Numerical model investigation of Crane Glacier response to collapse of Larsen B ice shelf, Antarctic Peninsula

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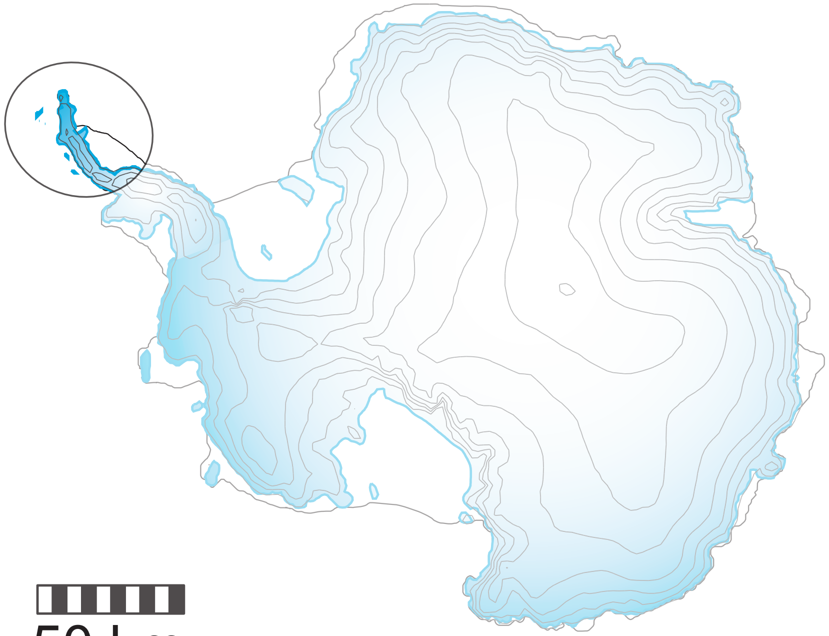
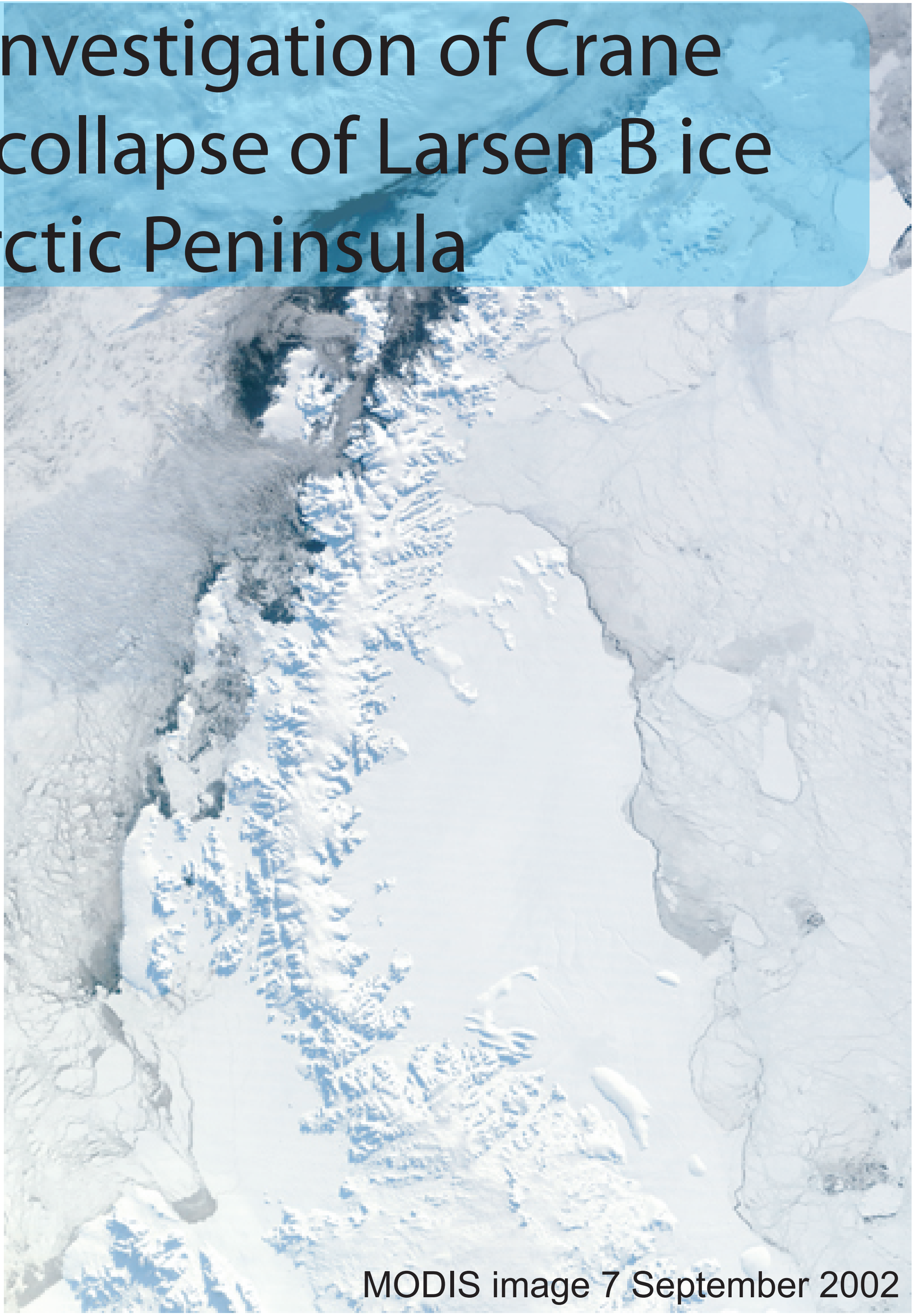


50 km



MODIS image 7 September 2002

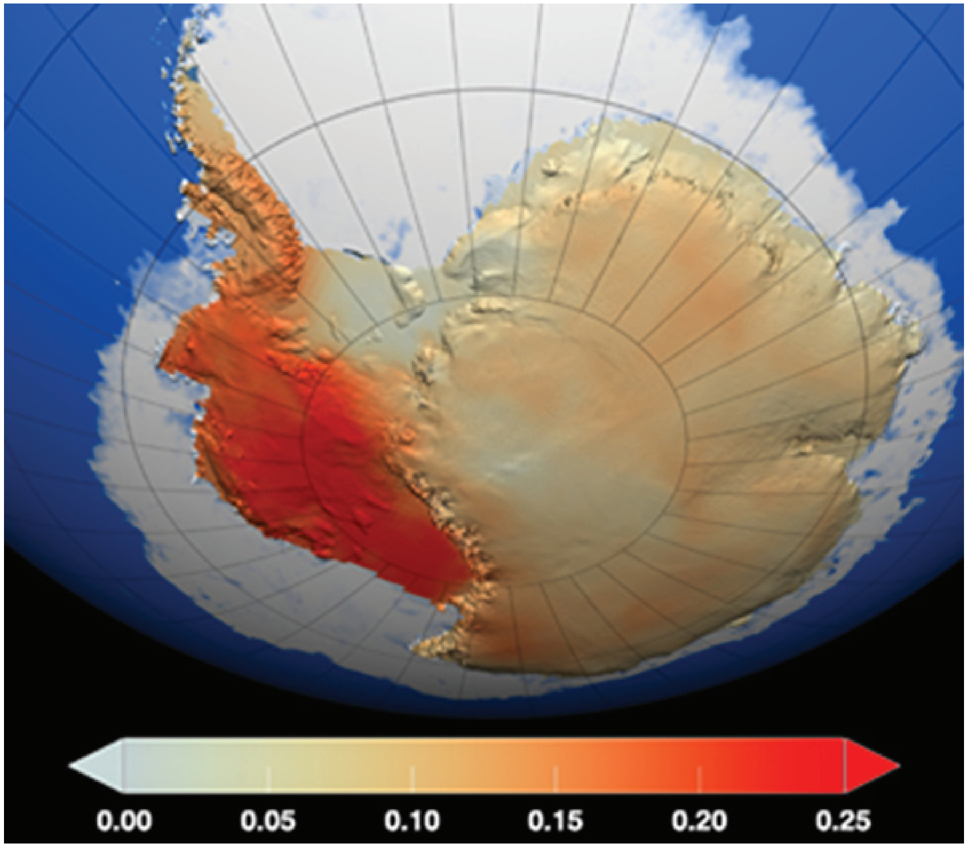
aaaaaaaaa!

Larsen B ice shelf collapse

rapid event

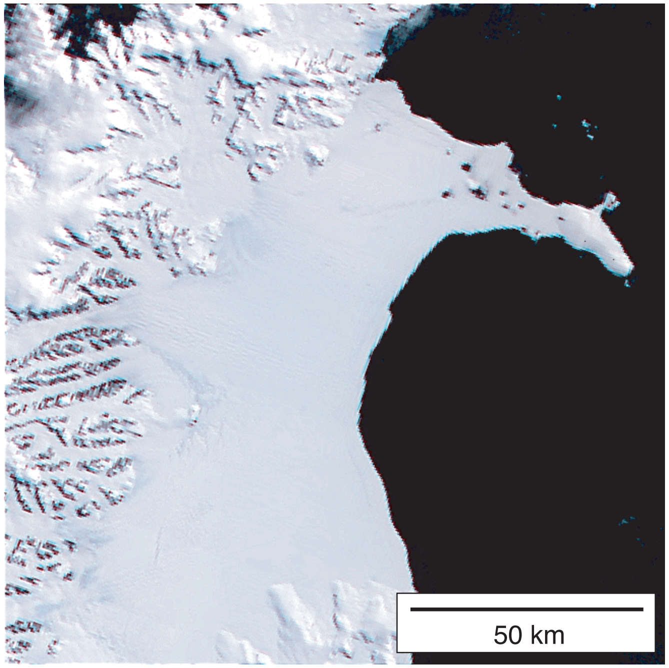
tied to regional warming

1957 to 2006 mean annual temperature trend
Steig et al., 2009, *Nature*, AWS + thermal infrared

