Process-based modeling of glacial till advection

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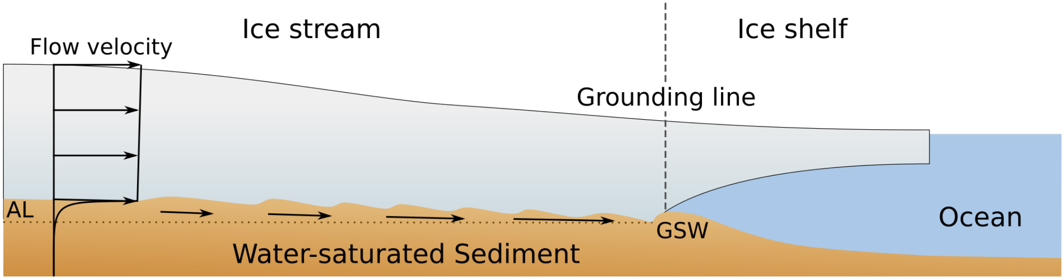
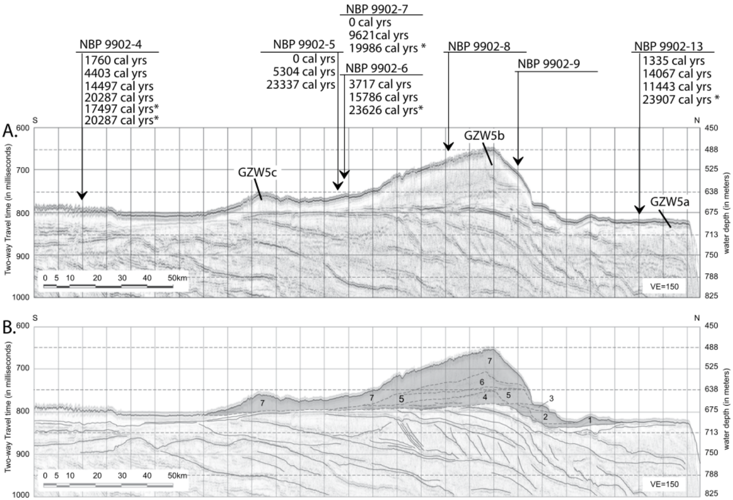
Subglacial sediment transport

