Fracture and Calving

Study of Ice as Material

Abb. 2A. Autorenporträt zu Joh. Jac. Scheuchzers *Itinera Alpina*, 1723. (Author's portrait of J.J. Scheuchzer's *Itinera Alpina* of 1723.)

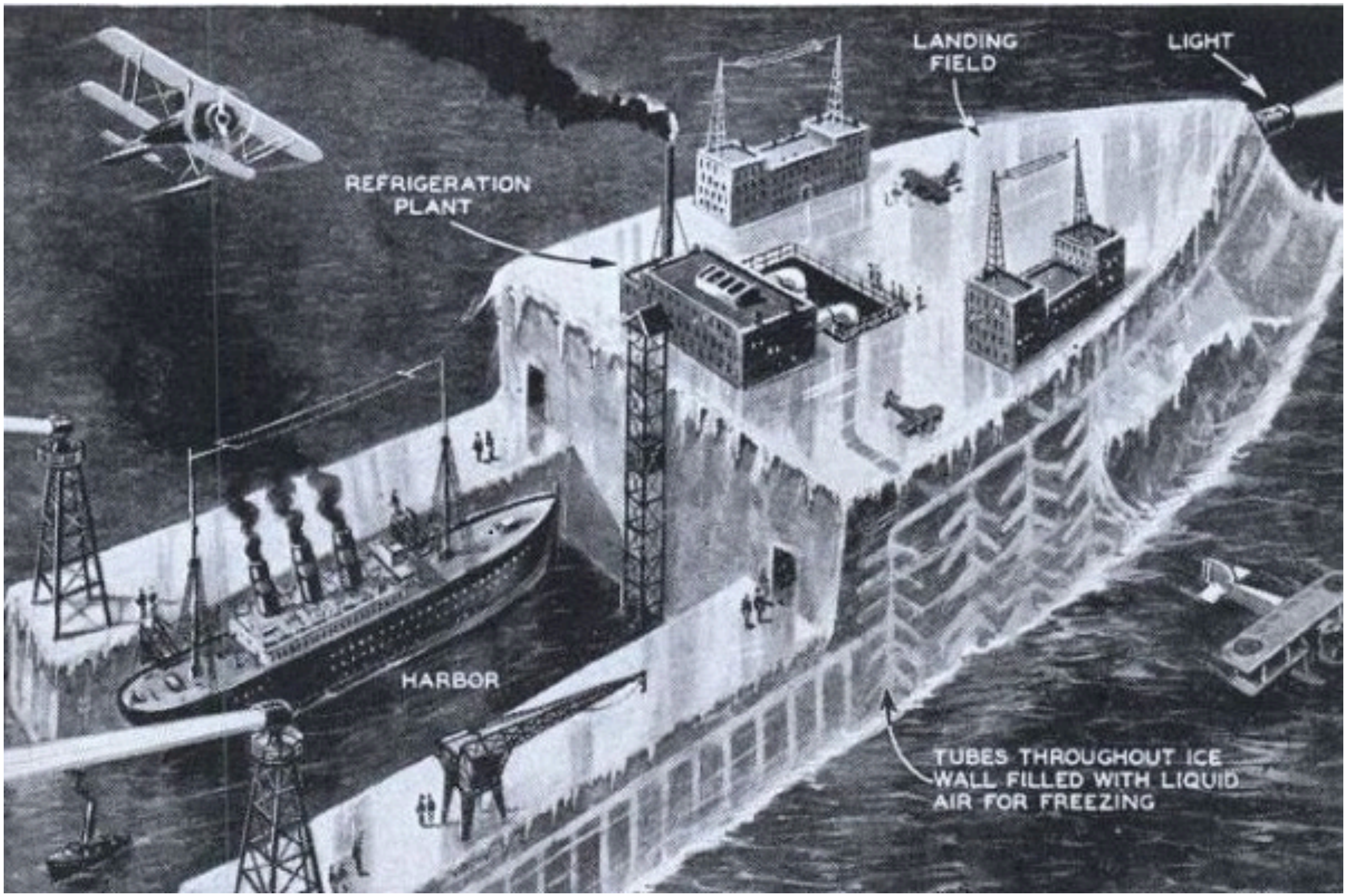
Abb. 2B. Titelkupfer zu Joh. Jac. Scheuchzers *Itinera Alpina*,1723. (Title plate of J.J. Scheuchzer's *Itinera Alpina* of 1723.)

Scheuchzer (1723): Fractures in glacier form in summer due to bubble expansion

Study of Ice as Material

WW2 - Project Habakkuk: The British say lets build an aircraft carrier out of ice in the middle of the North Atlantic

Study of Ice as Material

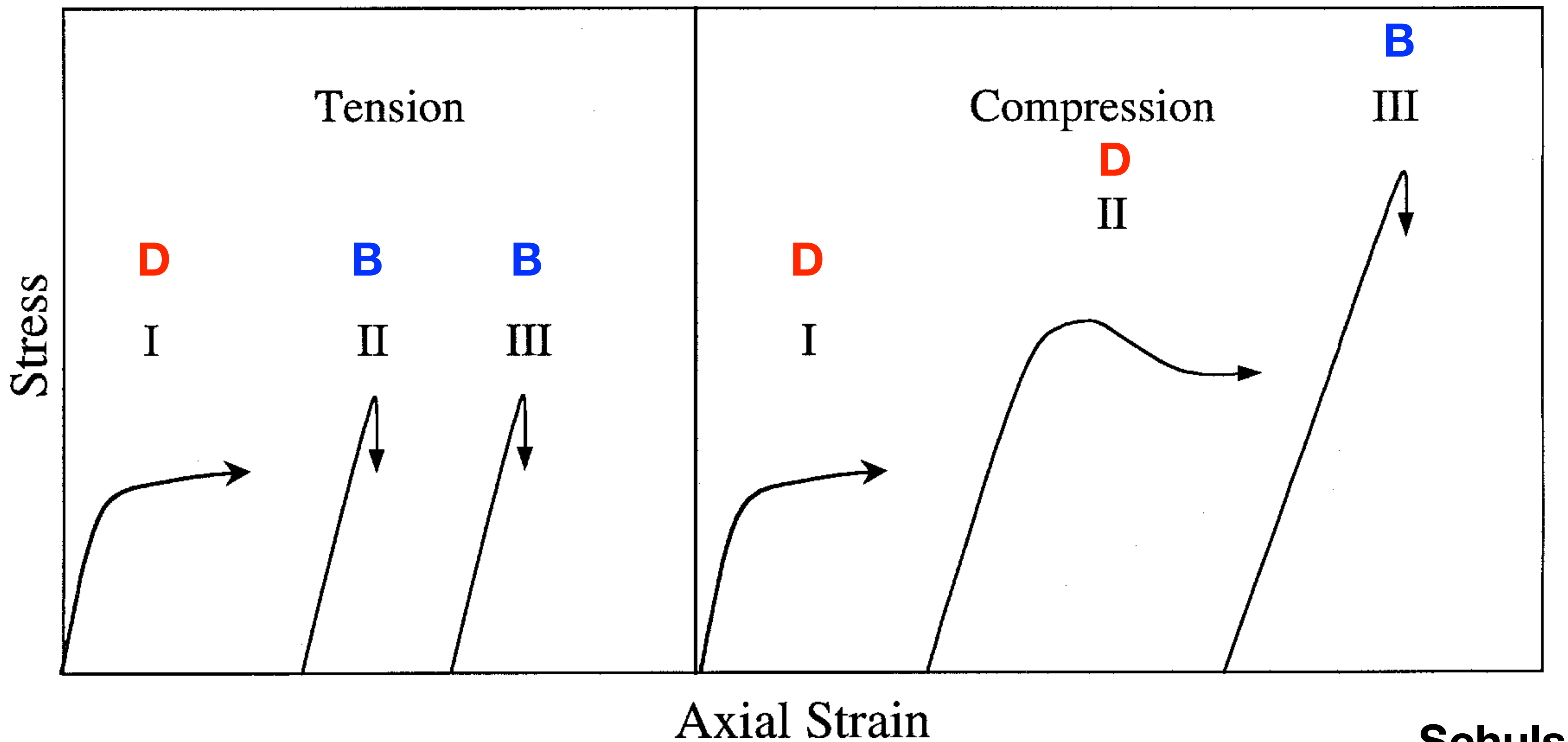


Turns out ice fractures pretty easily - not great for withstanding German torpedos - Pykrete (and the modern study of ice fracture) is born

Ductile-Brittle Transition

Ductile Behavior: material deformation without macroscopic dislocation (visible fractures)

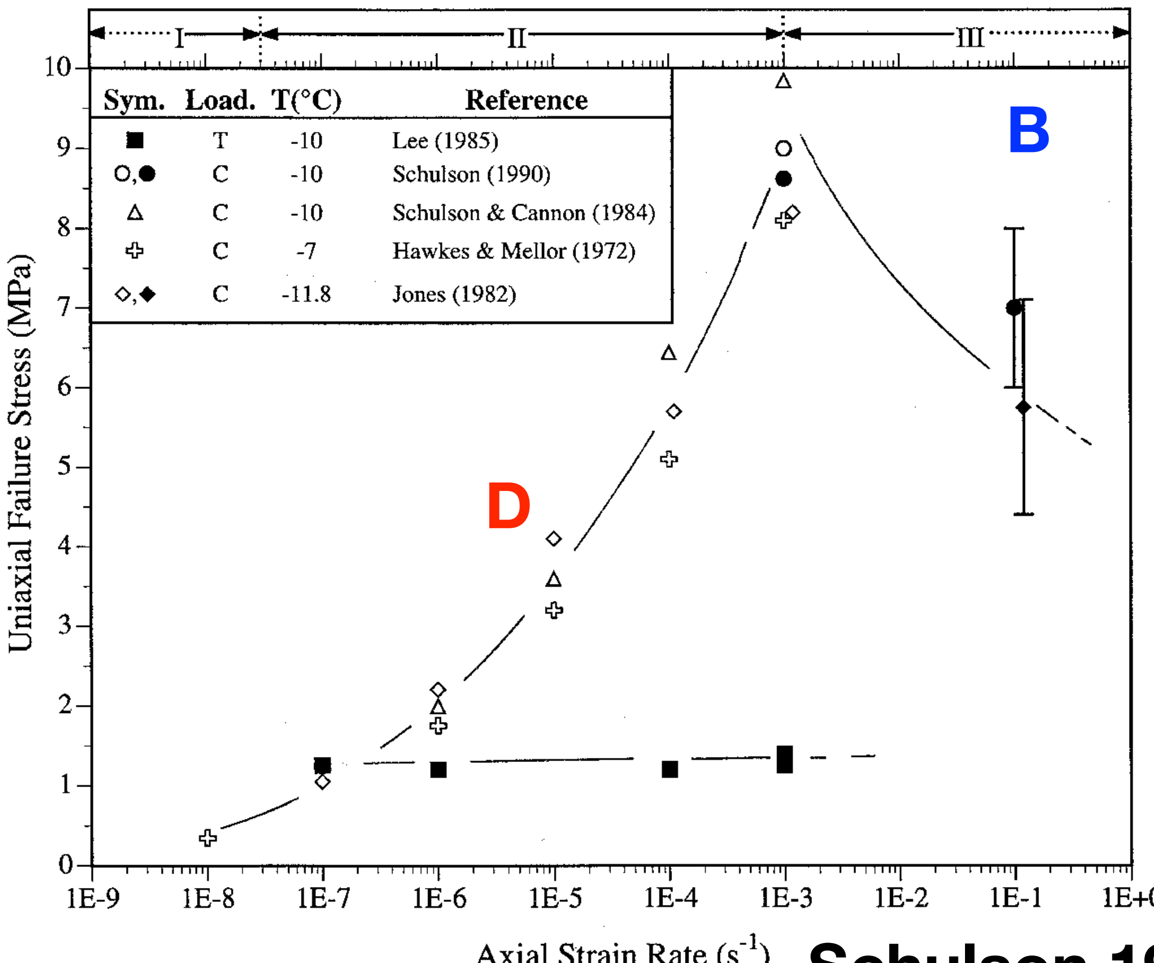
Brittle Behavior: material deformation through fracturing



Schulson 1999

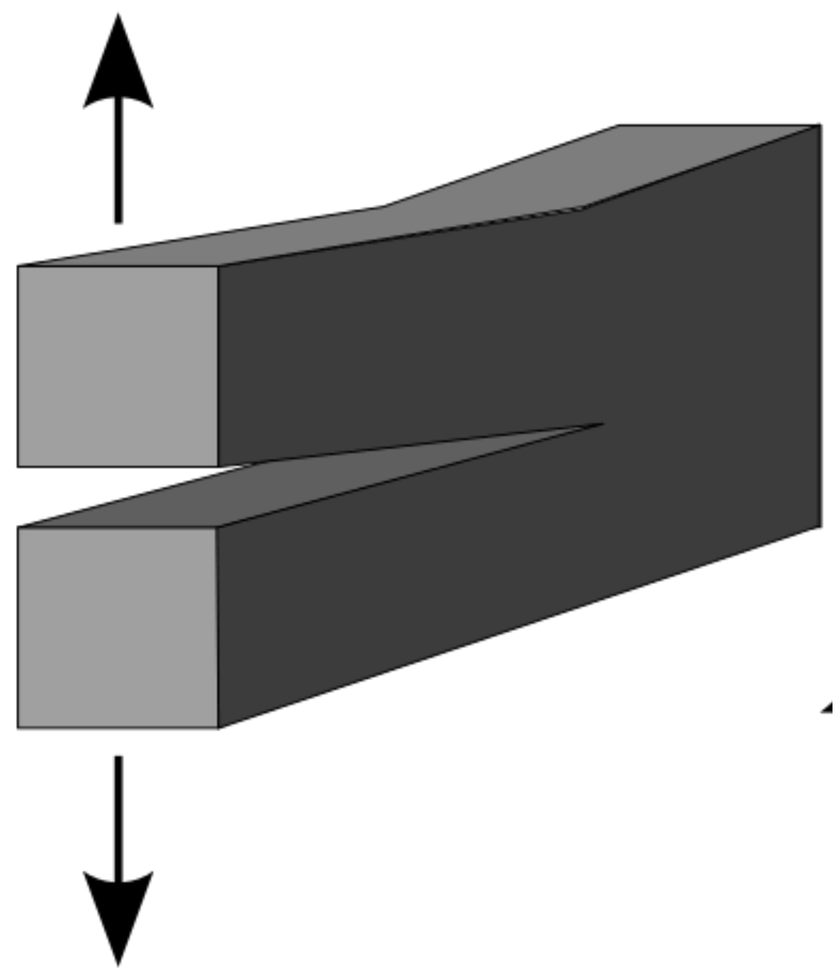
Ductile-Brittle Transition

The Ductile-Brittle Transition starts at (initially static) microscopic crack tips when stress build up becomes equal to (and then exceeds) the rate of local stress relaxation. At this point stress can only be relieved through extending the crack further causing the crack to grow from micro- to macroscopic.