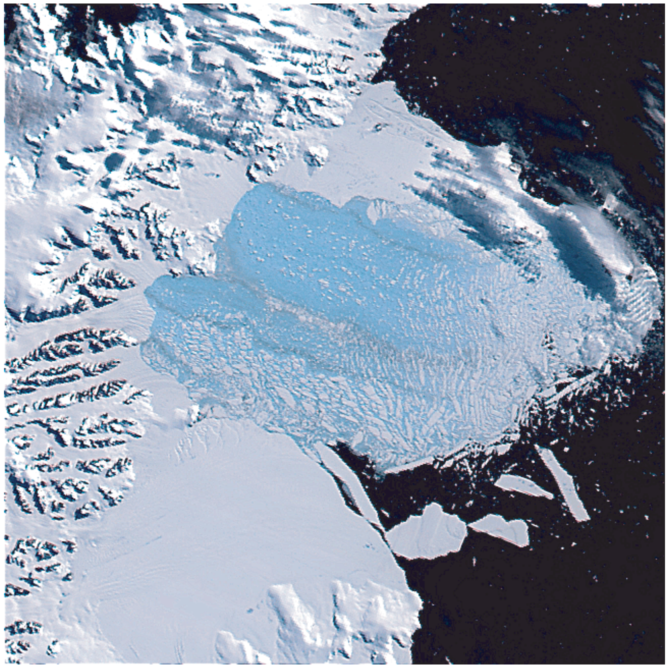


AP: 0.11 +/- 0.06 °C per decade

November 22
2001



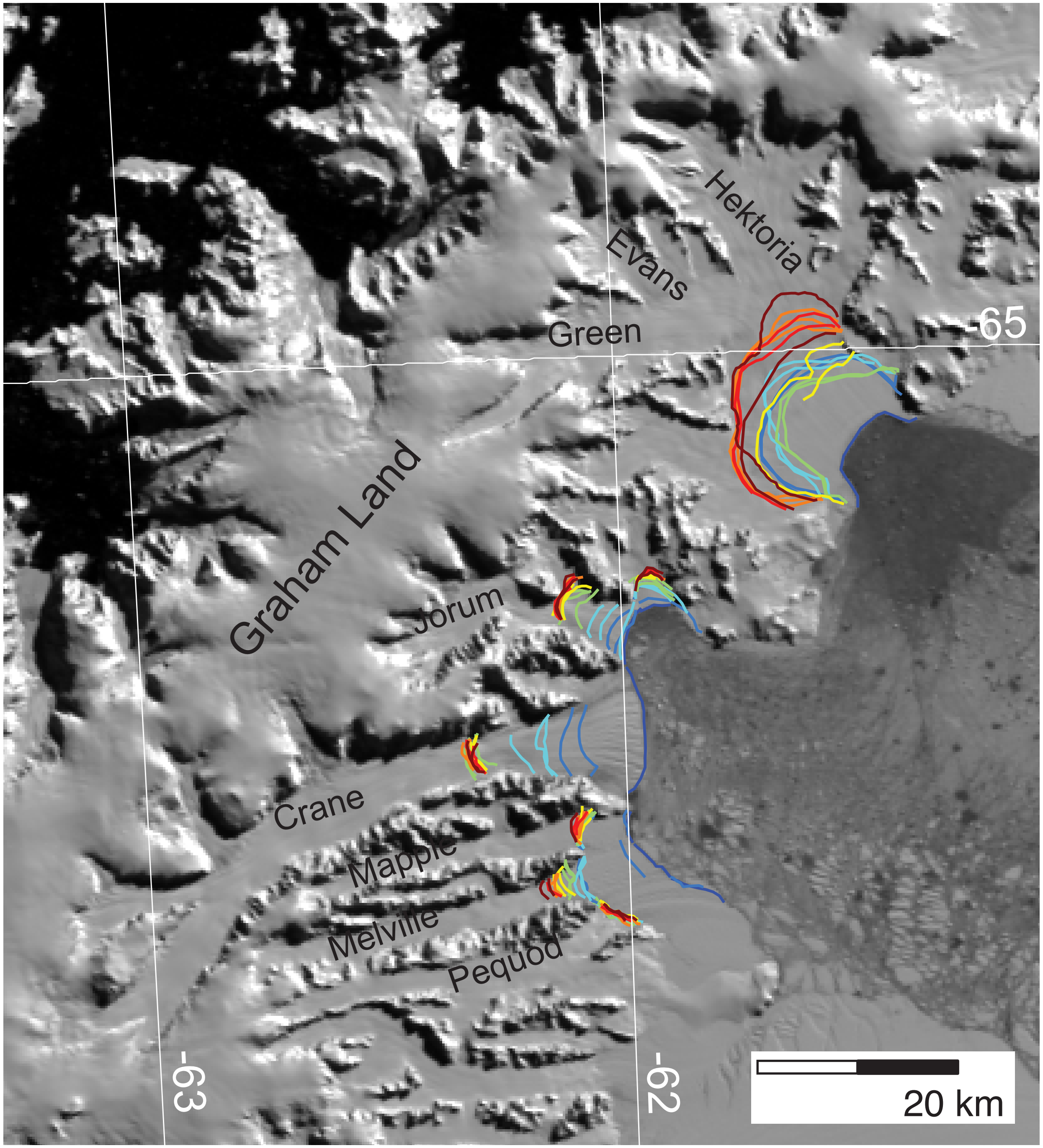
March 7
2002

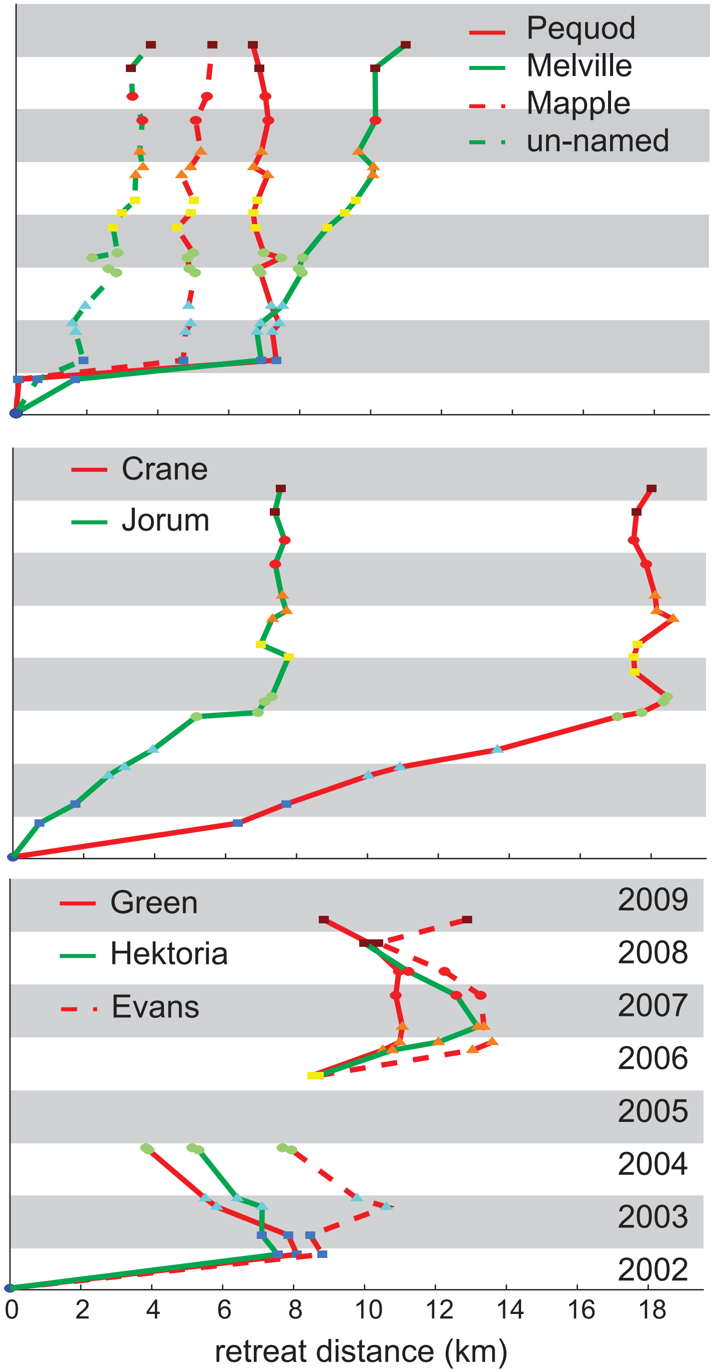


MODIS true color from NSIDC

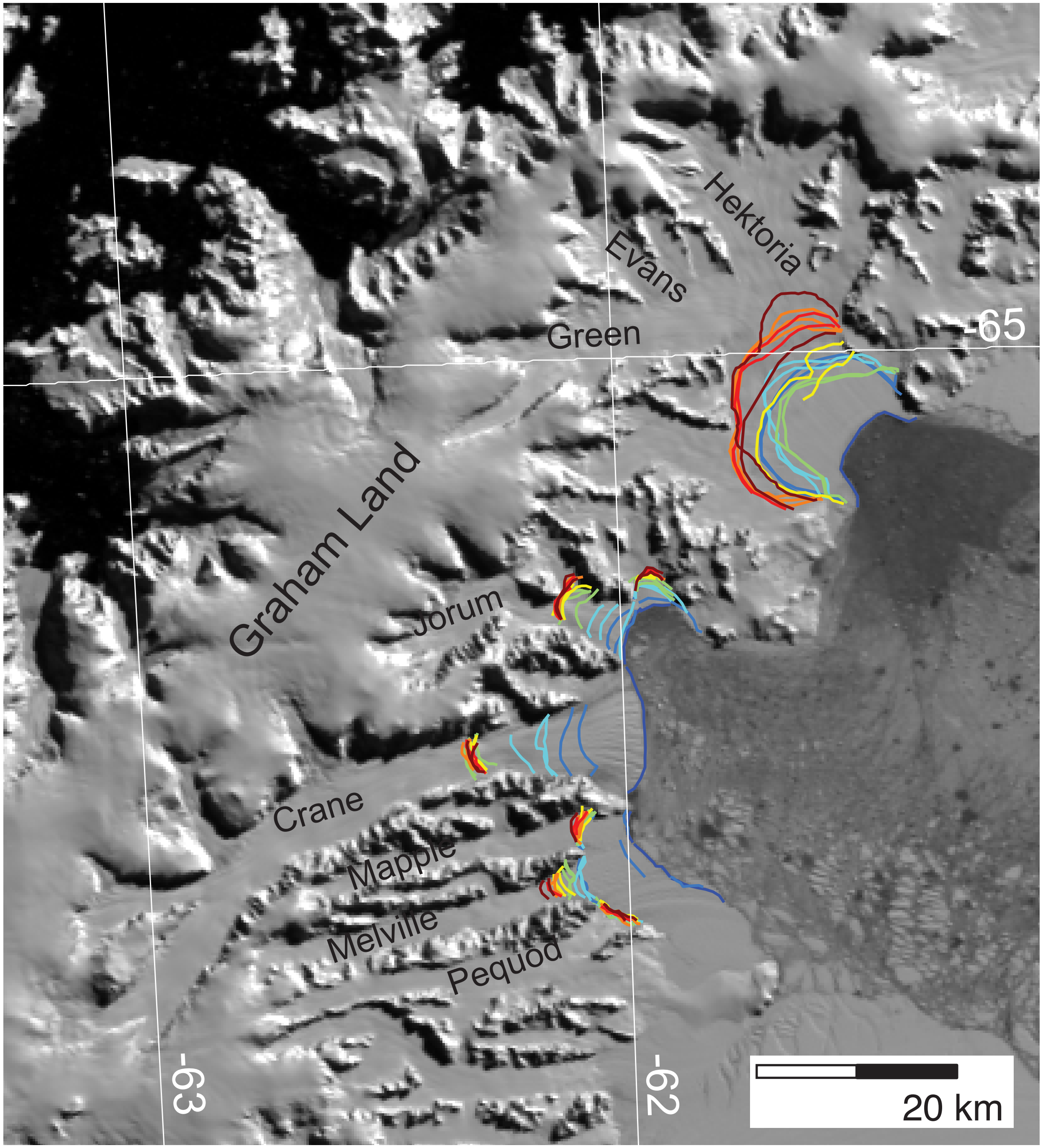
different patterns emerge over time

front location following ice shelf disintegration





different patterns emerge over time



tidewater calving retreat

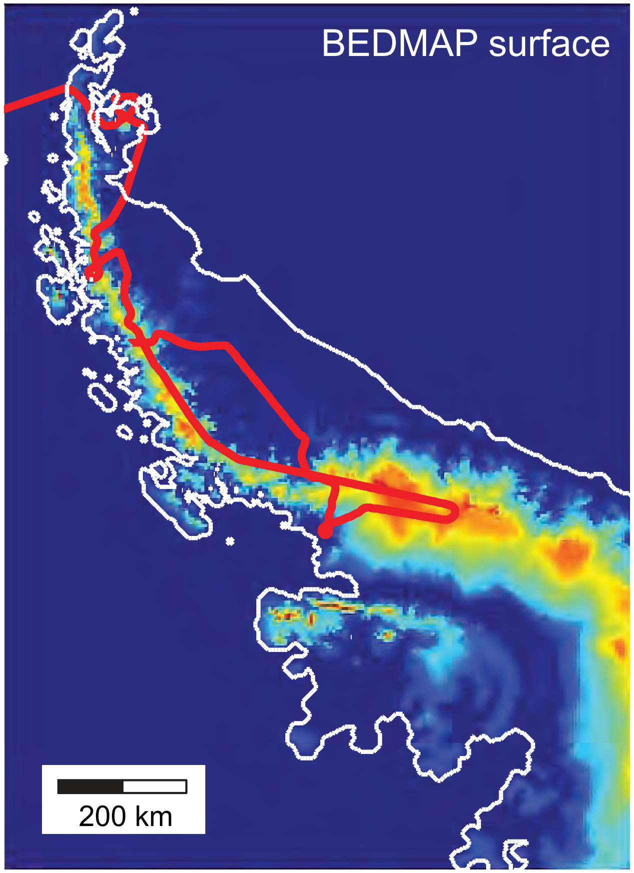
ice dynamics

