Subglacial soft matter

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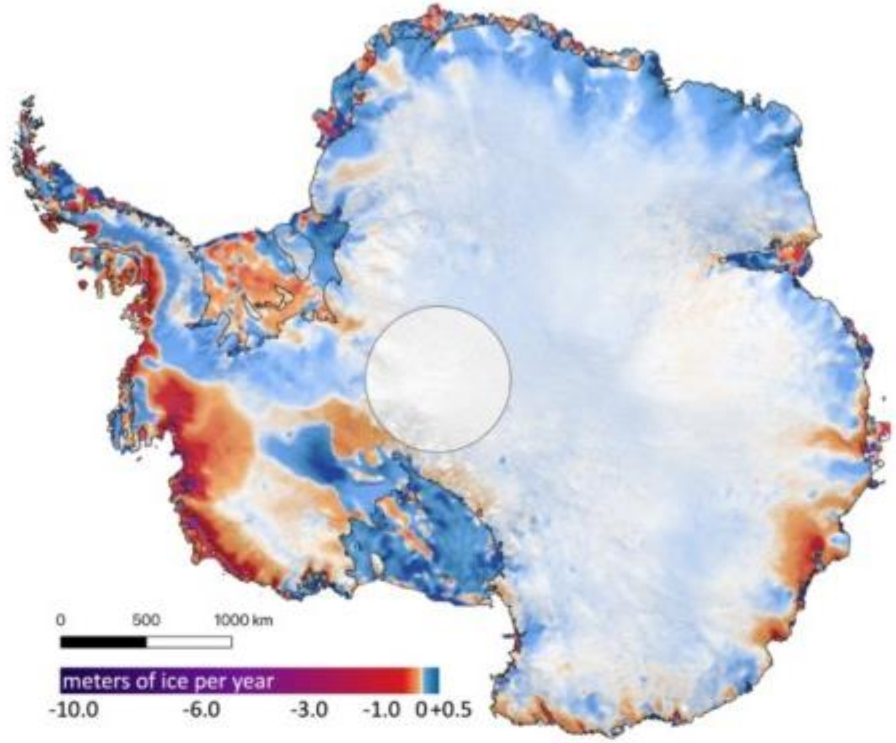
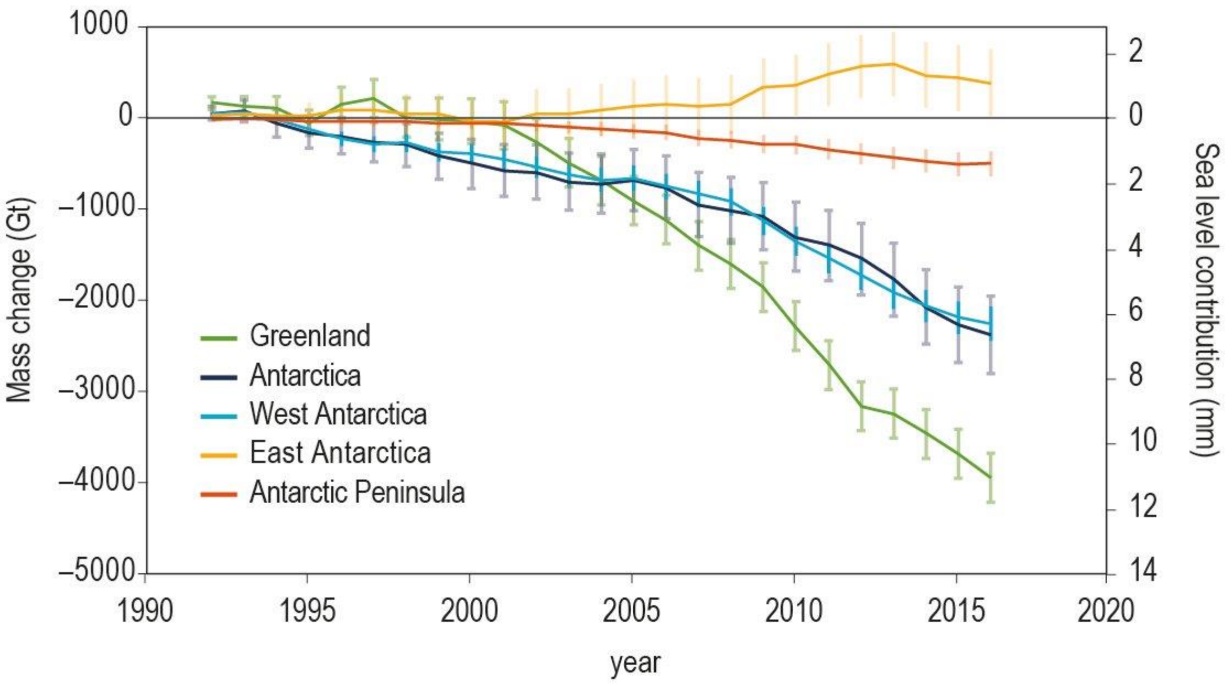
Motivation: understanding ice sheets

"The ice sheets on Greenland and Antarctica contain most of the fresh water on the Earth's surface. As a consequence, they have the greatest potential to cause changes in sea level."



Metres of ice lost per year since 2003
Smith et al. (2020) Science



Mass change of the Greenland and Antarctic Ice Sheets
IPCC 2019 – Special Report on Oceans and Cryosphere in a Changing Climate

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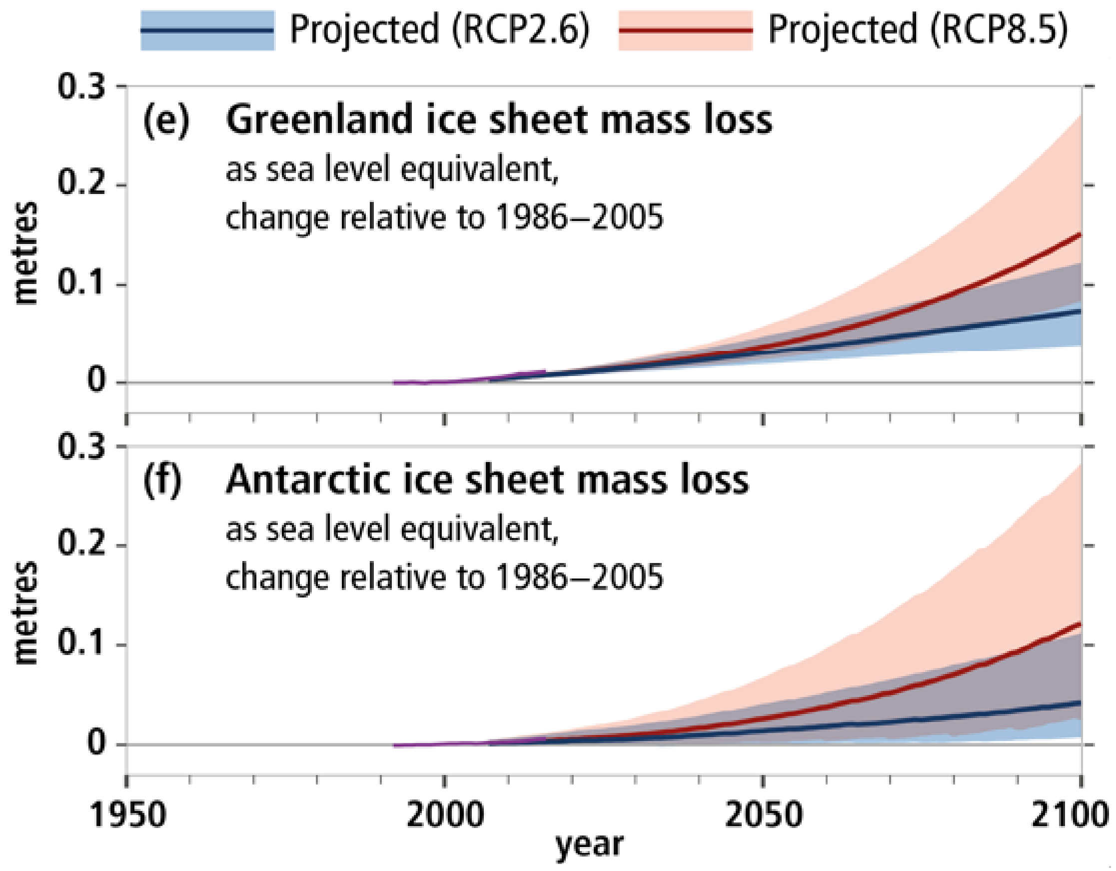
Large uncertainties

"There is a need to better understand the evolution of polar glaciers and ice sheets, and their influences on global sea level."

