# On the use of ‘physical’ models to understand glacier and ice sheets dynamics

Ginny Catania, Institute for Geophysics, University of Texas at Austin

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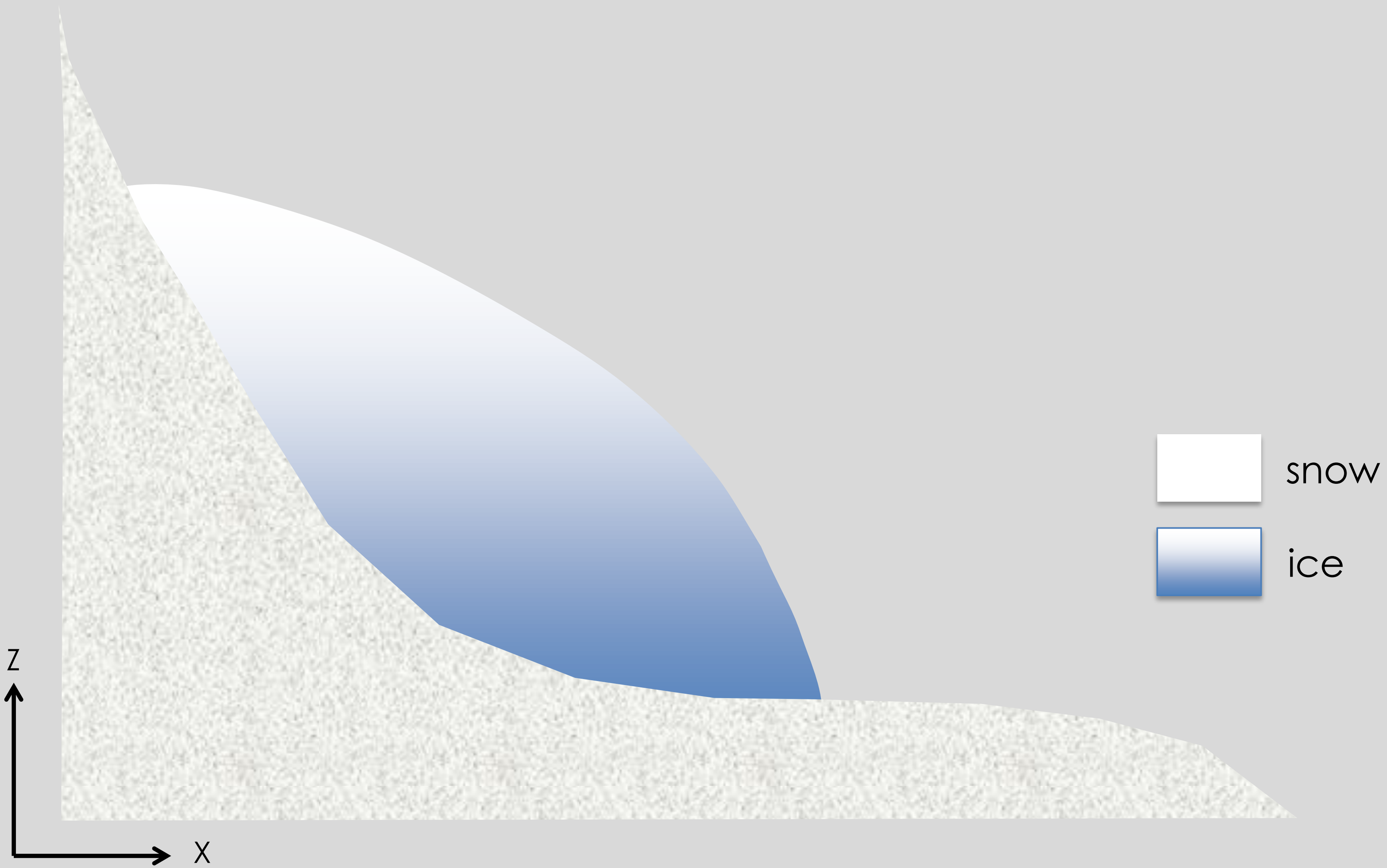
# Glacier Fundamentals



# Glacier Fundamentals

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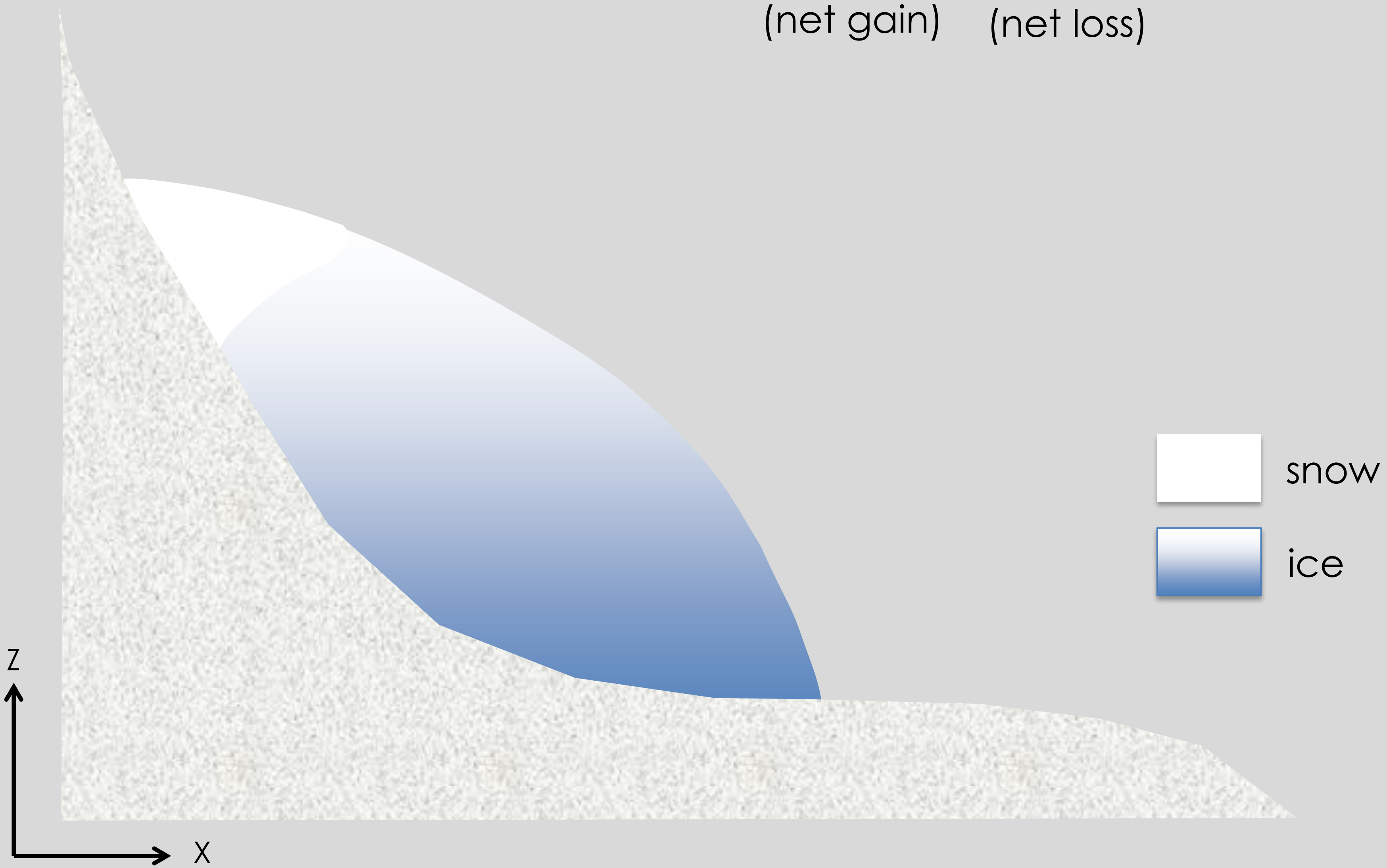
Net mass balance = accumulation - ablation

(net gain) (net loss)



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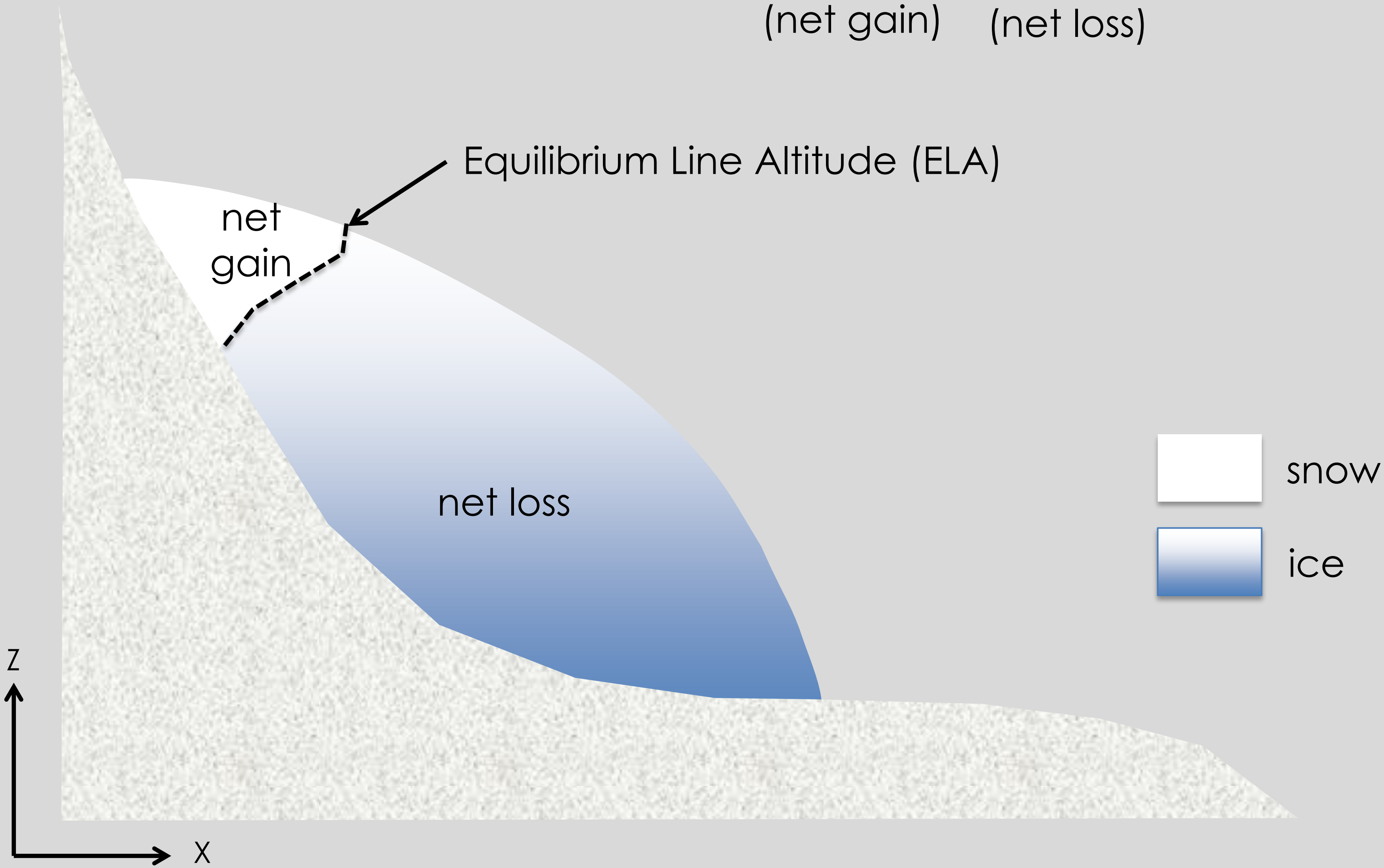
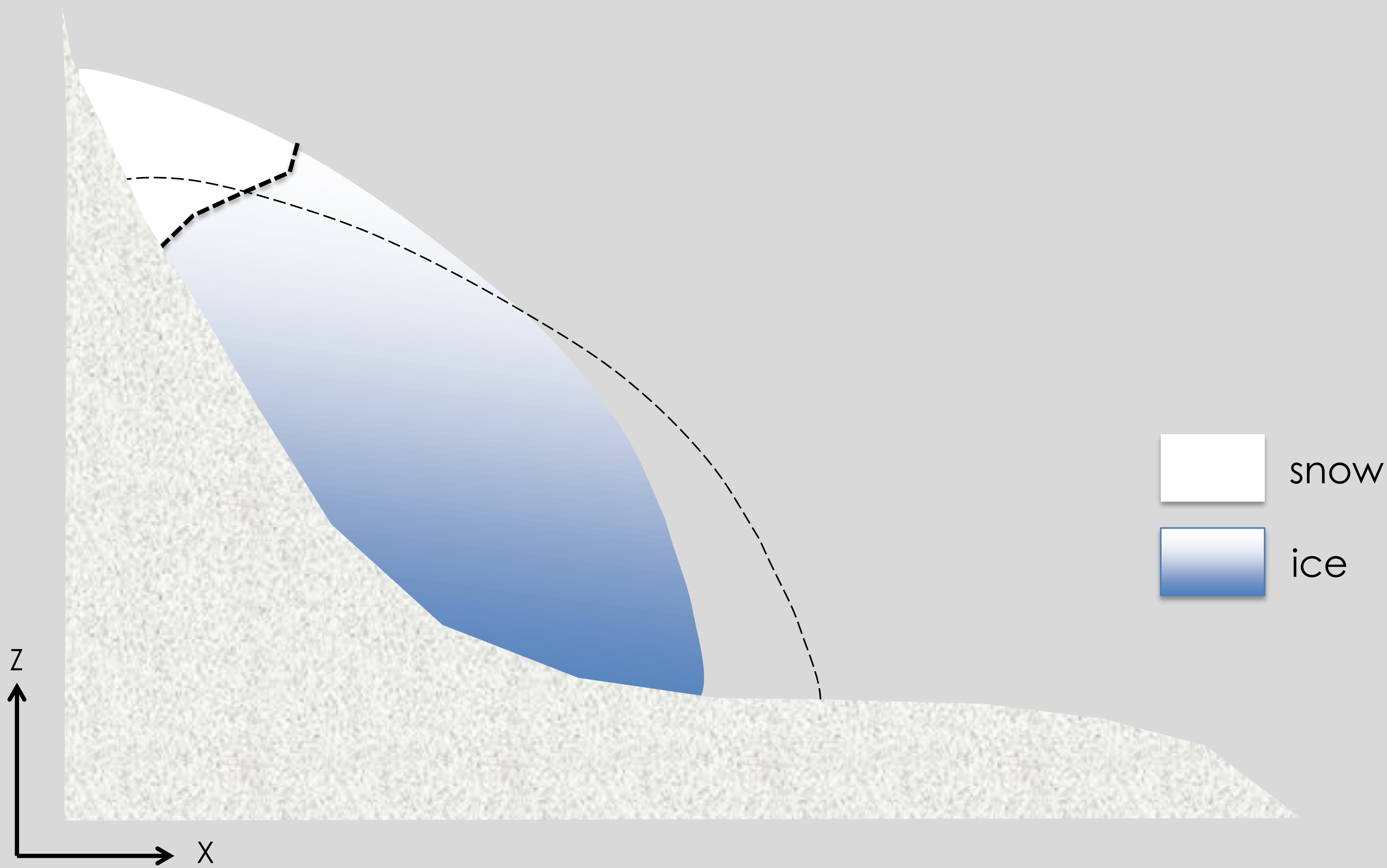


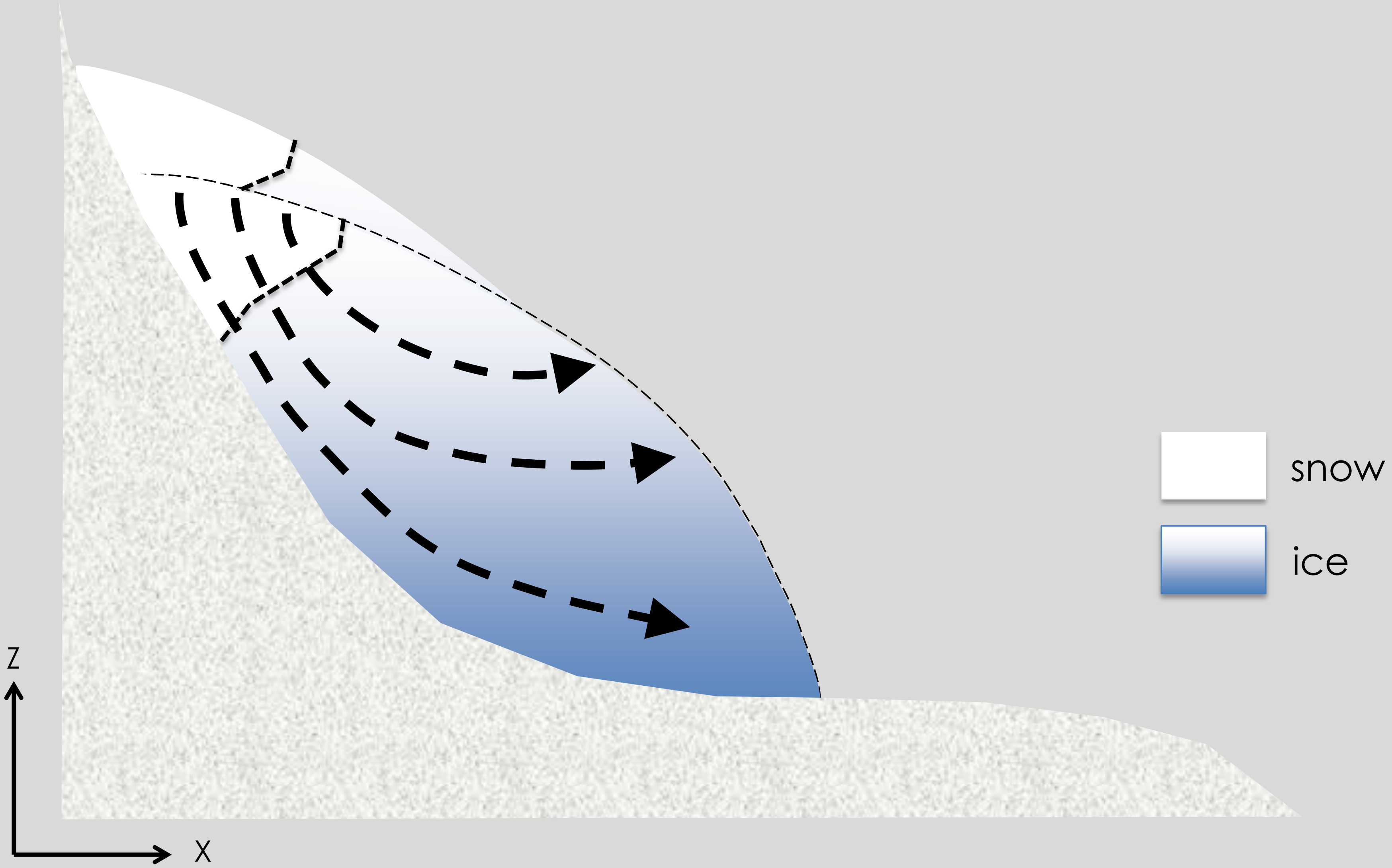
# Glacier Fundamentals

In the absence of flow, glaciers would steepen



## Glacier Fundamentals

Glacier flow conveys mass from high to low elevations

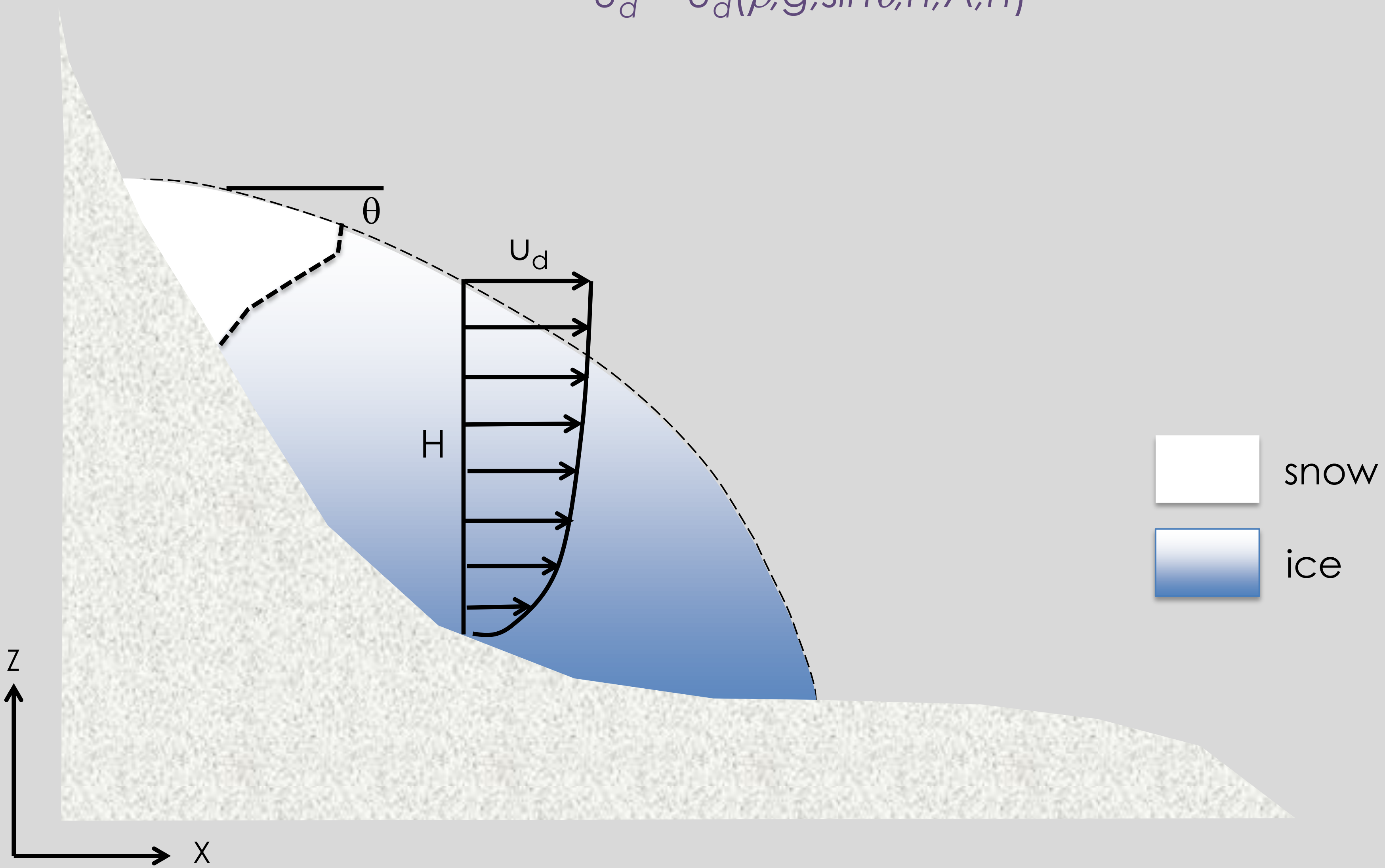


# Glacier Fundamentals

Glacier flow mechanisms:

Internal (viscous) deformation:

$u_d = u_d(\rho, g, \sin\theta, h, A, n)$



# Glacier Fundamentals

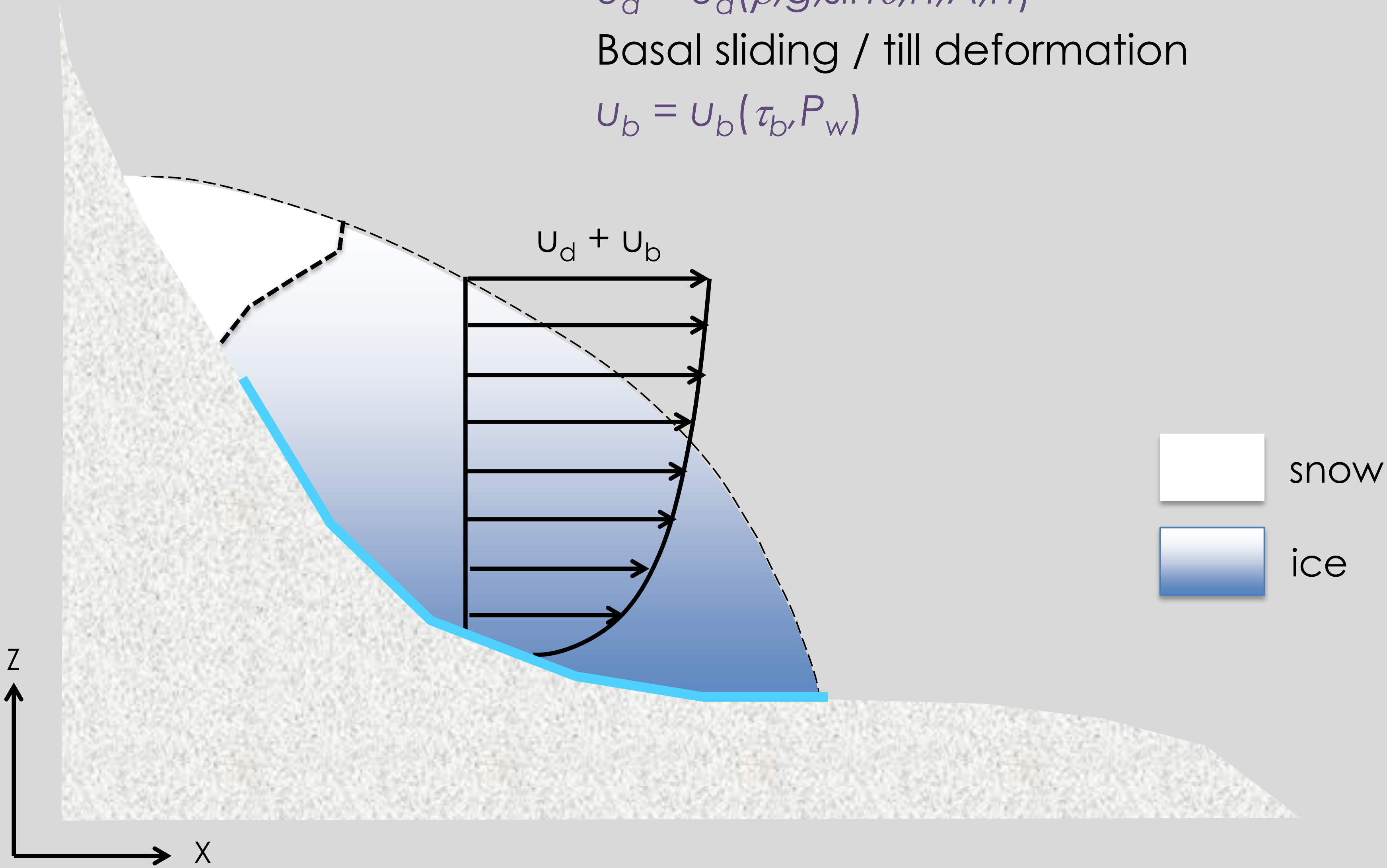
Glacier flow mechanisms:

Internal (viscous) deformation:

$u_d = u_d(\rho, g, \sin\theta, h, A, n)$

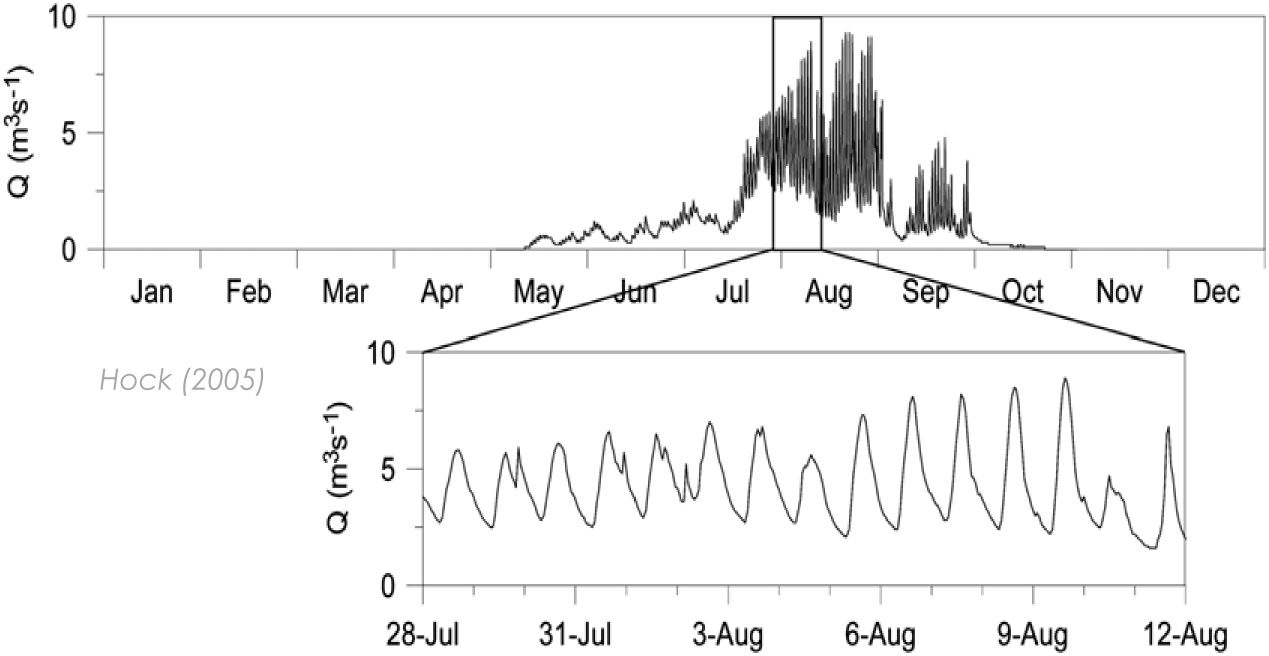
Basal sliding / till deformation

$u_b = u_b(\tau_b, P_w)$



# **Glacier Fundamentals:** basal sliding

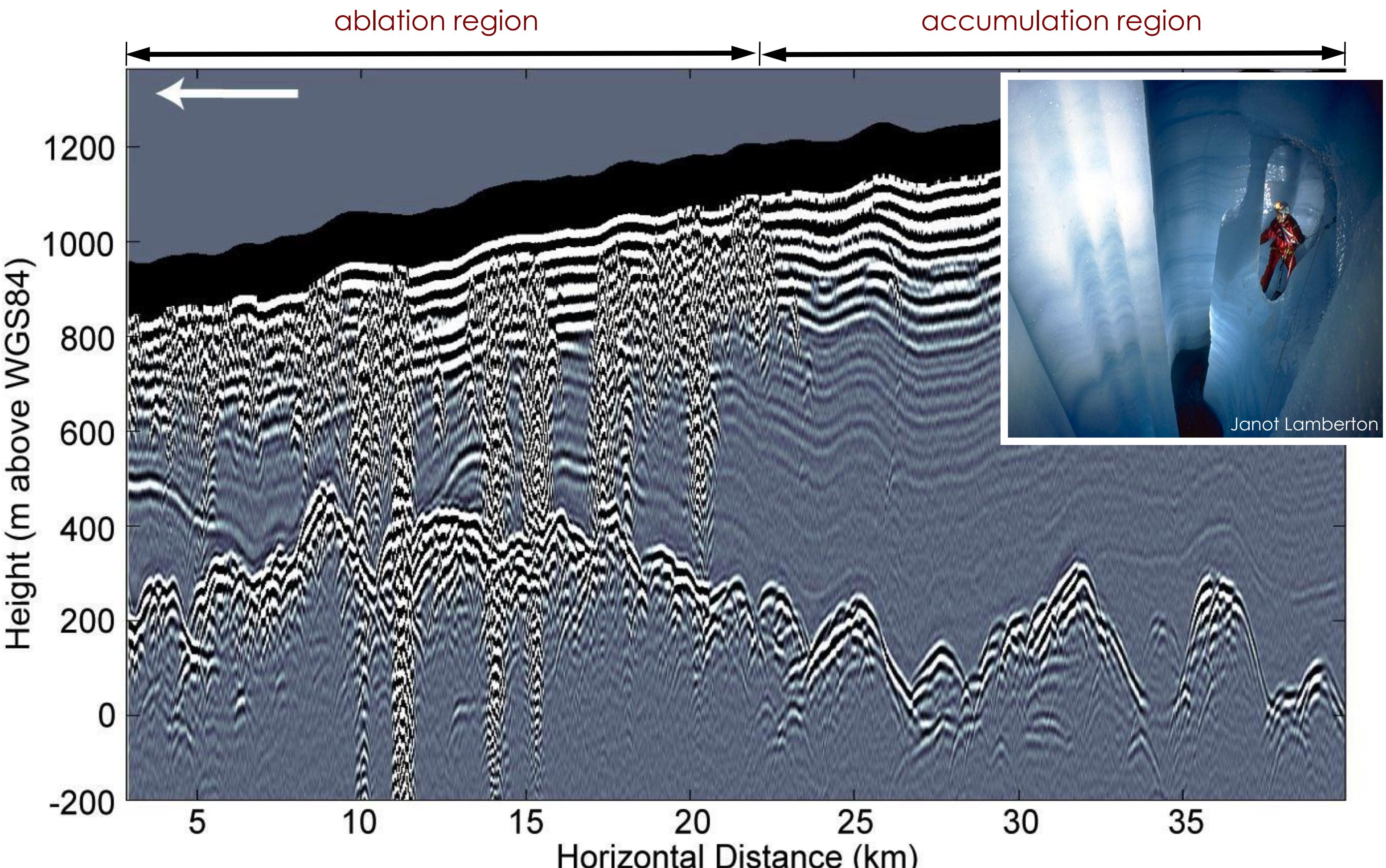
- glacier-fed streams show seasonal-daily variations in water discharge related to variations in solar radiation causing melt




*Hock (2005)*

# **Glacier Fundamentals:** basal sliding

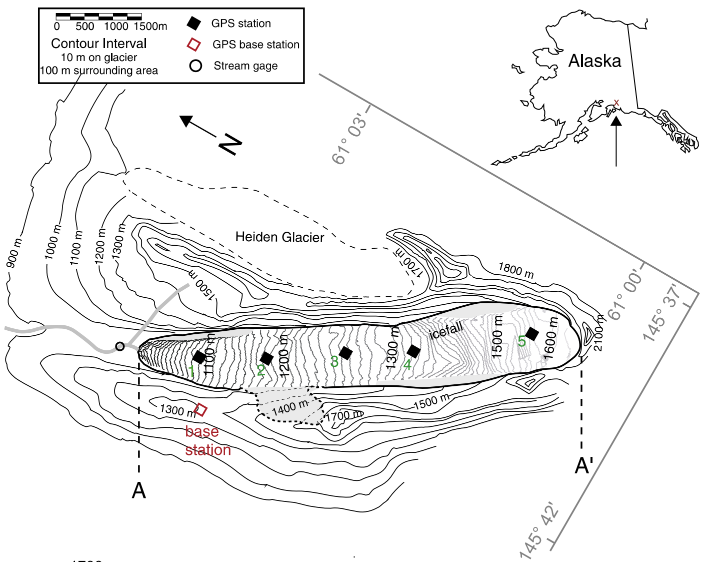
- variations in melt supply are routed through glaciers via moulins which deliver water to the bed

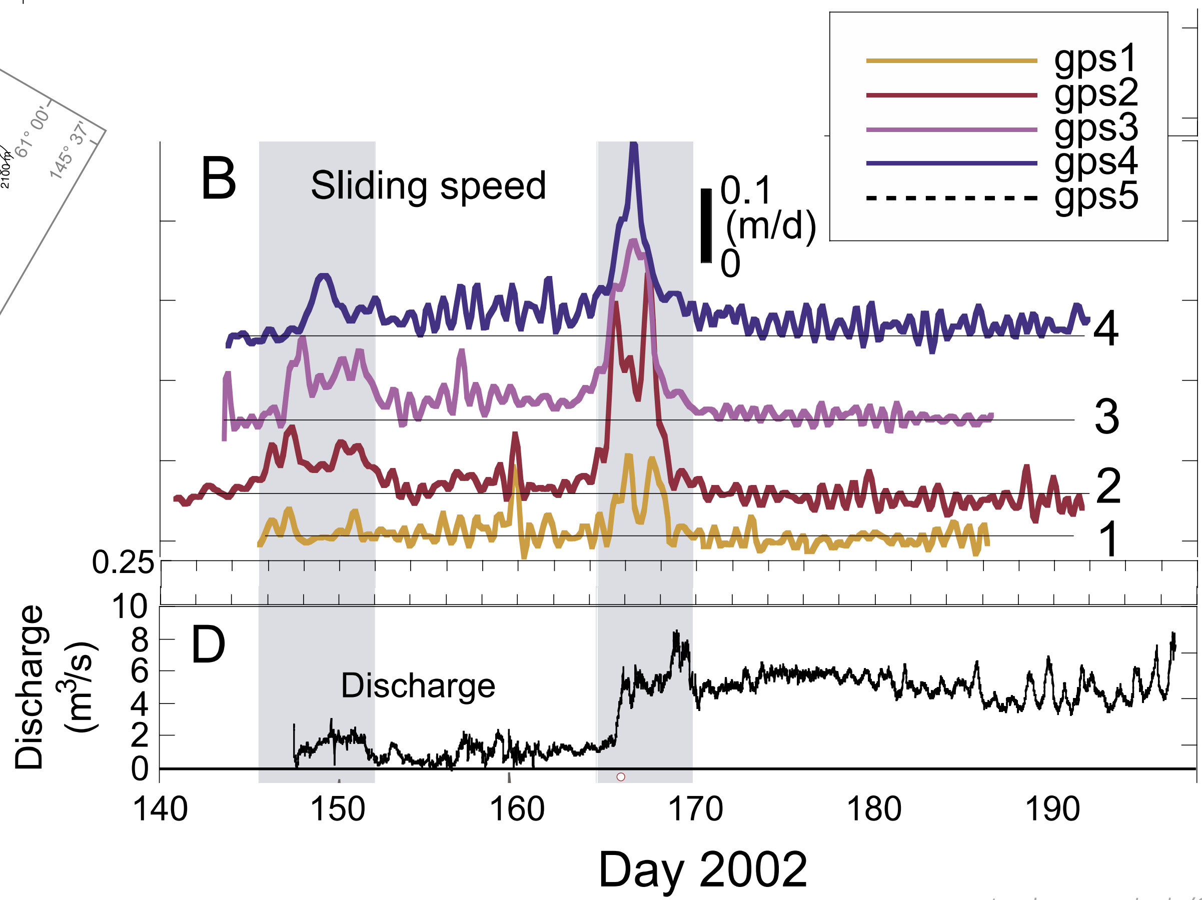



*Catania et al. (2010)*

# **Glacier Fundamentals:** basal sliding

- changes in water discharge are well-correlated to changes in ice flow speed
- what is the physical mechanism?