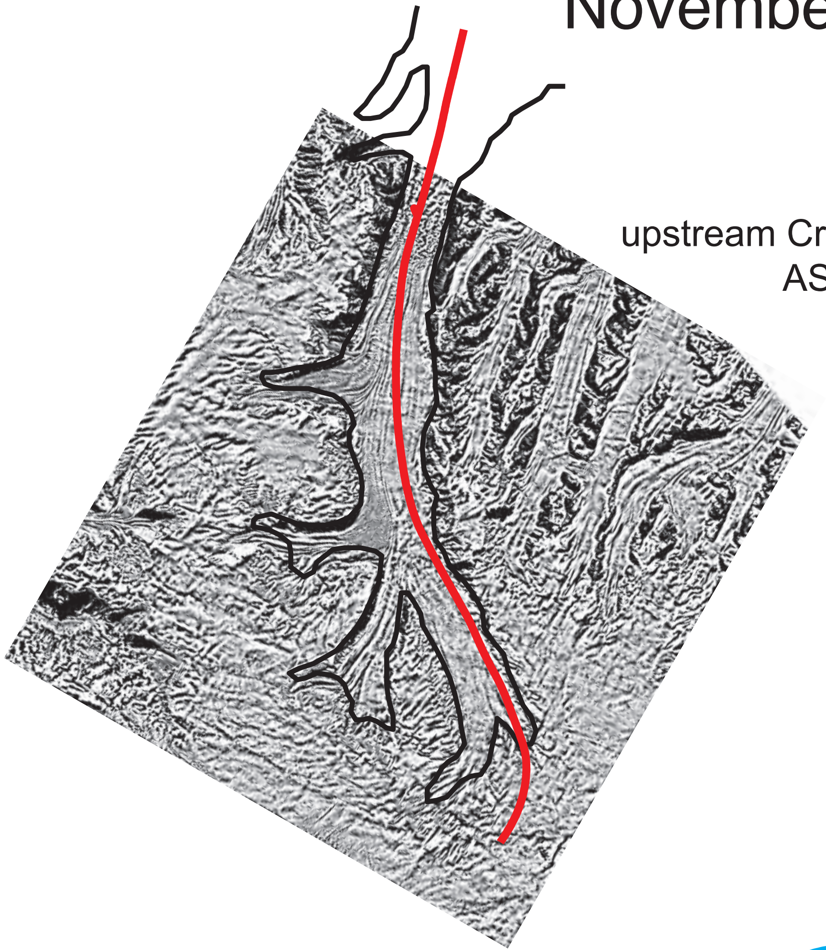
Crane Glacier

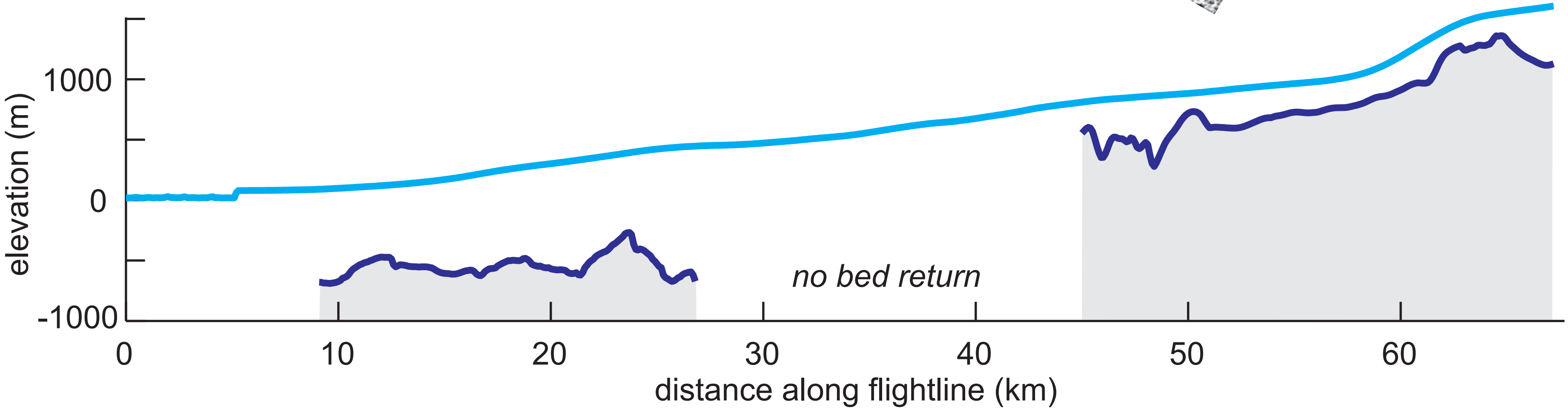
rapid change, large glacier
and we have some data

NASA/CReSIS/CECS airborne radar & laser

November 2002







tidewater calving instability

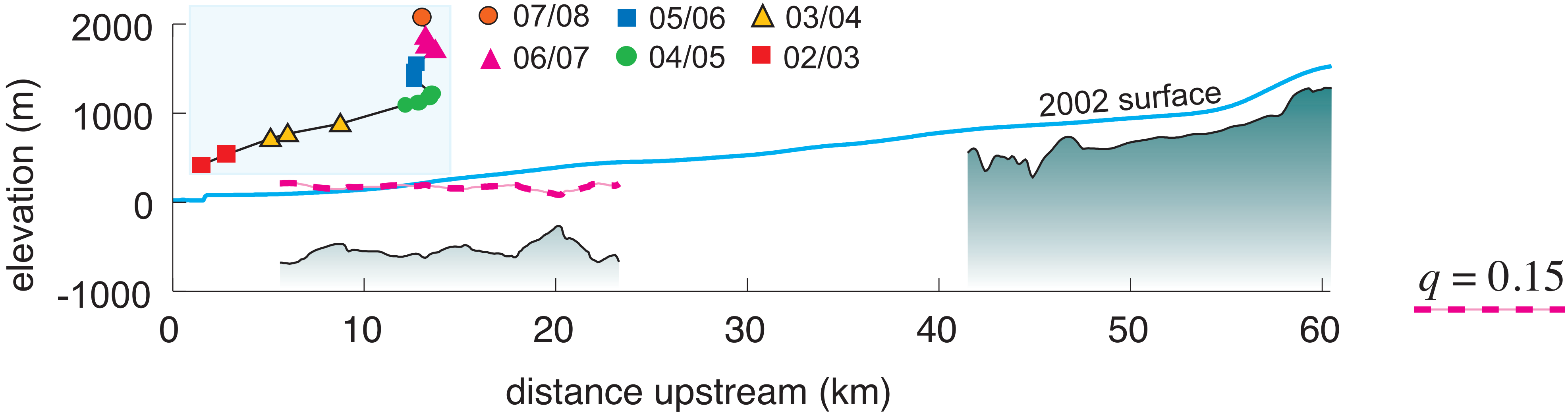
Mapple & Melville
photo: T. Scambos

height above buoyancy *(van der Veen; Vieli)*

$$h_c = \frac{\rho_{water}}{\rho_{ice}} (1 + q)\, d$$

h	ice thickness
h_c	critical thickness
d	water depth
q	emprical const.

