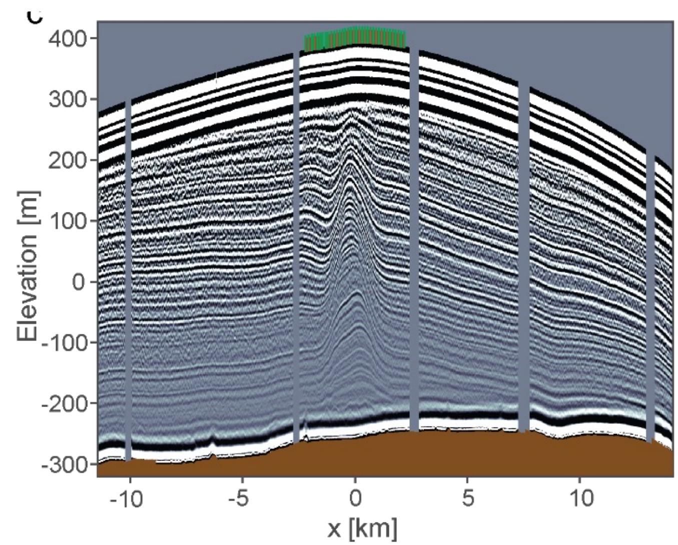
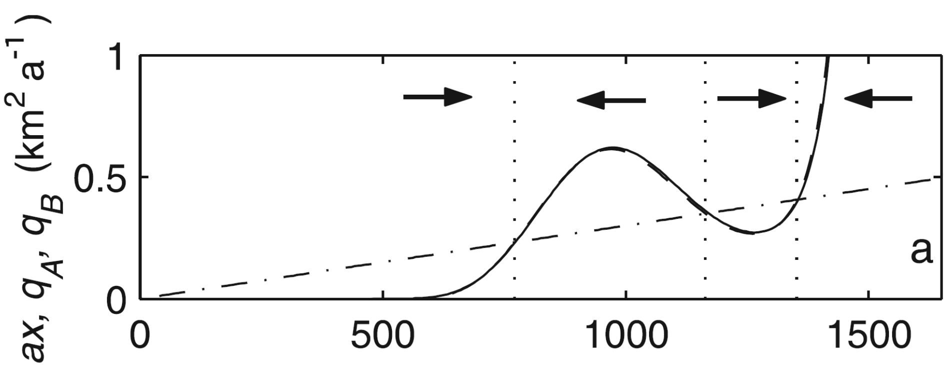
Glaciology
EESCGU4220

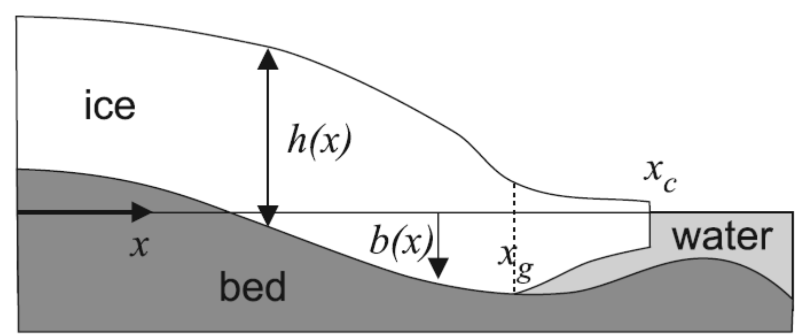
Lecture 8: Ice-flow extremes

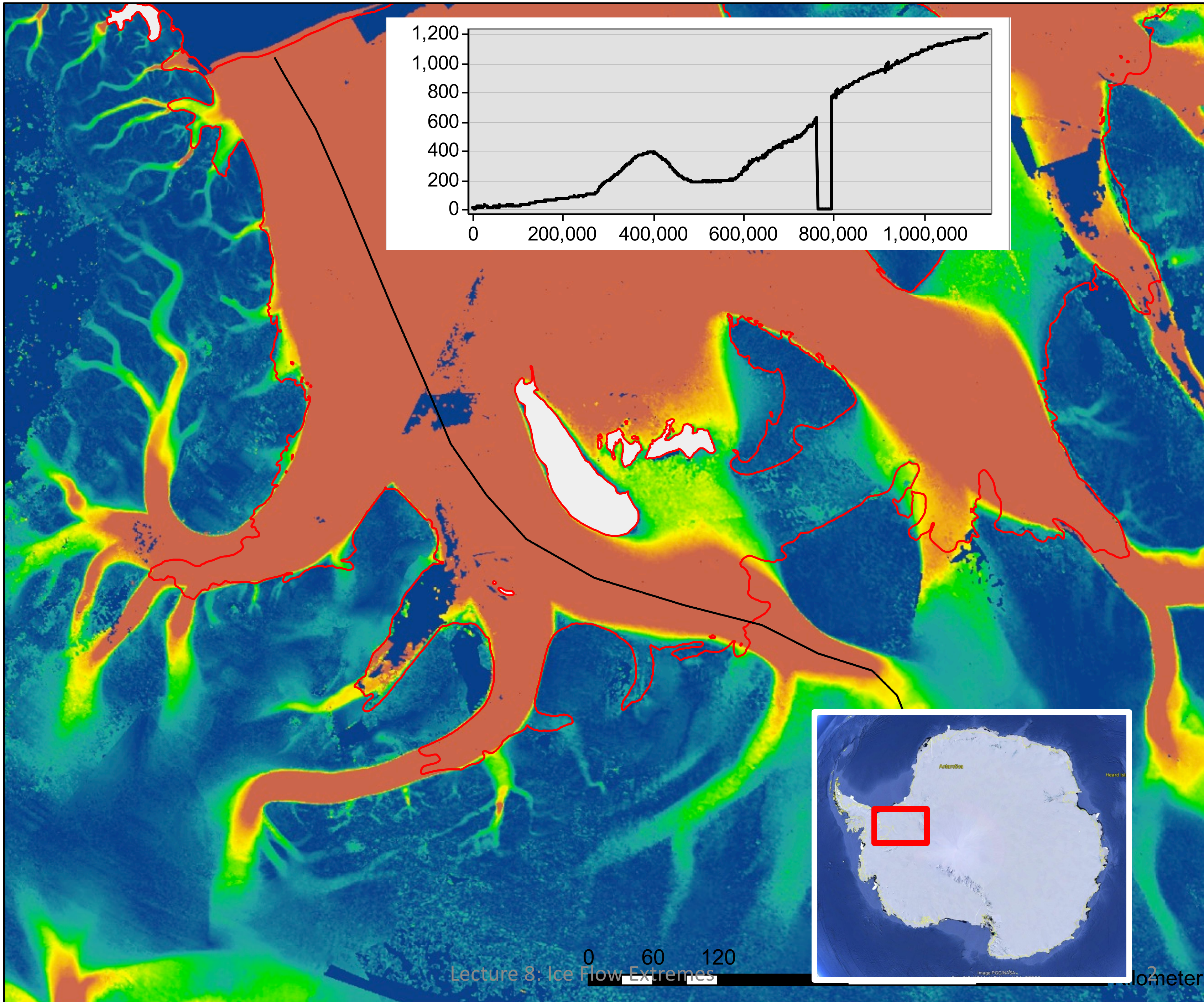


Ice divides ---- very slow and complex!

Grounding lines ---- usually fast and complex!



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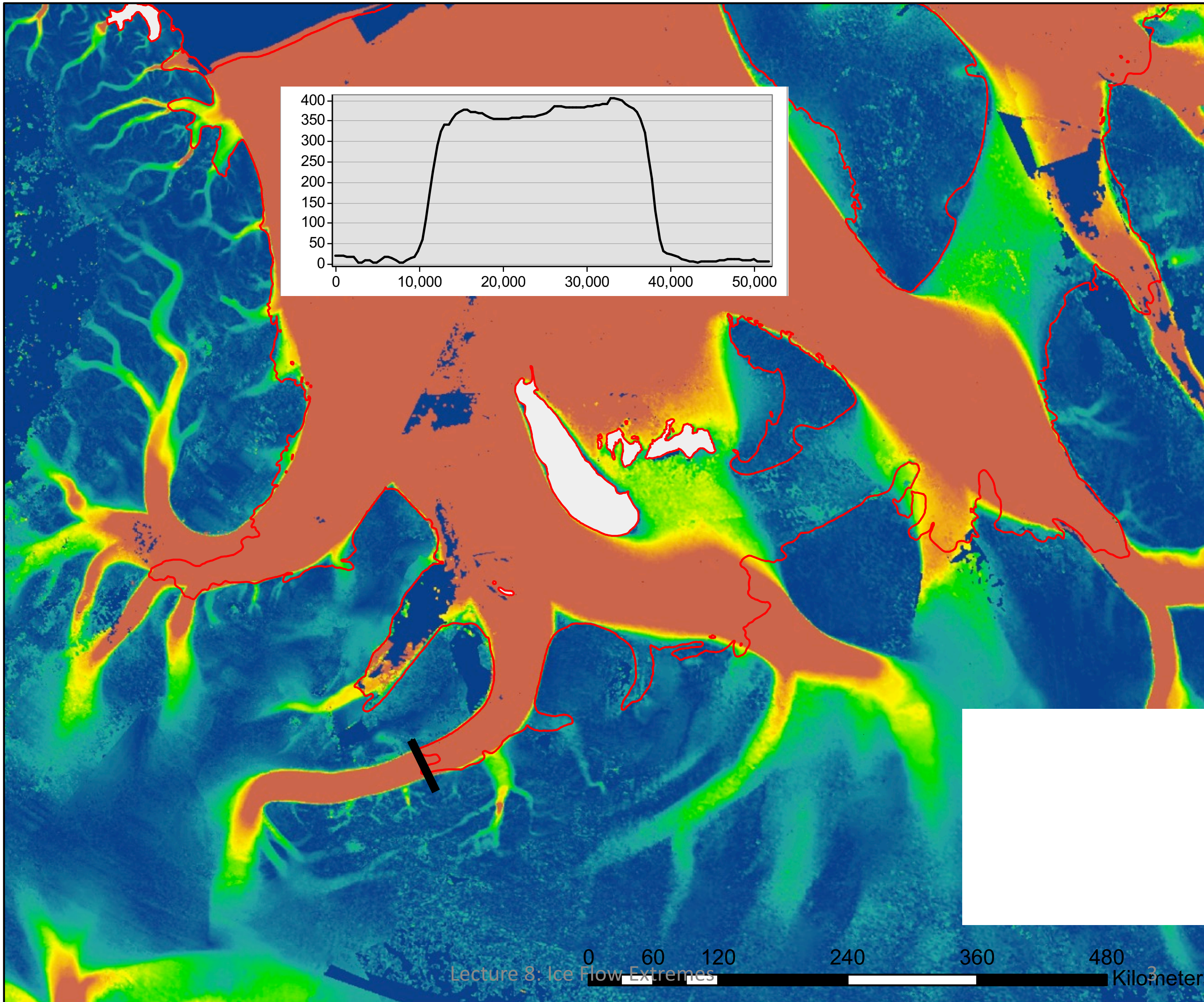
Kilometers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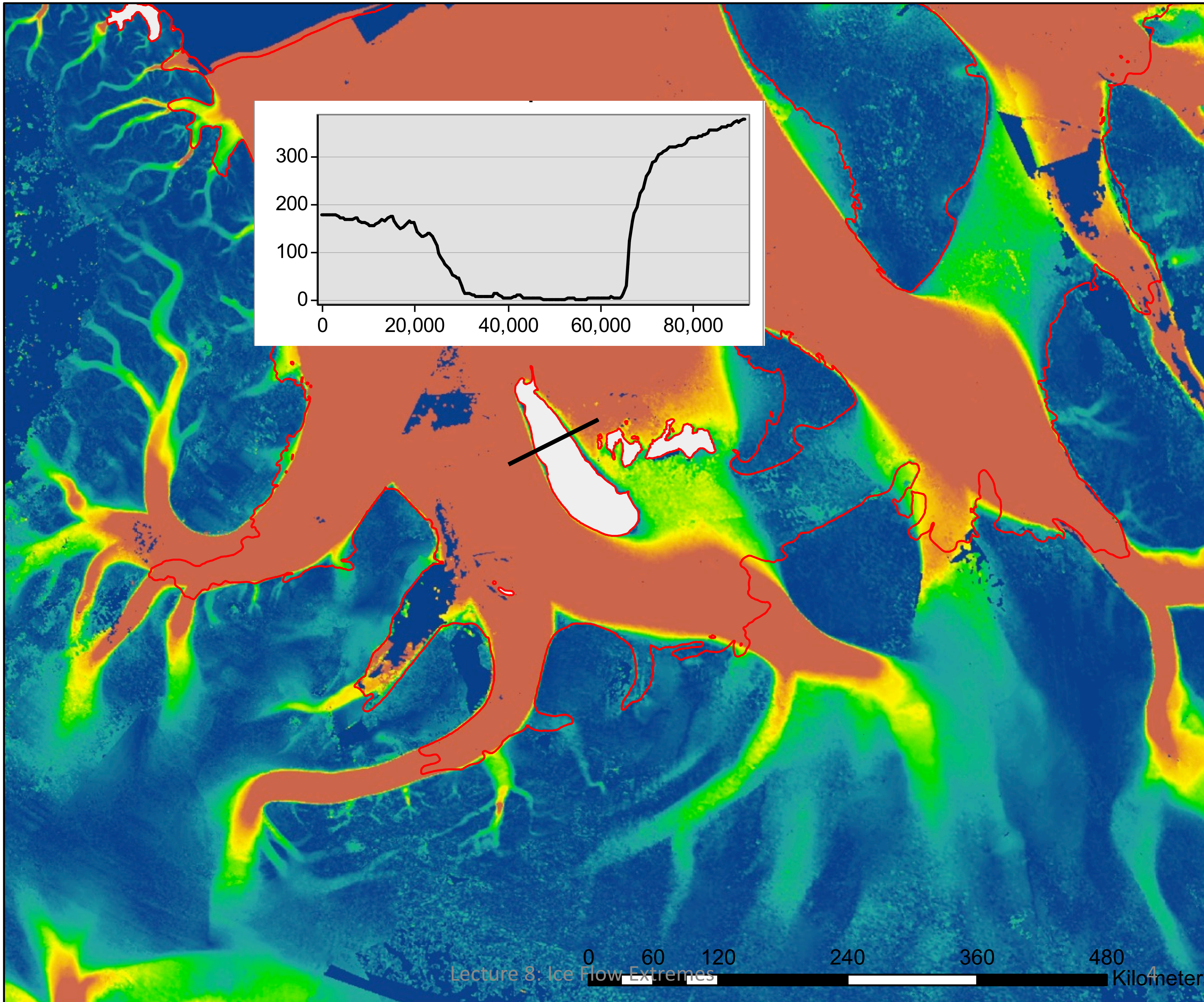
Kilometers