- IPCC 2019



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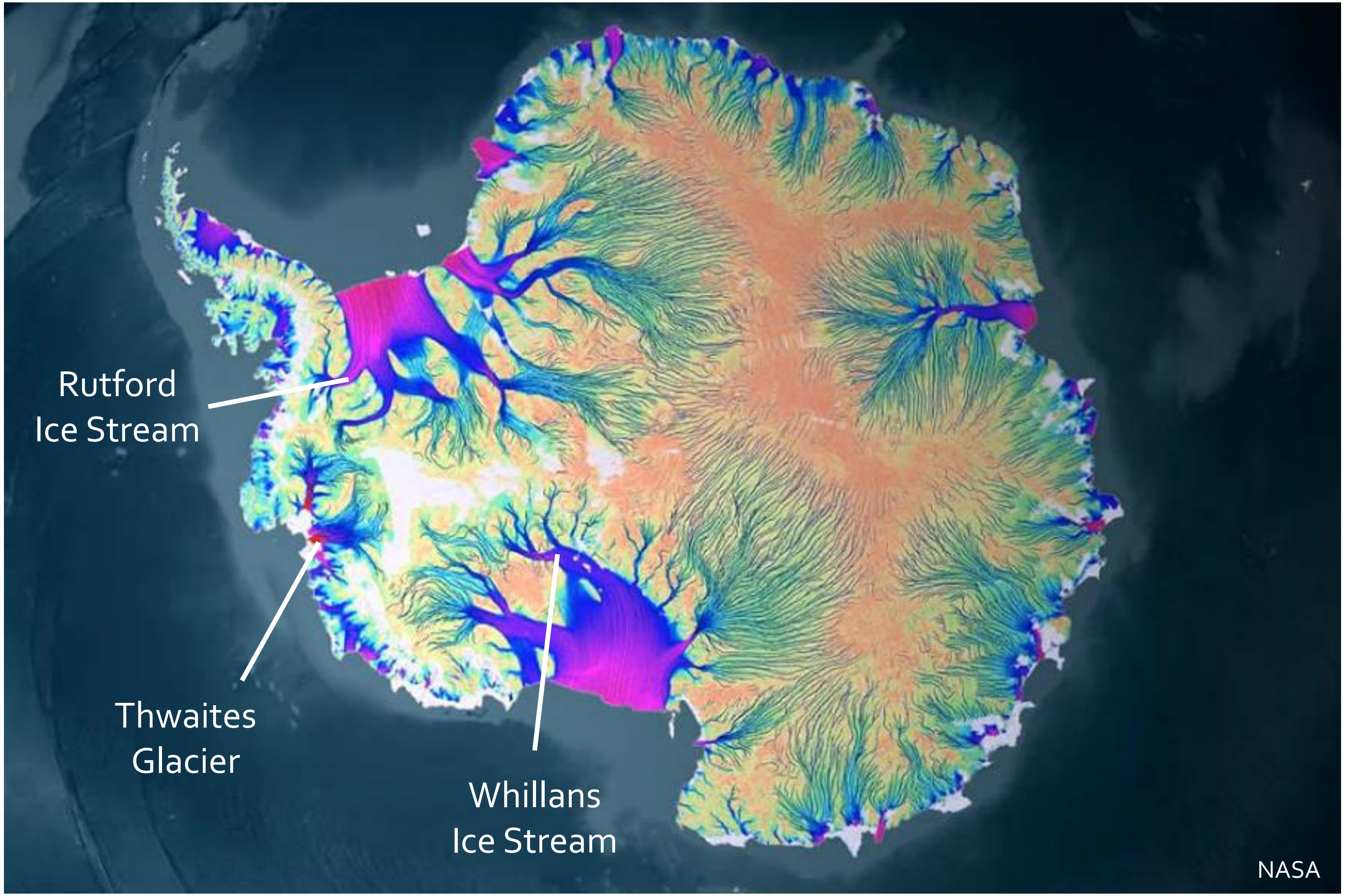
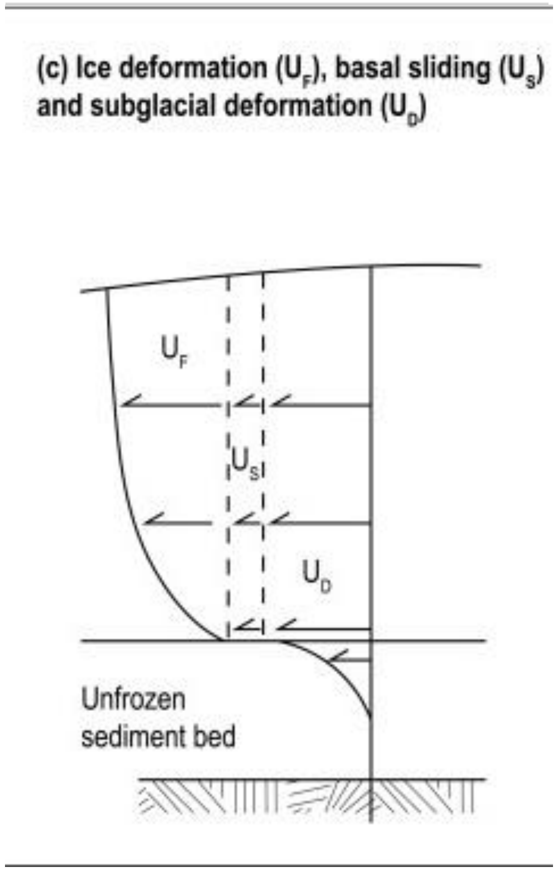
Glaciers and ice streams





From Boulton (1996)

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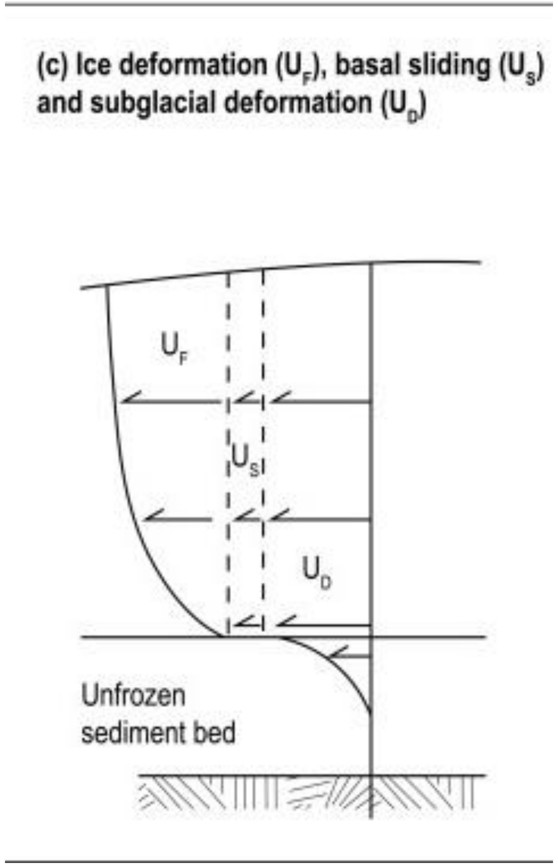
Ice sheet boundary conditions

- Huge model domain – 4500km wide
- Small scale features – detailed topography, shear bands on 1km scale
- Need to summarise sliding into a convenient function

$$u_b = f(\tau_b, N)$$

- How do we understand the dynamics sediment to translate into this functional form? What are the key parameters?



From Boulton (1996)

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Subglacial till

Some extremely large clasts

Evans et al. (2006) Earth Sci Rev

A majority of finer particles - sands, clays

Beneath ice: water-saturated (close to pressure-melting point)

Grain size	Abundance
Clays (<63µm)	~60%
Sand (63µm-2mm)	~30%
Gravel (>2mm)	~10%

Approximate grain size distribution, core samples from Western Amundsen Sea

Smith et al. (2011) Quart Sci Rev

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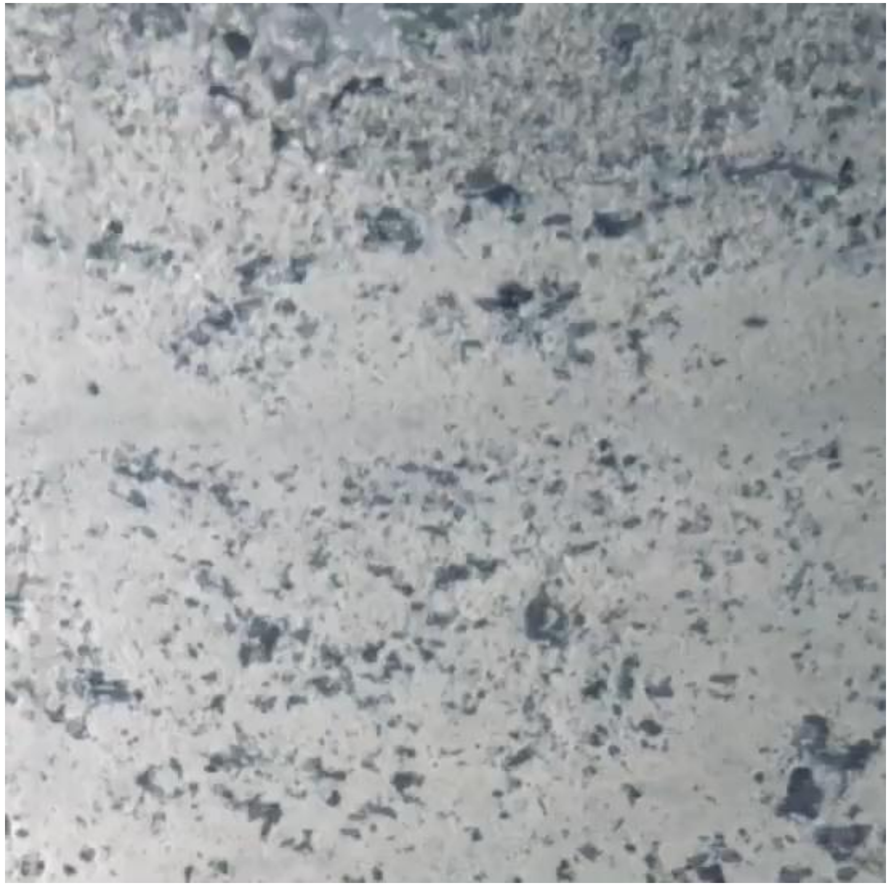
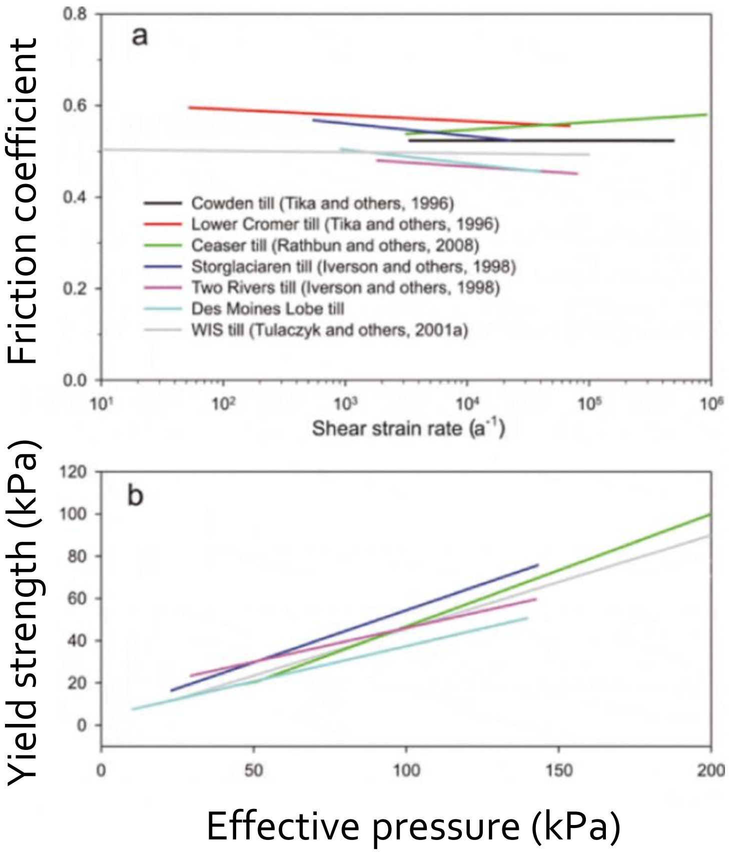
Modelling constraints

Experimental data



6 hour time-lapse of till under ice
Hansen & Zoet (2022) JGR

Challenging to recreate subglacial conditions!



Iverson (2010) J. Glac.