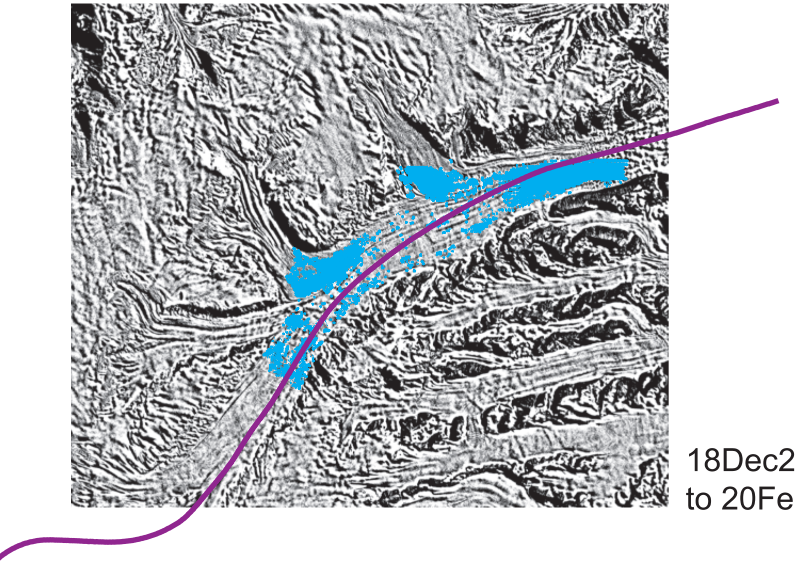
$h_c / h > 1$ retreat



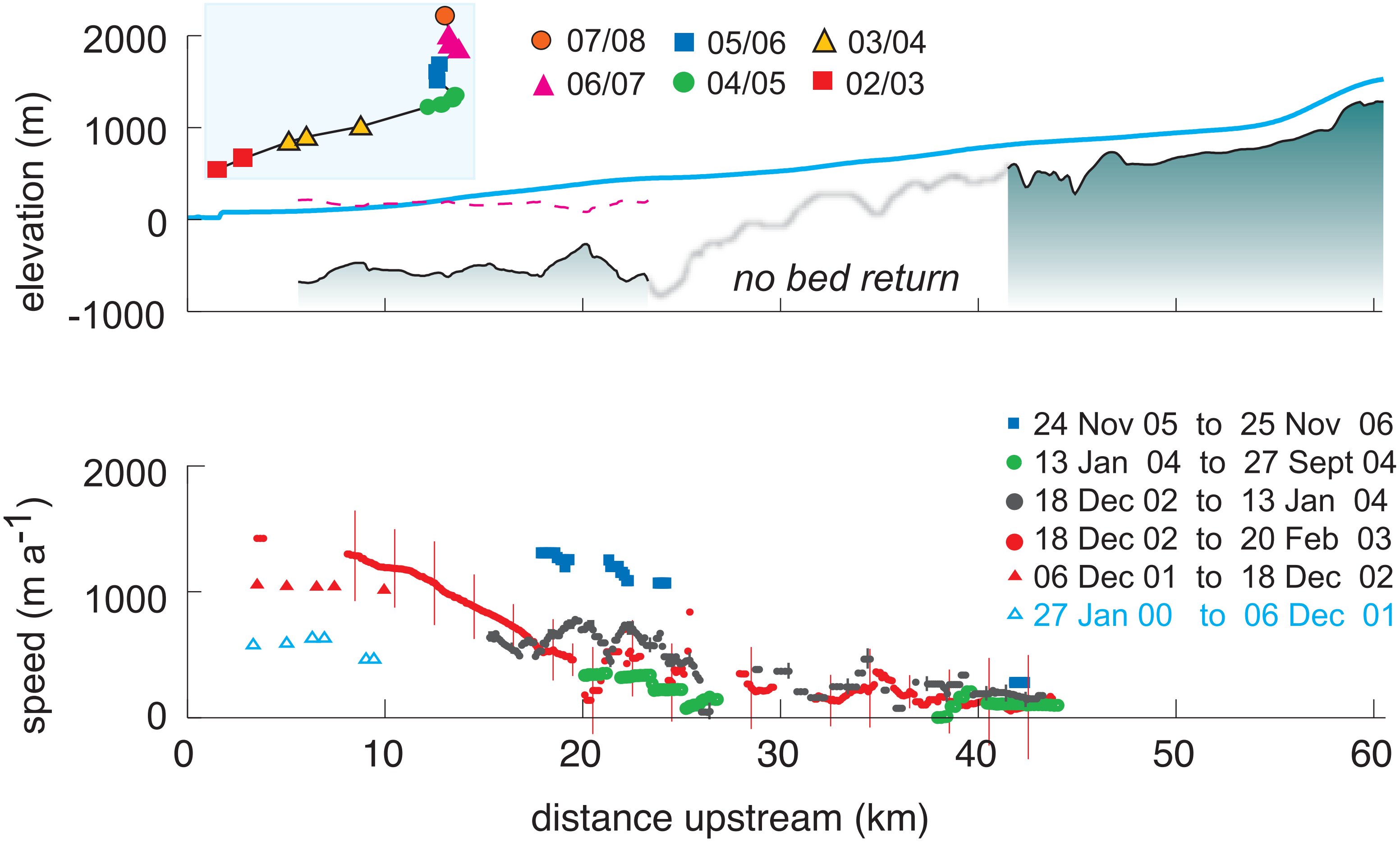
Crane Glacier speed

surface velocity from feature tracking
interpolated to flightline

instantaneous response
△ to ▲



18Dec2002
to 20Feb2003



2002: speed up
2004: slow down
2006: speed up

numerical model

finite element solver for momentum equation along flightline

two downstream boundary conditions

1) pre-collapse: ice + backpressure
2) post-collapse: water + air

three experiments

1) deformation only
2) deformation + sliding
3) deformation + sliding with steady-state front position

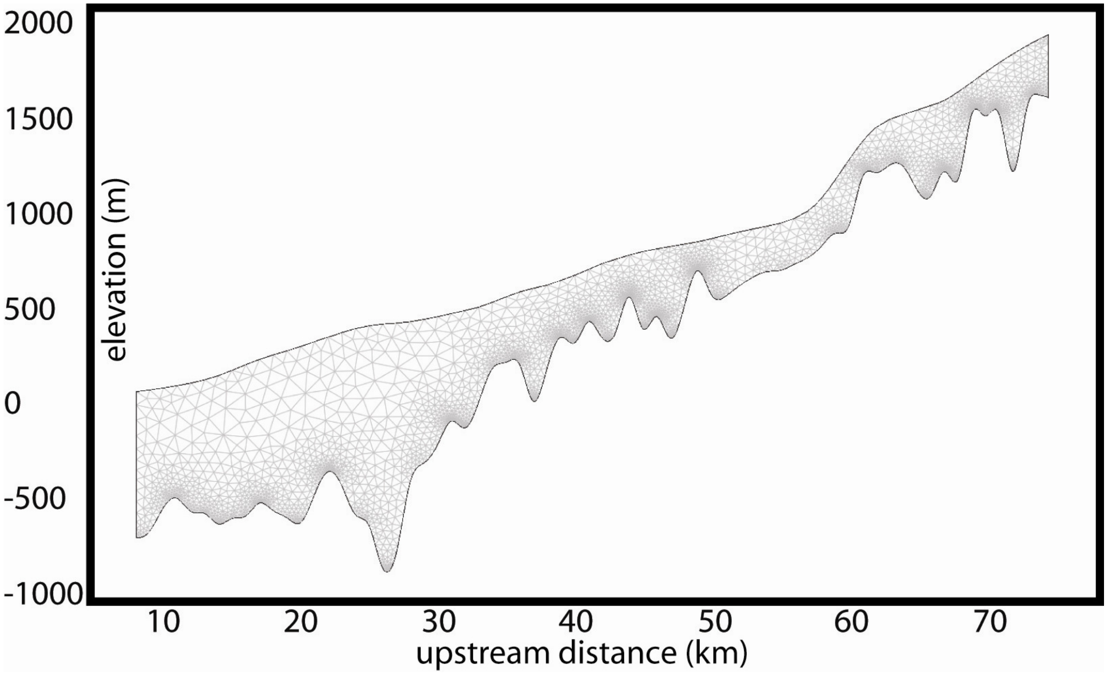


Figure 3.1 Mesh for the non-scaled models consists of 11501 nodes with an increase density near large gradients in the glacial geometry.

Table 3.1 Mesh statistics for non-scaled mesh.

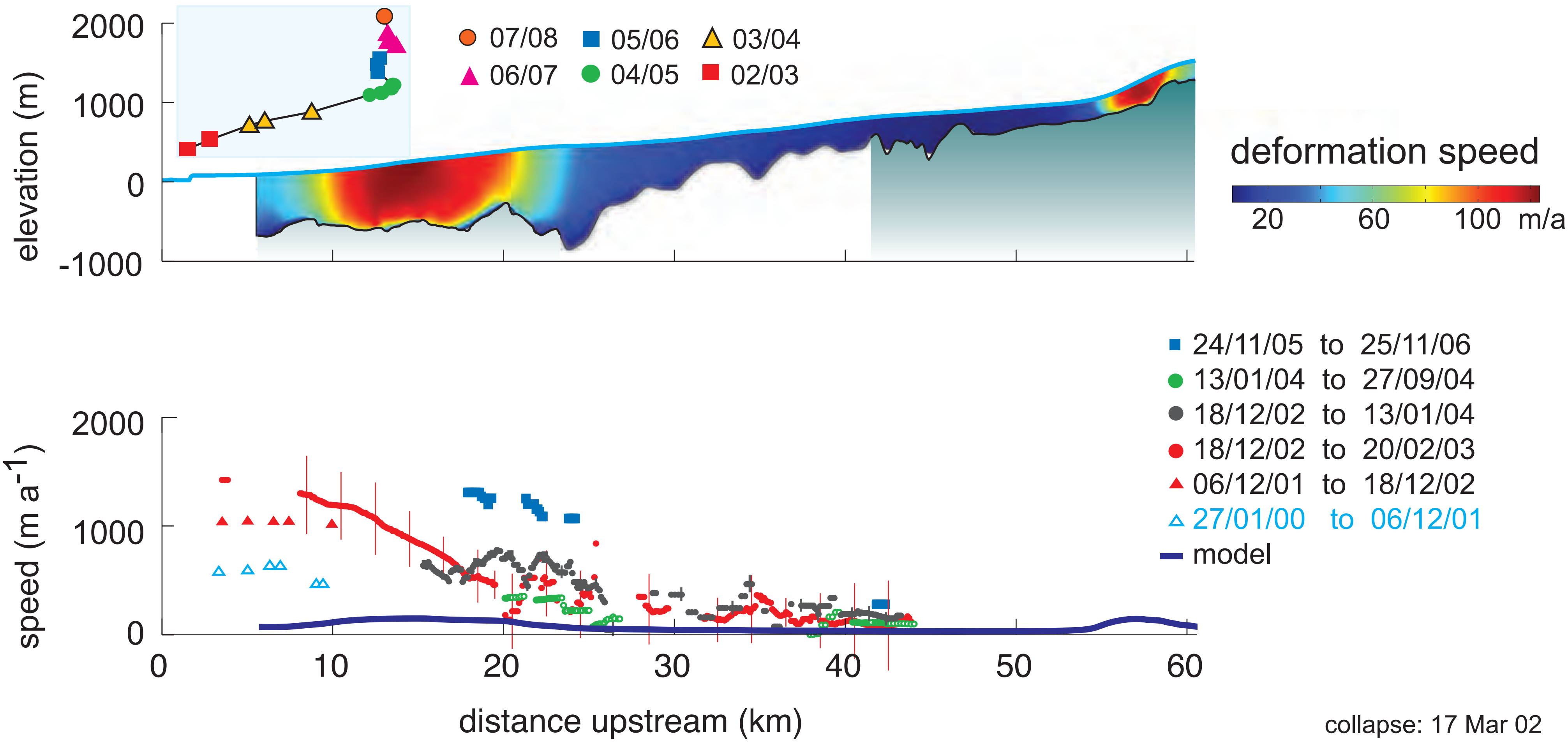
Quantity	Value
Number of Elements	11501
Minimum element quality	0.0446
Element area ratio	8.85×10^{-5}

numerical model

finite element solver for momentum equation along flightline

(no lateral drag)

estimate of missing bed from surface & observed velocity
estimated ice temperature
pressure condition at downstream end *ice* + *backpressure*



