The Role of Granular Mechanics and Porous Flow for Ice Sheet Behavior in a Changing Climate

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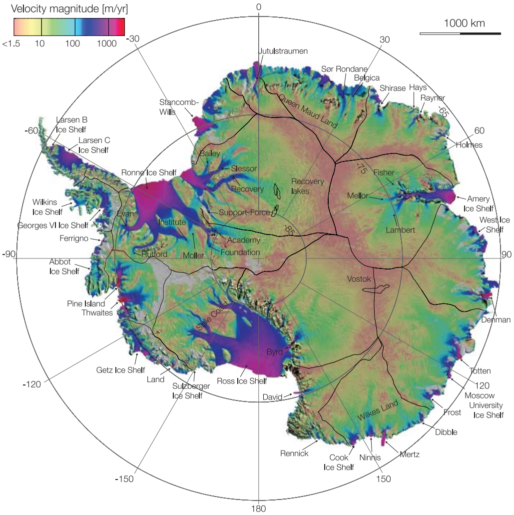
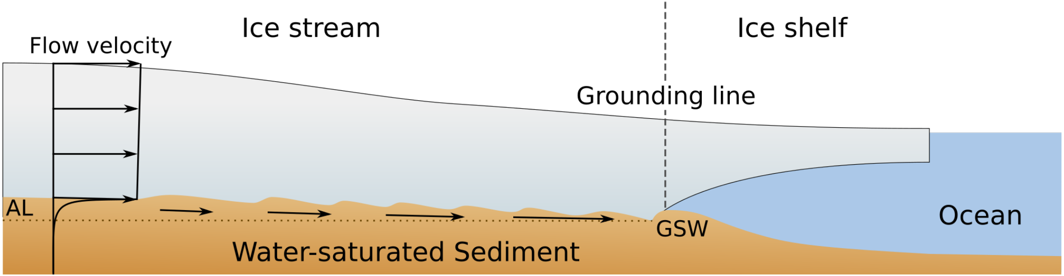
ESCO 2020: Climate MS, 2020-06-08