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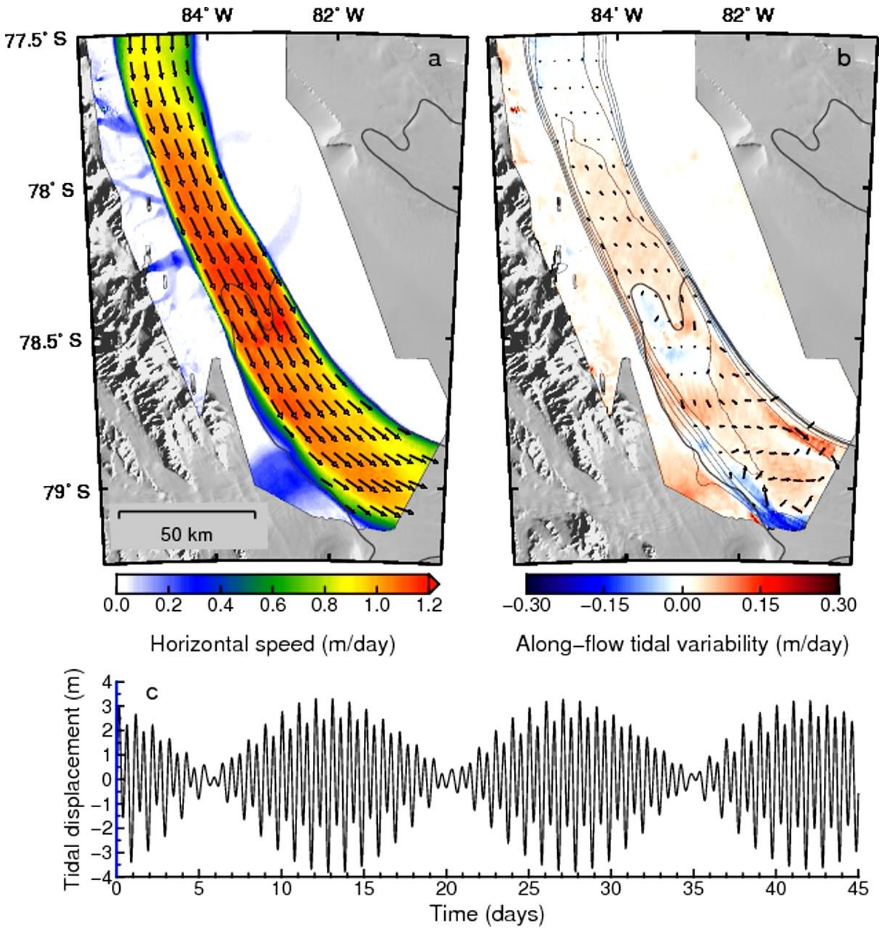
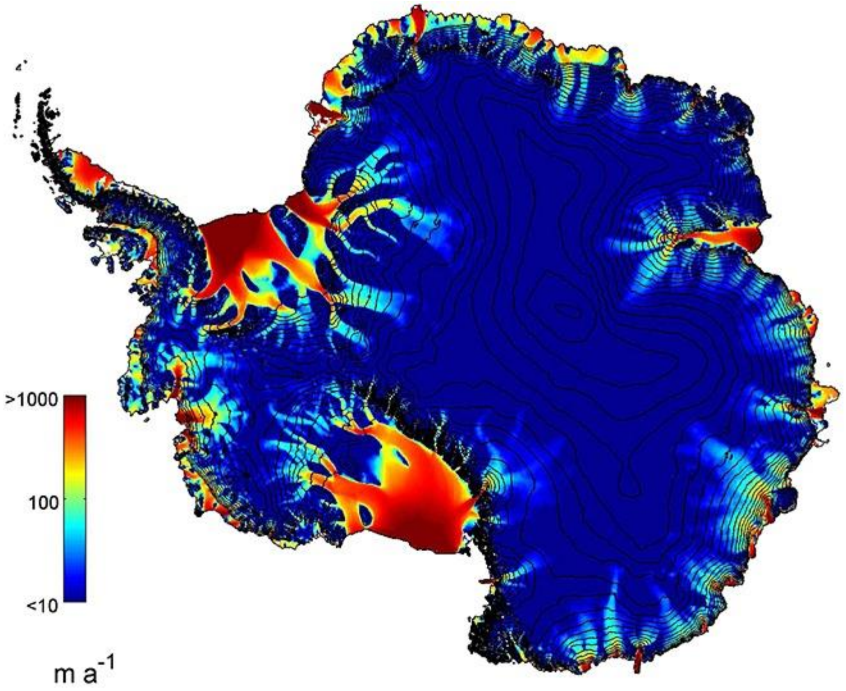
Modelling constraints

Surface velocity variations – in time and space



Tidal variation of the Rutford Ice Stream
Minchew et al. (2017) JGR



Modelled surface velocities in Antarctica
Athern et al. (2015) JGR

Other uncertainties – ice rheology, topography, etc

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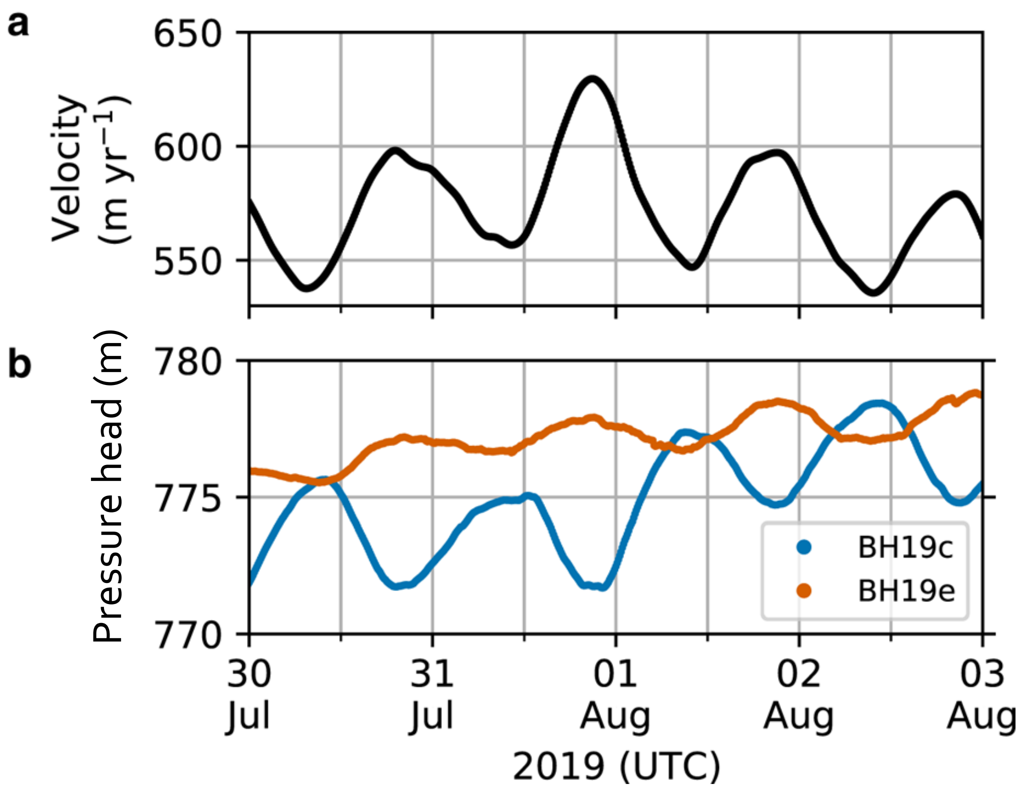
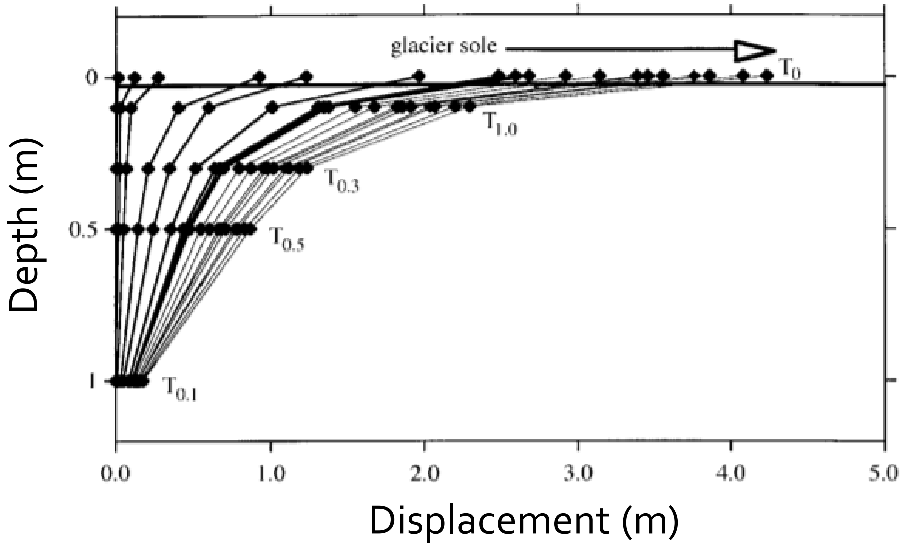
Modelling constraints

Borehole (in-situ) data



Ice surface velocity and borehole pressure head, Sermeq Kujalleq
Doyle et al. (2021) J. Glac.



Profiles of till displacement at hourly intervals, Breidamerkurjokull
Boulton & Dobbie (1998) PRSA

Spatially limited information – expensive field campaigns

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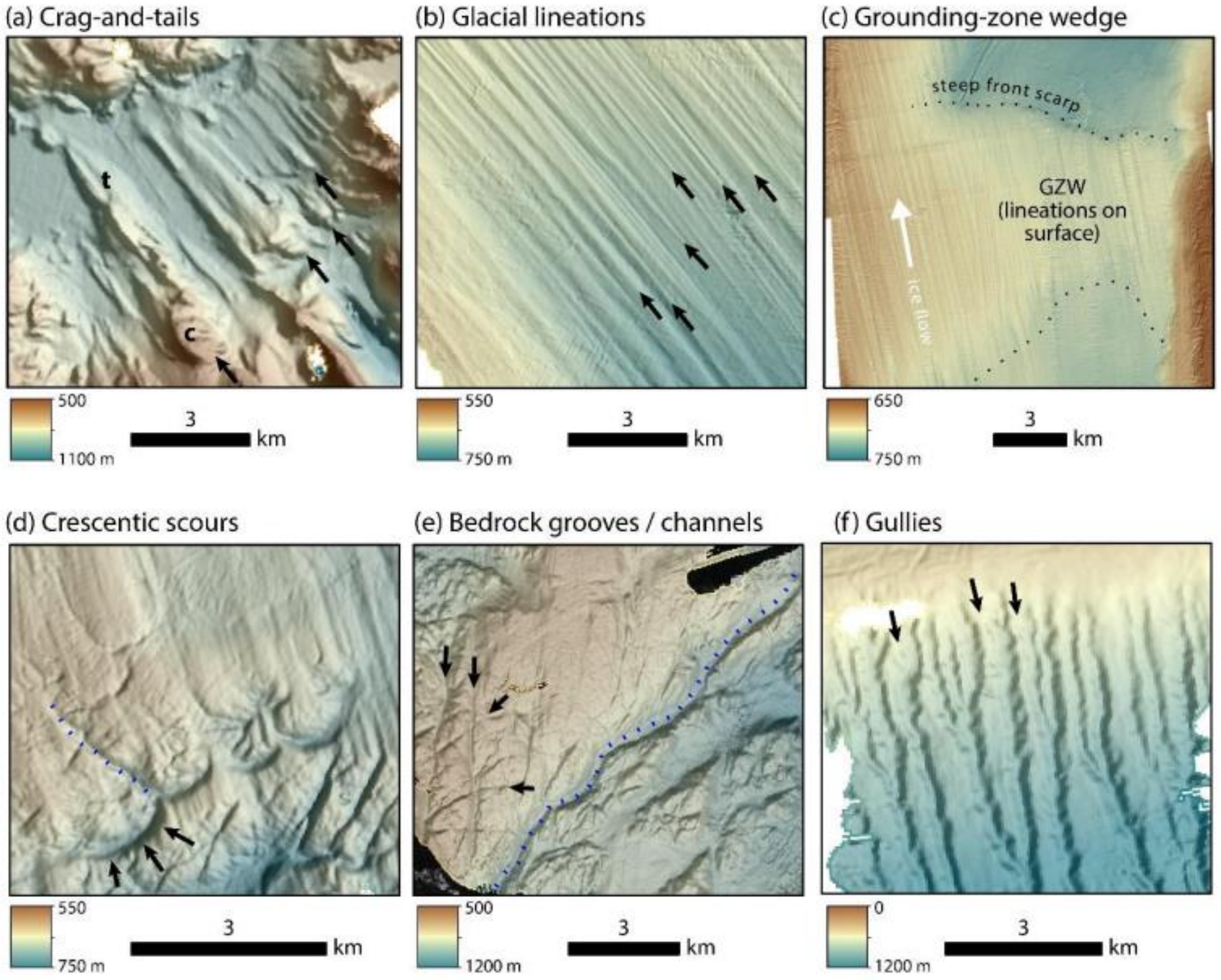
Modelling constraints