collapse: 17 Mar 02

instantaneous response to ice shelf loss

FEM solves momentum equation along flightline

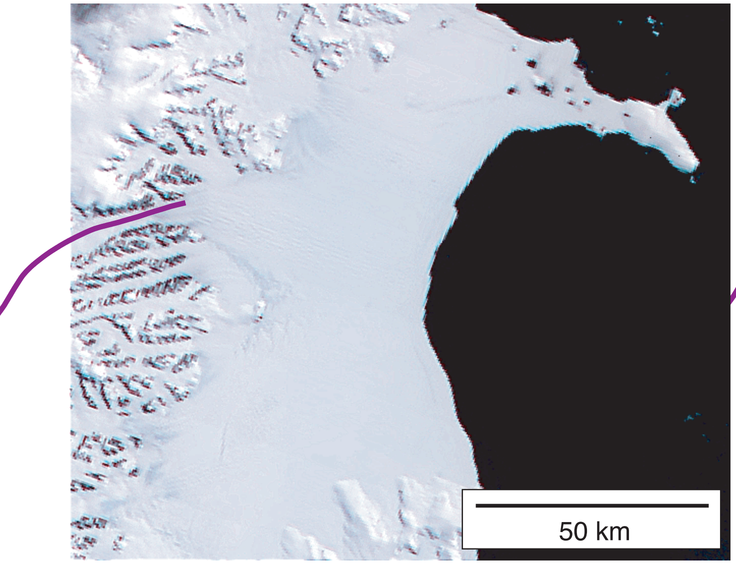
(no lateral drag)

pressure condition at downstream end

ice + backpressure

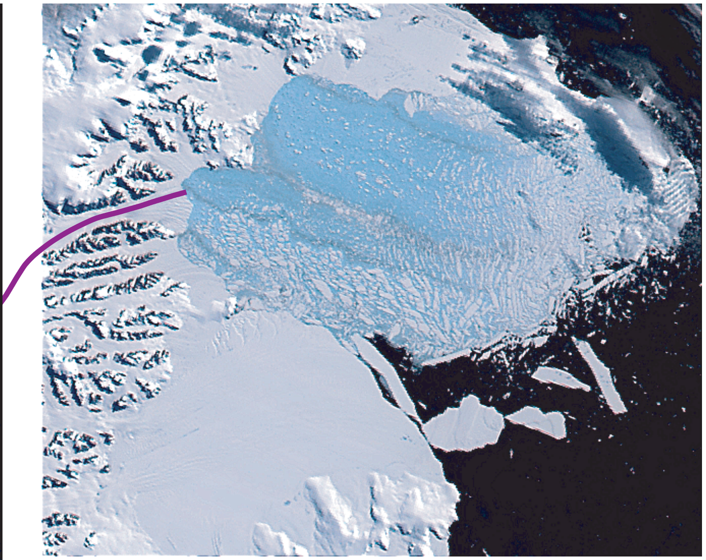
or

air & water



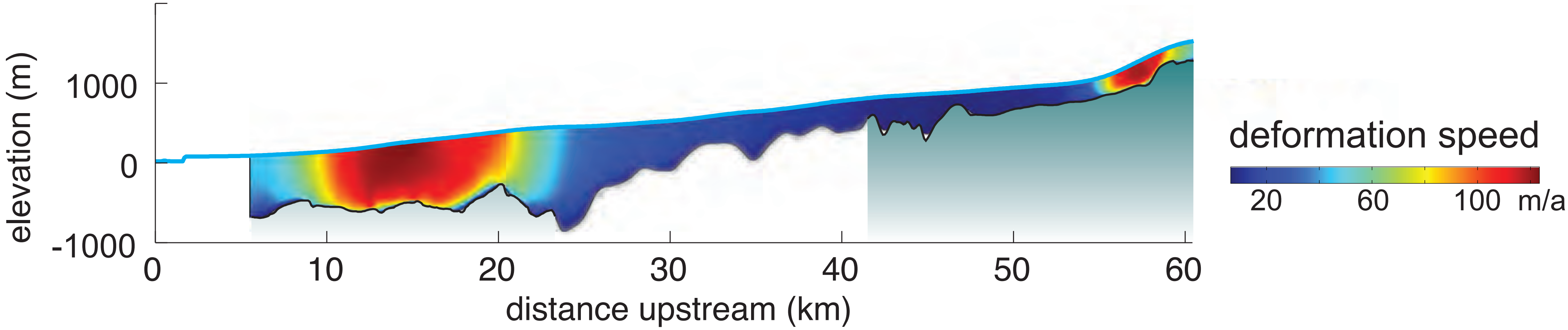
with ice shelf

$$\tau_{xx} = \rho_{ice} \cdot g \cdot (S-z) + \tau_{back}$$



air & water

$$\tau_{xx} = \begin{cases} 0 & z > sealevel \\ \rho_{water} \cdot g \cdot (sealevel-z) & z \le sealevel \end{cases}$$

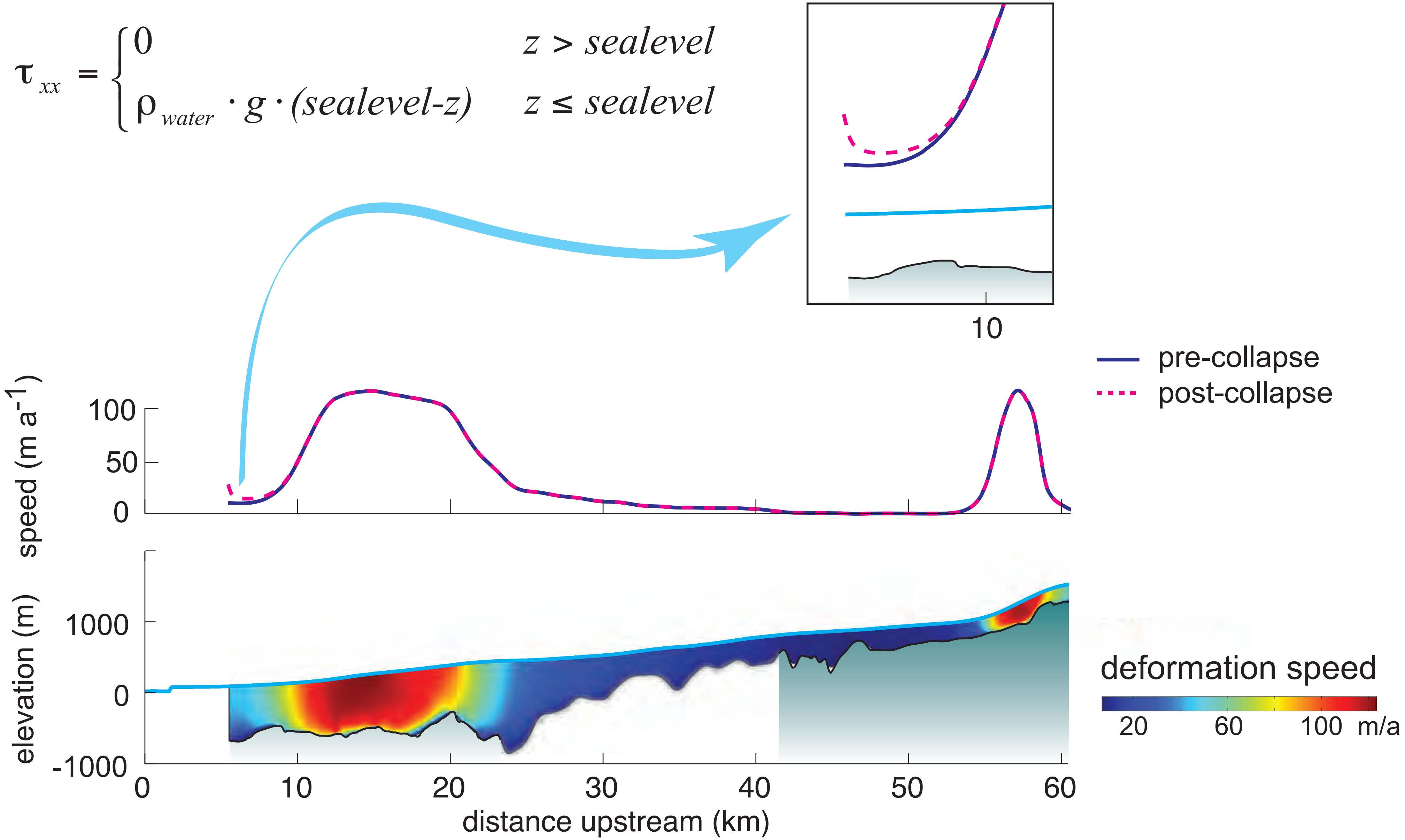


instantaneous response to ice shelf loss

ice deformation only
along flightline

$$\tau_{xx} = \rho_{ice} \cdot g \cdot (S\text{-}z) + \tau_{back}$$

$$\tau_{xx} = \begin{cases} 0 & z > sealevel \\ \rho_{water} \cdot g \cdot (sealevel\text{-}z) & z \leq sealevel \end{cases}$$



numerical model

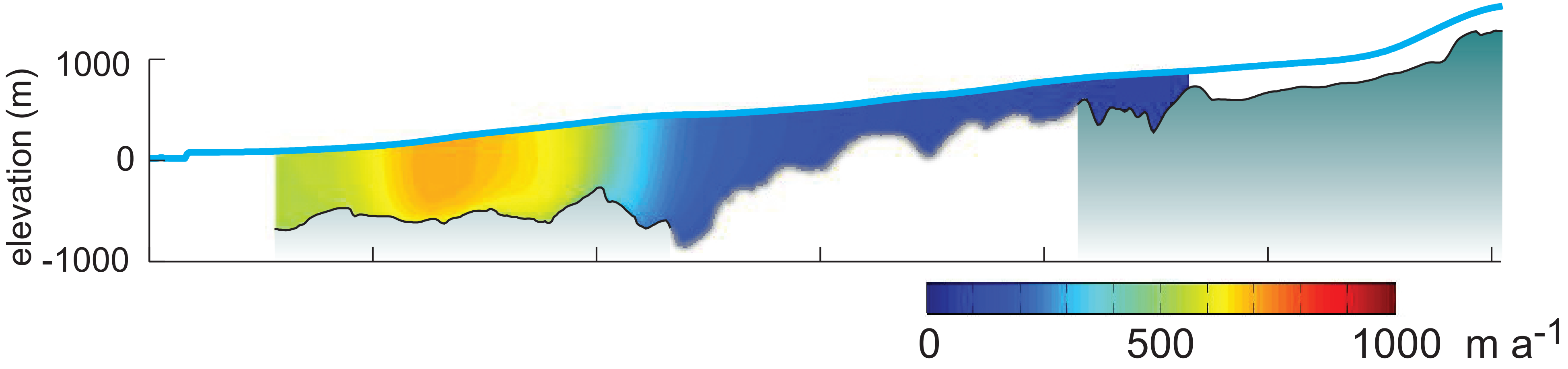
deformation + sliding relation

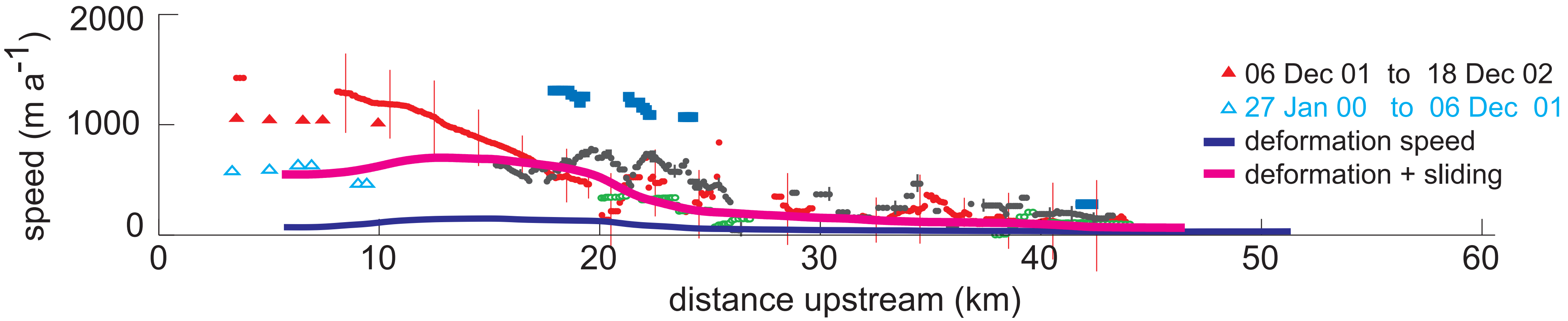
tuned to observed "pre-collapse" speed

$$u_b = k\,\tau_b^{\,q}\,p_e^{-1}$$

speed at the bed depends on

basal shear stress	τ_b
effective pressure	p_e (overburden - water)
tunable parameters	k, q, water level in p_e