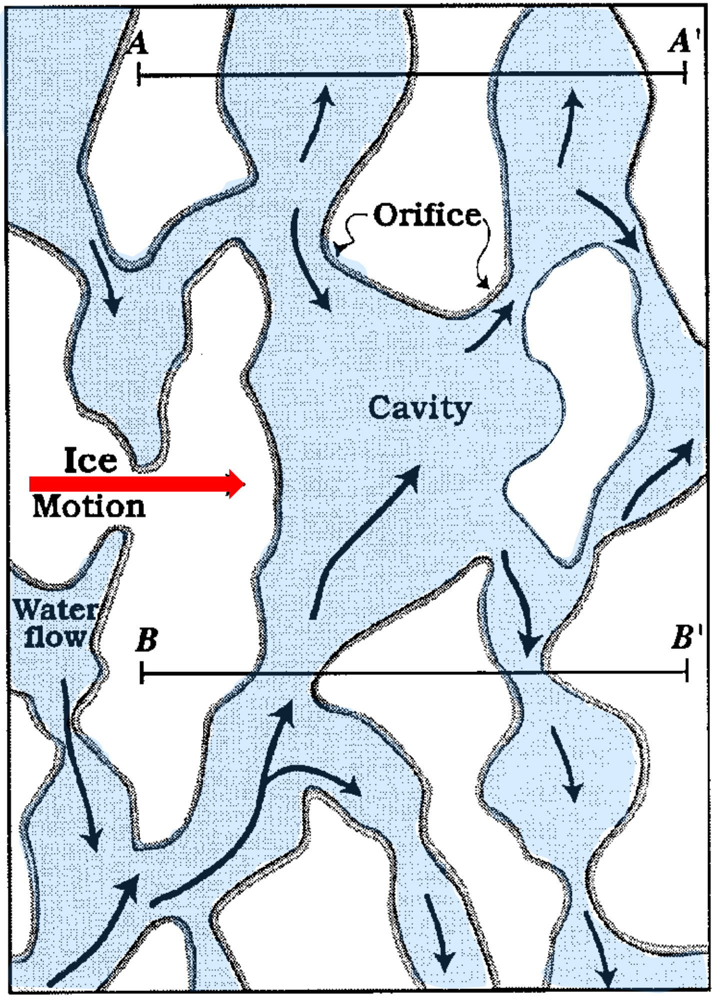


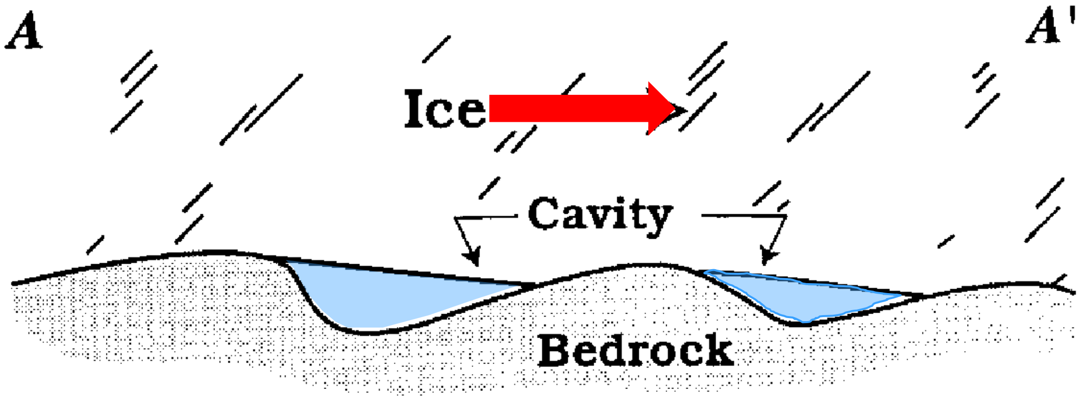




Anderson et al. (2004)

# **Glacier Fundamentals:** basal sliding

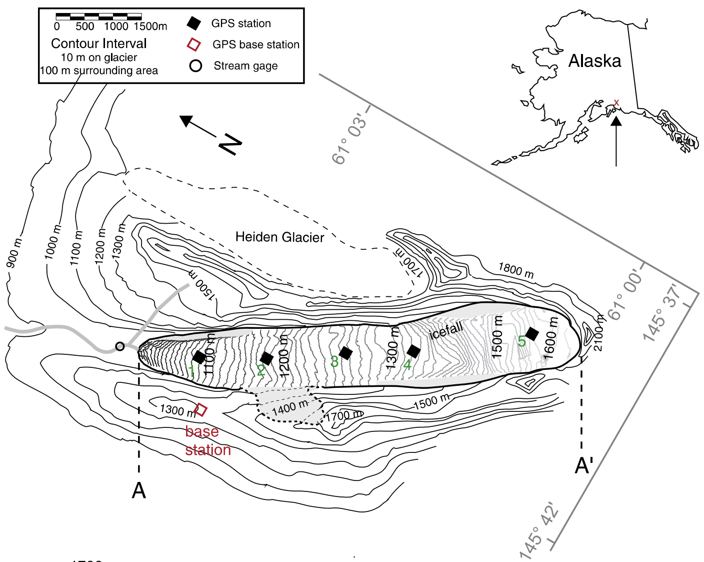
- distributed drainage system of linked cavities that form on the lee side of bed protrusions
- system operates at a higher water pressure because the drainage of water is inefficient
- cavities grow with increasing water pressure and sliding speed

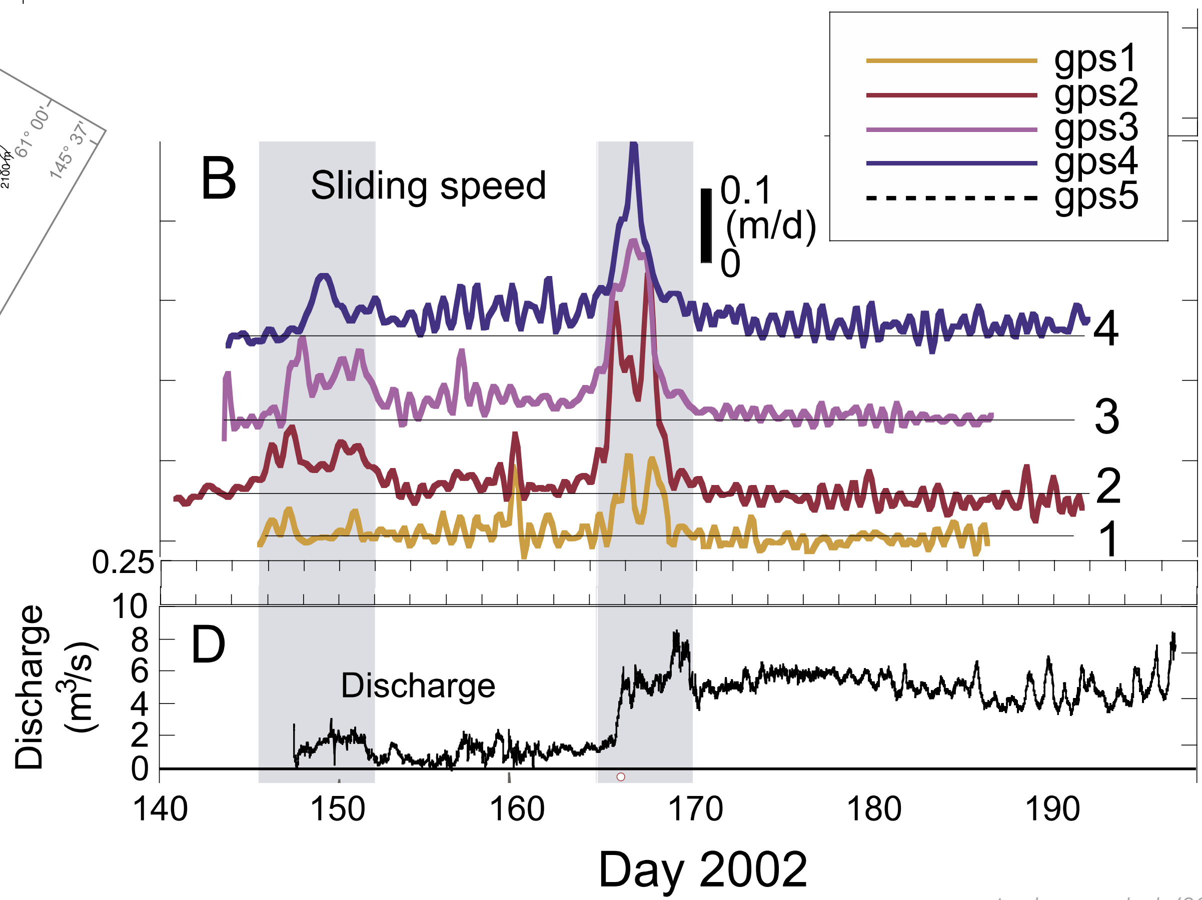


# **Glacier Fundamentals:** basal sliding

- changes in water discharge are well-correlated to changes in ice flow speed
- physical mechanism: drowning of bed obstacles

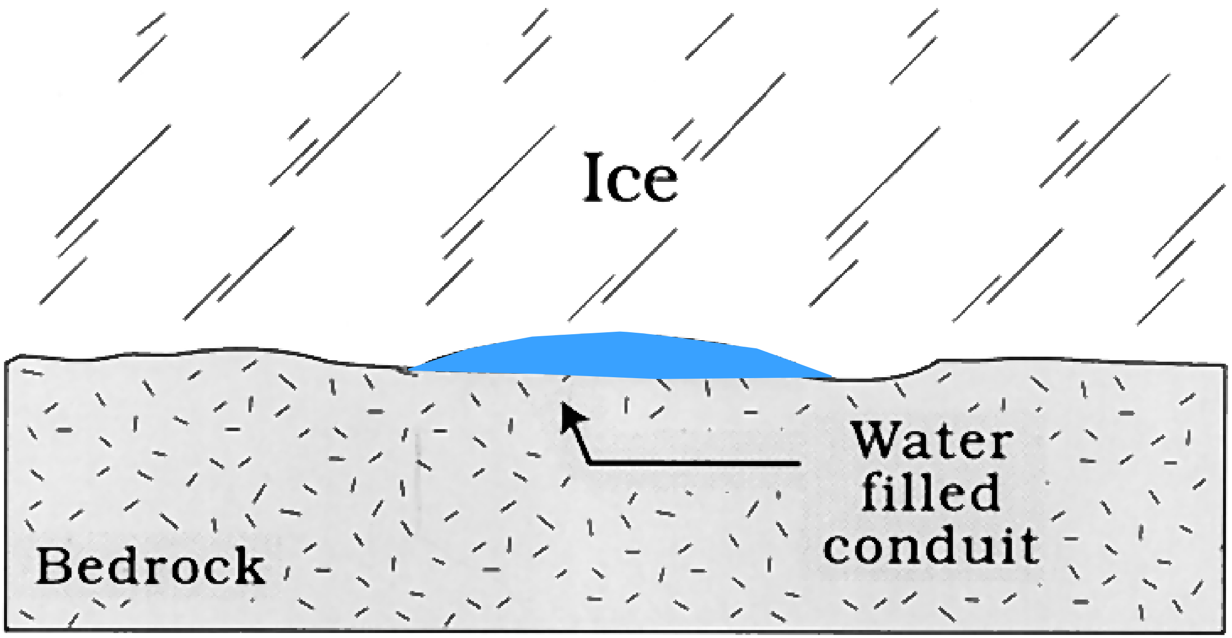


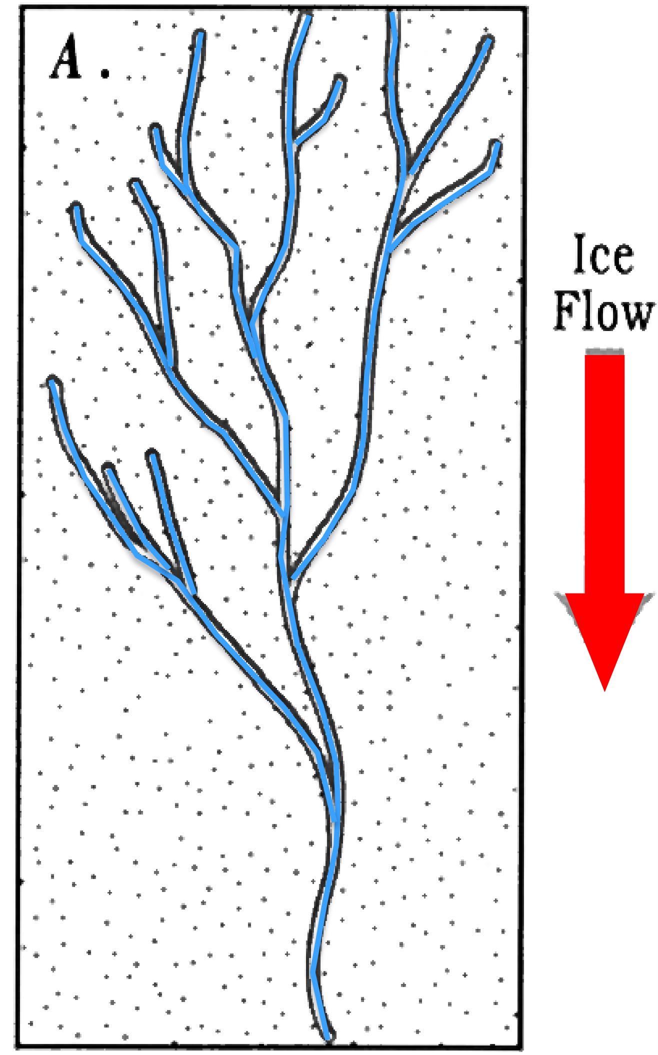




Anderson et al. (2004)

# **Glacier Fundamentals:** basal sliding

- as water supply increases channels cut up, into the ice and enlarge through melt
- channels operate at lower pressures and grow at the expense of smaller ones
- channels can efficiently transport water whereas cavities require high pressures to transport the same flux



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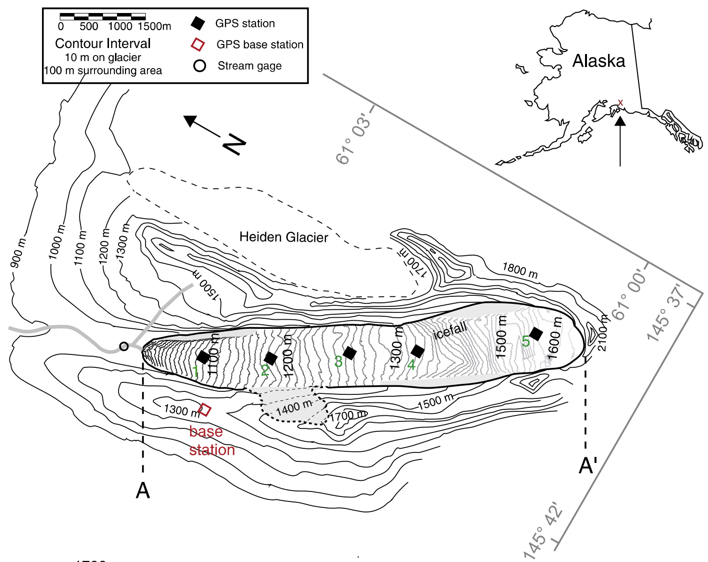


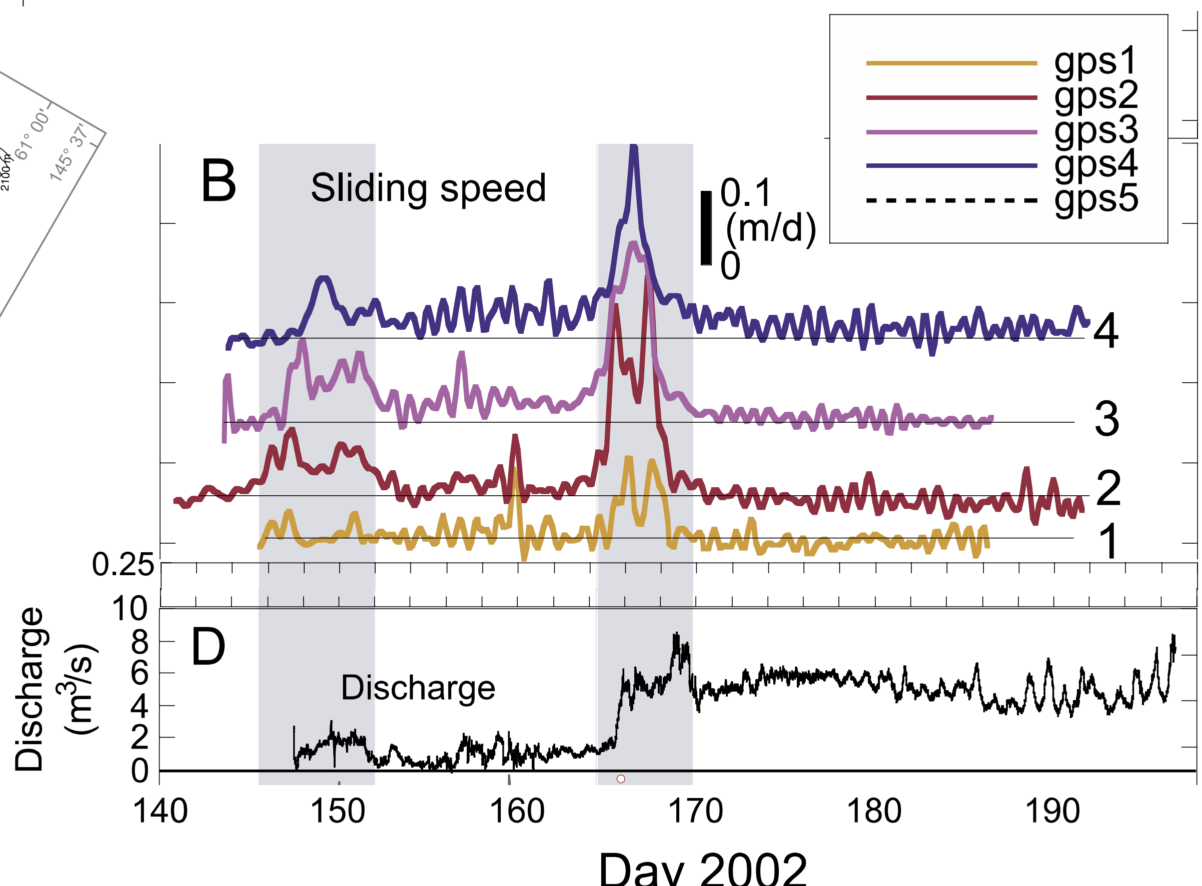


Anderson et al. (2004)

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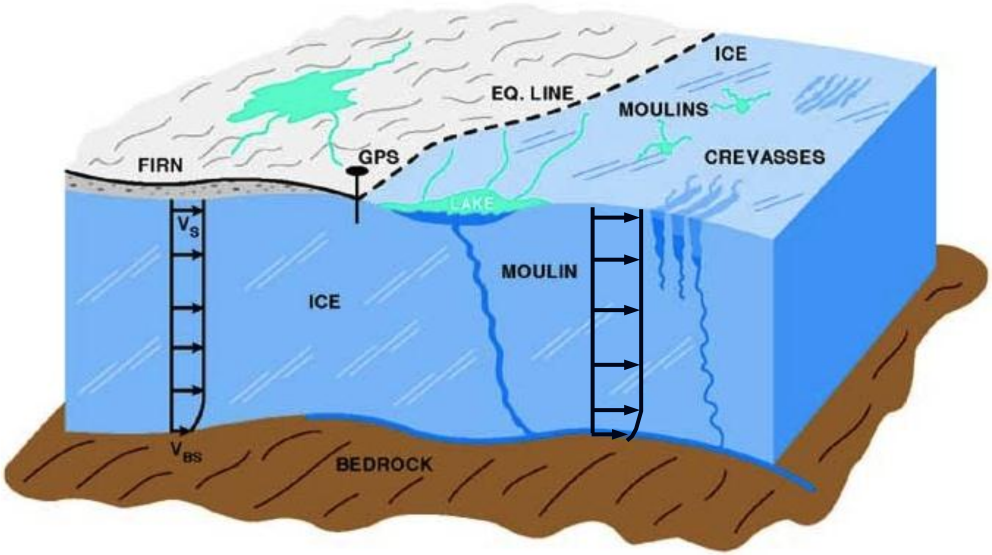
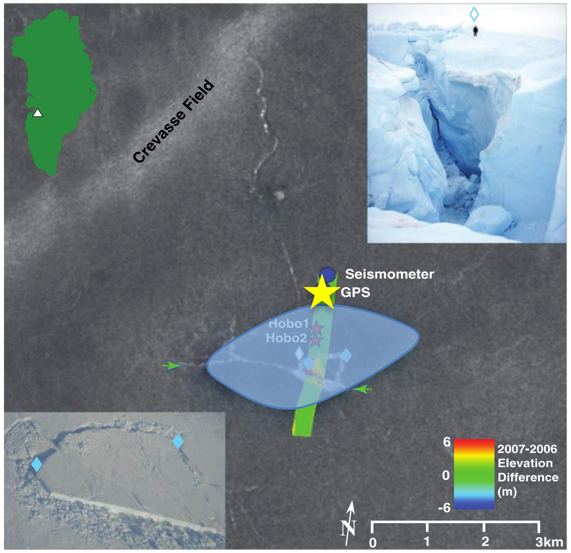
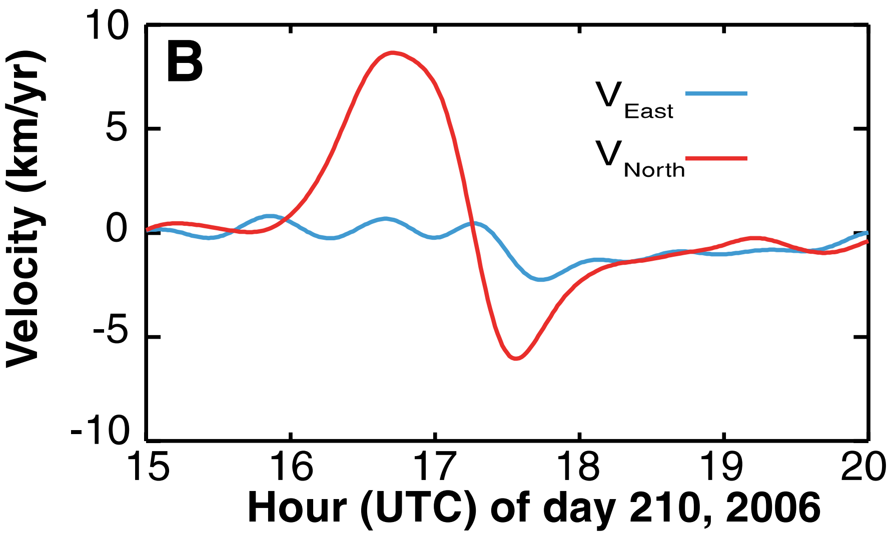
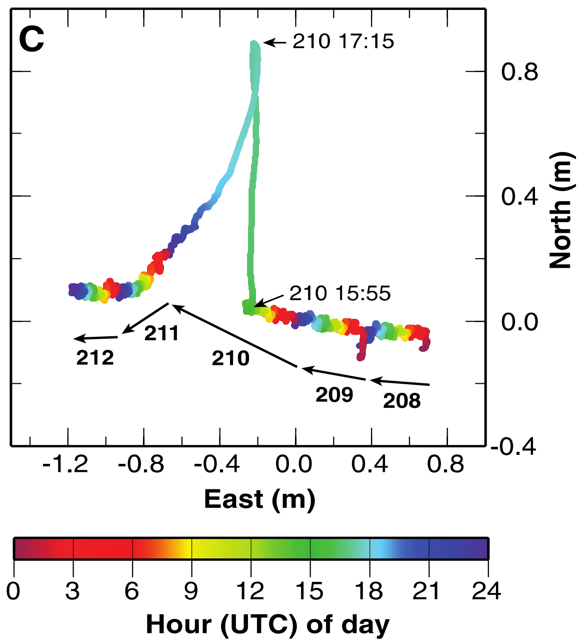


