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Control of the width of West Antarctica ice streams by internal melting in ice sheet at the margins

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Introduction

West Antarctica Ice streams (WAIS) characteristics:
•Some tens of km wide (40 to 80 km)
•Some hundreds of km long
•V from 100 to 800 m.yr^{-1}

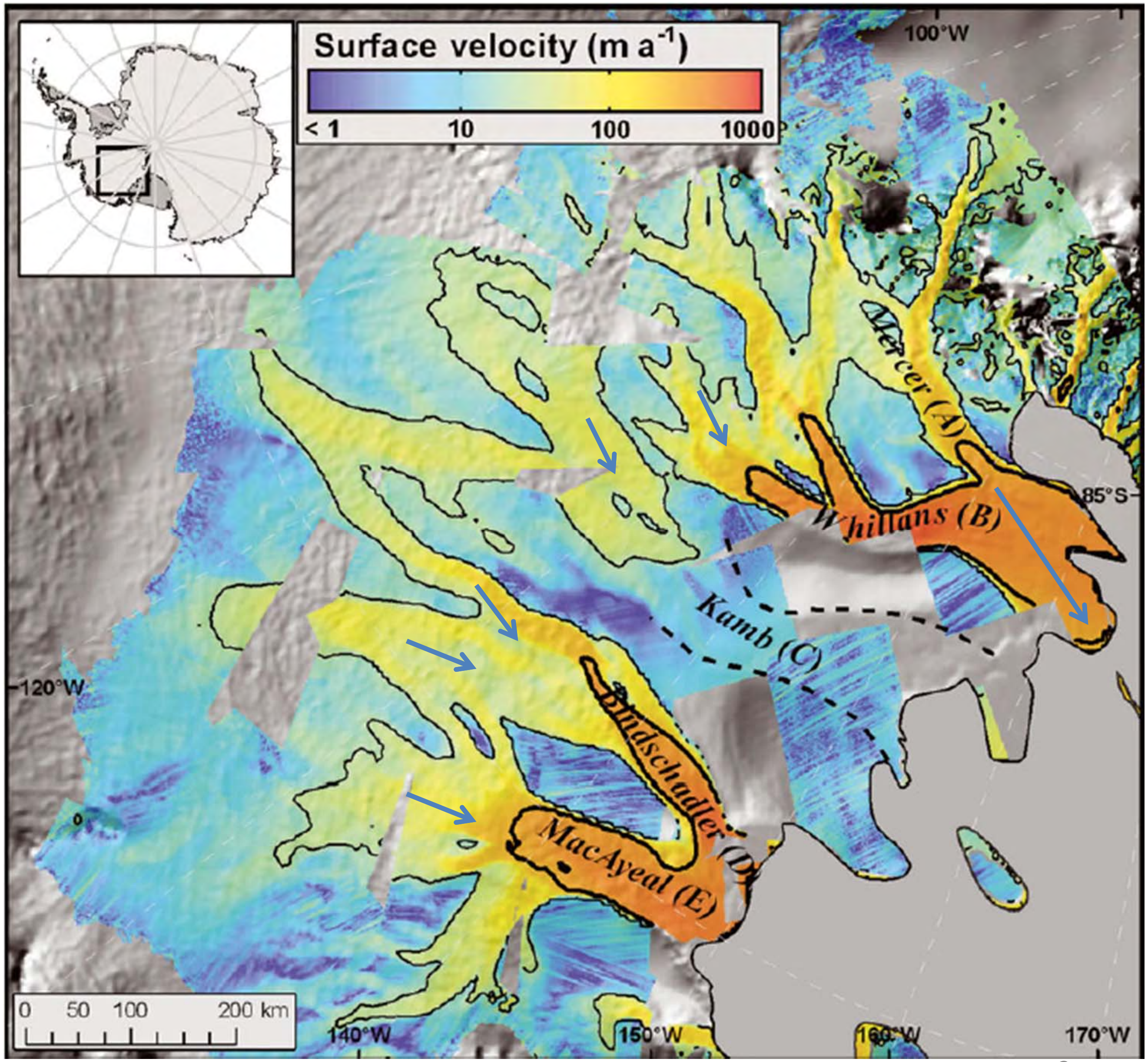


Fig.: Ross Sea ice streams. Interferometric synthetic aperture radar (InSAR) velocity (from Joughin et al., 2002) overlaid on a hillshade of the surface digital elevation model (Bamber et al., 2009). Velocity contours shown are 25 m/a (thin line) and 250 m/a (thick line).

Modified from [Le Brocq, Payne, Siegert & Alley, J. Glac., 2009]

