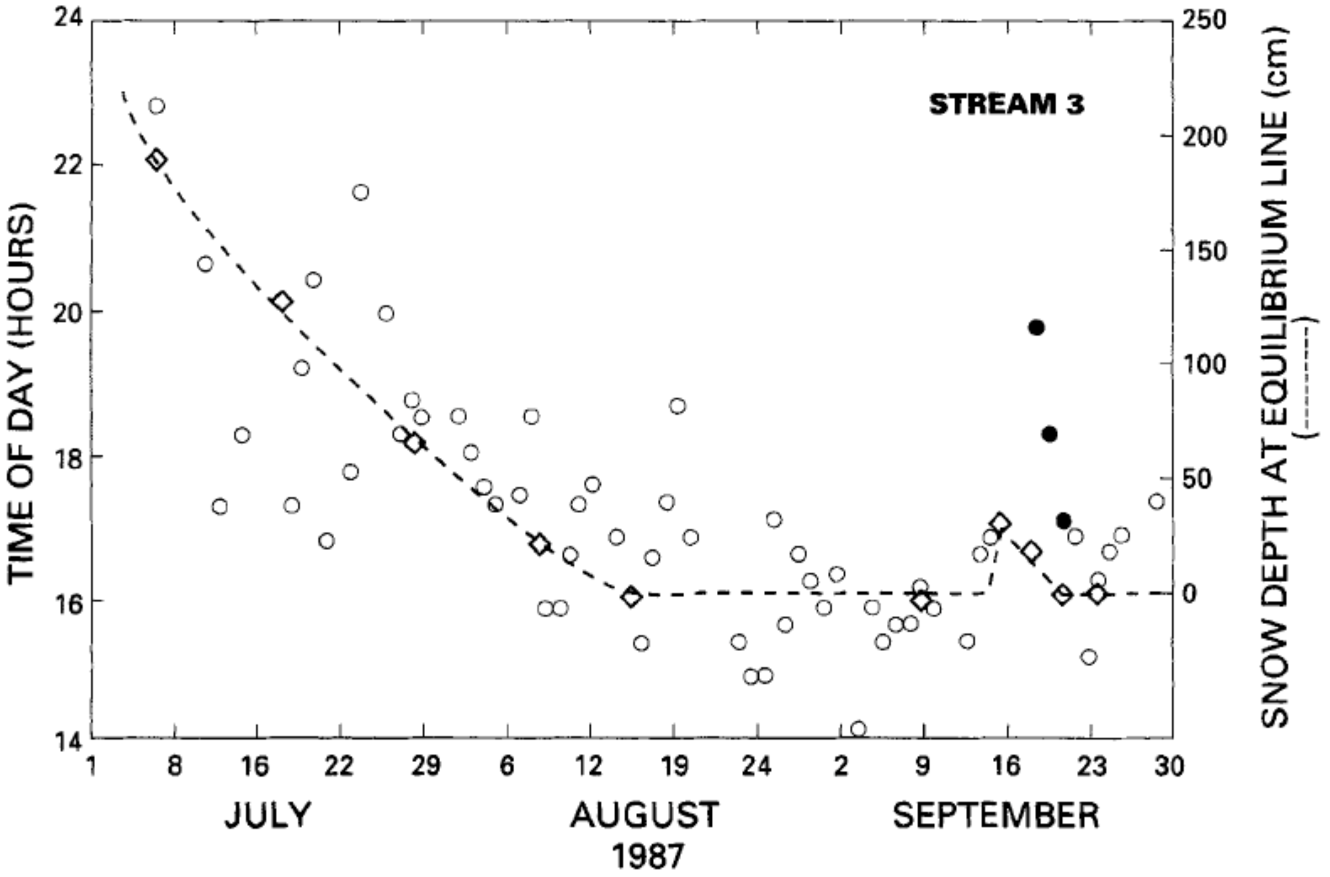


Figure 3. Time of daily peak water discharge for stream 3 at South Cascade Glacier, Washington, USA. The broken line is the interpolated snow depth at the equilibrium line; open diamonds indicate measured thickness; closed circles are times of peak daily discharge following a snowfall (adapted from Fountain,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

Fountain (1996), *Hydrological Processes* 10: 509-521.