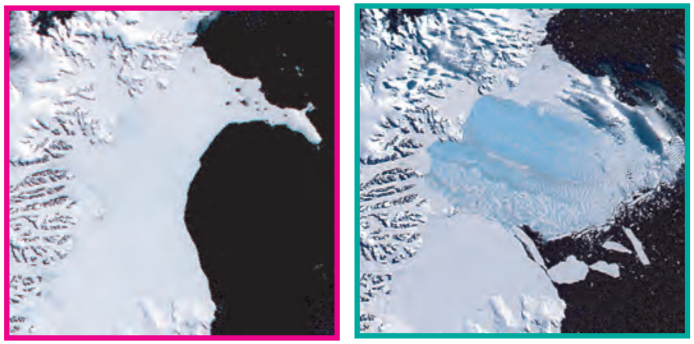


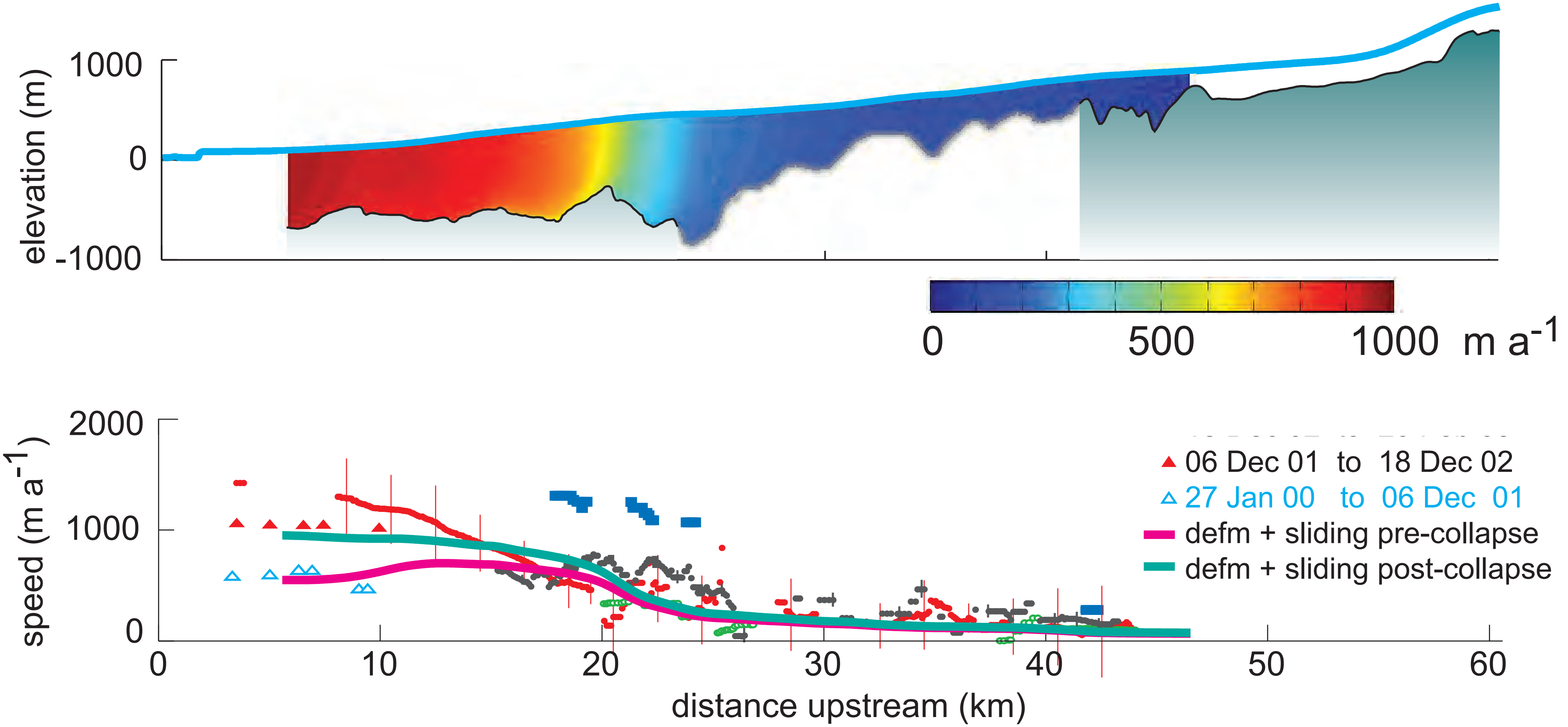


instantaneous response to ice shelf loss

deformation + sliding along flightline

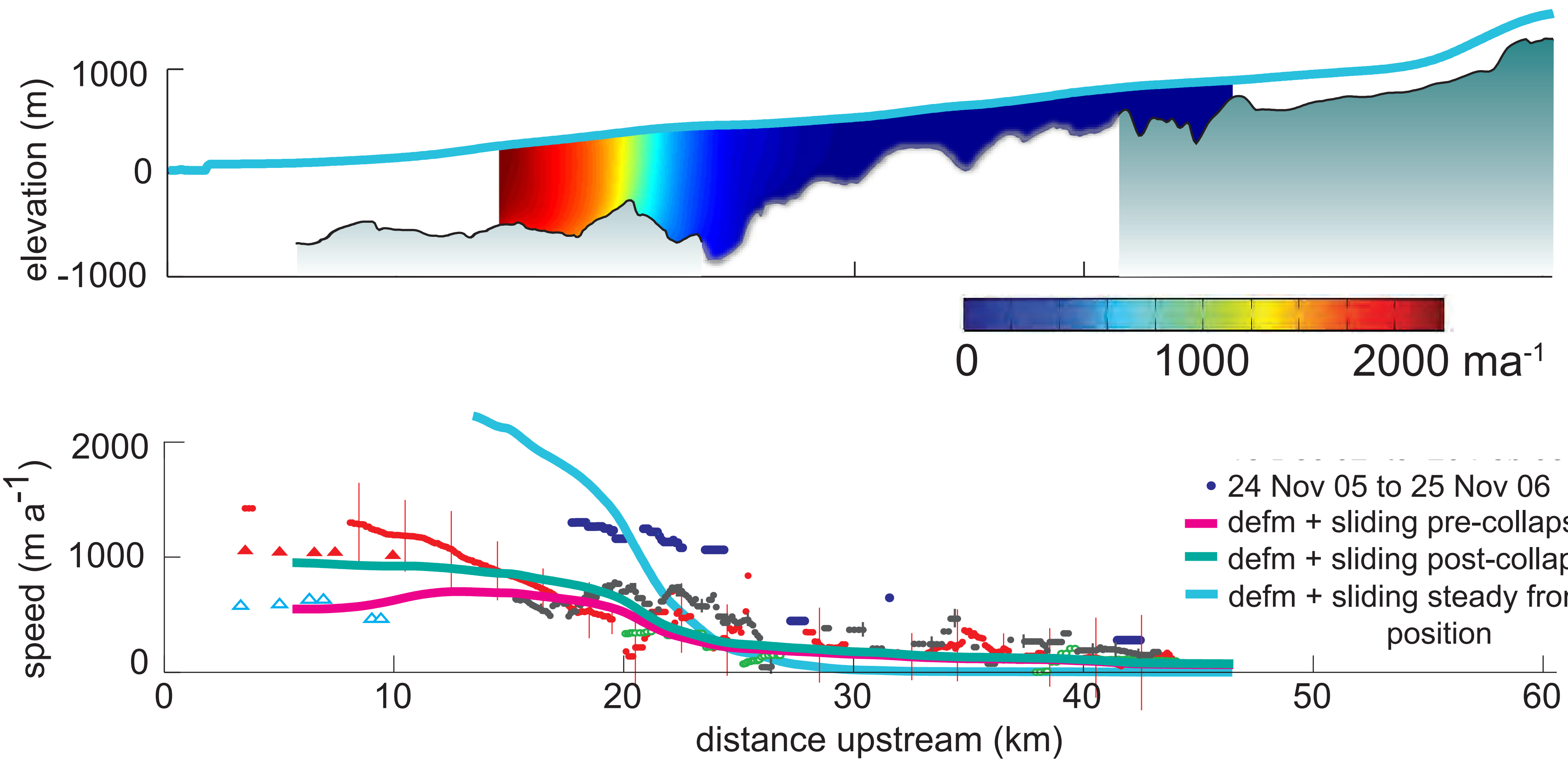
replace ice+backpressure with water+air



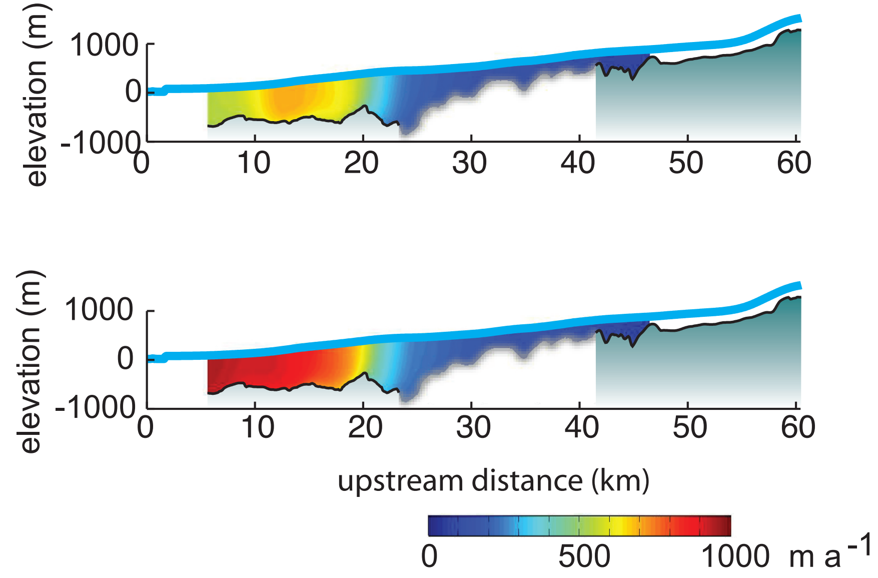


model velocity with steady front location

deformation + sliding along flightline



conclusion



tidewater calving

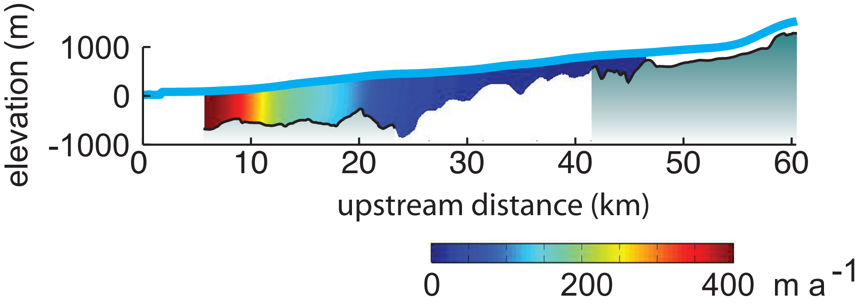
front retreat matches prediction

instantaneous response

dominated by sliding

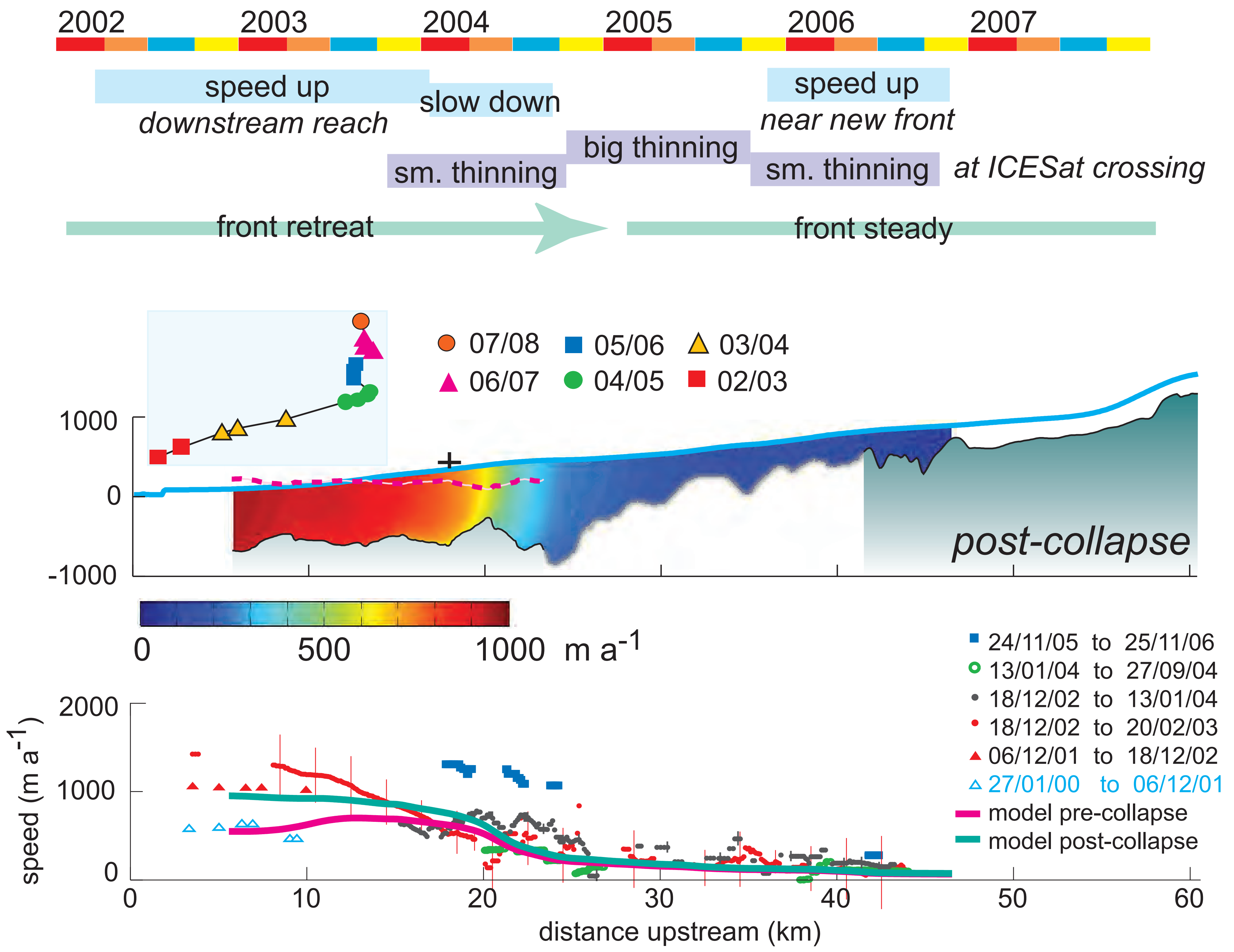
amplification of stress perturbation

$$u_b = k \tau_b^{q} p_e^{-1}$$