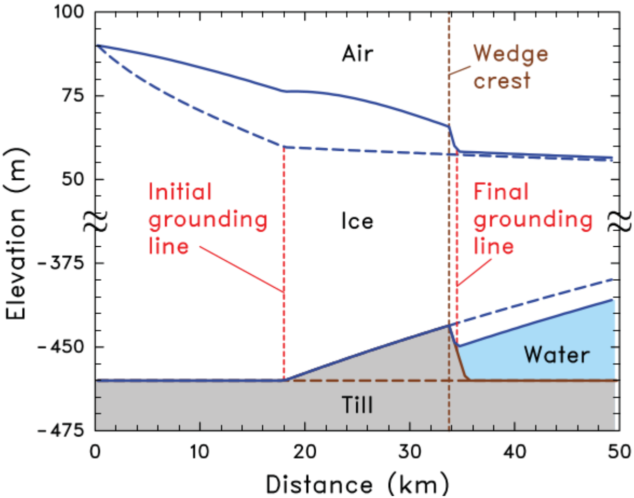


Palaeo-grounding zone wedges



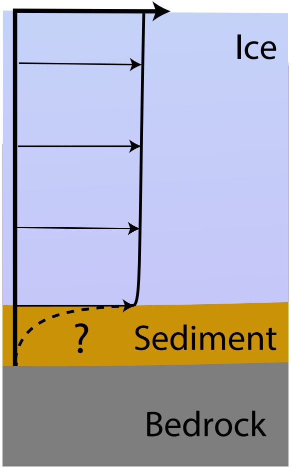
Bart et al. 2017 *Scientific Reports*

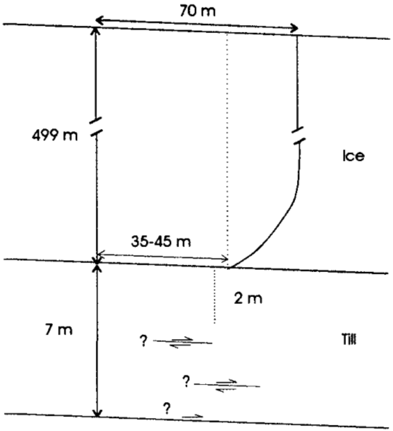
Ice-stream stabilization



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

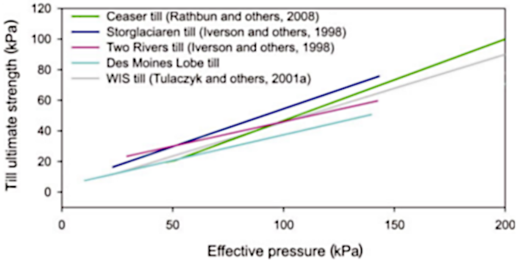
Mohr Coulomb

Charles-Augustin de Coulomb, b. 1736

Christian Otto Mohr, b. 1835

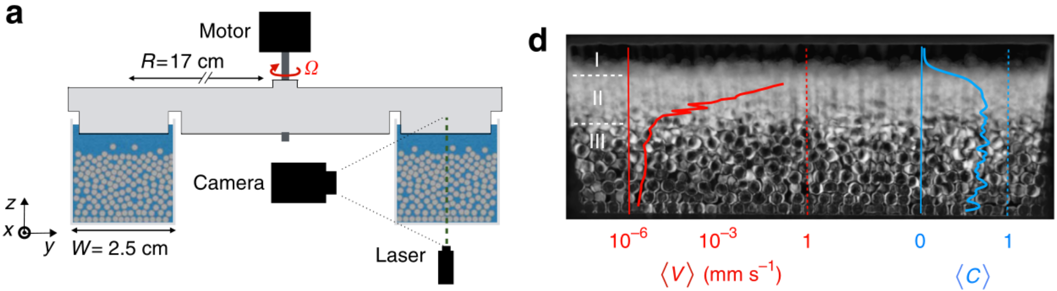
Karl von Terzaghi, b. 1883

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



Iverson 2010 *J. Glaciol.*

Phase transitions in granular materials



Houssais et al. 2015 *Nat. Comm.*

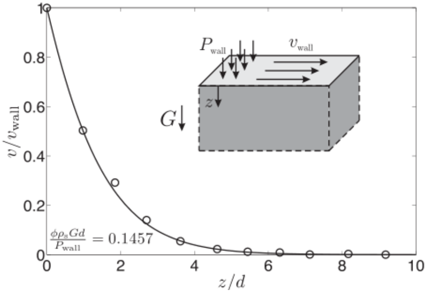
Non-local granular fluidity rheology

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

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

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

$$\xi(\mu) = \frac{Ad}{\sqrt{|\mu - \mu_s|}}$$



Henann and Kamrin 2013 *PNAS*

CNGF-PF: Cohesive NGF w. pore fluid

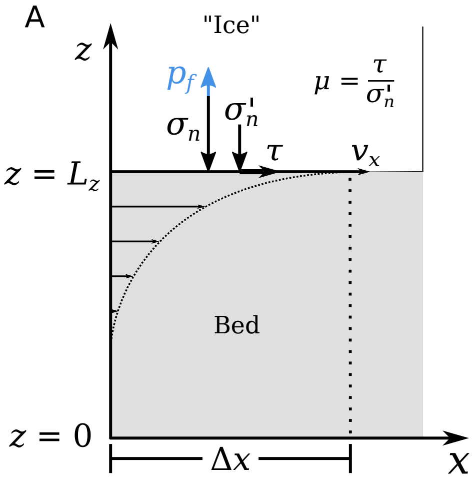
$$\frac{\partial p_\mathrm{f}}{\partial t} = \underbrace{\frac{1}{\eta_\mathrm{f}(\alpha + \phi \beta_\mathrm{f})} \nabla \cdot (k \nabla p_\mathrm{f})}_{\text{Spatial diffusion}}$$