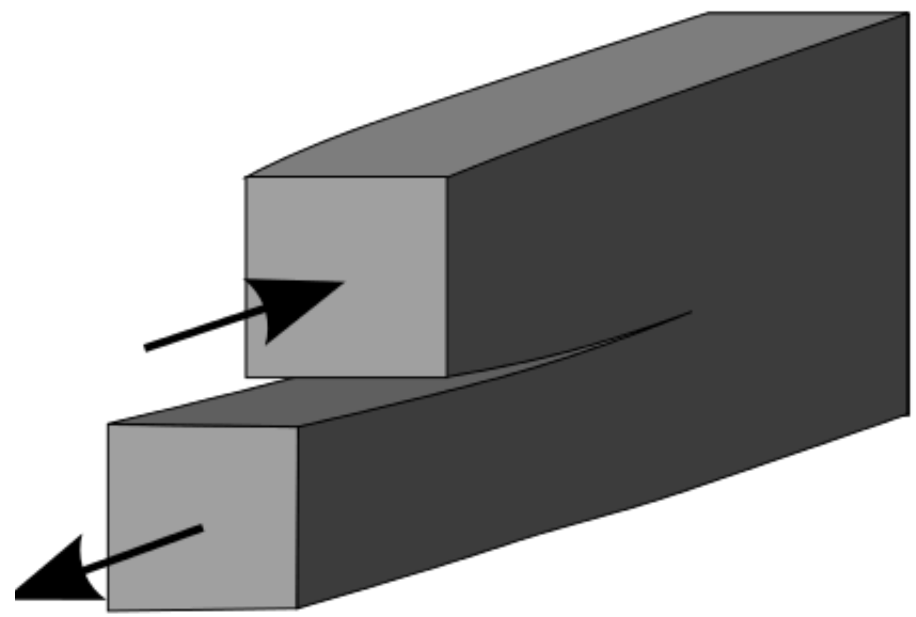
Schulson 1999

Fracture modes



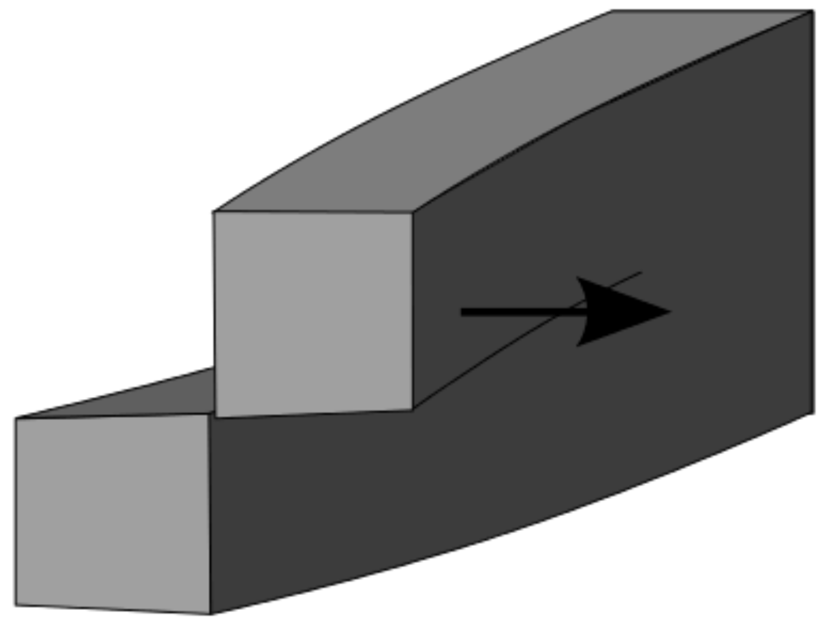
Mode I:
Opening

Fracture modes



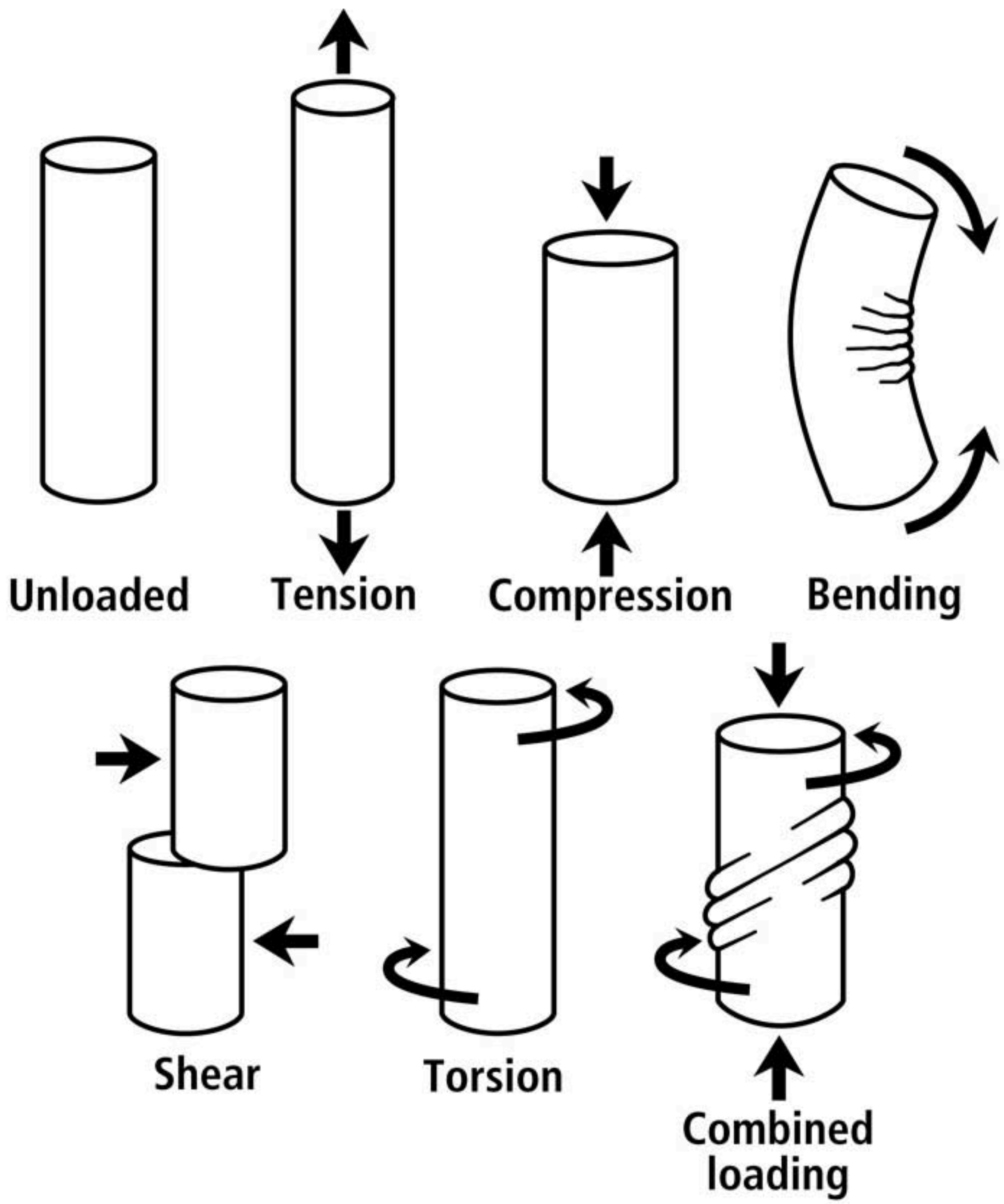
Mode II:
In-plane shear

Fracture modes



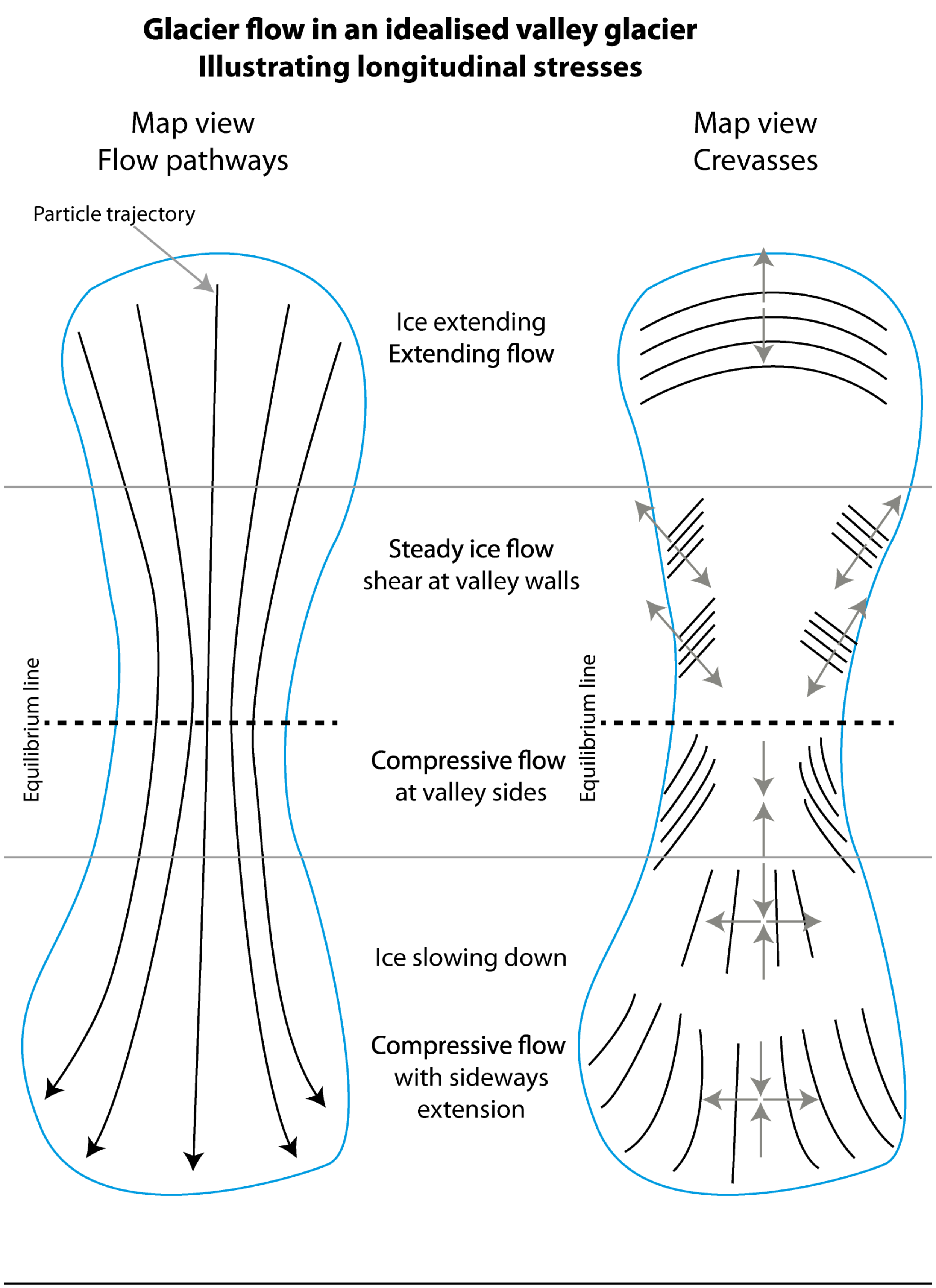
Mode III:
Out-of-plane shea

Surface crevasses



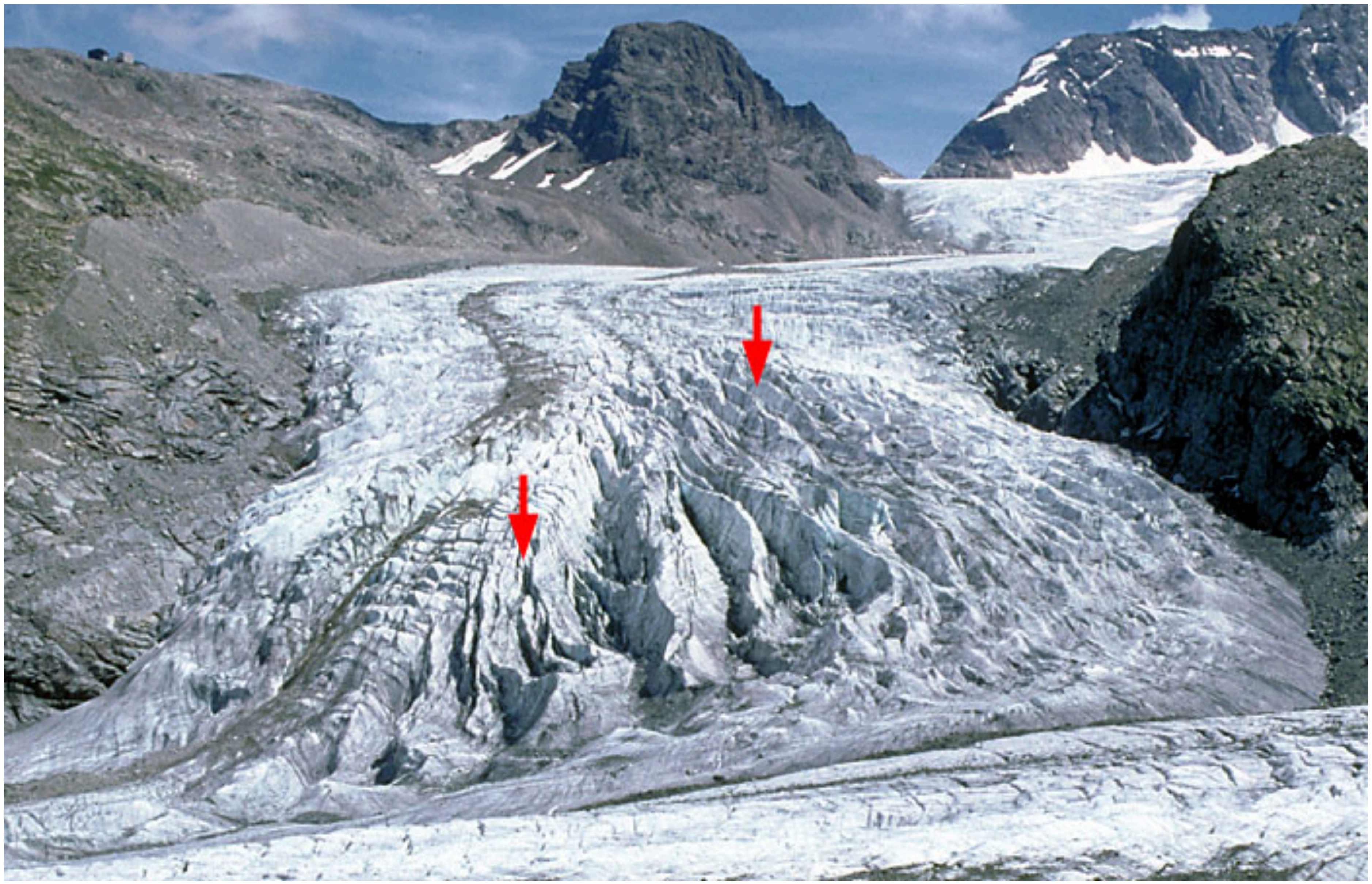
Most fractures in glaciers occur in tension - Mode I fracture - direction in which ice is the weakest

Surface crevasses



Generally three types of crevasses which form in different type of flow environments: longitudinal, transverse, shear crevasses

Surface crevasses



Longitudinal crevasses form in places where valley is becoming wider

Surface crevasses

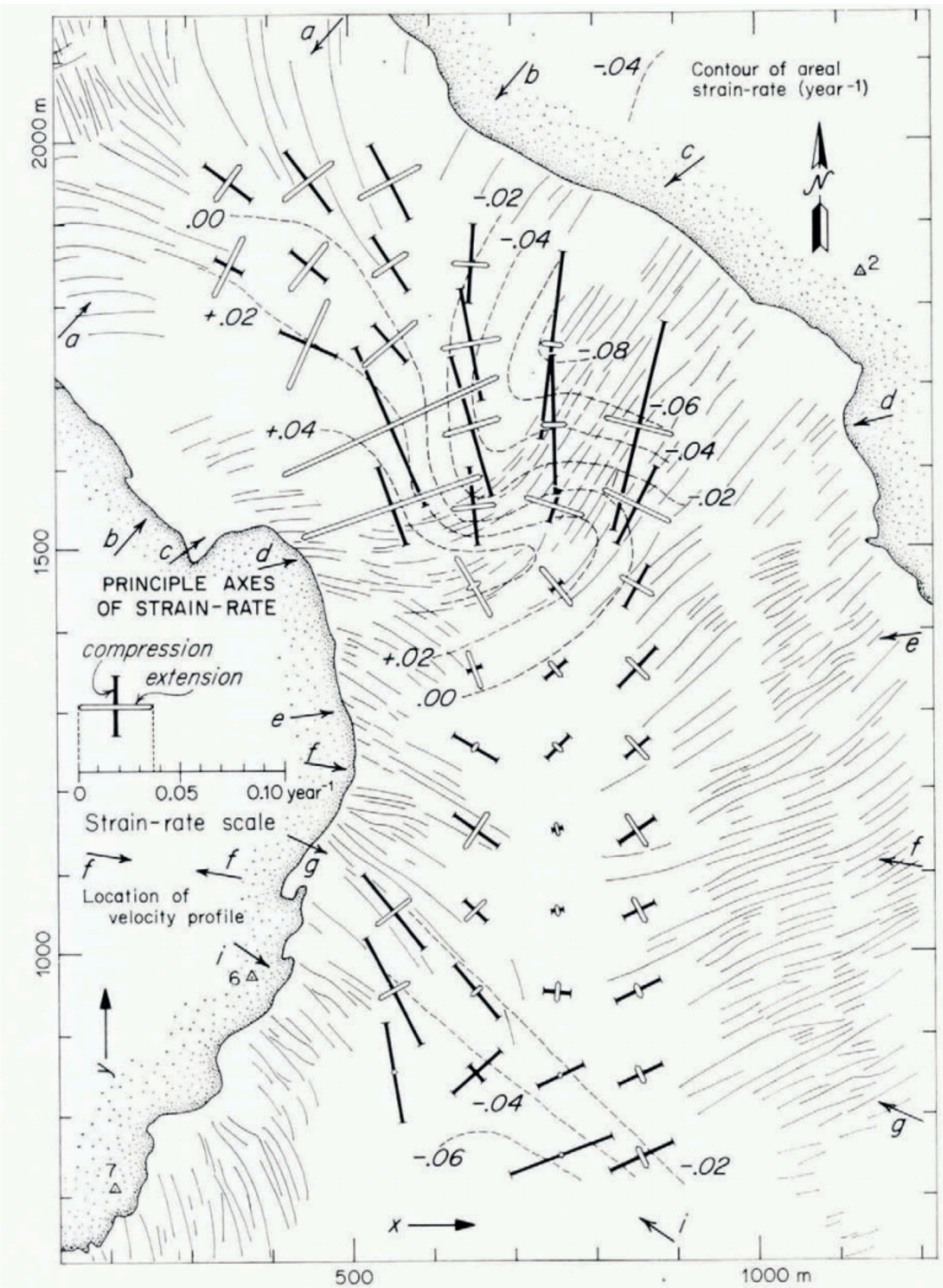
Transverse crevasses form in places where flow is extensional or there is a drop in topography

Surface crevasses

Shear or herring-bone crevasses form in places where flow is shearing - typically near the lateral edge of a glacier

