Modelling Calving in Elmer/Ice

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Overview

- About Calving
- Theory
- Calving Implementation
- Mesh Adaptation
- Discrete Element

Iceberg Calving

- Critical for ice-sheet stability & sea level
- Occurs on various spatial scales
- Links to climate
- Fundamentally a fracture problem
- Challenging in a continuum model

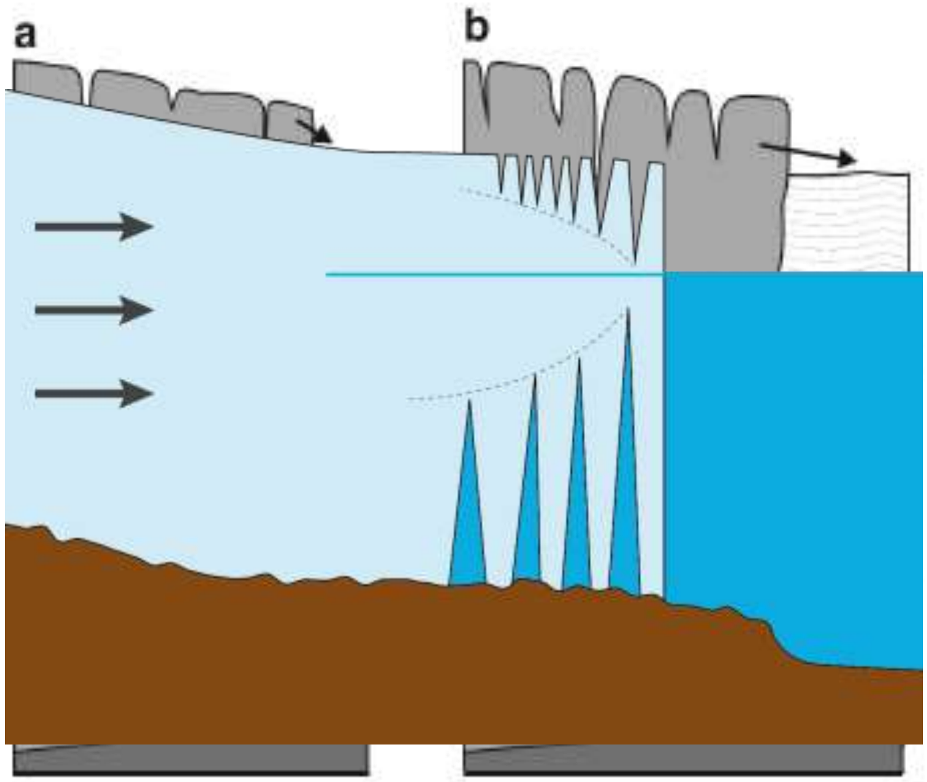
Theoretical Framework for Calving

Diverse range of processes, but fundamentally:

“Calving occurs when crevasses penetrate the glacier.”

Surface crevasses may:

- Reach sea level, and fill with seawater, leading to hydrofracture
- Overlap with basal crevasses



Various modes of calving. Source: van der Veen (2002)

Computing Crevasse Depth

- Linear Elastic Fracture Mechanics

$$K_I = \int_{z=H-d}^{z=H} \beta(z, d, H)\,\sigma_{xx}(x,y)\,dz$$

$$K_I > K_{IC}$$

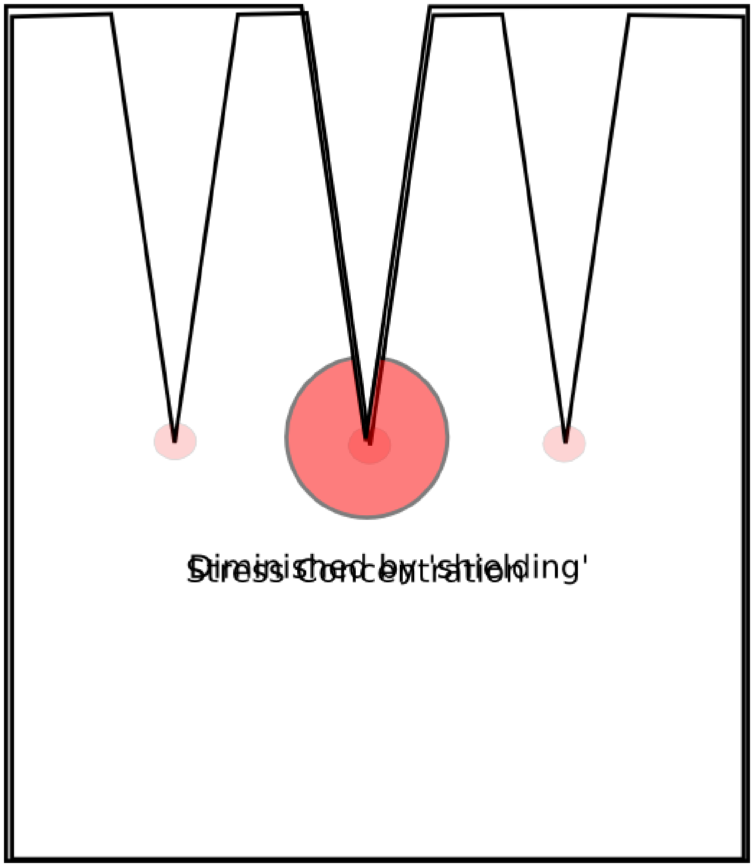
Krug et al. (2014)

- Nye Criterion

$$\sigma_1 > 0$$

- Account for water pressure

$$\sigma_1 + P_w > 0$$



Computing Crevasse Depth (cont.)