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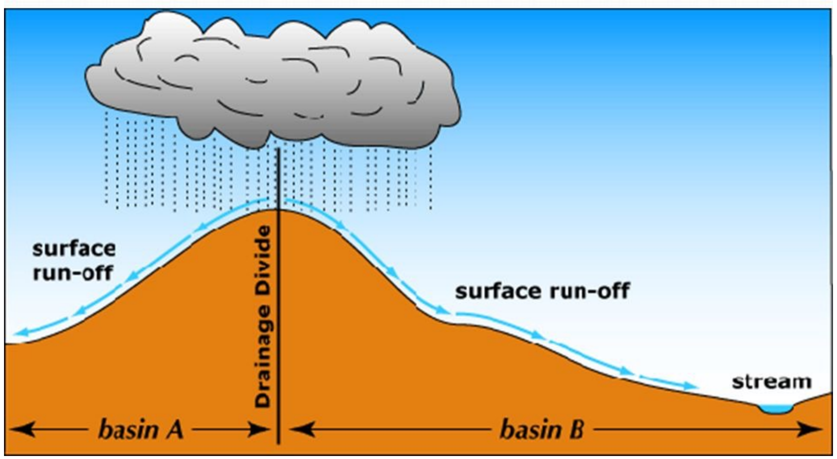
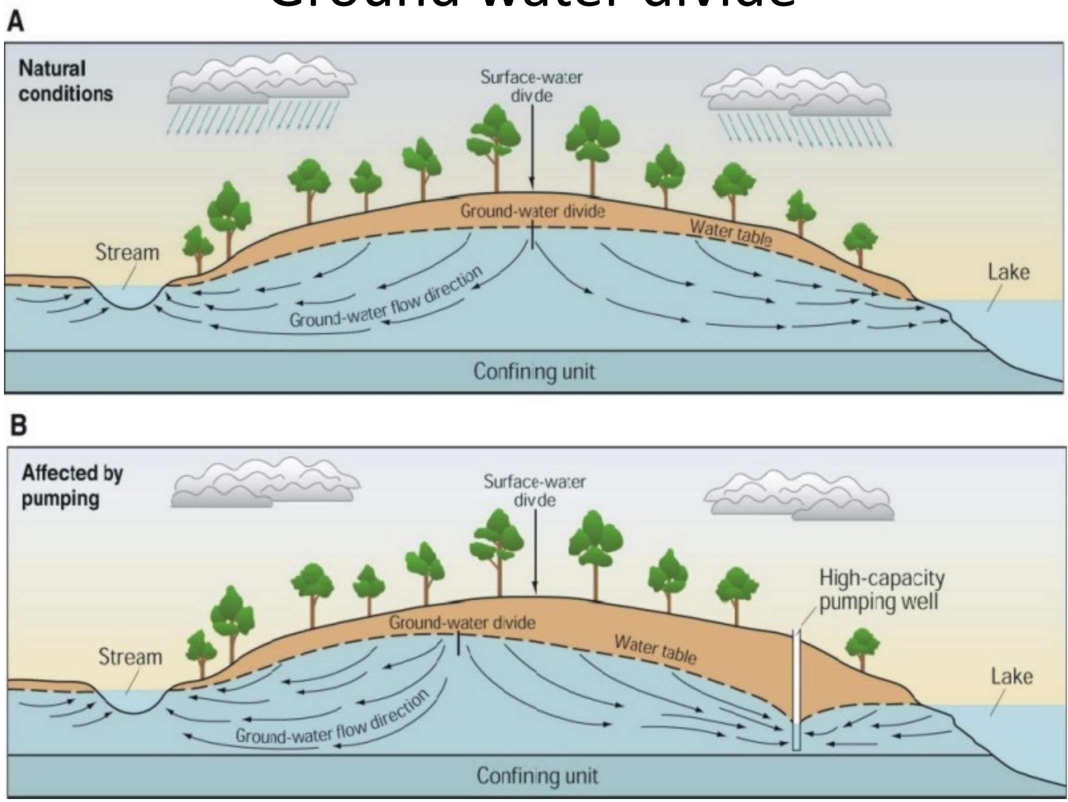
Kilometers

Surface water divide



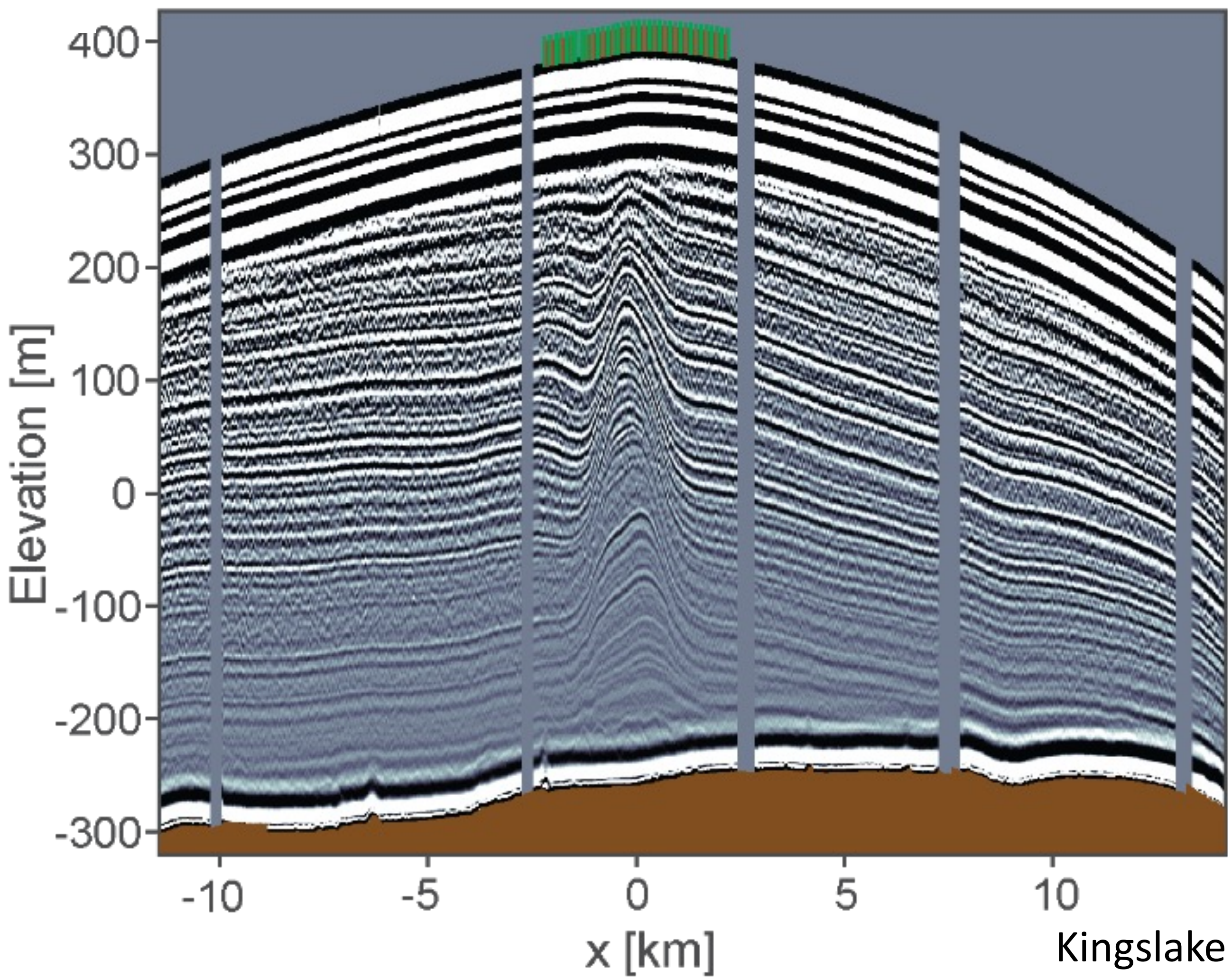
Cornelia Gibbs: Rivers an Introduction. http://slideplayer.com