Surface crevasses

Meier et al. 1974

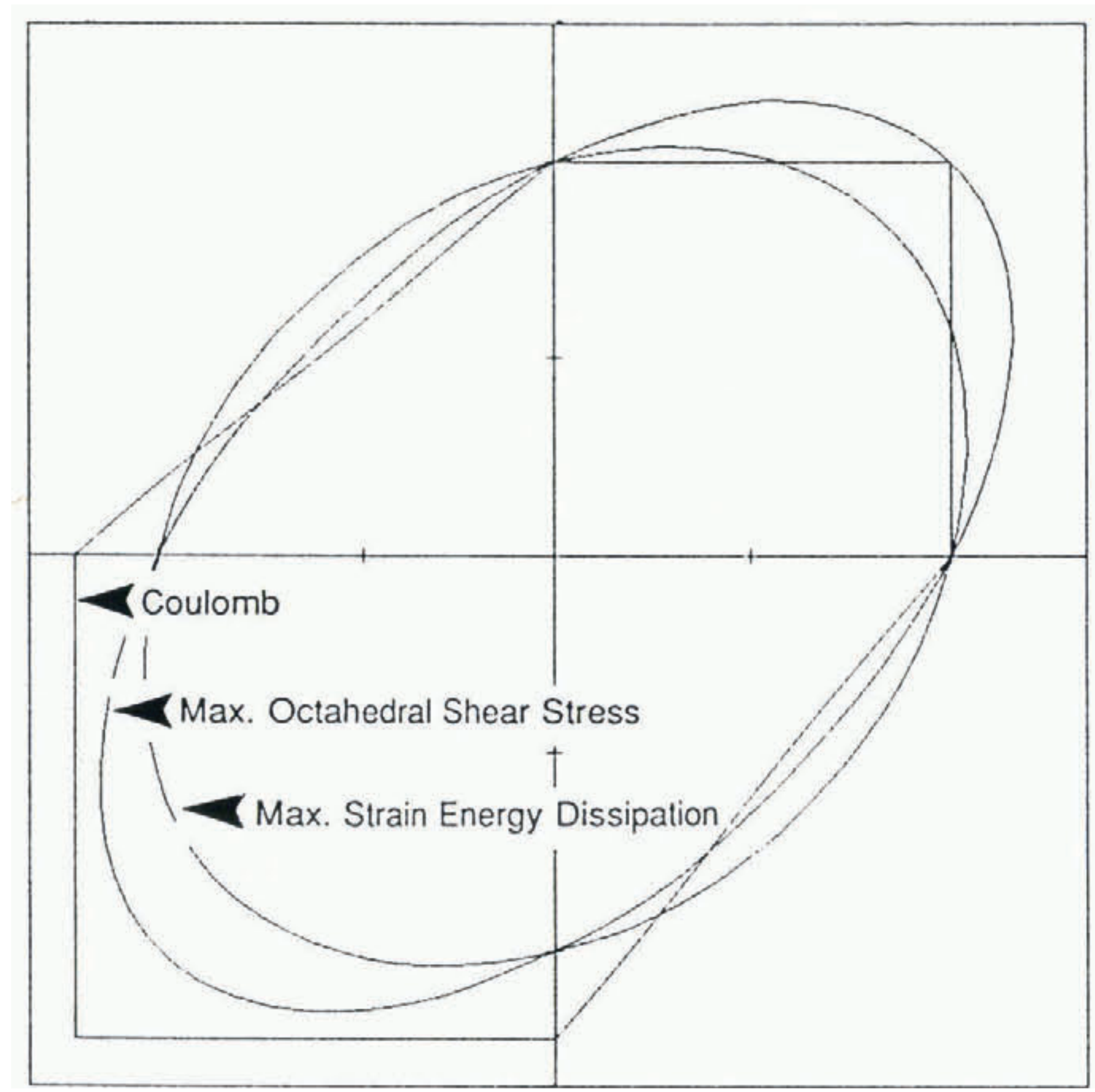


The <u>direction of principle tensile strain rate will tend to perpendicular to the direction that the crack will propagate</u>

(except sometimes the principal strain rate is aligned with the principal stress)

Surface crevasses

Observations of crevasses co-located with measurements of strain rate (which can be converted to stress using Glen's constitutive law) can be used to estimate "failure envelopes" for glacial ice



Vaughan 1993

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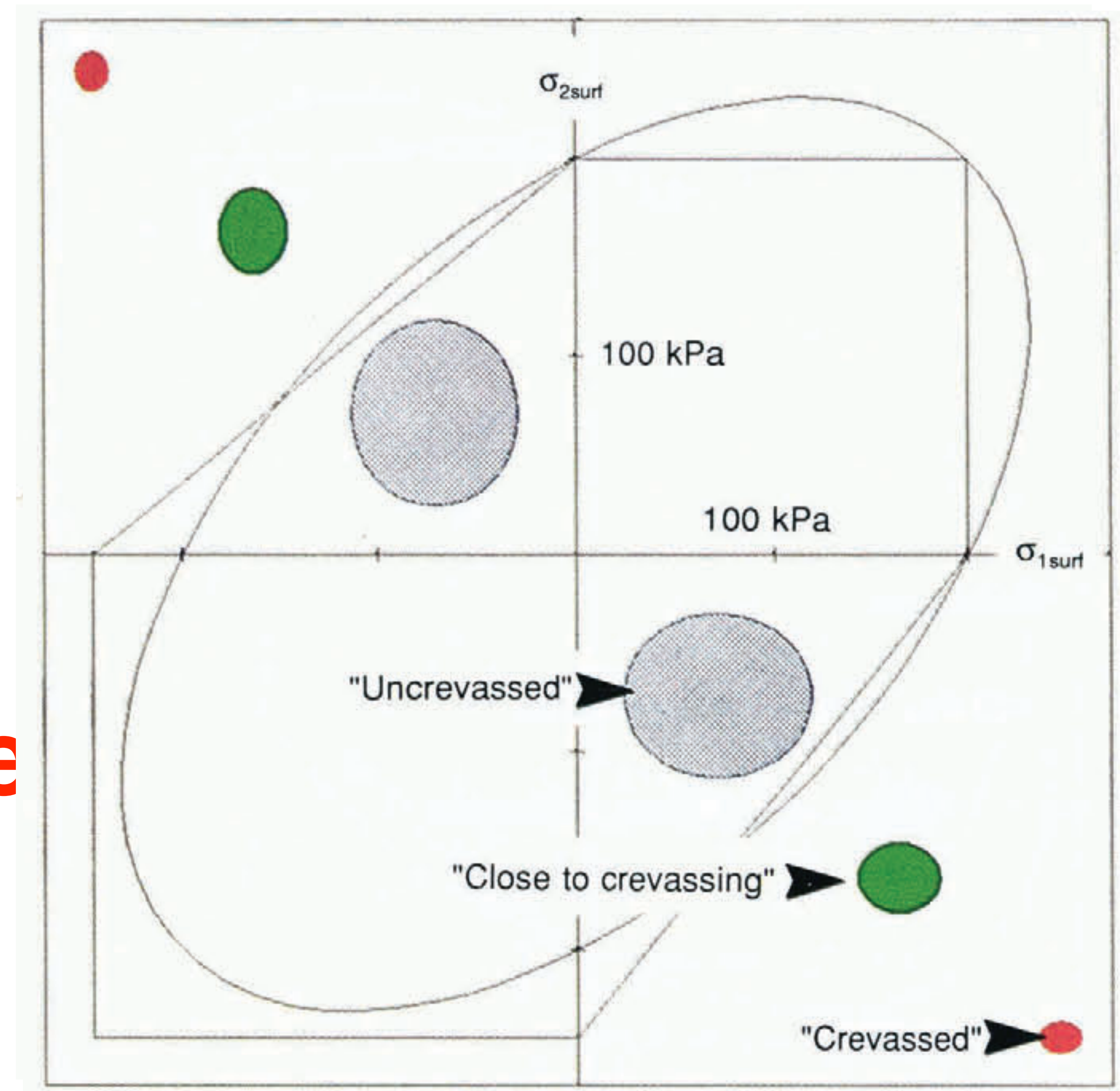

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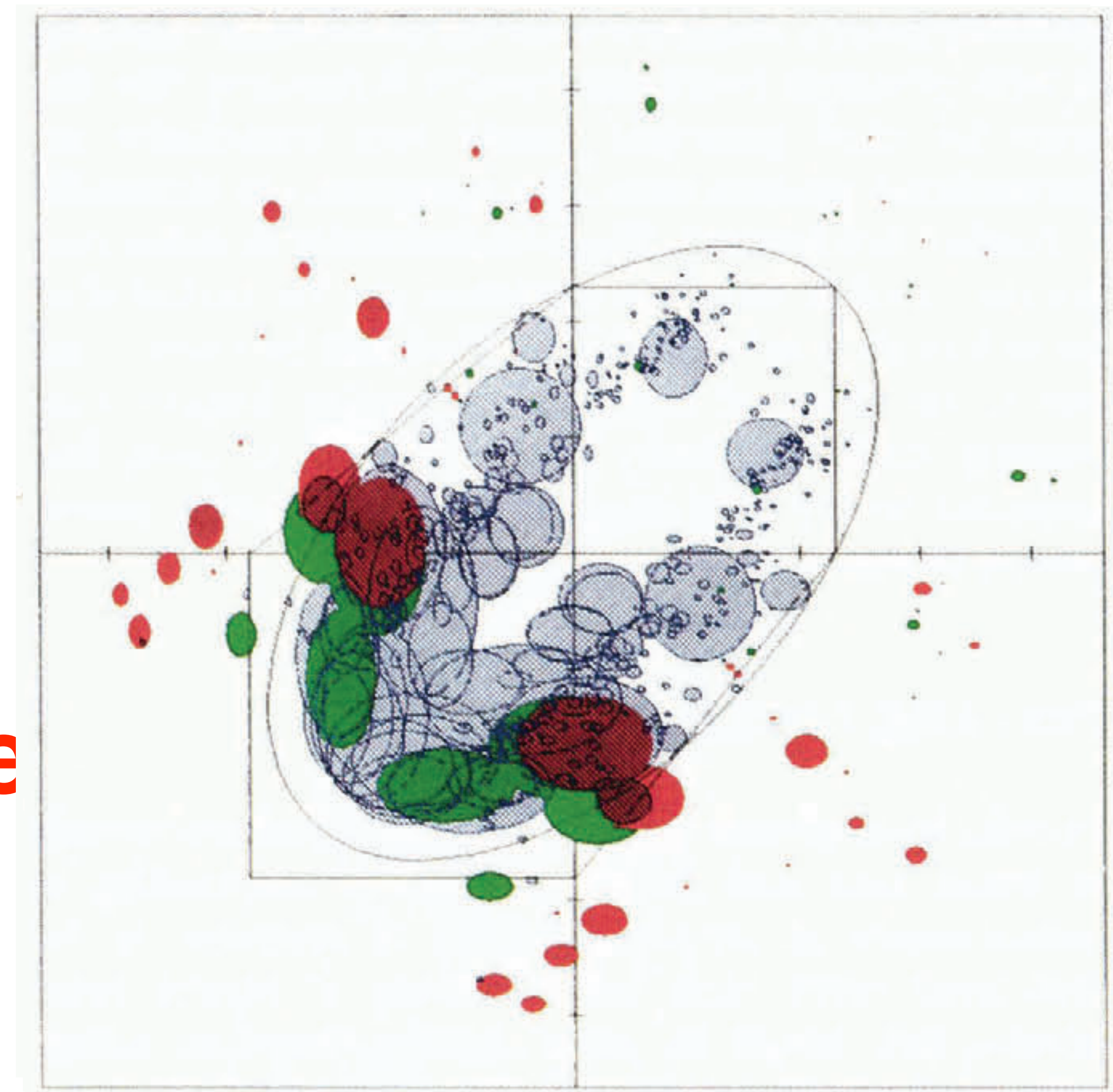
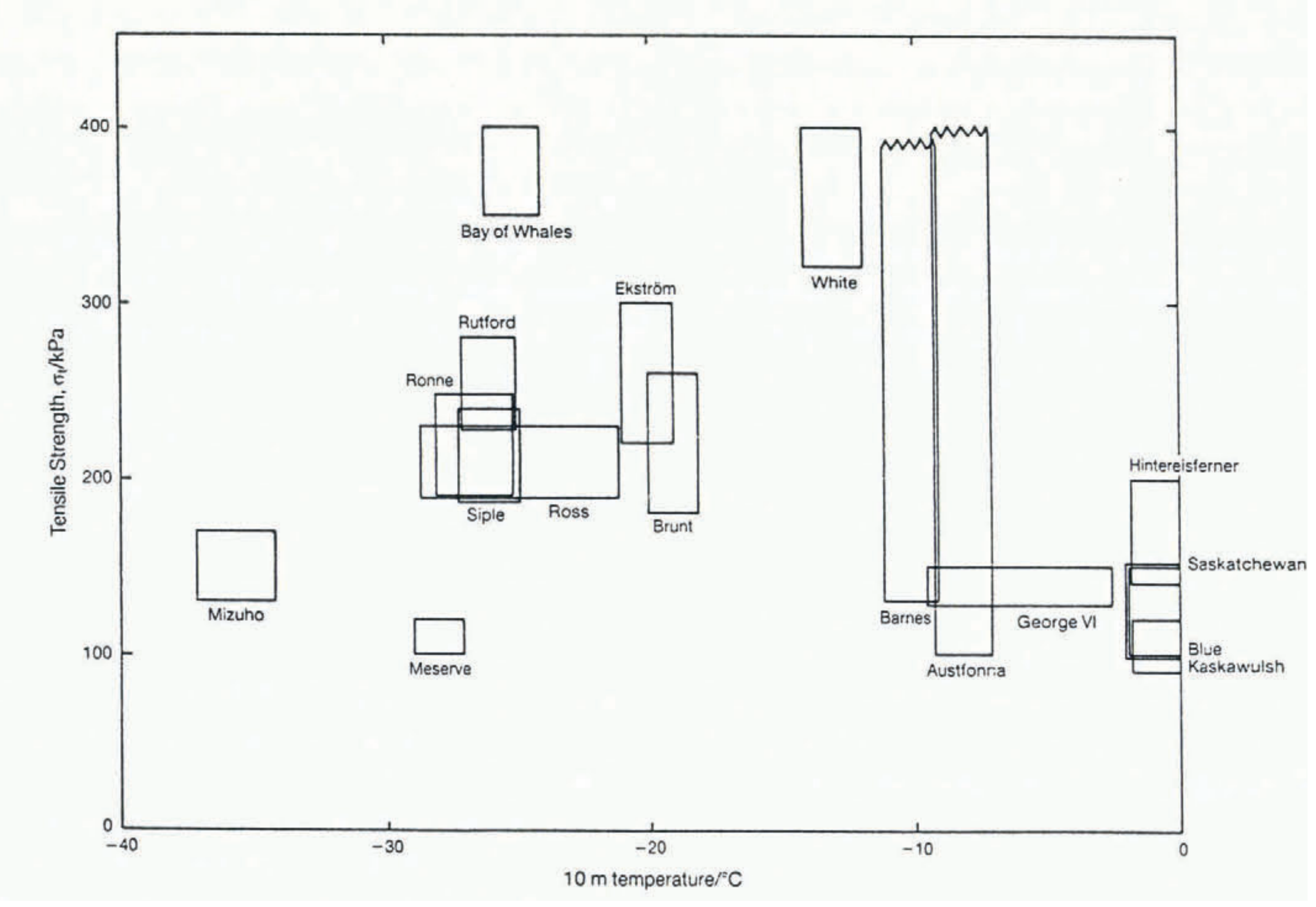


Vaughan 1993

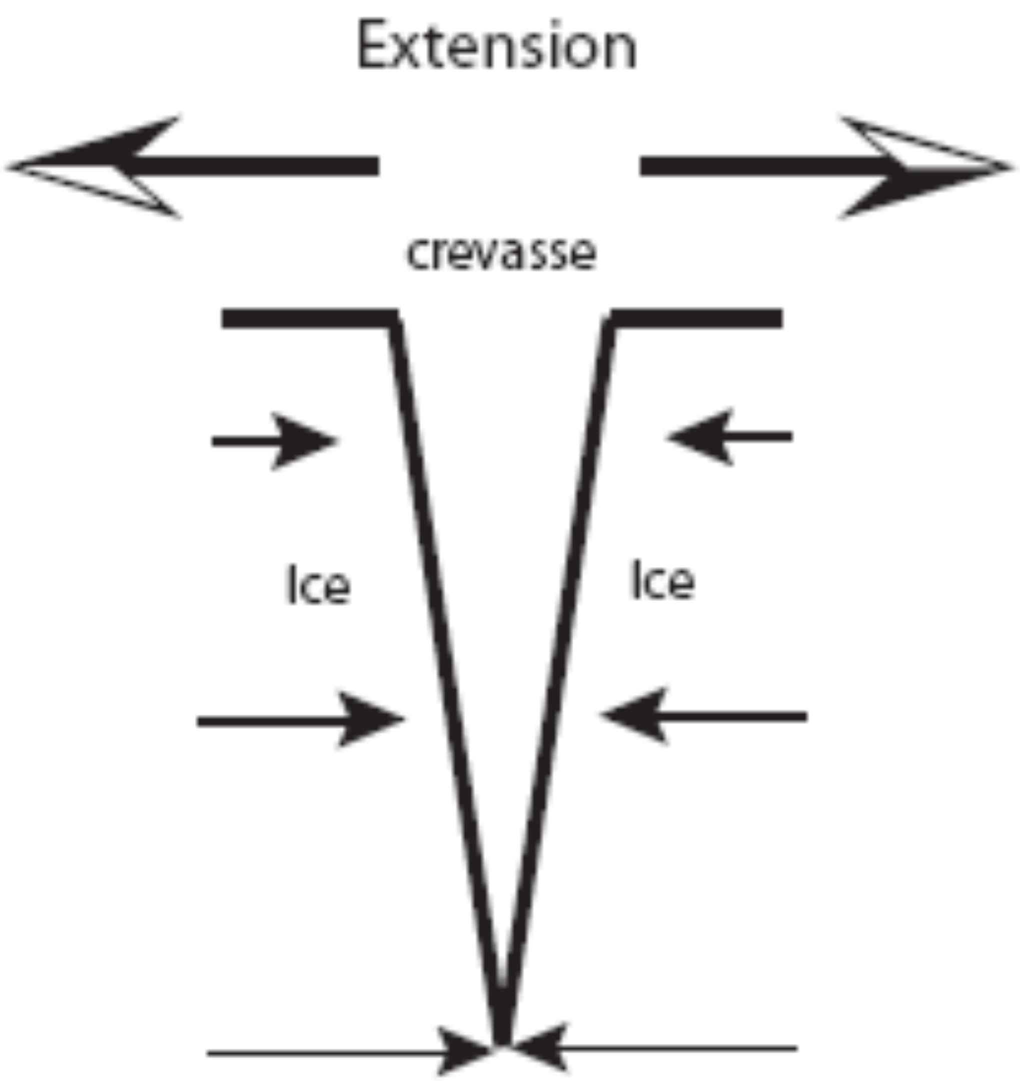
Surface crevasses

The problem: maximum tensile strength (i.e. the stress at fracture) seems to vary from 90 kPa to 320 kPa) - depends on many microscopic properties of ice - not just temperature



