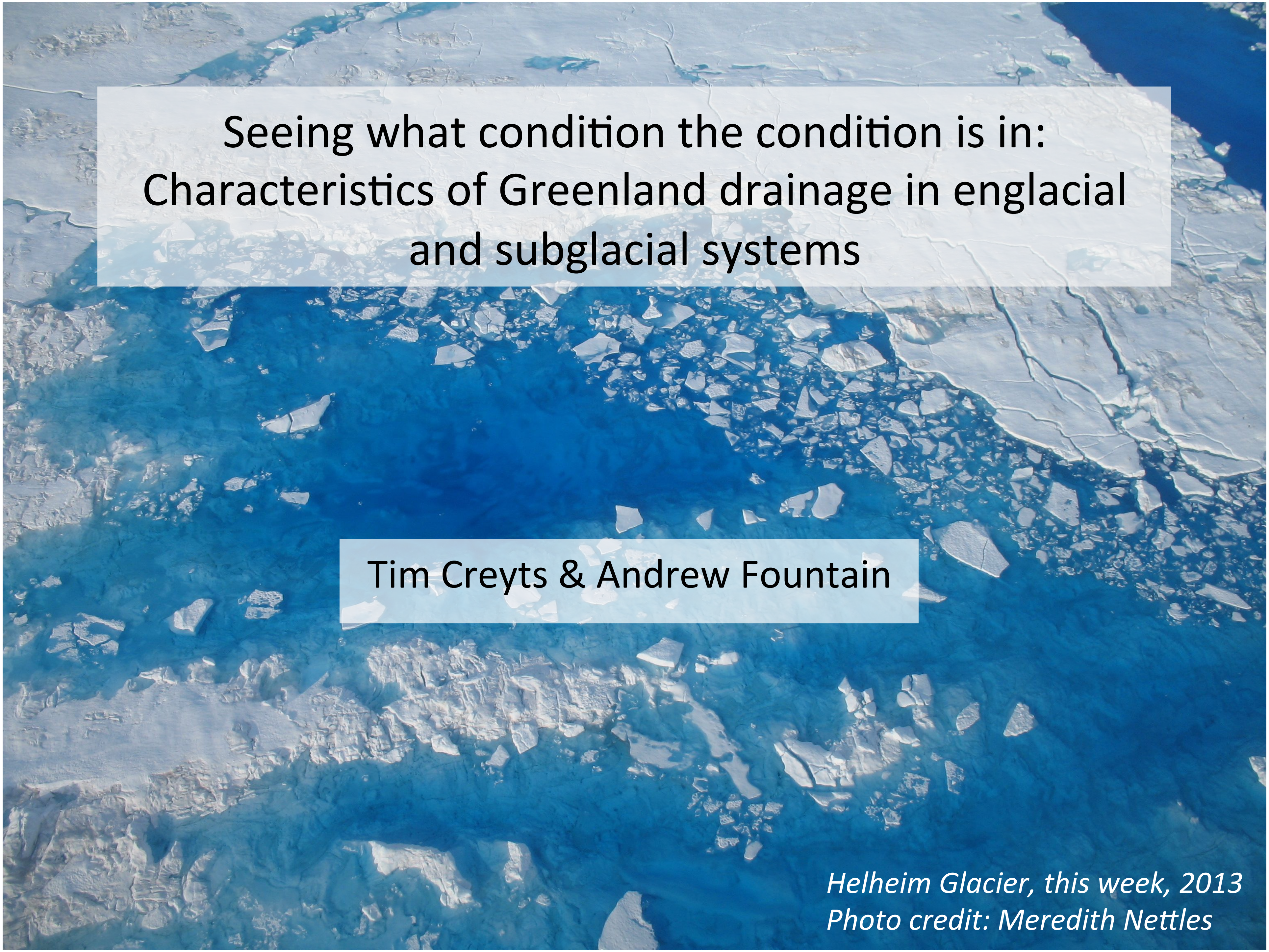
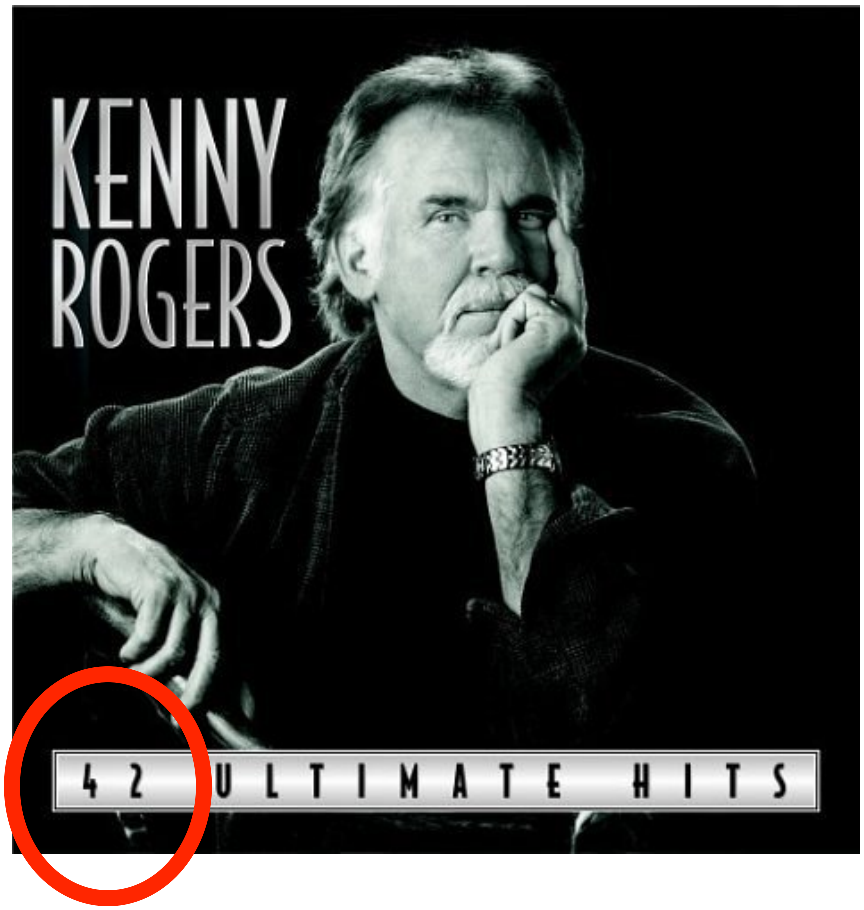
Seeing what condition the condition is in: Characteristics of Greenland drainage in englacial and subglacial systems

Tim Creyts & Andrew Fountain



Helheim Glacier, this week, 2013
Photo credit: Meredith Nettles

What is that reference?

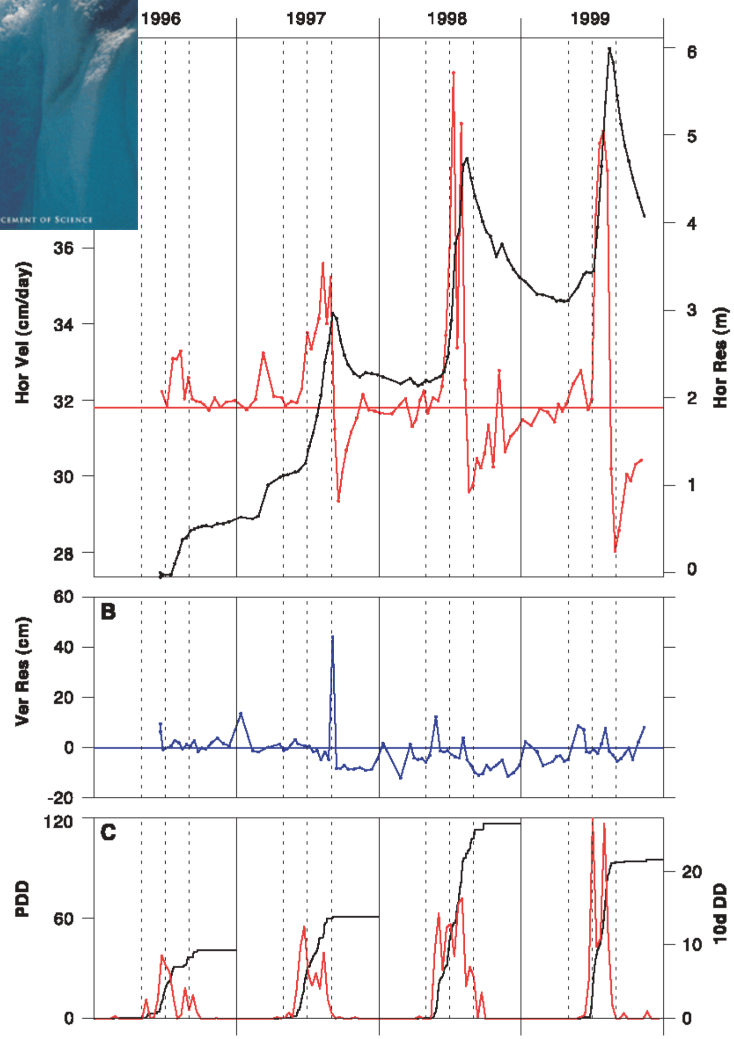


- Homework: download this later (This is not necessarily a recommendation)
- 42: Means that there will be an answer in the talk(!)
- The protagonist (Greenland?) goes to the doctor (Scientists, you?) to see what his condition is (not good?)