Ground water divide



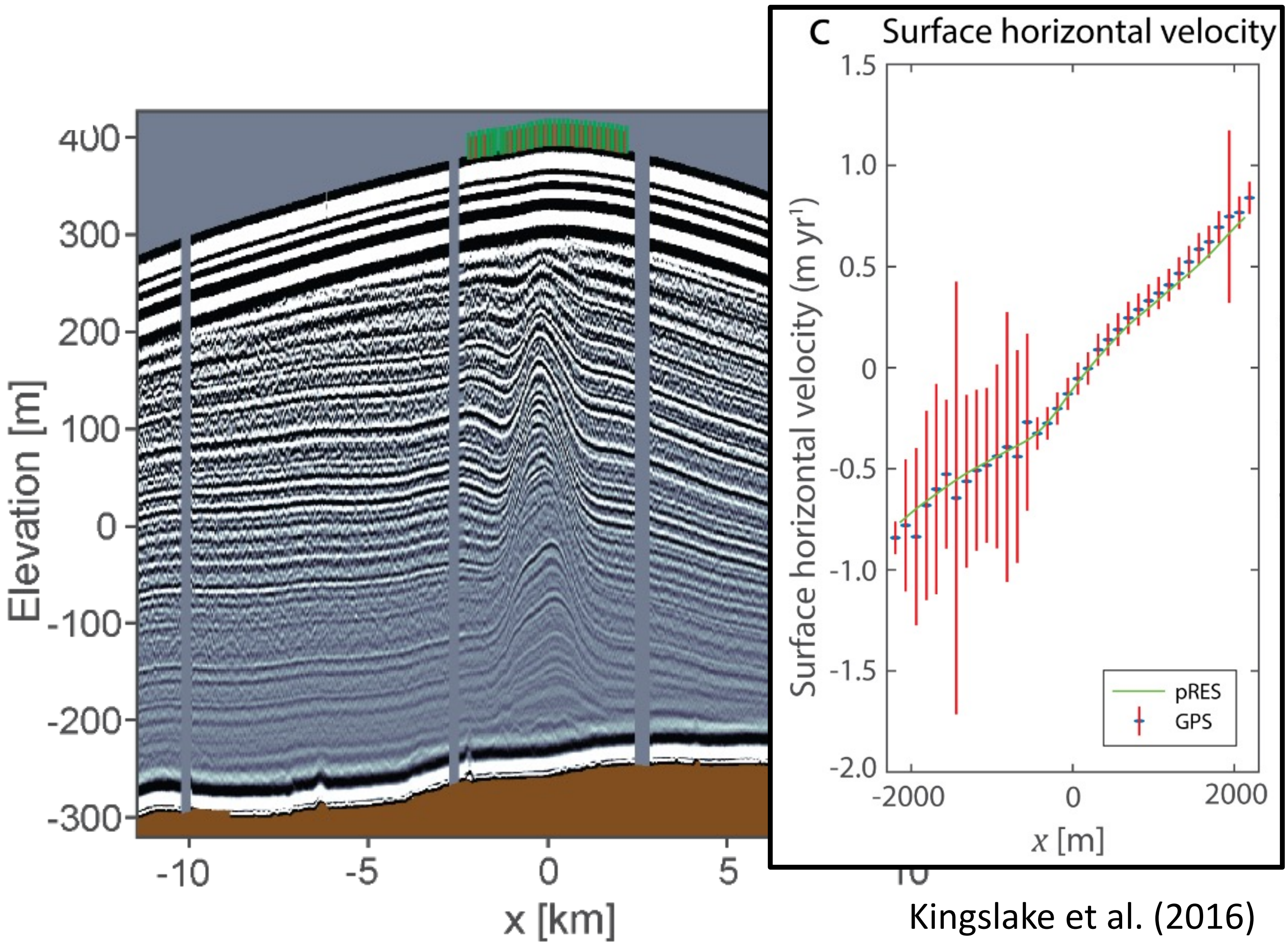
USGS

Ice divide



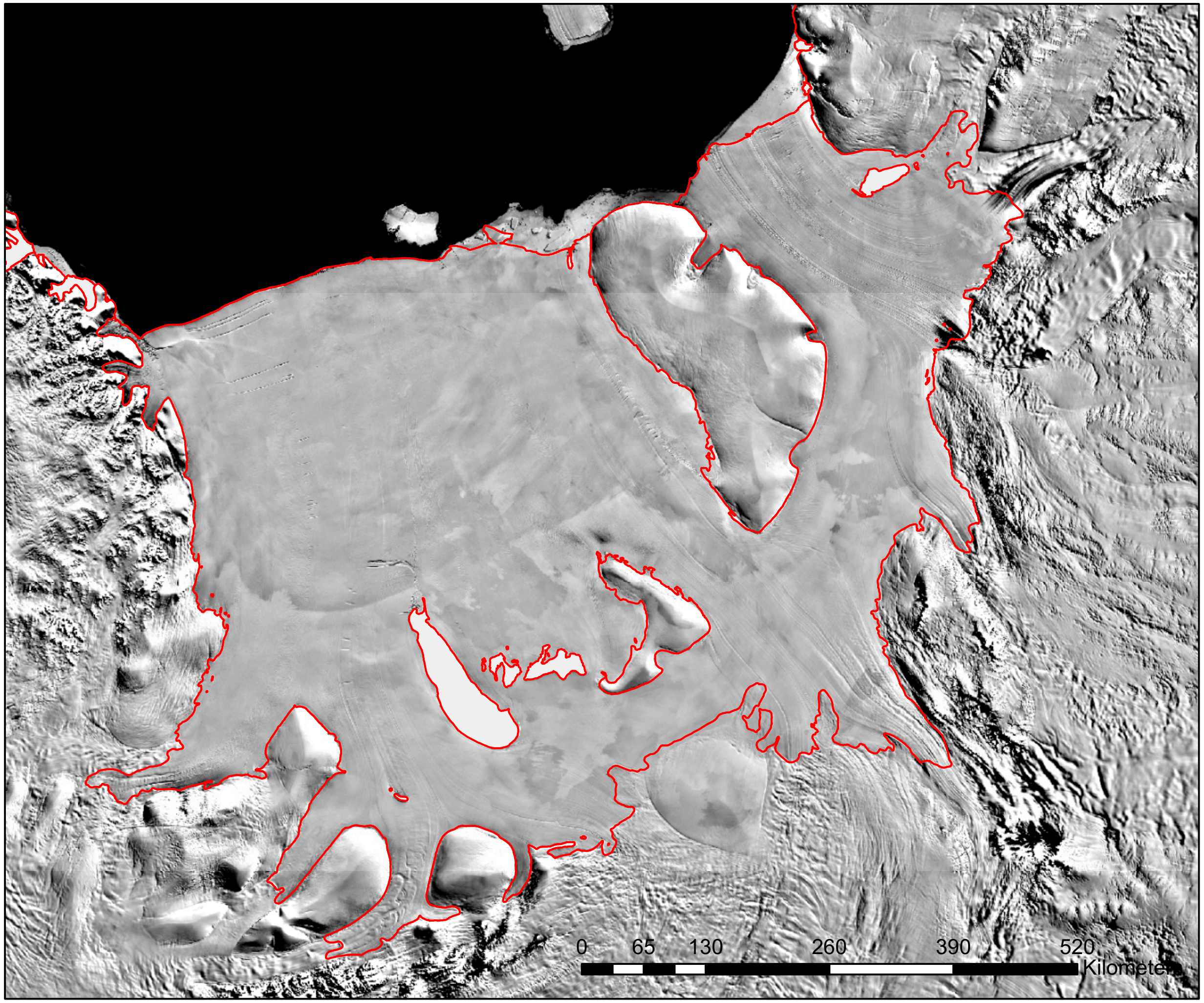
Kingslake et al. (2016)

Ice divides



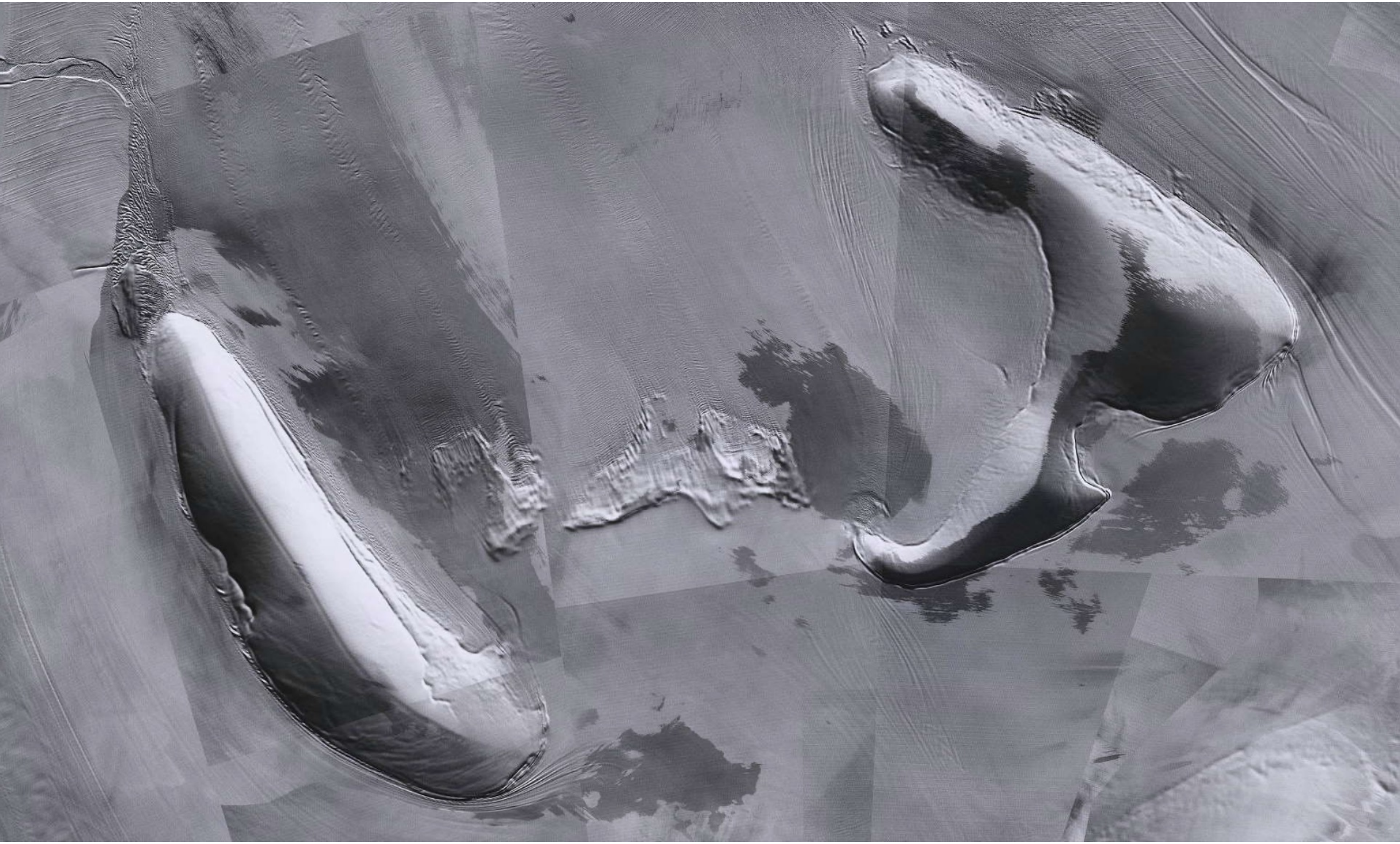
Kingslake et al. (2016)

Ice divides from satellite imagery



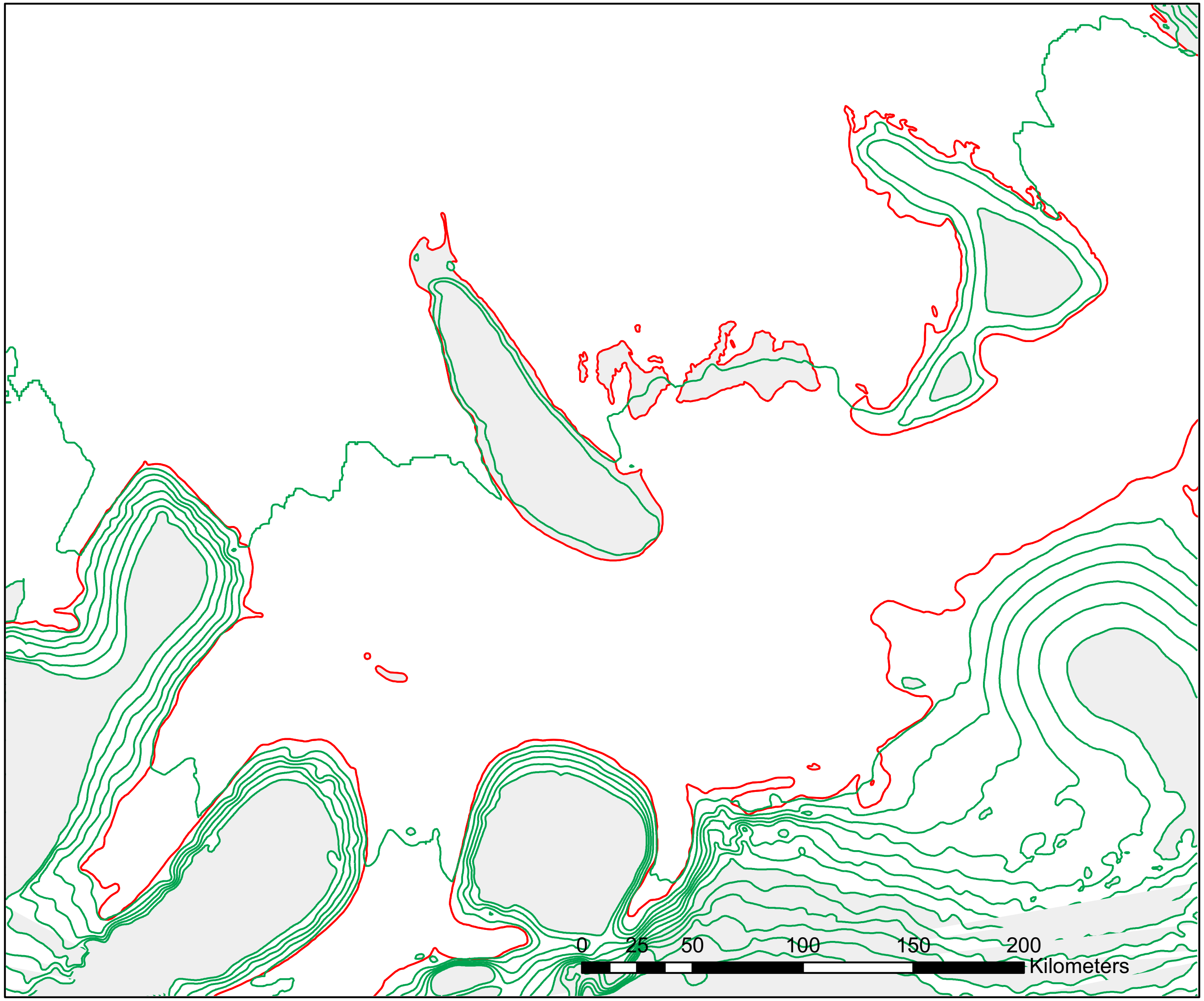
MODIS mosaic of Antarctica (MOA); Scambos et al. (2005)

Ice divides from satellite imagery



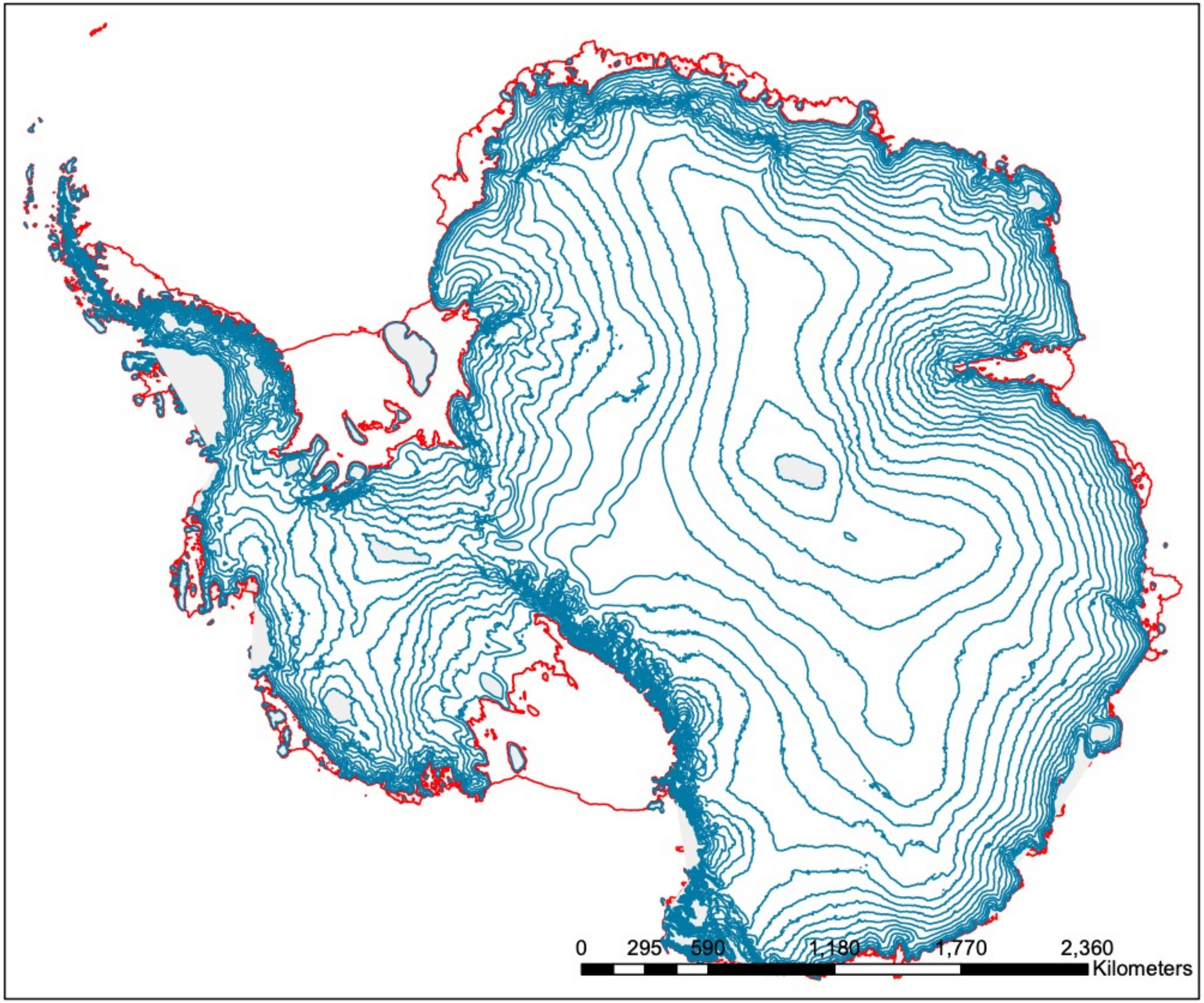
MODIS mosaic of Antarctica (MOA); Scambos et al. (2005)