Vaughan 1993

Nye's zero stress theory of fracture depth



Remember from our discussion of hydrology:

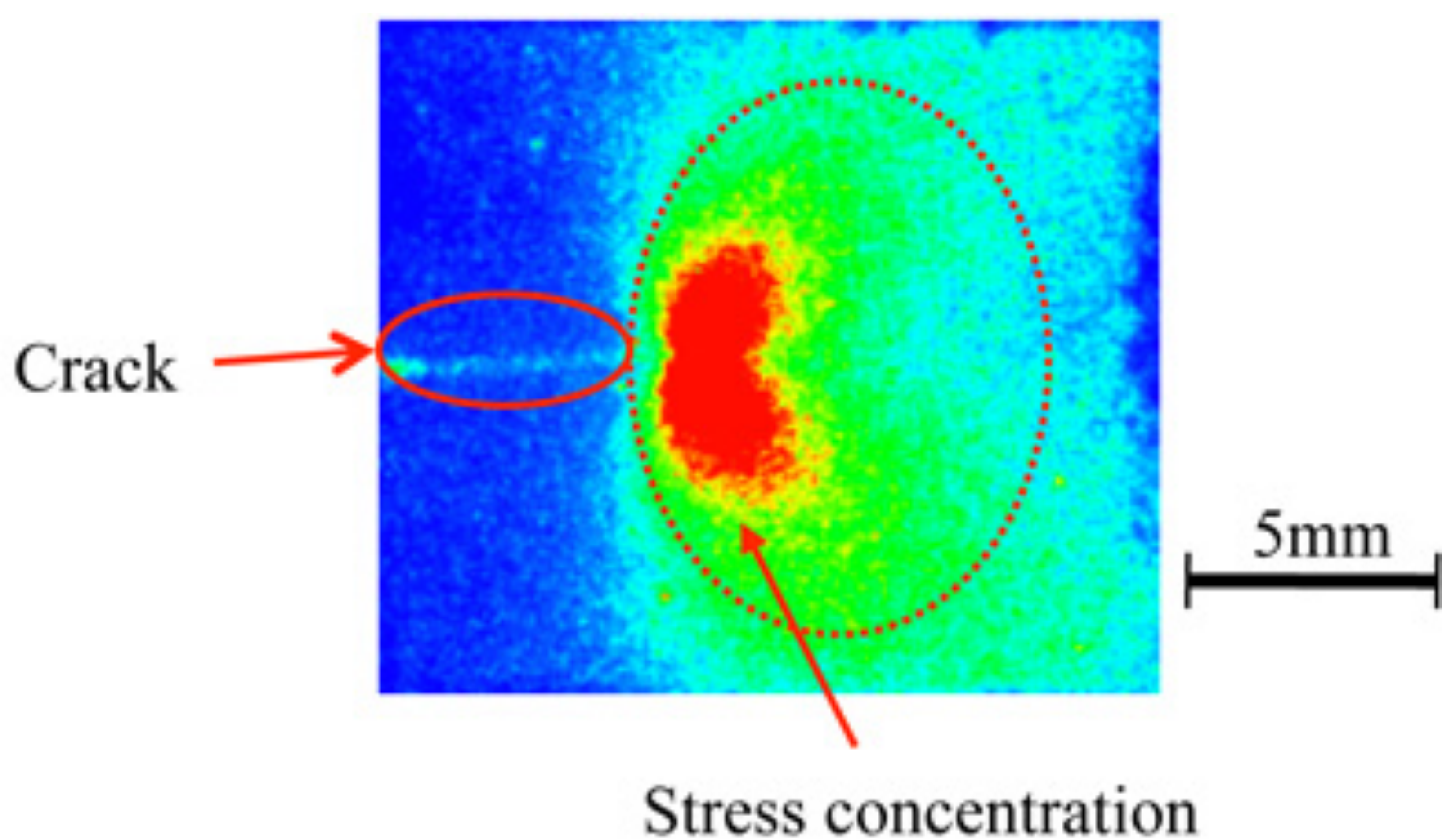
$$\tau_{xx} = \rho_i g d$$

Tensile stress opening fracture

Lithostatic stress (ice weight) closing fracture at depth

The problems with Nye zero stress theory

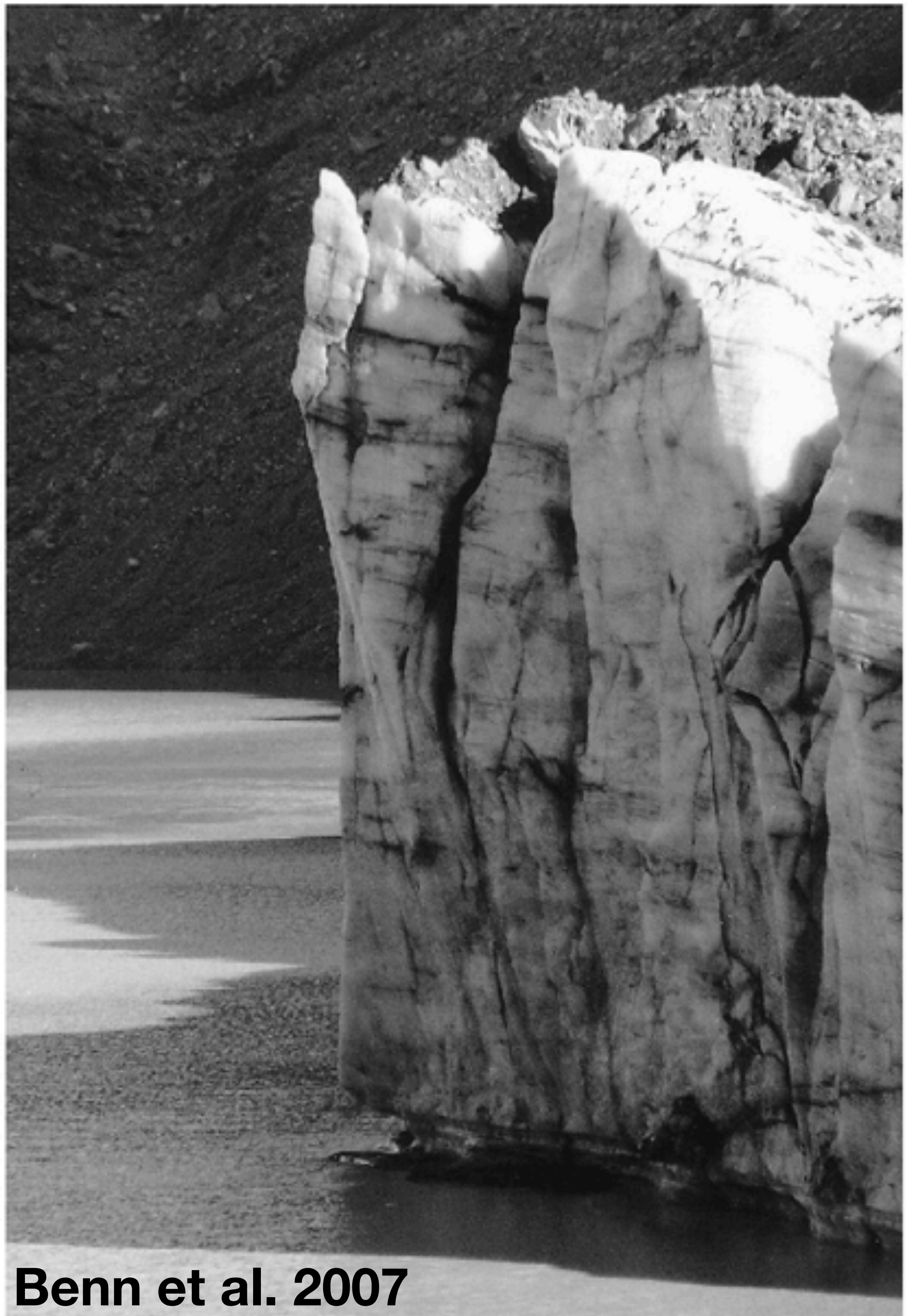
- Ice has fracture toughness greater than zero
- The large scale stresses are not the same as the stresses near a fracture's crack tip



Fracture mechanics

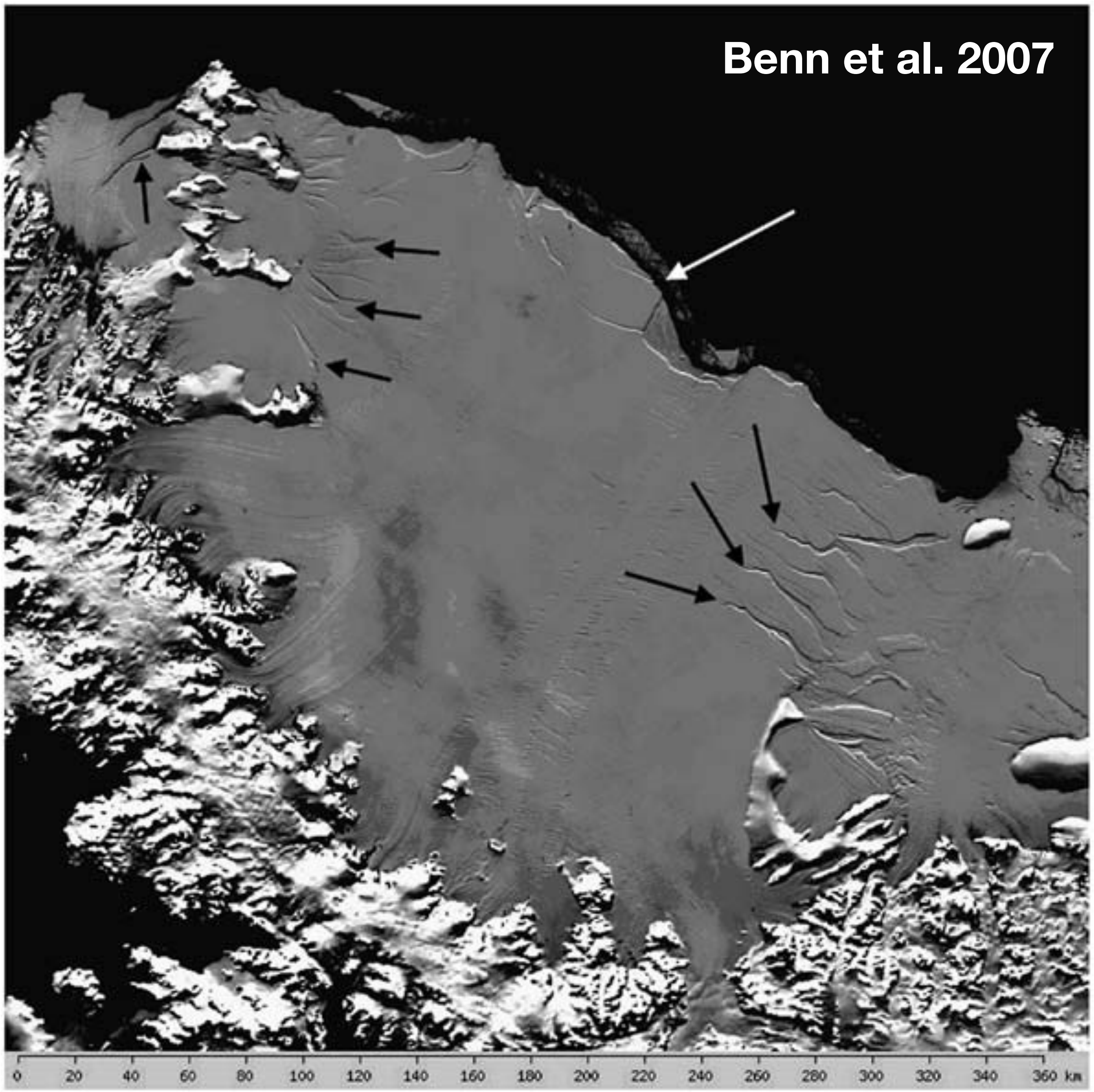
- To the board! LEFM discussion from van der Veen Ch. 8

Iceberg calving



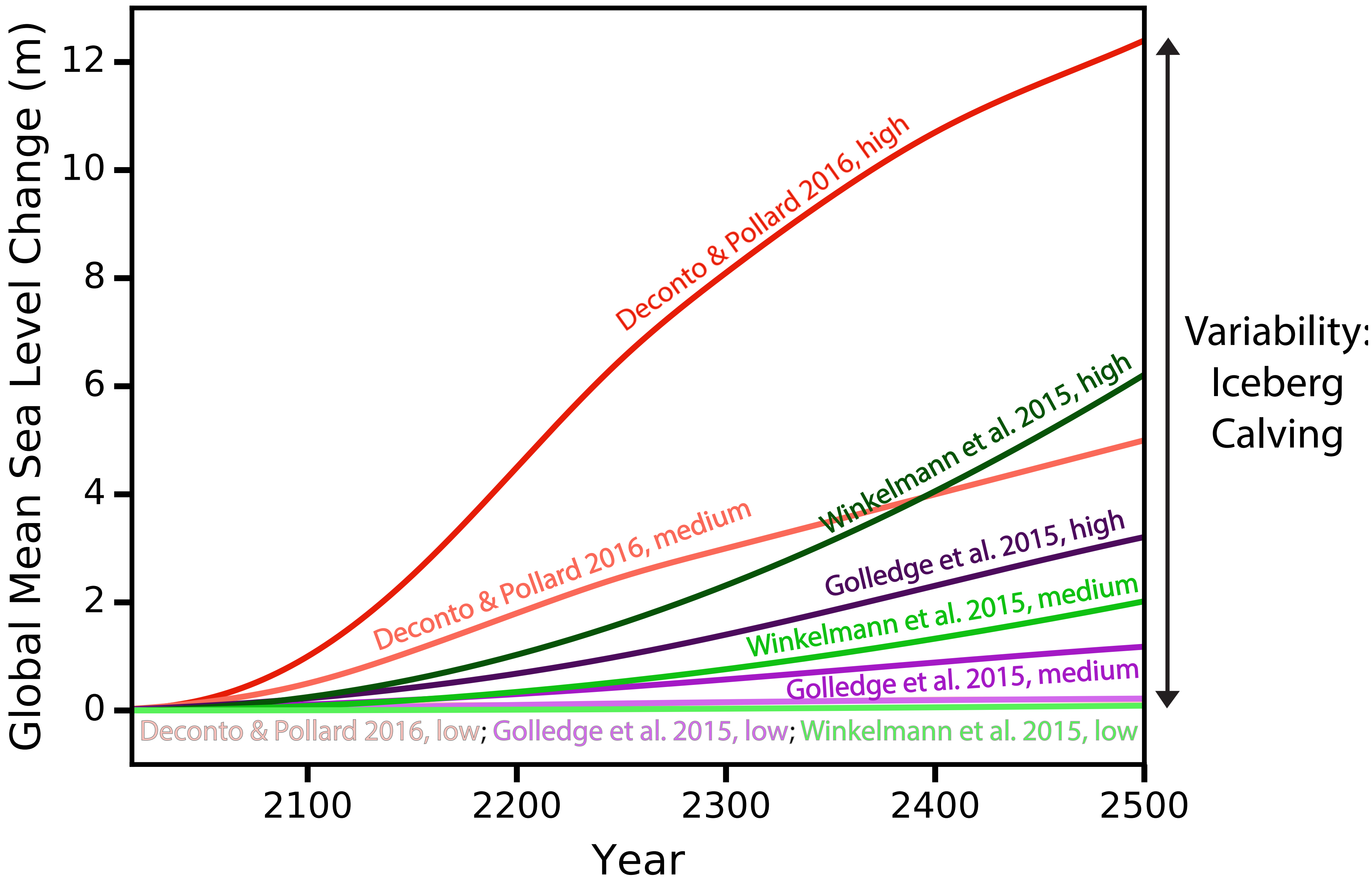
Fractures that penetrate all the way to the base and all the way through the width of a glacier near the glacier terminus in the ocean lead to iceberg *calving*