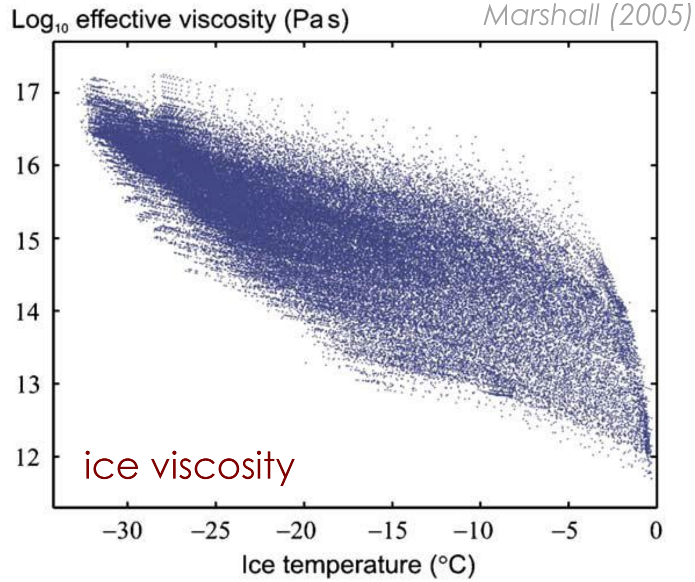

*from Das et al. (2008)*

# **Physical Model:** discharge variability

# **Physical Model:** discharge variability

- polydimethyl-siloxane (PDMS) used in tectonics experiments
- non-Newtonian at strain rates larger than $10^{-2}\ s^{-1}$
- Newtonian at strain rates used in experiments ($10^{-4}\ s^{-1}$)
- scale geometry, density, time and rheology

Marshall (2005)




*Geometry:*

$$\frac{H_m}{W_m} = 0.1 \qquad \frac{H_i}{W_i} = 0.1$$

*Density:*

$$\frac{\rho_m}{\rho_w} = 0.97 \qquad \frac{\rho_i}{\rho_w} = 0.91$$

| Quantity | Model | Ice |
|---|---|---|
| Thickness (m) | ~0.1 | ~1000 |
| Width (m) | ~1 | ~100000 |
| Density $kg/m^3$ | 970 | 910 |
| Viscosity (Pa s) | $5 \times 10^4$ | $10^{11}$-$10^{17}$ |
| $\dot{\varepsilon}$ ($s^{-1}$) | $10^{-4}$ | $\sim 10^{-9}$ |

*Time:*

$$t_m = \left(\frac{\eta_m \rho_i H_i}{\eta_i \rho_m H_m}\right) t_i$$

for $t_i$ = 1 day, $t_m$ ~7min

*Rheology:*

$$Re_i = \frac{\rho_i v_i H_i}{\eta_i} \sim 10^{-9}$$

(small, laminar)

$$Re_m = \frac{\rho_m v_m H_m}{\eta_m} \sim 10^{-12} - 10^{-15}$$

*Rheology:*

$$\eta_i = \left(\frac{\rho_i}{\rho_m} \frac{H_i}{H_m} \frac{\dot{\varepsilon}_m}{\dot{\varepsilon}_i}\right) \eta_m \sim 10^{14}\ \text{Pa s}$$

# **Physical Model:** discharge variability


camera: horizontal surface velocity

acoustic sensor: surface elevation

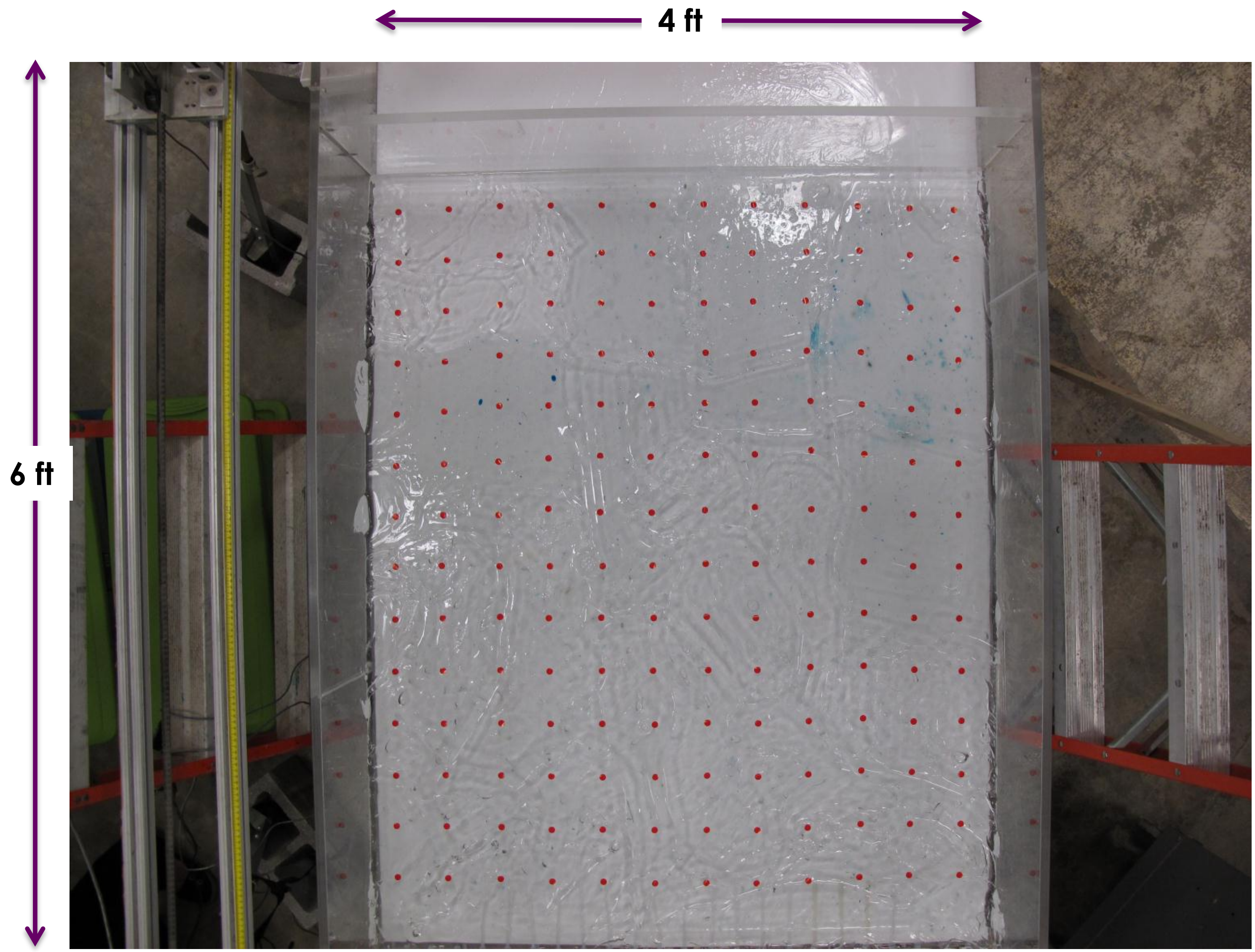
distributed discharge valves vary water input

pressure tank: keeps water pressure high and uniform across width

flow meter: water discharge

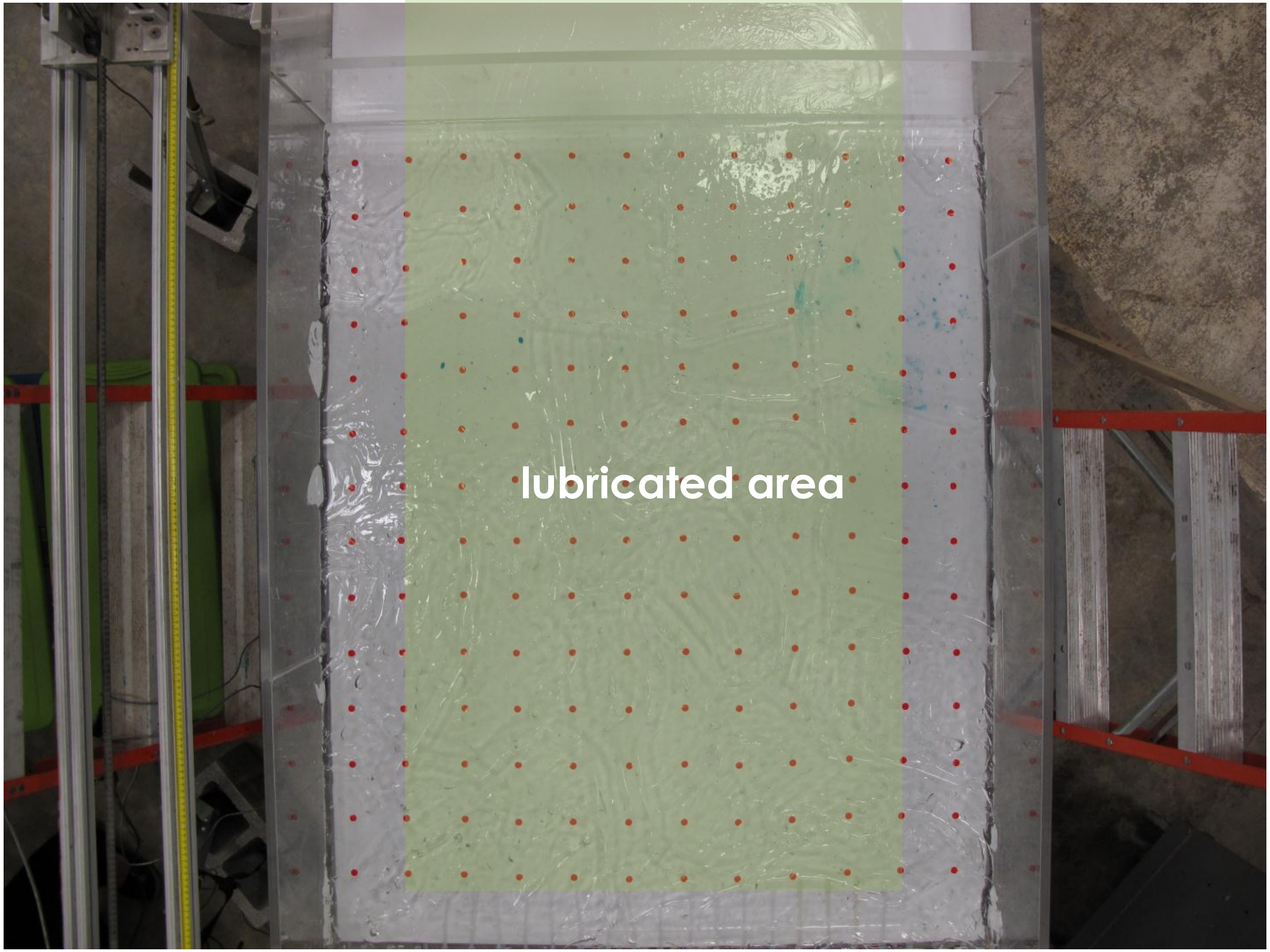
**Physical Model:** discharge variability

- polymer is loaded to achieve a ~10 cm thick layer of polymer
- held in place temporarily with plexiglas wall
- no slope



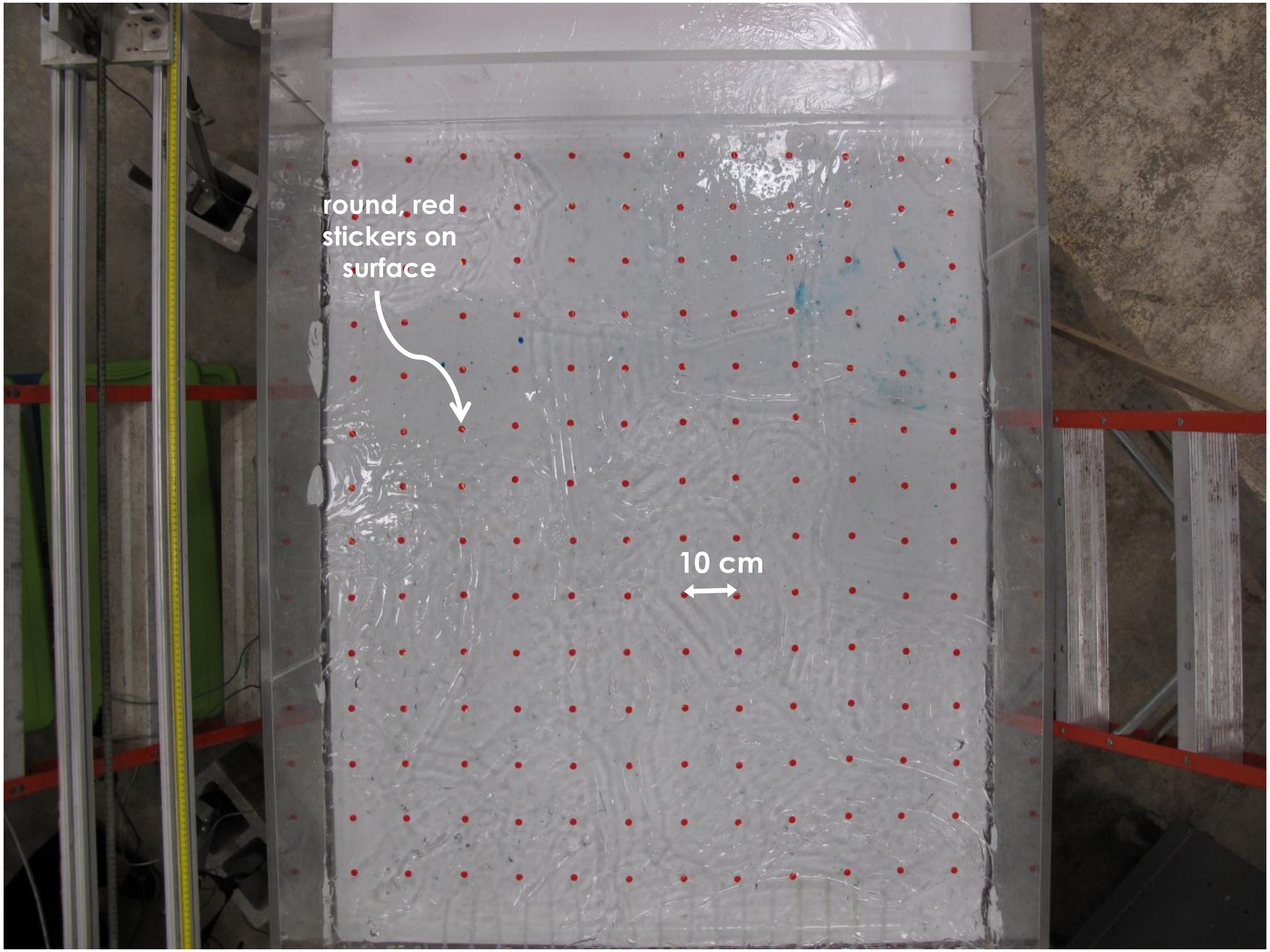
# **Physical Model:** discharge variability

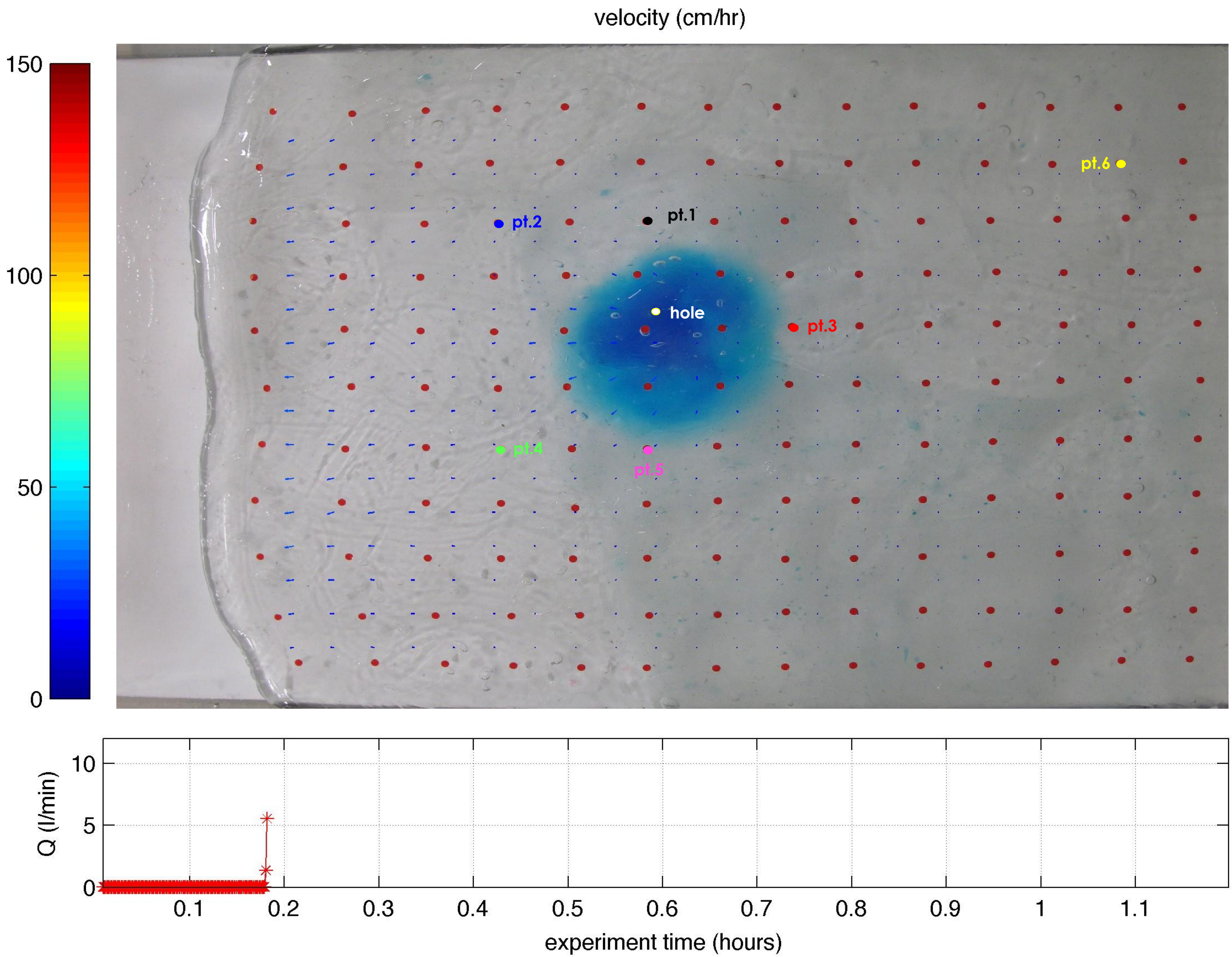
- lubricant is applied over the plexiglas box before polymer is loaded
- reduces friction at the polymer/box interface
- lack of lubricant at edges provides a water-tight seal on flume edges