$Q=WHU$

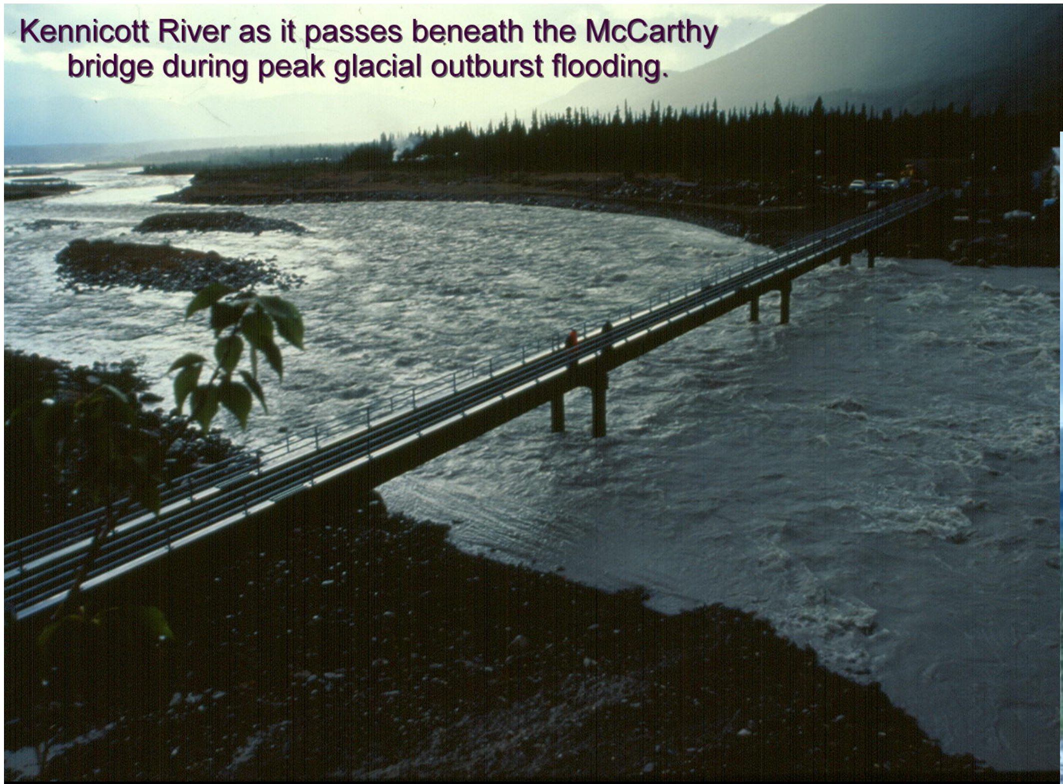
$W(H)$ from the geometry of the channel

We need U, the vertically-averaged velocity

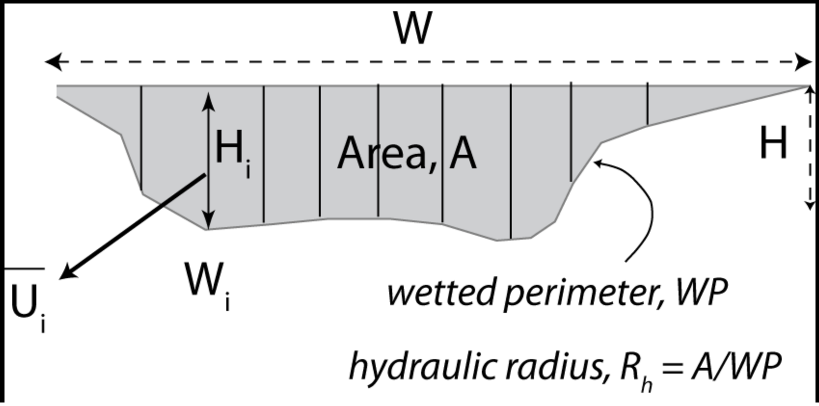
- current metering
- salt dilution
- theory

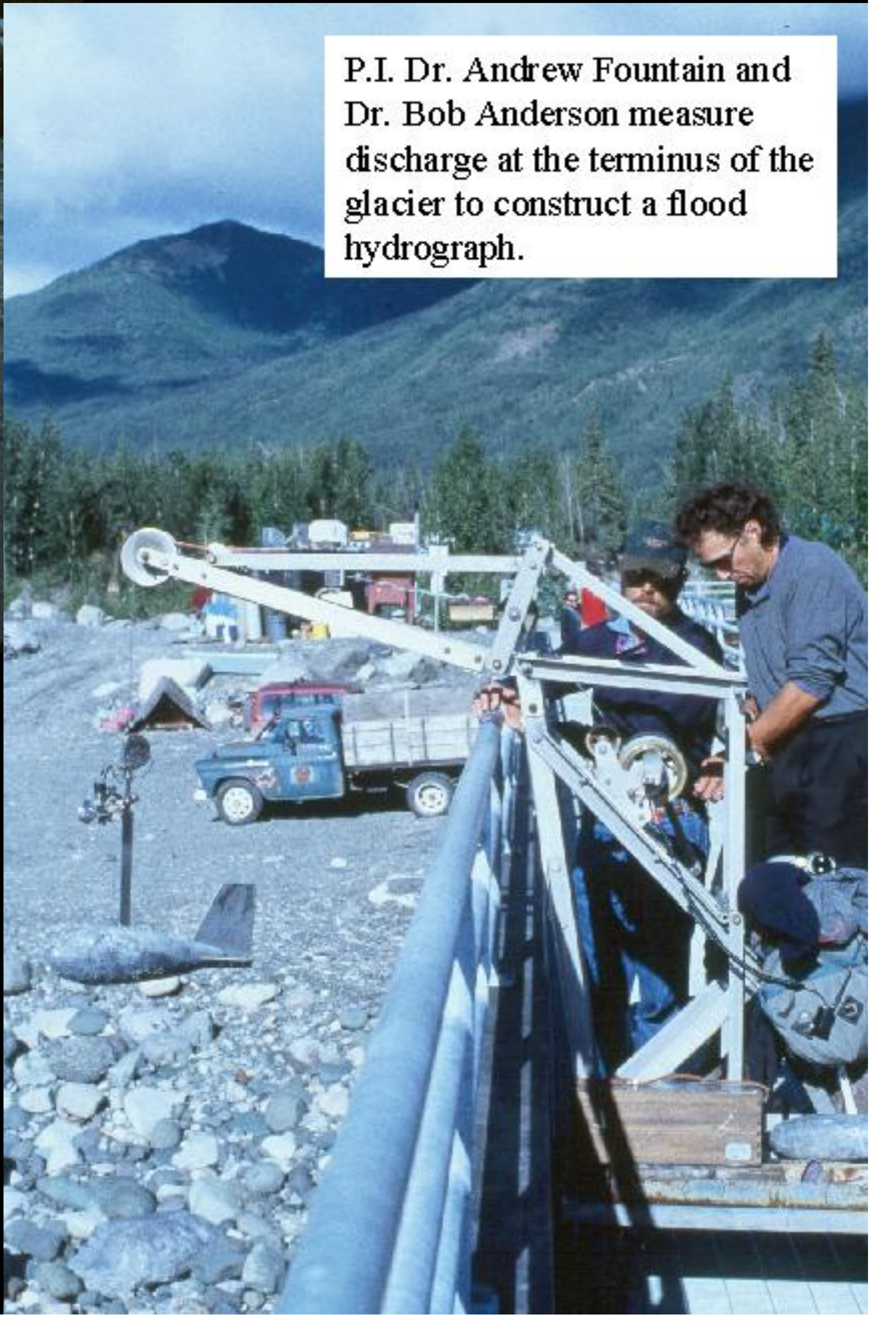
What should the rating curve look like?