Iceberg calving



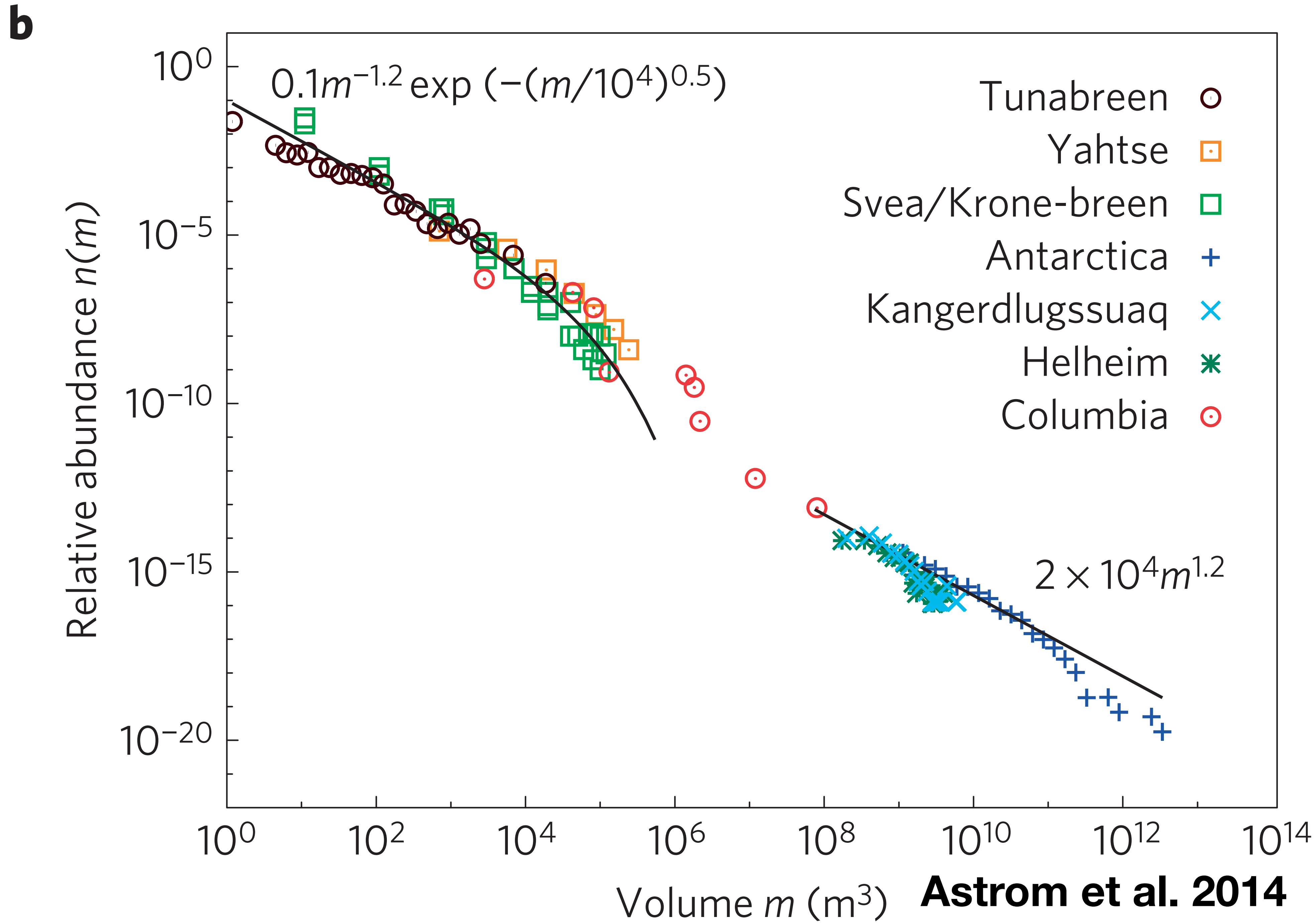
For marine ice sheets, calving can be the most important way in which ice is lost from the glacier (compared to surface/ocean melt)

Iceberg calving



Calving is also one of the biggest unknowns in ice sheet models and the reason why there are large differences in sea level rise prediction between ice sheet models

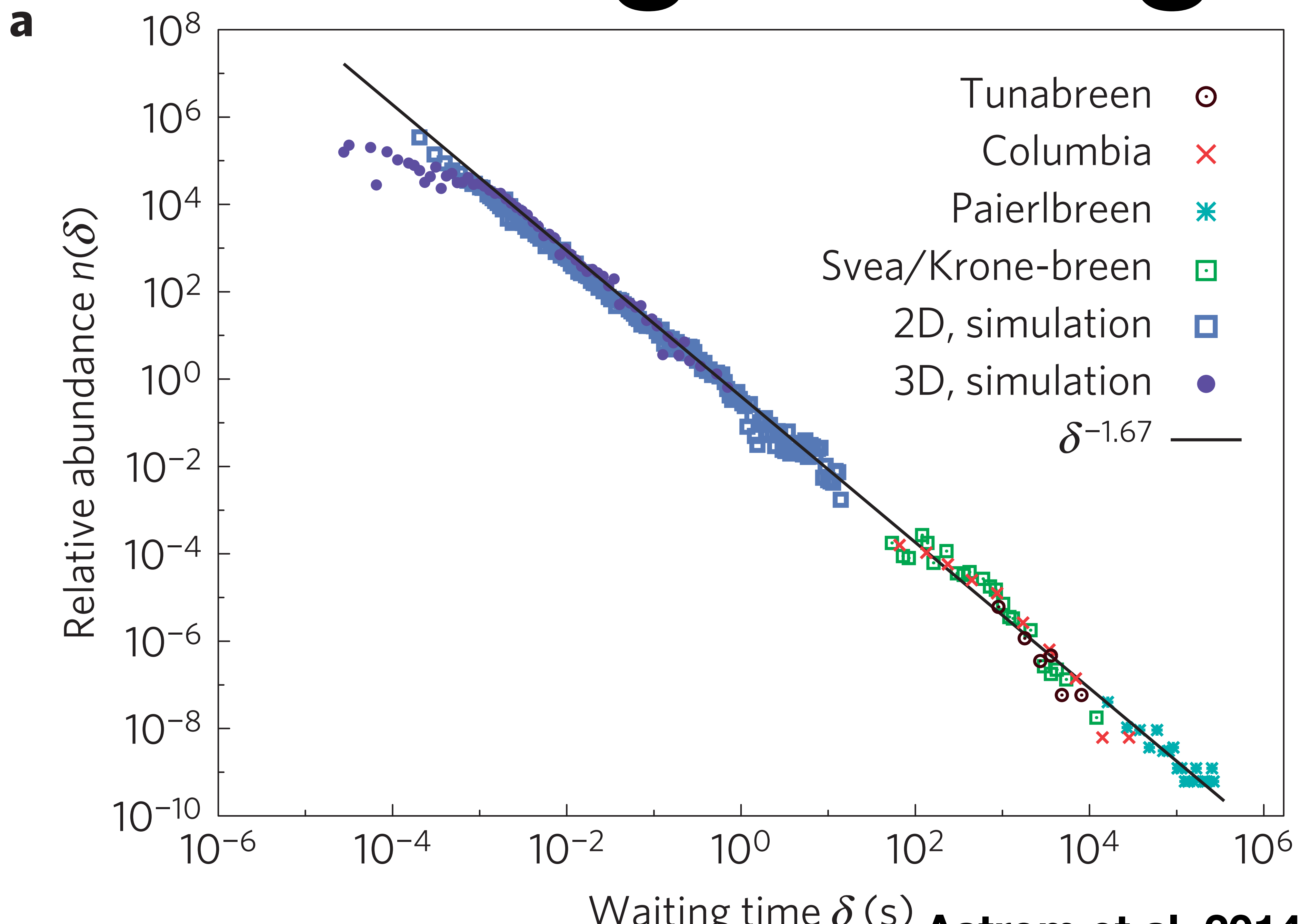
Iceberg calving



Astrom et al. 2014

Calving occurs across a wide range of scales - from person sized (1 m^3) to state-sized (10^{12} m^3)

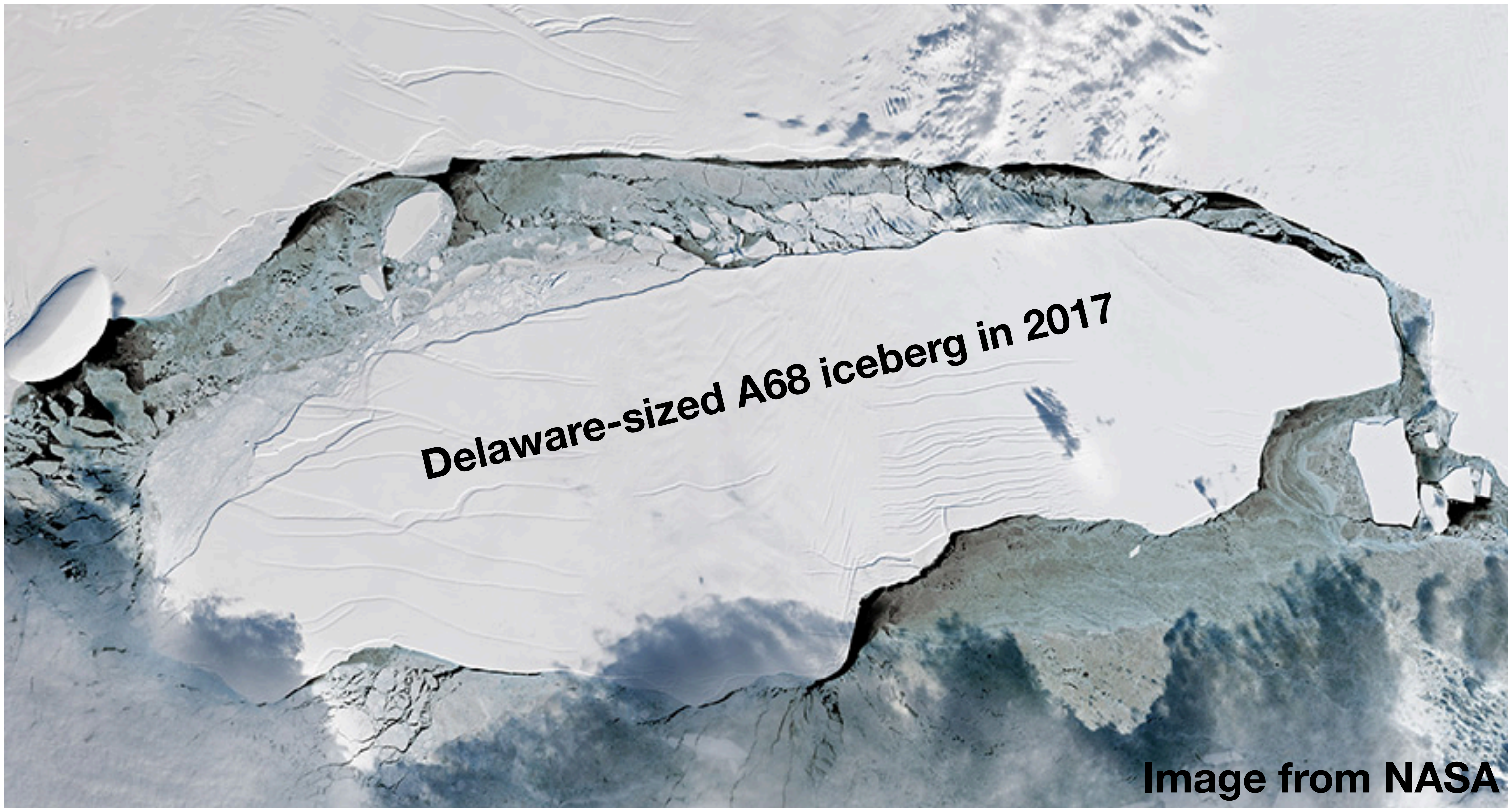
Iceberg calving



Astrom et al. 2014

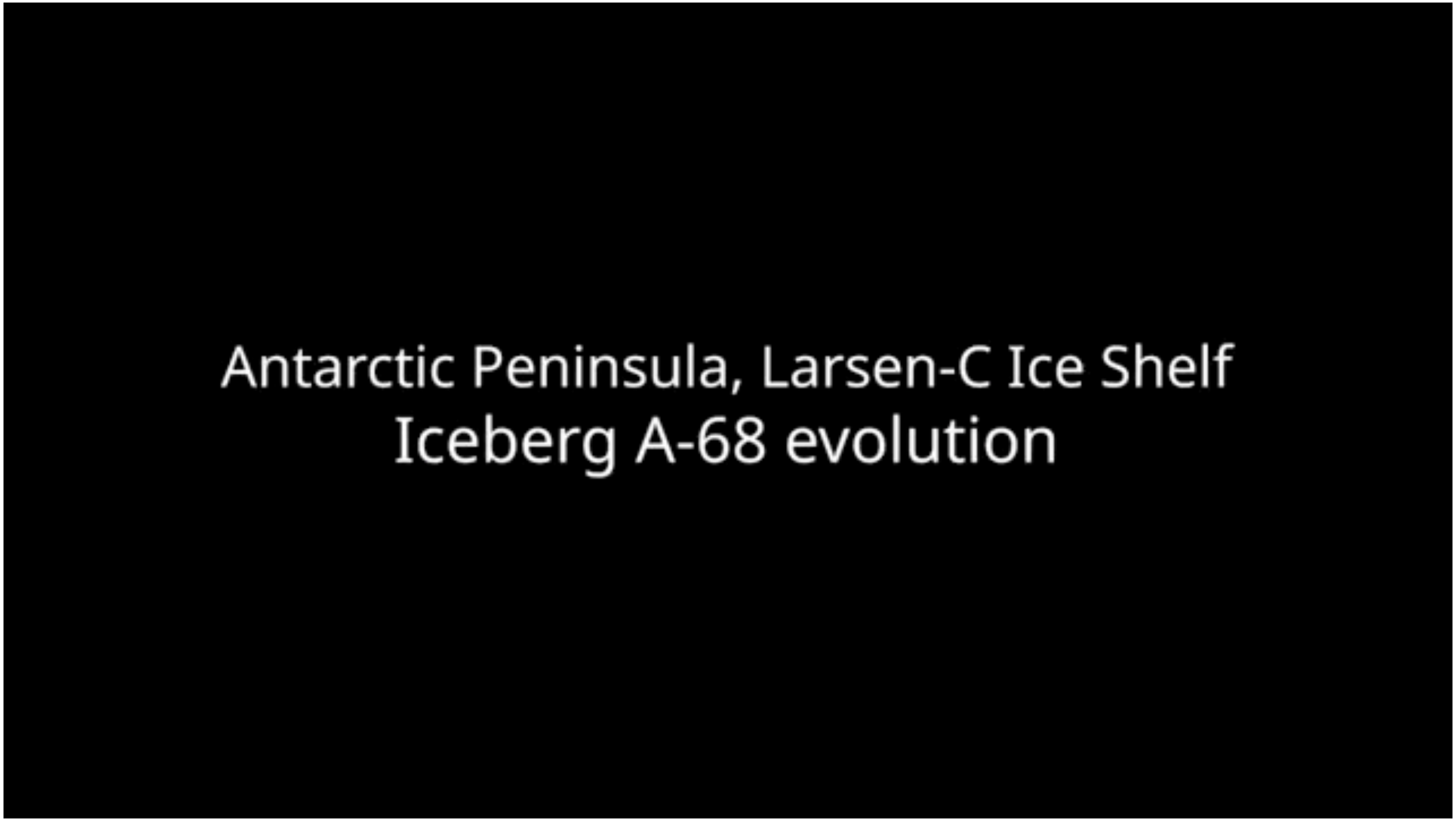
Calving intervals also occur across a wide range of time scales - from seconds to decades

Styles of calving



Tabular iceberg rifting: very large icebergs that are larger horizontally than vertically, detach due to rifting in ice shelves

Styles of calving



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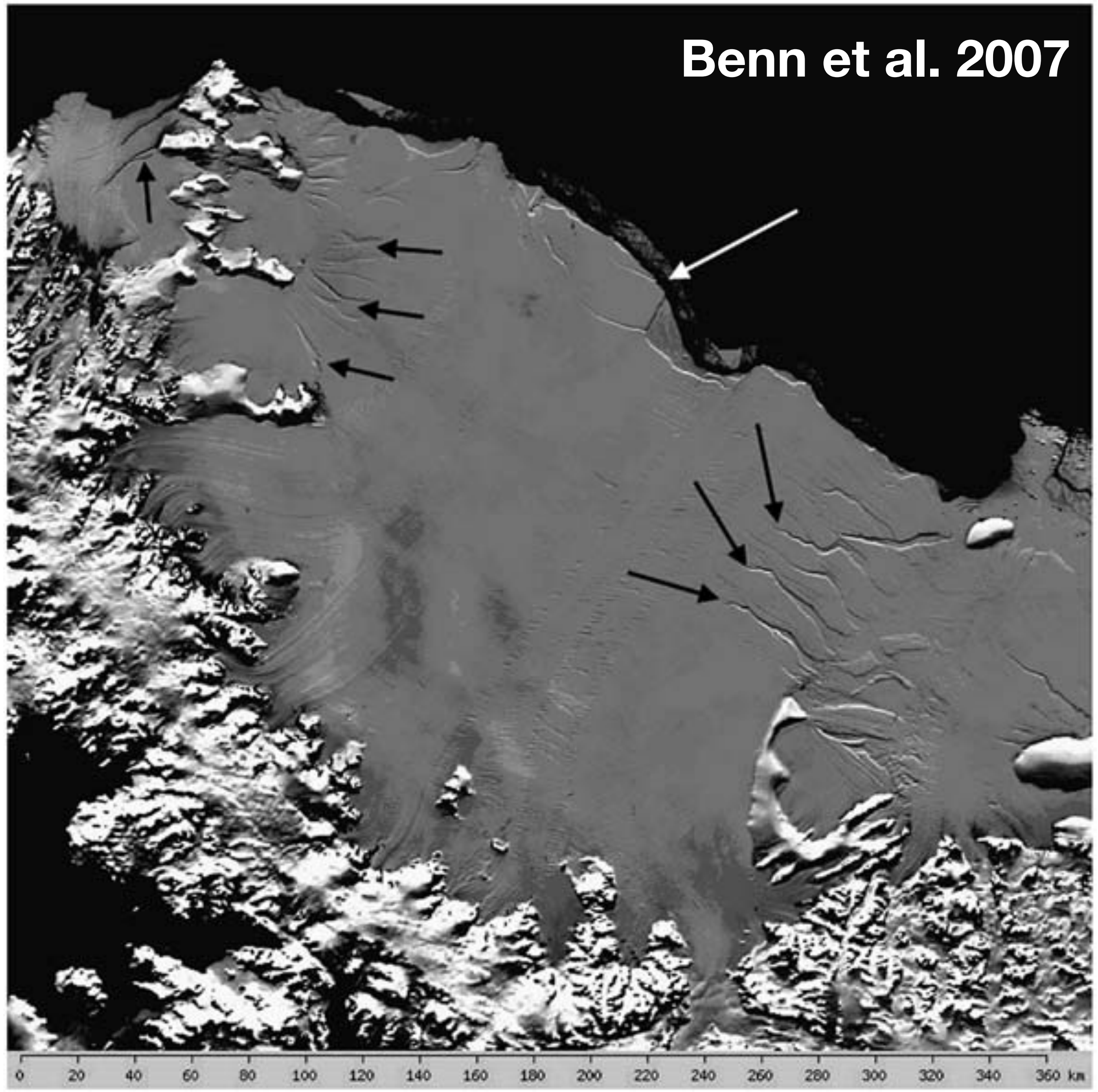