Formerly glaciated regions



Bedforms in the Amundsen Sea Embayment
Hogan et al. (2020) Cryosphere

A snapshot in time – must reconstruct ice conditions

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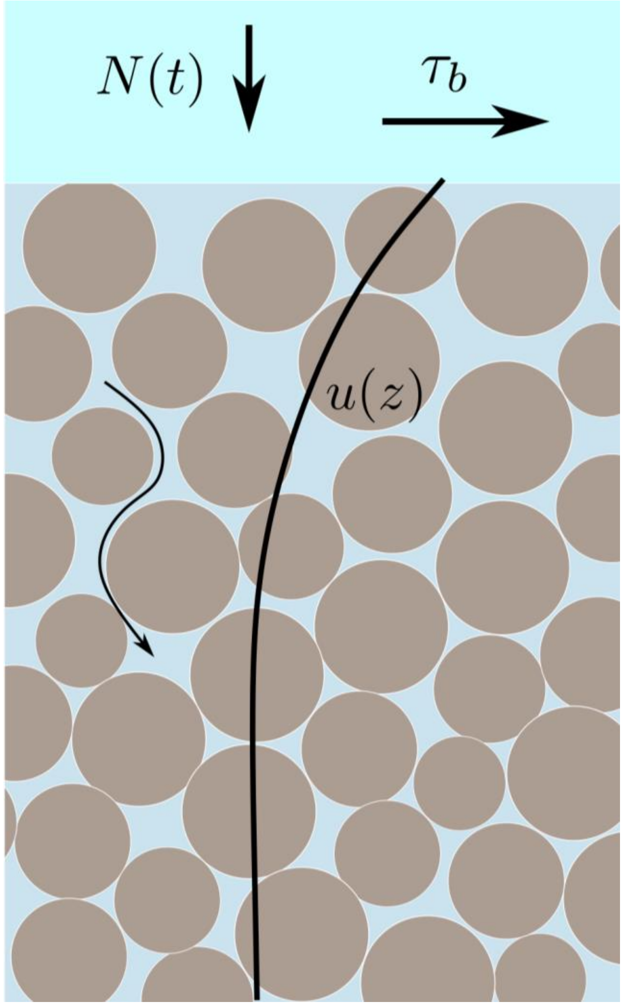
Subglacial till – a water-saturated granular material



Want to capture:

- Steady rheology
- Response to time-dependent forcing
- Flow of water through granular matrix
- Profiles of pressure, porosity, and displacement
- Continuum description

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Viscous granular rheology

- Viscous inertial number parametrises friction coefficient and solid fraction

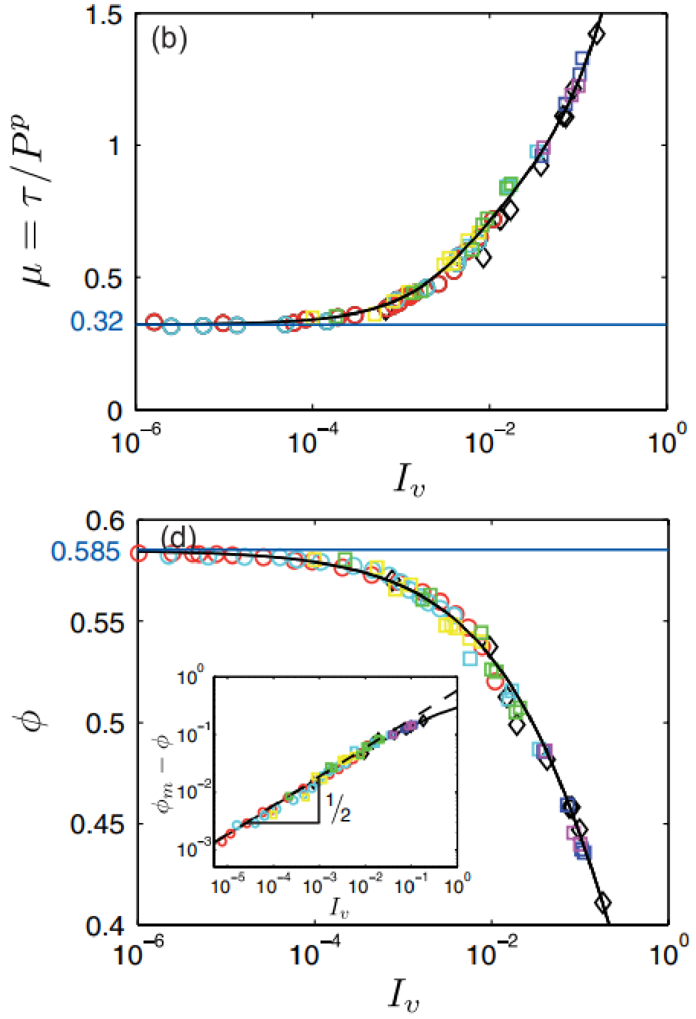
$$I_\nu = \frac{\eta\dot{\gamma}}{N}$$

- Yield stress linear in effective pressure
- Shear rate increases with shear stress above yield

$$\tau = \mu_1 N + M\sqrt{\eta\dot{\gamma}N}$$

- Solid fraction decreases with shear rate

$$\phi = \frac{\phi_m}{1 + b\sqrt{\frac{\eta\dot{\gamma}}{N}}}$$



Boyer et al. 2011 (PRL)

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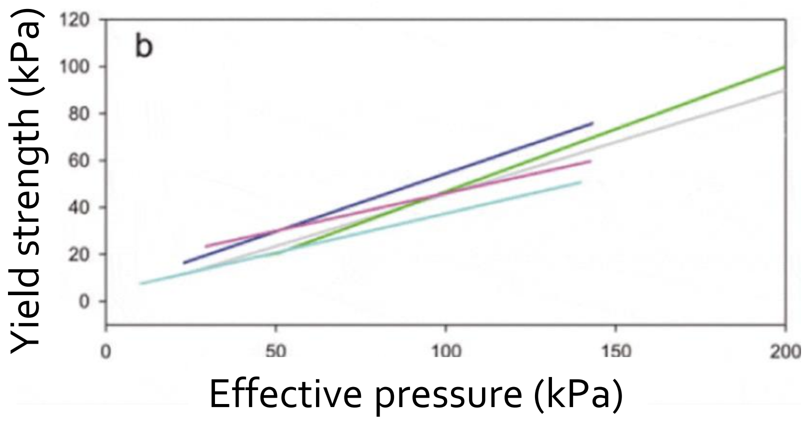
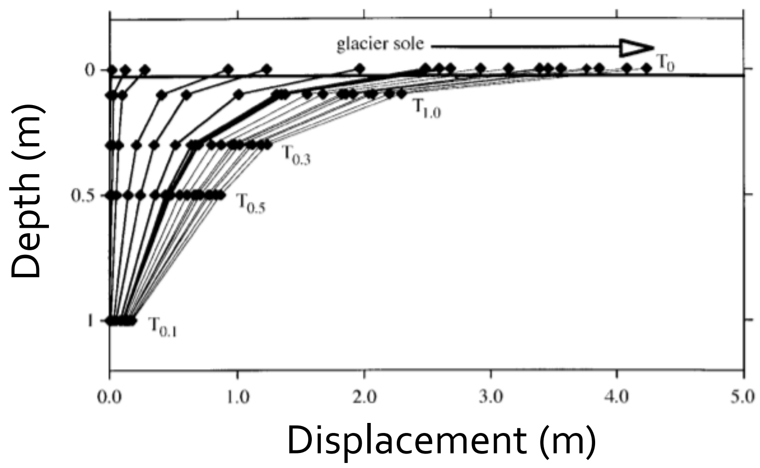
Comparison to subglacial till

- Yield stress linear in effective pressure
- Shear rate increases with shear above yield stress



Iverson (2010) J. Glac.

$$\tau = \mu_1 N + f(\dot{\gamma}, N) \implies \dot{\gamma} = F(\tau - \mu_1 N, N)$$



Boulton & Dobbie (1998) PRSA

Use depth profiles to fit rheological parameters

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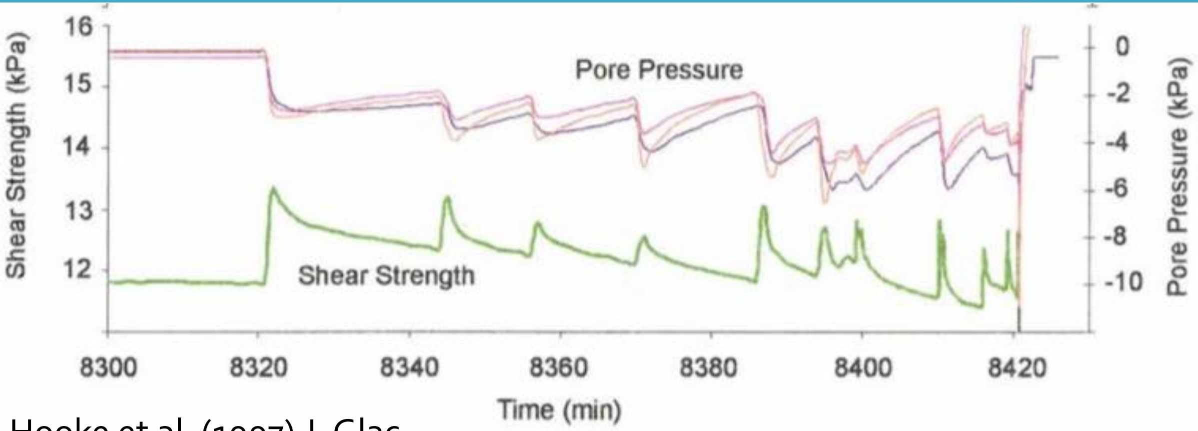
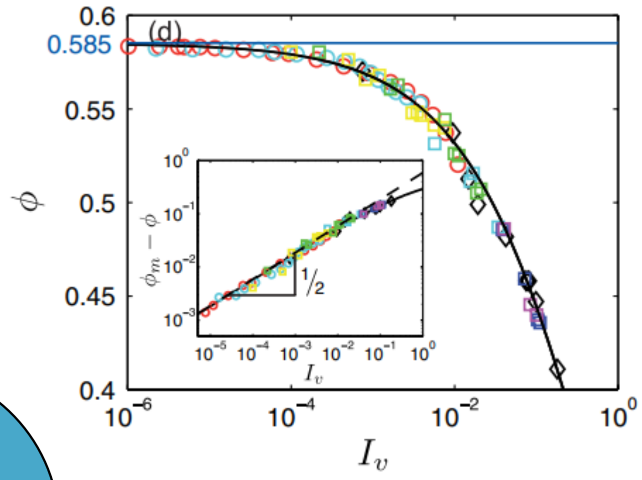
Dilatant strengthening