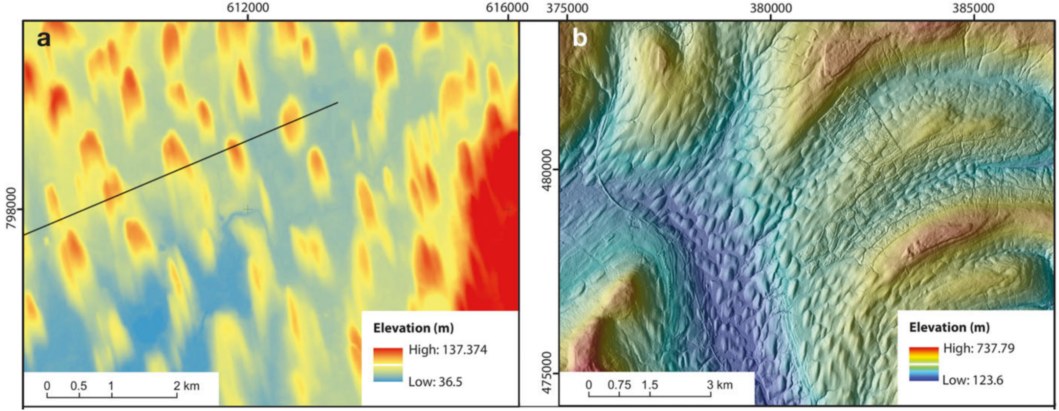


Rignot et al. 2011 *Science*

Subglacial sediment transport

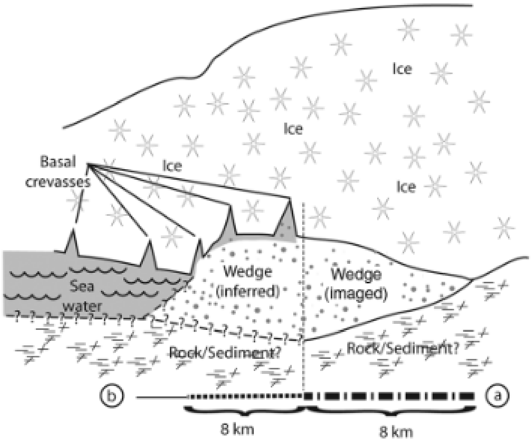


Subglacial sediment transport



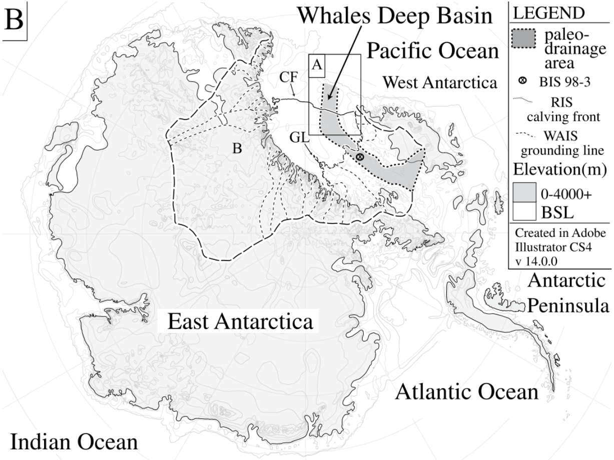
Clark et al. 2018 *Earth Surf. Process. Landforms*