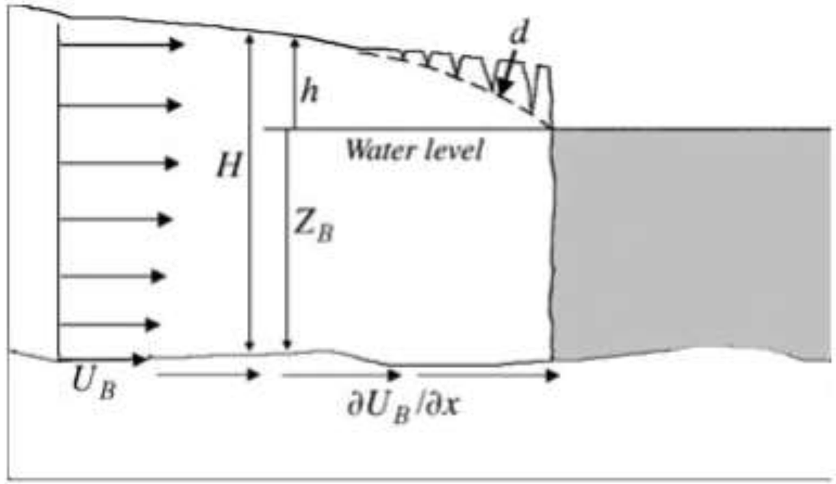
Surface crevasses:

$$d_{\mathrm{s}} = \frac{1}{\rho_{\mathrm{i}} g}\left(\tau_{xx} + \rho_{\mathrm{w}} g d_{\mathrm{w}}\right)$$

Bottom crevasses:

$$d_{\mathrm{b}} = \frac{\rho_{\mathrm{i}}}{\rho_{\mathrm{w}} - \rho_{\mathrm{i}}}\left(\frac{\tau_{xx}}{\rho_{\mathrm{i}} g} - H_{\mathrm{float}}\right)$$

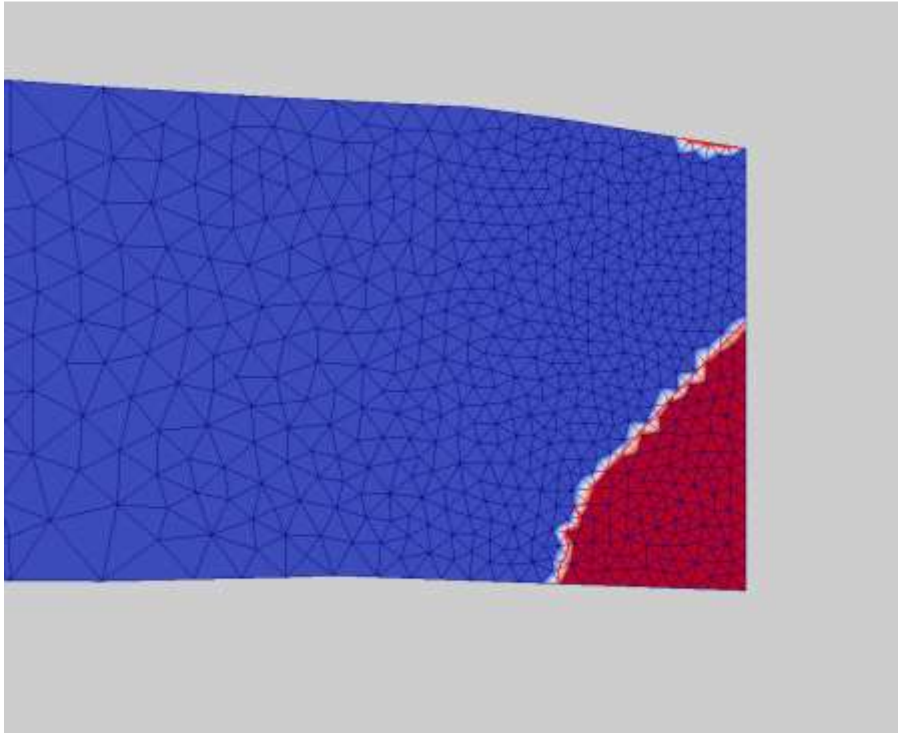
$$H_{\mathrm{float}} = H - \frac{\rho_{\mathrm{w}}}{\rho_{\mathrm{i}}} Z_{\mathrm{B}}$$



From D.I.Benn et al. Earth-Science Reviews 82(2007)

Implementation: Calving.F90

- Compute stress at each timestep
- Cycle through all nodes, marking connected groups with open crevasses
- Either:
    - Look for surface crevasses reaching waterline
    - Look for surface and basal crevasses meeting
- Identify furthest inland crevassing point, which defines the new front
- Define Mesh Update BC on front using this info

