

Modelling the source of glacial earthquakes

P. Bonnet ^{1 2 3}, V. Yastrebov ², A. Mangeney ^{1 4}, O. Castelneau ³,
A. Leroyer ⁵, P. Queutey ⁵, M. Rueckamp ⁶, E. Stutzmann ¹, J.-P.
Montagner ¹, A. Sergeant ⁷

¹IPGP, Université de Paris, Seismology Group, CNRS

²MINES ParisTech, PSL University, Centre des Matériaux, CNRS

³ENSAM, CNAM, Procédés et Ingénierie en Mécanique et Matériaux, CNRS

⁴Inria, Laboratoire J.-L. Lions, ANGE team, CEREMA, CNRS, Paris, France

⁵Centrale Nantes, LHEEA, METHRIC Team, CNRS

⁶Alfred Wegener Institute Helmholtz, Bremerhaven, Germany

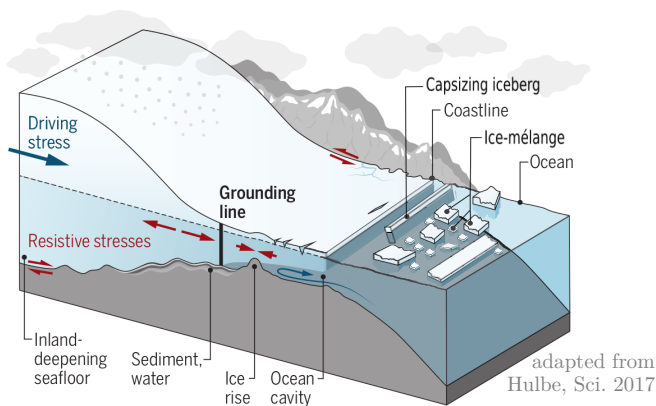
⁷Aix Marseille Univ, CNRS, Centrale Marseille, LMA, France



Outline

- 1 Context: dynamic discharge at glacier front
- 2 Mechanical model
- 3 Simulation results
- 4 Conclusions

Dynamic ablation processes at glacier terminus



The processes that control ablation at tidewater glacier termini are complex: it involves interactions between the bedrock, the glacier, the icebergs, the ice-mélange, the water and the atmosphere.

ICEBERG CAPSIZE

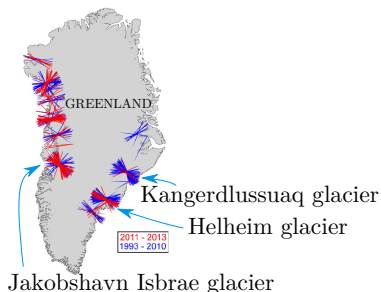


Capsize of a $\approx 18 \text{ km}^3 \approx 18 \text{ gT}$ iceberg (May 2014) at the calving front of the Jakobshavn Isbrae. Credit: J. E. Box, R. Wernberg-Poulsen, J. Larsen [movie](#)

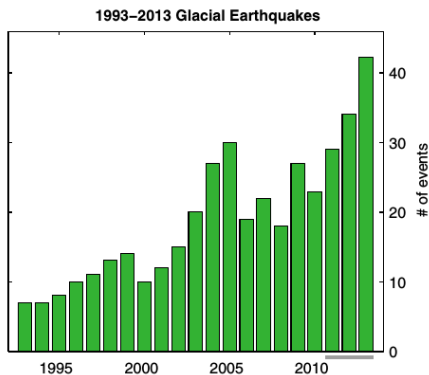
The capsizes of cubic kilometer scale icebergs close to a glacier front can destabilize the glacier and generate large water motion

Glacial earthquakes located at the front of Greenland glaciers have been observed since ≈ 2003 (Ekström et al, Science, 2003)

Map of force azimuth
and location
(Olsen, Nettles, JGla, 2017)



Number of events each year

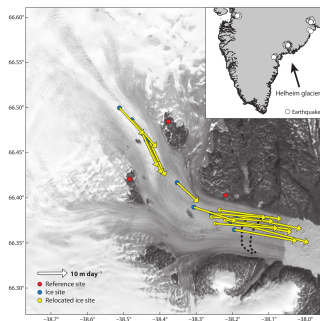


Increasing number of icequakes from iceberg capsize: what do seismic waves tell us about the physical processes at glacier fronts?