Outline

1. Some observations of Greenland hydrology
2. Detour into driving stress
3. Englacial hydrology
4. Conclusions

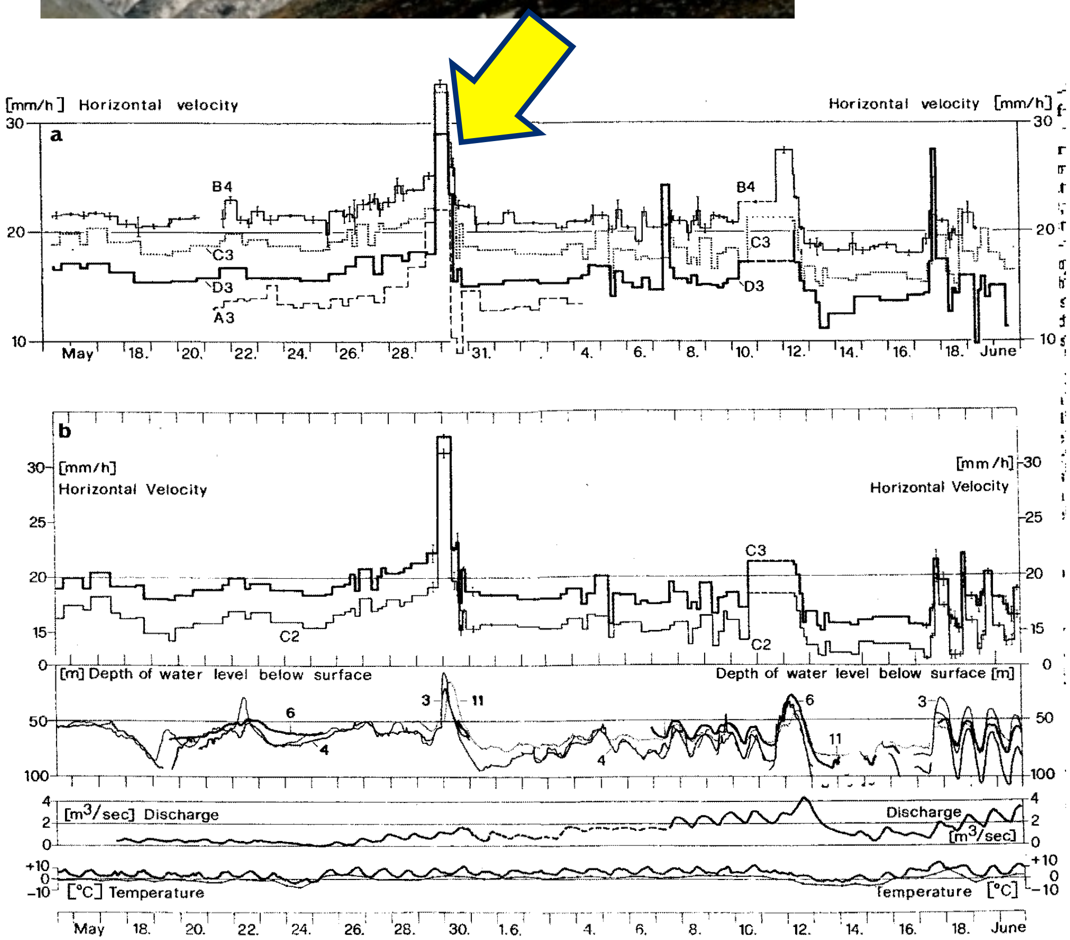
An influential paper in Greenland Hydrology



- GPS Observations Near Swiss Camp, Zwally et al., 2002
- Summertime speedup of ~10% corresponds to surface meltwater production
- A lot of papers show similar behavior in the ablation zone of the Greenland Ice sheet
  - e.g., Joughin et al., 2008; van de Wal et al., 2008; Shepherd et al., 2009; Bartholomew et al., 2010; Sundal et al., 2011; Palmer et al., 2011; Hoffman et al., 2011 + others.

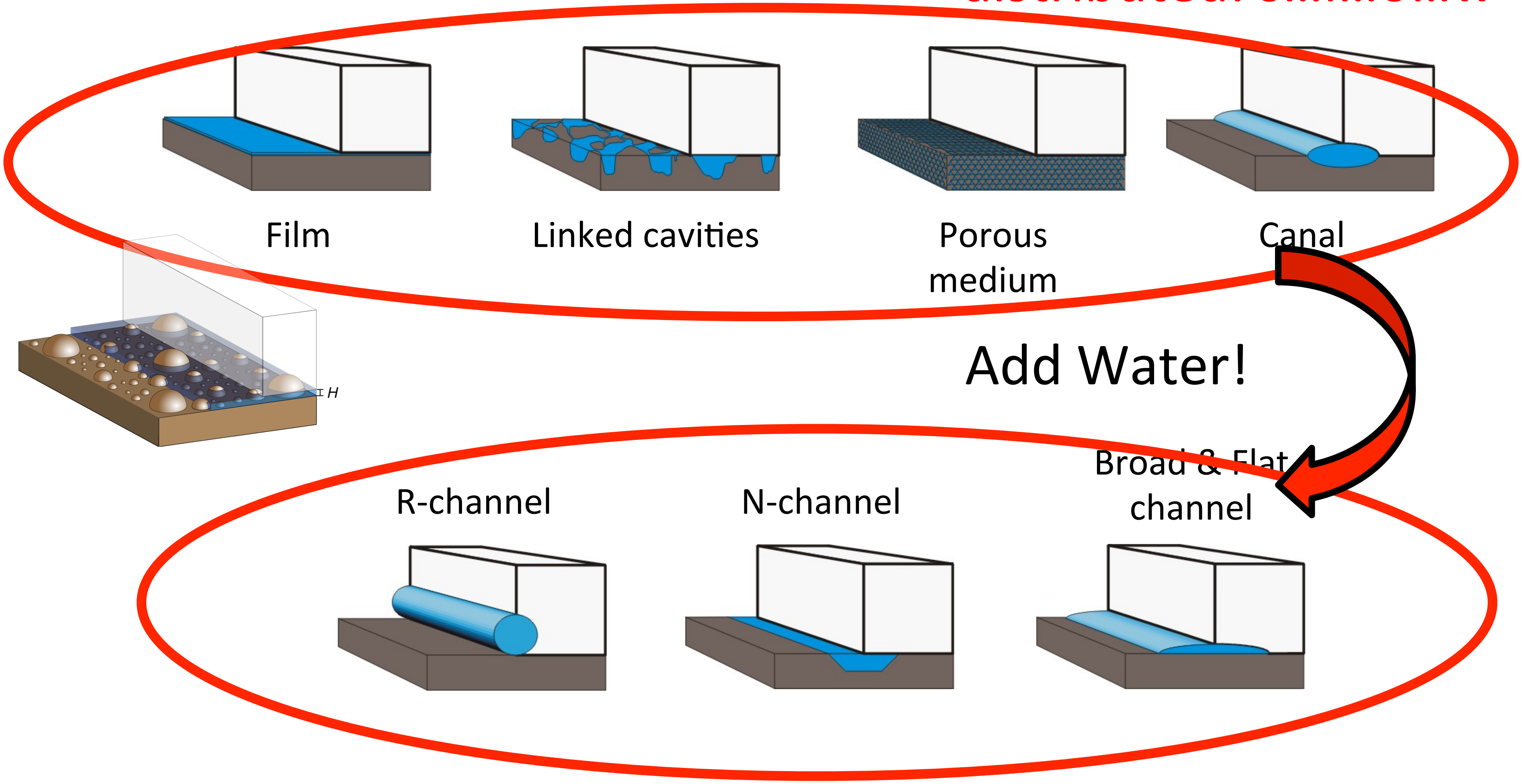
Similar speed-ups are well known in the mountain glacier literature

- Example at Findelengletscher, Switzerland from Iken and Bindschadler, 1986
- “Spring Event” correlates with high water in the glacier
- Ice separates from the bed as water lifts the glacier
- Enhanced basal lubrication causes an increase in speed
- Examples from many glaciers worldwide
- Truly, it is an off-the-charts phenomenon



What is happening physically?