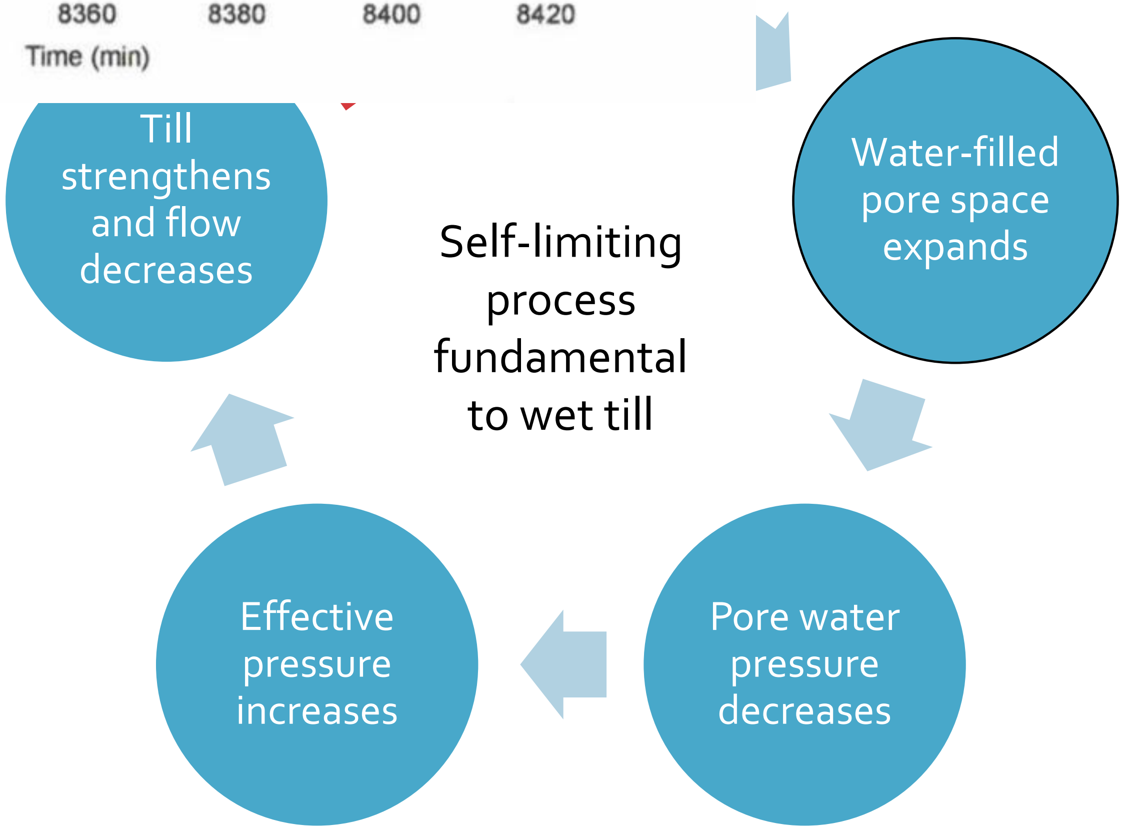


Hooke et al. (1997) J. Glac.



Boyer et al. (2011) PRL

$$\phi = \frac{\phi_m}{1 + b\sqrt{\frac{\eta\dot{\gamma}}{N}}}$$



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Modelling shear dilation

- Shear rate/effective pressure sets change in solid fraction

$$\phi = \phi(I_\nu)$$

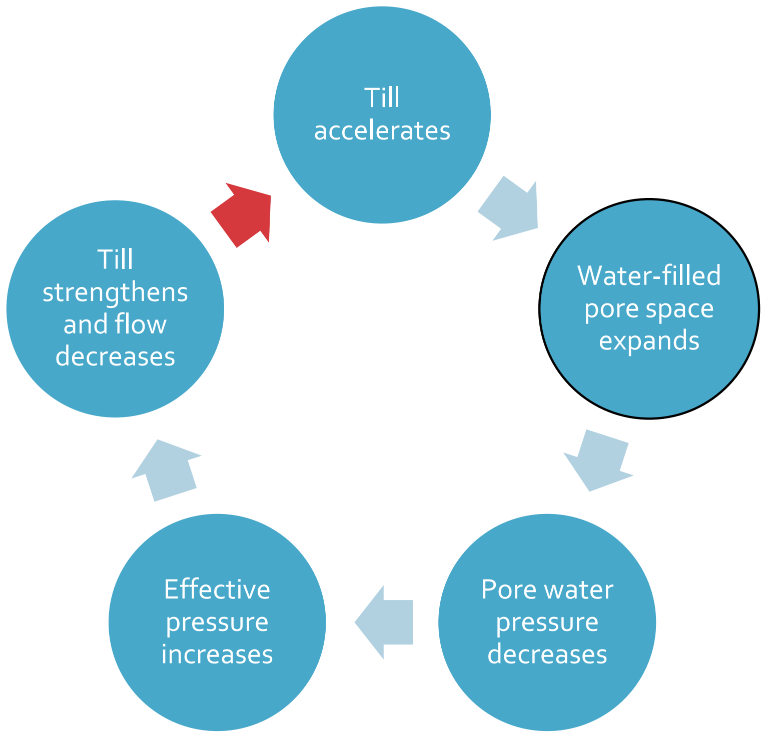
- Water flows into the changing pore space

$$\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial z}(v_s \phi) = 0$$

- Darcy's law links flow to water pressure

$$-\frac{k}{\eta(1-\phi)}\left(\frac{\partial p_w}{\partial z} - \rho_f g\right) = (v_f - v_s)$$

- Water pressure alters effective pressure and feeds back into shear rate through rheology



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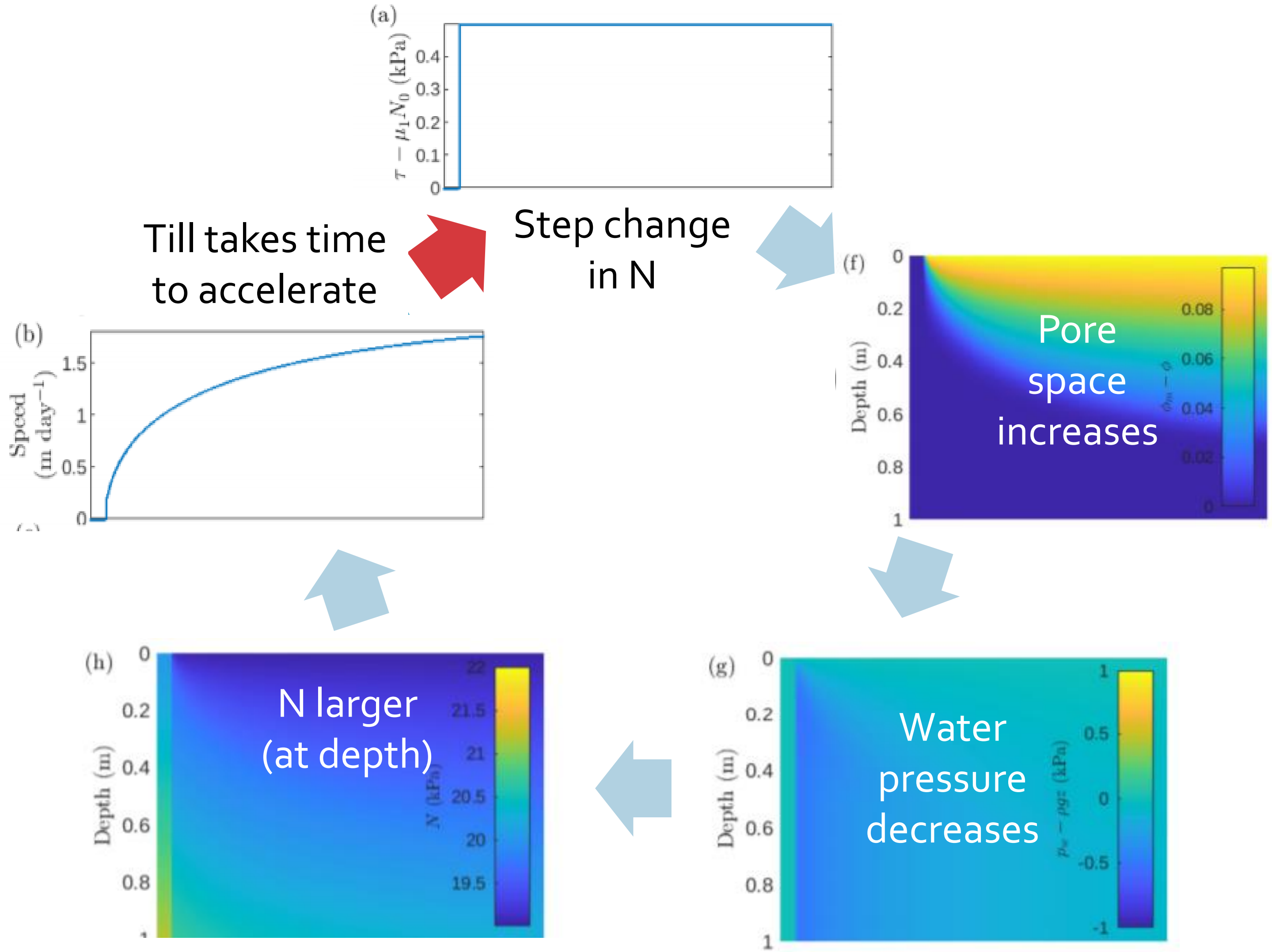
Model results