# **Physical Model:** discharge variability

- stickers are placed on the surface in a 10 cm grid to measure surface horizontal velocity field




velocity (cm/hr)
150
100
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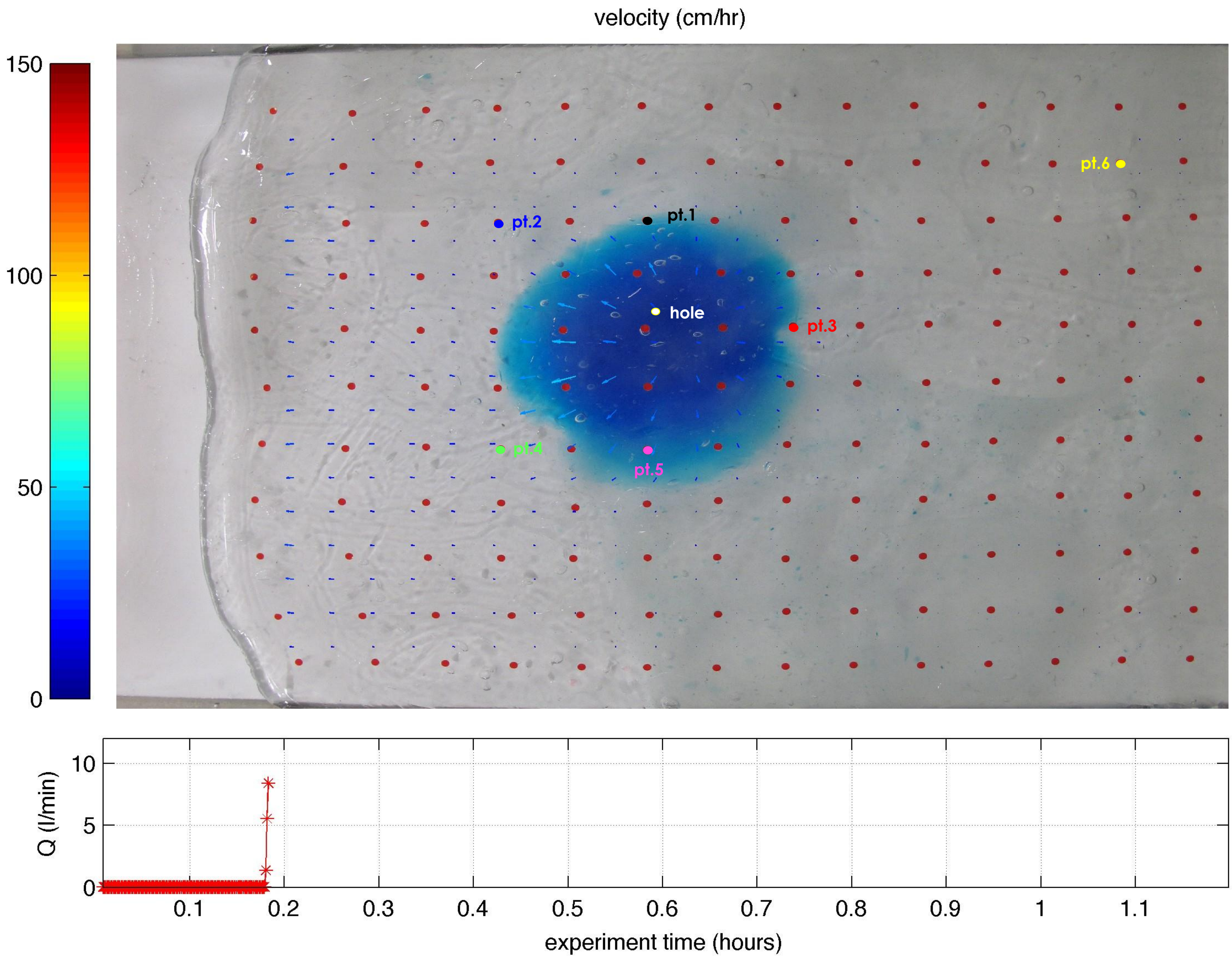
0
pt.1
pt.2
pt.3
pt.4
pt.5
pt.6
hole
Q (l/min)
10
5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
experiment time (hours)



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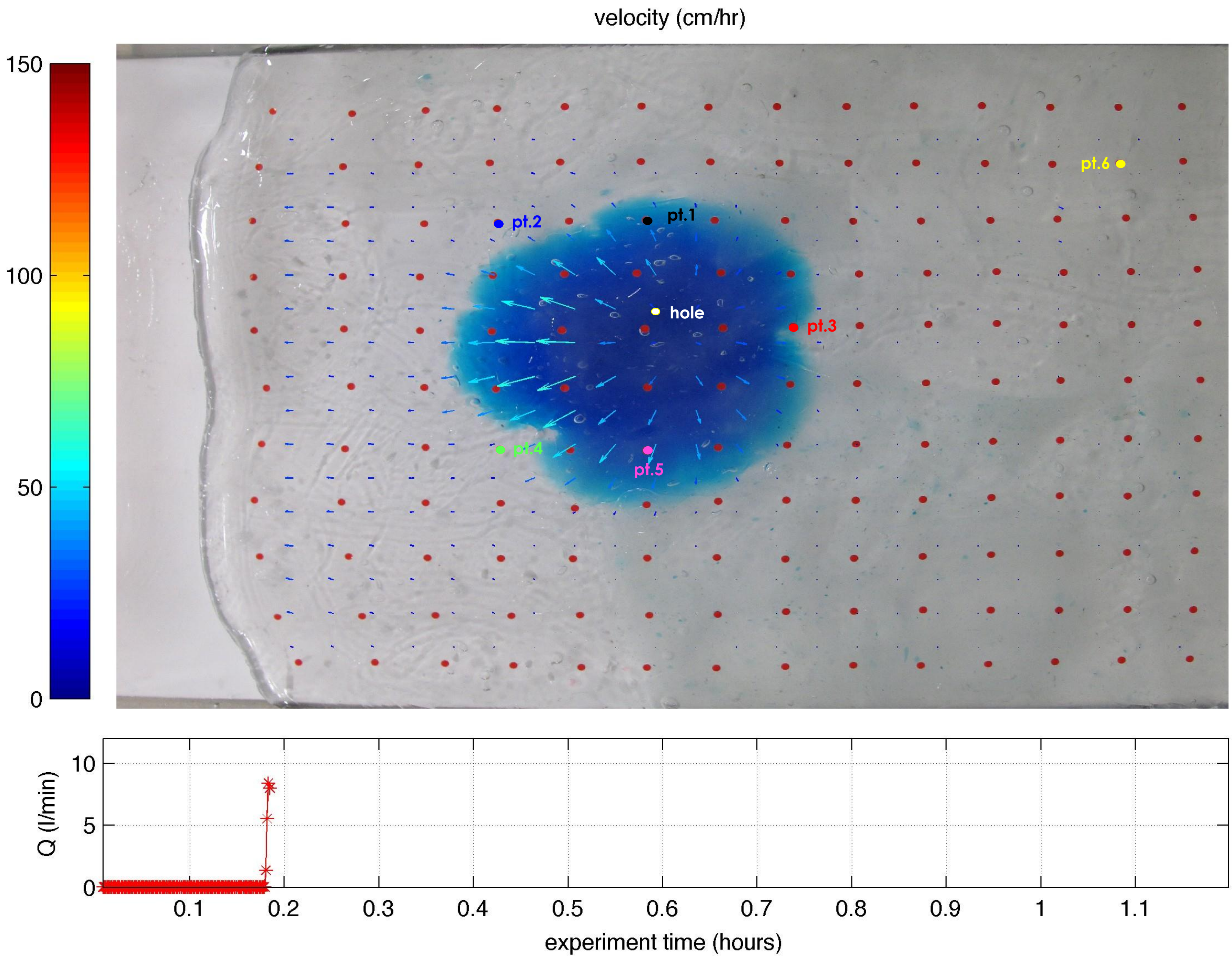
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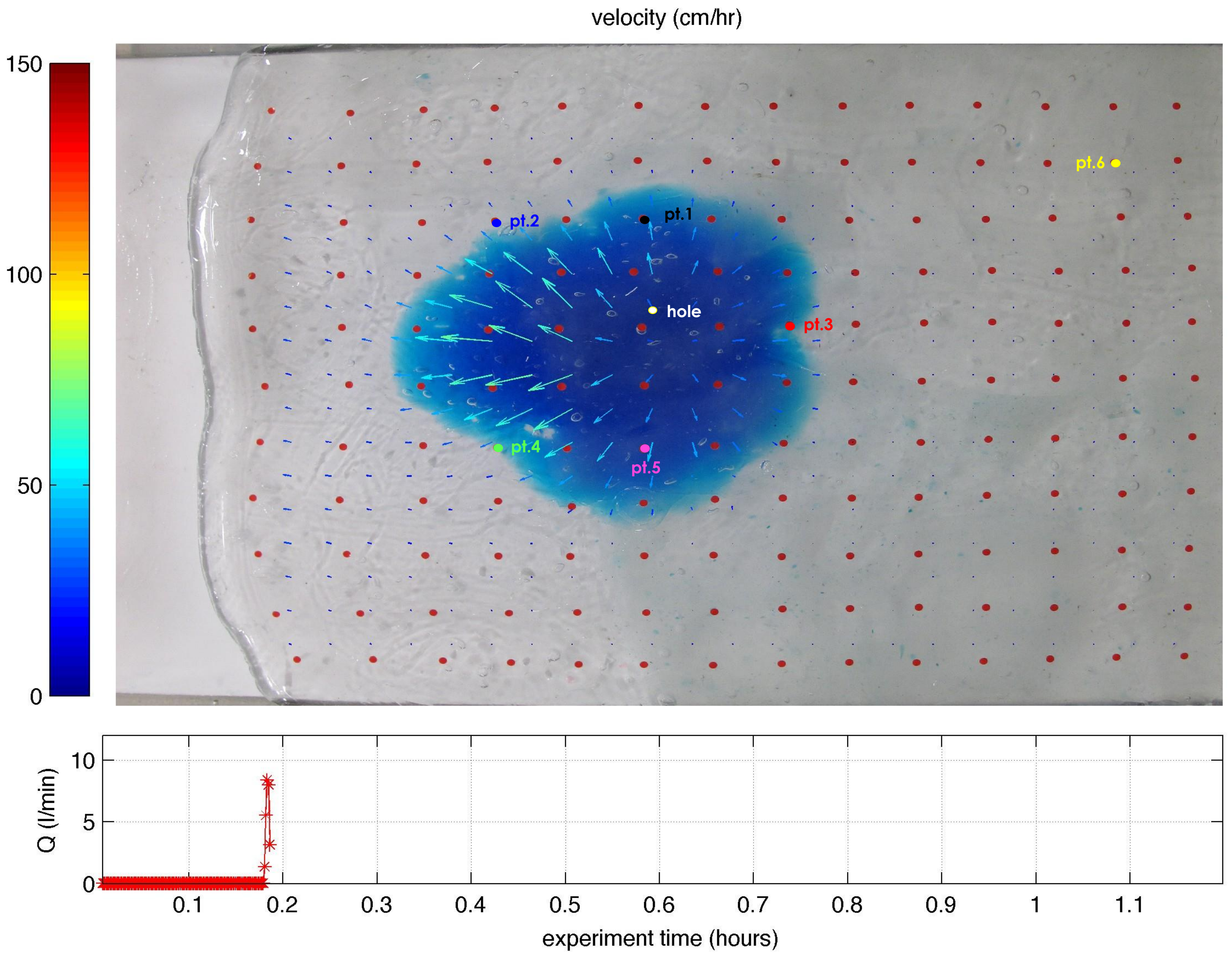
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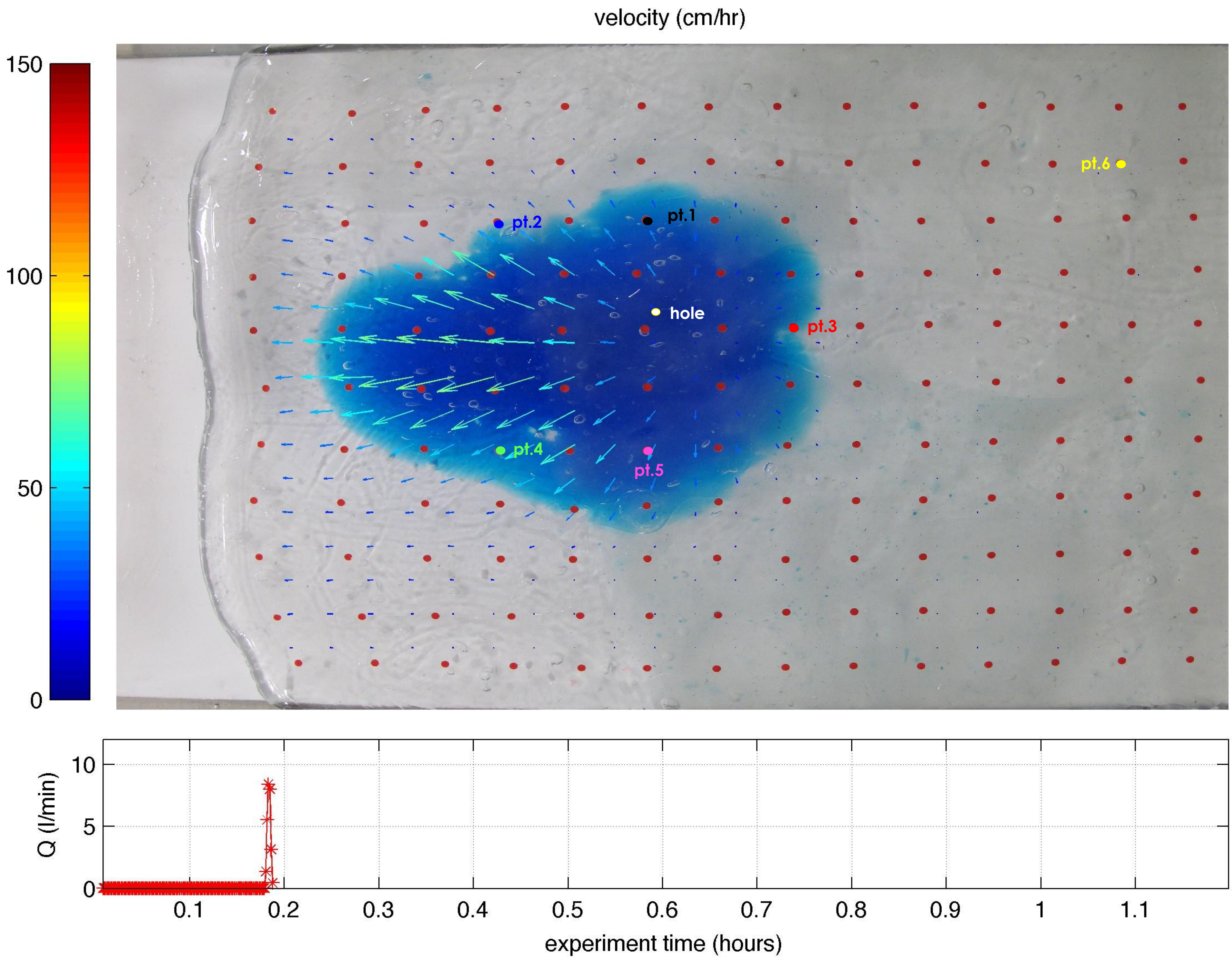
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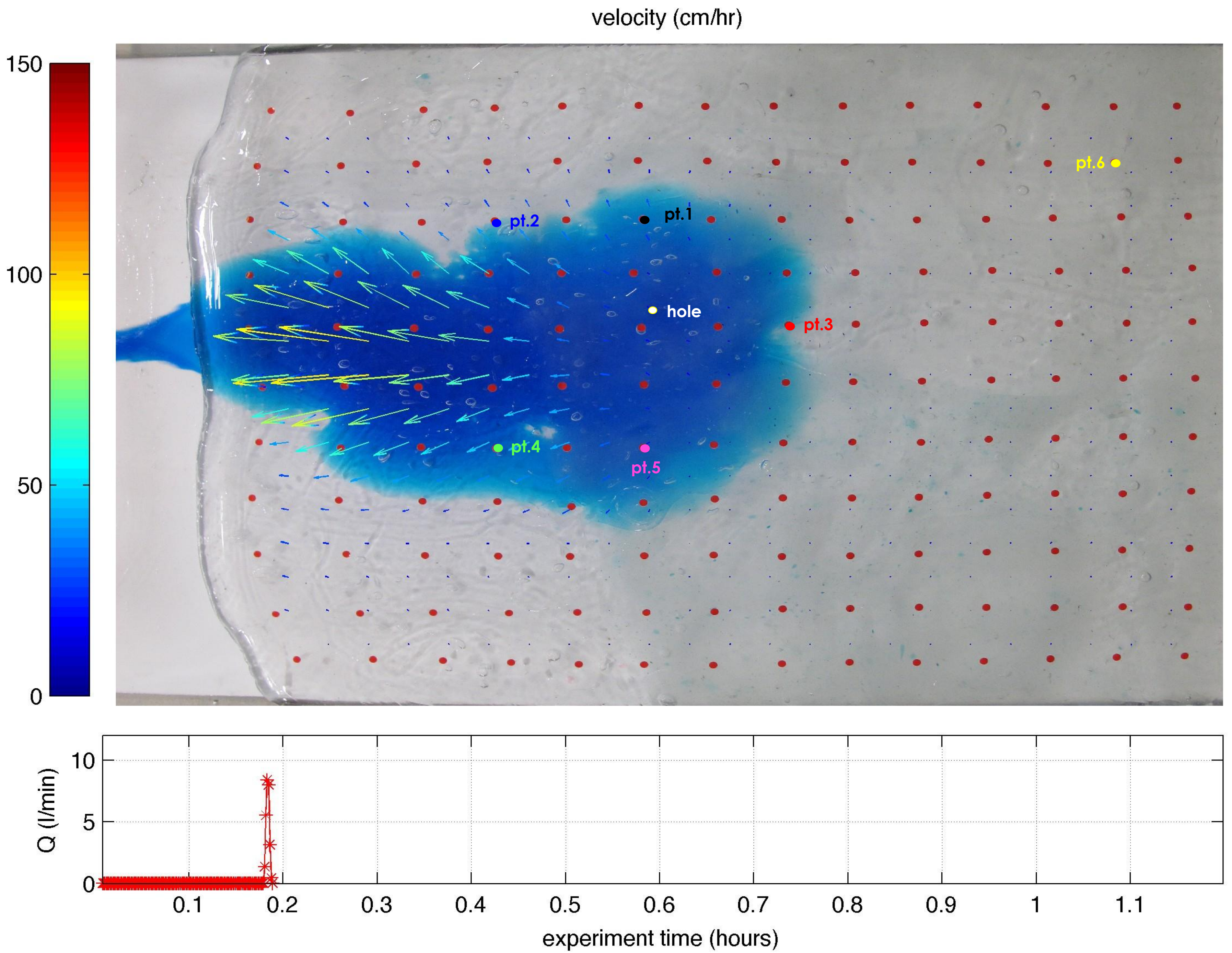
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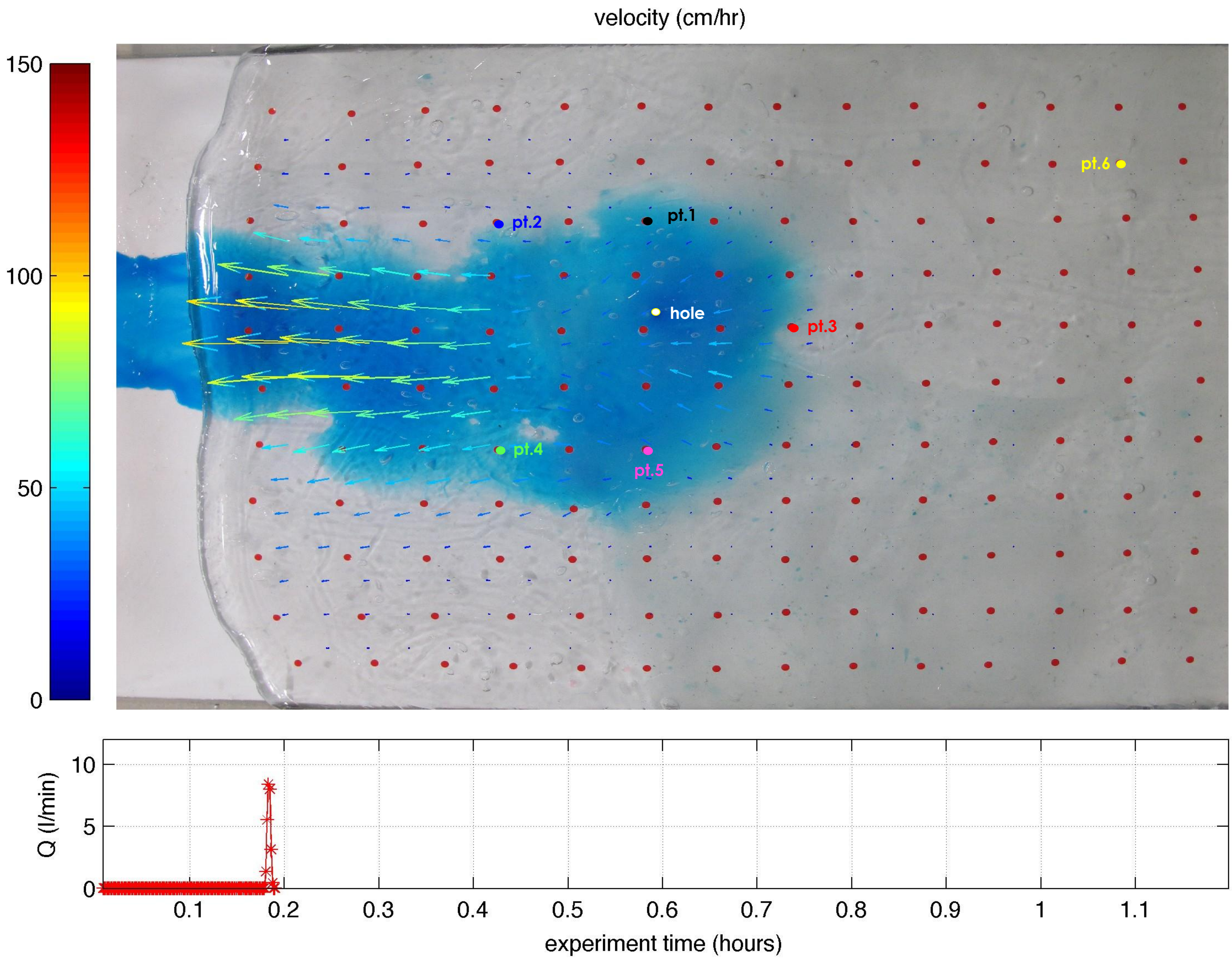