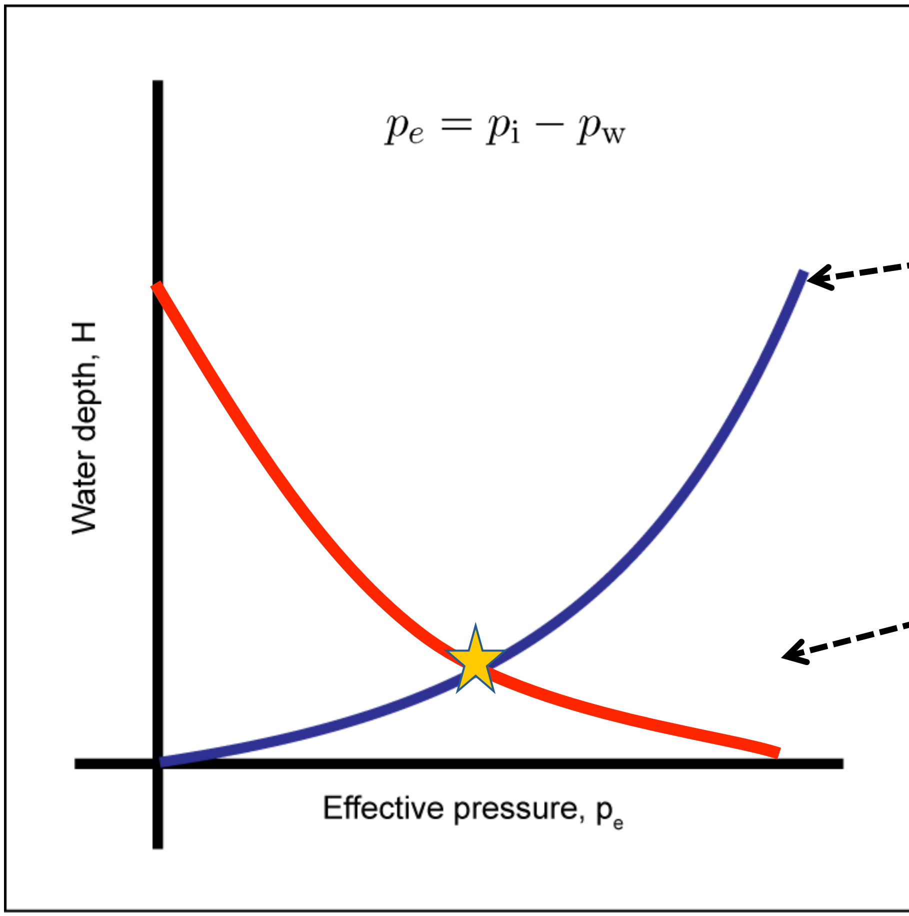
“Winter” mode: distributed: s…l…o…w



Fast , channelized drainage with low slip

Thresholds for hydraulic transitions are not well understood

Hysteresis between distributed drainage morphologies and channelized morphologies....



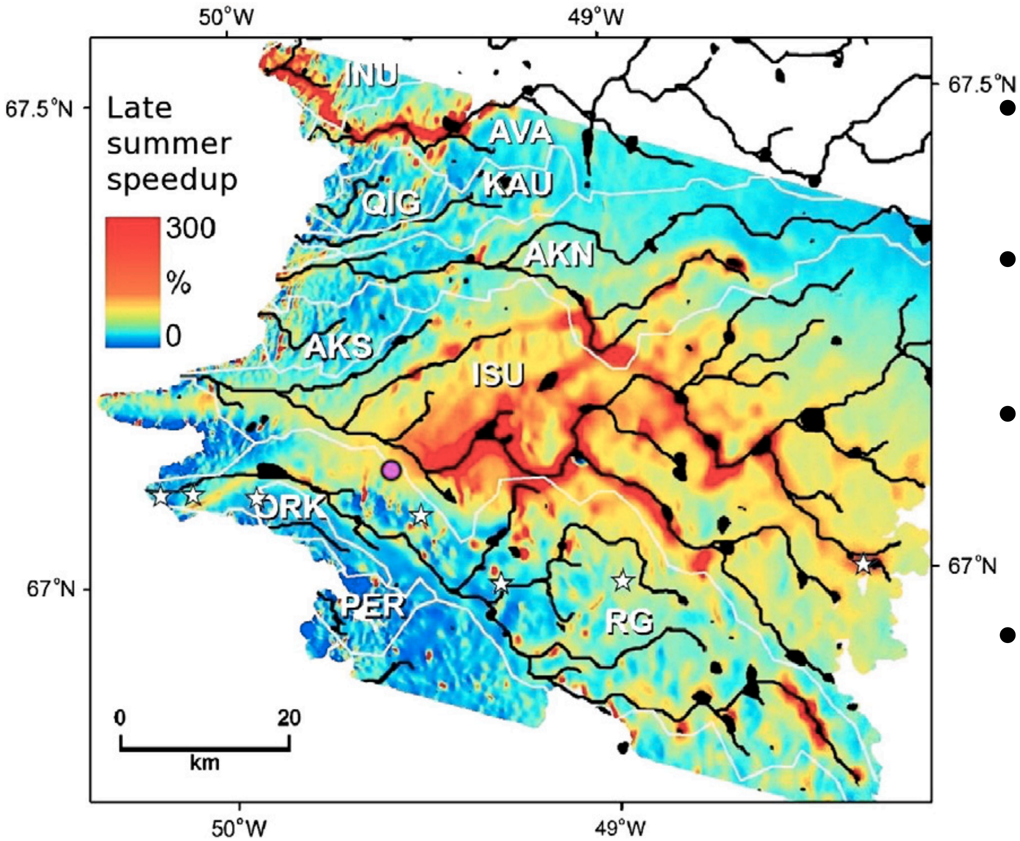
<u>Fast types</u>: Discharge increases with effective pressure, collects water, inhibits fast flow

$$Q \propto p_e^n$$

<u>Slow types</u>: water decreases with increasing effective pressure, lubricates the bed, causes fast flow

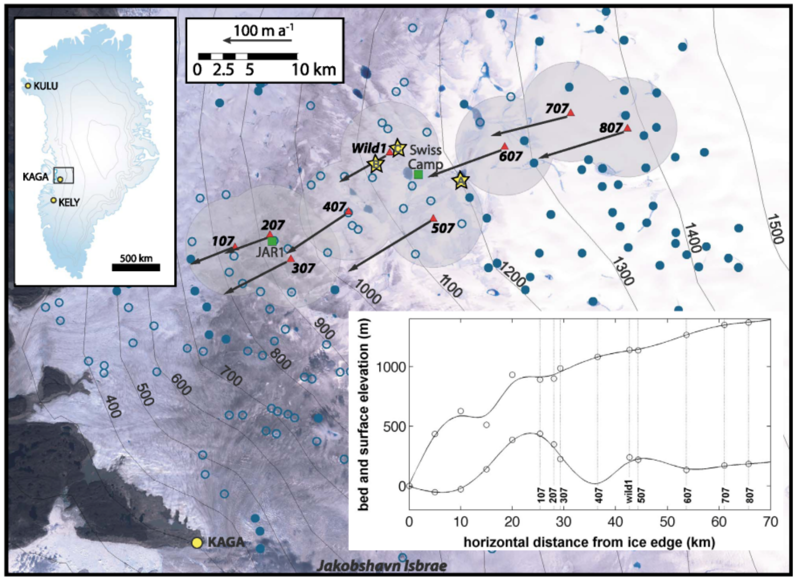
$$Q \propto p_e^{-n}$$

What are the spatial patterns?

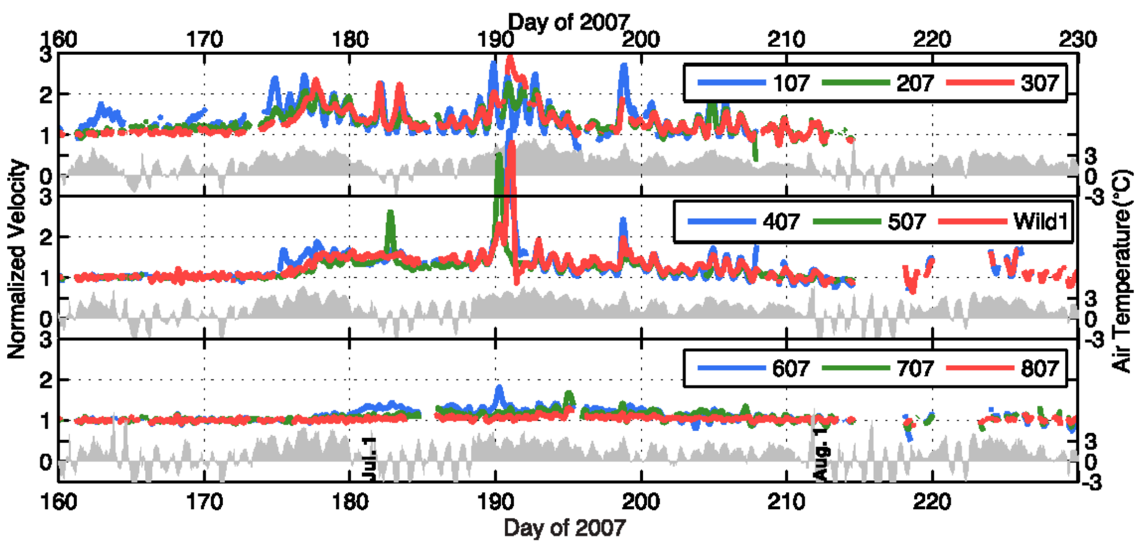


Palmer et al, 2011

- Land terminating Glacier, data from 1995
- Speed ups extend over 100 km inland
- Pattern of speed-ups follows surface (rather than bed) drainage patterns
- Speed correlates with water availability (surface meltwater production: PDD index)
- Seems to be a causal relationship between surface water and bed velocities via drainage through the ice sheet.