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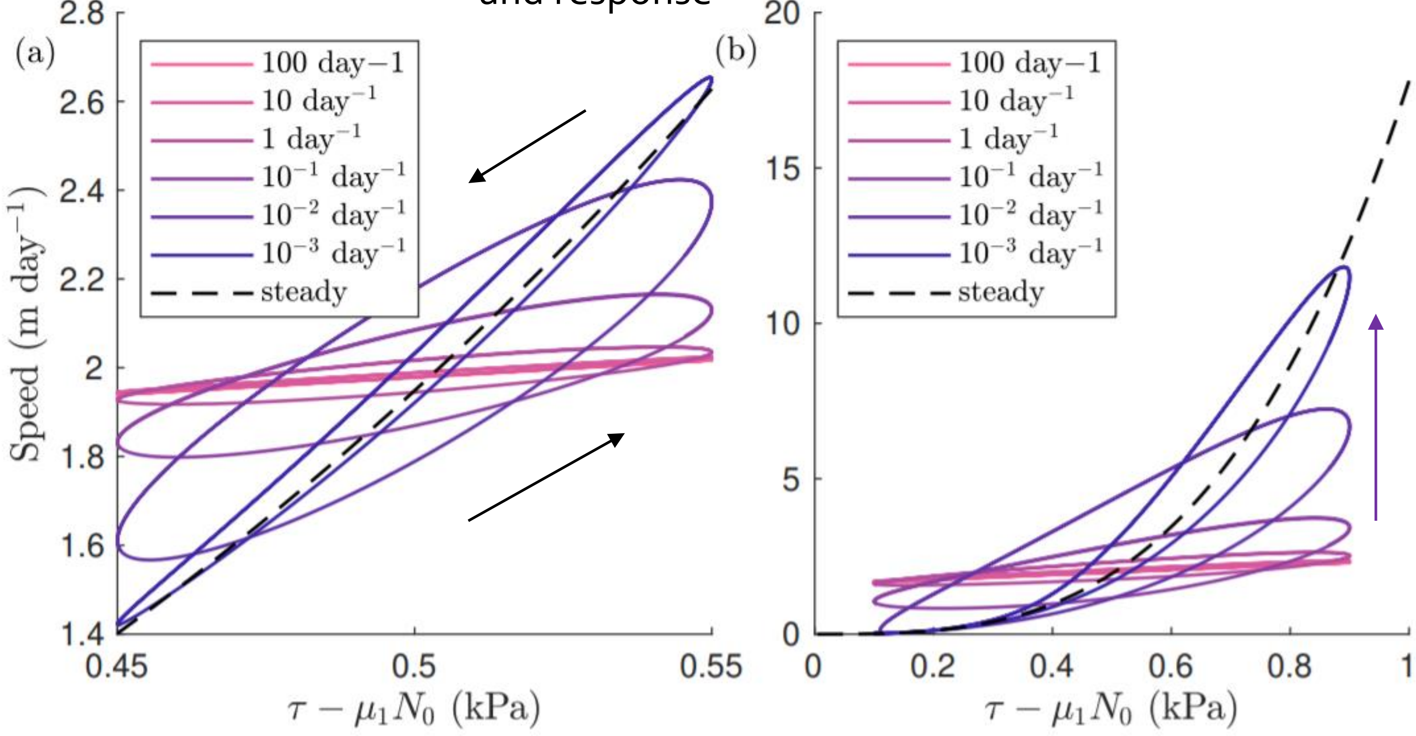
Response to periodic forcing

Lag between forcing and response



Small pressure fluctuations

Large pressure fluctuations

Induced water pressures equilibrate over time

Obtain a time-dependent sliding law (small amplitude case is diffusional)

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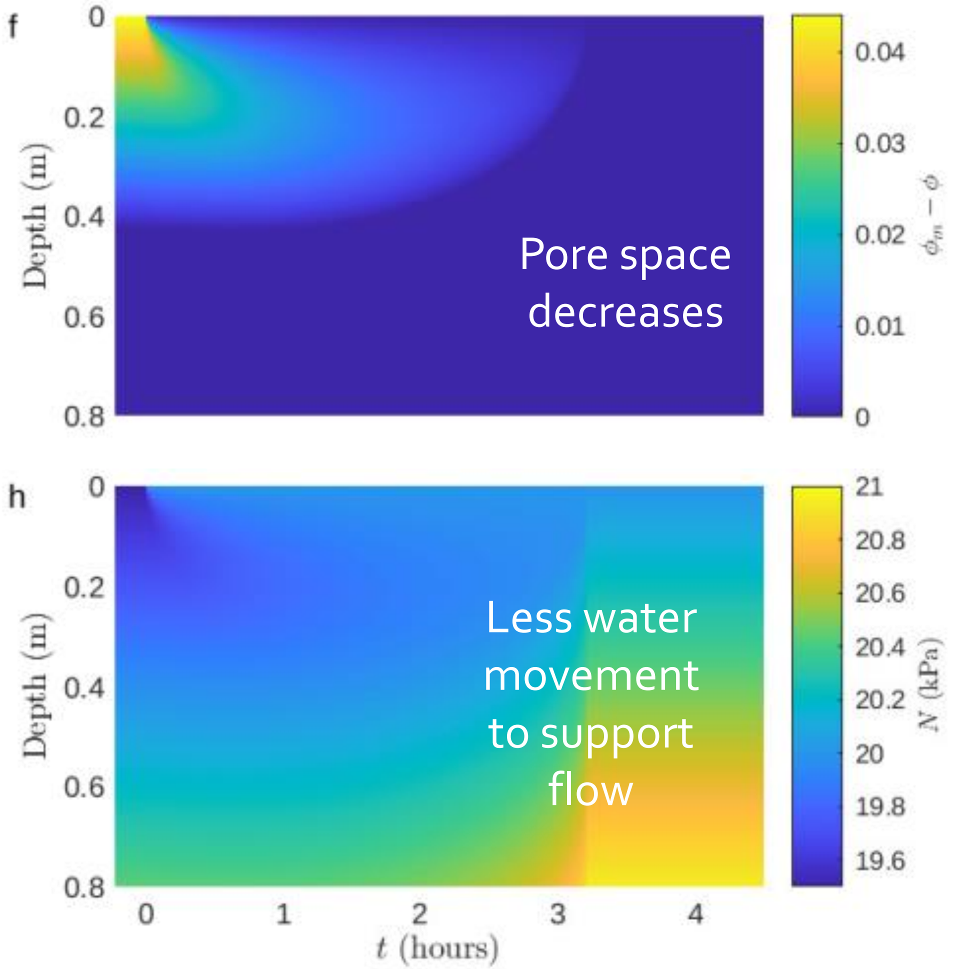
Jamming under compaction

- Compaction drives water out of pore space
- Higher water pressure, lower N
- Initially flow sustained near constant rate

- Shutdown happens rapidly
- Complex pattern of behaviour from simple forcing



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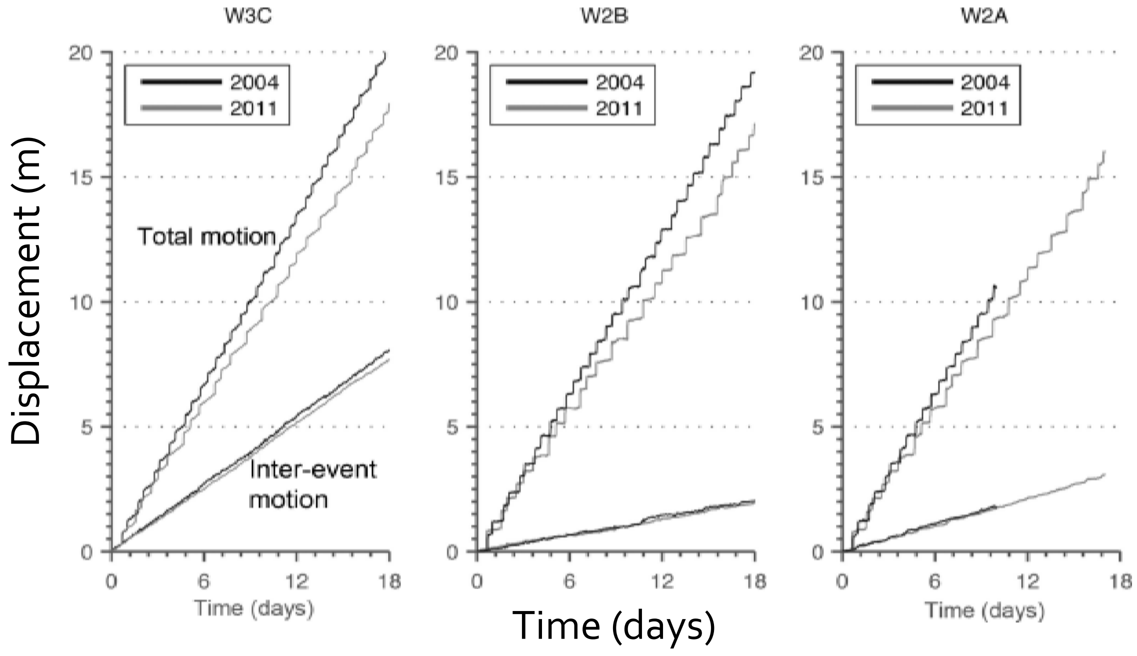
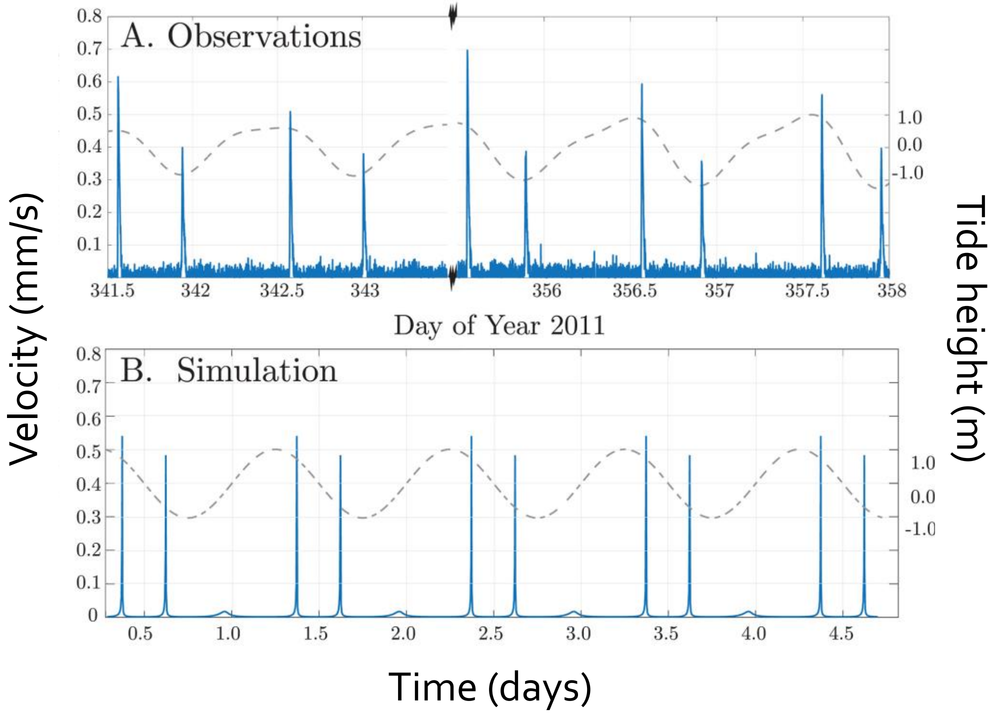
Slip-stick motion at Whillans

- ~30 mins of rapid motion per day
- Elasticity of both grain contacts and ice may play a role
- Modelling very sensitive to mean effective pressure – potential for sudden ice stream speed-up



Tidally-paced slip-stick motion of the Whillans Ice Stream
Winbury et al. (2014) J.Glac.