$Q(H)$


Kennicott River as it passes beneath the McCarthy bridge during peak glacial outburst flooding.

Direct measurement of river discharge, USGS Protocol… points on a rating curve




P.I. Dr. Andrew Fountain and Dr. Bob Anderson measure discharge at the terminus of the glacier to construct a flood hydrograph.

An aside: what sets their shapes?
how or why do these streams meander?

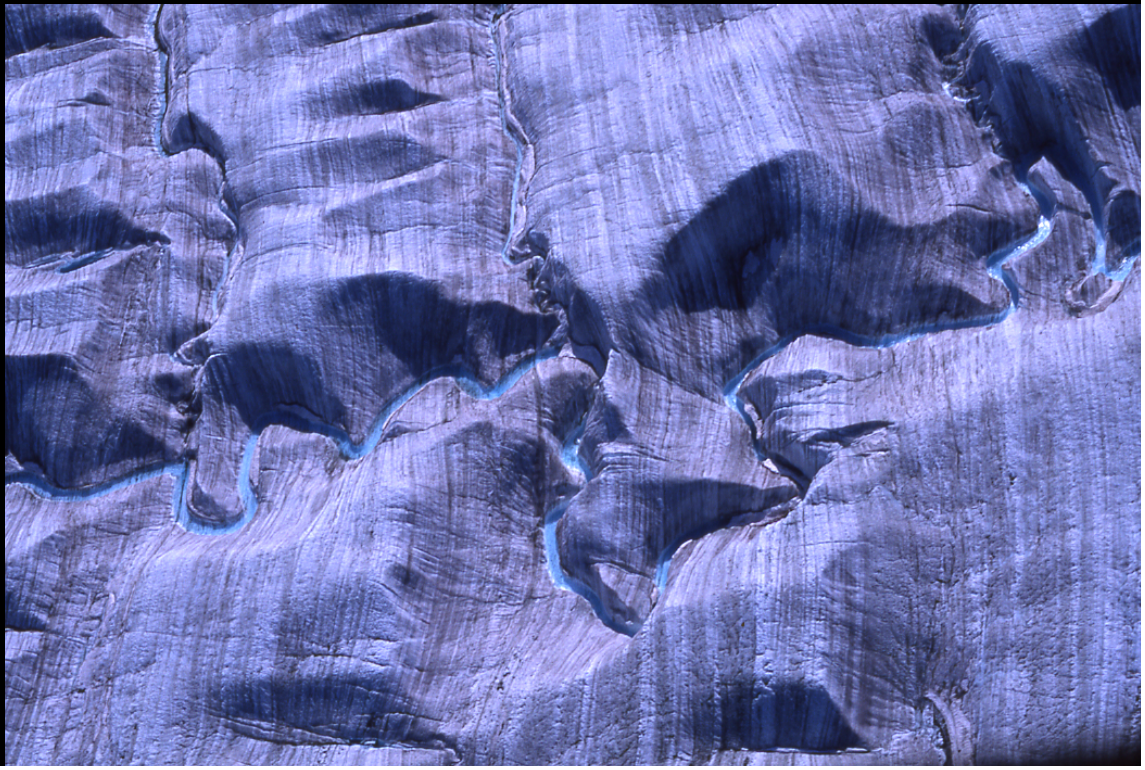
How does it melt ice if 0°C?

Heat source in turbulent dissipation.