Field evidence of channel at margins

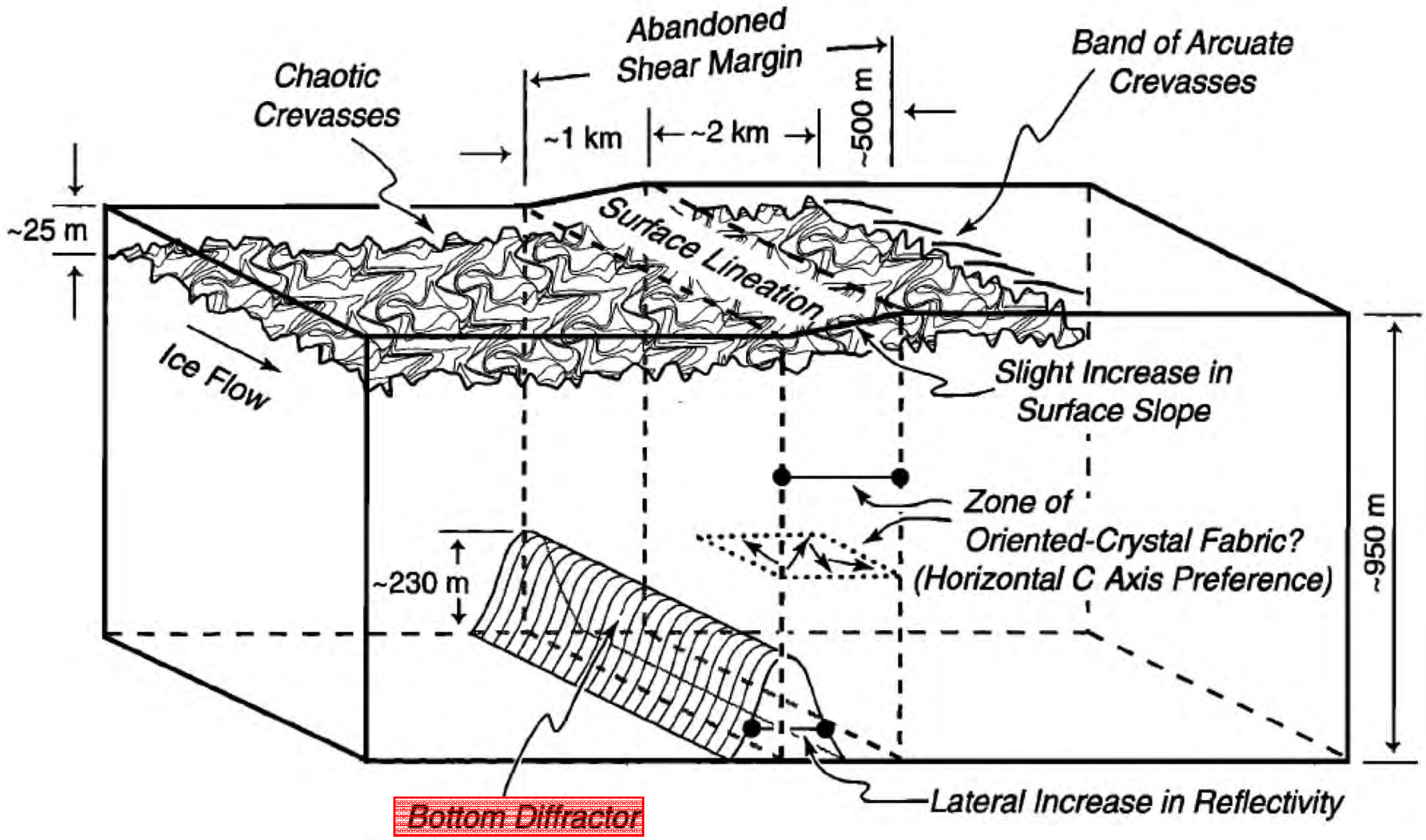
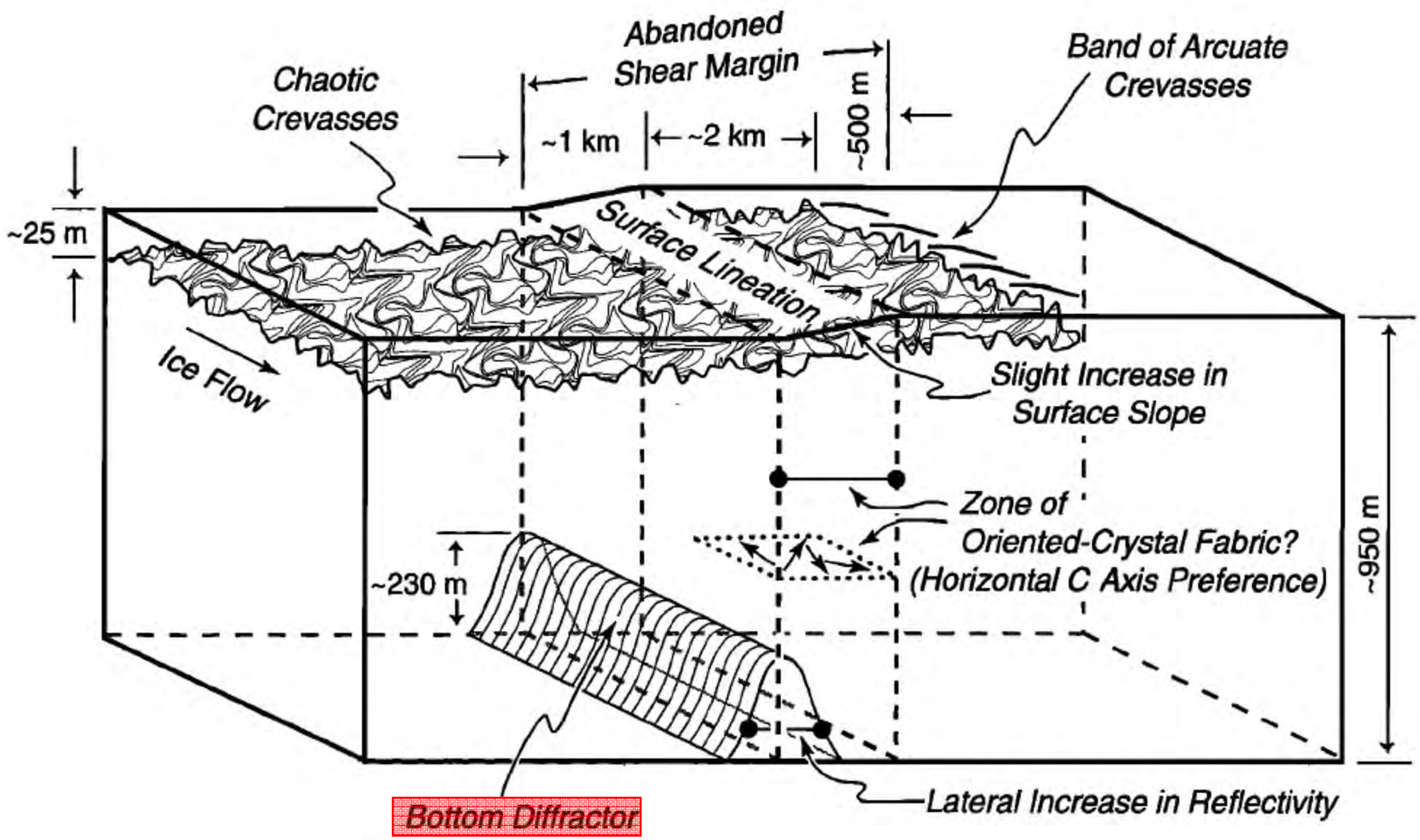


Fig.: Clarke et al. [2000] have used high-power radar system at now abandoned shear margin and have found bottom diffractors.

Field evidence of channel at margins



They argue that at least some of the diffractions originate from entrained ***morainal debris*** at the base of recently abandoned shear margin of ice stream B.

→ One of the possible mechanisms is meltwater processes depositing sediment in a subglacial stream.

Field evidence of channel at margins

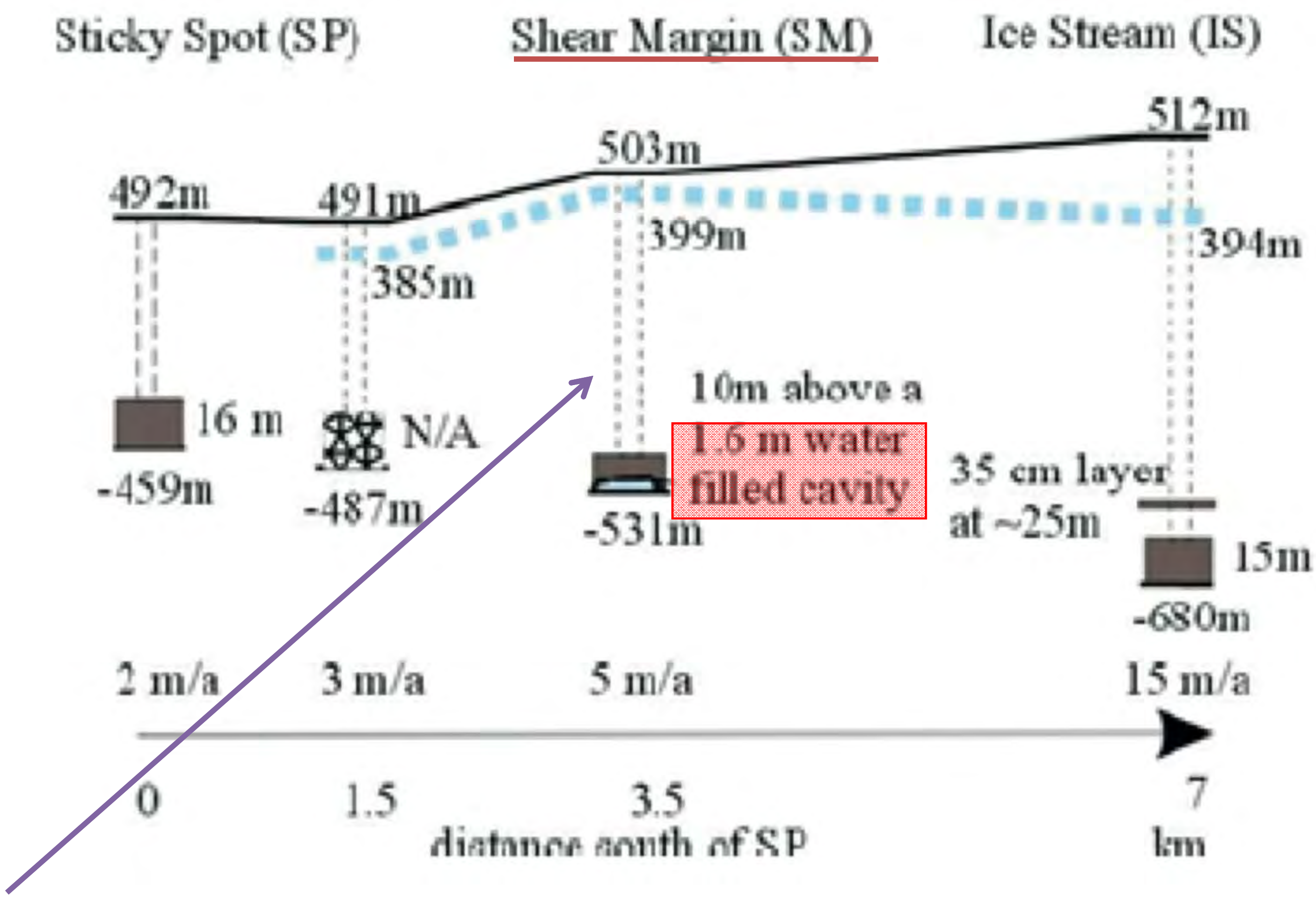
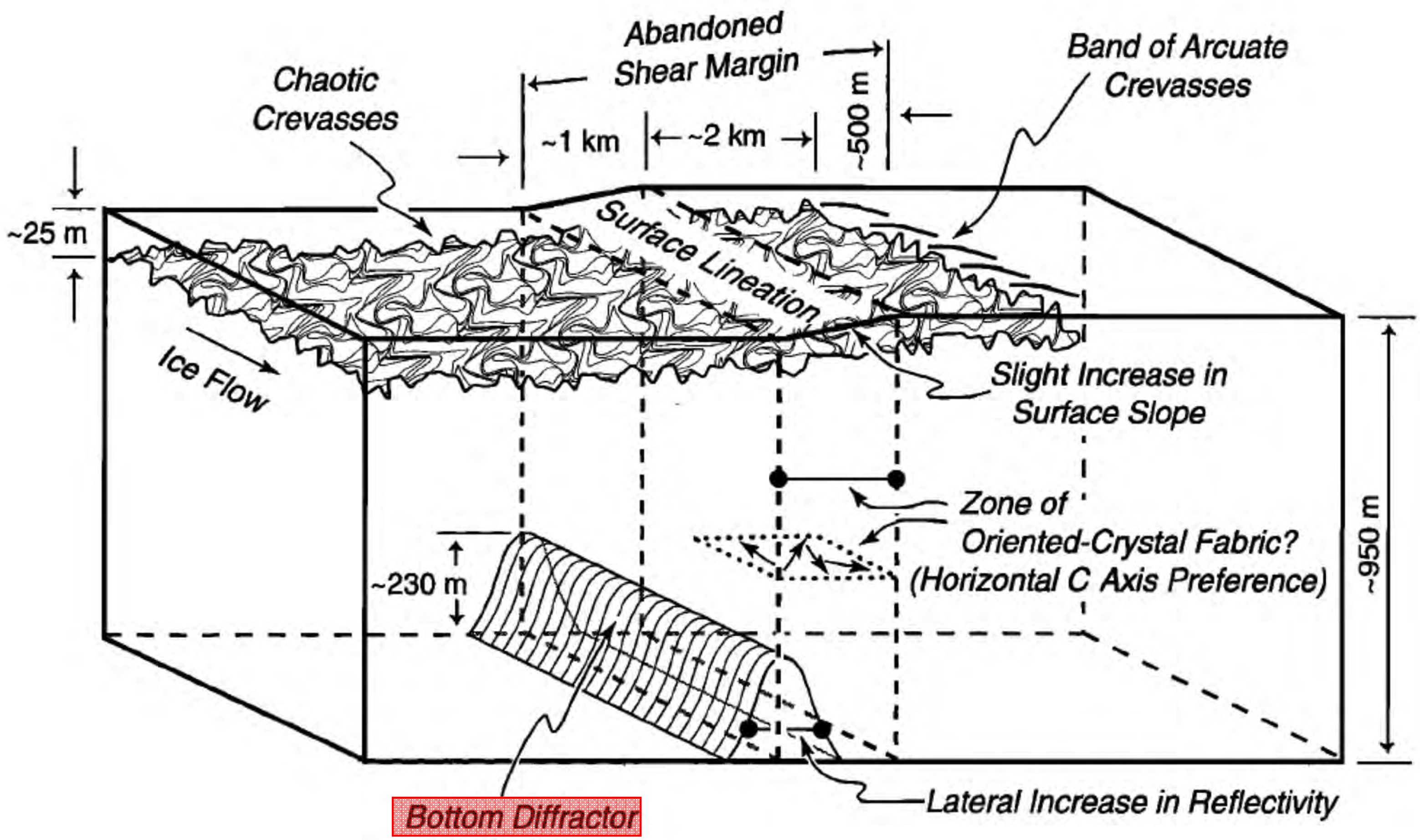