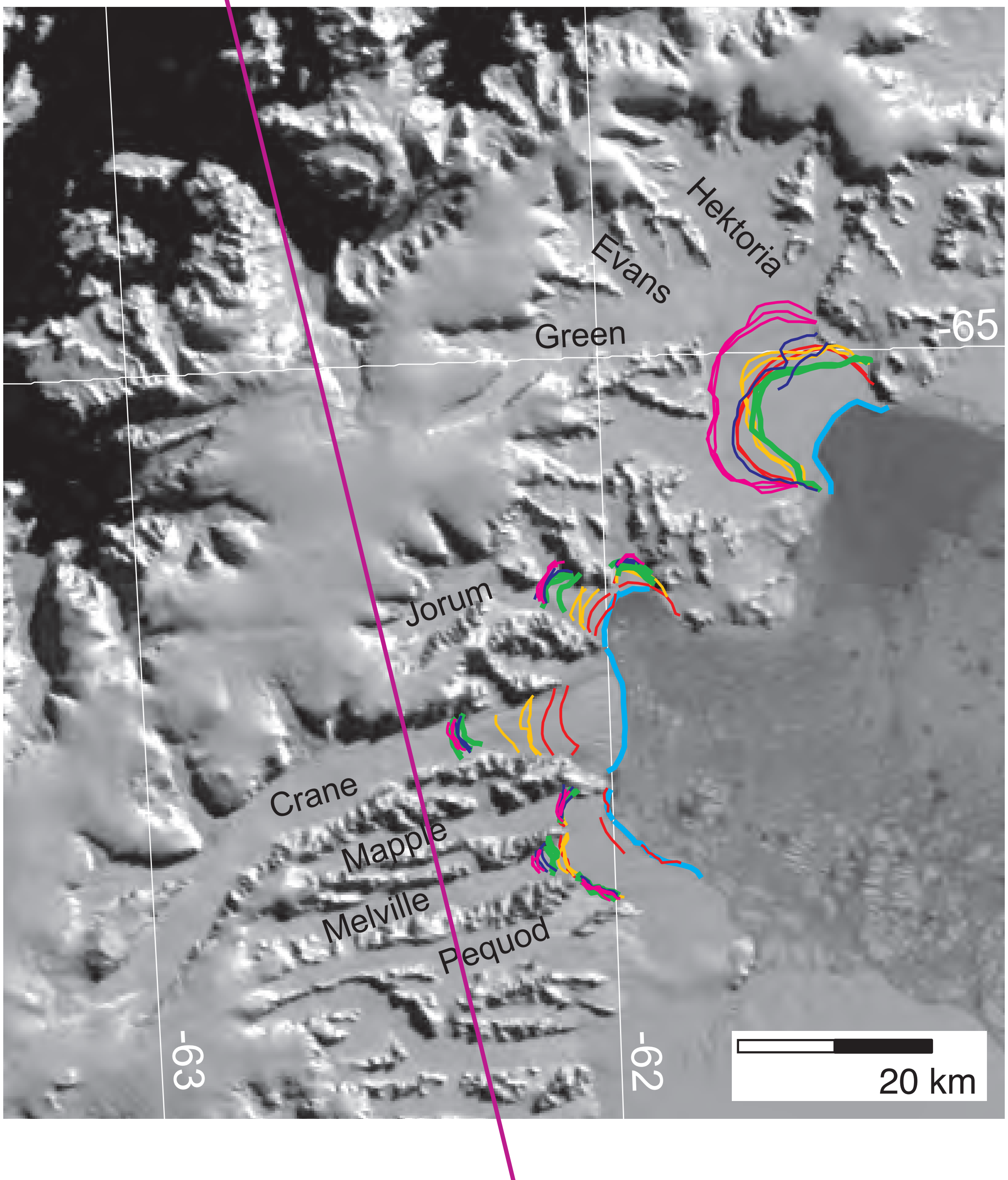
steady state front position

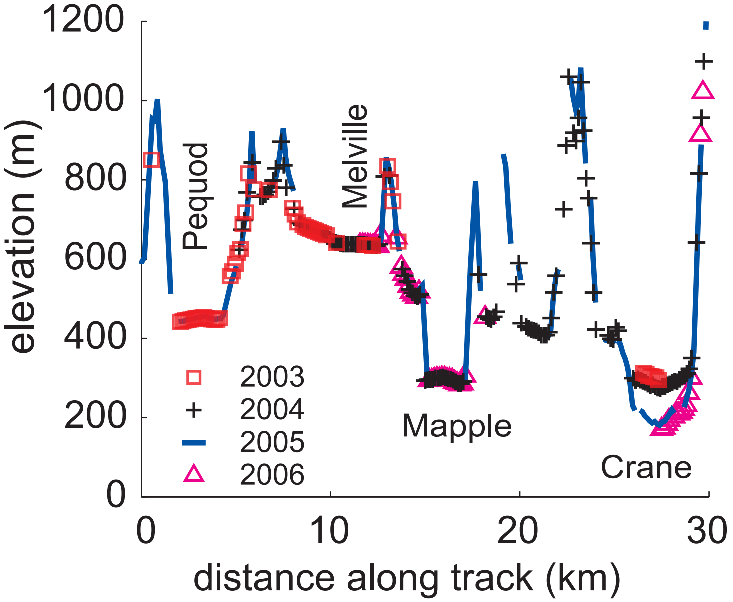
model velocity matches observations

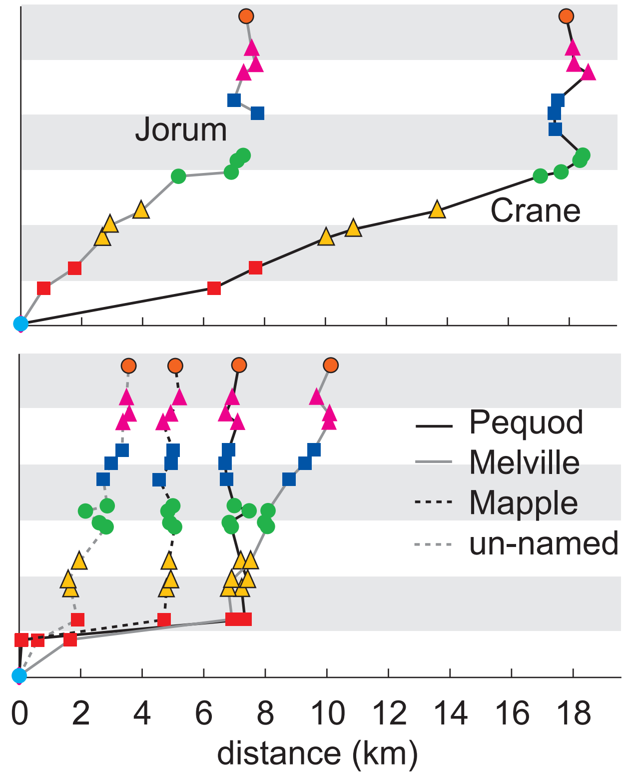

2002
2003
2004
2005
2006
2007
speed up
downstream reach
slow down
big thinning
sm. thinning
sm. thinning
at ICESat crossing
speed up
near new front
front retreat
front steady
07/08
05/06
03/04
06/07
04/05
02/03
1000
0
-1000
+
post-collapse
0
500
1000 m a^{-1}
24/11/05 to 25/11/06
13/01/04 to 27/09/04
18/12/02 to 13/01/04
18/12/02 to 20/02/03
06/12/01 to 18/12/02
27/01/00 to 06/12/01
model pre-collapse
model post-collapse
speed (m a^{-1})
2000
1000
0
0
10
20
30
40
50
60
distance upstream (km)