  Strain heating = product of stress*strain rate

The channel meander problem

  this is NOT about sediment pointbars shoving the flow



Gates Glacier

For the most part ice is impermeable…but…

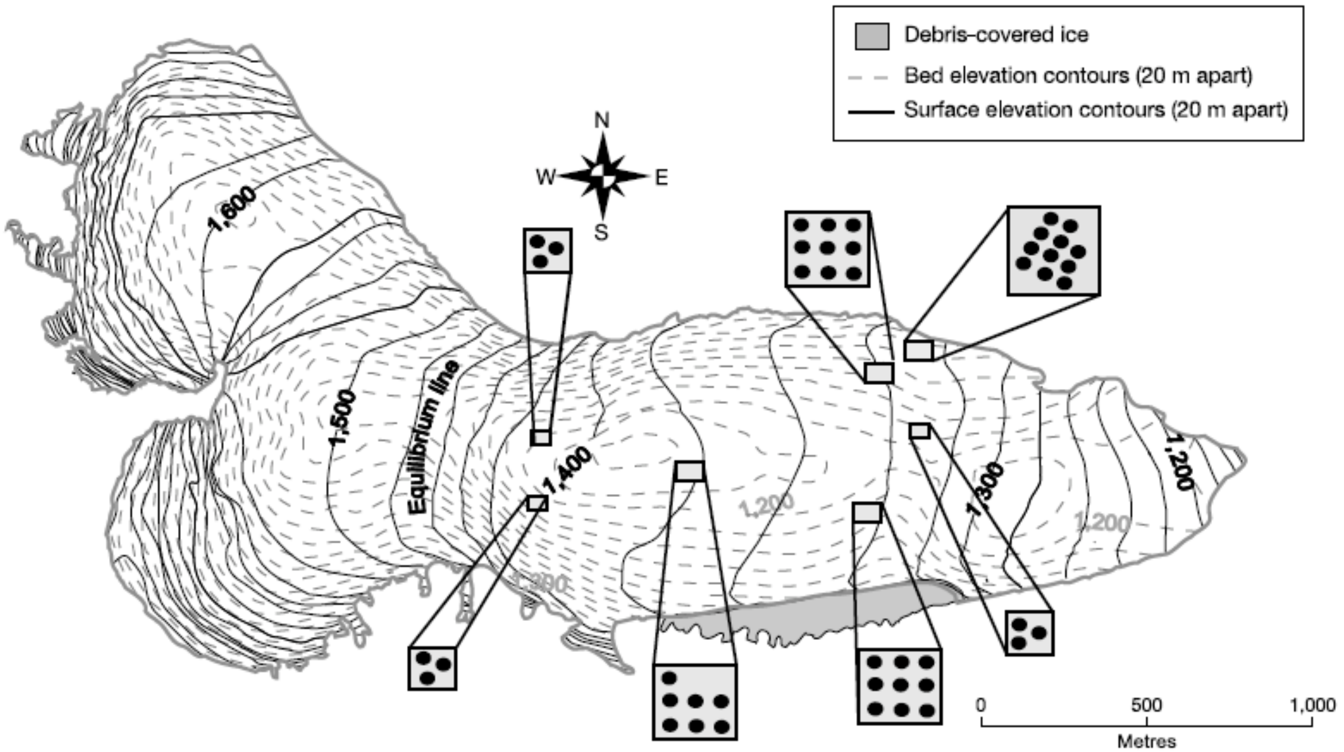


Figure 1 Map of Storglaciären showing the location of the drill sites. Four sites were composed of at least seven holes, each 10 m apart in a grid plan, and three sites were composed of three holes, each ~20 m apart in a triangular plan. All sites were drilled in the over-deepened section of the glacier with the exception of the first set in the upper right.

Fountain et al. (2005) *Nature* 433: 618-621.

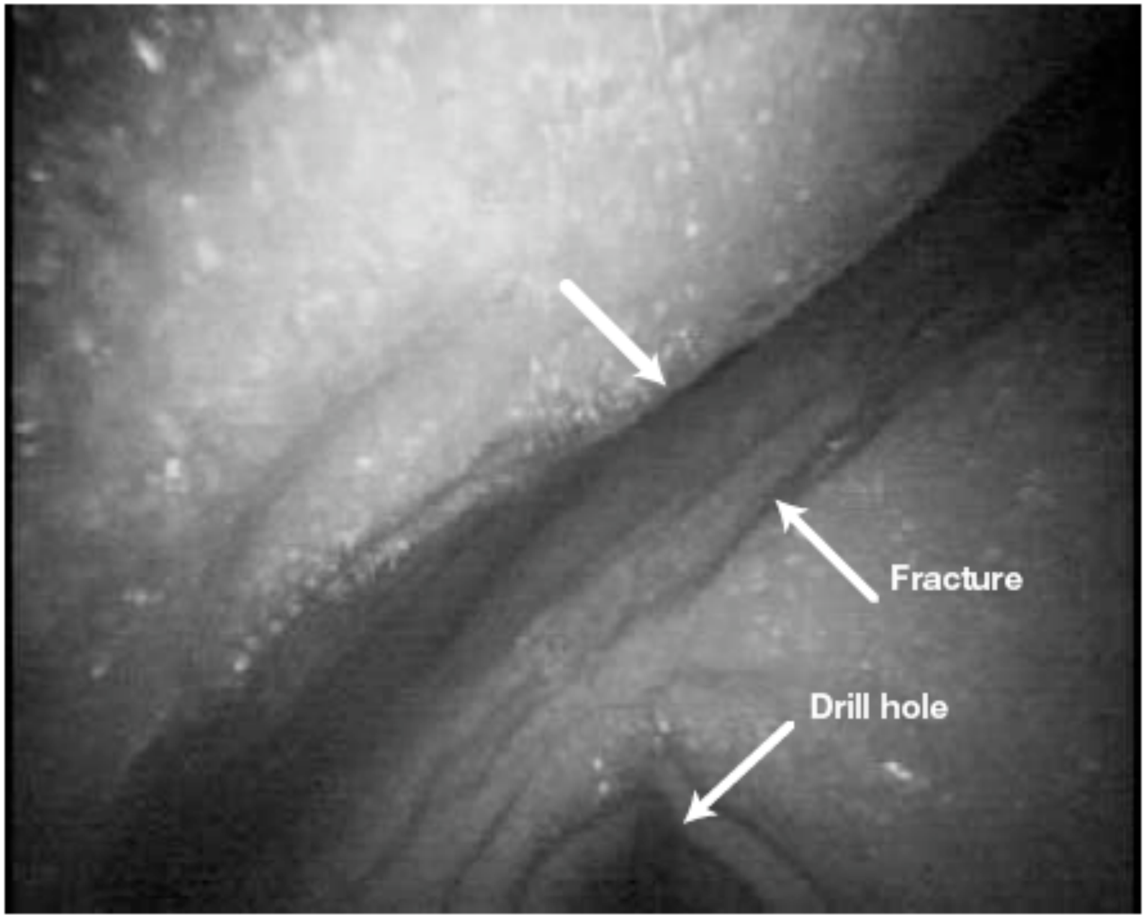


Figure 2 Video image of an englacial fracture. The fracture width is about 4 cm and the continuation of the vertical drill hole is identified. The camera is tilted obliquely downward towards the fracture.