Fig.: Borehole observation at the shear margin of ice stream C shows a 1.6 m tall water-filled cavity. Video of the borehole shows horizontal acceleration of particles sinking into the cavity, indicating flow of water within the cavity -- part of channel?

Modified from [Vogel PhD Thesis, 2004] and [Vogel et al., GRL, 2005]

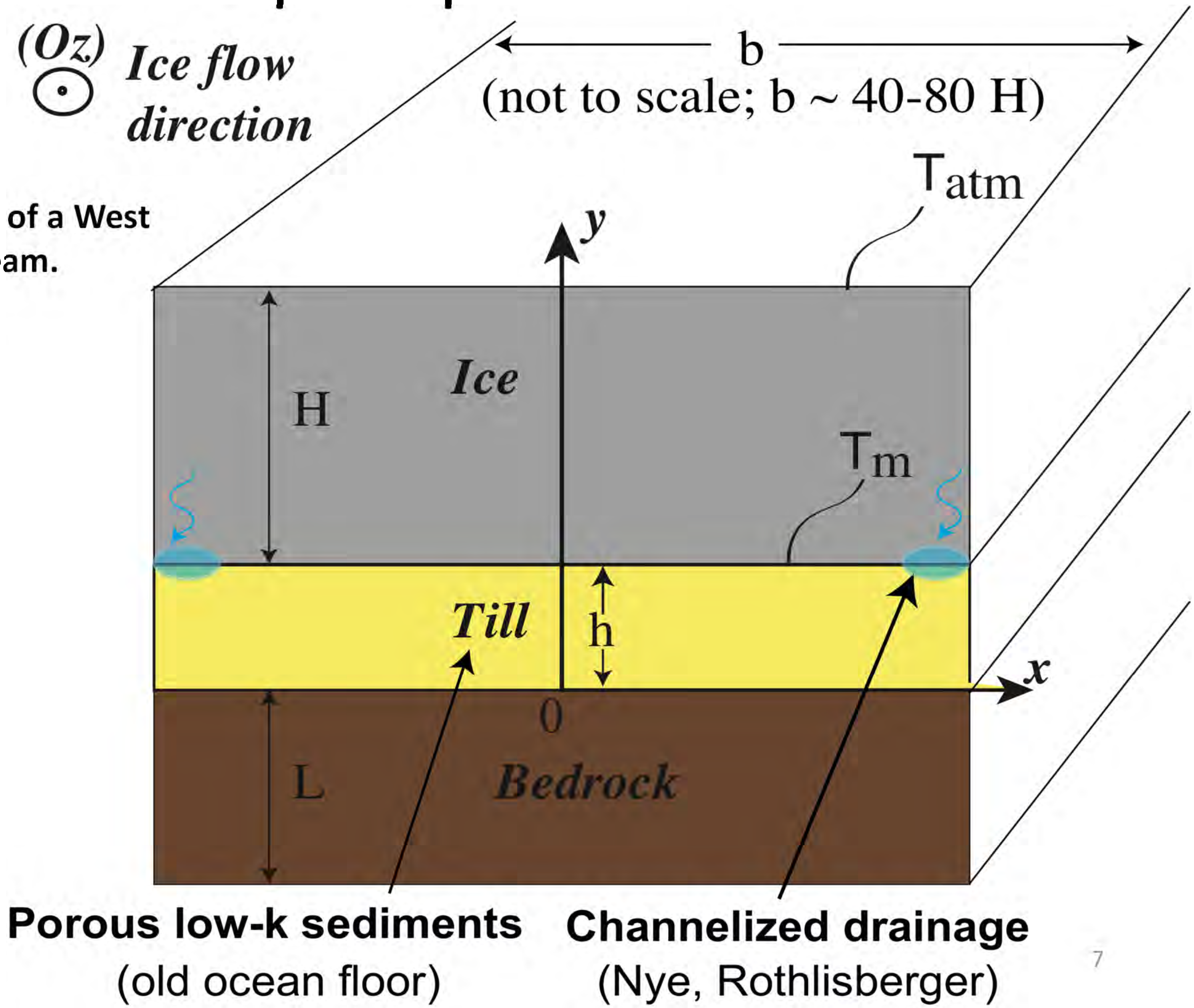
Field evidence of internal melting at margins



Clarke et al. [2000], in order to explain the bottom diffractors, have also invoked ***partial melting*** in temperate ice to a height of ≈230 m that developed du to strain heating.

Open question

Fig.: Cross section of a West Antarctica ice stream.