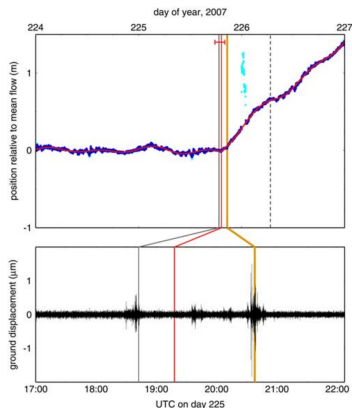
Glacier motion during calsize

Nettles et al, GRL, 2008

GPS campaign on Helheim



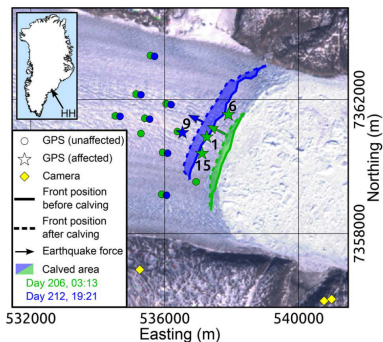
Step-like velocity change



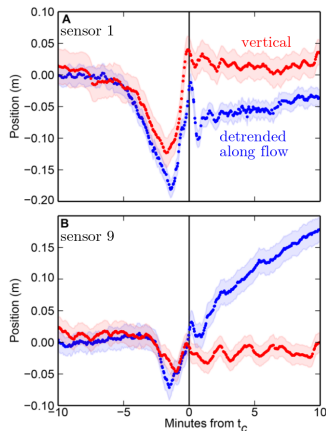
Step-wise change in the velocity: what do surface measurements tell us about the physical processes at glacier fronts?

Glacier motion during calsize Murray et al, Science, 2015

GPS campaign on Helheim

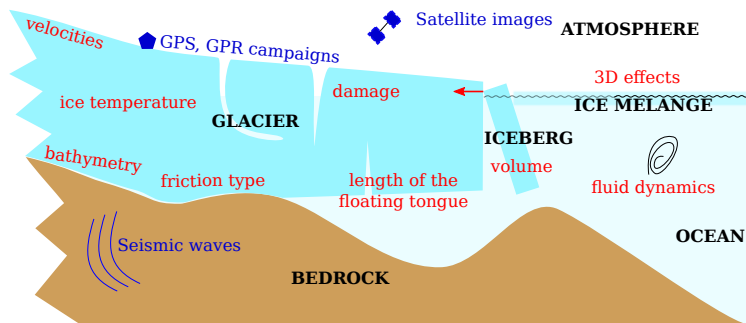


Reverse motion



Reverse motion at the surface: what do surface measurements tell us about the physical processes at glacier fronts?

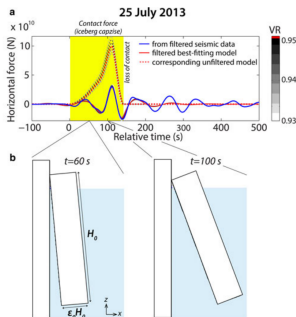
The aim of the work



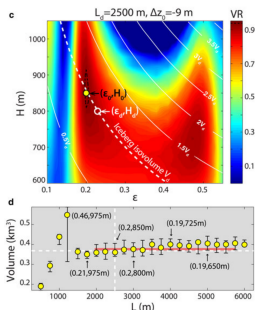
- Extract physical information: basal properties, glacier tongue length, iceberg size, ice rheology, type of capsizing
- Using a mechanical model of the glacier and the capsizing iceberg
- Constrained with GPS measurements and seismic data