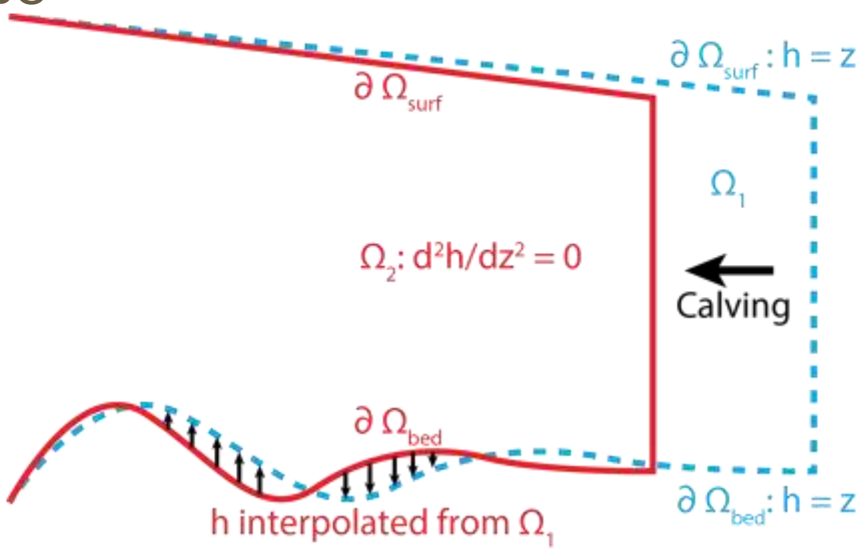


See: Todd and Christoffersen (2014)