Fountain et al. (2005) *Nature* 433: 618-621.

The drilling and radar results point to copious water-filled cavities within temperate ice. Images showed that 80% of these cavities were steeply dipping fractures, most of which were hydraulically connected, forming an englacial hydraulic system.

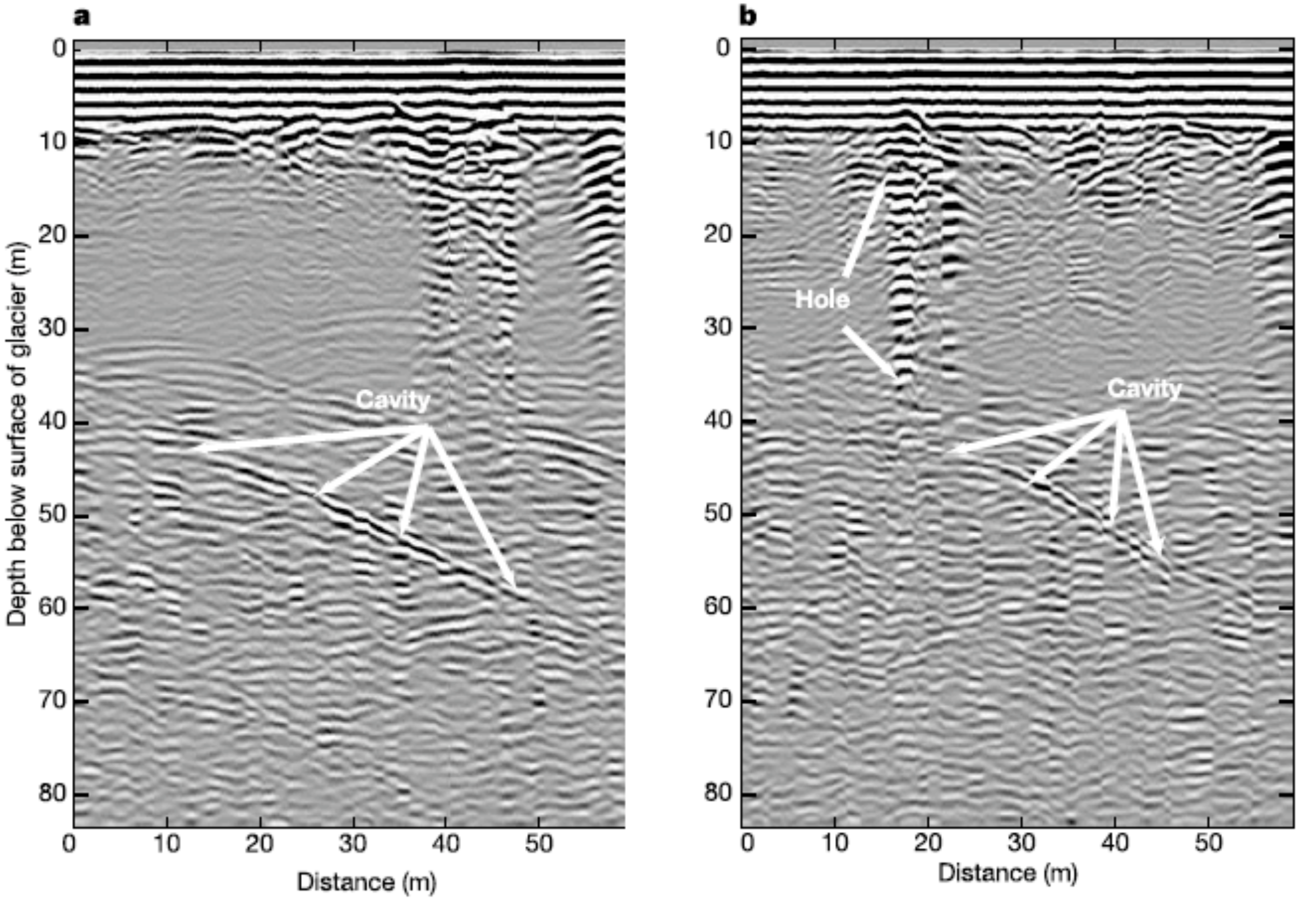


Figure 3 Radar (50-Mhz) reflections from the glacier interior showing a dipping reflector before and after drilling. **a**, The radar reflections before drilling with a hot water drill; **b**, the reflections after intersecting the top of the reflector at a depth of 38 m near a distance of 18 m. The reflector, inferred to be a fracture, dips to the north (right), with the strongest reflection between depths of ~40 and ~55 m.

Fountain et al. (2005) *Nature* 433: 618-621.