Open question

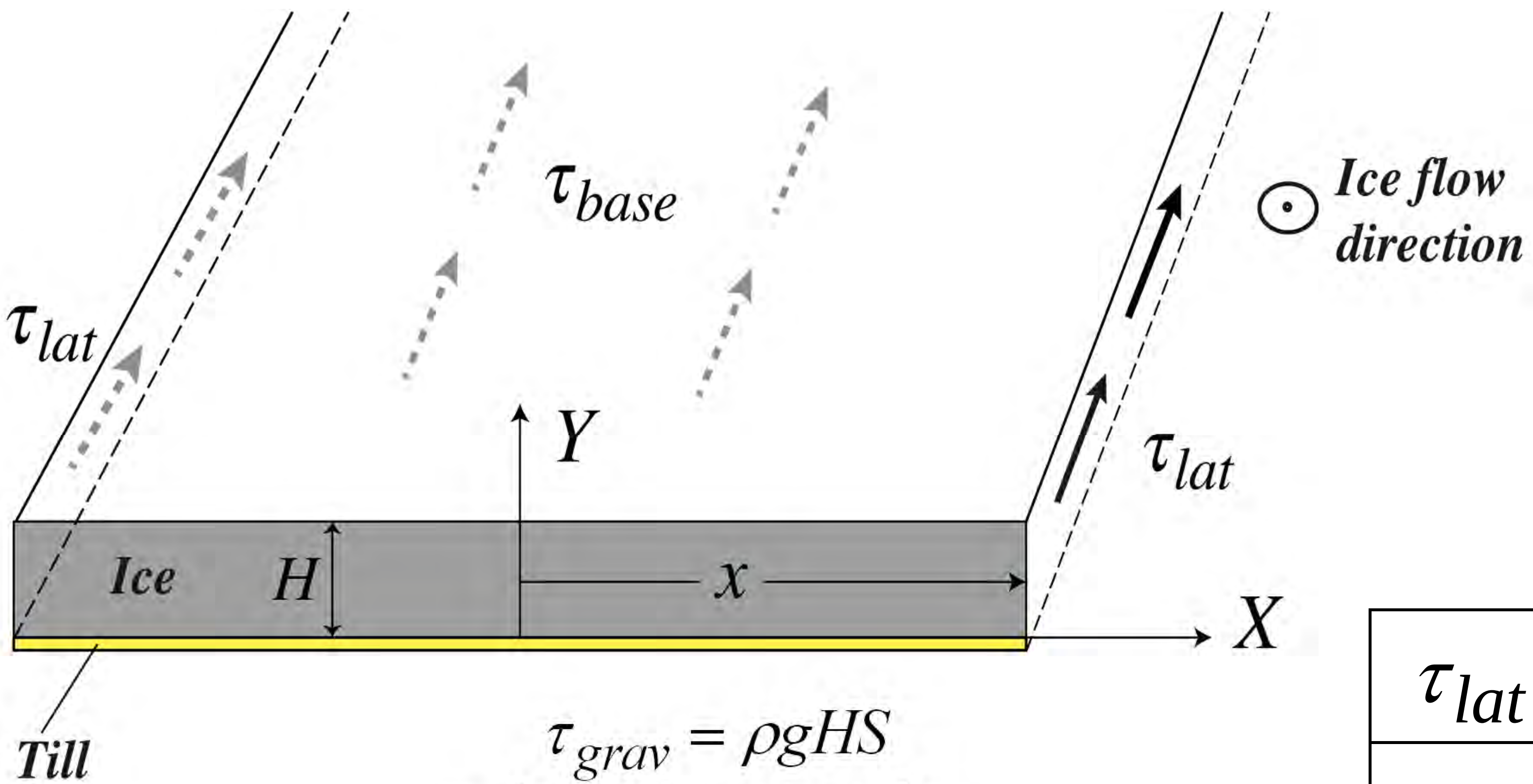
Could the 40 to 80 km widths of West Antarctic ice streams be controlled by onset of melting within the ice sheet at the stream margins ?

Outline

- **Evidence of internal melting of the ice sheet at stream margins in West Antarctica**

- **How meltwater rains downward ? What water fluxes are involved ? What are the possible consequences of this drainage for fast-flowing ice streams ?**

1/ Evidence of internal melting



$\tau_{grav} = \rho g H S$
= downslope gravity
force per unit base area

$$\tau_{lat} H = (\tau_{grav} - \tau_{base})_{avg}\, x$$

(neglecting any variation in net axial
force in sheet, as justified by
Whillans and van derVeen [*J. Glac.* 1993])

τ_{lat}	lateral drag
τ_{base}	Basal drag
H	Ice thicknes s
x	Distance from the center

Heating source at WAIS margins

$$\tau_{lat} H = (\tau_{grav} - \tau_{base})_{avg}\, x$$

- τ_{lat} develops and increases ~linearly with distance *x.*
- Rheological creep law for ice, Glen's law: $\left(\dot{\gamma}_{lat} = 2B^{-3}\tau_{lat}^{3}\right)$ with $B = B(T)$
- Lateral shear strain rate $d\gamma_{lat}/dt$ increases as $(\tau_{lat})^3$ (Glen's law); heating rate in the ice increases as $(\tau_{lat})^4$, ~as x^4.

→ **Heating source τ_{lat} ($d\gamma_{lat}/dt$) quickly becomes a significant heat source within the ice sheet and may induce internal melting at a large enough distance *x* from the center**

Simple temperature profile at WAIS margins

- Steady state
- For simplicity we do not consider vertical advection of ice as:
  . ice accumulation at top and melting at base making
  the ice column colder
  . basal freeze-on making the ice column warmer

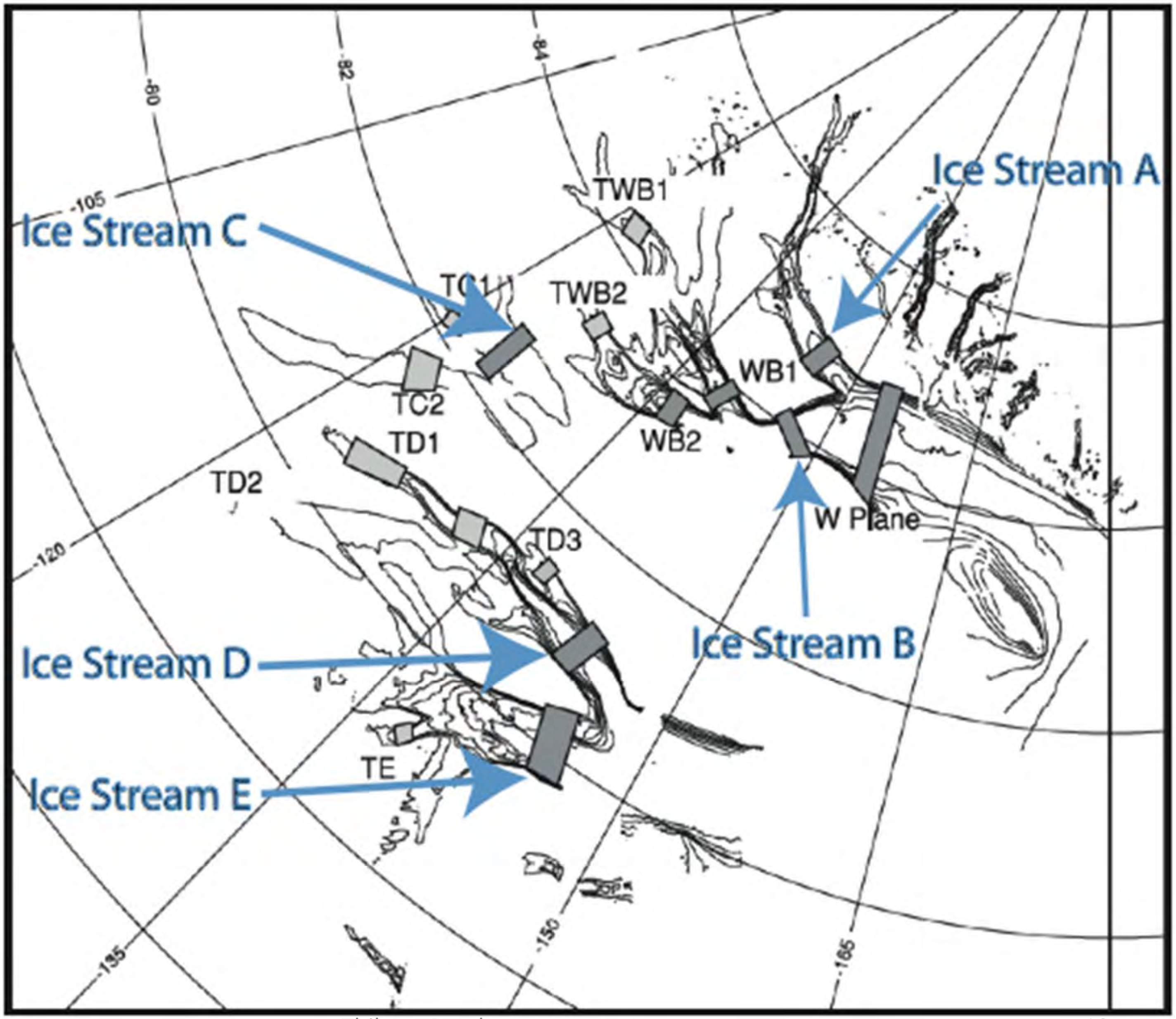
$$K\frac{\partial^2 T}{\partial y^2}+\tau_{lat}\dot{\gamma}=0$$