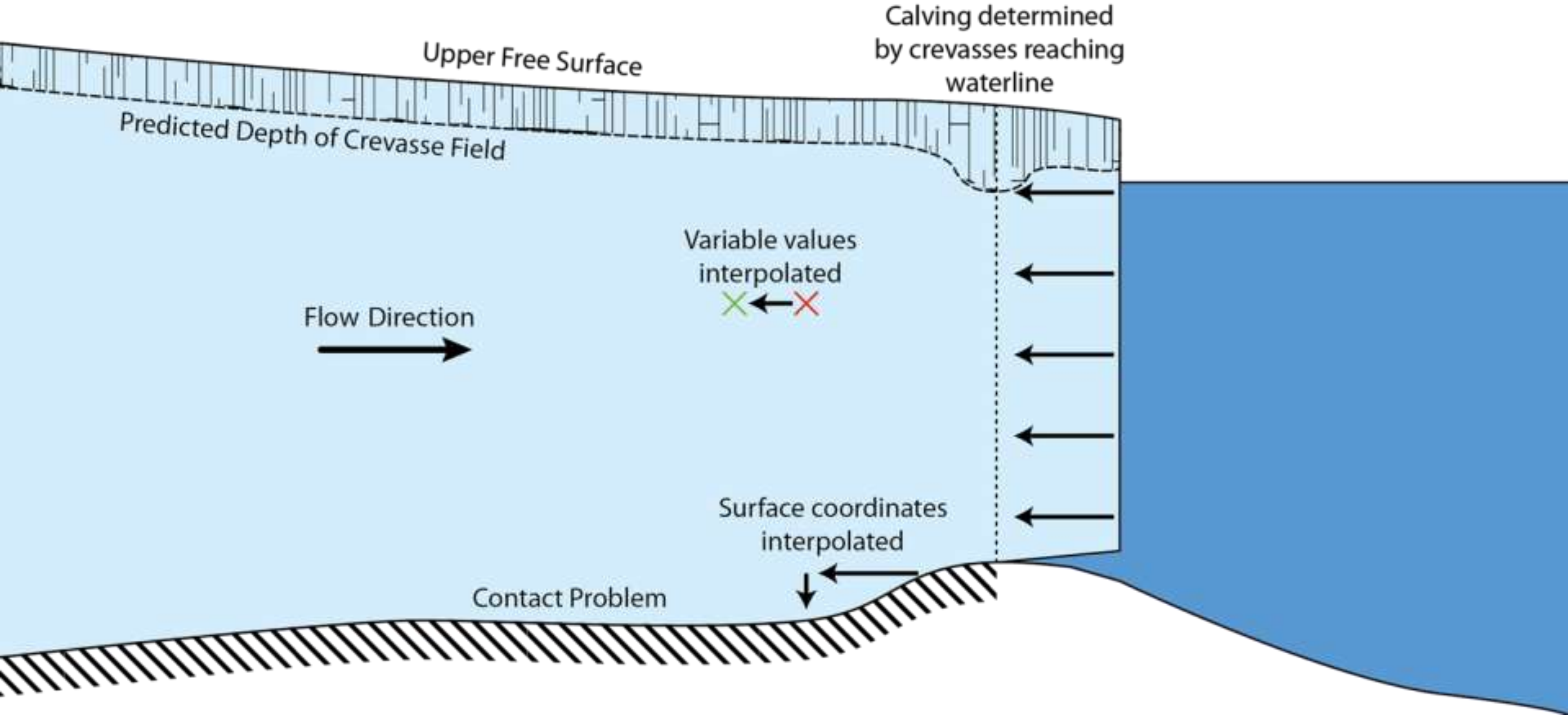
TwoMeshes.F90

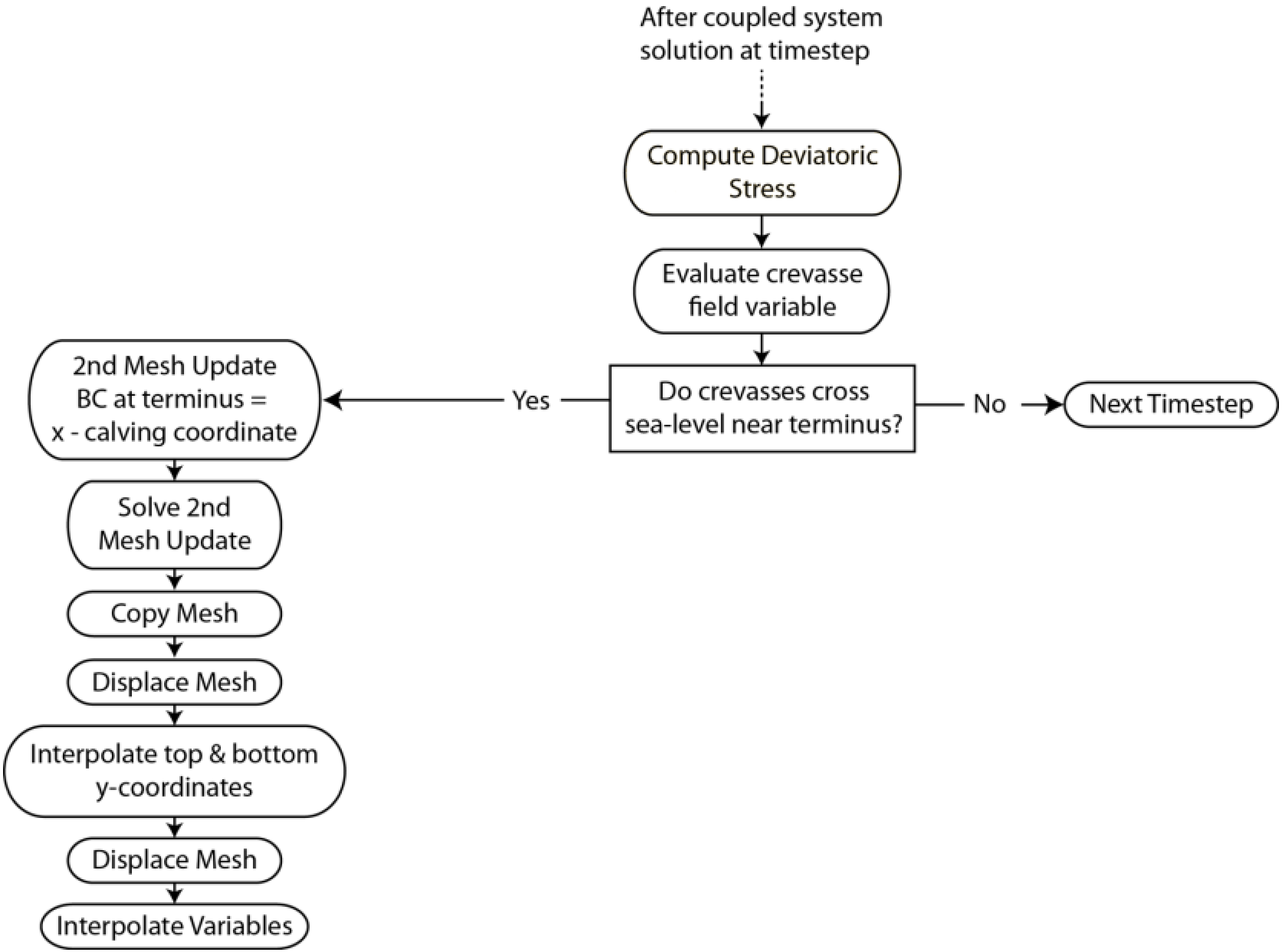
Developed by Peter Råback, CSC

1. Mesh Update with Calving Dirichlet BC
2. Duplicate mesh & translate
3. Interpolate (1D) Height BCs
4. Solve 1D (z) Laplace equation
5. Deform new mesh
6. Interpolate (2D) field variables