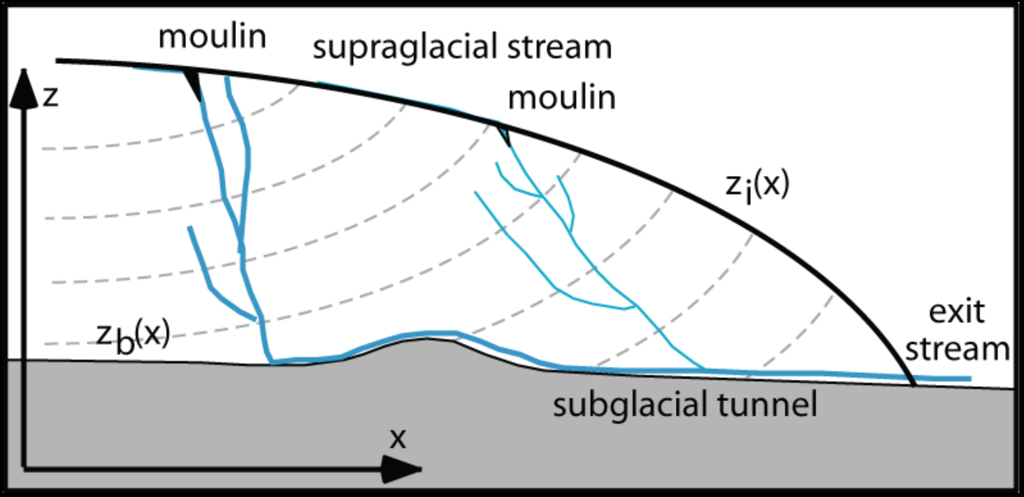
How should the water pressure field be oriented englacially?

Consider it a groundwater problem

- fluid moves normal to equipotentials
- potential = elevation head + pressure head
- equipotentials are tilted upglacier at 11x the ice slope

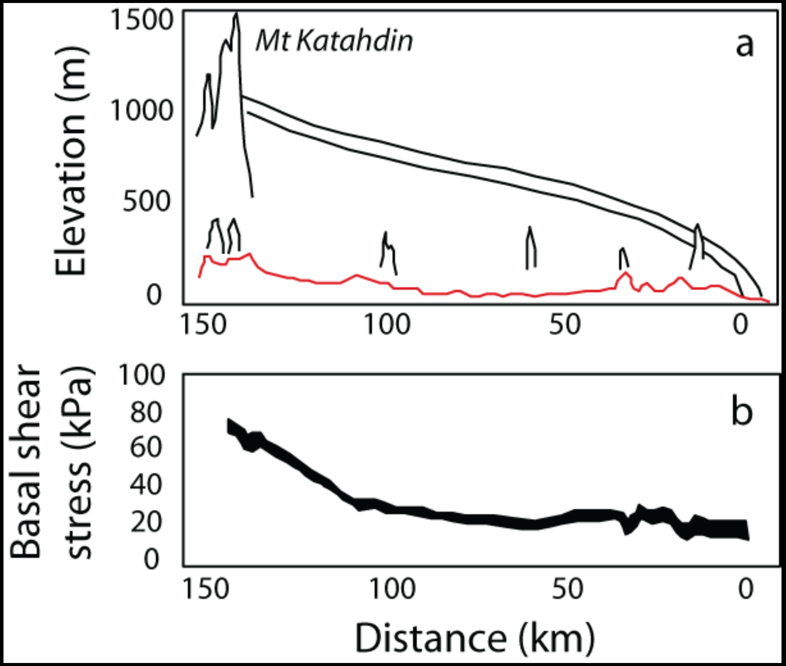
Relevance to eskers:

- ice can climb UP subgacial topography
- as long as the bed slopes are < 11x the ice surface slope