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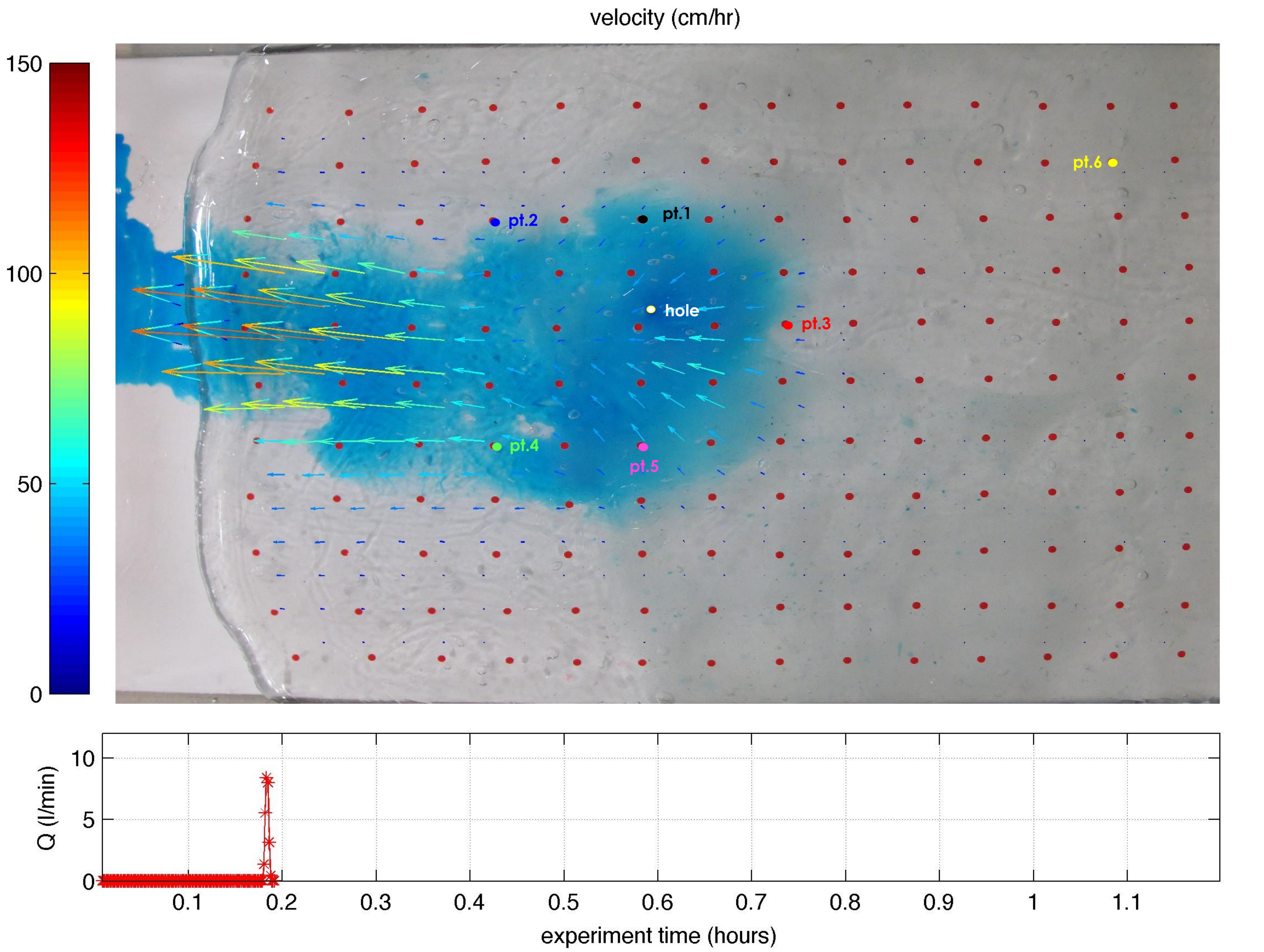

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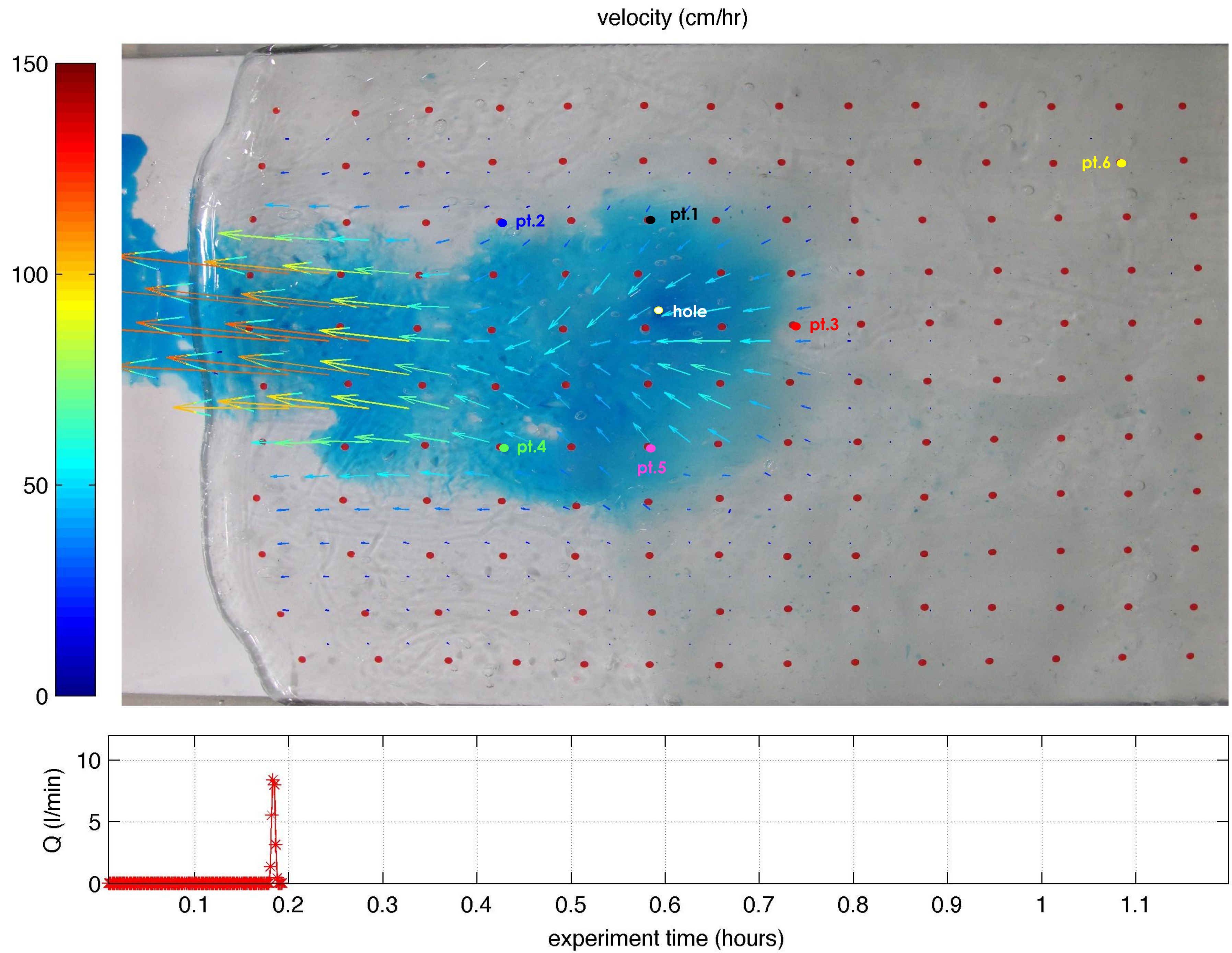

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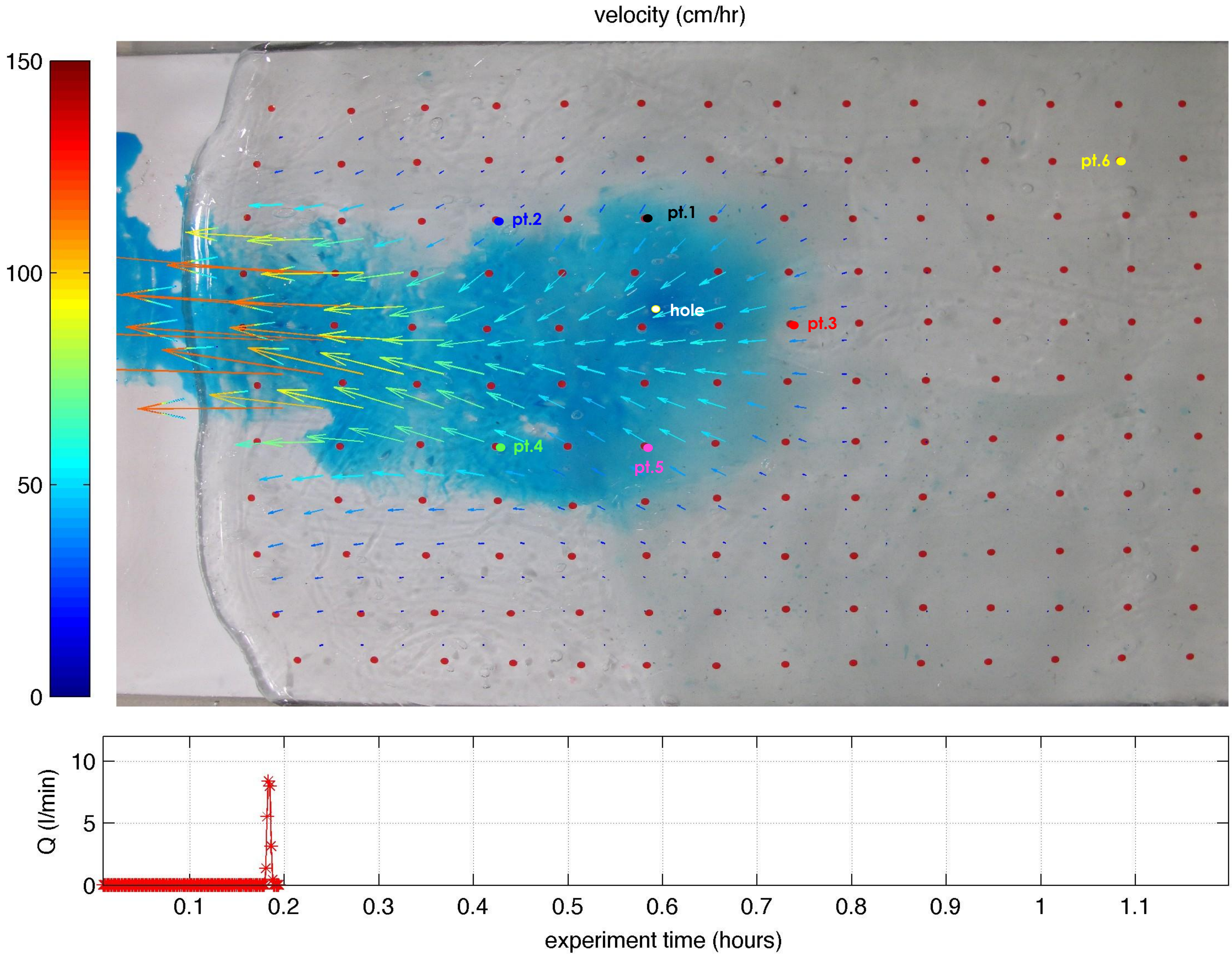

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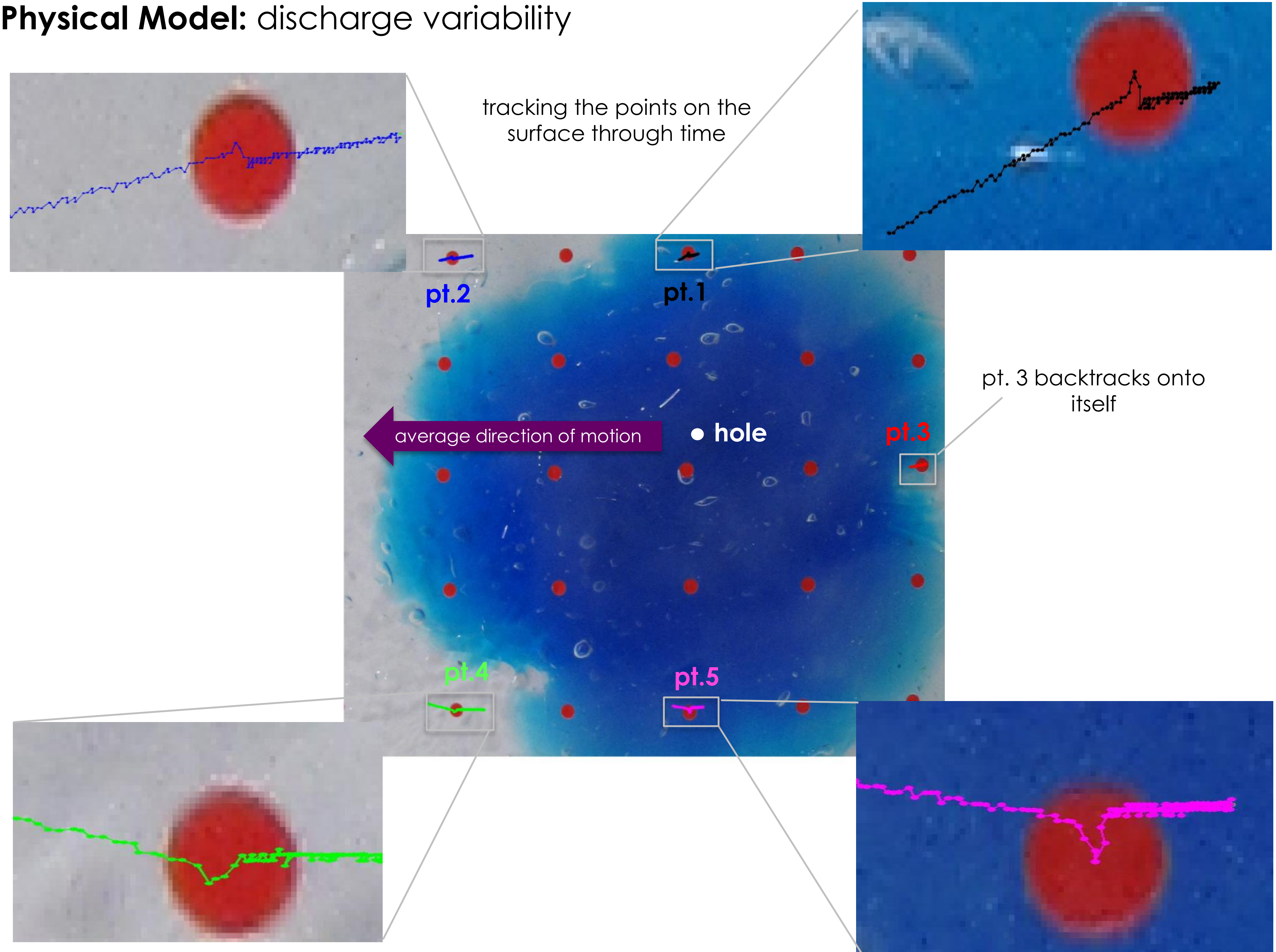
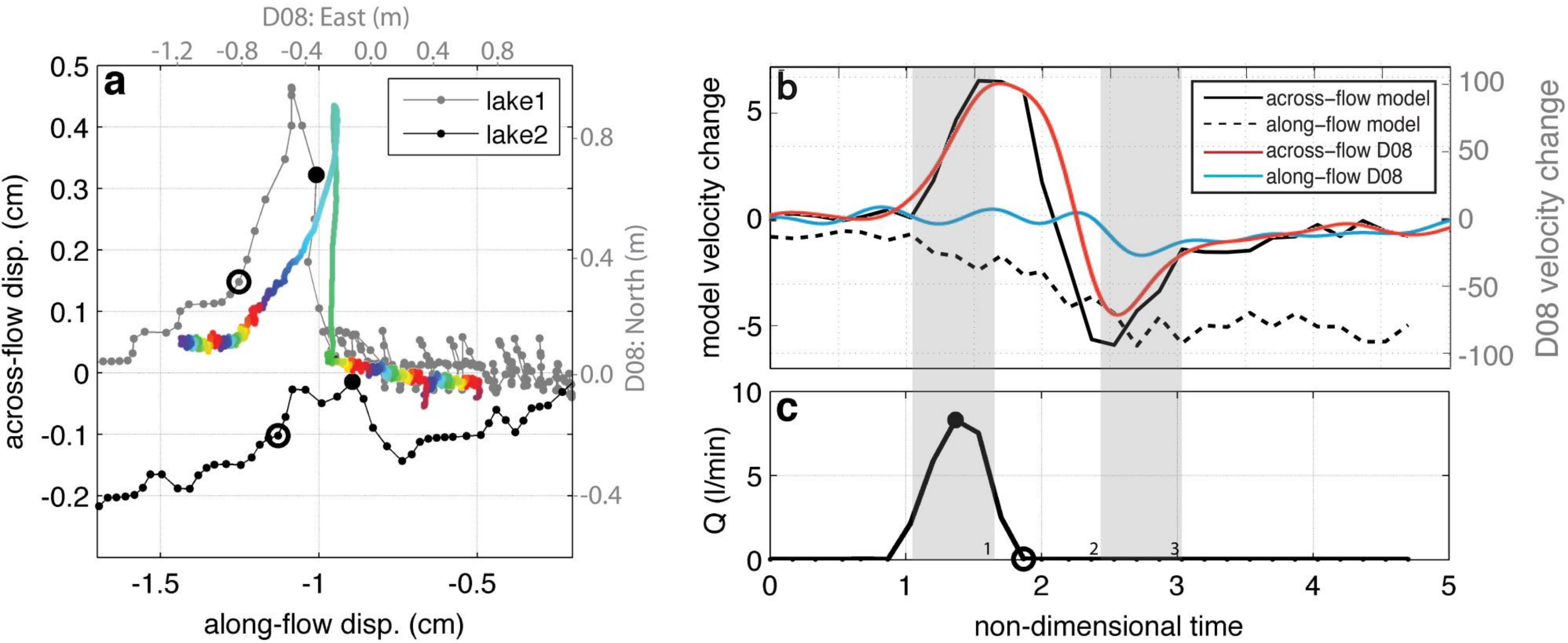
# **Physical Model:** discharge variability



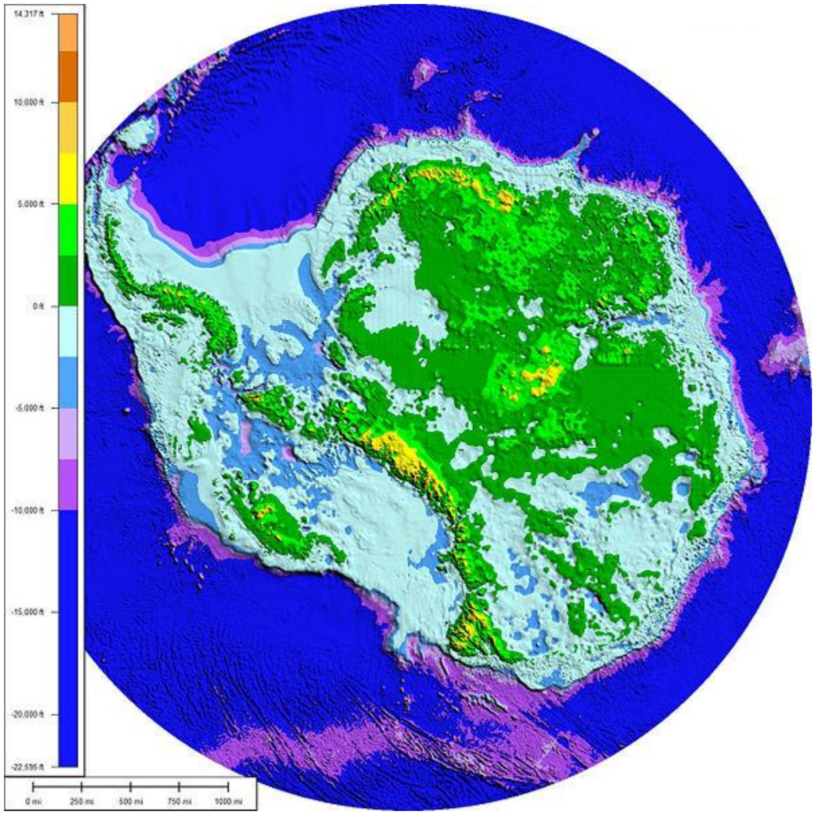
**Physical Model:** discharge variability