- Array of GPS stations on the glacier surface
- Able to watch a seasonal velocity wave move up the glacier
- There are also daily variations in velocity as well as events.
- Increases in velocity are 6-41% above background spring velocities
- The duration of increase is about 40 days
- Infer significant ice-bed separation

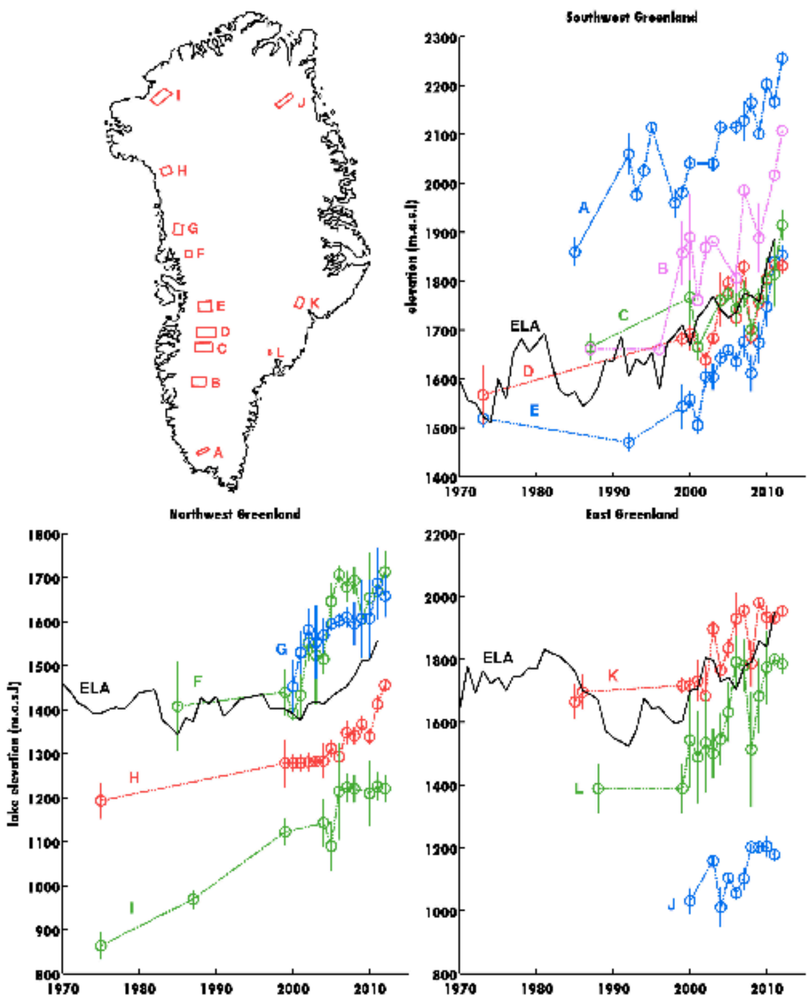


Mounting evidence suggests seasonal evolution of subglacial drainage mitigates or counteracts the ability of surface runoff to increase basal sliding.

They concluded that "increases in summer melting may not guarantee faster seasonal ice flow."

Hoffmann et al, 2011

Trend in supraglacial lake locations



Howat et al., 2013

- 40 years of satellite data
- Trend is that the highest lakes are moving up in the ablation zone
- Ice discharge and slip will be moving up in the catchments too (vis-à-vis the last slide)
- Time-dependent component of warming that needs to be addressed in the drainage-and-slip dynamics models.

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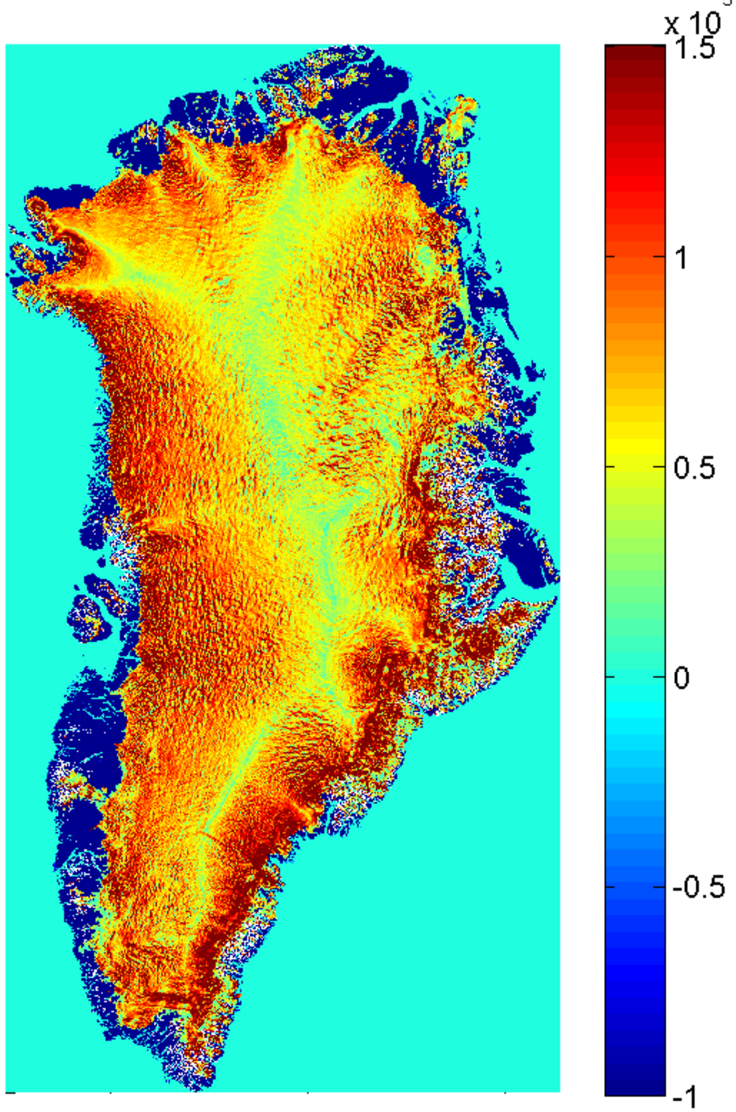
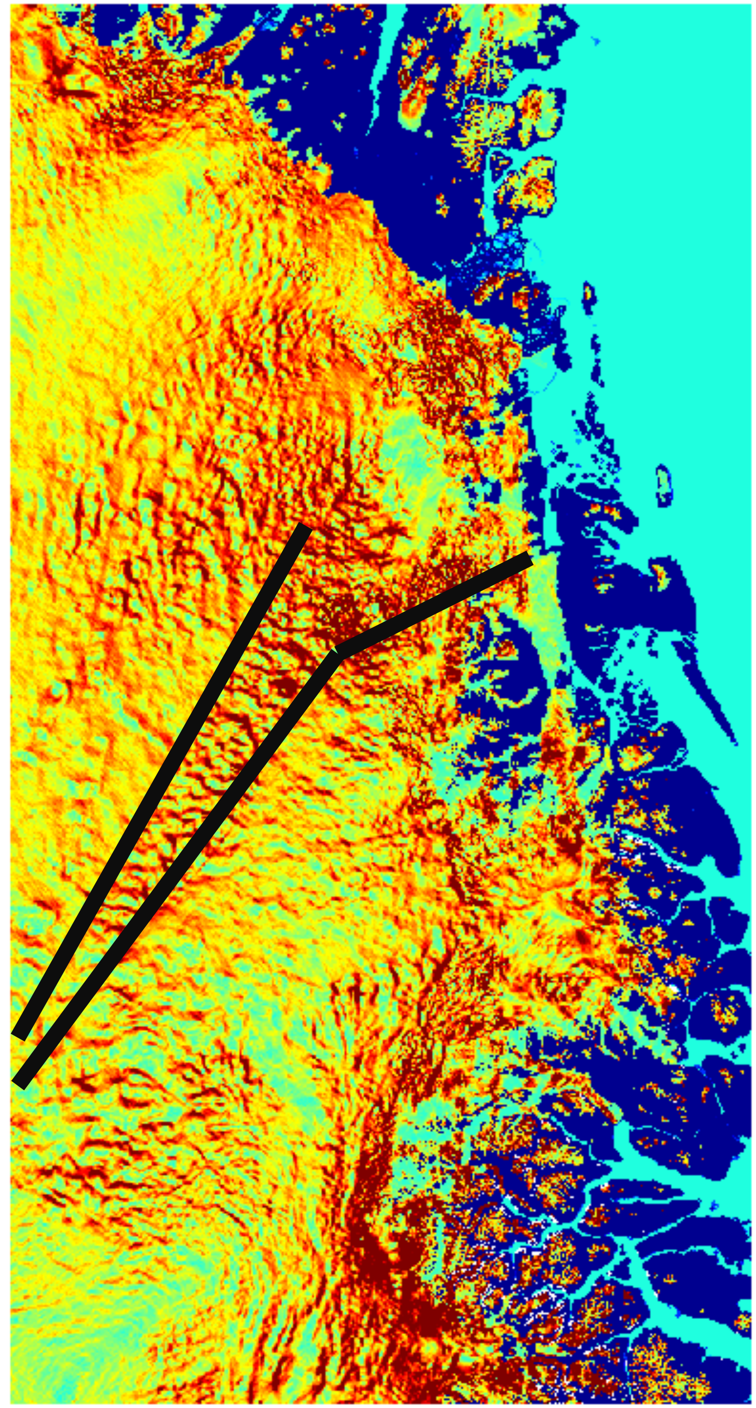
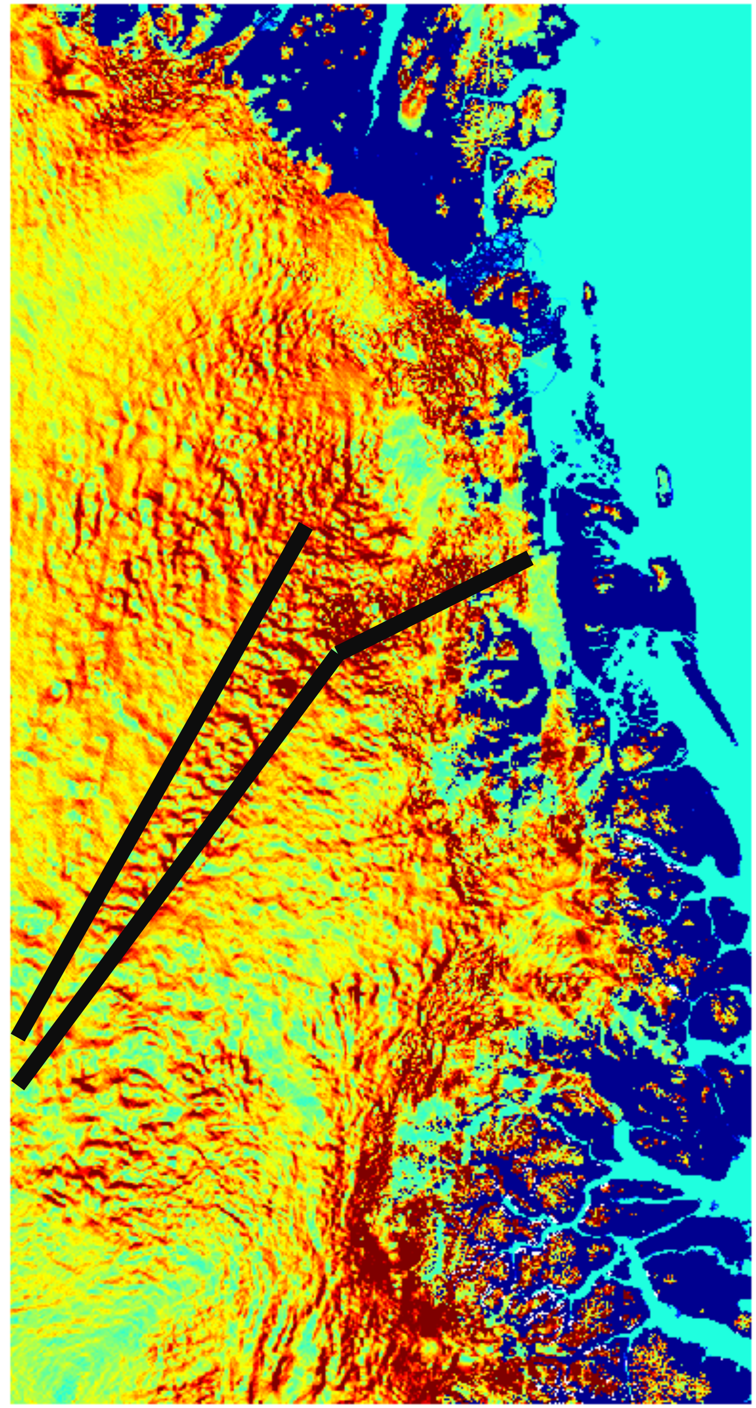
Do the stress