Tilted equipotentials

Ice thickness field deduced
From topography over which
LGM eskers climbed



Shreve eskers GSA Bulletin

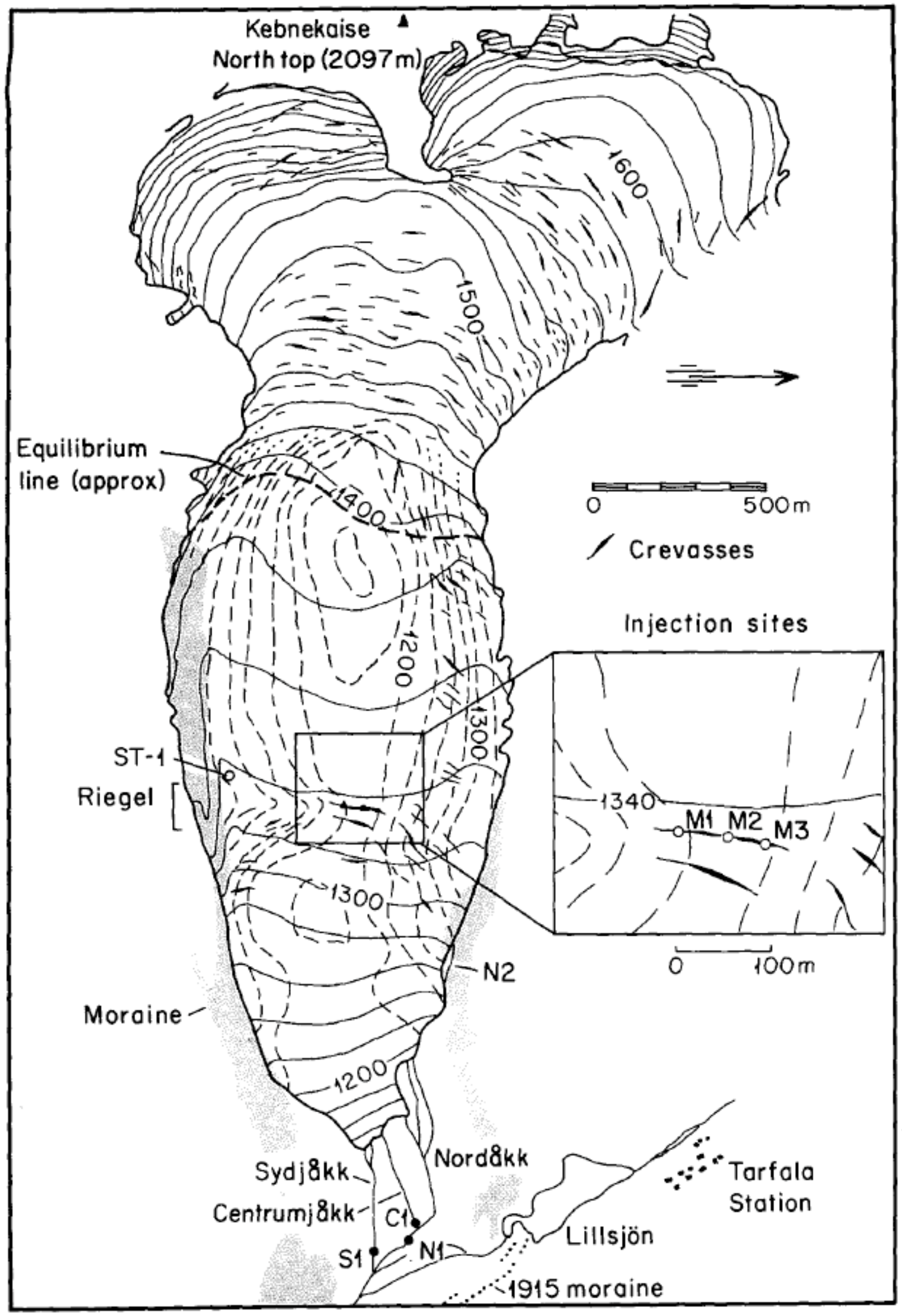
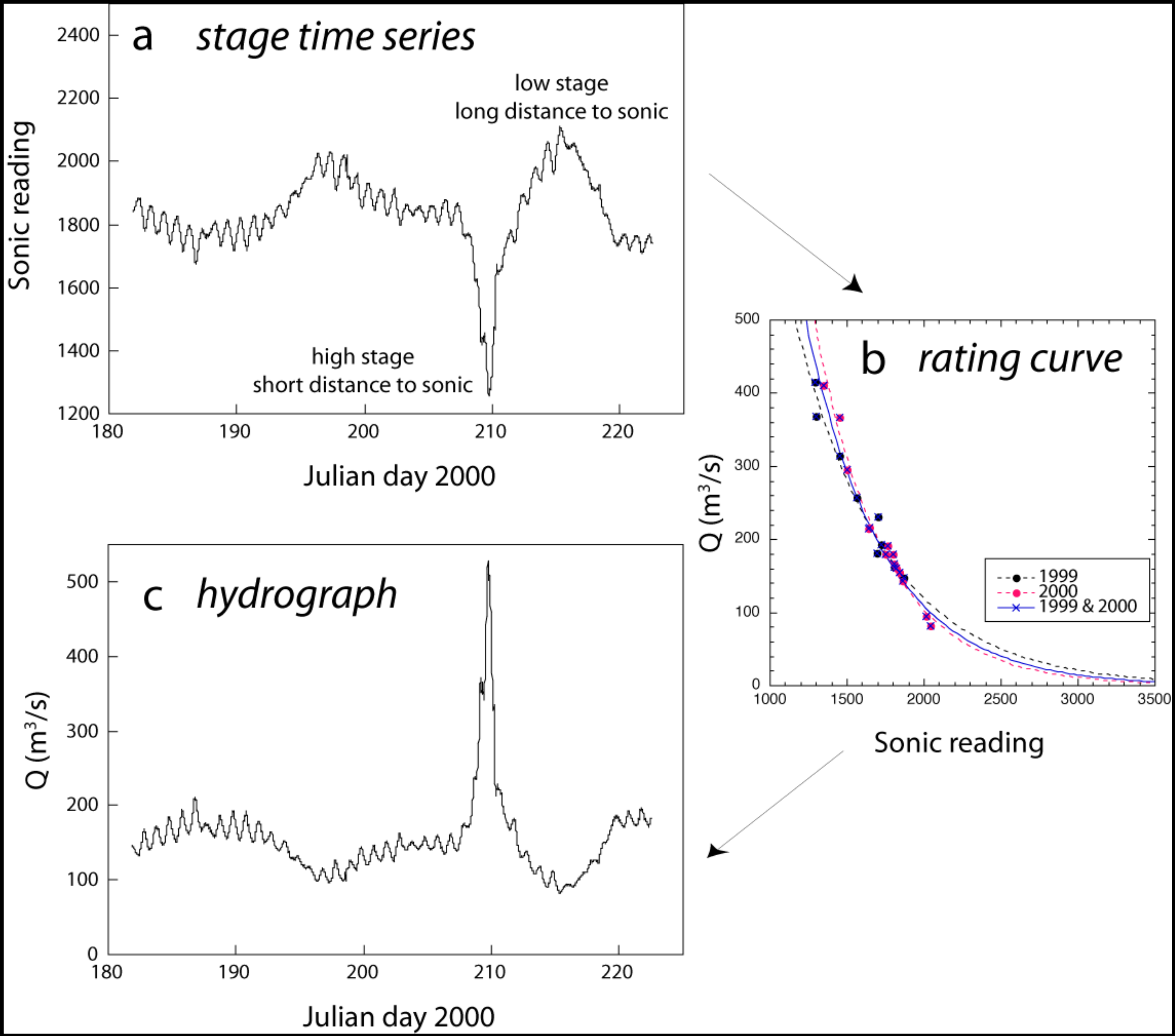


Figure 1. Map of Storglaciären showing locations of sampling sites and of moulins used as injection sites.