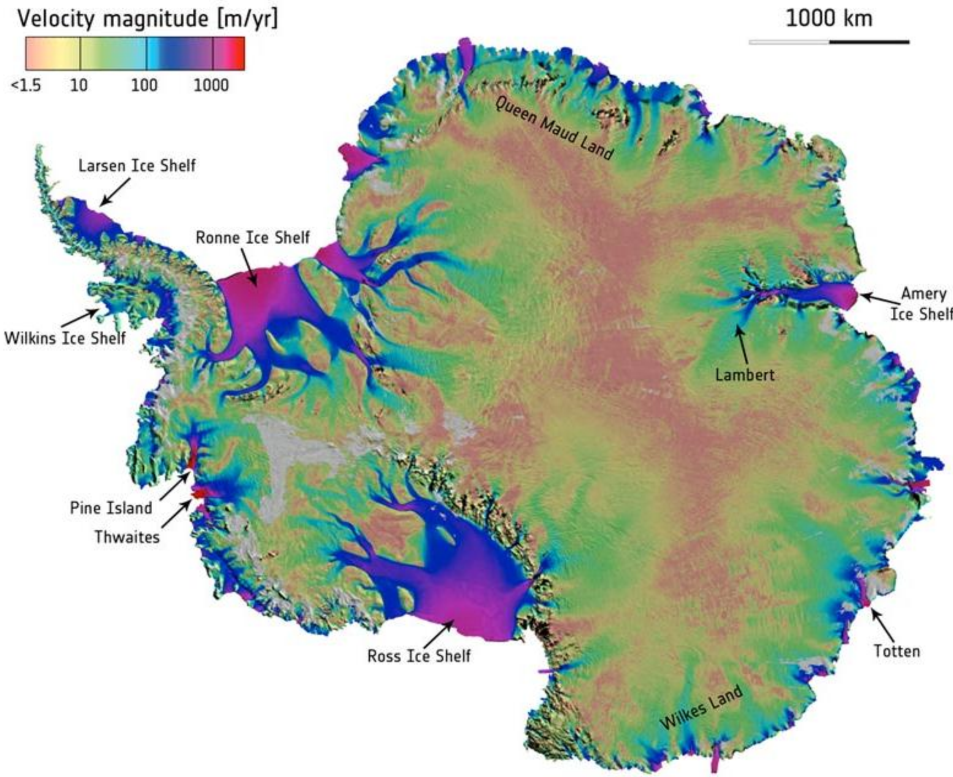



- overburden is important in that it re-sets the system when discharge decreases

# **Glacier Fundamentals:** basal sliding

- what about channel system beneath glaciers underlain with sediments?

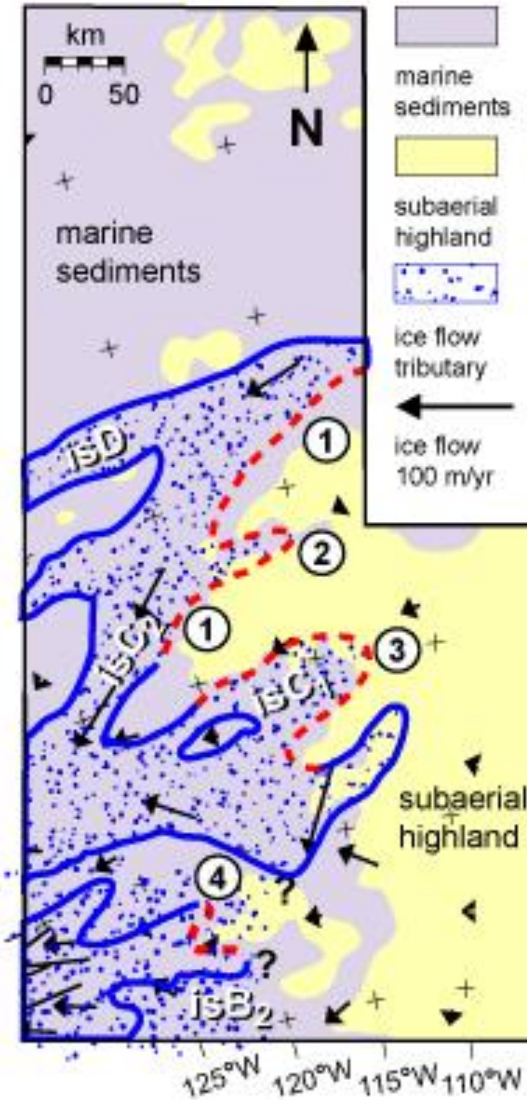



Rignot et al. (2012)

# **Glacier Fundamentals:** basal sliding






*Behar, 2013; Studinger et al. (2001)*

**Physical Model:** ice stream subglacial drainage

*Catania and Paola (2001)*

# **Physical Model:** ice stream subglacial drainage

- near-flat surface slope creates lateral pressure gradients on scale of downstream pressure gradients
- causes intricate braided channel network

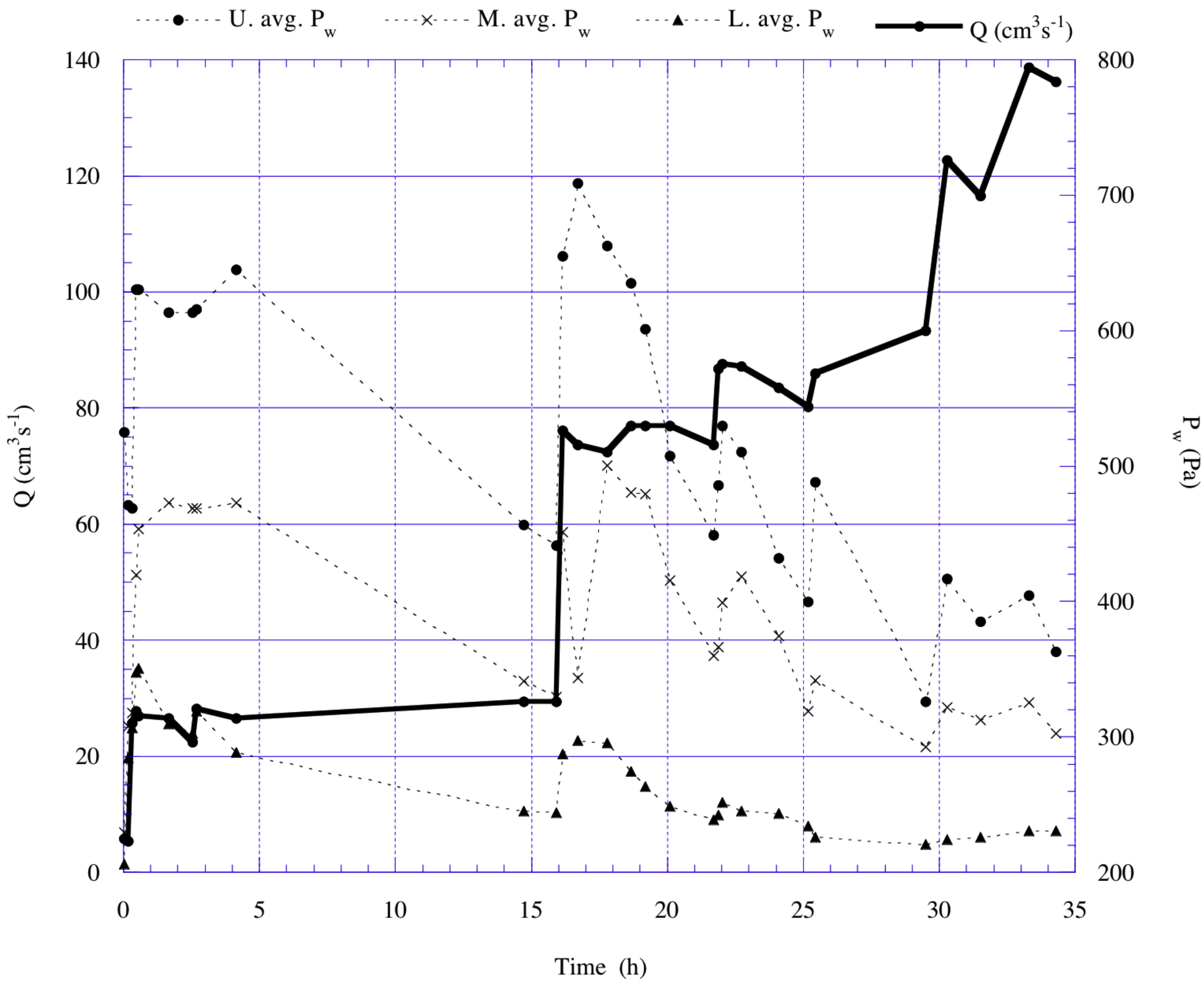
*Catania and Paola (2001)*

**Physical Model:** ice stream subglacial drainage

*Catania and Paola (2001)*

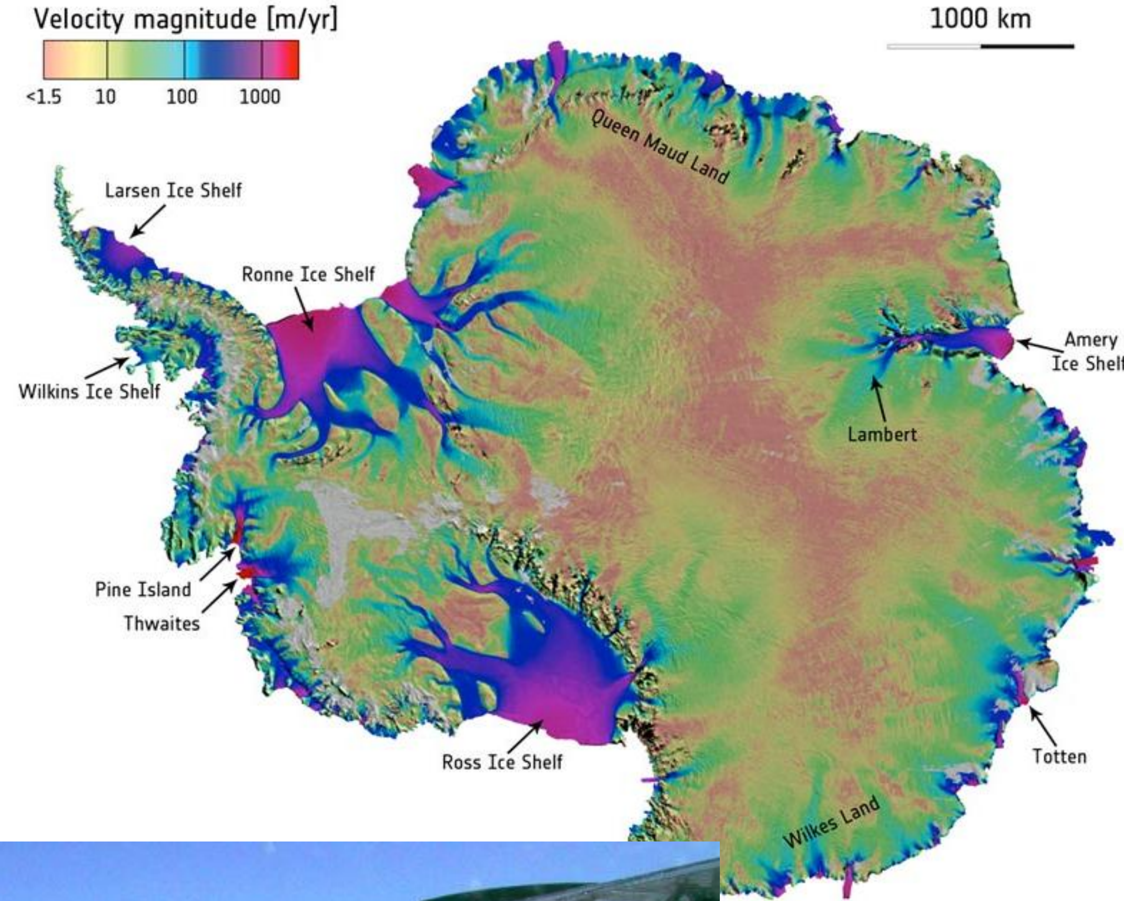
**Physical Model:** ice stream subglacial drainage

- increases in water flux cause increases in pressure in the system
- but, sediment erosion allows for drops in pressure over time; depend on sediment supply from upstream and erodibility of substrate to maintain high pressure




Catania and Paola (2001)

**Glacier Fundamentals:** ice streams




*Rignot et al., (2001)*

**Glacier Fundamentals:** ice stream force balance

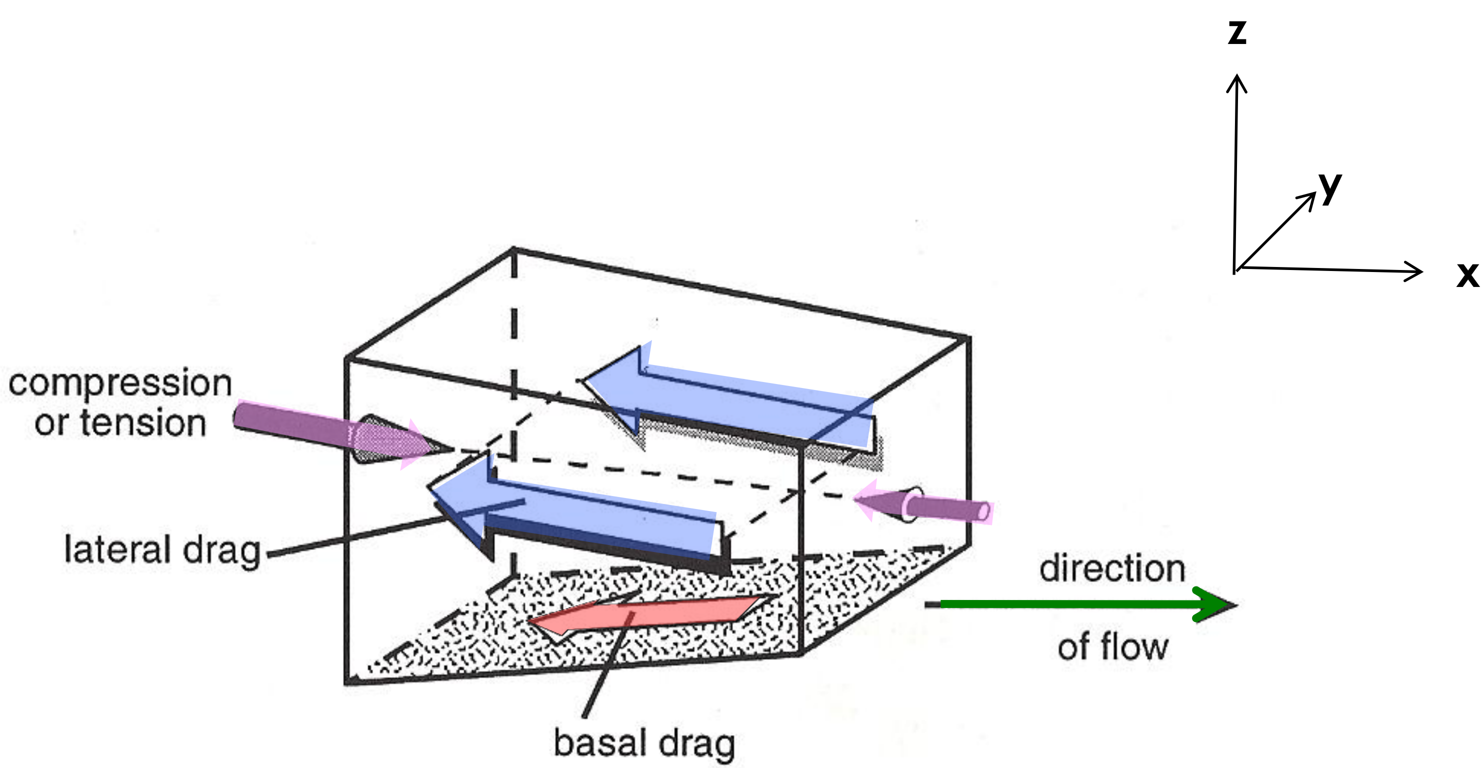
Gravitational Driving Stress

Basal Drag

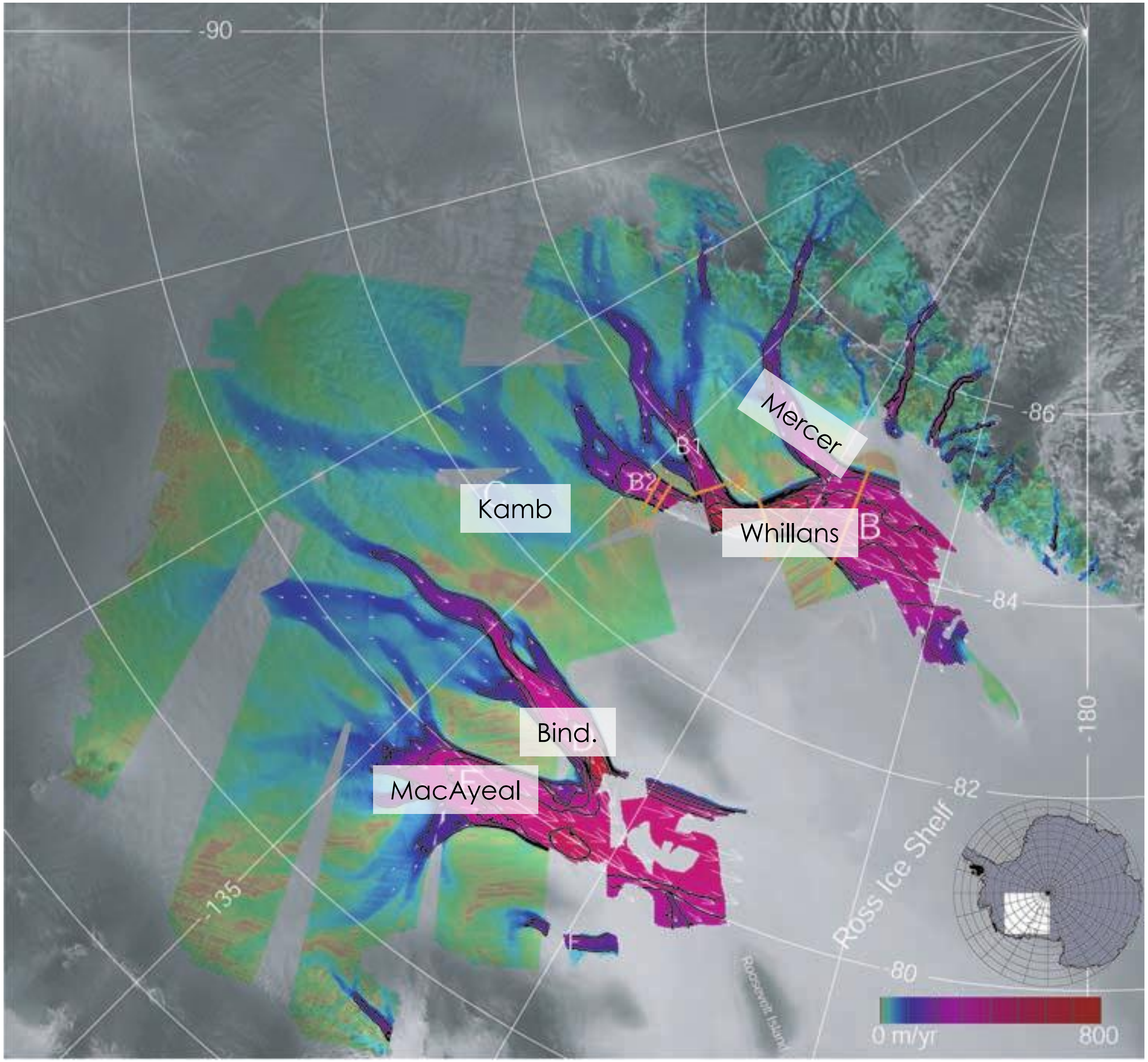
Compression Extension

Lateral Drag

$$\tau_{dx} = \tau_{bx} - \frac{\partial}{\partial x} H R_{xx} - \frac{\partial}{\partial y} H R_{xy}$$