- “Ribbons” of alternating high stress and low stress
- The low stresses imply slip
- There are coupled slip/no slip areas over the ice sheet
- Water is likely lubricating the areas that are slipping
- *See Olga’s poster*



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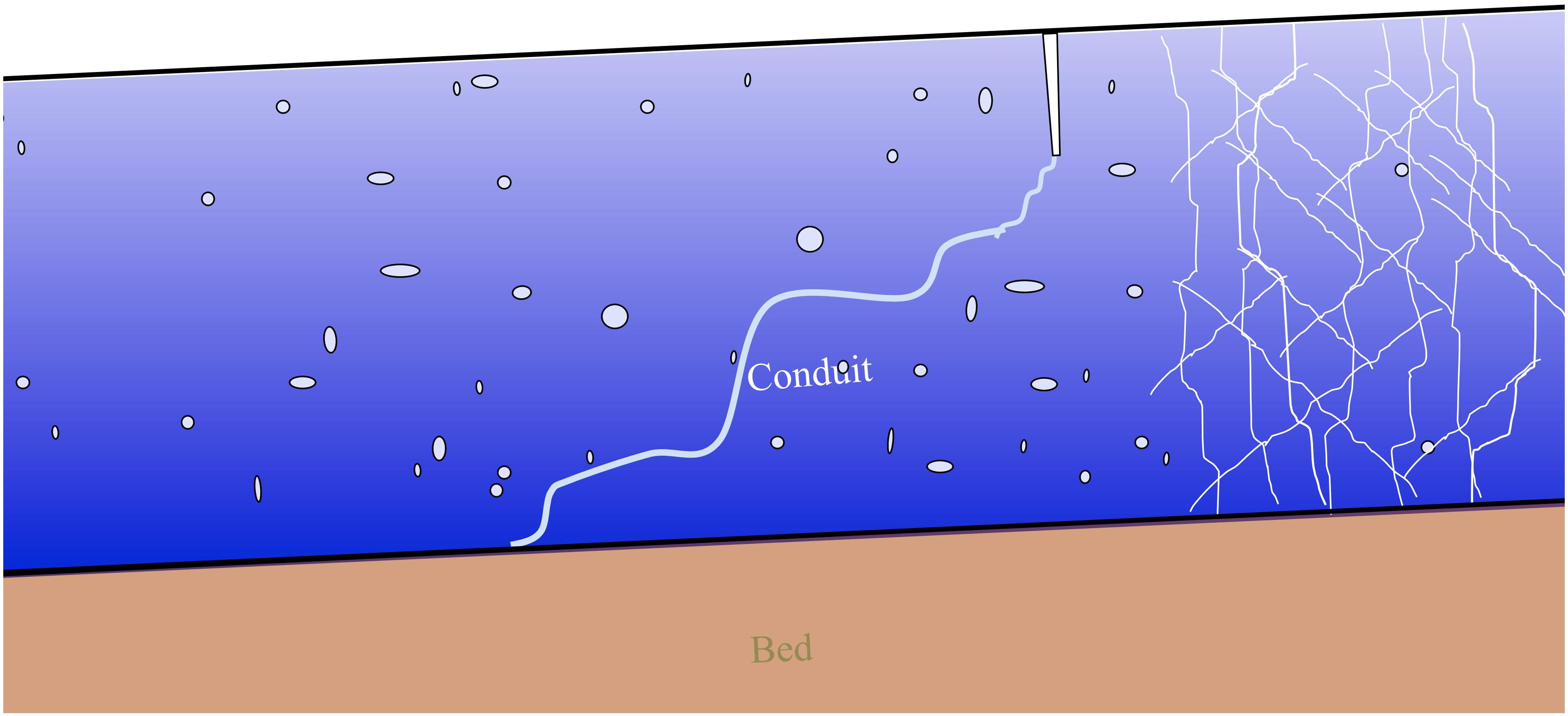
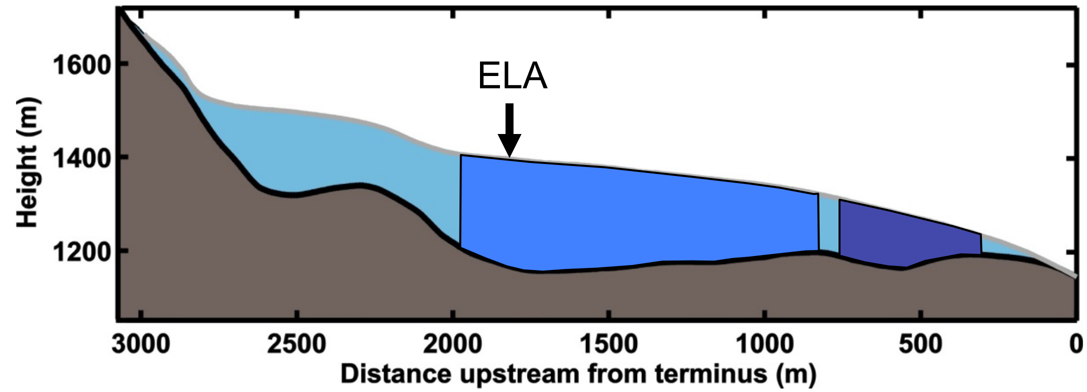
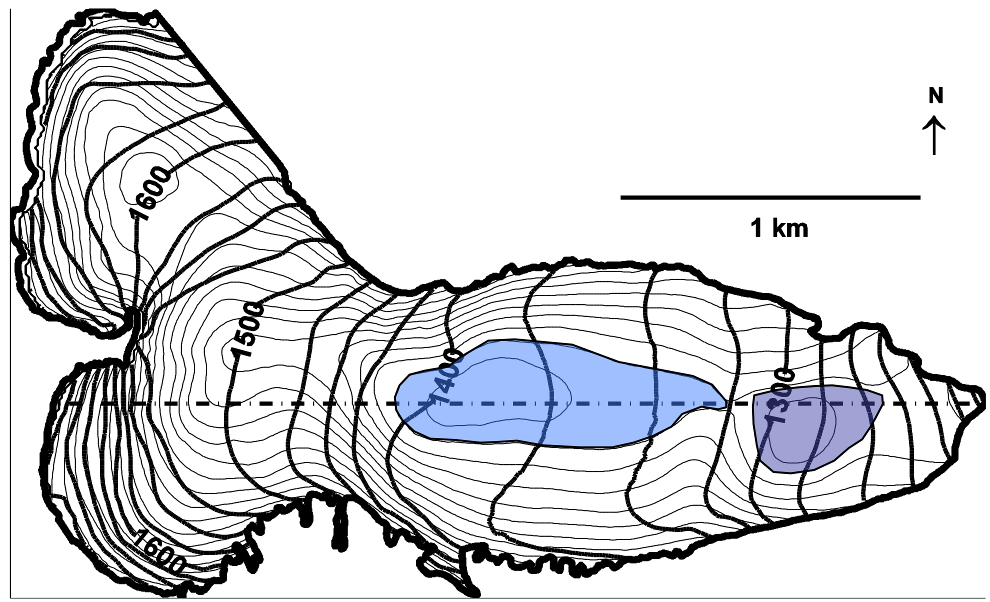
Englacial Hydrology is important for three reasons