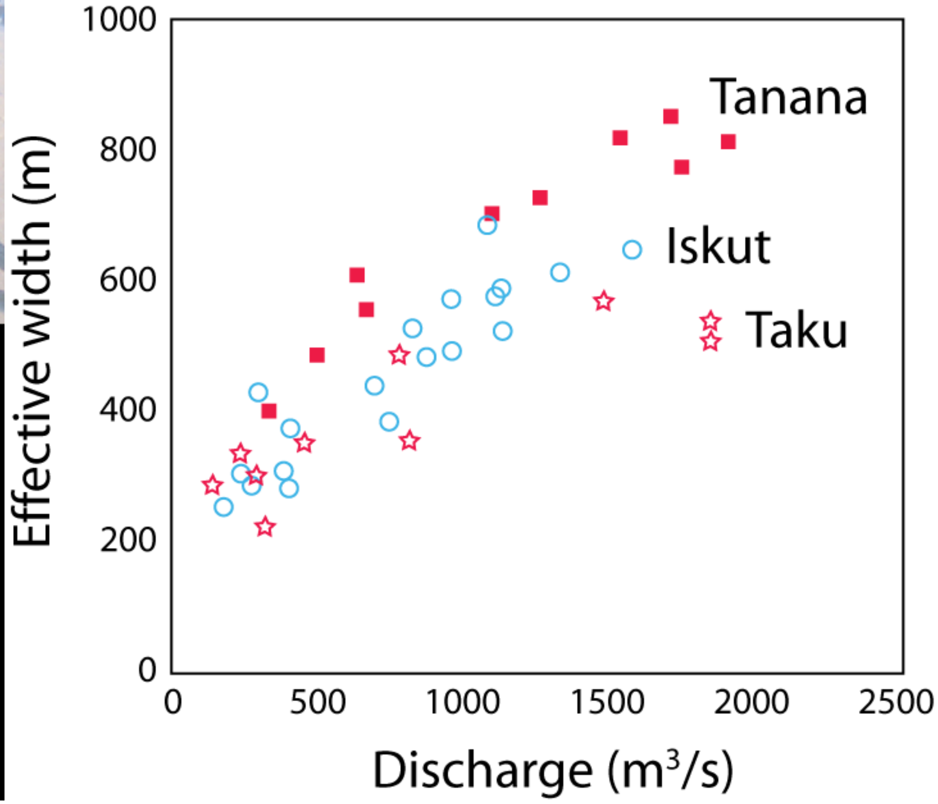
Note two outlet streams… a result of surface topography of ice driving flow in divergent directions.

Hock and Hooke (1993) *GSA Bull* 105: 105: 537-546.

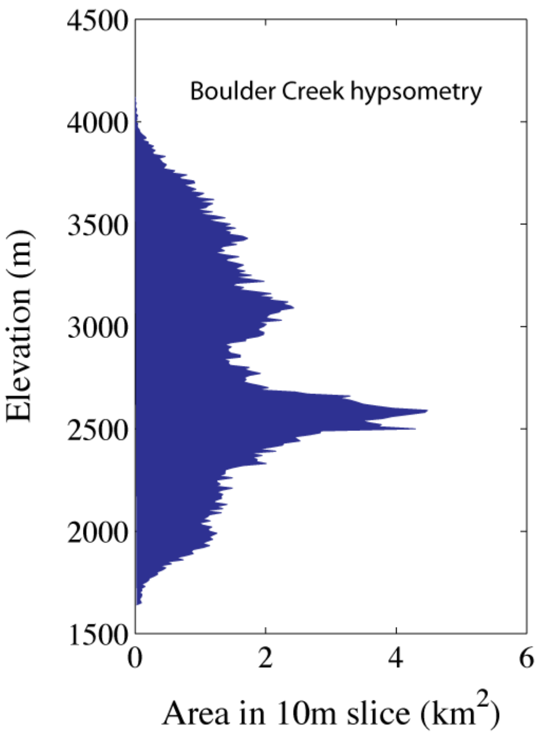

a stage time series
Sonic reading
2400
2200
2000
1800
1600
1400
1200
180
190
200
210
220
Julian day 2000
low stage
long distance to sonic
high stage
short distance to sonic
b rating curve
Q (m³/s)
500
400
300
200
100
0
1000
1500
2000
2500
3000
3500
Sonic reading
1999
2000
1999 & 2000
c hydrograph
Q (m³/s)
500
400
300
200
100
0
180
190
200
210
220
Julian day 2000

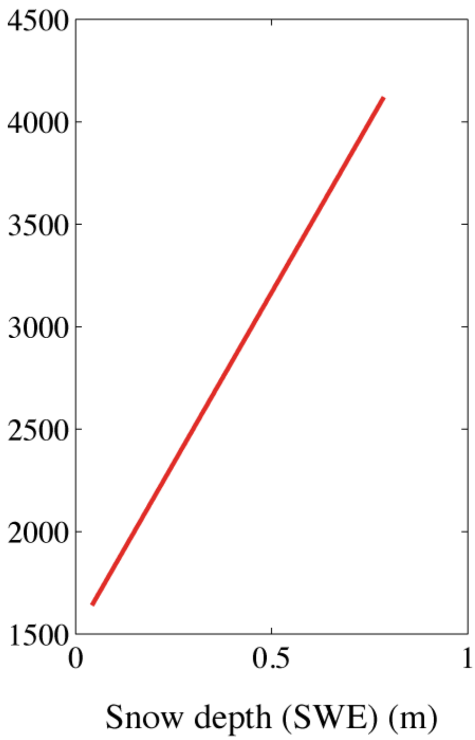
But what about braided rivers?

$Q \sim W$



Smith et al.





Late season support of
Runoff by glacier melt -
Especially important
In bad water years