Rate-and-state modelling
Lipovsky & Dunham (2017) JGR

"A fundamental question arising out of our work is what physical processes are responsible for [this] behavior"

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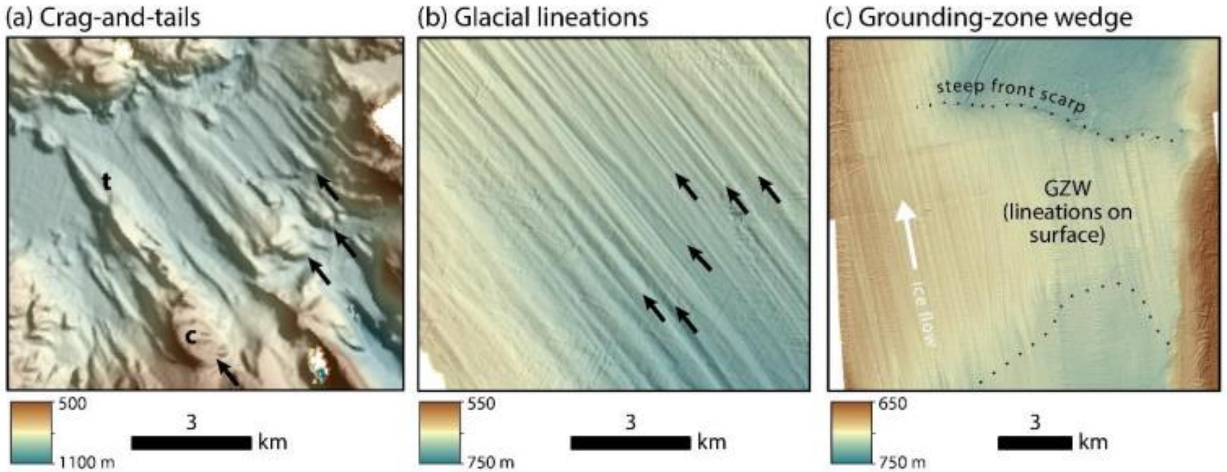
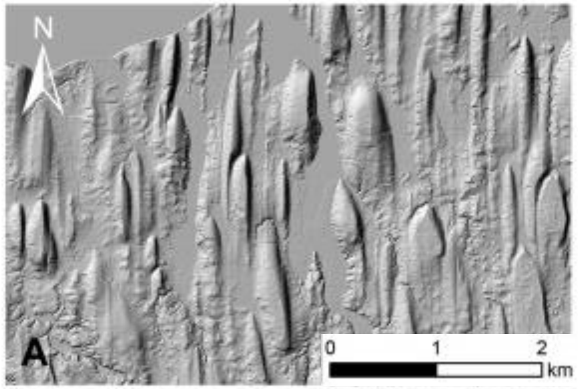
Erosion and bedforms

- Relatively* accessible record of past deformation and till transport
- Beginning to get corresponding record from present-day glaciers (radar etc)
- Quantitative test of till deformation models
    - Wide range of different patterns (flow aligned and cross-flow)
    - Strong wavelength selection



Hogan et al.(2020) Cryosphere



Drumlins
Sookhan et al. (2021) Q. Sci Rev

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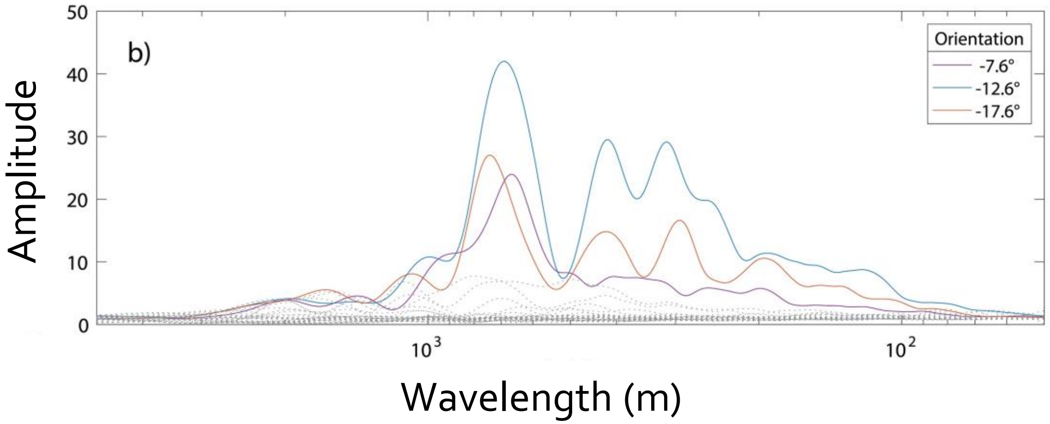
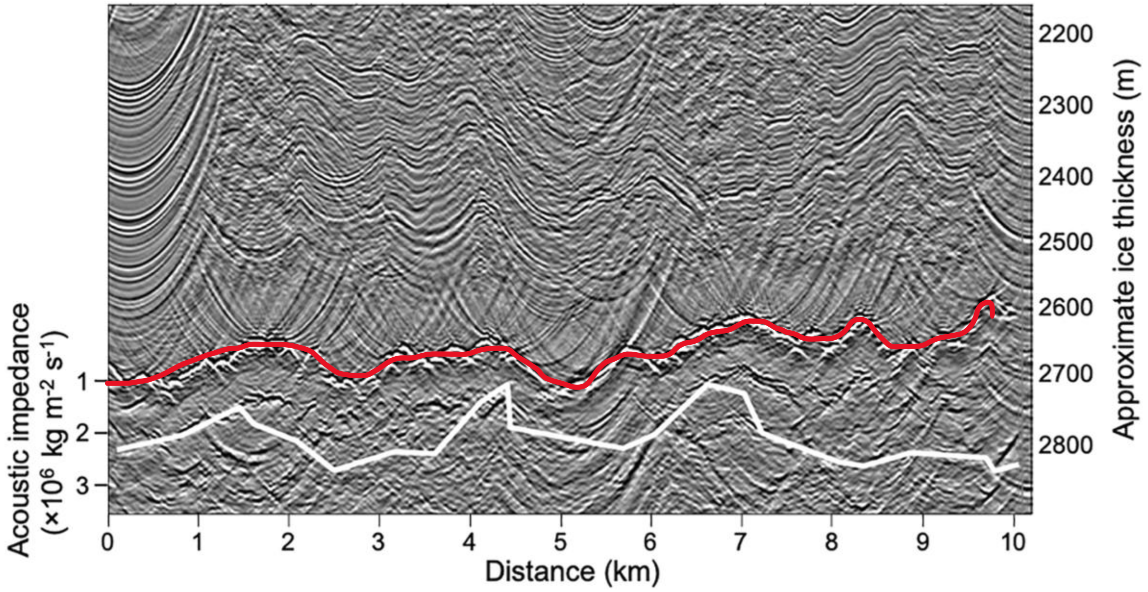
Water flow and till erosion

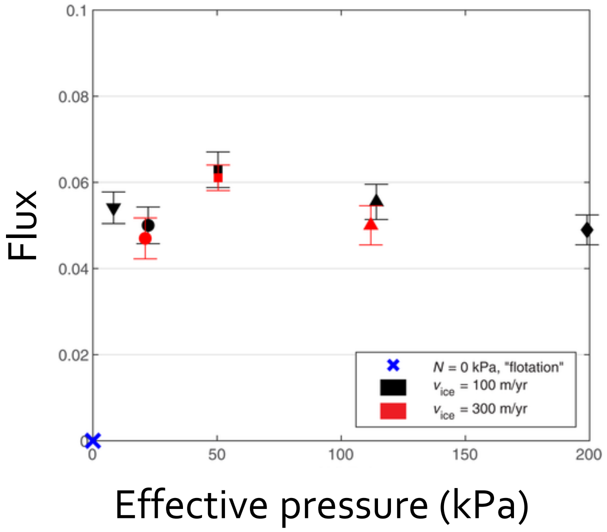
- How do mega-scale lineations form?
- New hydrology data from below active ice streams



Clear wavelength – instability mechanism?
Spagnolo et al. (2017) JGR



Crests appear to be a wetter or softer material
Muto et al. (2019) EPSL



Sediment flux can be non-monotonic in effective pressure
Hansen & Zoet (2022) JGR

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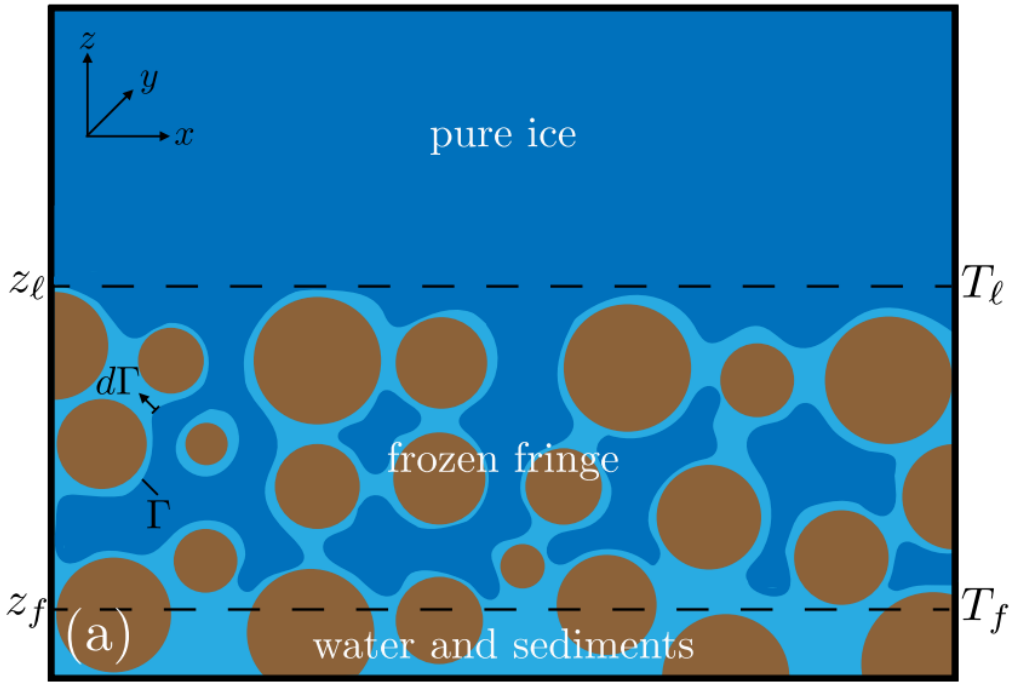
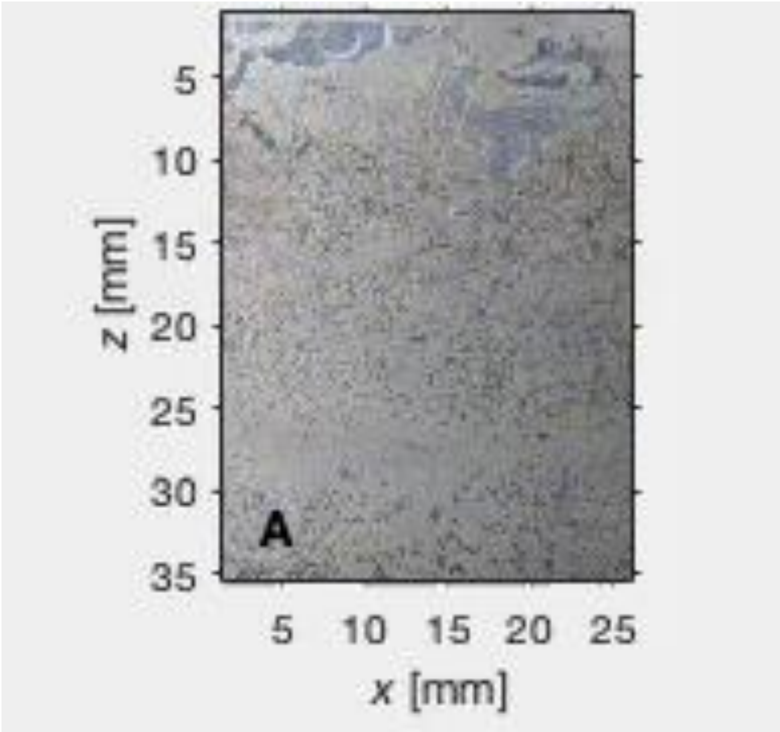
Phase change within till