- τ_{lat} and $\dot{\gamma}$ uniform in depth
- T(y=H)=T$_{atm}$ and $T(y=0)=T_m$

$$T(y)=T_m+(T_{atm}-T_m)\frac{y}{H}+\frac{\tau_{lat}\dot{\gamma}_{lat}H^2}{K}\frac{y}{H}\left(1-\frac{y}{H}\right)$$

Modified from [Joughin, Tulaczyk, Bindschadler & Price, J. Geophys. Res., 2002]

Fig. 5: Location of margins temperature profile and force balance calculations .



Ice stream	H (m)	$\dot{\gamma}_{lat}$ $(10^{-2}.yr^{-1})$	$\tau_{lat}(kPa)$
A	1242	2.6	131.5
B	846	9.0	191.1
C	1805	0.7	90
D	888	3.2	134.2
E	916	6.3	171.9

Table: Ice streams characteristics from Joughin et al., J. Geophys. Res., 2002.

$$T(y) = T_m + (T_{atm} - T_m)\frac{y}{H} + \frac{\tau_{lat}\dot{\gamma}_{lat}H^2}{K}\frac{y}{H}\left(1 - \frac{y}{H}\right)$$

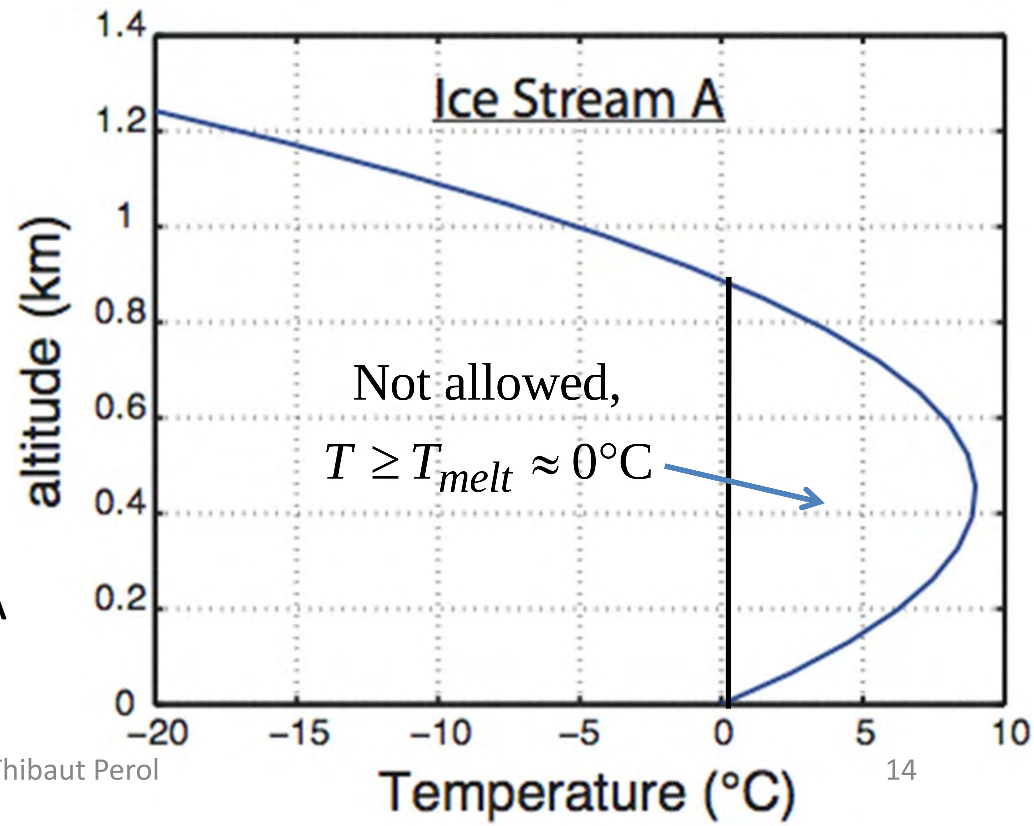
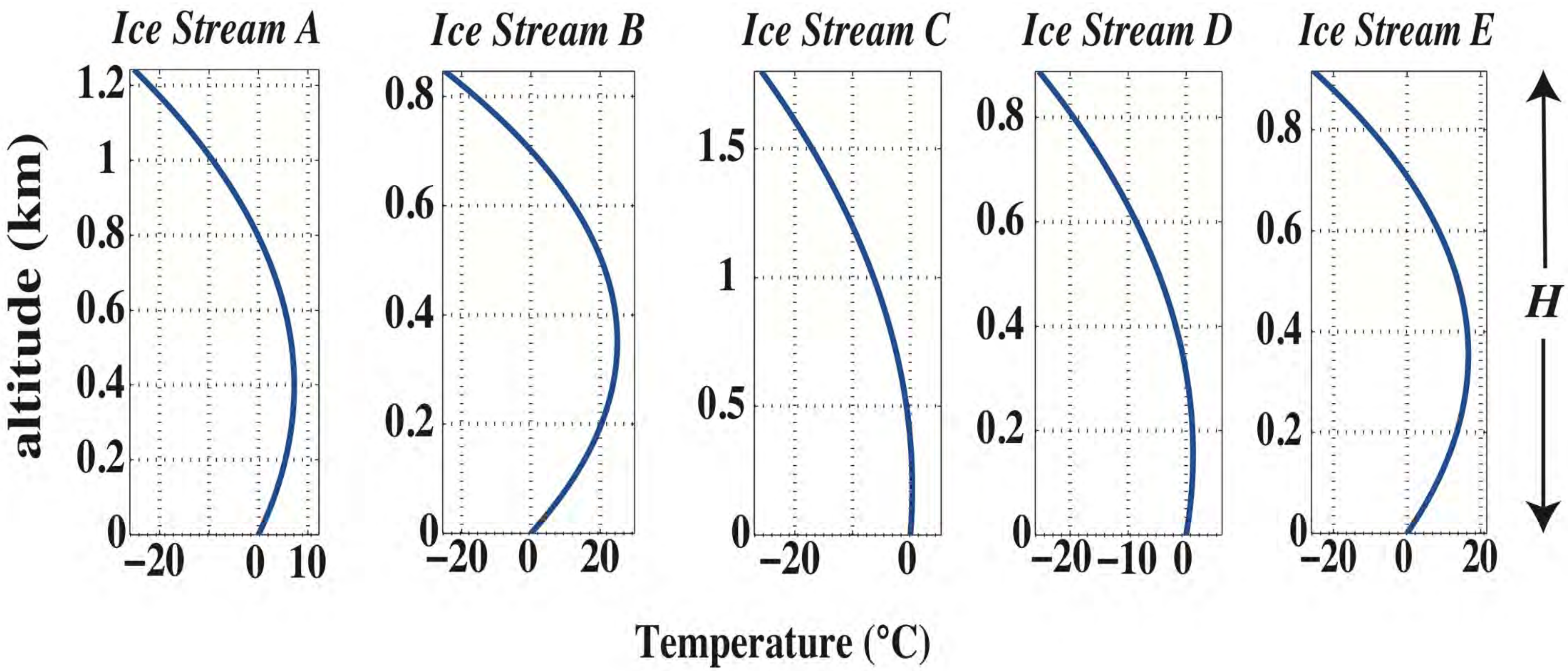