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

Damsgaard et al. 2020 *Commun. Earth Env.*

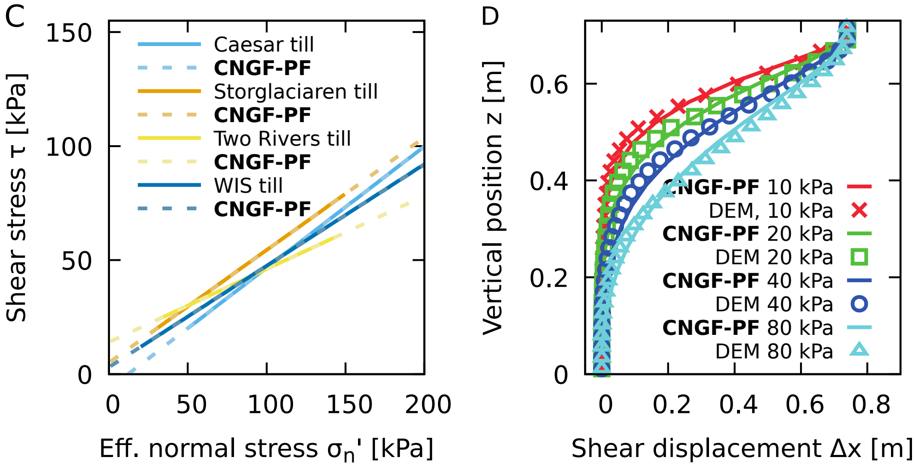
Validation

Model setup



Damsgaard et al. 2020 *Commun. Earth Env.*

Continuum model validation



Damsgaard et al. 2020 *Commun. Earth Env.*

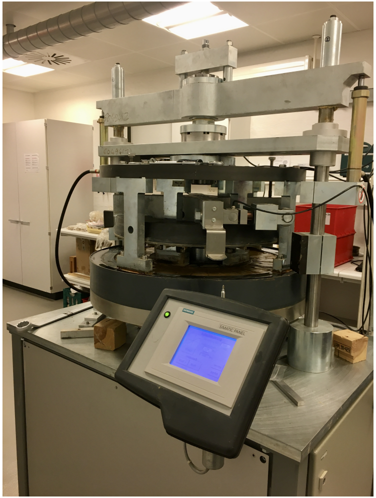
Ring-shear experiments vs. continuum model

Mid Danish Till

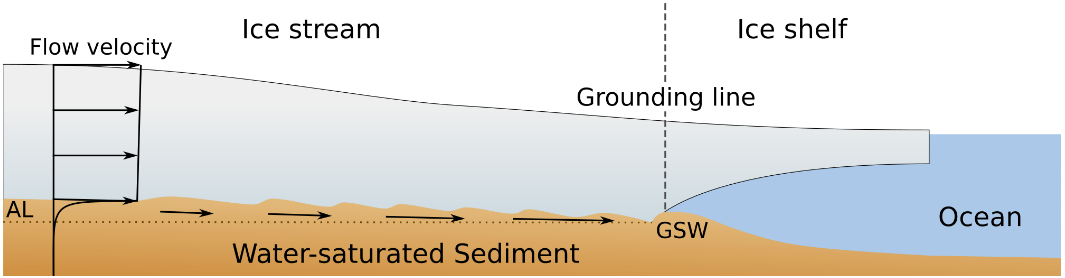
LGM advance

Bimodal GSD:
medium sand and clay

Subglacial traction till



Ice-water-till coupling



Coupling to ice-sheet model

PARALLEL ICE SHEET MODEL

`https://pism-docs.org`

Evolution of basal topography:

$$\frac{\partial b}{\partial t} = -\nabla \cdot \mathbf{q}_{\mathrm{t}}$$

Computed on staggered grid.

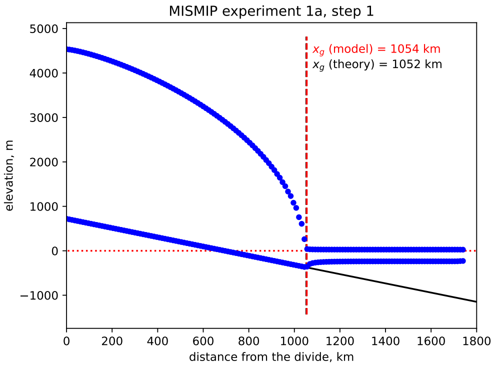
Till flux ($\mathbf{q}_{\mathrm{t}}$) depends on:

- basal velocity ($\mathbf{v}_{\mathrm{SSA}}$)
- till frictional coefficient (μ)
- till cohesion (C)
- effective normal stress (N')

Source: `git://src.adamsgaard.dk/pism` (`tillflux` branch)