Where is the bed of an ice stream?

The ice-till interface is not a simple region



Model for frozen fringe depth in static sediment
Meyer et al. (2019) EPSL



Fringe growth in ring shear device
Hansen & Zoet (2022) JGR

Frozen fringe influences bed strength, permeability, sediment transport

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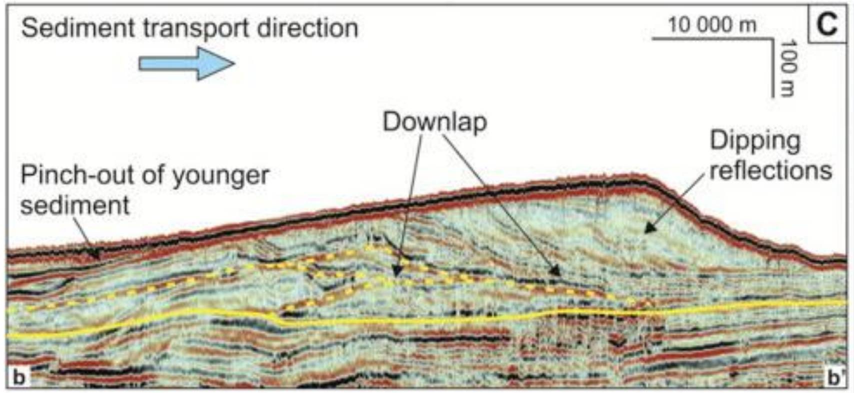
Feedback between bed and ice

- Classical result: ice sheets are unstable to runaway retreat
- Topographic pinning – drag reduces ice flux and thinning
- Till transport towards grounding line develops into a wedge
- Wedge may help to stabilise ice – depending on strength

Viscous model of wedge formation
Kowal and Worster (2020) JFM



Internal structure of a grounding zone wedge
Batchelor & Dowdeswell (2015) Marine Geology

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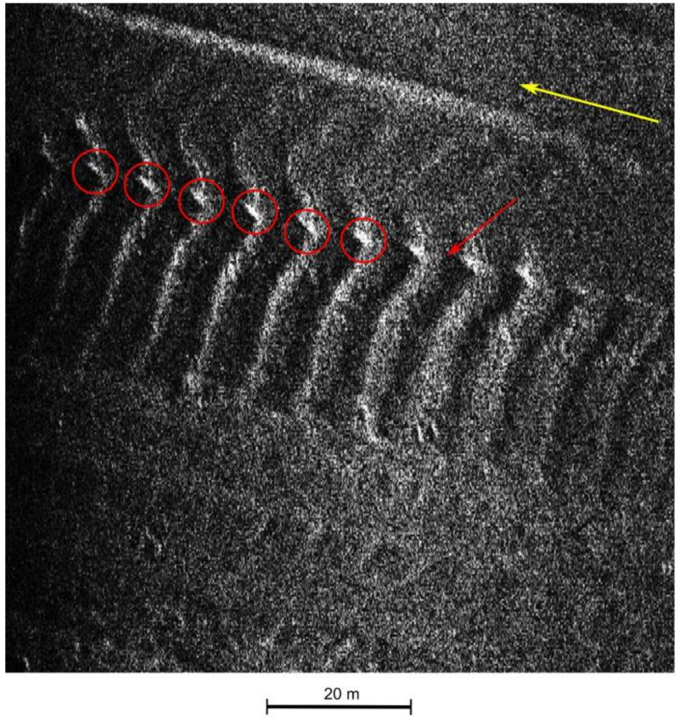
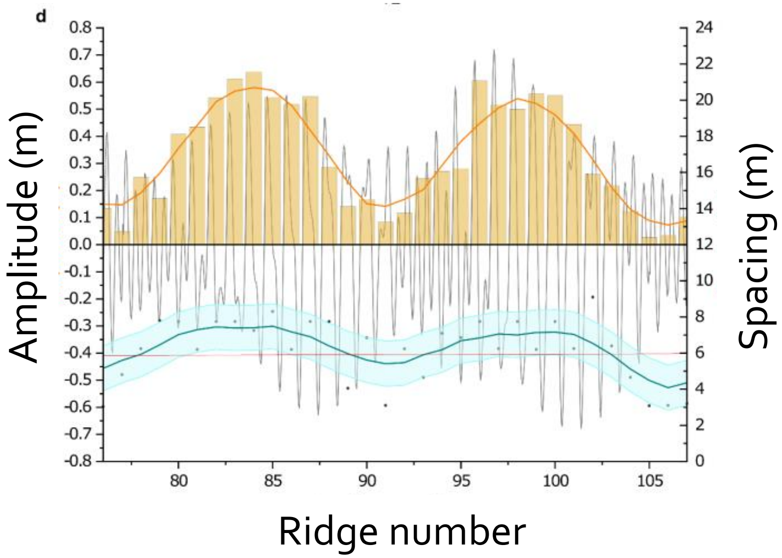
Tidal landforms



Ribbed ridges at the Thwaites grounding line
Graham et al. (2022) Nature Geosci.

Ongoing modelling work with Kelly Hogan (BAS) and Ali Graham (USF)

- Apparent signature of extremely rapid tidally-modulated ice sheet retreat
- Formation mechanism – how do we think about sediment behaviour on these timescales
    - Erosion (dunes)?
    - Deposition (grounding zone wedges)?
    - Extrusion (footprints, moraines)?



Tiny structures – 6m wide, 50cm tall
14-landform periodicity to spacing and amplitude

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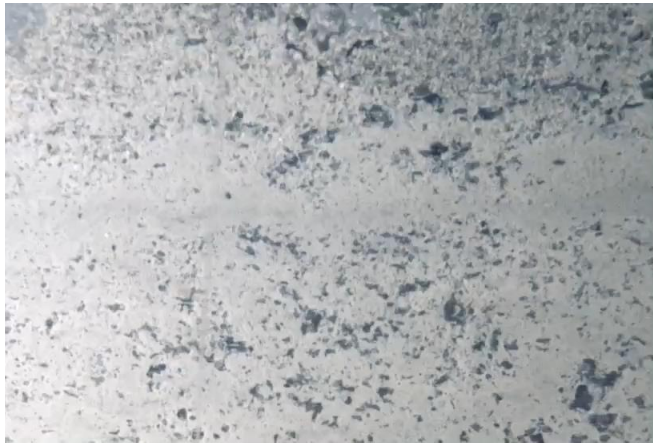
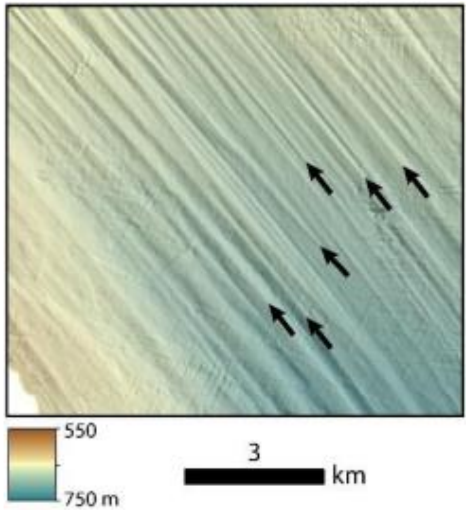
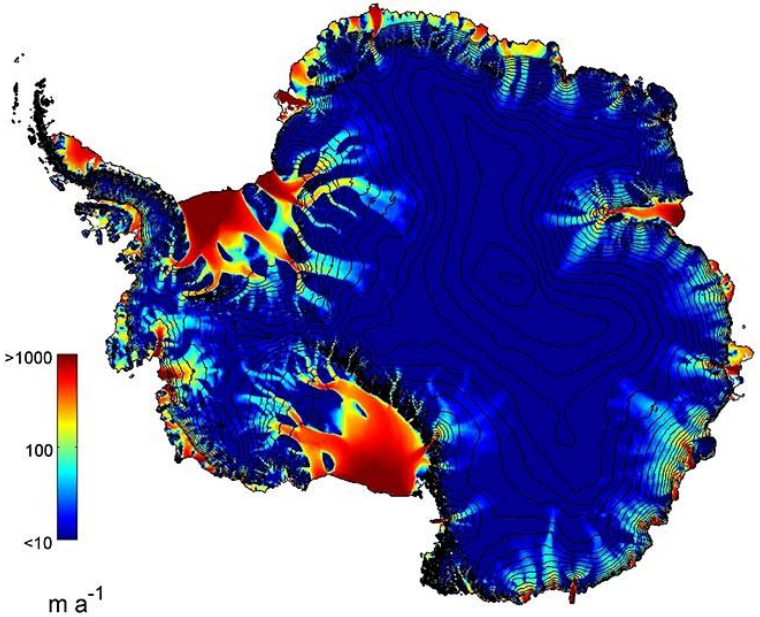
Final thoughts





With thanks to:
Jerome Neufeld, Duncan Hewitt, Brent Minchew, Ali Graham, Kelly Hogan

- Ideas from fluid dynamics/ granular flows have natural applications in glaciology
- Rapidly increasing data availability in fast-changing climate
- Important impact for understanding ice sheet futures



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