Ice divides from a digital elevation model



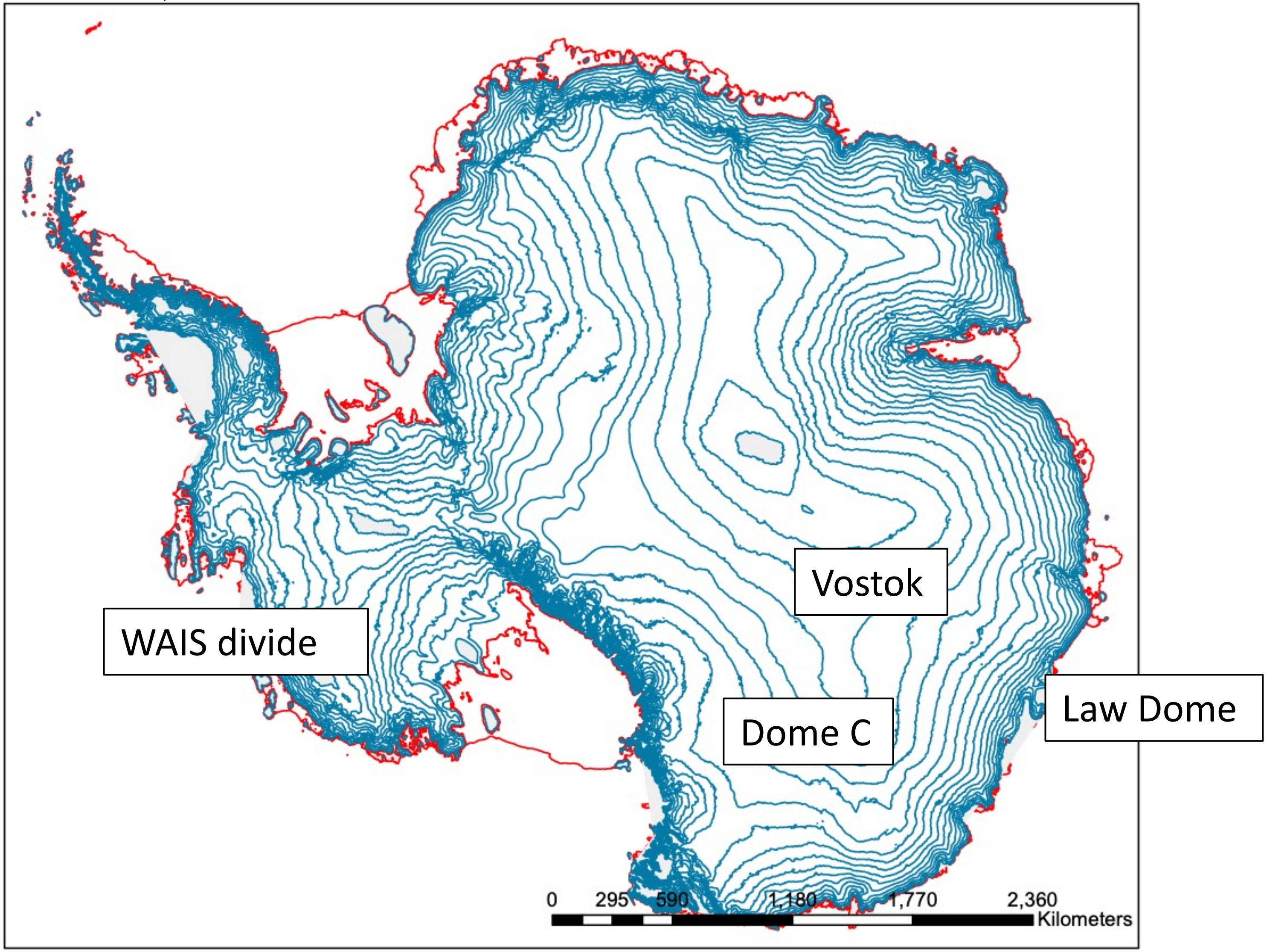
Fretwell et al. (2013)

Ice divides from a digital elevation model



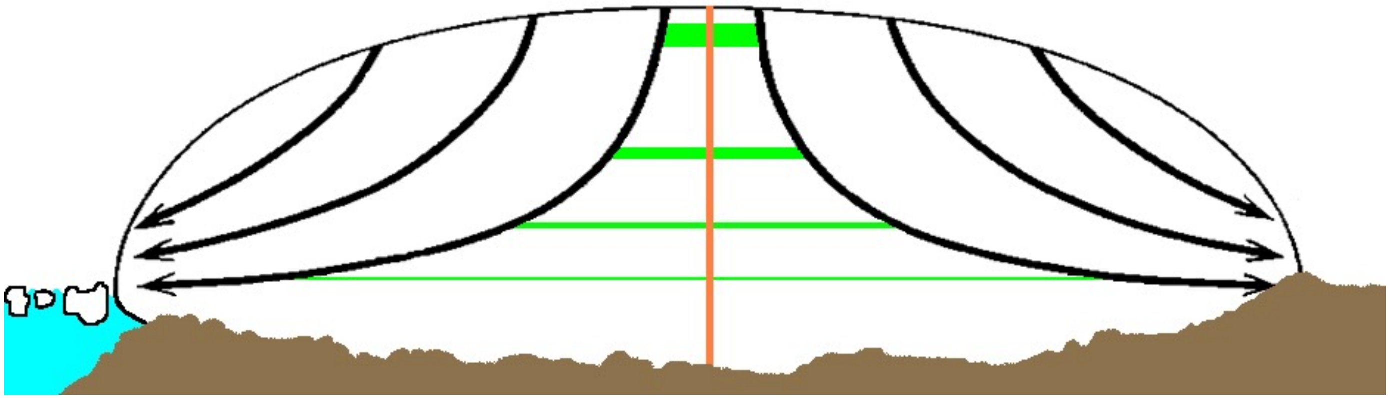
Fretwell et al. (2013)

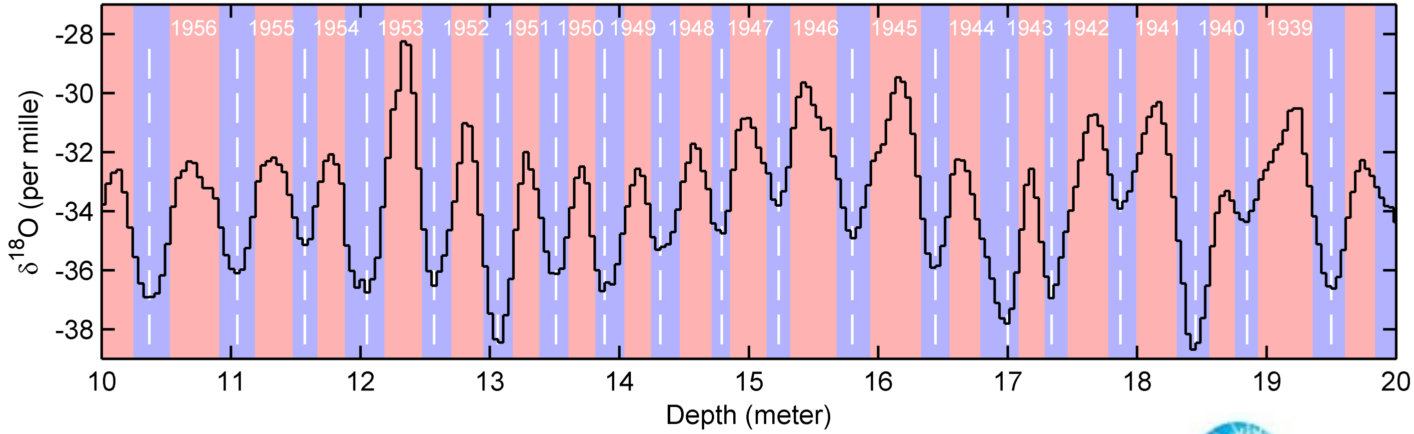
Ice divides, ideal for ice cores



Fretwell et al. (2013)

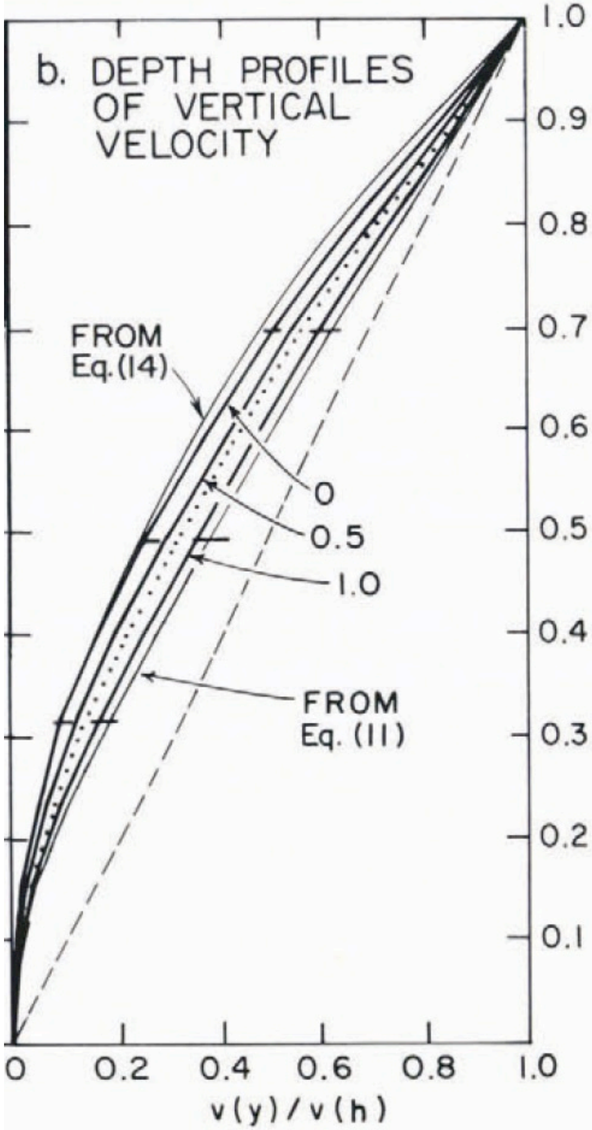
Ice divides, ideal for ice cores





CENTRE FOR ICE AND CLIMATE

Modelling the vertical flow at ice divides



$$d_{xx} = \frac{\partial u}{\partial x}, \qquad d_{yy} = \frac{\partial v}{\partial y},$$

$$\varepsilon = \left(\frac{d_{xx}^2}{2} + \frac{d_{yy}^2}{2} + d_{xy}^2 \right)^{1/2}.$$

$$\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} - \frac{\partial p}{\partial x} = 0,$$

$$\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} - \frac{\partial p}{\partial y} - \rho g = 0$$

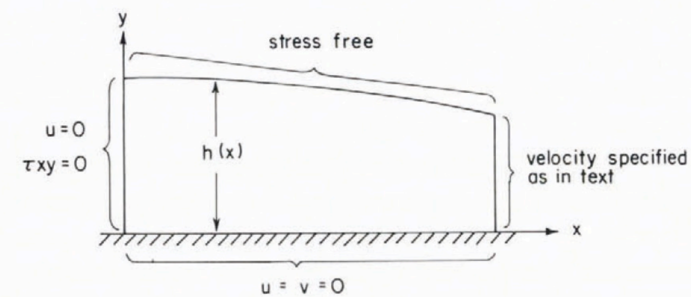
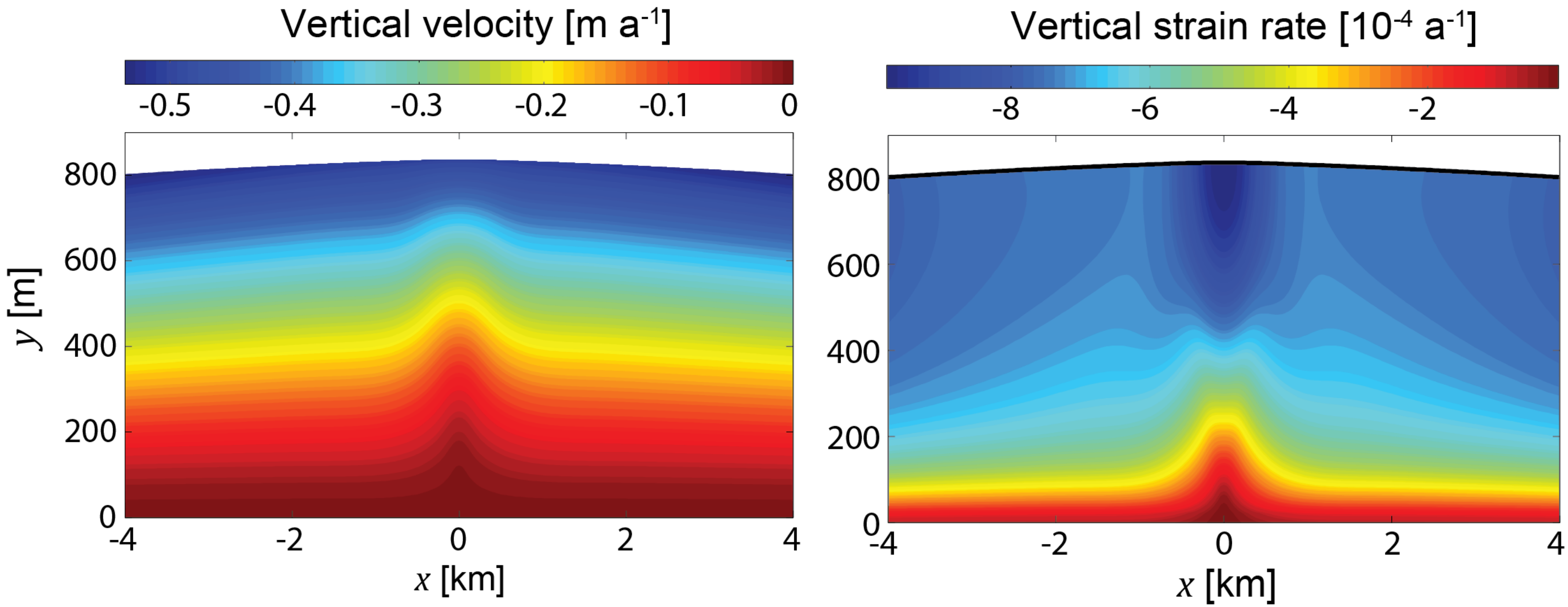


Fig. 1. Idealized cross-section of two-dimensional symmetric ice divide.