Iceberg volumes inverted from seismic signals Sergeant et al, A. Gla, 2019

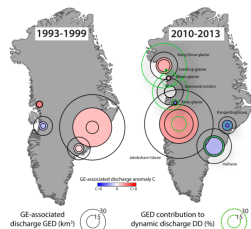
Source force: contact iceberg - glacier



Iceberg volume estimation



Evolution of the discharged volumes



Calculation of the volumes of capsizing icebergs at 8 glaciers in 1993-2013: iceberg capsizing accounts for at least 6% of ice-sheet losses

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Finite element model

Simulations of the response of a glacier to iceberg capsizing:

- finite element modelling of a glacier - bedrock - iceberg: Z-set Sergeant et al, JGR 2018; Sergeant et al, A. Gla, 2019
- simplified iceberg contact force: SAFCIM model Bonnet et al, GJI, 2020

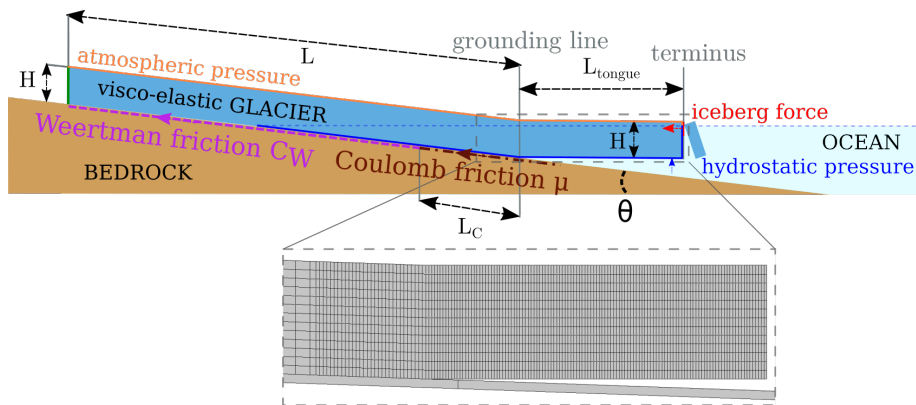
Ice rheology: Maxwell law an elastic behaviour in series with a viscous dash pot, the strain rate tensor is expressed by $\epsilon_{tot} = \epsilon_e + \epsilon_p$

- **Elastic behaviour:** $\sigma = C \cdot \epsilon_e$, Young's modulus E , Poisson's ratio ν
- **Glen's flow law:** $\sigma' = 2\eta\dot{\epsilon}_p$, with $\eta = (1/2A^{-1/n}\dot{\epsilon}_{eff}^{(1-n)/n})$, with σ' the deviatoric Cauchy stress tensor, $\dot{\epsilon}_{eff}$ the 2nd invariant of $\dot{\epsilon}_p$, and $A(\omega, T^*)$ the flowrate factor.

Basal friction laws

- **Weertman law:** $\tau_b = Cu_b^M$, basal tangential traction τ_b , velocity u_b
- **Coulomb law:** if $\tau_b < \mu\sigma$, $u_b = 0$; else $\tau_b = \mu\sigma$, with σ_n the normal contact stress

Setup of the numerical experiments



We assess the influence of the ice properties, the basal friction, the glacier geometry and the type of capsizing on the glacier dynamics.