Grounding-zone wedges



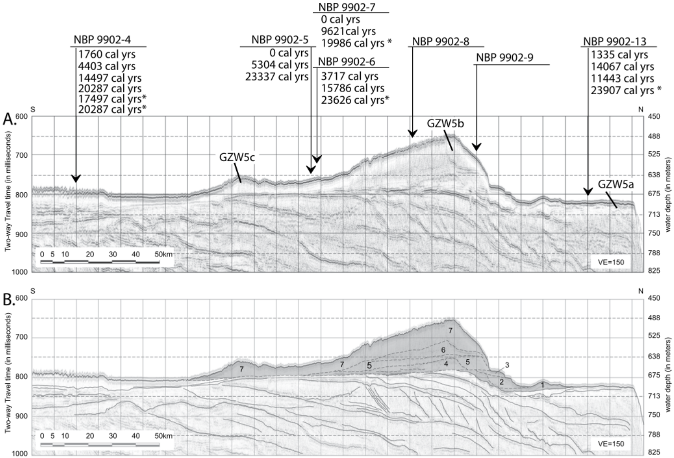
Anandakrishnan et al. 2007 *Science*

Palaeo-grounding zone wedges



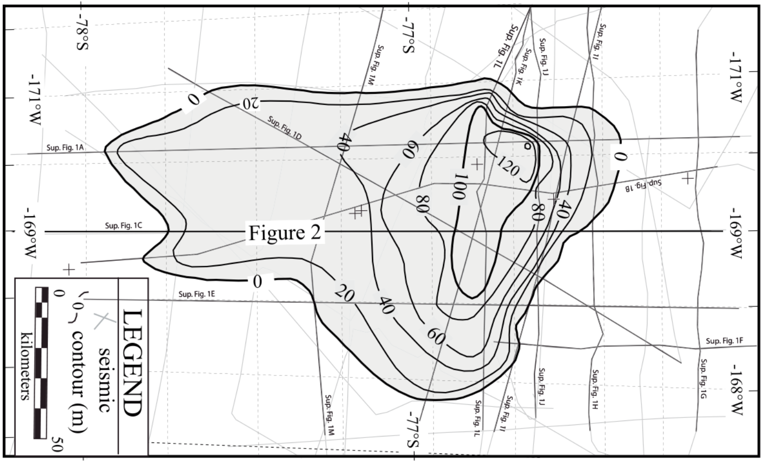
Bart et al. 2017 *Scientific Reports*

Palaeo-grounding zone wedges



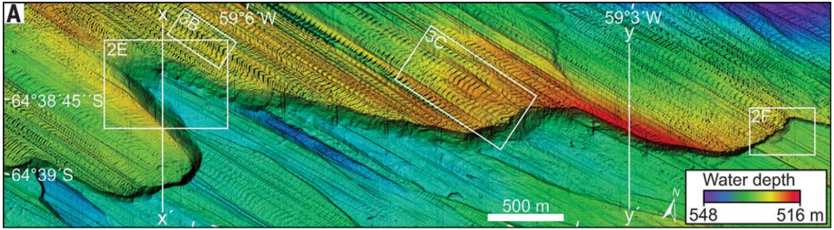
Bart et al. 2017 *Scientific Reports*

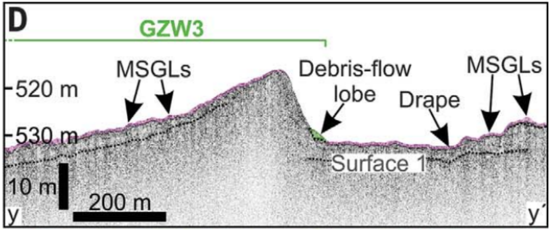
Palaeo-grounding zone wedges



Bart et al. 2017 *Scientific Reports*

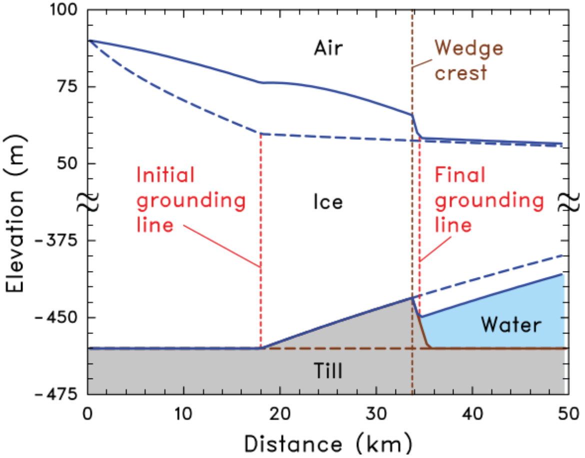
Palaeo-grounding zone wedges





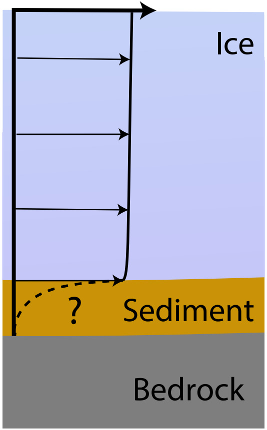
Dowdeswell et al. 2020 *Science*

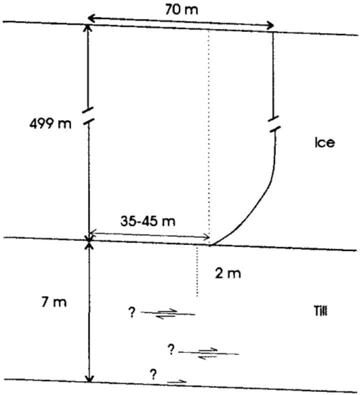
Ice-stream stabilization



Alley et al. 2007 *Science*

Subglacial sediment transport





Truffer et al. 2000 *J. Glaciol*
Truffer and Harrison 2006 *J. Glaciol*

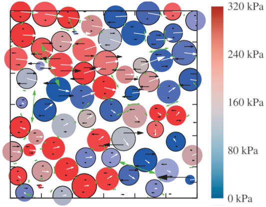
No model for till transport

$\Downarrow$

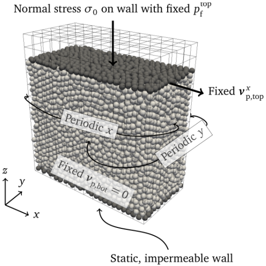
No physically-based modeling

Granular modeling

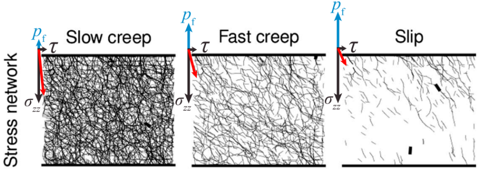
Particle-scale modeling: Discrete-element method