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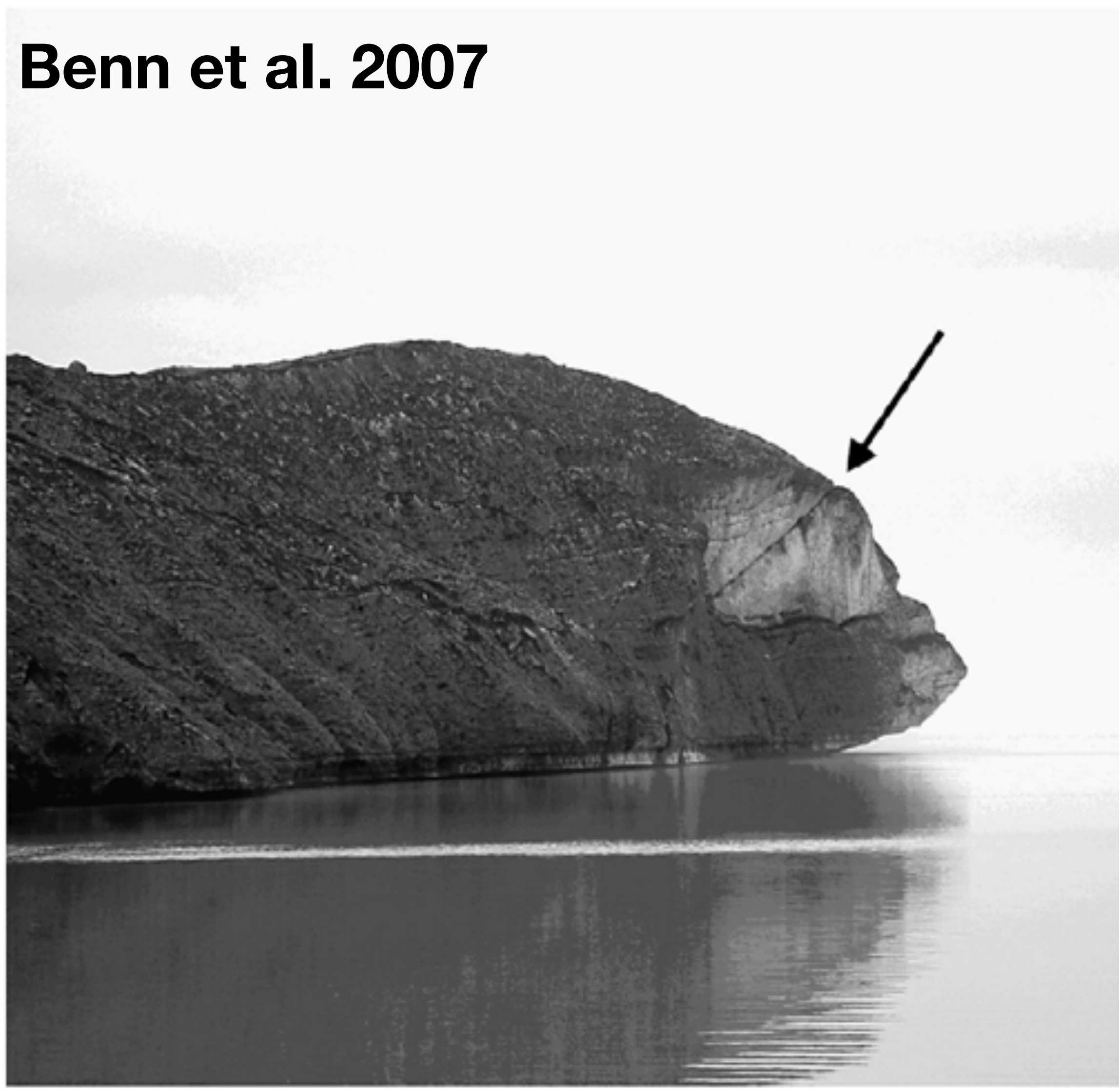
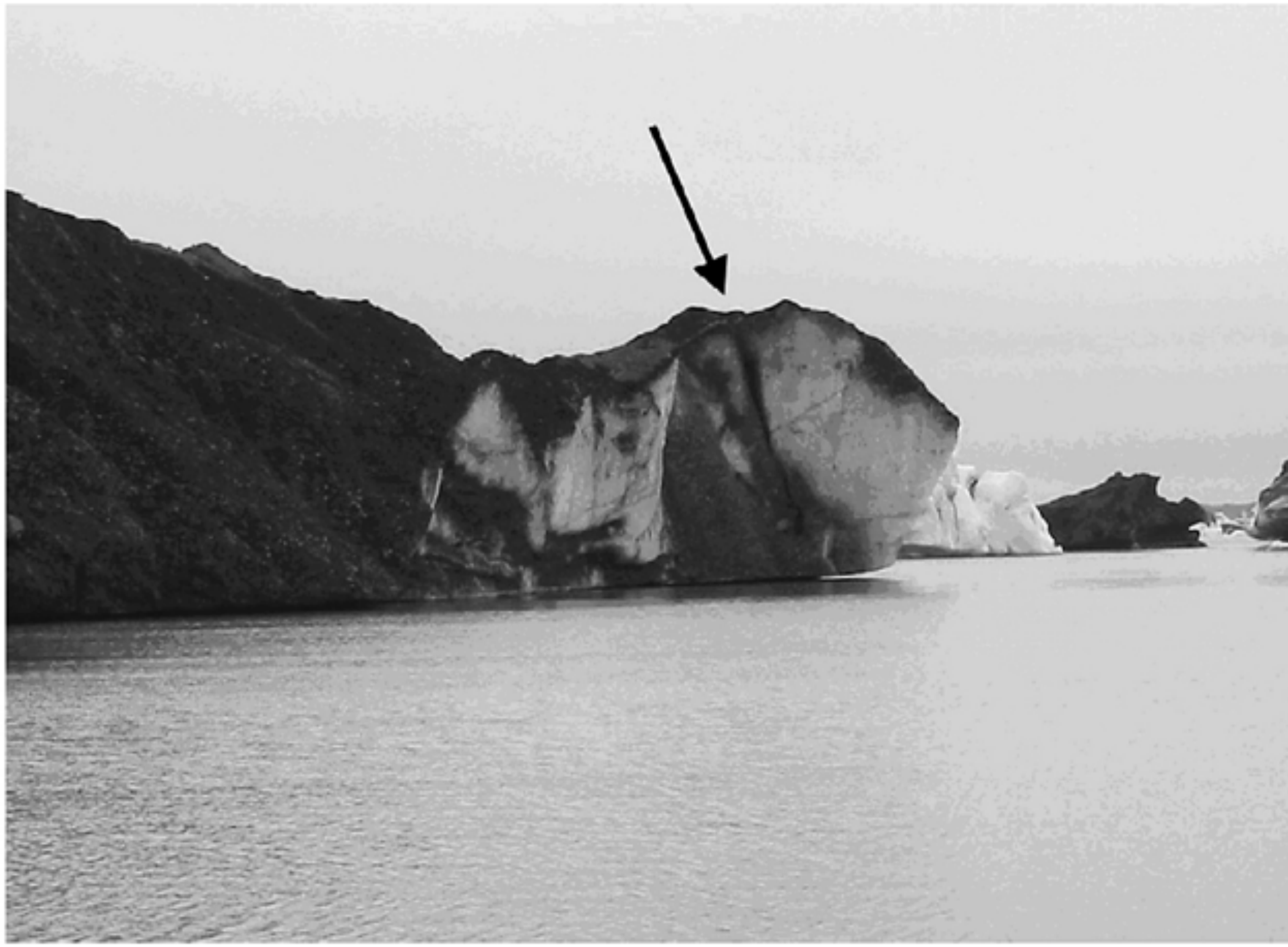
Styles of calving

Tidewater glacier detachment and rotation: full thickness calving event

Styles of calving





Melt undercutting and overhang collapse

The spectrum of calving

after Cuffey and Paterson, Ch. 4.6

$$\frac{dL}{dt} = u_L - \dot{c} - \dot{m}$$

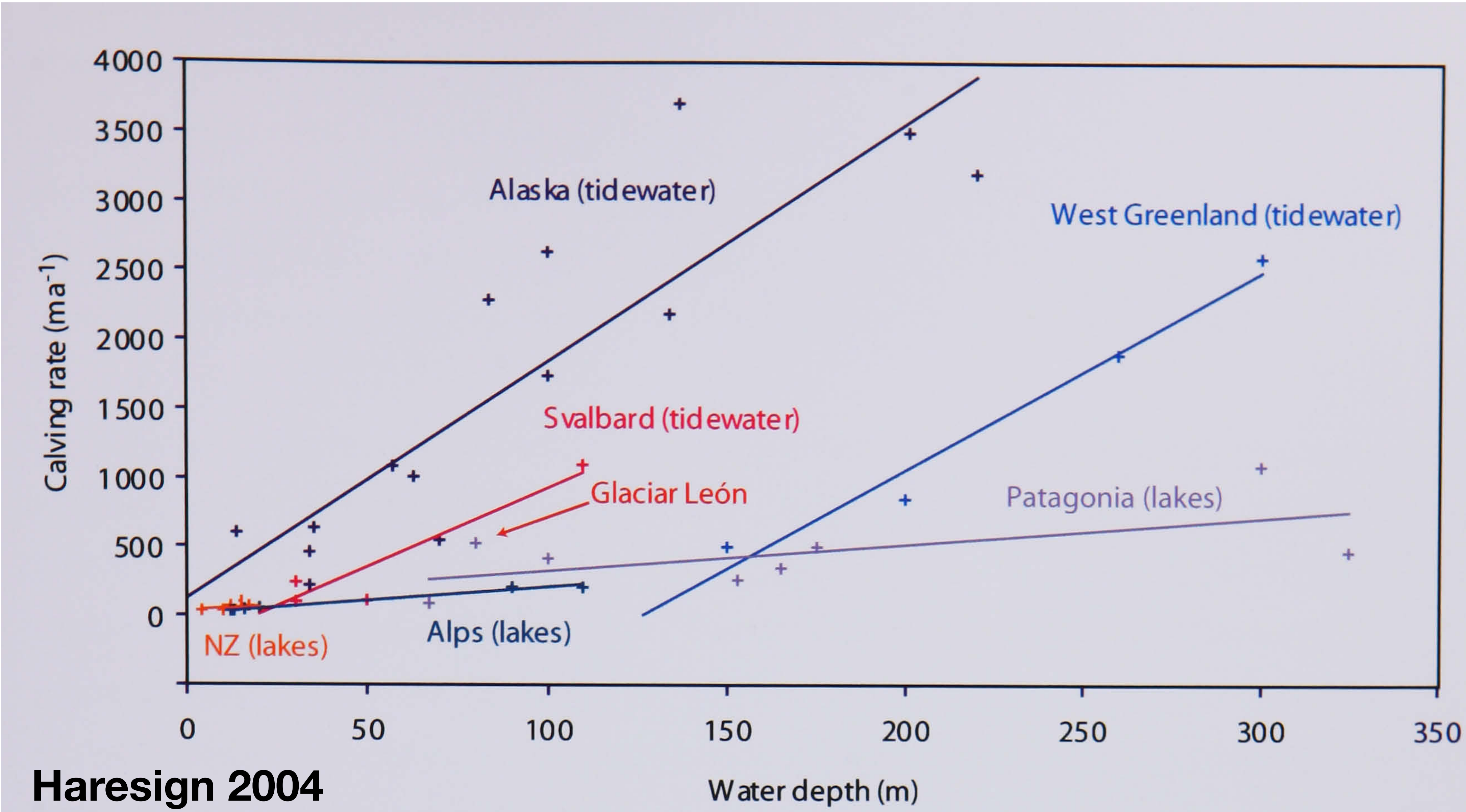
Terminus change — Ice velocity into terminus — Calving rate — Ocean melt rate

One idea: calving either

(a) Removes all ice that flow to the terminus, keeping the terminus near balance (i.e. calving passively responds to large-scale ice flow)

(b) Responds to other processes (leading to potentially large terminus changes)

The many calving laws

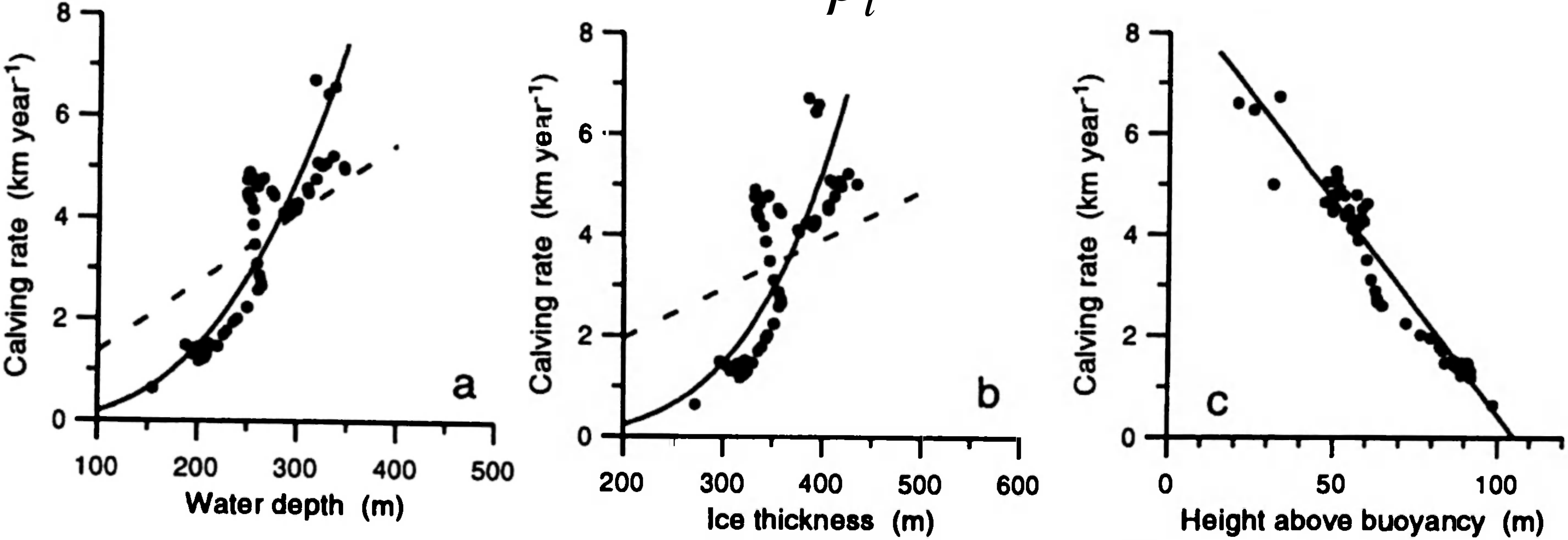


Haresign 2004

Many studies have found an empirical (linear) relationship between the water depth at tidewater glaciers and their calving rate - freshwater calving is slower due to the lower density