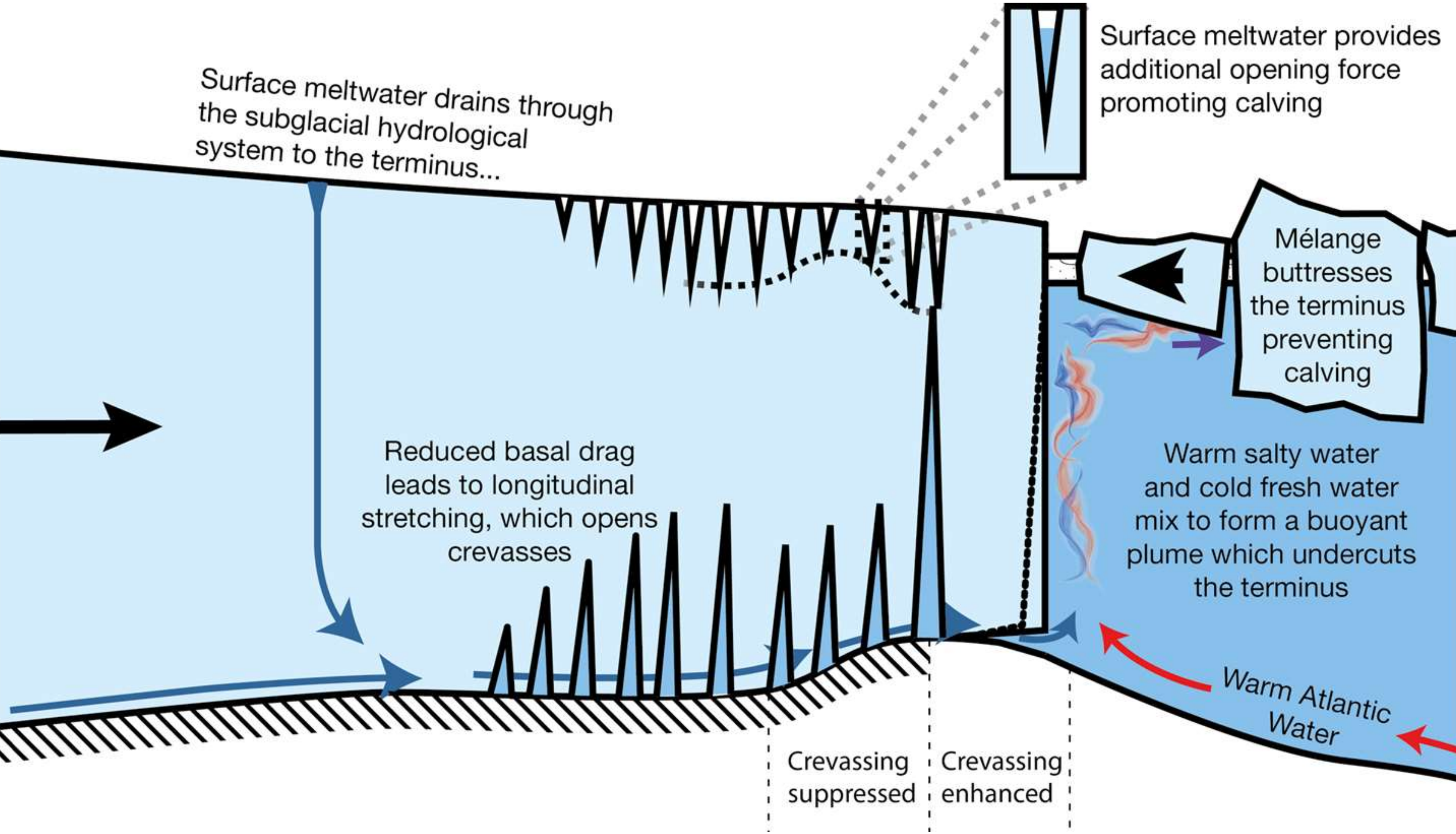


Method Overview




After coupled system solution at timestep
Compute Deviatoric Stress
Evaluate crevasse field variable
Do crevasses cross sea-level near terminus?
Yes
No
Next Timestep
2nd Mesh Update BC at terminus = x - calving coordinate
Solve 2nd Mesh Update
Copy Mesh
Displace Mesh
Interpolate top & bottom y-coordinates
Displace Mesh
Interpolate Variables

Applying Climate Forcing



Applying Climate Forcing

Climate Forcing	**Applied via...**
Submarine Melting	Free Surface Accumulation Flux
Ice mélange backstress	External Pressure BC
Water in surface crevasses	Directly in Calving.F90
Subglacial Hydrology	Solvers (but this is tricky!)

Stress History

High stress regimes leave ice weakened/damaged

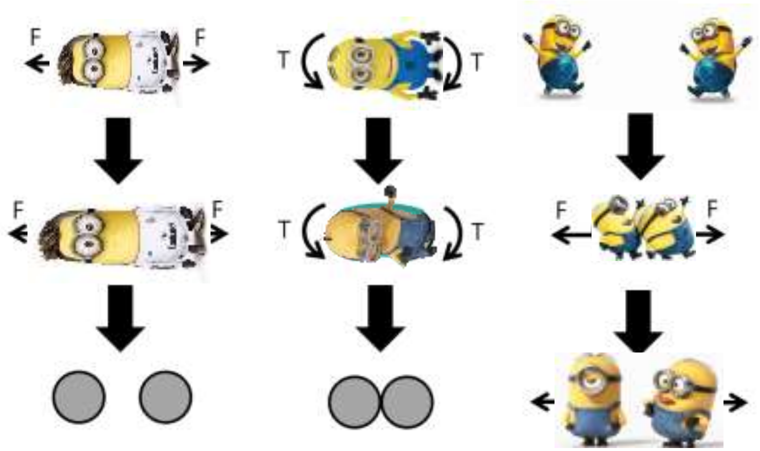
USF_Damage.F90 (implemented by Jean Krug)

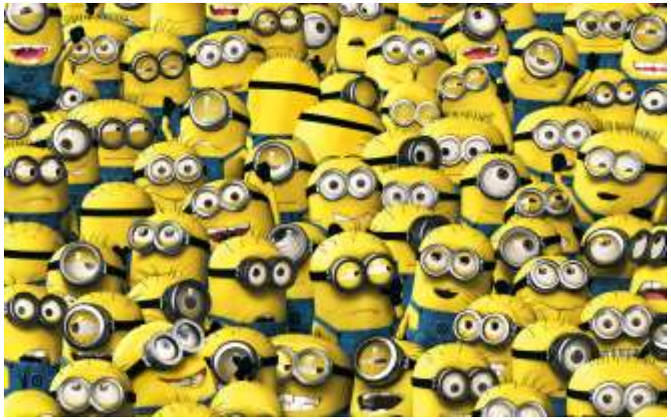
- Define scalar variable ‘damage’ at all nodes
- Stress above threshold increases damage
- Damage is advected down glacier
- Modifies stress/strain relationship
- Requires Discontinuous Galerkin