- Can be a major reservoir of stored water in the glacier
- Affects the flux rate of water reaching the bed
- Controls the spatial distribution of water reaching the bed



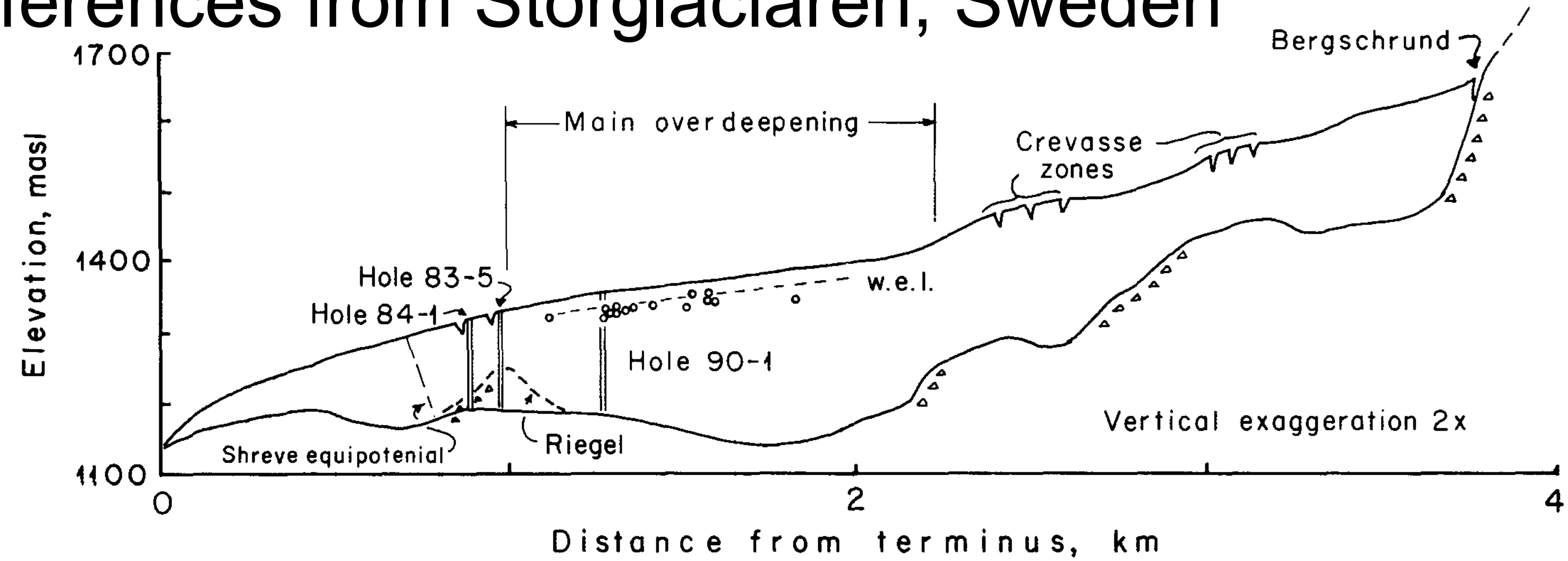
Inferences from Storglaciären, Sweden





In the absence of either the pressure of overlying ice or upstream water pressure (~approximately ice overburden pressure), these overdeepenings would pond water

Inferences from Storglaciären, Sweden



- Hooke (1991) observed
  - In the main overdeepening, upstream of the riegel (or bedrock \`sill') water pressures are high and exceed flotation
  - Glaciohydraulic supercooling and ice formation was observed in the boreholes
- Based on additional data, Fountain et al (2005) suggested that a fracture network was the main hydraulic pathway

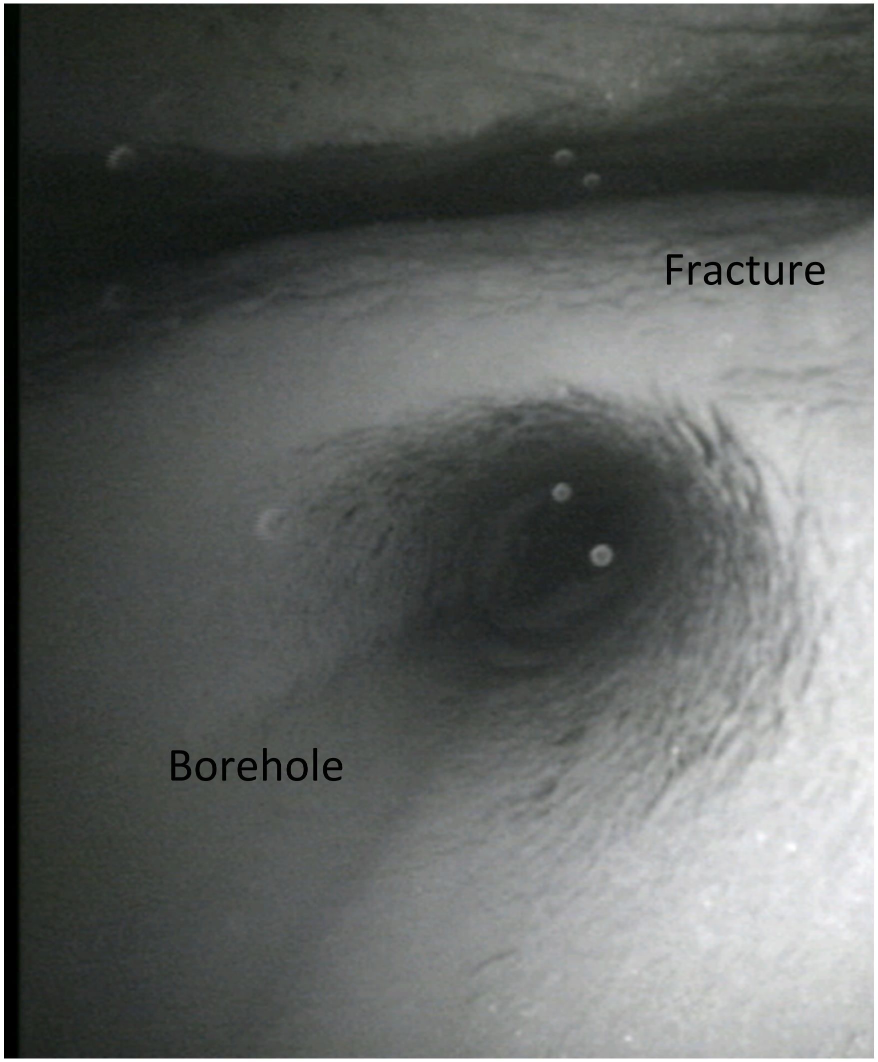
So how is water routed through the ice?