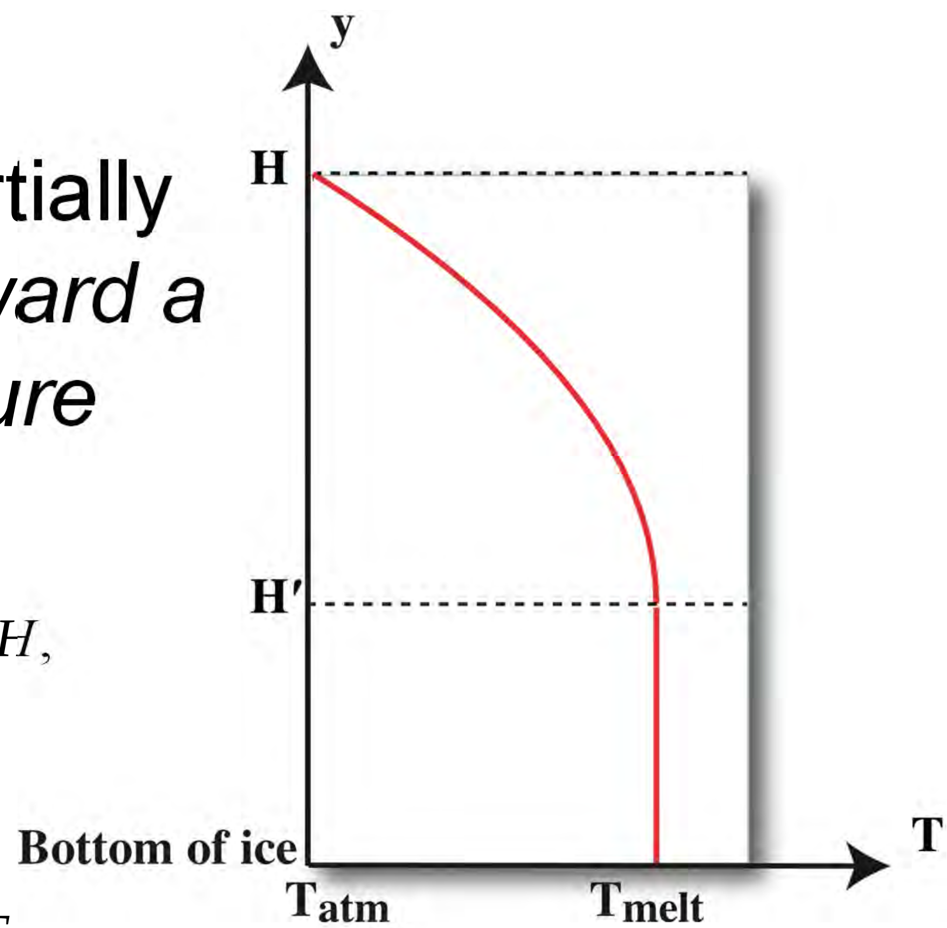
Fig.: First approximation of ice stream A margins temperature.
(assuming T_{atm}=−20°C)

Simple temperature profile at WAIS margins



Predicted margin temperatures are in excess of melting over some depth range for all five profiles. This supports the possibility that internal melting within the ice sheet is related to why margins are where they are.

Approximate model of partially melted marginal zone: *Toward a more realistic temperature profile*



- $\dot{\gamma}(\equiv \dot{\gamma}_{lat})$ is assumed uniform for $0 < y < H$,

  $\tau_{lat} = B(T)(\dot{\gamma}/2)^{1/3}$.

- For $0 < y < H'$: $T = T_{melt} \approx 0^\circ \mathrm{C}$
- For $H' < y < H$: $K\dfrac{d^2T}{dy^2} + \tau_{lat}\dot{\gamma} \approx K\dfrac{d^2T}{dy^2} + 2B_{avg}(\dot{\gamma}/2)^{4/3} = 0,$

  where $B_{avg} \equiv B\big((T_{melt} + T_{atm})/2\big)$.

1/ Solution, $H' < y < H$: $K(T - T_{melt}) + B_{avg}(\dot{\gamma}/2)^{4/3}(y - H')^2 = 0$

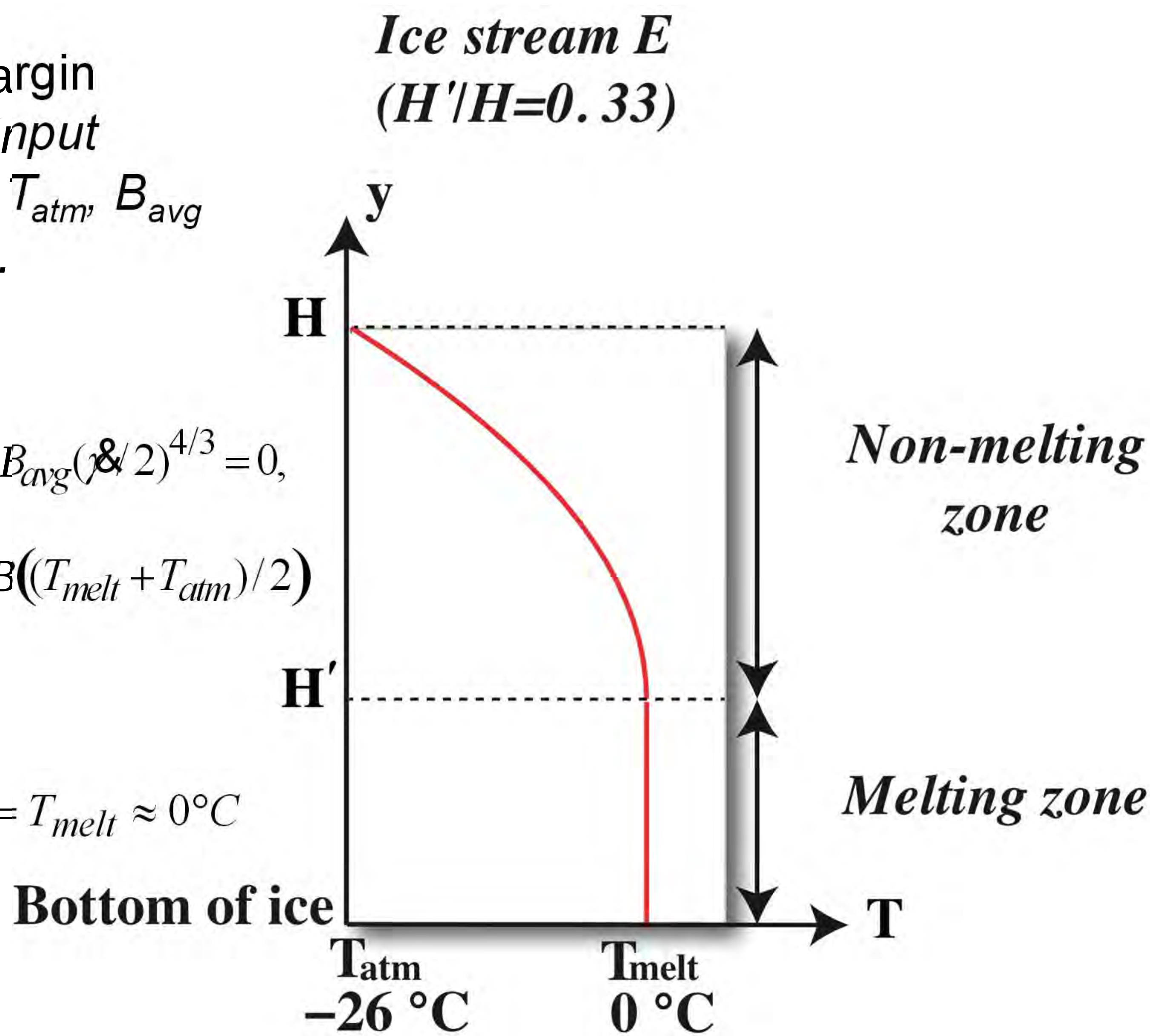
2/ $\Rightarrow K(T_{melt} - T_{atm}) = B_{avg}(\dot{\gamma}/2)^{4/3}(H - H')^2$ (determines H')

Fig : Ice stream E margin temperature profile. *Input parameters: H, T_{melt}, T_{atm}, B_{avg} and shear strain rate.*

$$\text{For } H' < y < H : K\frac{d^2T}{dy^2} + 2B_{avg}(\dot{\gamma}/2)^{4/3} = 0,$$

$$\text{where } B_{avg} \equiv B\left((T_{melt} + T_{atm})/2\right)$$

$$For\ \ 0 < y < H' :\ T = T_{melt} \approx 0°C$$



Ice stream	B_{avg} $(kPa.yr^{1/3})$	$\dot{\gamma}_{meas}$ $(10^{-2}.yr^{-1})$	H'/H	$\dot{\gamma}_{H'=O^+}$ $(10^{-2}.yr^{-1})$	$\dot{\gamma}_{meas}/\dot{\gamma}_{(H'=0^+)}$
A	498	2.6	0.11	2.1	1.2
B	490	9.0	0.44	3.8	2.4
C	517	0.7	Not melted	1.2	0.6
D	498	3.2	Not melted but close	3.6	0.9
E	498	6.3	0.33	3.4	1.9

Table: Results of the approximate model of partially melted marginal zone.