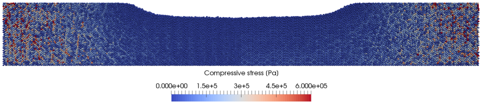
Damsgaard et al. 2013 *J. Geophys. Res.*



Damsgaard et al. 2015 *The Cryosphere*



Damsgaard et al. 2016 *Geophys. Res. Lett.*



Damsgaard et al. 2017 *J. Glaciol.*

Particle-scale modeling: Discrete-element method

sphere

`git://adamsgaard.dk/sphere`

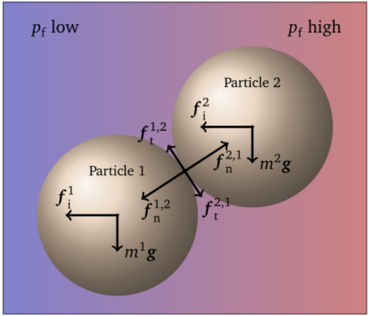
C++, Nvidia C, cmake, Python, Paraview

massively parallel, GPGPU

detailed physics and fluid-grain coupling

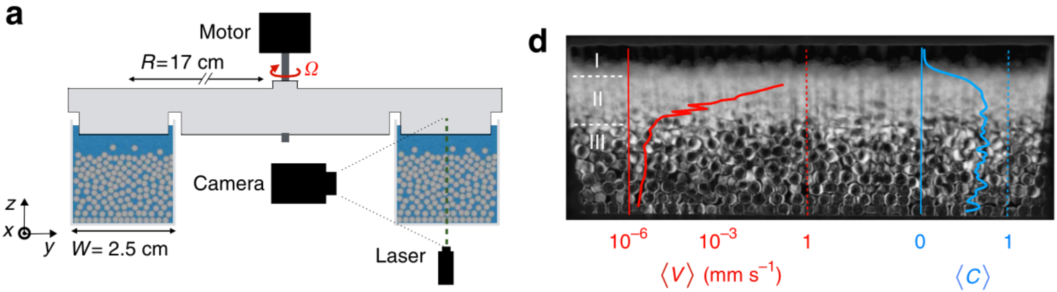
20,191 LOC

3 months on nvidia tesla k40



Continuum modeling of granular mechanics

Phase transitions in granular materials



Houssais et al. 2015 *Nat. Comm.*

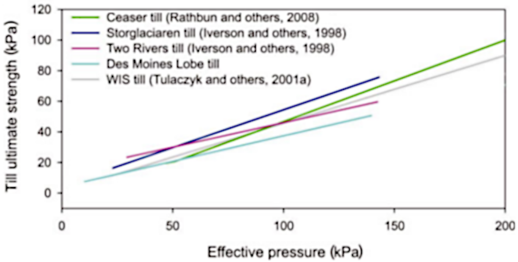
Mohr Coulomb

Charles-Augustin de Coulomb, b. 1736

Christian Otto Mohr, b. 1835

Karl von Terzaghi, b. 1883

$$\tau \leq \mu N + C$$



Iverson 2010 *J. Glaciol.*

Local rheology for dense granular flows: $\mu(I)$, $\Phi(I)$

$$I = \frac{\dot{\gamma} d}{\sqrt{N/\rho}}$$

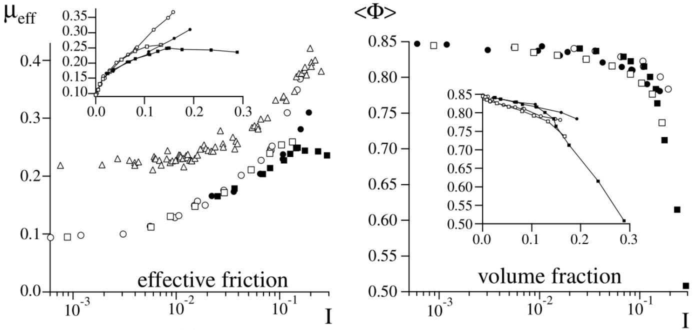
Jop et al. 2005 *J. Fluid Mech.*:

$$\tau = \mu(I) N$$

$$\mu(I) = \mu_s + \frac{\mu_2 - \mu_s}{I_0/I + 1}$$

Pouliquen et al. 2006 *J. Stat. Mech.*:

$$\Phi(I) = \Phi_{max} - (\Phi_{max} - \Phi_{min}) I$$



Non-local granular fluidity rheology

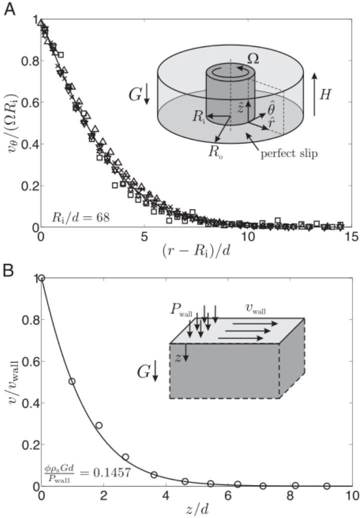
$$\dot{\gamma} = g(\mu, N)\mu$$

$$g_{\mathrm{local}}(\mu, N) = \begin{cases} \sqrt{d^2 N/\rho_{\mathrm{s}}}(\mu - \mu_{\mathrm{s}})/(b\mu) & \text{if } \mu > \mu_{\mathrm{s}} \\ 0 & \text{if } \mu \leq \mu_{\mathrm{s}} \end{cases}$$

$$\nabla^2 g = \frac{1}{\xi^2(\mu)}(g - g_{\mathrm{local}})$$

$$\xi(\mu) = \frac{Ad}{\sqrt{|\mu - \mu_{\mathrm{s}}|}}$$

Henann and Kamrin 2013 *PNAS*

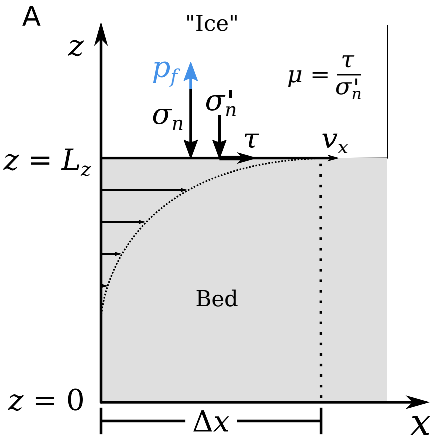


CNGF-PF: Cohesive NGF w. pore fluid

$$\frac{\partial p_\mathrm{f}}{\partial t} = \underbrace{\frac{1}{\phi \mu_\mathrm{f} \beta_\mathrm{f}} \nabla \cdot (k \nabla p_\mathrm{f})}_{\text{Spatial diffusion}}$$