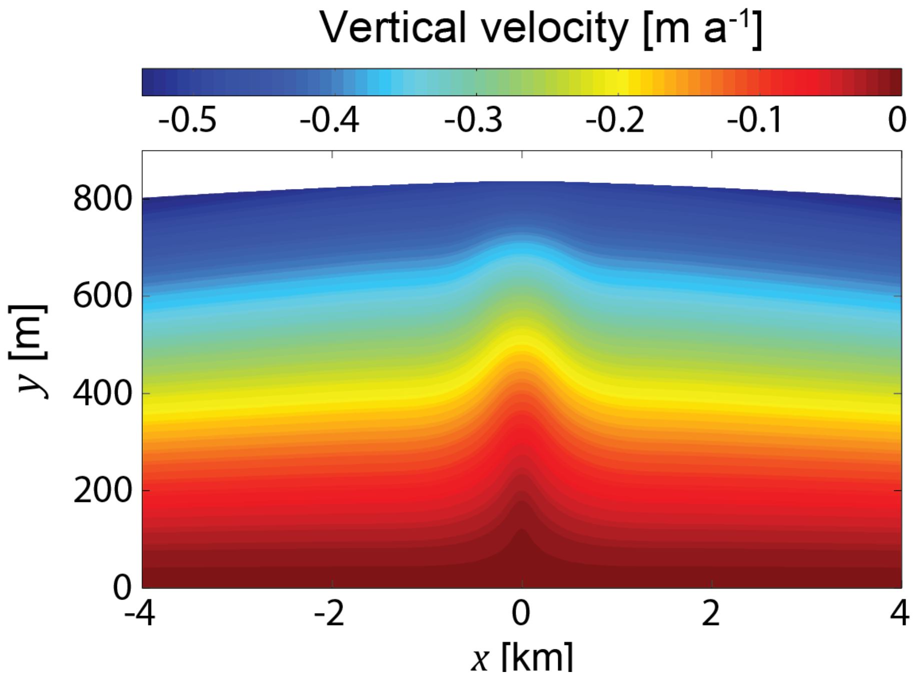
Raymond (1983)

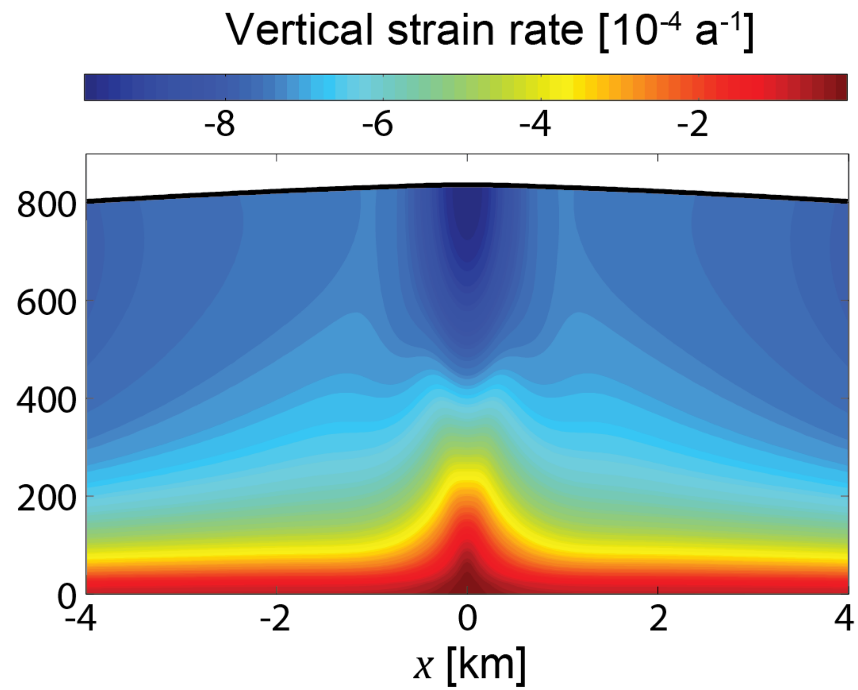
Modelling the vertical flow at ice divides

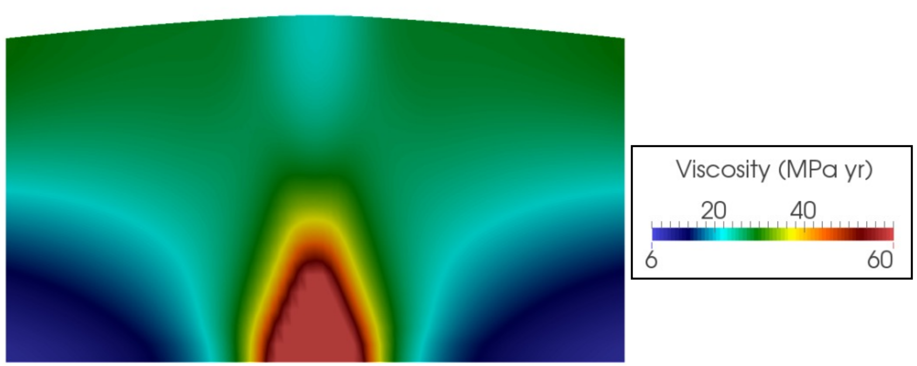


Kingslake et al. (2014)

Modelling the vertical flow at ice divides

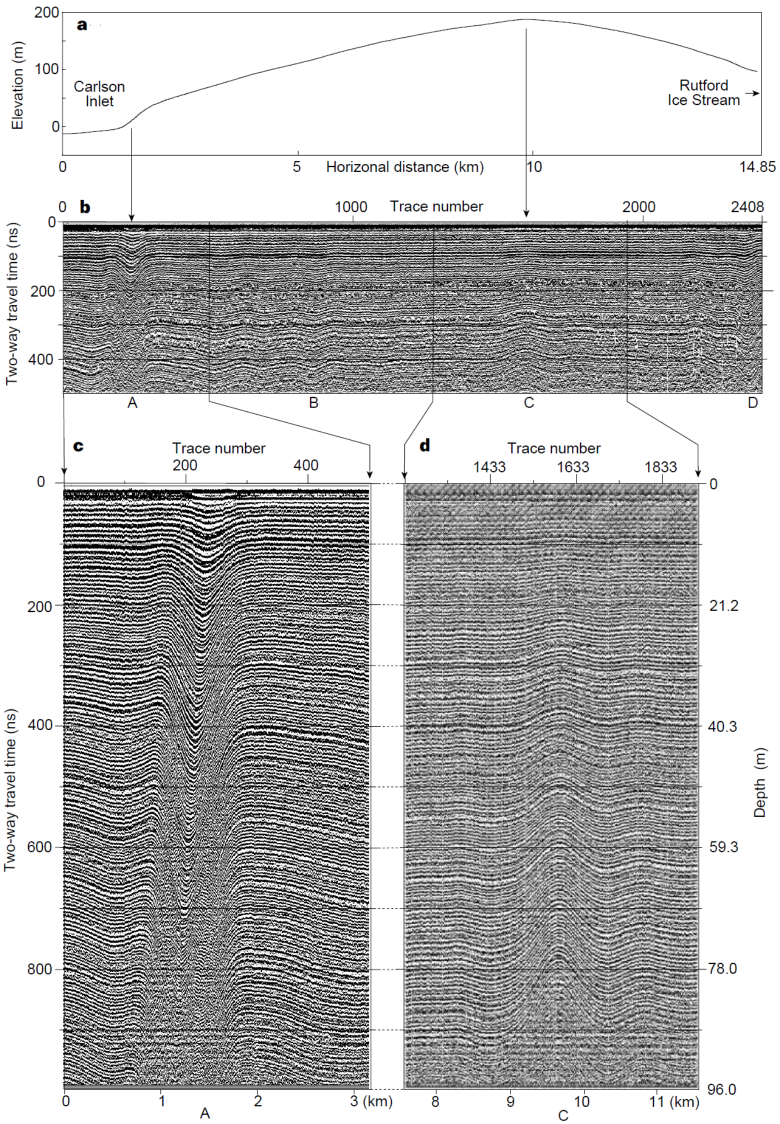






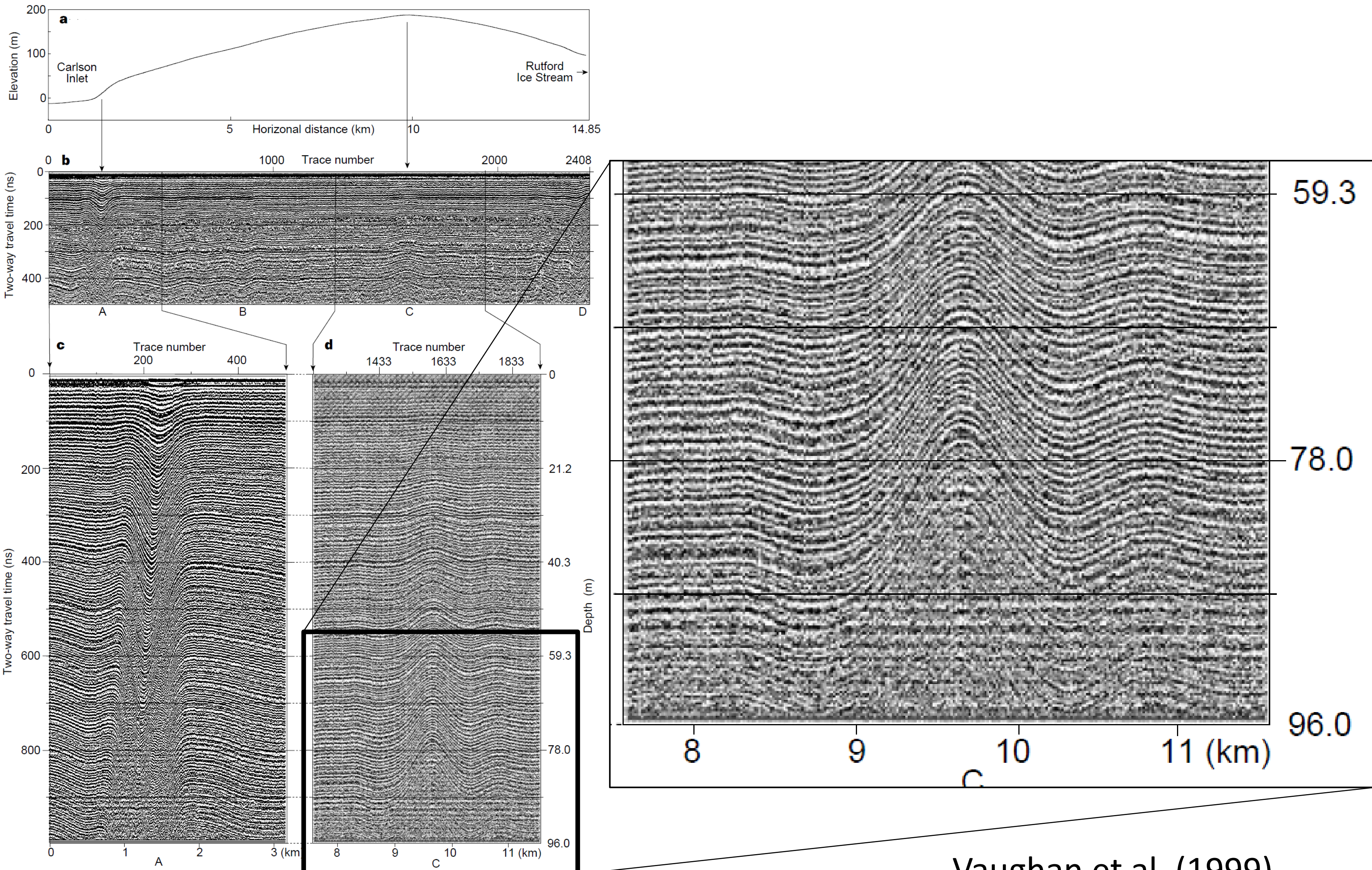
Kingslake et al. (2014)

The first observed "Raymond Bumps"