Outline

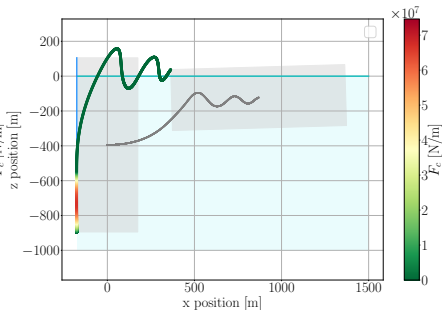
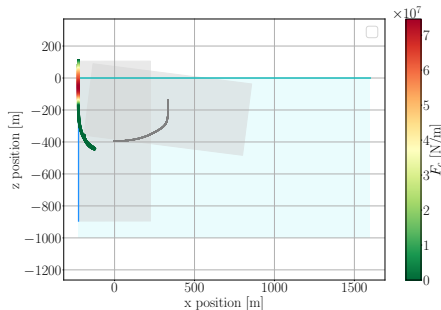
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The two types of capsize

Iceberg aspect ratio ε is taken such that amplitude(F_c) is maximum

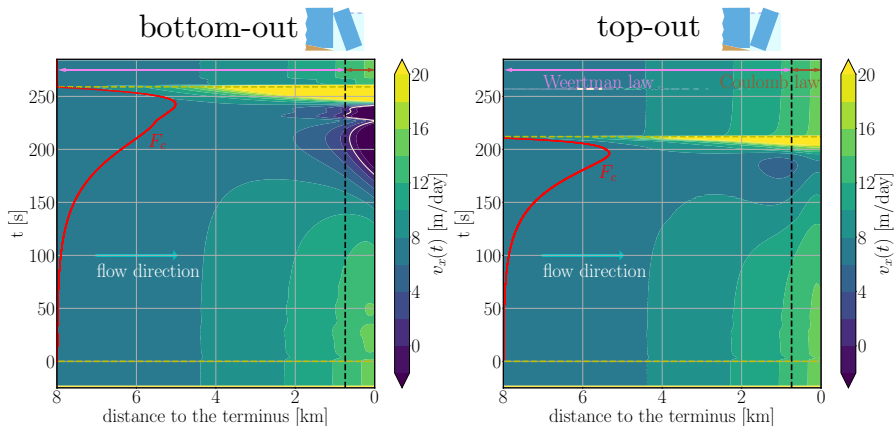
bottom-out  $\varepsilon=0.45$

top-out  $\varepsilon=0.35$



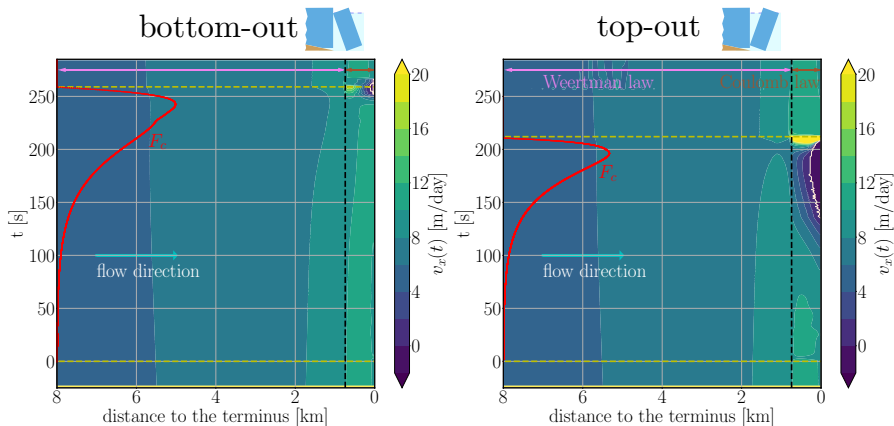
- bottom-out capsize induces a force on the top part of the terminus
- top-out capsize induces a force on the bottom part of the terminus

Grounded glacier: velocities at the free surface



At the free surface: reverse horizontal motion for the bottom-out capsize

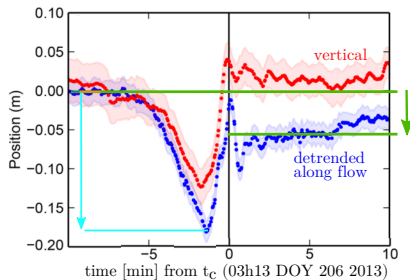
Grounded glacier: velocities at the basal interface