See: Krug, J., et al. (2014)

Discrete Element (Particle) Model

- “Frozen” particles
- represented by beams
- Impurities, etc. represented by random values of beam parameter
- Cracks = beams exceeding an elastic threshold load
- Repulsive force against overlap of particles
- Glacier represented by (a lot of) particles (~1 – 10 m^3 in size)
- Initially dense package



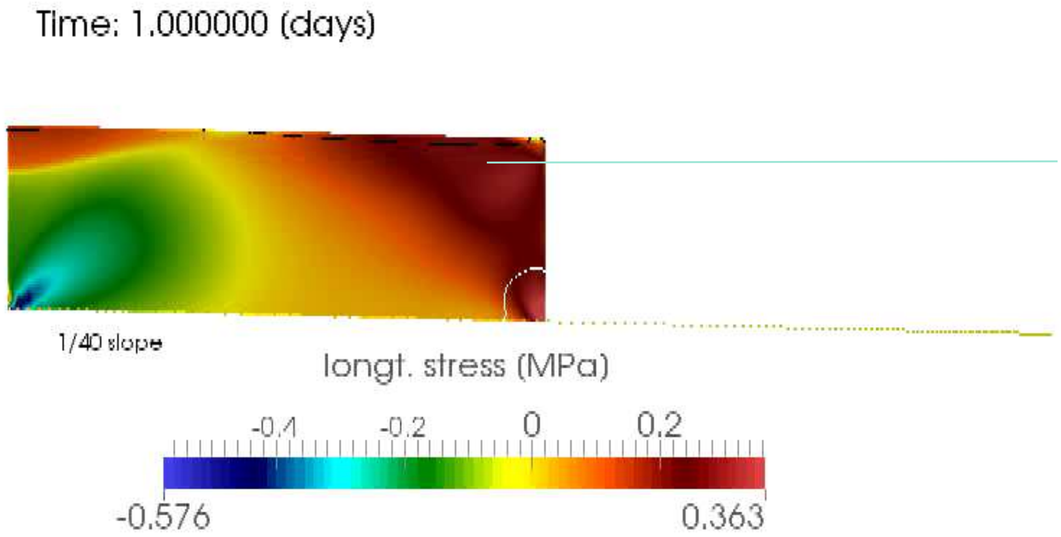


Gratitude to Universal Pictures
Apologies to Joe Todd (who hates minions)