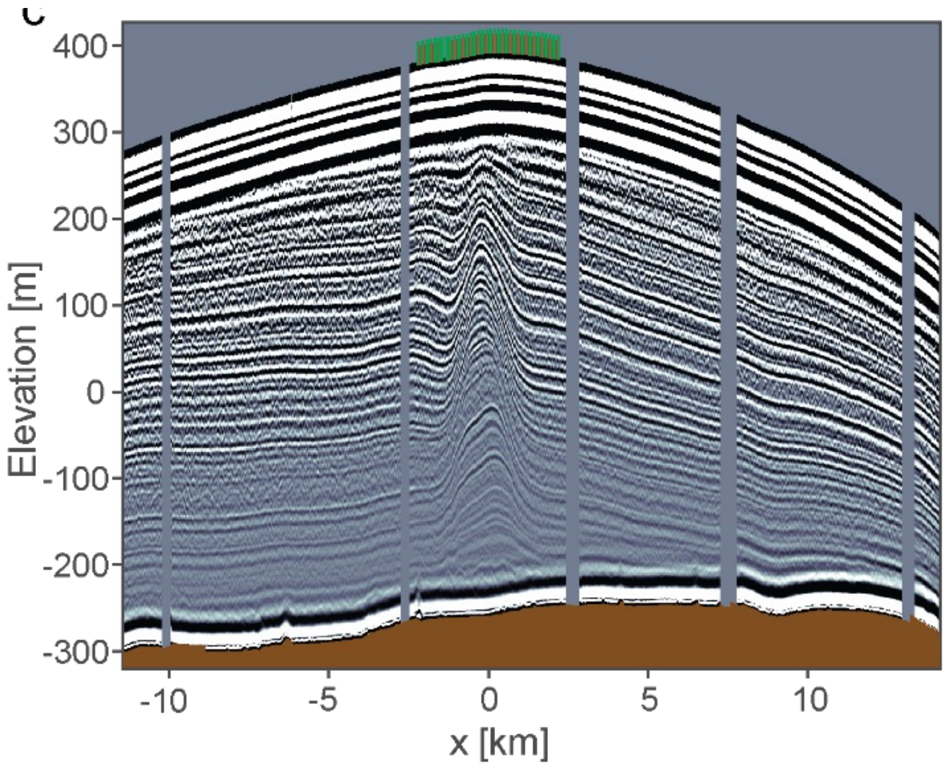
Vaughan et al. (1999)

The first observed "Raymond Bumps"

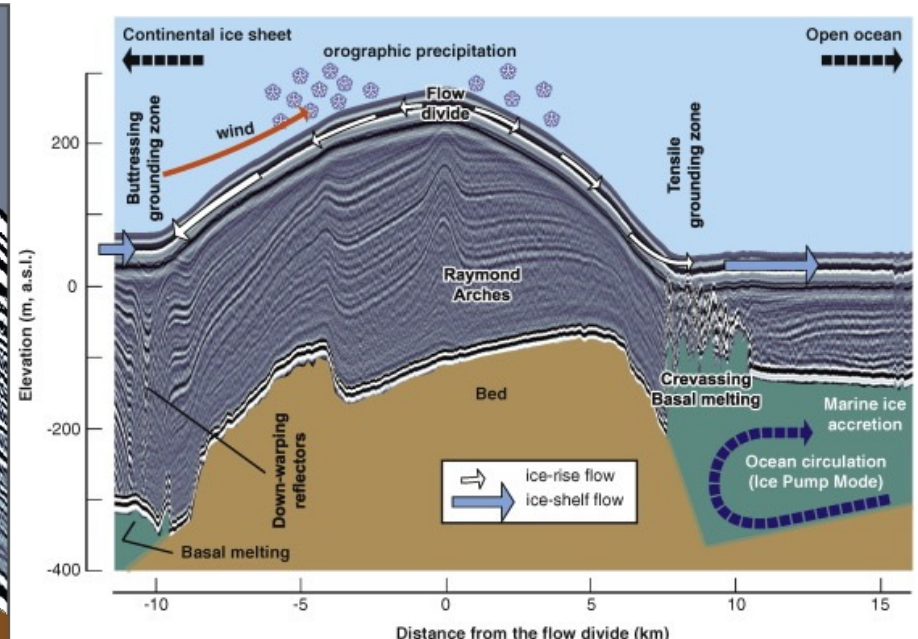


Vaughan et al. (1999)

Raymond Bumps have now been observed in many places.



Kingslake et al. (2016)



Matsuoka et al. (2015)

The Raymond effect has even been measured!

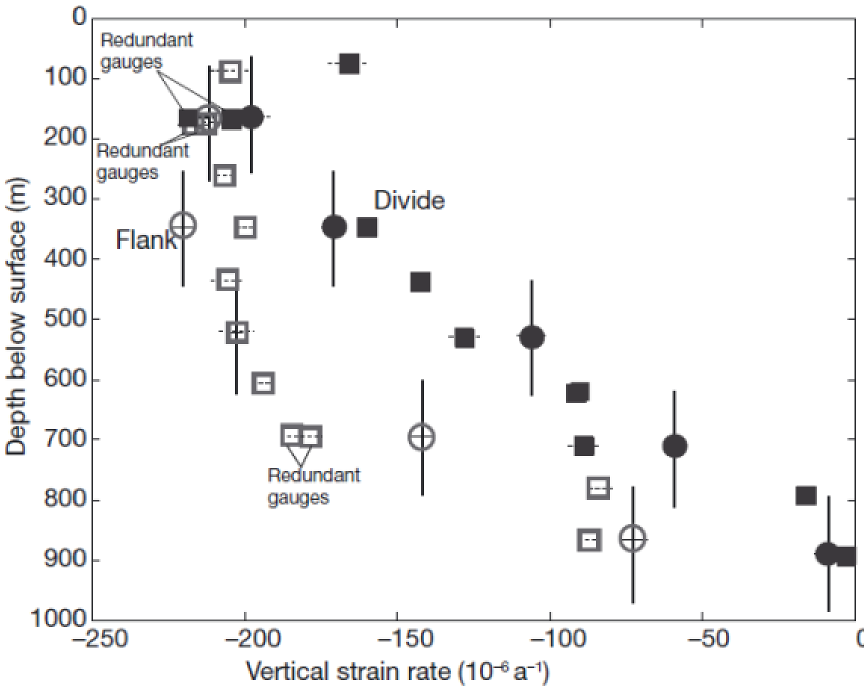
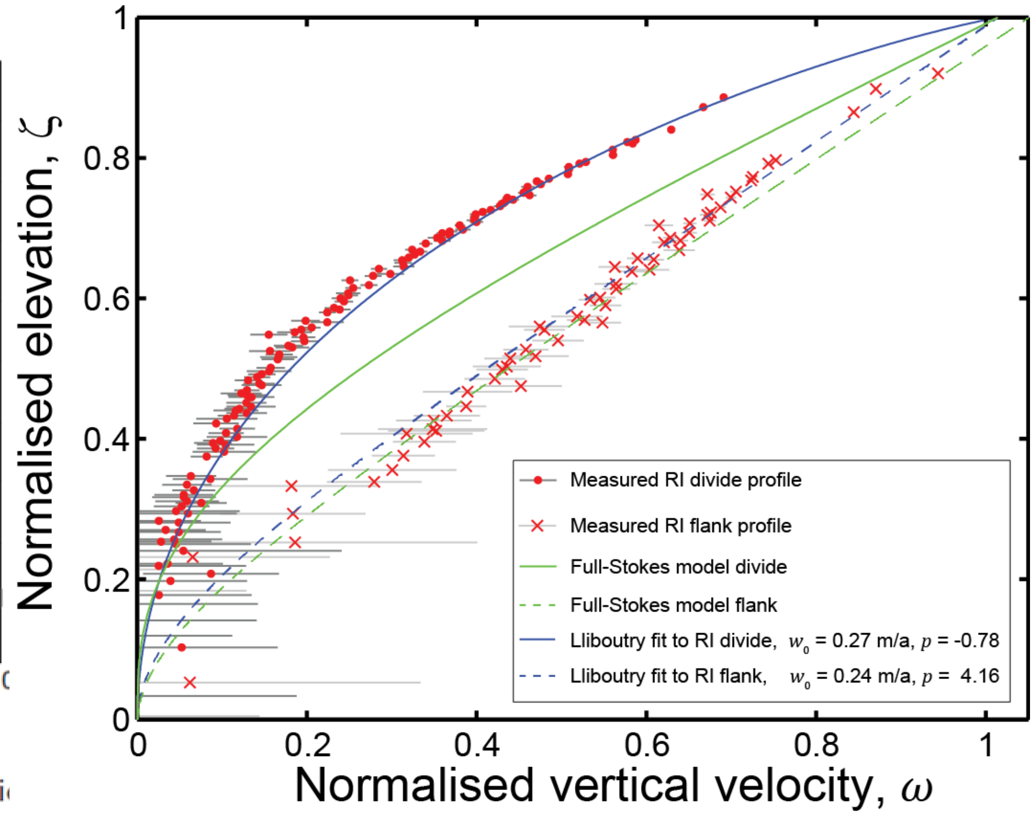


Fig. 4. Strain-rate data from the wire (squares) and fiber-opti (circles) instruments. The open symbols are flank-site measurements,

Pettit et al. (2011)



Kingslake et al. (2014)

Flux at the grounding line controls mass loss in Antarctica

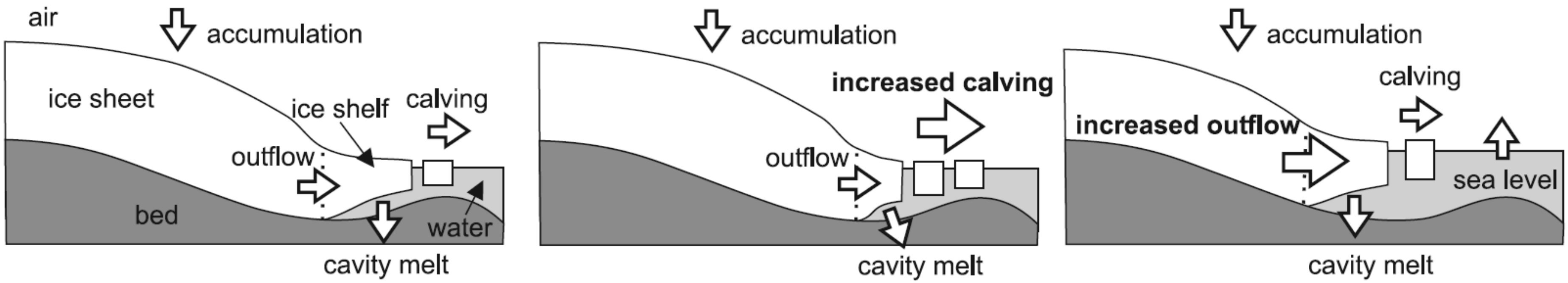


Figure 1. Main components in the mass balance of a marine ice sheet.

Schoof (2007)

The marine ice sheet instability

- Proposed by Weertman

STABILITY OF THE JUNCTION OF AN ICE SHEET AND AN ICE SHELF

By J. WEERTMAN

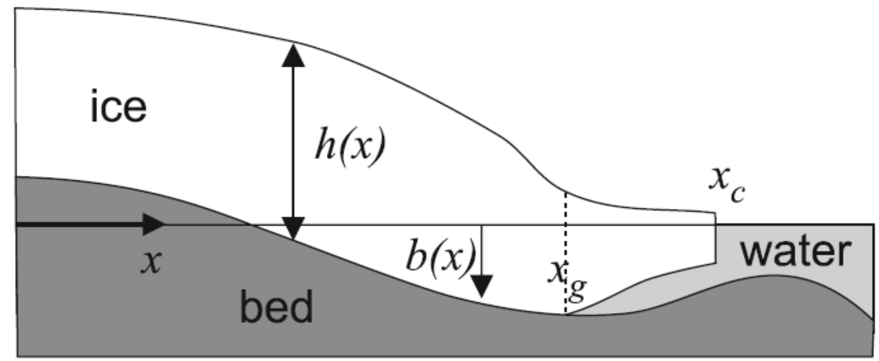
→ If a grounding line retreats into deeper water, flux will increase and cause further retreat (a positive feedback).

- Much debated.

- Eventually Schoof (2007) derived a 'boundary layer' model that has been widely accepted.

Schoof's (2007) theory

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = \boldsymbol{b}$$



$$b(x) = -\left[729 - 2184.8 \times \left(\frac{x}{750\ \mathrm{km}}\right)^2 + 1031.72 \times \left(\frac{x}{750\ \mathrm{km}}\right)^4 - 151.72 \times \left(\frac{x}{750\ \mathrm{km}}\right)^6\right]\ \mathrm{m},$$

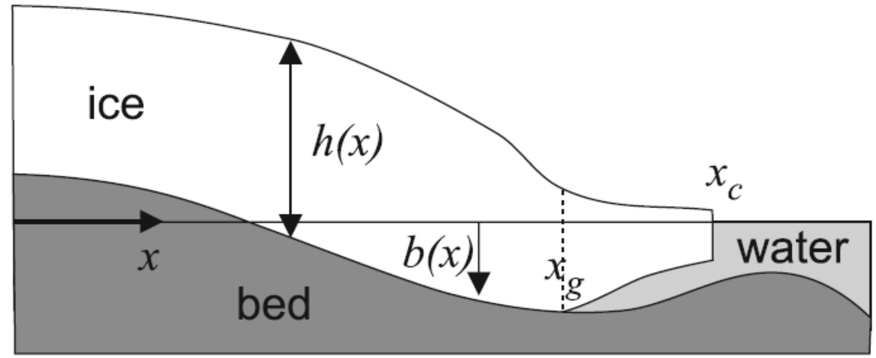
Schoof's (2007) theory

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = \dot{b}_i$$

Specific mass balance

Mass conservation

In steady state: $q = \dot{b}_i x$



$$b(x) = -\left[729 - 2184.8 \times \left(\frac{x}{750\ \mathrm{km}}\right)^2 + 1031.72 \times \left(\frac{x}{750\ \mathrm{km}}\right)^4 - 151.72 \times \left(\frac{x}{750\ \mathrm{km}}\right)^6\right] \mathrm{m},$$

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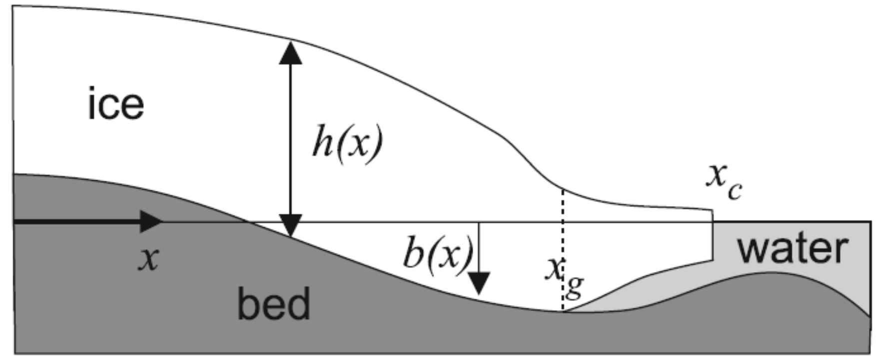
Specific mass balance