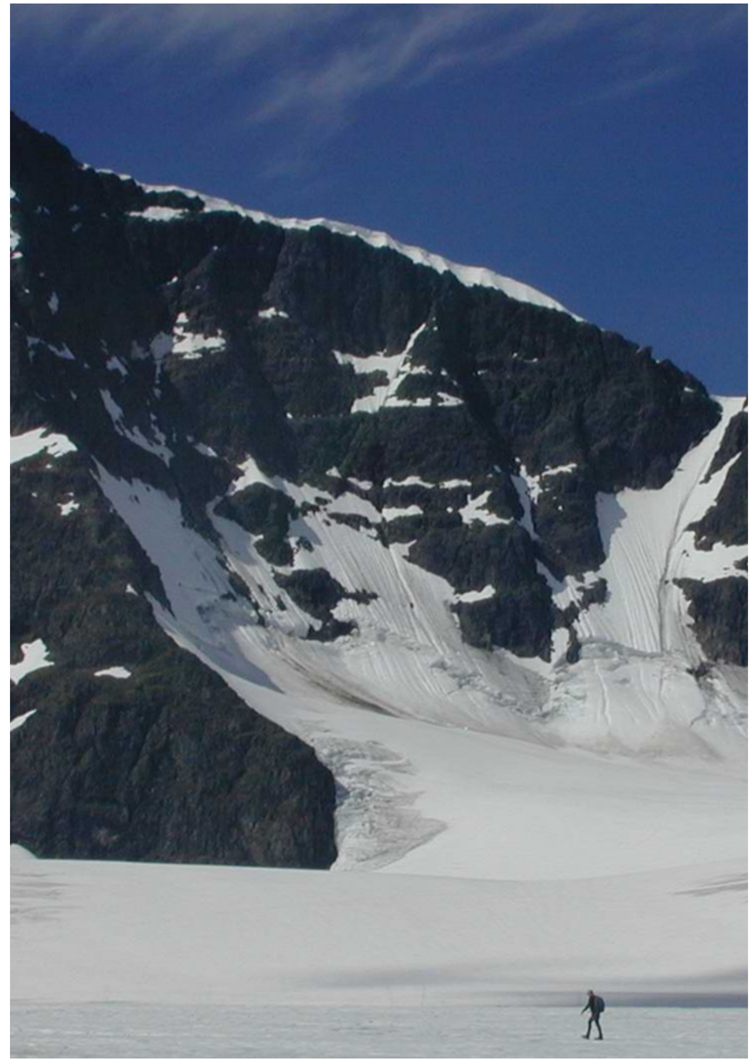
- Moulins
- Fractures
- ~~Three-grain boundaries~~

Konrad Steffen

Jeff Vervoort

Fractures in temperate ice are ubiquitous and at depth without surface expression

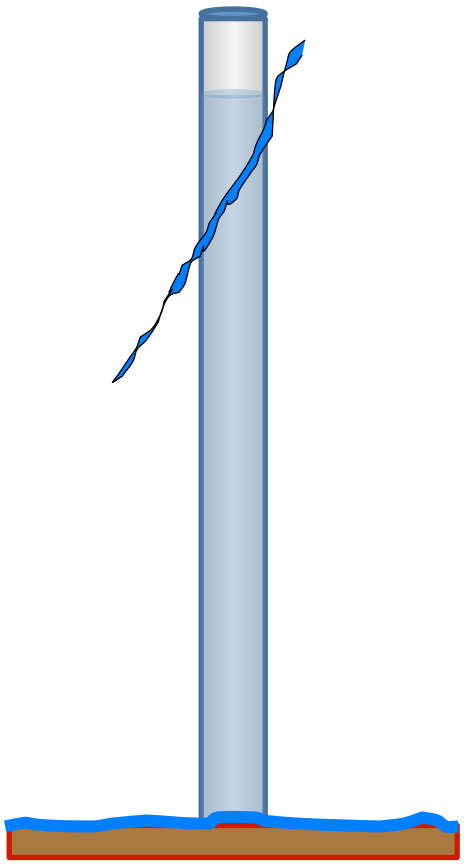




Storglaciaren Depth 183m
Fountain et al., 2007

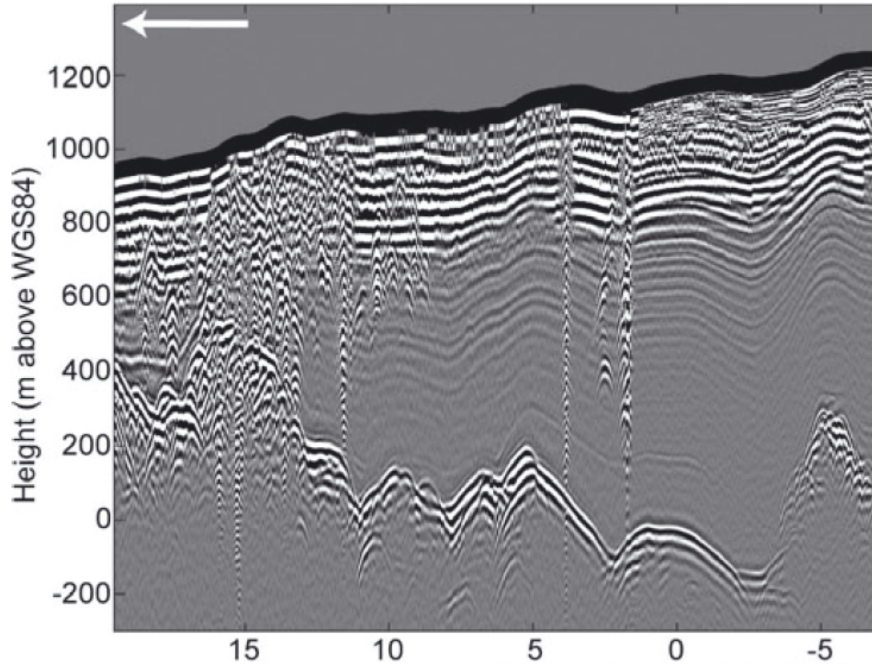
Estimates of Englacial Porosity

Direct Estimates from boreholes	
Hodge (1976)	0.4%
Harper and Humphrey (1995)	0.5%
Pohjola (1994)	1.3%
Inferred from Water Storage	
Tangborn et al., (1975):	0.1% - 2.3%
Östling and Hooke, (1986):	0.3%
Stenborg (1970)	1 %
Walder and Driedger, (1995):	0.2%
Anderson et al., (1998):	0.1%
Inferred from Radar Measurements	
Murray et al., (2007):	0 - 3.9%
Bradford et al., (2009):	0 - 2.5%



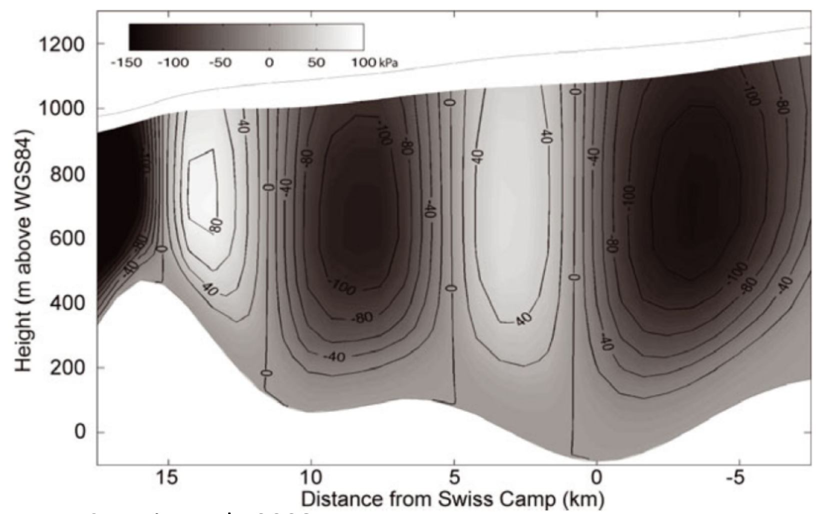
Surface water can penetrate cold ice through hydrofracturing that warms the ice at depth and creates passageways (moulins) for the infiltration of water to the bed

Allianz



Spatial pattern of englacial pathways may control subglacial hydrology.

Conversely uphill flow of subglacial water can close pathways forcing water to flow through cracks in the ice.