Coupled simulations

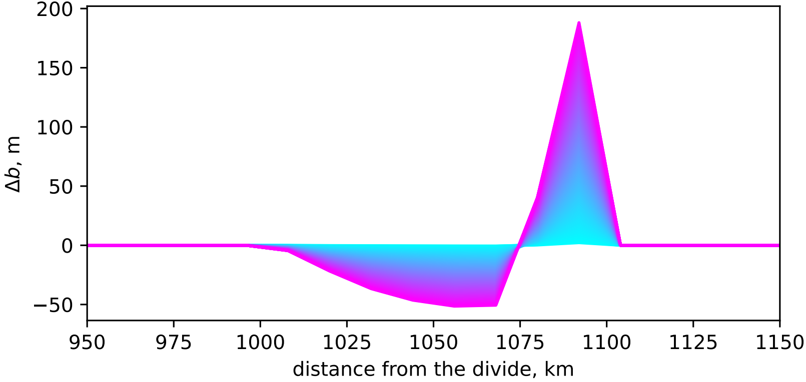
Geometry: MISMIP, EXP 1/2



- Thermomechanical, 3D, SIA+SSA
- Plastic Mohr-Coulomb basal friction
- CNGF-PF till flux
- Darcian subglacial hydrology with mass conservation
- Constant or constantly rising sea level

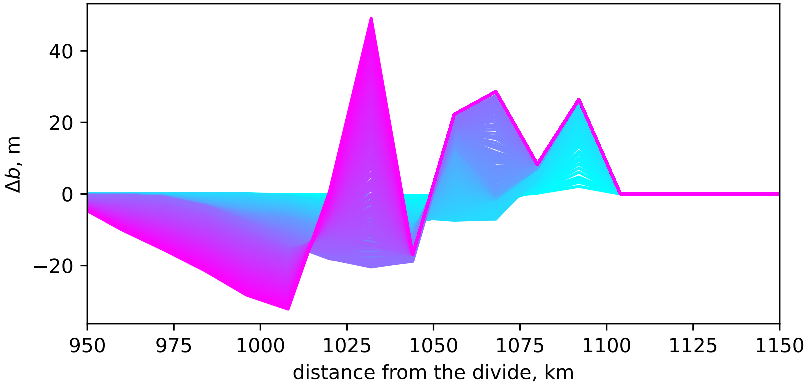
Source: `git://src.adamsgaard.dk/pism-exp-gsw`

Coupled simulation I: Constant sea level for 10 ka



blue (early) → magenta (late)

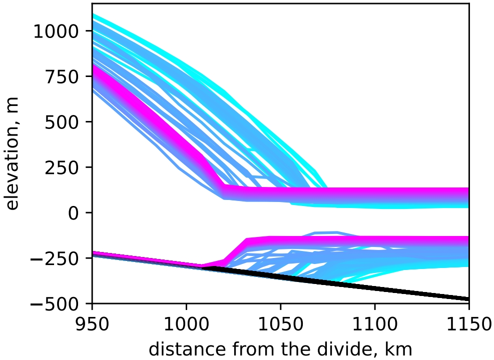
Coupled simulation II: Rising sea level (1 cm/a) for 10 ka



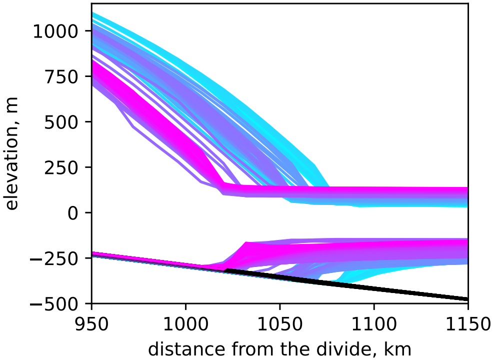
blue (early) → magenta (late)

Coupled simulation II: Rising sea level (1 cm/a) for 10 ka

No till transport:



With till transport:



blue (early) → magenta (late)

Conclusions

- First-principles granular rheology for coupled ice-water-till simulations
- Rheology consistent with critical-state sediment mechanics and laboratory experiments
- Implemented in PISM
- Towards testable field predictions of subglacial deformation and soft-bed glacial geomorphology

Still lots to do!

- Hard-bed erosion (abrasion, quarrying)
  (e.g., Ugelvig et al. 2016 *J. Geophys. Res. Earth Surf.*)
- Basal freeze-on and sediment transport in basal ice
  (e.g., Meyer et al. 2018 *Nat. Commun.*)
- Glaciofluvial sediment transport
  (e.g., Damsgaard et al. 2017 *J. Glaciol.*)
- Isostatic adjustment to sediment deposition/erosion
  (e.g., Bueler et al. 2007 *J. Glaciol.*)
- Glaciotectonics and large-scale thrusting/faulting