Mass conservation



$$b(x) = -\left[729 - 2184.8 \times \left(\frac{x}{750\text{ km}}\right)^2 + 1031.72 \times \left(\frac{x}{750\text{ km}}\right)^4 - 151.72 \times \left(\frac{x}{750\text{ km}}\right)^6\right] \text{m}, \quad (10)$$

In steady state: $q = \dot{b}_i x$

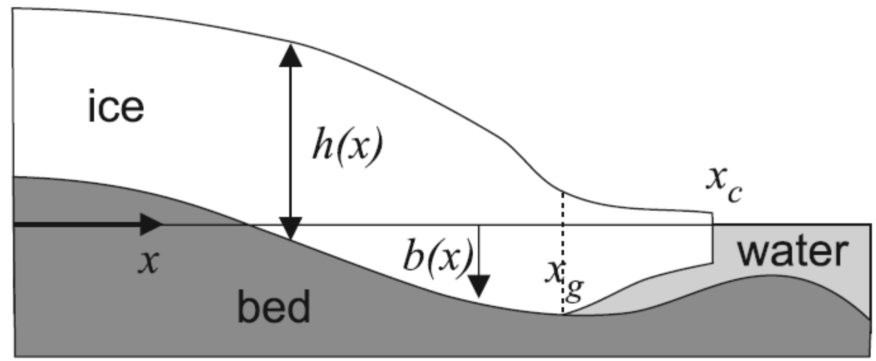
Flux at the grounding line:

$$\boxed{q(x_g) = \left(\frac{\bar{A}(\rho_i g)^{n+1}(1-\rho_i/\rho_w)^n}{4^n C}\right)^{\frac{1}{m+1}} \left[h(x_g)\right]^{\frac{m+n+3}{m+1}}}$$

Schoof's (2007) theory

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = \dot{b}_i$$

Specific mass balance



Mass conservation

$$b(x) = -\left[729 - 2184.8 \times \left(\frac{x}{750\text{ km}}\right)^2 + 1031.72 \times \left(\frac{x}{750\text{ km}}\right)^4 - 151.72 \times \left(\frac{x}{750\text{ km}}\right)^6\right] \text{m},$$

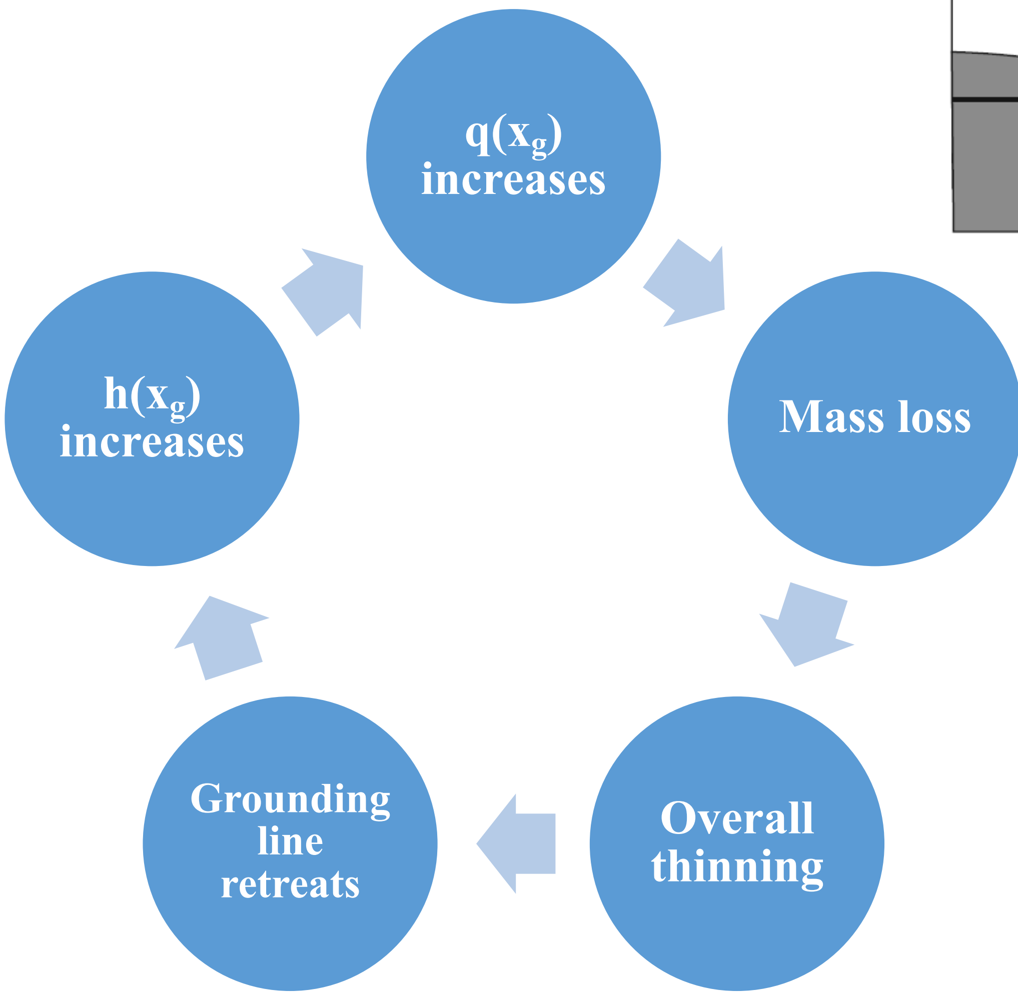
In steady state: $q = \dot{b}_i x$

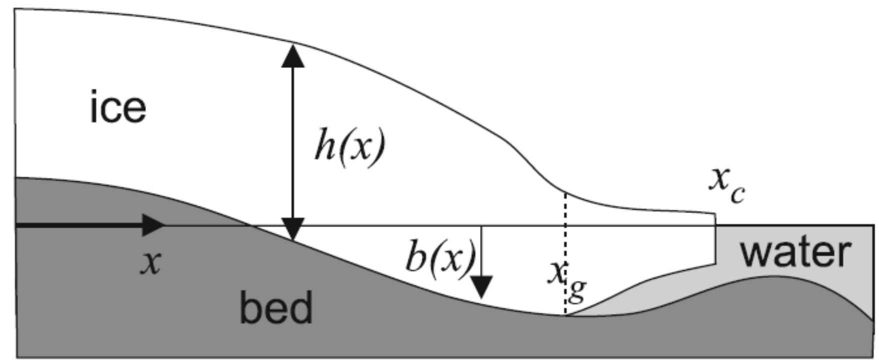
Flux at the grounding line:

$$\boxed{q(x_g) \propto h(x_g)^{4.75}}$$

This quantifies a key part of the marine ice sheet instability!

The marine ice sheet instability



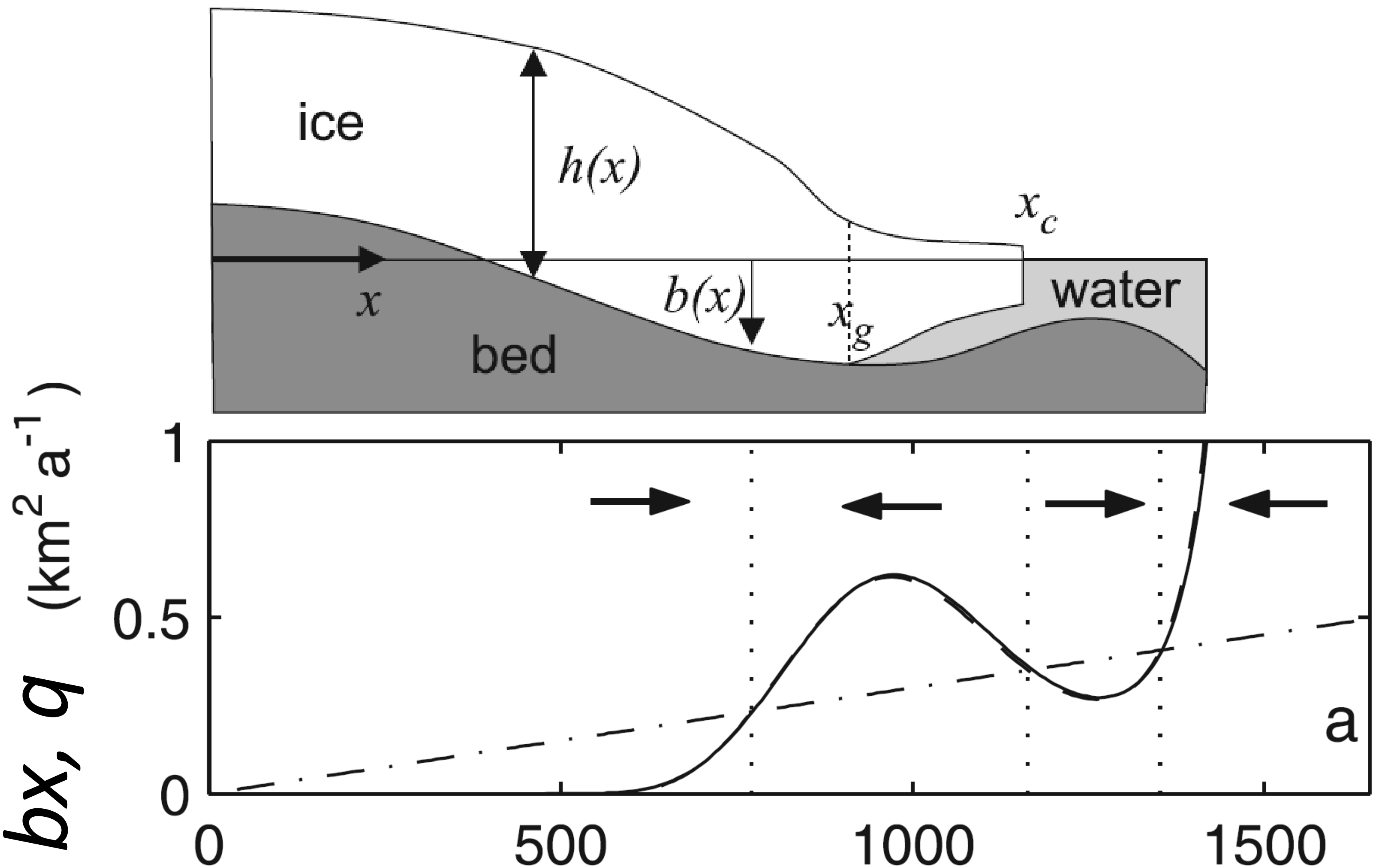


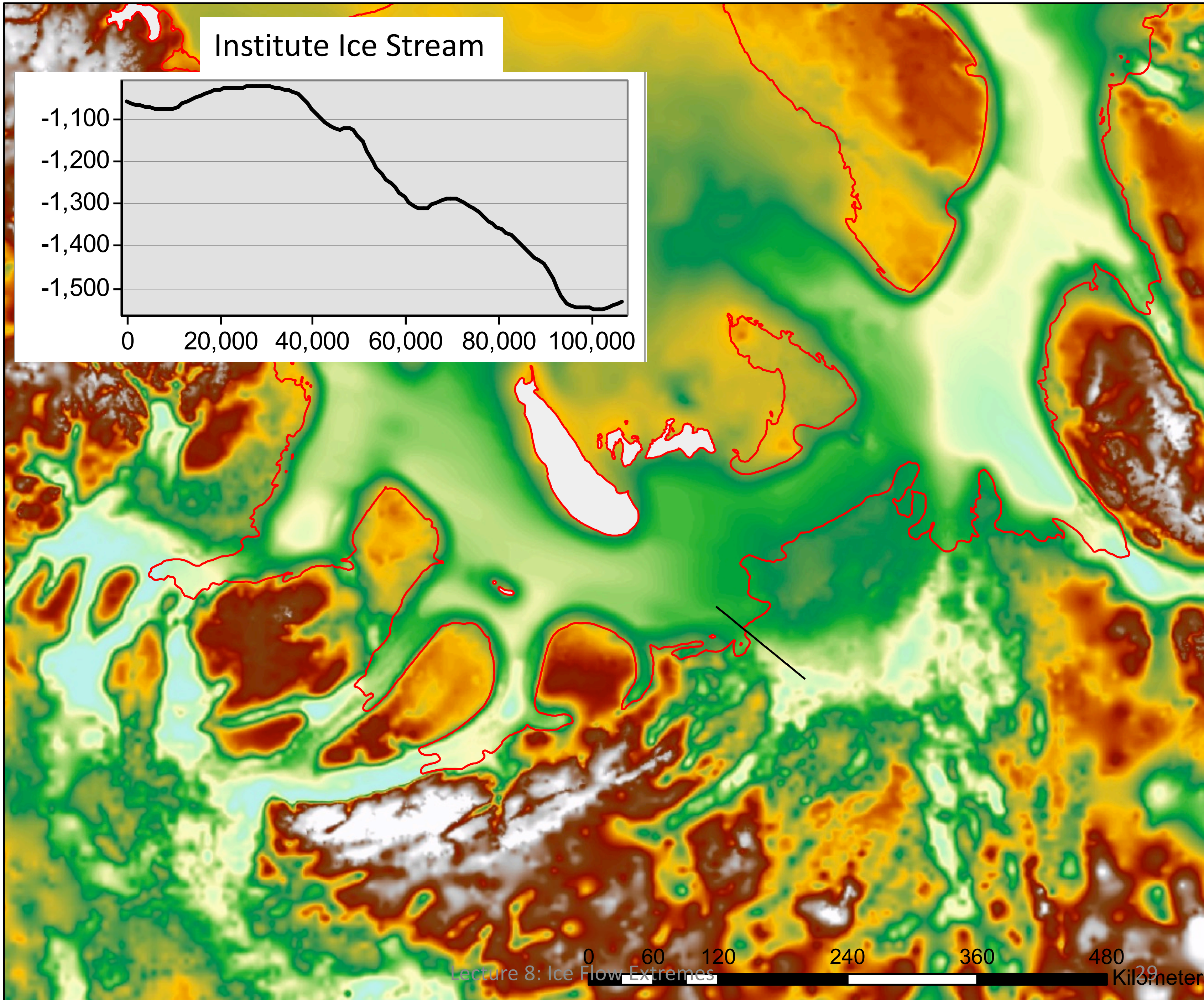
$$\boxed{q(x_g) \propto h(x_g)^{4.75}}$$