$$\sigma'_\mathrm{n} = \sigma_\mathrm{n} - p_\mathrm{f}$$

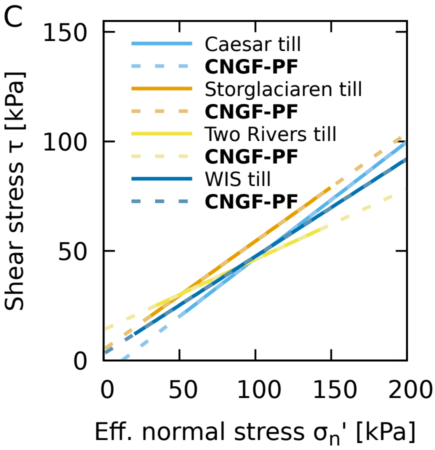
Model setup



Damsgaard et al. *In review*

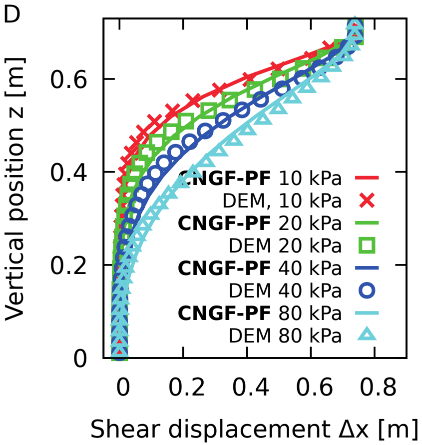
Validation

Mohr Coulomb



Damsgaard et al. *In review*

Strain distribution



Damsgaard et al. *In review*

Granular modeling: Discrete-element method vs. continuum model

sphere

`git://adamsgaard.dk/sphere`

C++, Nvidia C, cmake, Python, Paraview

massively parallel, GPGPU

detailed physics and fluid-grain coupling

20,191 LOC

3 months on nvidia tesla k40

1d-fd-simple-shear

`git://adamsgaard.dk/1d_fd_simple_shear`

C99, makefiles, gnuplot

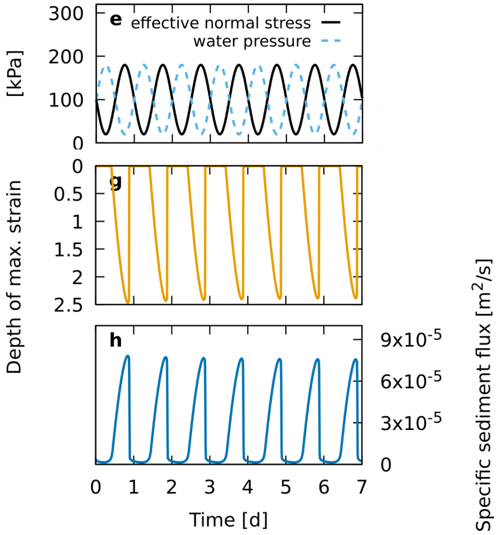
single threaded

simple physics, simple fluid-grain coupling

2,348 LOC

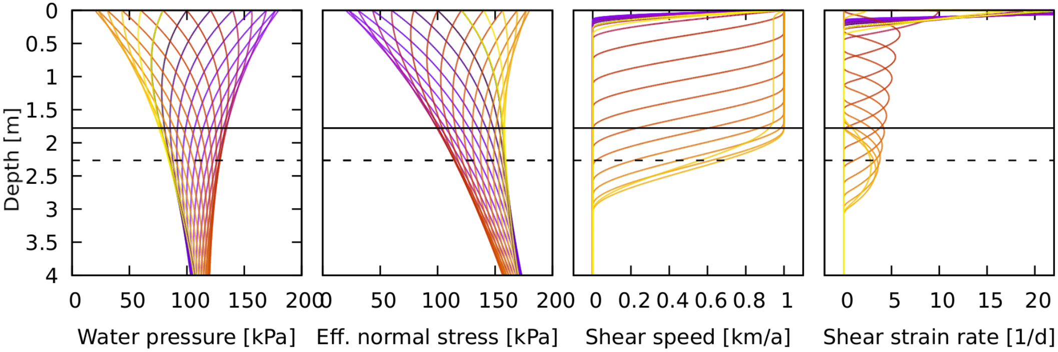
70 ms on 2012 laptop

Water-sediment simulations



Damsgaard et al. *In review*

Water-sediment simulations



Damsgaard et al. *In review*

Deep or shallow deformation?

$$d_s = \sqrt{\frac{k}{\phi \eta_f \beta_f \pi f}}$$

Damsgaard et al. *In review*

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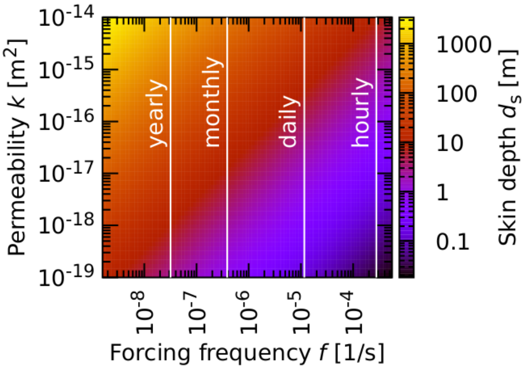
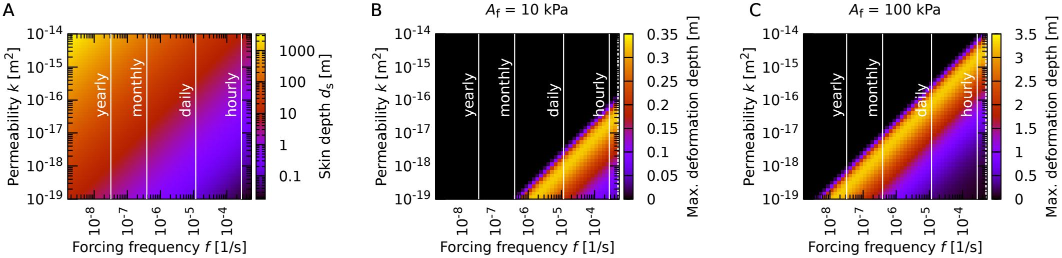
$$d_s = \sqrt{\frac{k}{\phi \eta_f \beta_f \pi f}}$$