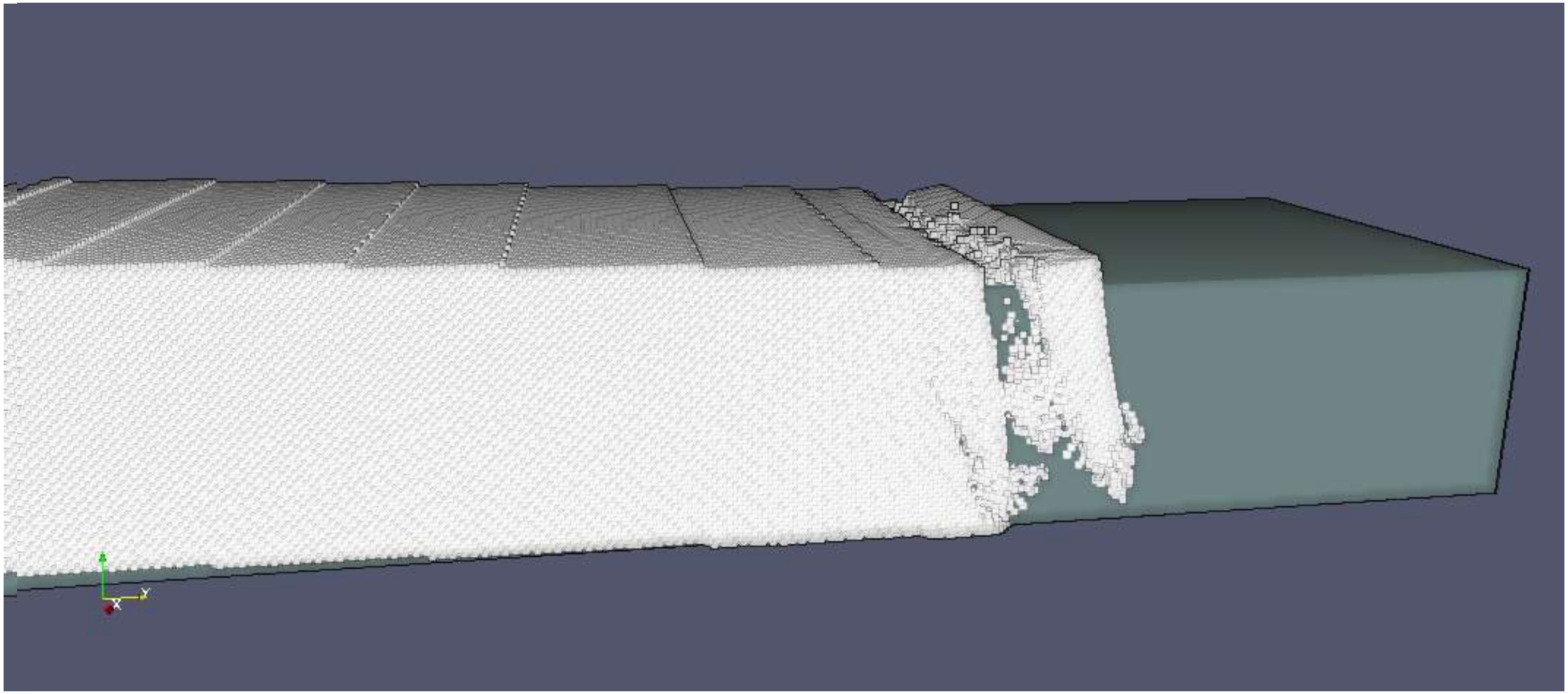
Helheim experiment

- 2000m of block with ~700m constant thickness
- Constant inlet velocity of $u_{\rm in} = 8000\,{\rm m\,a}^{-1}$
- Low basal friction $u_{\rm b} = c_{\rm sl}\tau_{\rm b}$
- 0 + 1/40 slope