ICESat laser altimeter
track 0018

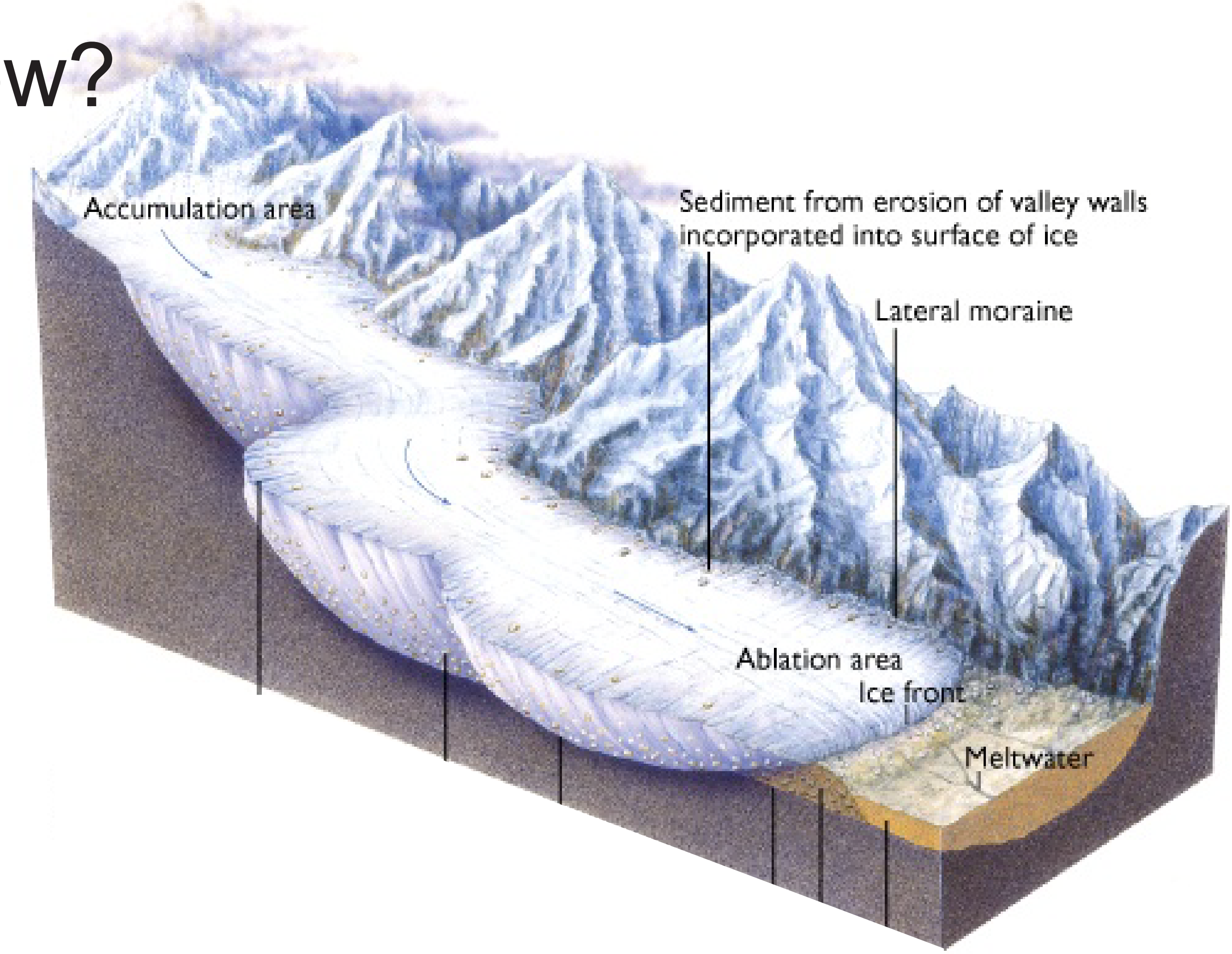
patterns emerge over time



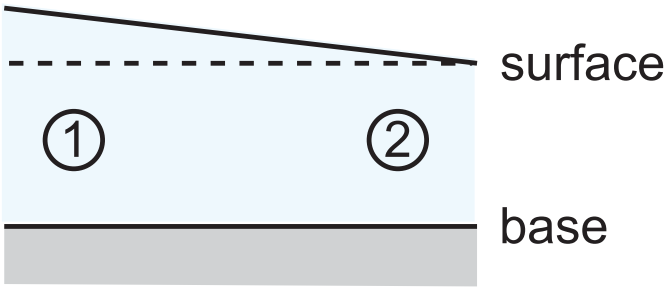




Why does ice flow?



from Press & Siever



gravitational driving stress:

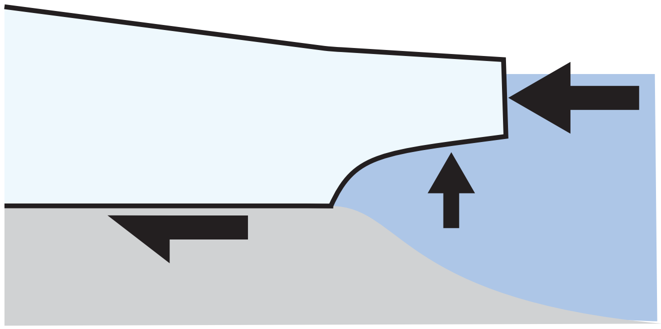
extra pressure at ① compared to ② yields

a stress gradient, ice deforms (flows) in response

resistive stresses:

forces applied at boundaries yield stresses

that must balance (or “dissipate”) the driving stress



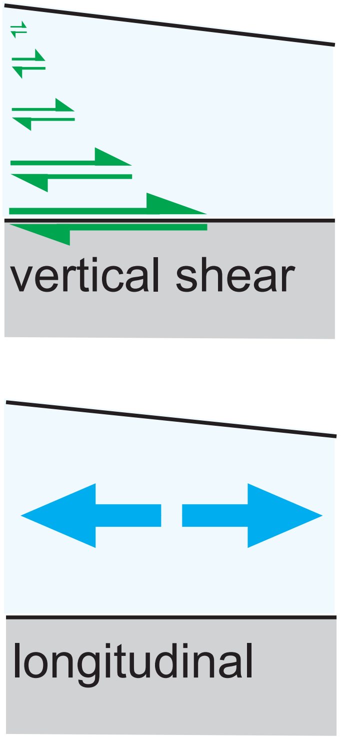
glacier flow

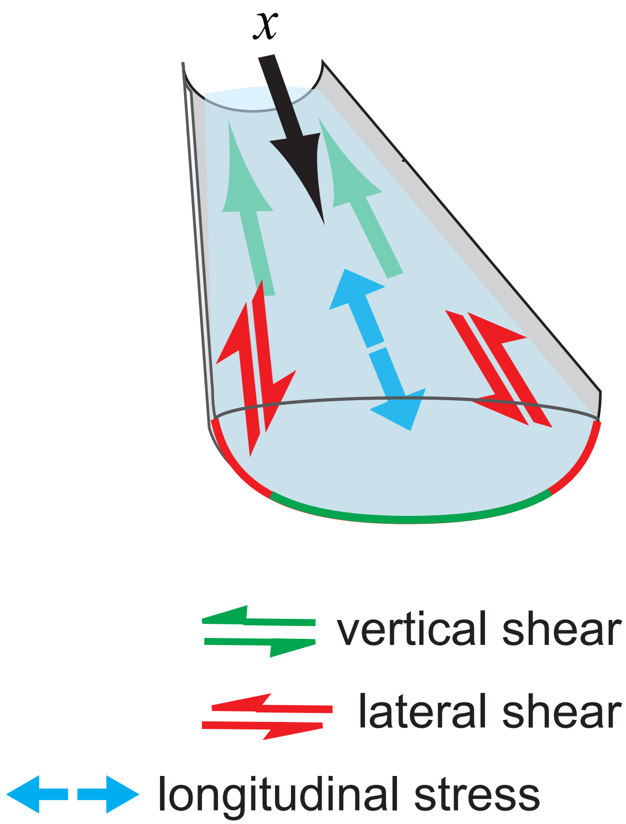
conservation of momentum

$$\frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j = 0 \qquad i,j \ \{x,y,z\}$$

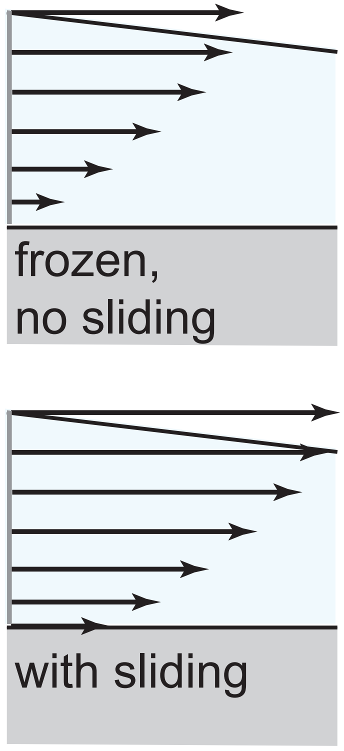
$$x: \ \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} = 0 \quad , \quad z: \ \frac{\partial \tau_{zz}}{\partial z} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial x} = \rho g$$

stresses





horizontal velocity



glacier flow

constitutive relationship between stress τ_{ij} and strain rate $\dot{\varepsilon}_{ij}$

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

u_i	ice velocity

for isotropic ice:

$$\dot{\varepsilon}_{ij} = A\,\tau_e^{n-1}\,\tau_{ij}$$

τ_e	frame-invariant effective stress
n	empirical
A	empirical “rate factor” (has an Arrhenius form) temperature-dependent