Mass balance

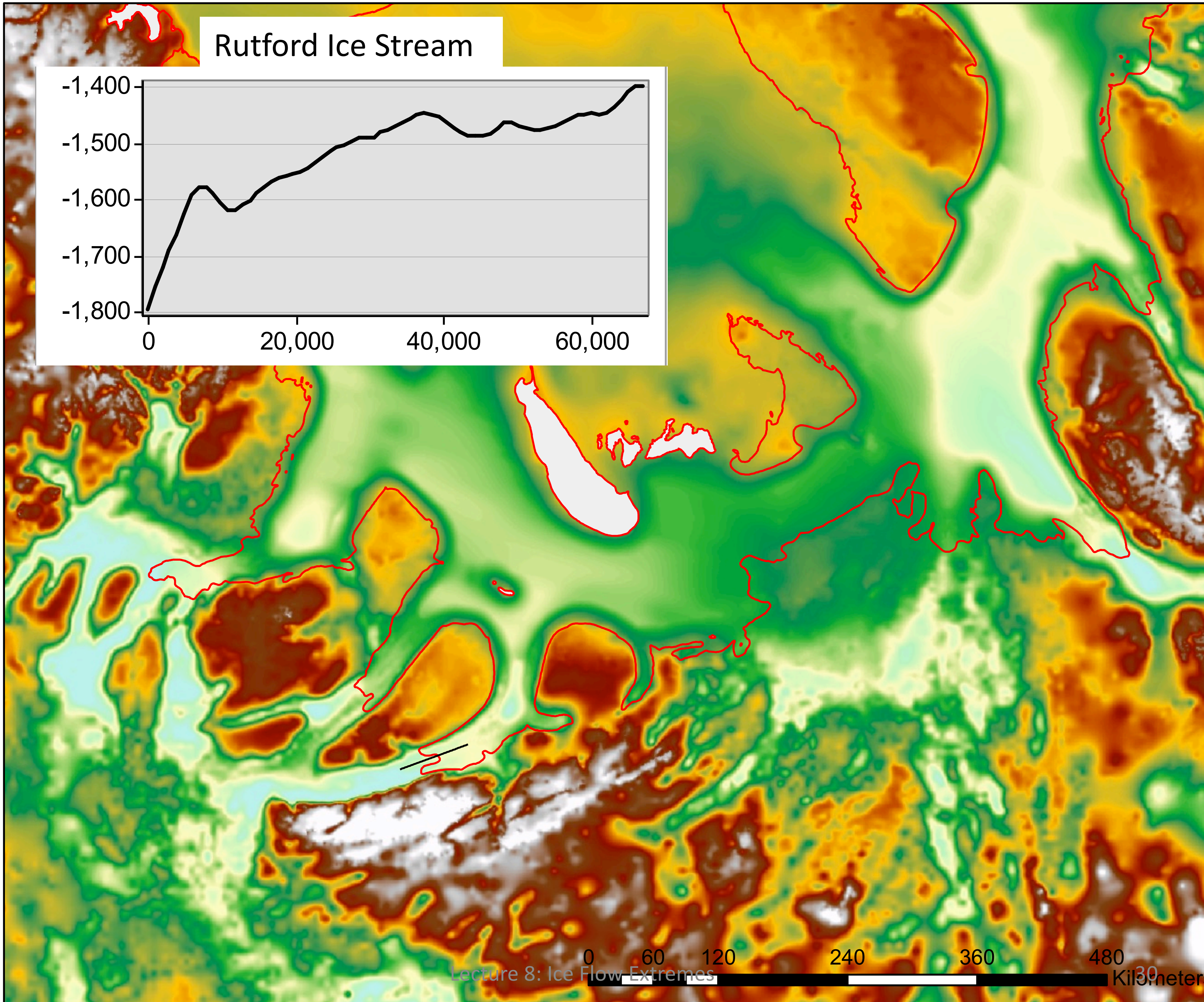
$$\boxed{q(x_g) \propto h(x_g)^{4.75}}$$

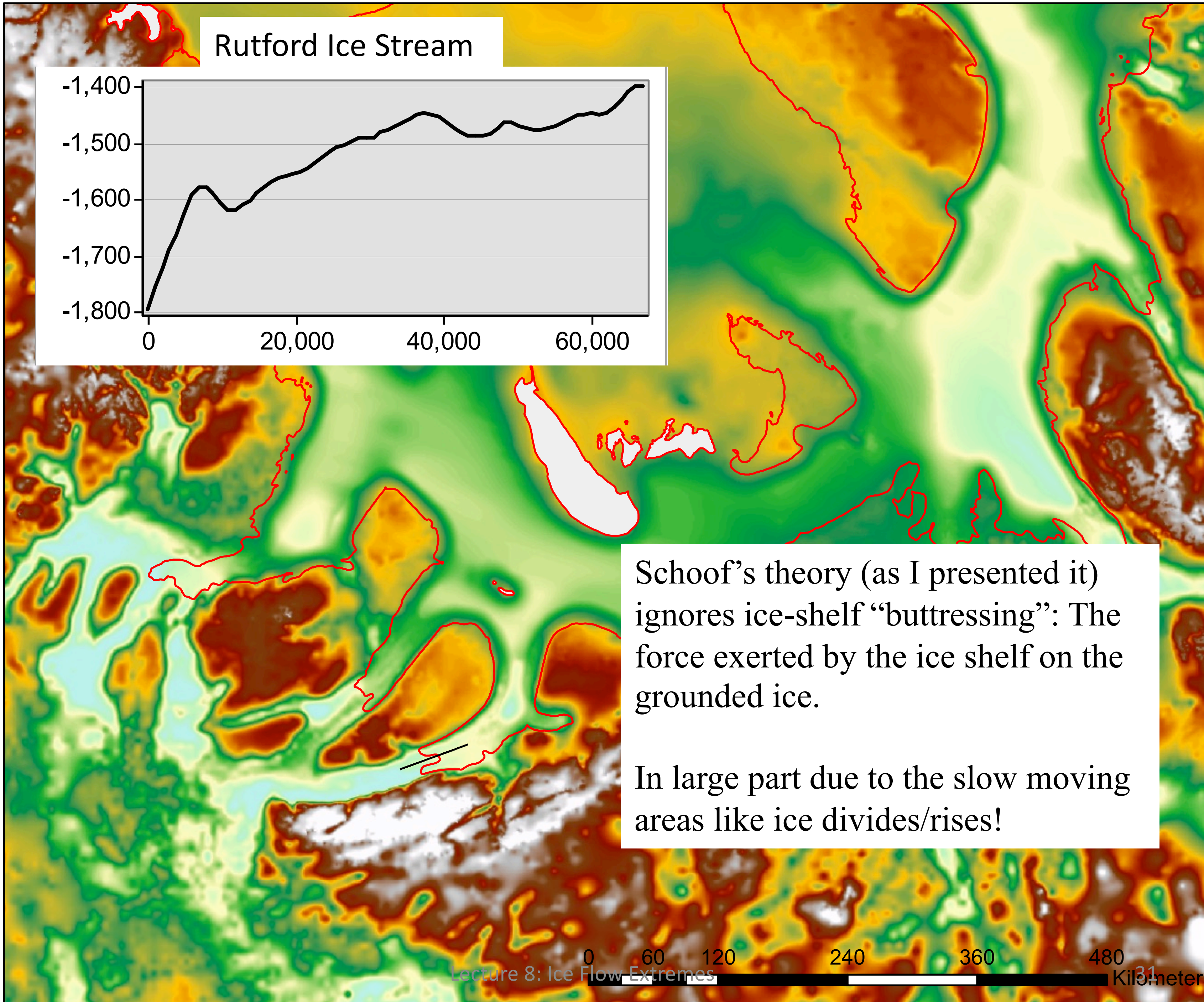
$$\boxed{q = \dot{b}_i x}$$





Institute Ice Stream
-1,100
-1,200
-1,300
-1,400
-1,500
0
20,000
40,000
60,000
80,000
100,000
0
60
120
240
360
480
Kilometers


Rutford Ice Stream
-1,400
-1,500
-1,600
-1,700
-1,800
0
20,000
40,000
60,000
0
60
120
240
360
480
Kilometers

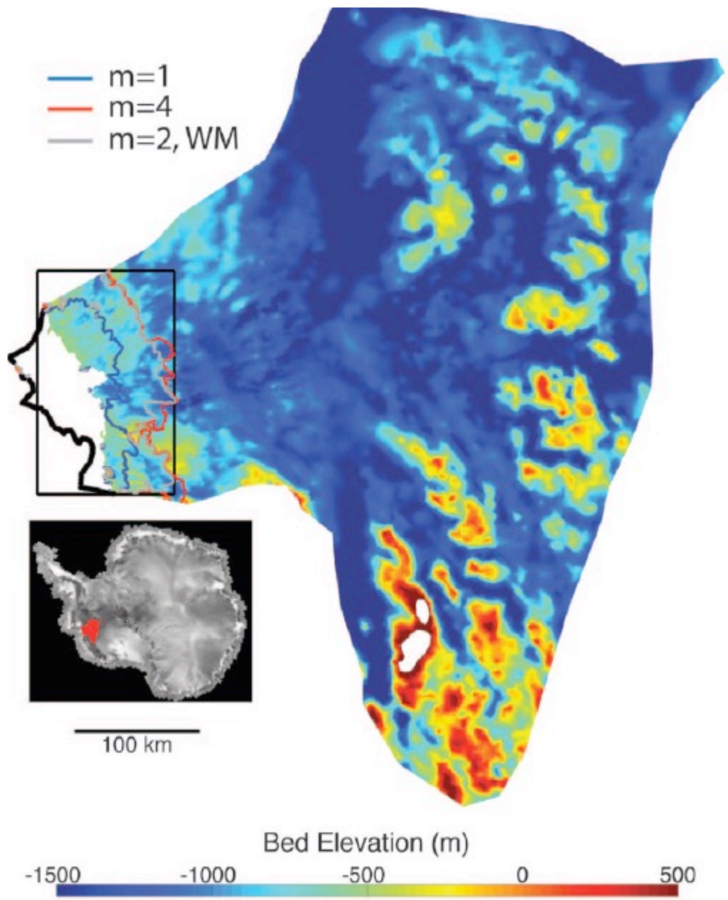


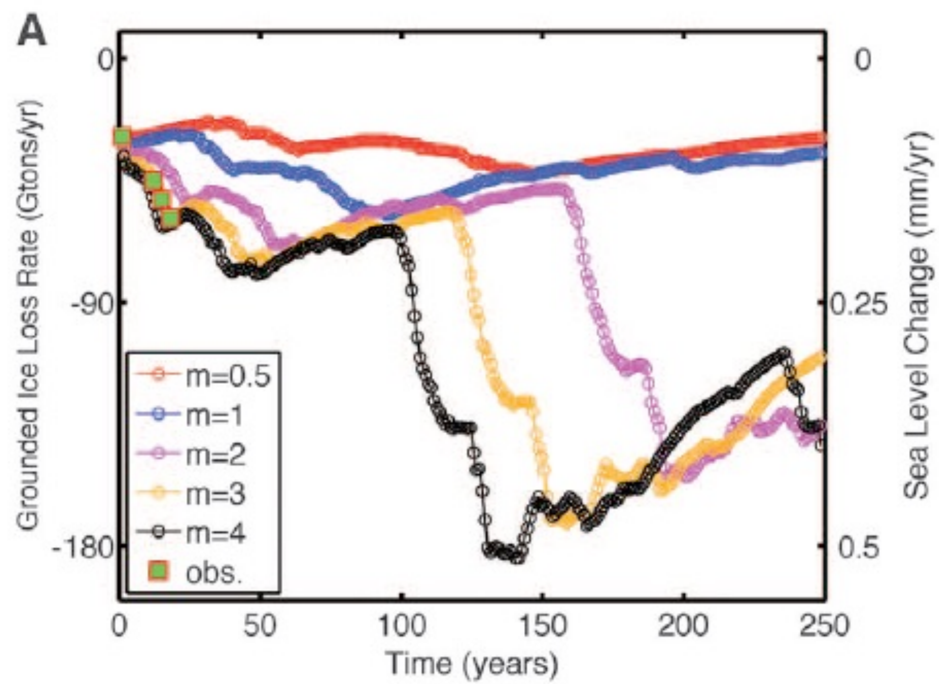
Schoof's theory (as I presented it) ignores ice-shelf "buttressing": The force exerted by the ice shelf on the grounded ice.

In large part due to the slow moving areas like ice divides/rises!

Marine Ice Sheet Collapse Potentially Under Way for the Thwaites Glacier Basin, West Antarctica

Ian Joughin, Benjamin E. Smith, Brooke Medley





Reading

Mercer 1978:

West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster

https://www.nature.com/articles/271321a0

Summary

- Ice divides are slow moving regions that form in the interior of ice sheets and on isolated domes (ice rises) near the coast.
- Nonlinear ice rheology causes deep ice to stagnate beneath divides and causes upwarping in isochrones (Raymond bumps).
- The grounding line separates grounded ice from floating ice.
- Flux through the grounding line partly controls Antarctic mass balance.
- Theory suggests that grounding lines migrate unstably (MISI).
- Ice-shelf buttressing stabilizes grounding lines.

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