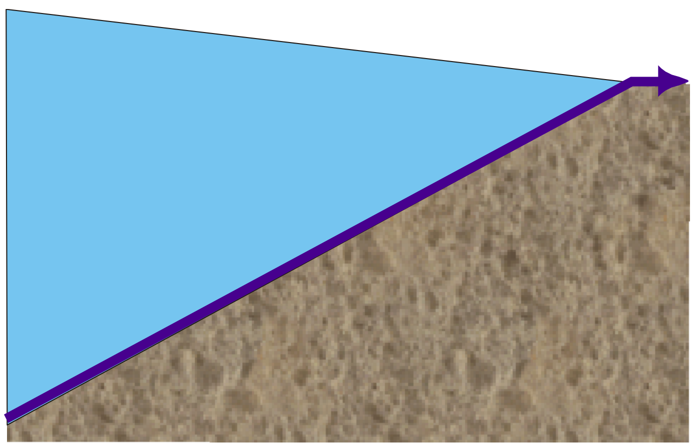
Catania et al., 2008

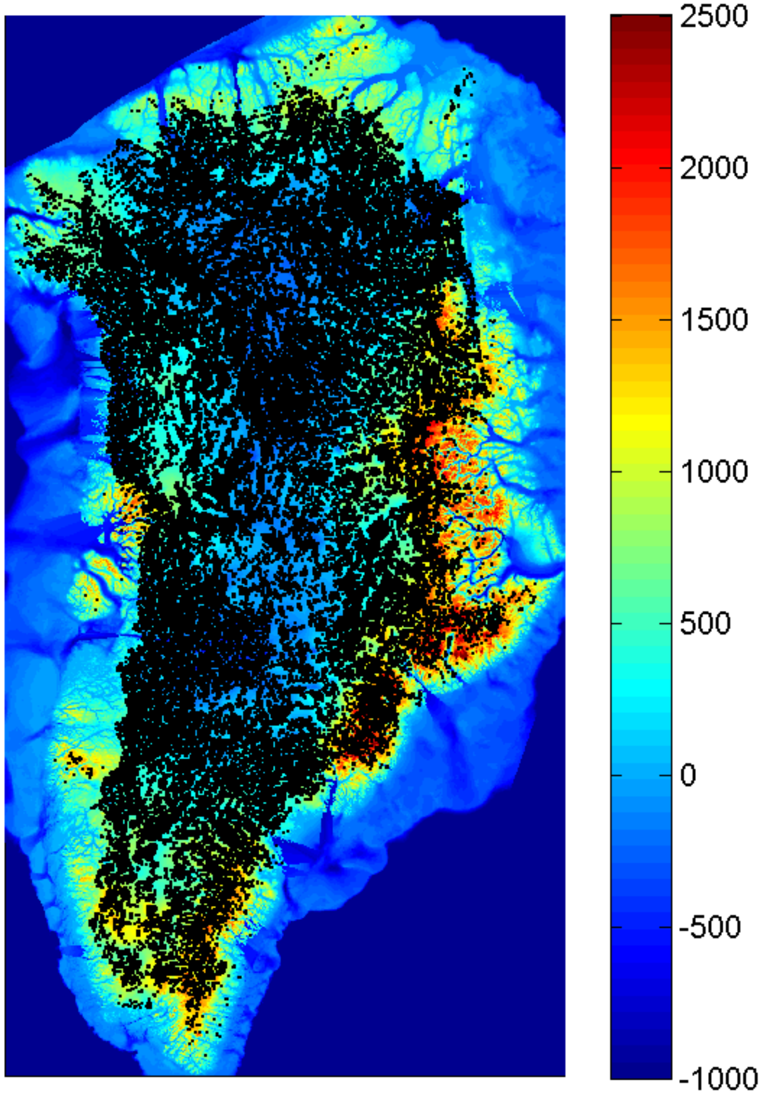
Supercooling: a mechanism of forcing water upward

Gives a ratio that is a combination of constants:

$$\mathcal{R} = -\frac{\left(1 + \beta c_p^{\mathrm{w}} \rho^{\mathrm{w}}\right) \rho^{\mathrm{i}}}{\rho^{\mathrm{w}} - \left(1 + \beta c_p^{\mathrm{w}} \rho^{\mathrm{w}}\right) \rho^{\mathrm{i}}} \sim -\frac{\tan \alpha^{\mathrm{b}}}{\tan \alpha^{\mathrm{r}}}$$

Supercooling criterion: Bed slopes must be < -1.7 to -2.2 times the surface slope for supercooling to occur

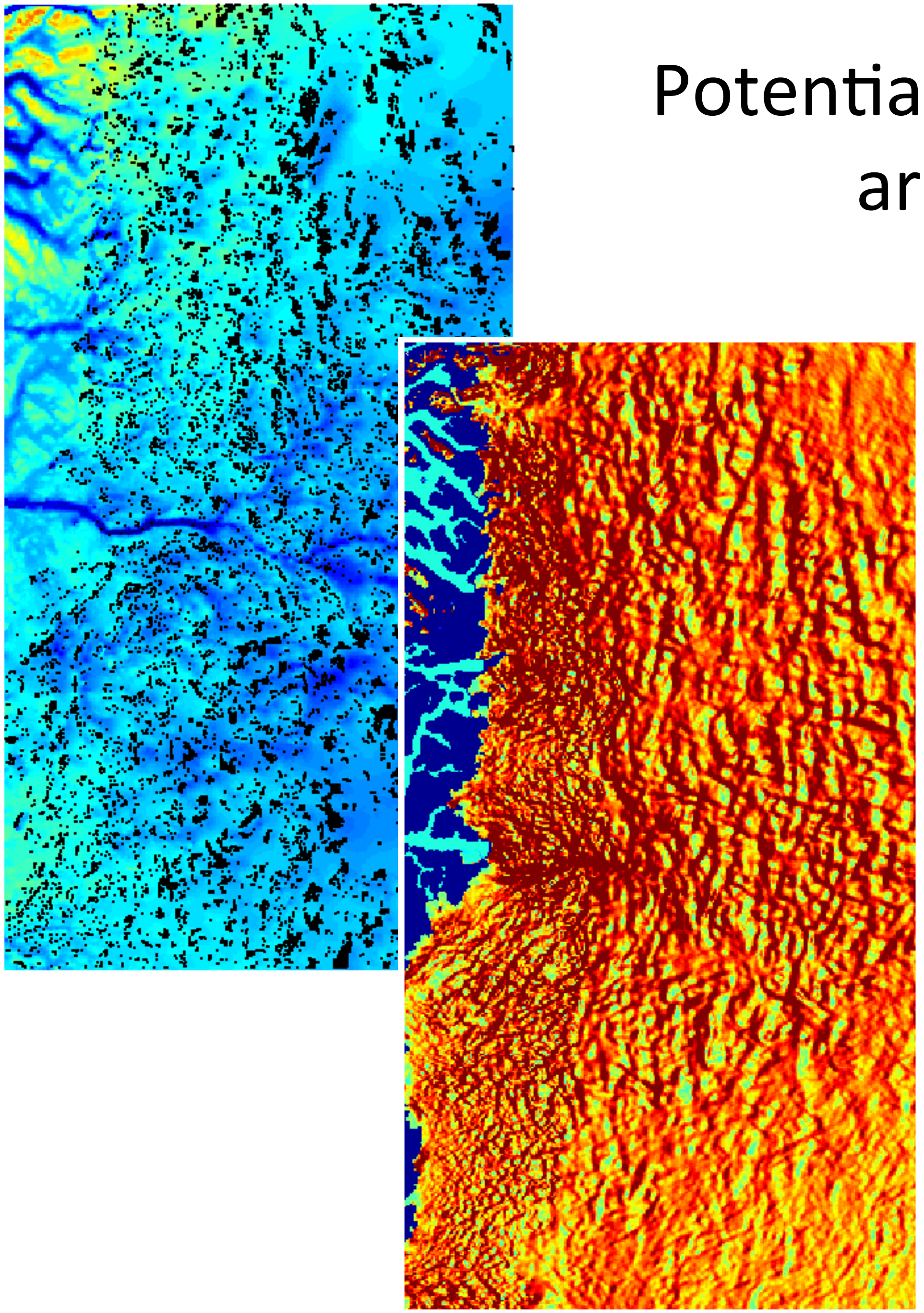




Potential supercooling locations across Greenland

- Lots of potential throughout Greenland to have water move upward through an englacial aquifer
- This might mean that basal routes are not preferred (?)

Potential supercooling locations around Jakobshavn



- Very little in the throat of the glacier
- Follows the variations in driving stress
- This is a direct result of both being dependent on surface slope
- Much potential for englacial water transport near the coast

Conclusions

- The ice discharge effects of seasonal surface melt on sliding appear
- Stick-slip behavior is widespread over Greenland
- Englacial hydrology probably matters
- What do we need?
  - Measurements of drainage, including aspect ratio, distribution of water locally
  - Permeability along the bed
  - Effective pressure (?)
  - Measurements of englacial permeability
  - Fracture spacing information
  - Inferences from broad scale instruments: radar, satellites, etc.

Thanks!

- This talk has benefitted from conversations with: Ian Hewitt, Winnie Chu, Mike Wolovick, Christian Schoof, Robin Bell, & Prasad Gogienini
- Funding through NSF-OPP
- Happy Birthday Mom!