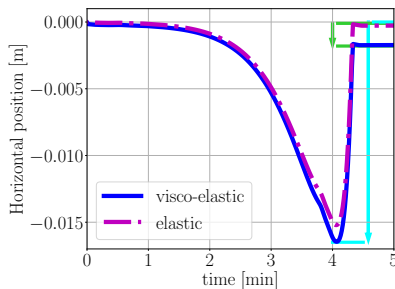
At the basal interface: Reverse horizontal motion for the top-out capsize

Qualitative comparison with field measurements

Field measurements
adapted from Murray et al, 2015
Position at the surface

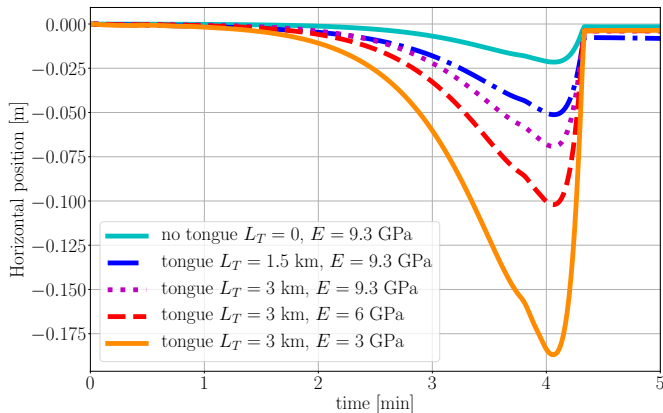


Simulations for a grounded terminus
and Young's modulus $E = 9.3$ GPa,
Position at the surface



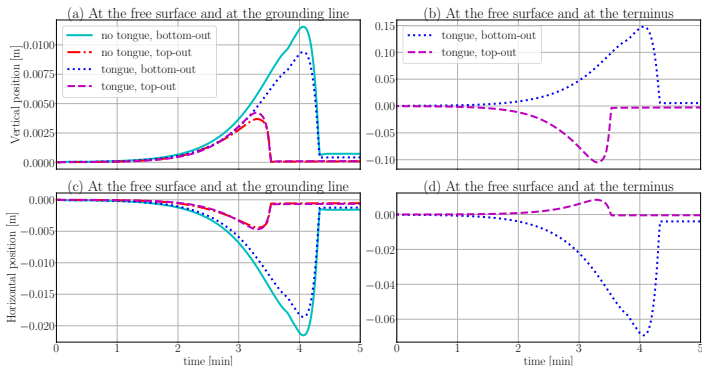
- the reverse motion is mainly an elastic compression
 - the viscous response of the glacier also induces a residual displacement
 - displacements are 10 times smaller than in the field
- include a floating tongue and decrease the Young's modulus ?

Effect of the tongue length and Young's modulus



For the bottom-out capsize: the amplitude of the horizontal reverse motion increases for a longer tongue L_T and smaller Young's modulus E
 $\rightarrow$ what about the vertical motion and the top-out capsize?

Deformation of the floating tongue Bonnet et al, in prep



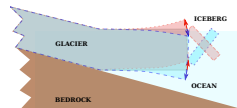
Similar behaviour before the grounding line, with and without the tongue

Simulation results close to terminus:

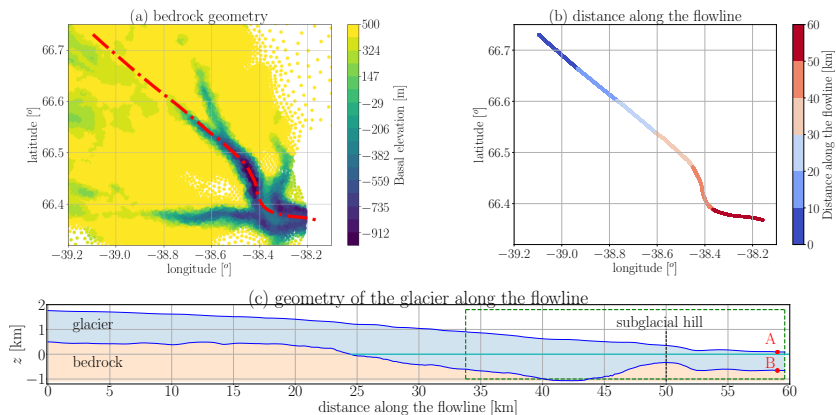
- bottom-out capsizes: reverse and upwards motion
- top-out capsizes: downflow and downwards motion

Field measurements close to terminus for bottom-out: reverse and downwards

→ include complex geometry in simulations ?



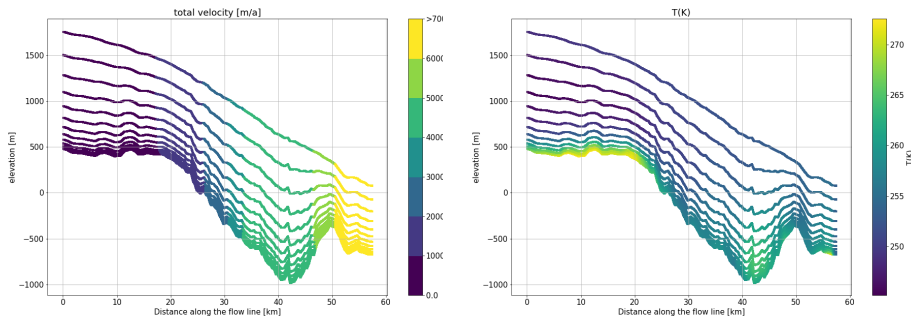
Modelling the Helheim glacier



Two dimensional modelling along the central flowline

Modelling the Helheim glacier

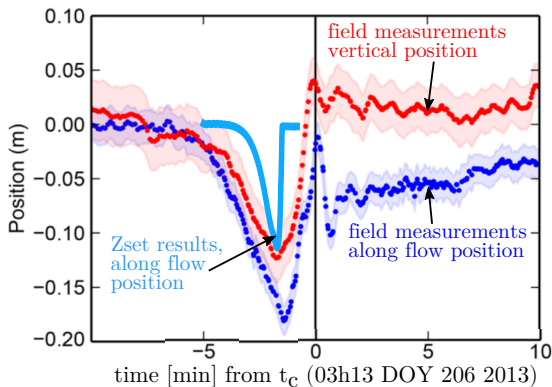
Collaboration with M. Rueckamp (AWI) for initialisation of our model: the geometry and flow parameters are calculated from the surface velocities, and surface temperature with an ISSM inversion



We integrated the geometry and the temperature dependant viscous behaviour in the finite element solver Zset

Quantitative comparison with field measurements

Simulations results with the Helheim glacier ($L_T = 4.5$ km, $E = 3$ GPa)



- the amplitude of the displacements are smaller than in the field
 - the duration of the reverse motion is shorter than in the field
- a coupling with a fluid-dynamics model to include the hydrodynamic effects could improve the predictions (ongoing work)

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Local and global impact of iceberg capsize

What interesting information can we extract from GPS measurements and seismic signals using a mechanical model?

- Calculate **volumes of icebergs** to reduce the uncertainties on ice-sheet mass losses
Sergeant et al, JGR, 2018 Sergeant et al, A. Gla, 2019,
Validation of the mechanical model in Bonnet et al, GJI, 2020
- Constrain the geometry, rheology and friction parameters through a **multi-parameter modelling of the response of glacier to iceberg capsize on glacier stability**
Bonnet et al, in prep
- Estimate the importance of fluid motion during iceberg capsize, and its impact on **water column mixing**
Bonnet et al, GJI, 2020