The many calving laws

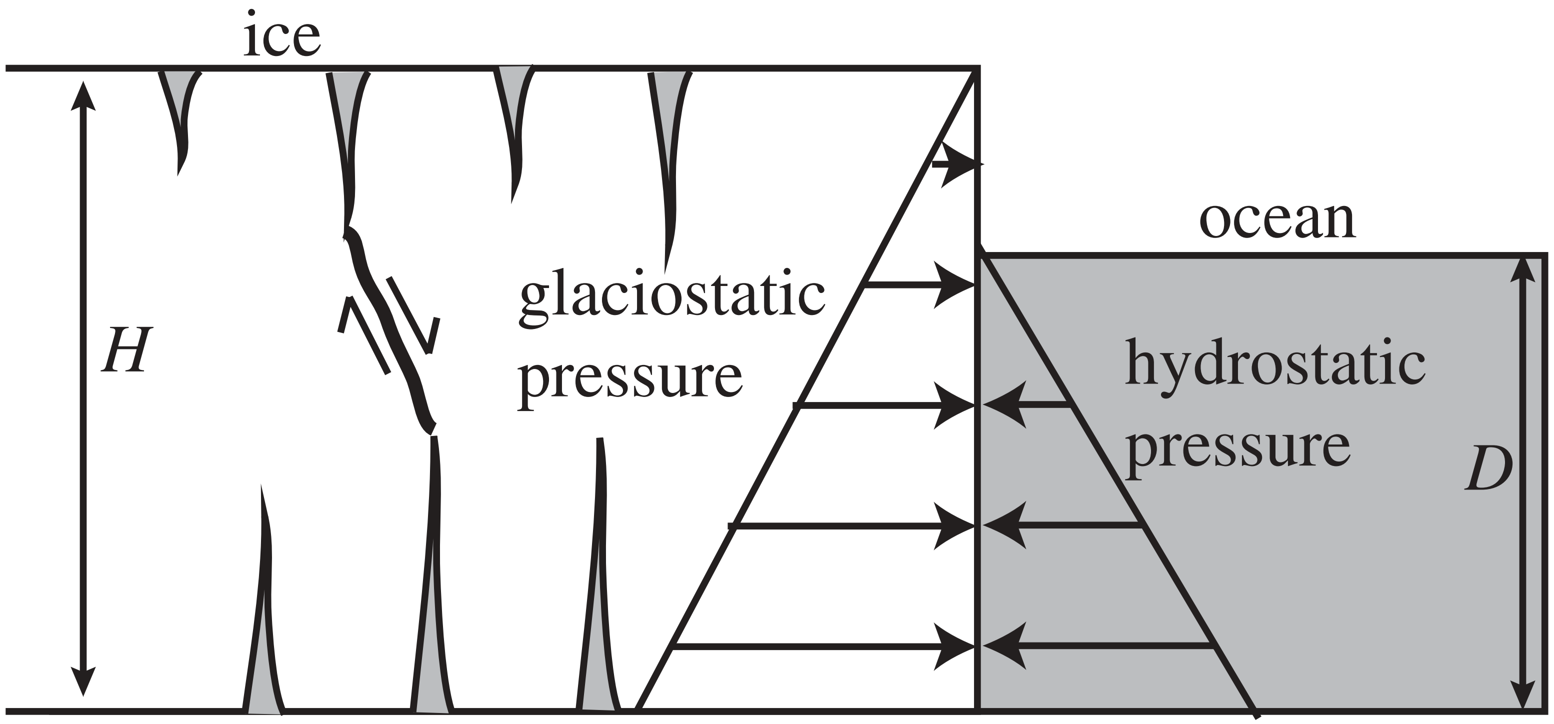
$$H_b = H - \frac{\rho_w}{\rho_i} D$$



van der Veen 1996

Other studies have found a more general relationship between calving rate and height above buoyancy (H_b), but this type of calving law would not permit the formation of floating ice from tidewater glaciers

The many calving laws



Bassis and Walker 2012

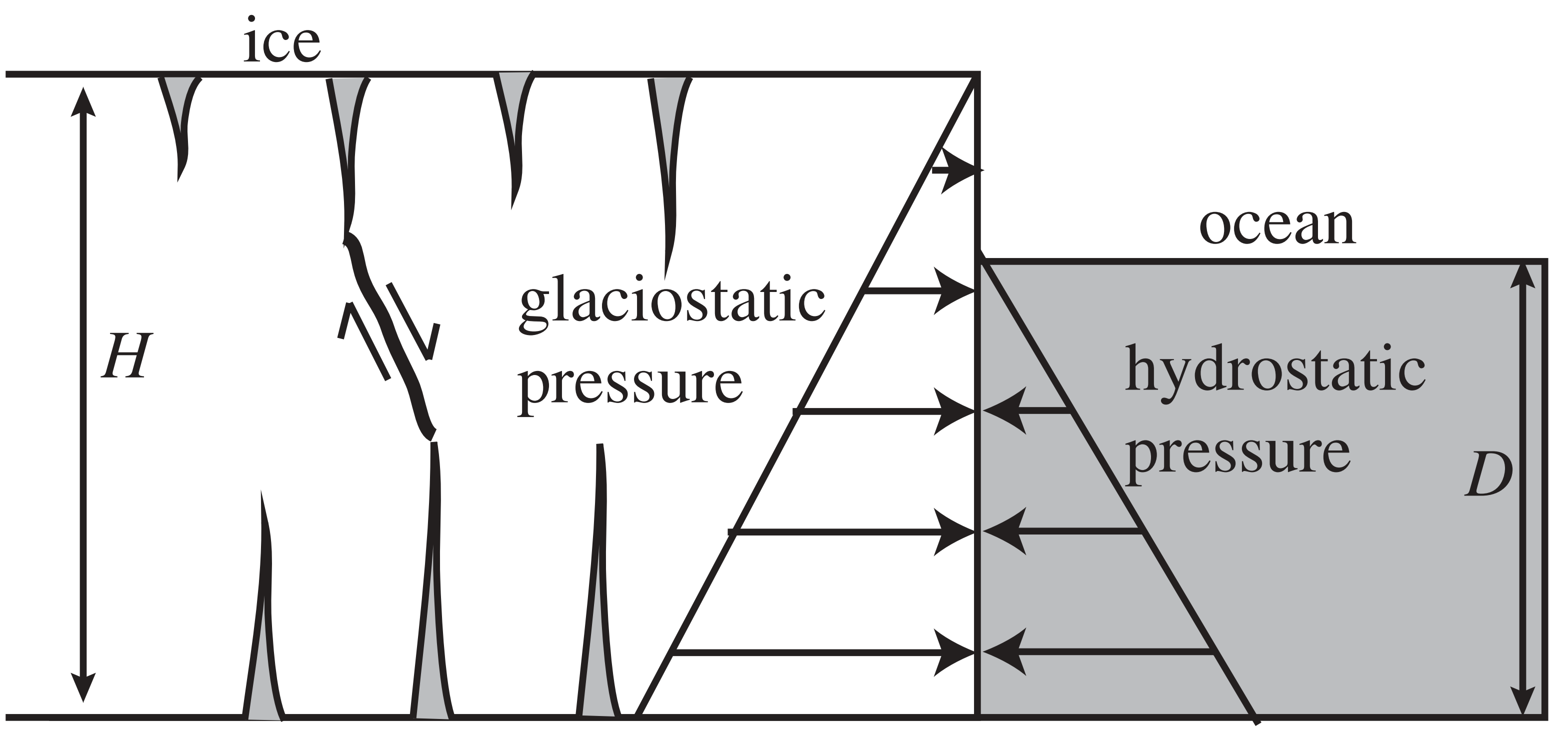
$$S_{xx} = \frac{1}{2}\rho_i g H \left[1 - \left(\frac{\rho_w}{\rho_i}\right)\left(\frac{D}{H}\right)^2\right].$$

$$\bar{\tau}_c = \frac{1}{H}\int_0^H \tau_c \, \mathrm{d}z.$$

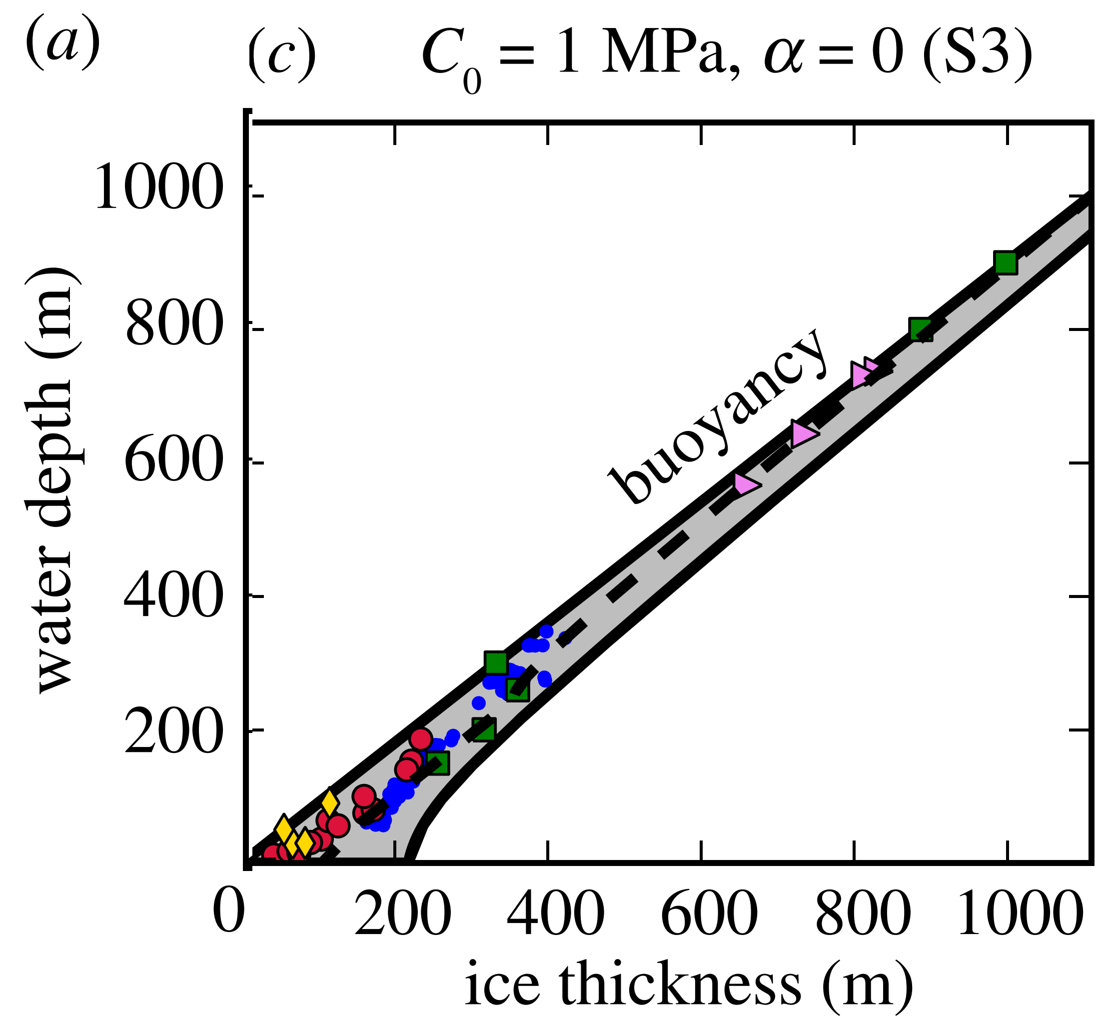
$$H_{\max} = \frac{\bar{\tau}_c}{\rho_i g} + \sqrt{\left(\frac{\bar{\tau}_c}{\rho_i g}\right)^2 + \frac{\rho_w}{\rho_i} D^2}.$$

A recently "fashionable" calving law assumes that ice thickness at the terminus has a maximum height, and above this height will fail structurally at a very high rate

The many calving laws



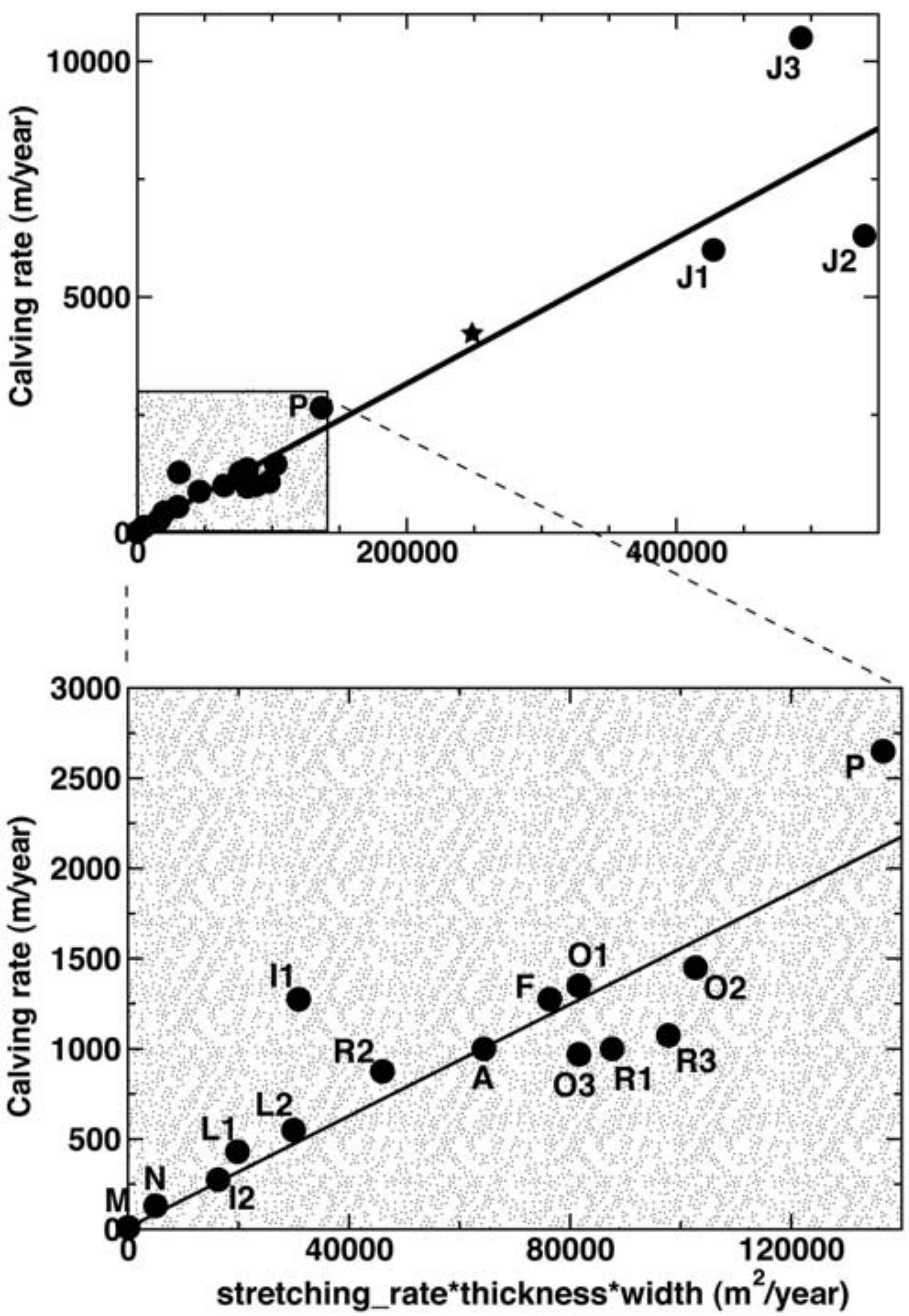
Bassis and Walker 2012



The result is a "marine ice cliff instability" that prevents marine ice cliffs on earth from exceeding a particular height above the water line - this is essentially a height above buoyancy threshold

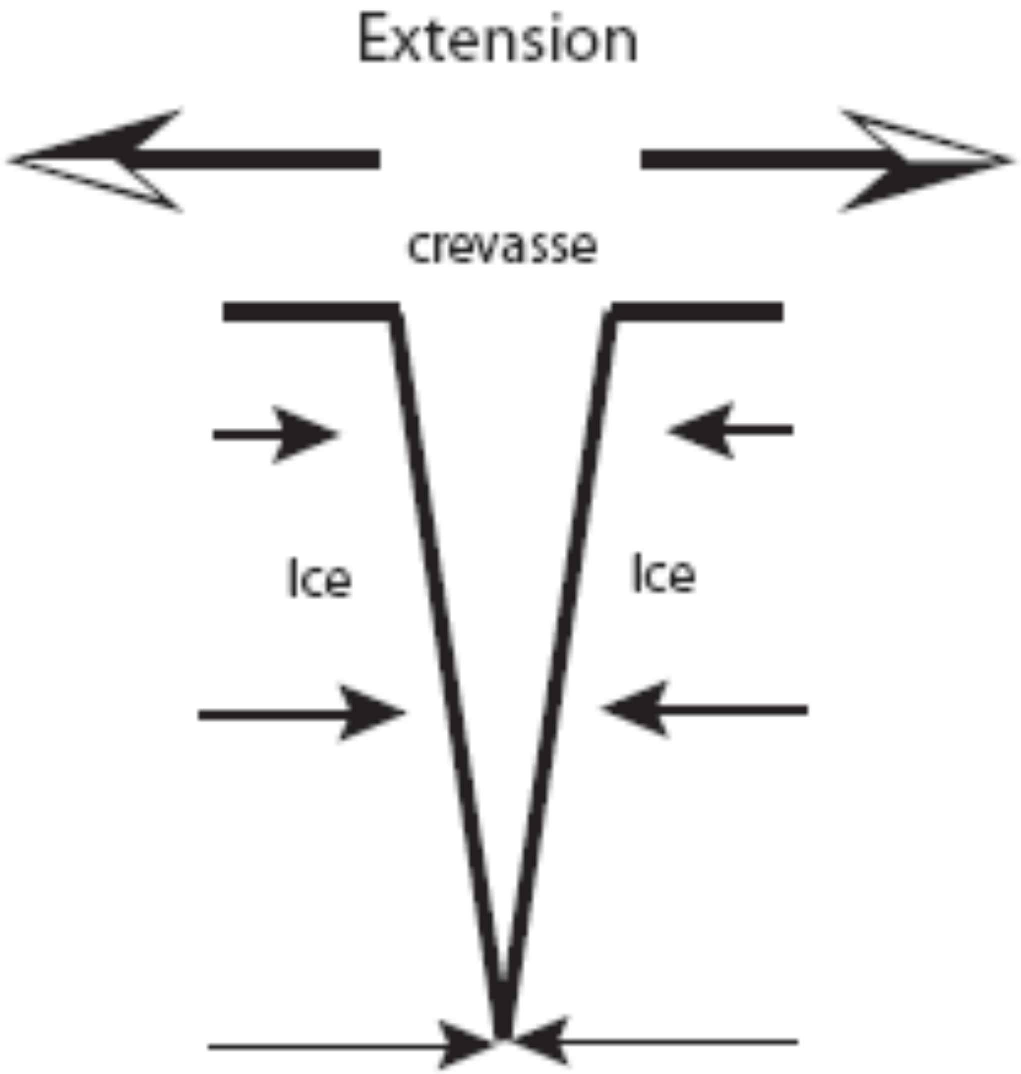
The many calving laws

Alley et al. 2008



Calving rate is proportional to strain rate at ice shelf calving front - works pretty well on average, but on for ice shelves undergoing rift-type calving