Since lateral shear strain rate of ice stream D is really close to the level at which internal melting occurs, **the results are compatible with the hypothesis that the margin of fast flowing ice is undergoing internal melting !**

Force equilibrium gives us the average lateral shear $\bar{\tau}_{lat}$ stress

$$H\bar{\tau}_{lat} \approx H'B_{melt}(\dot{\gamma}/2)^{1/3} + (H - H')B_{avg}(\dot{\gamma}/2)^{1/3}, \quad \left(\text{where } B_{melt} = B(T_{melt})\right)$$

$$\bar{\tau}_{lat} = \left(\frac{K\left(T_{melt} - T_{atm}\right)B_{avg}^3}{H^2} \right)^{1/4} \frac{\frac{B_{melt}}{B_{avg}}\frac{H'}{H} + \left(1 - \frac{H'}{H}\right)}{\left(1 - \frac{H'}{H}\right)^{1/2}}$$

For $T = T_{avg} = -13°\text{C}$ (i.e., $T_{atm} = -26°\text{C}$, $T_{melt} = 0°\text{C}$),

$K = 2.32\ \text{W/m °C}$ and $B_{avg} = 498\ \text{kPa yr}^{1/3}$; also, $B_{melt} = 247\ \text{kPa yr}^{1/3}$

$$\Rightarrow \left(\bar{\tau}_{lat}\right)_{H'=0^+} = 131.36\ \text{kPa}$$

$$\Rightarrow \frac{\left(\bar{\tau}_{lat}\right)_{H'=H/2}}{\left(\bar{\tau}_{lat}\right)_{H'=0^+}} = \frac{1 + B_{melt}/B_{avg}}{\sqrt{2}} = 1.044 \quad \text{for ice stream D}$$

Recalling $\bar{\tau}_{lat} \propto x$ (= distance from ice stream centerline):

3/ Massive drainage to the bed associated with melting causes channel development

Melt generation and water permeation through the partially melted ice

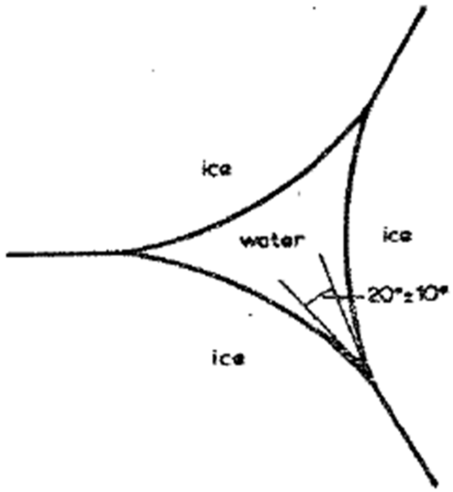


Fig. 2. Cross-section of a vein of liquid situated at a grain edge, where three grain boundaries meet. The figure is drawn for a dihedral angle φ equal to 20°, as measured for ice—water by Ketcham and Hobbs (1969).

J. F. Nye and F. C. Frank, [*J. Glac.,* 1973], building on Frank's [*Nat.,* 1968] analysis of melt convection in Earth's mantle.

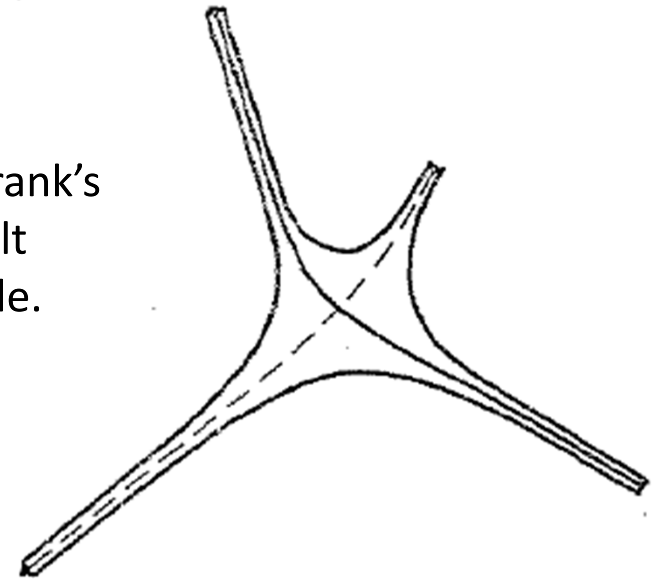


Fig. 3. A junction between four water veins in polycrystal-line ice. The figure is a tetrahedron with non-spherical faces and with open corners.

$$\text{Permeability } k = \alpha n^2 d_g^2$$

$n =$ porosity, d_g = grain size (1-10 mm in ice), $\alpha \approx 1/2000$ to 1/1500

Darcy Law: $\vec{q} = -\frac{k}{\mu_w}(\vec{\nabla} p - \rho_w \vec{g})$, $k = \alpha n^2 d_g^2$

$$\Rightarrow \; q_y = -\frac{\alpha n^2 d_g^2}{\mu_w}(\rho_w - \rho_i)g \;\; (\text{assuming } \vec{\nabla} p = \rho_i \vec{g})$$

Melt production:

Melt rate per unit volume $\dot{m} = \tau_{lat}\dot{\gamma} / L$, L = latent heat,

$$\tau_{lat} = B\frac{2B_{melt}}{L}\left(\frac{\dot{\gamma}}{2}\right)^{1/3} F(n) \text{ with, e.g., } F(n) = 1 - n$$

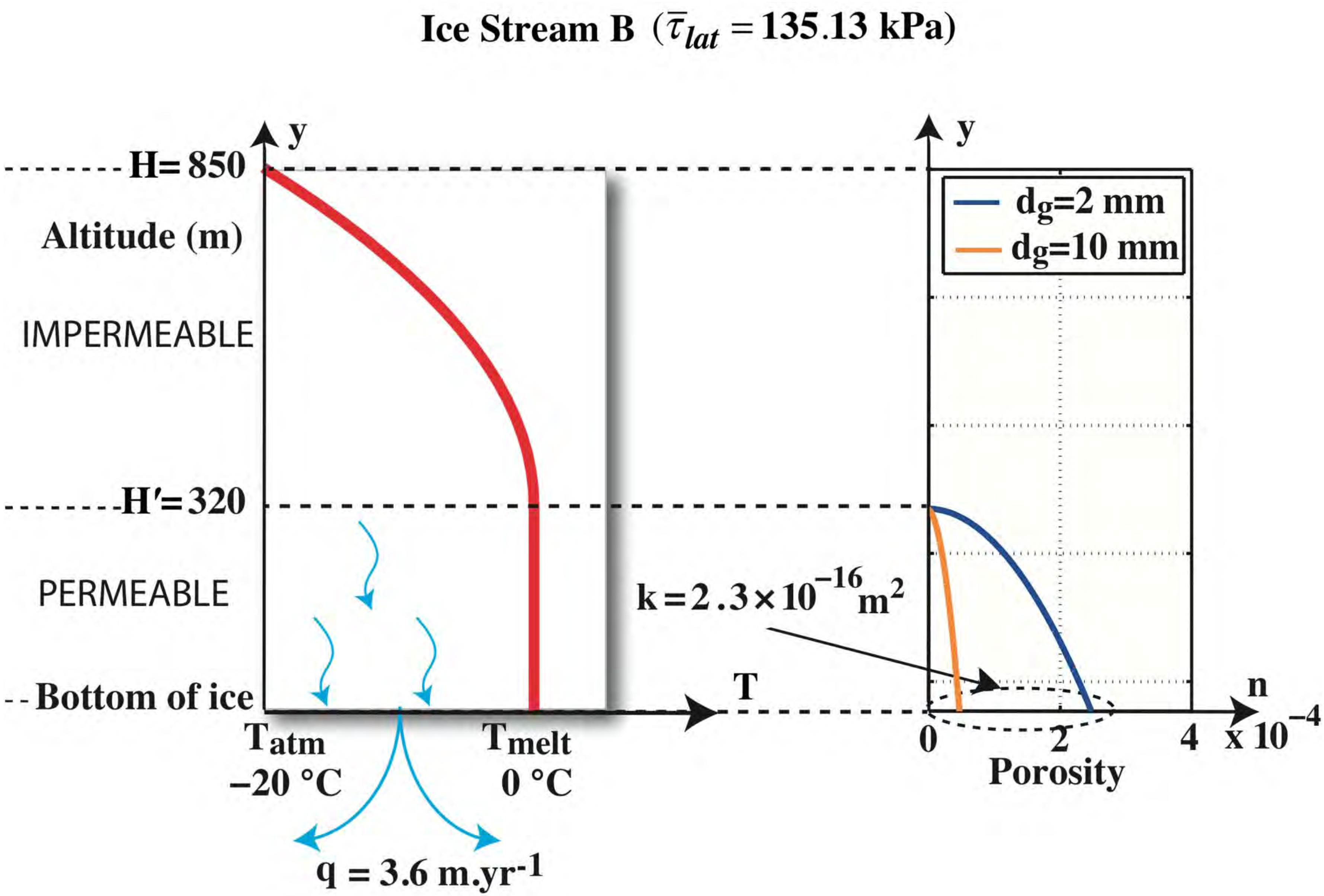
Mass conservation $\vec{\nabla}\left(\rho_w \vec{q}\right) = \dot{m}$:

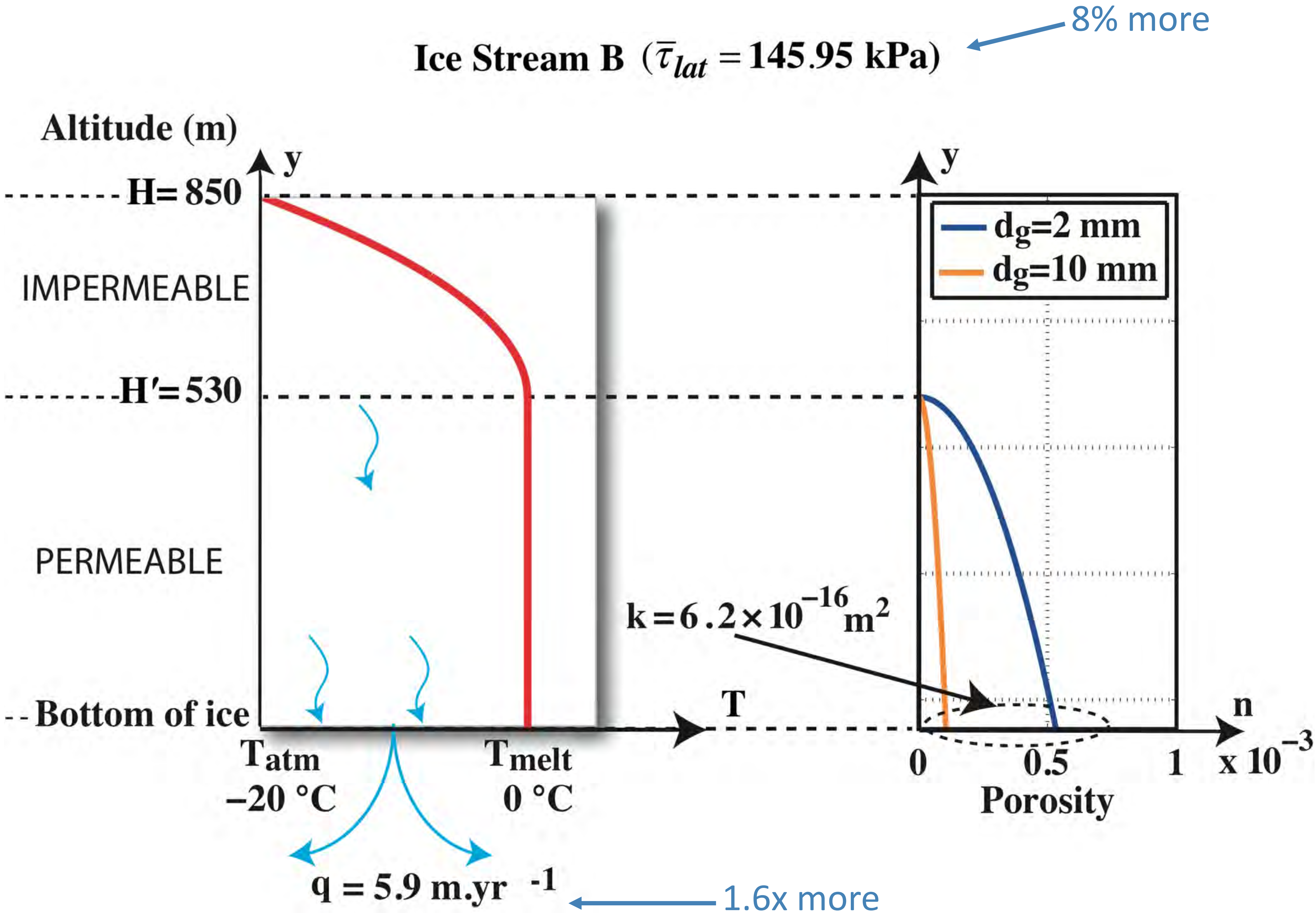
$$\frac{\rho_w \alpha\left(\rho_w - \rho_{ice}\right)g}{\mu_w}\frac{d}{dy}\left(n^2 d_g^2\right) - \frac{2B_{melt}}{L}\left(\frac{\dot{\gamma}}{2}\right)^{4/3} F(n) = 0$$

(we solve with d_g = constant, 2 or 10 mm, and $\alpha = 1/1500$;

functions like $F(n) = 1 - n^{\lambda}$, $\lambda \geq 1$, have negligible effect

on results compared to $F(n) = 1$.)


Ice Stream B ($\overline{\tau}_{lat} = 135.13$ kPa)
y
H= 850
Altitude (m)
IMPERMEABLE
H′=320
PERMEABLE
Bottom of ice
T
Tatm
−20 °C
Tmelt
0 °C
q = 3.6 m.yr-1
y
dg=2 mm
dg=10 mm
k = 2.3 × 10−16 m2
n
0
2
4
x 10−4
Porosity


8% more
Ice Stream B ($\bar{\tau}_{lat}$ = 145.95 kPa)
Altitude (m)
y
H= 850
IMPERMEABLE
H′= 530
PERMEABLE
Bottom of ice
T
Tatm
−20 °C
Tmelt
0 °C
q = 5.9 m.yr -1
1.6x more
y
dg=2 mm
dg=10 mm
k = 6.2 × 10−16 m2
n
0
0.5
1
x 10−3
Porosity

Conclusions

• Our approximate model of margins predicts that margins are partially melted for 4 of the 5 ice streams in West Antarctica.

• Then, we argue that internal melting within the ice sheet is related to why margins are where they are.

• We predict meltwater production within the ice sheet at margins, and explore how it rains downward and creates a massive drainage to channelized drainage at margins bed.

Perspectives

$$N_c = P_i - p_w = K_2 \frac{G^{11/24} Q_w^{1/12}}{n_m^{1/4}} B$$

with

$$K_2 = [(\rho_i L_f K_1)^{1/3} (\rho_w g)^{1/8}]^{-1}$$

Using $Q_w = q_w \times 100 \text{ km} \times 1 \text{ km}$

we find $N_c = 0.4 \text{ MPa}$

$\tau_{base} \approx 10 \text{ kPa} = 0.01 \text{ MPa}$

$\Rightarrow N \approx 0.02 \text{ MPa}$ with f=0.5

P_i	Ice overburden pressure
p_w	Water pressure in channel
G	Force per unit volume driving water flow
Q_w	Water discharge in channel
n_m	Manning roughness coefficient
B	Creep parameter
L_f	Latent heat
K_1	Constant equal to 0.139
q_w	Darcy flux at bed margins because of ice internal melting

- Effective stress N_c on bed adjacent to the channels is much larger than N in central region of the ice stream.
- N_c locks ice sheet to the bed outboard of the R-channel and creates limit of the width of stream of fast-flowing ice.