http://www.swansea.ac.uk/media/HELHEIM%20GLACIER%20SUMMER%202010.jpg



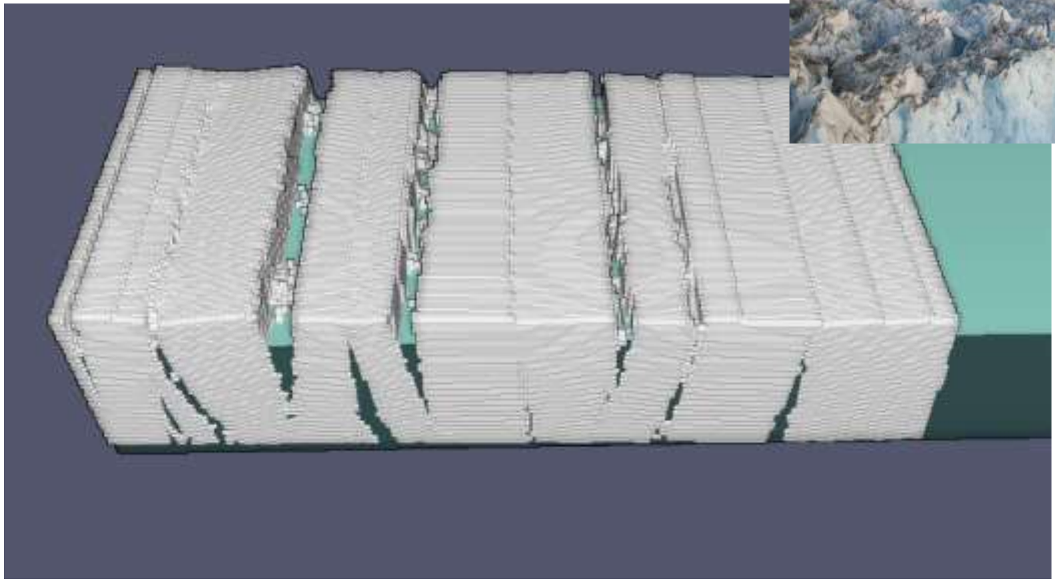
Helheim experiment



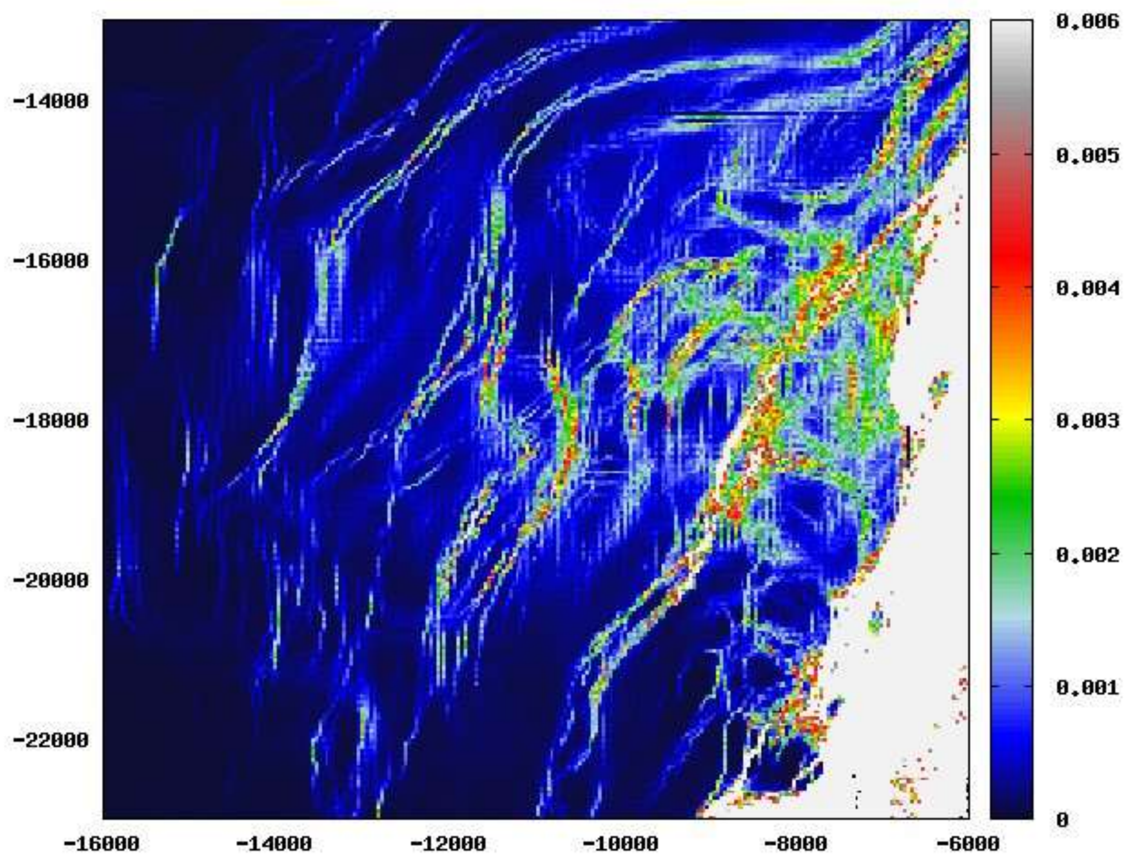
Helheim experiment

Helheim experiment

(Photo by Meredith Nettles,
Taken from
http://blogs.ei.columbia.edu)



Austfonna

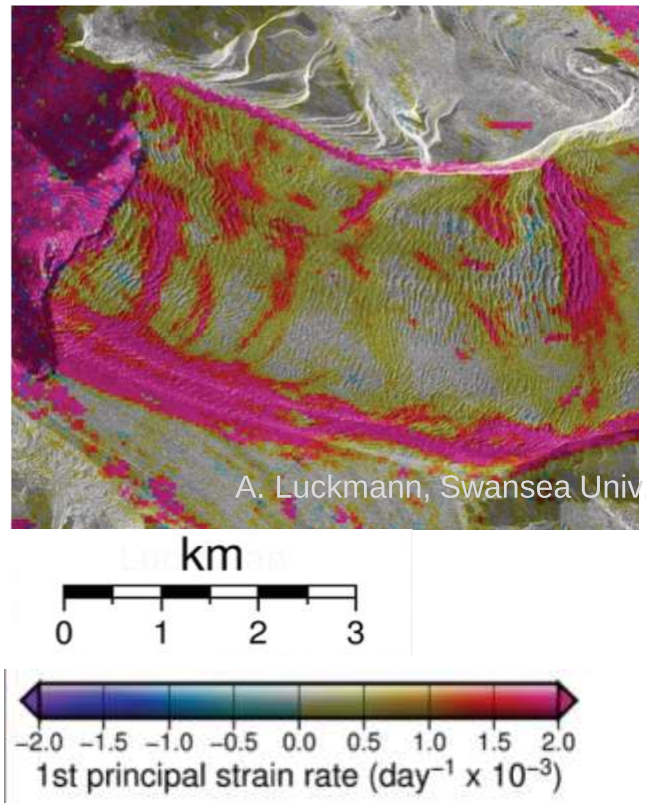


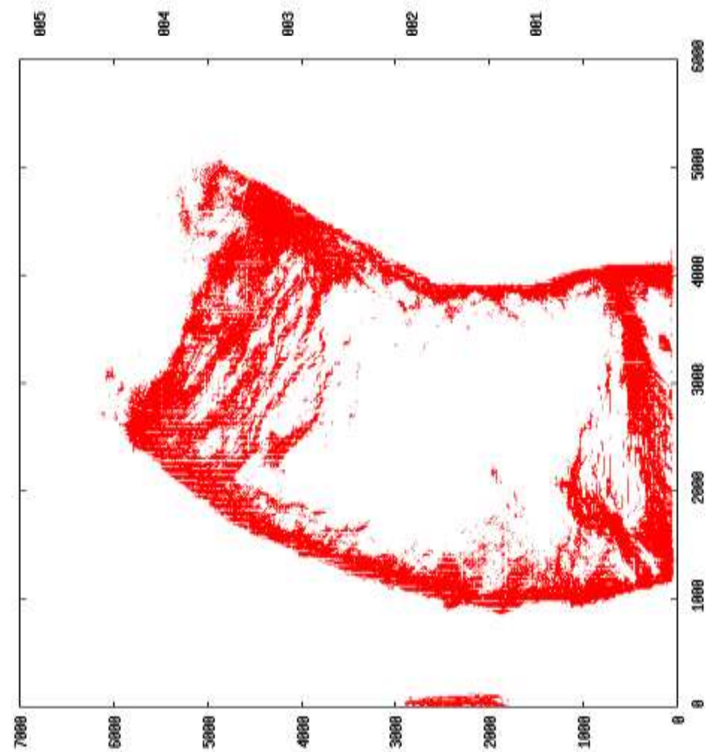
Austfonna B3: Strain field (i.e. crevasse patterns) at the calving front in the high velocity region of 2011. This represent the simulated onset of surging and the consequent breakup and calving at terminus.

Results from within SVALI by Jan Åström (CSC, FIN) and Yongmei Gong (UoH, FIN)

Kronebreen

Similar for Kronebreen





Kronebreen: Computed strain field
Kronebreen: Computed crevasse field

Results from within SVALI by Jan Åström (CSC, FIN) and Dorothée Vallot (UUppsala, SWE)

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