The many calving laws



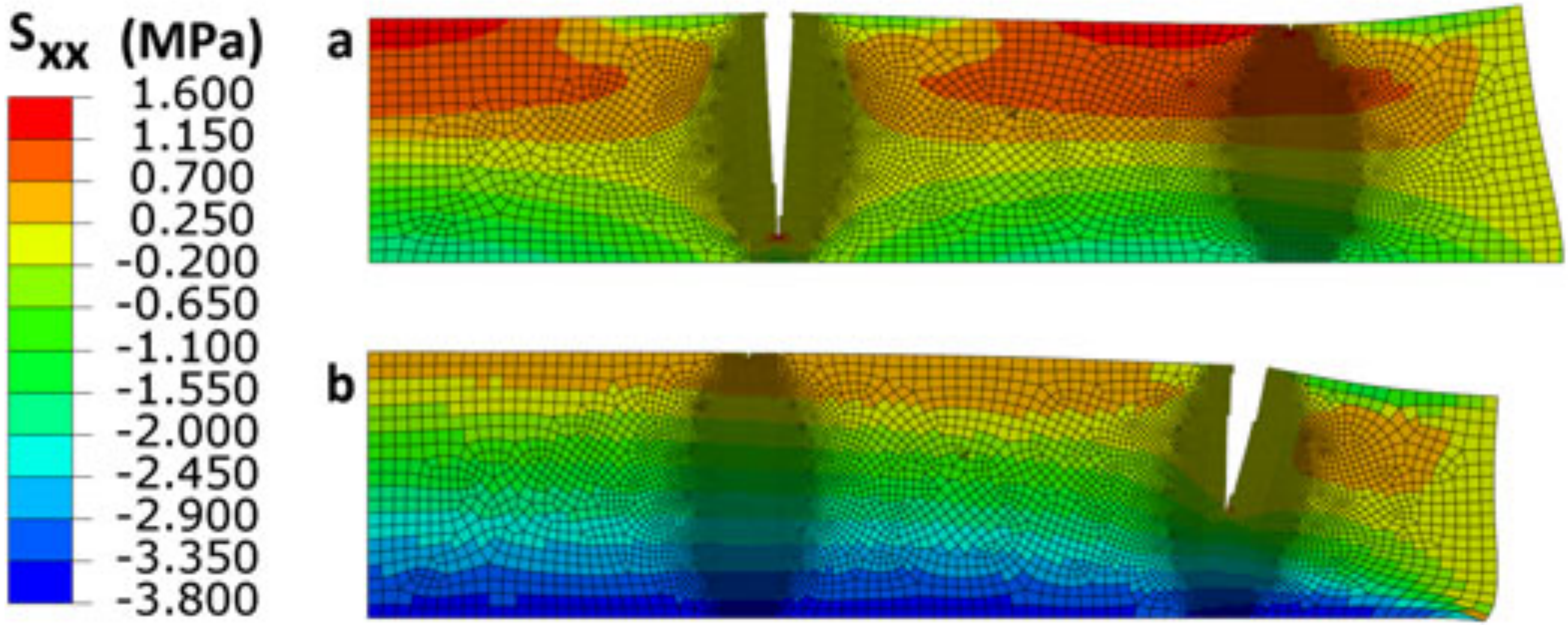
$$\tau_{xx} = \rho_i g d$$

Tensile stress opening fracture

Lithostatic stress (ice weight) closing fracture at depth

If the tensile stress is large enough or there is enough water in fractures, fracture depth will grow to the thickness of the glacier - produced full thickness calving events

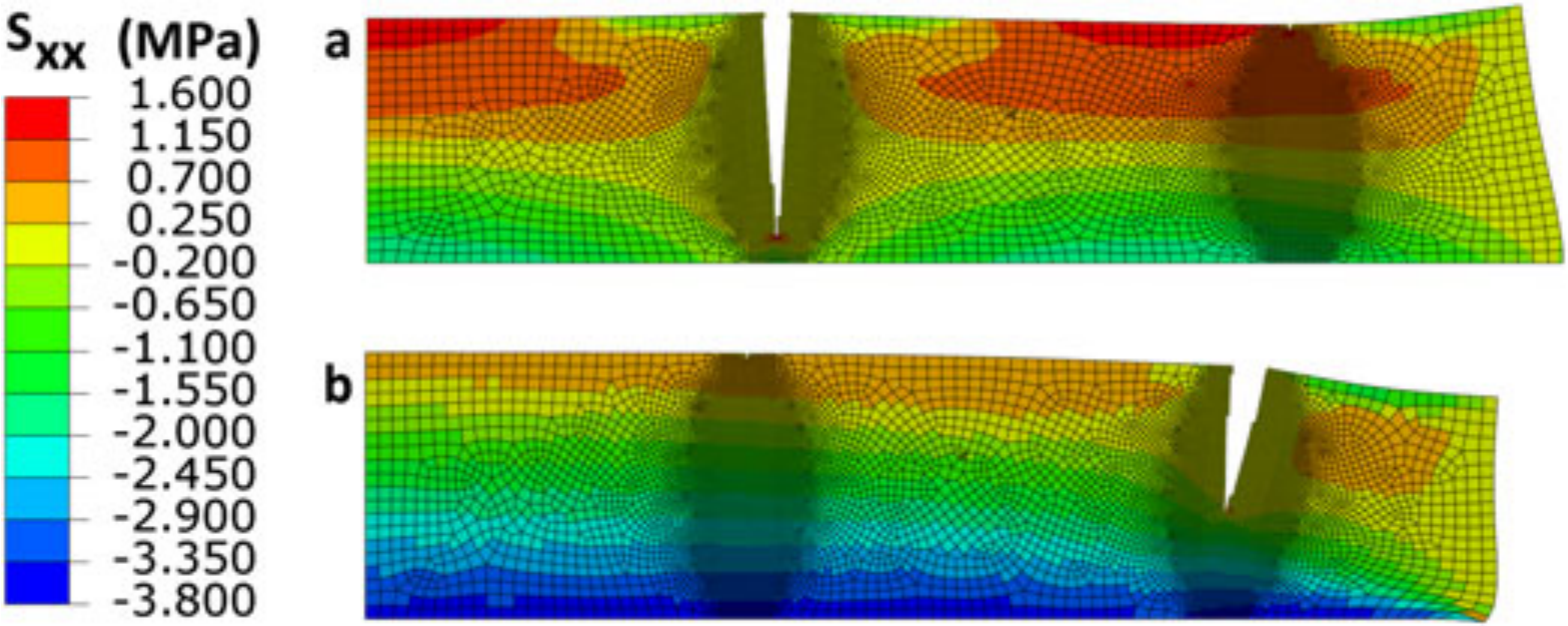
Process-rich models



Duddu et al. 2013

Ultimately, empirical calving laws are good at reproducing observations under a limited set of circumstances. However, they do not arise from a basic consideration of the processes which cause calving (fracture) and fail when things change

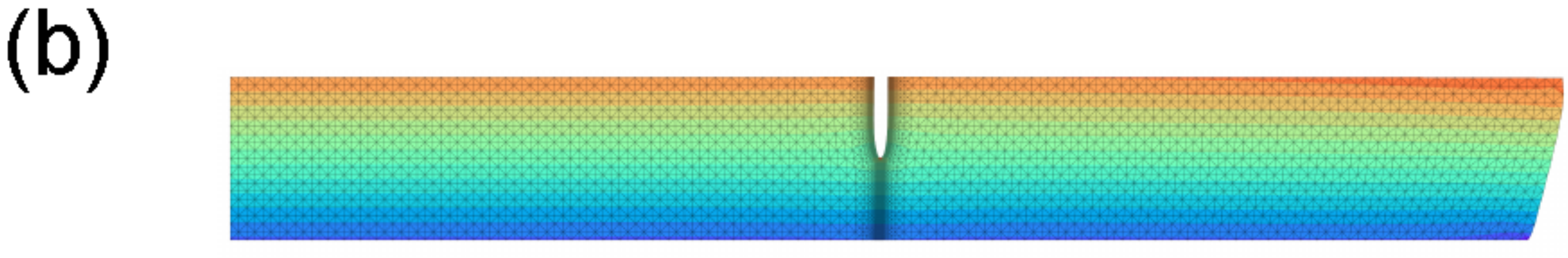
Process-rich models



Duddu et al. 2013

Damage mechanics models - add a damage parameter that is created in places with high stress (essentially represents all the microscopic fractures) and is moved around the glacier and determines the ice rheology and propensity to fracture

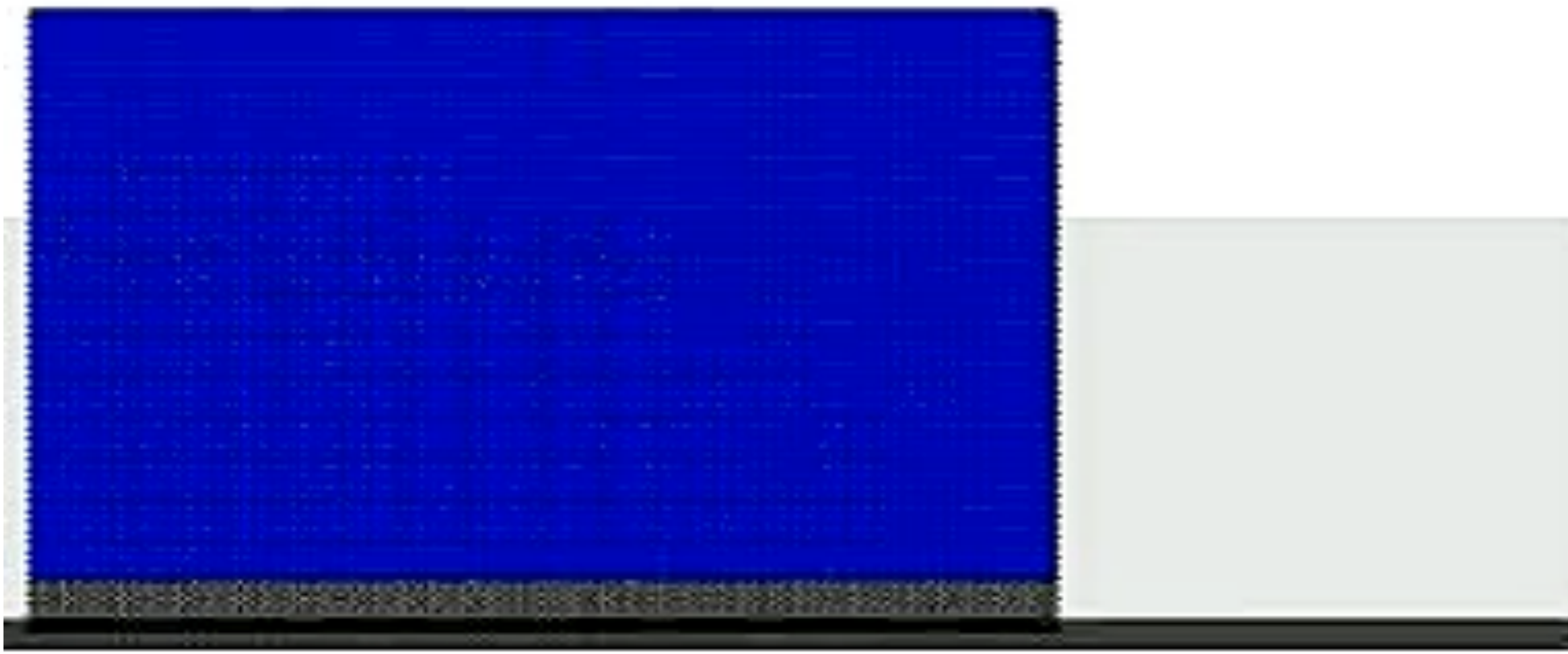
Process-rich models



Jimenez and Duddu 2018

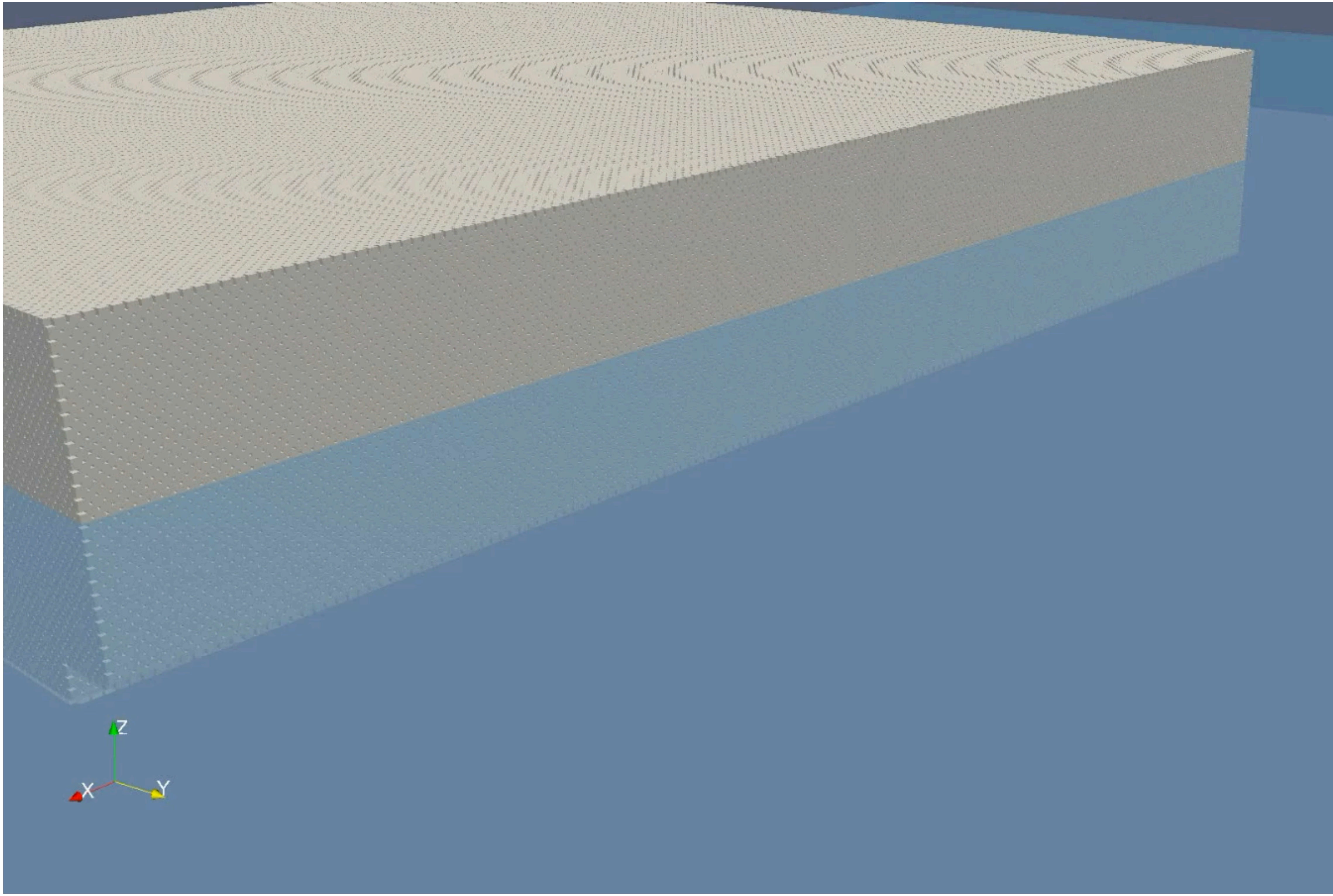
Linear Elastic Fracture Mechanics (LEFM) can be used to determine how fractures propagate and eventually cause calving, but they require good estimates of stress intensity factors (SIFs), which assume a lot about the geometry and boundary conditions

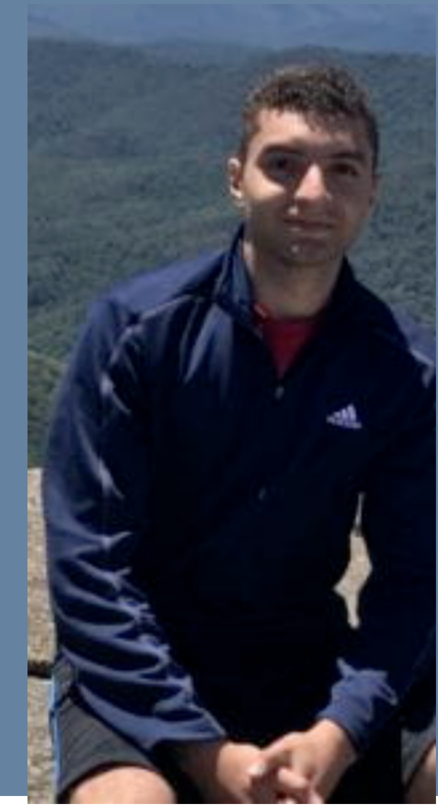
Process-rich models



Discrete Element Models (DEMs) treat the glacier as many blocks connected by brittle beams. Is perhaps the closest to the “real” glacier physics - but…is incredibly computationally expensive

Process-rich models





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