Damsgaard et al. *In review*

Deep or shallow deformation?

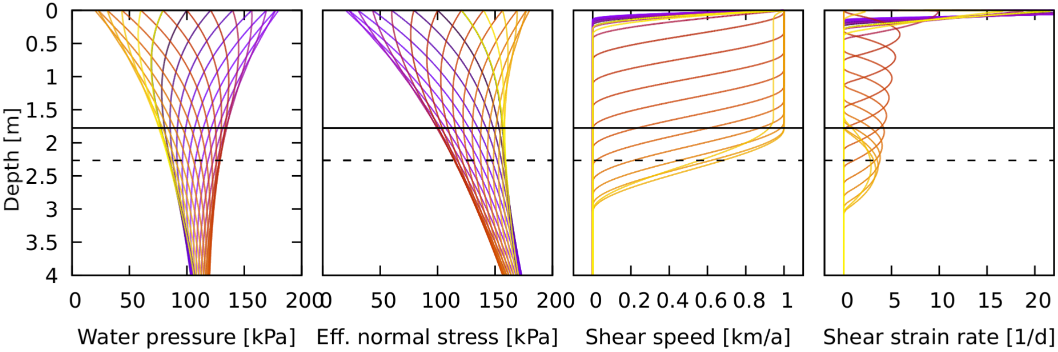


Maximum deformation depth: z'

$$0 = \sqrt{2}\sin\left(\frac{7\pi}{4} - \frac{z'}{d_s}\right) + \frac{(\rho_s - \rho_f)Gd_s}{A_f}\exp\left(\frac{z'}{d_s}\right)$$

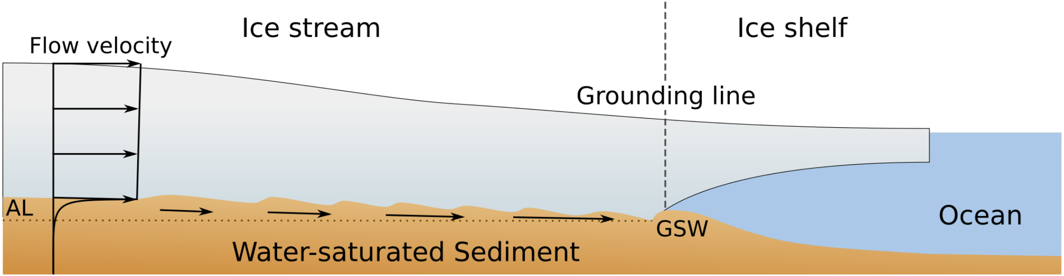
Damsgaard et al. *In review*

Water-sediment simulations



Damsgaard et al. *In review*

Next steps: Ice-water-sediment coupling



Conclusions

- First-principles granular rheologies promising for coupled simulations
- Rheology consistent with critical-state sediment mechanics and laboratory experiments
- Computationally lightweight compared to particle-based methods
- Towards testable field predictions of subglacial deformation and glacier dynamics

Resources

Slides:

`https://adamsgaard.dk/npub/esco2020-damsgaard.pdf`

Source code:

`https://src.adamsgaard.dk/1d_fd_simple_shear`

Preprint: “Evolving basal slip under glaciers and ice streams”

`https://arxiv.org/abs/2002.02436`