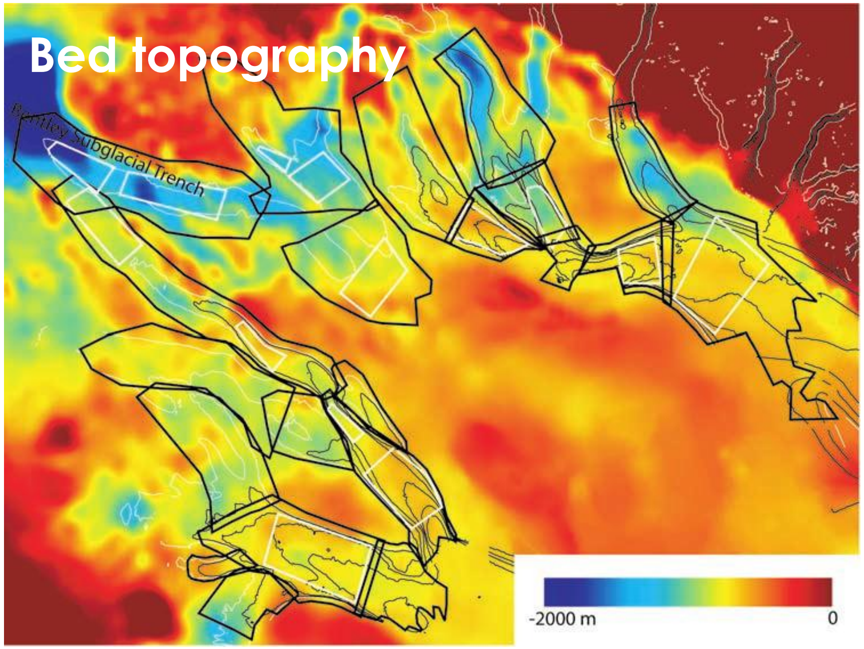


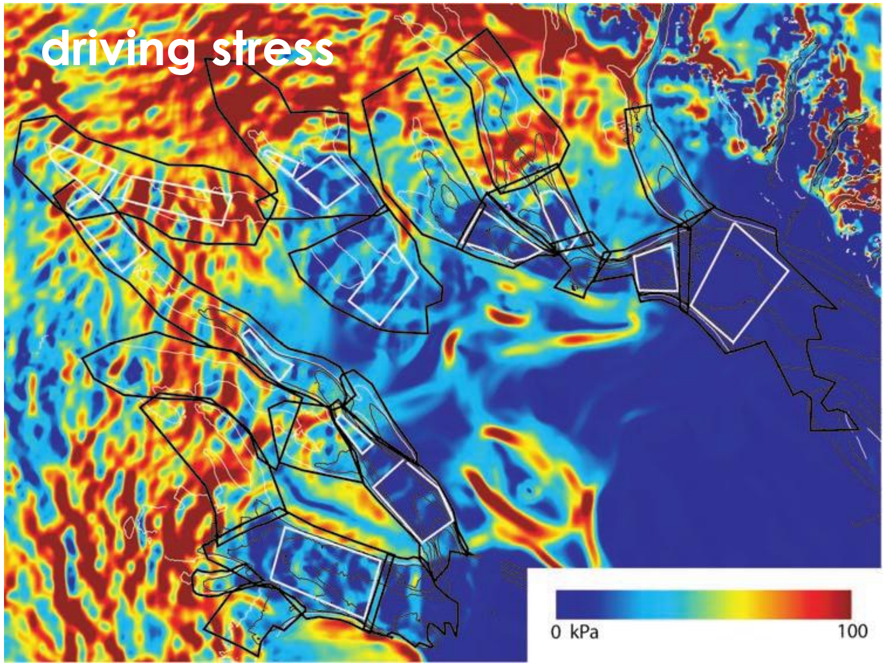
# **Glacier Fundamentals:** ice stream force balance




*Joughin et al., (2004)*

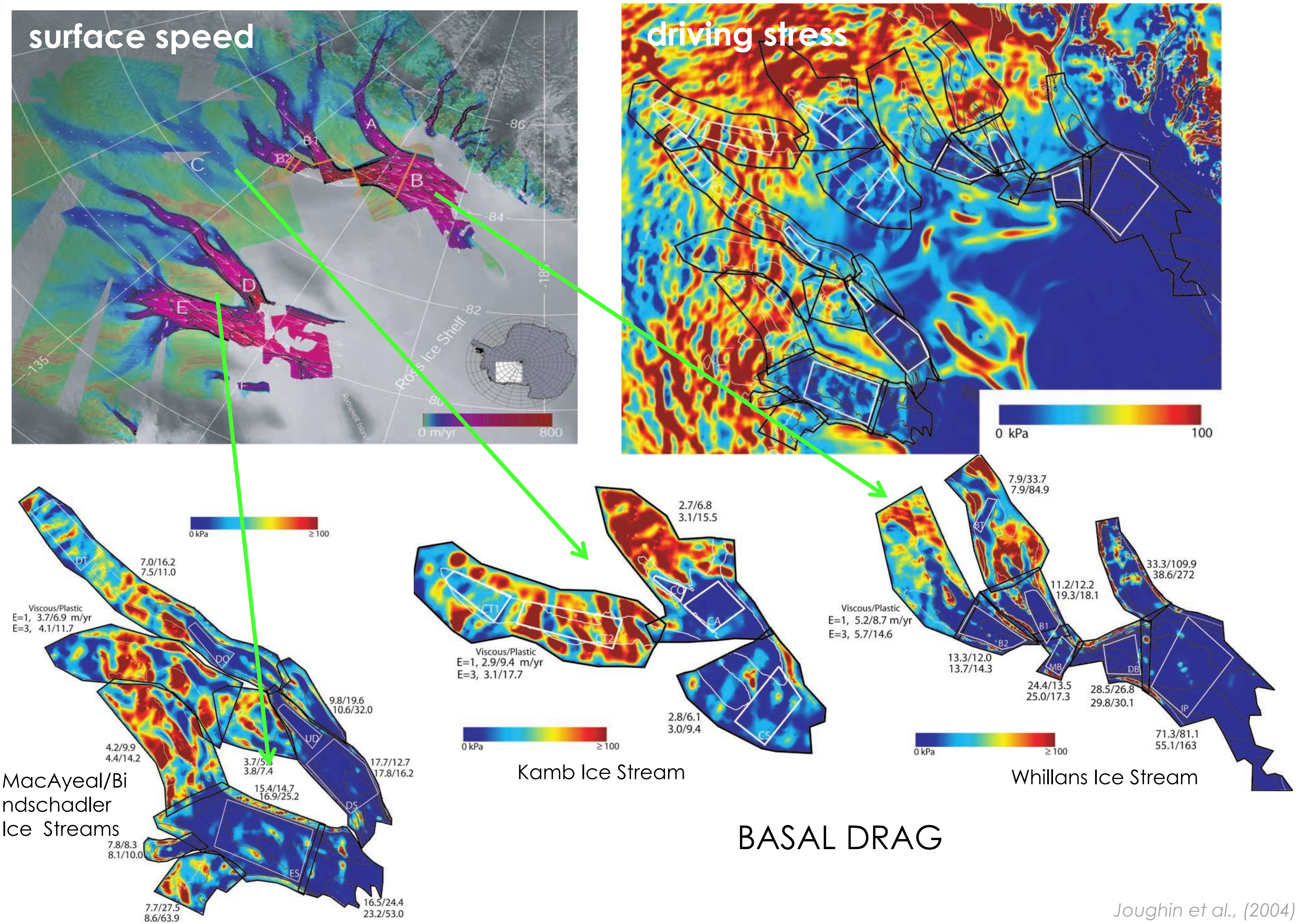
**Glacier Fundamentals:** ice stream force balance



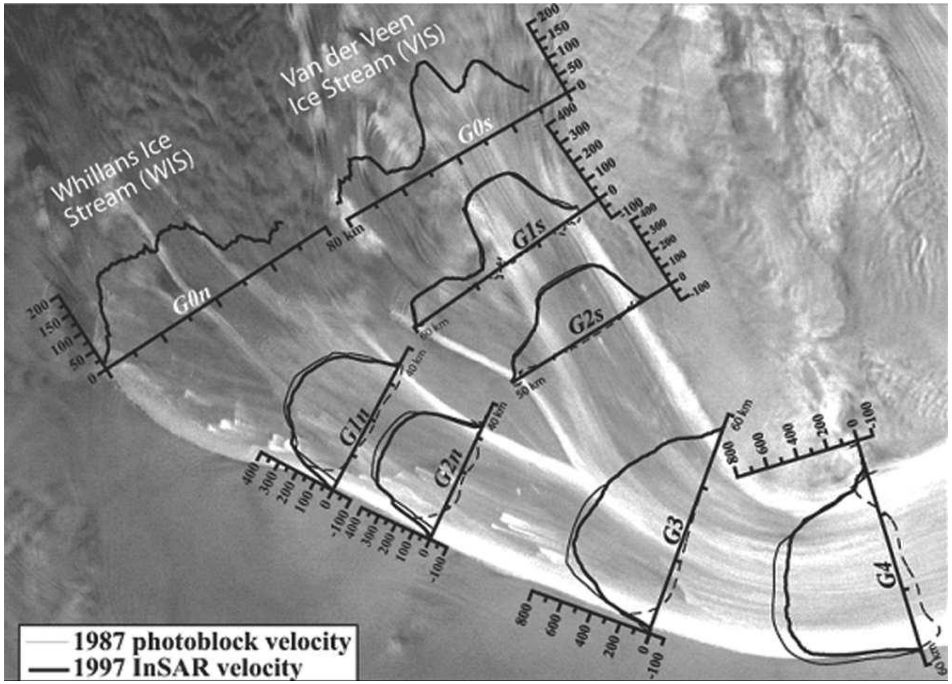

*Joughin et al., (2004)*

# **Glacier Fundamentals:** ice stream force balance




*Joughin et al., (2004)*

# **Glacier Fundamentals:** ice stream force balance




Basal Drag — Compression Extension (0) — Lateral Drag

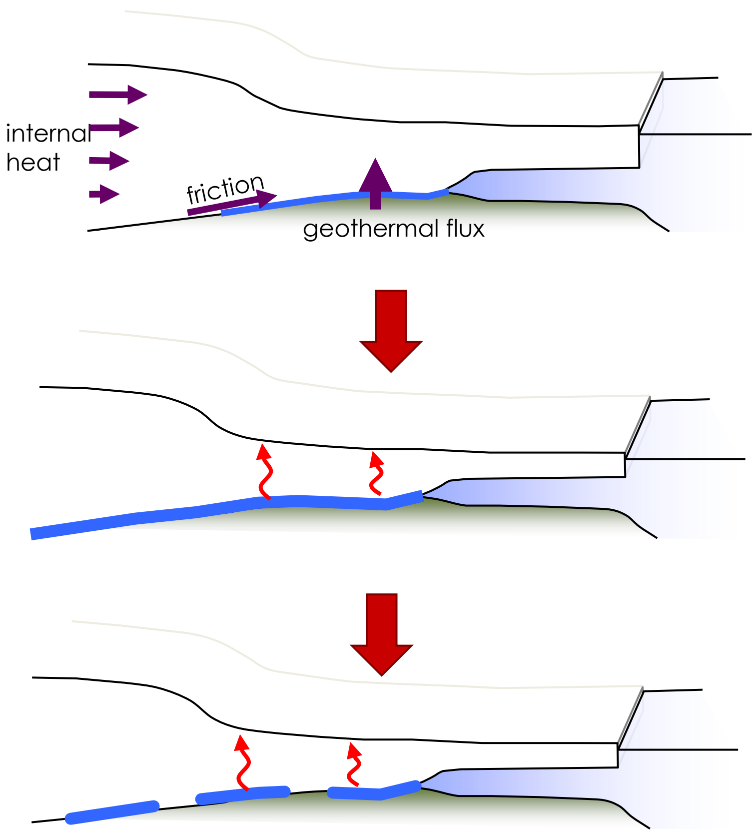
$$\tau_{dx} = \tau_{bx} - \frac{\partial}{\partial x} H R_{xx} - \frac{\partial}{\partial y} H R_{xy}$$

| Transect | Driving stress kPa | percent supported by sides in 1987 | lateral drag $\tau_w$ 1997 kPa | percent supported by sides in 1997 | basal drag $\tau_{bx}$ 1997 kPa |
|---|---|---|---|---|---|
| G0n–G1n | $13.3 \pm 1.1$ | | $7.1 \pm 0.9$ | **~53%** | $6.2 \pm 1.4$ |
| G1n–G3n | $13.1 \pm 1.0$ | **~100%** | $11.8 \pm 2.1$ | **~90%** | $1.3 \pm 2.3$ |
| G3–G4 | $11.7 \pm 0.9$ | **~68%** | $7.2 \pm 0.9$ | **~61%** | $4.5 \pm 1.3$ |

**over time more of the driving stress is supported by bed**

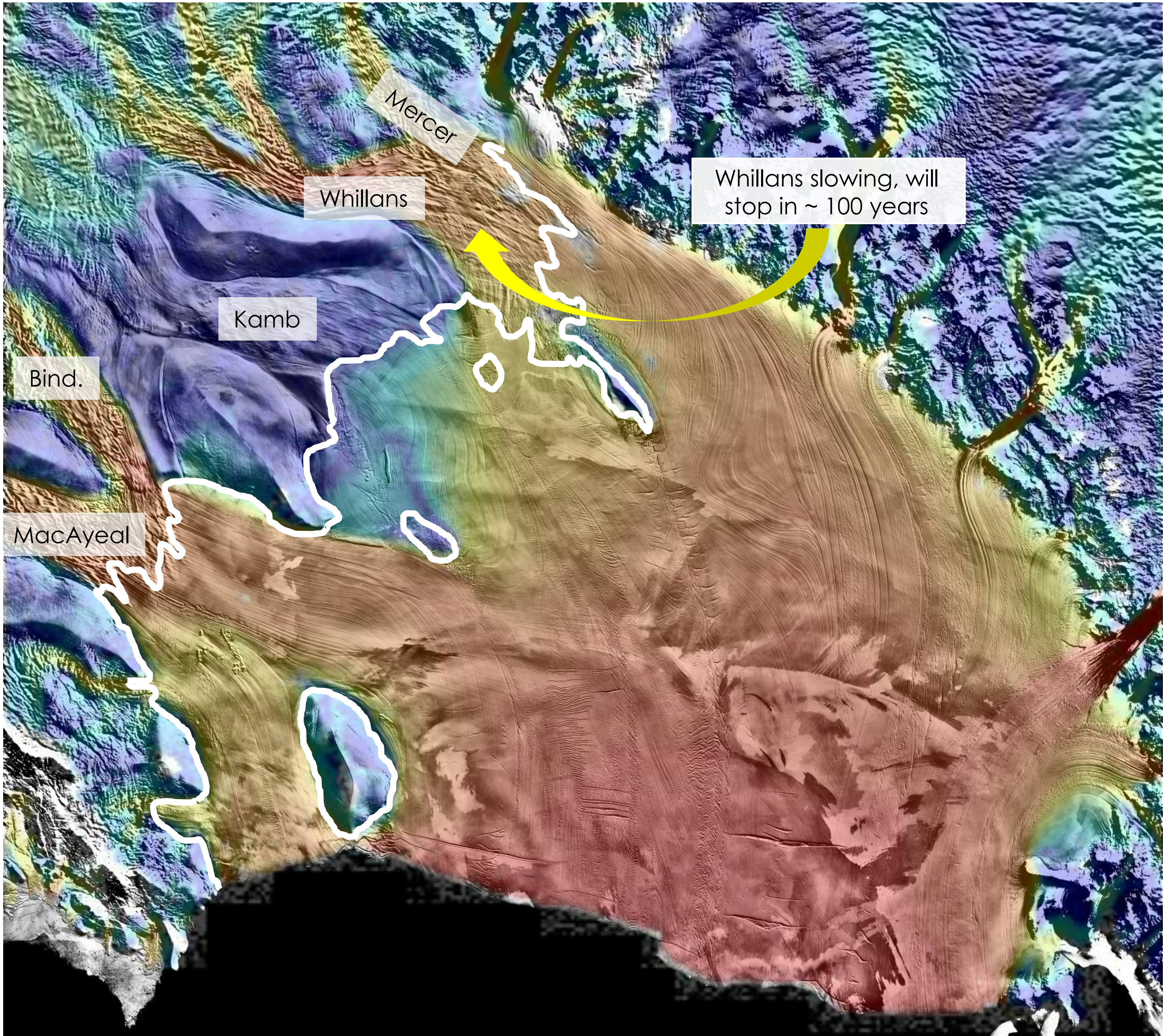
*Stearns et al. (2005)*

# **Glacier Fundamentals:** ice stream force balance

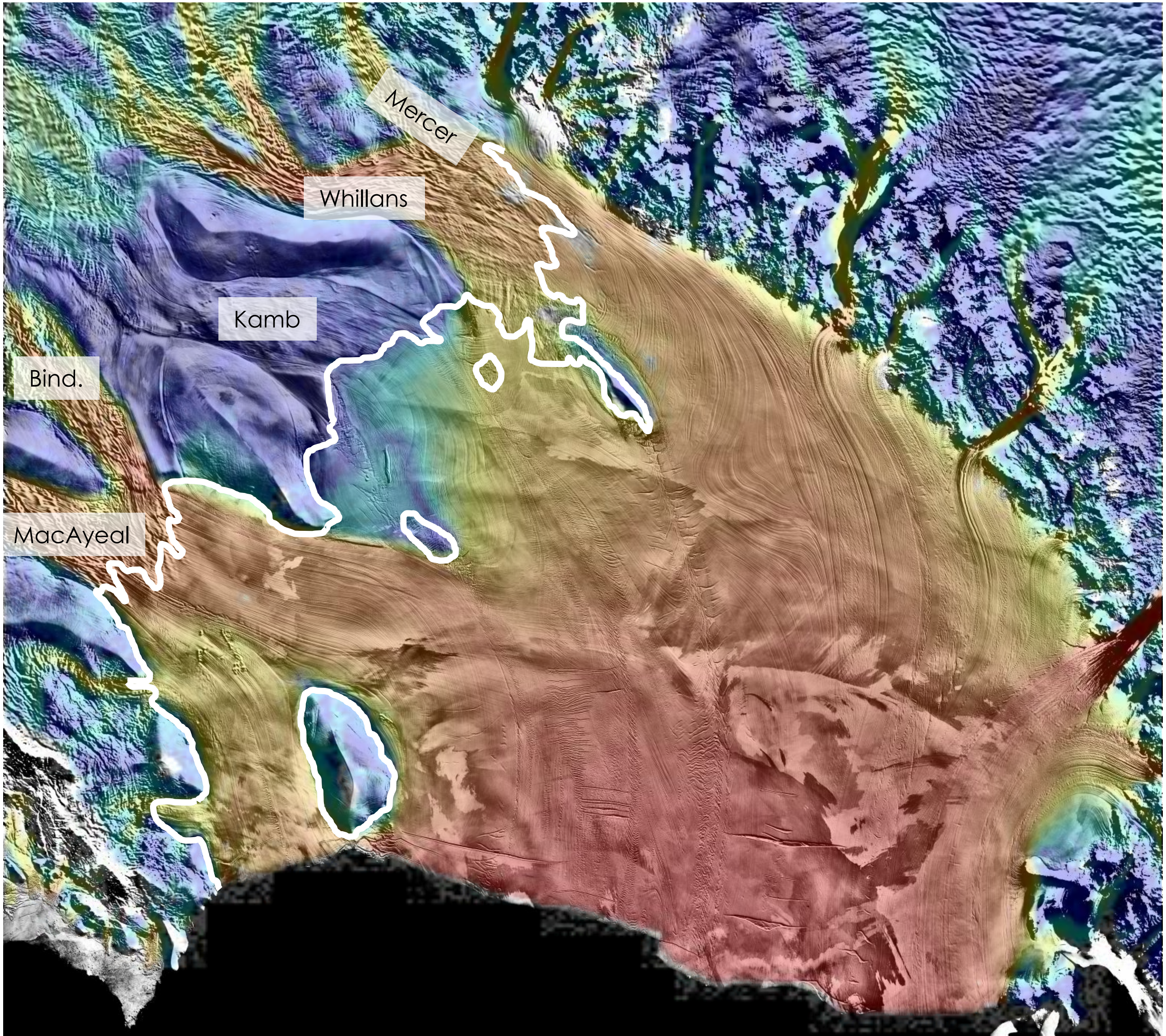



- thick ice/subglacial volcanism systems provide basal lubrication that permit fast flow
- fast flow leads to thinning, which steepens the internal temperature gradient causes freezing at the basal interface
- lubrication is removed or reduced, ice stream eventually stops

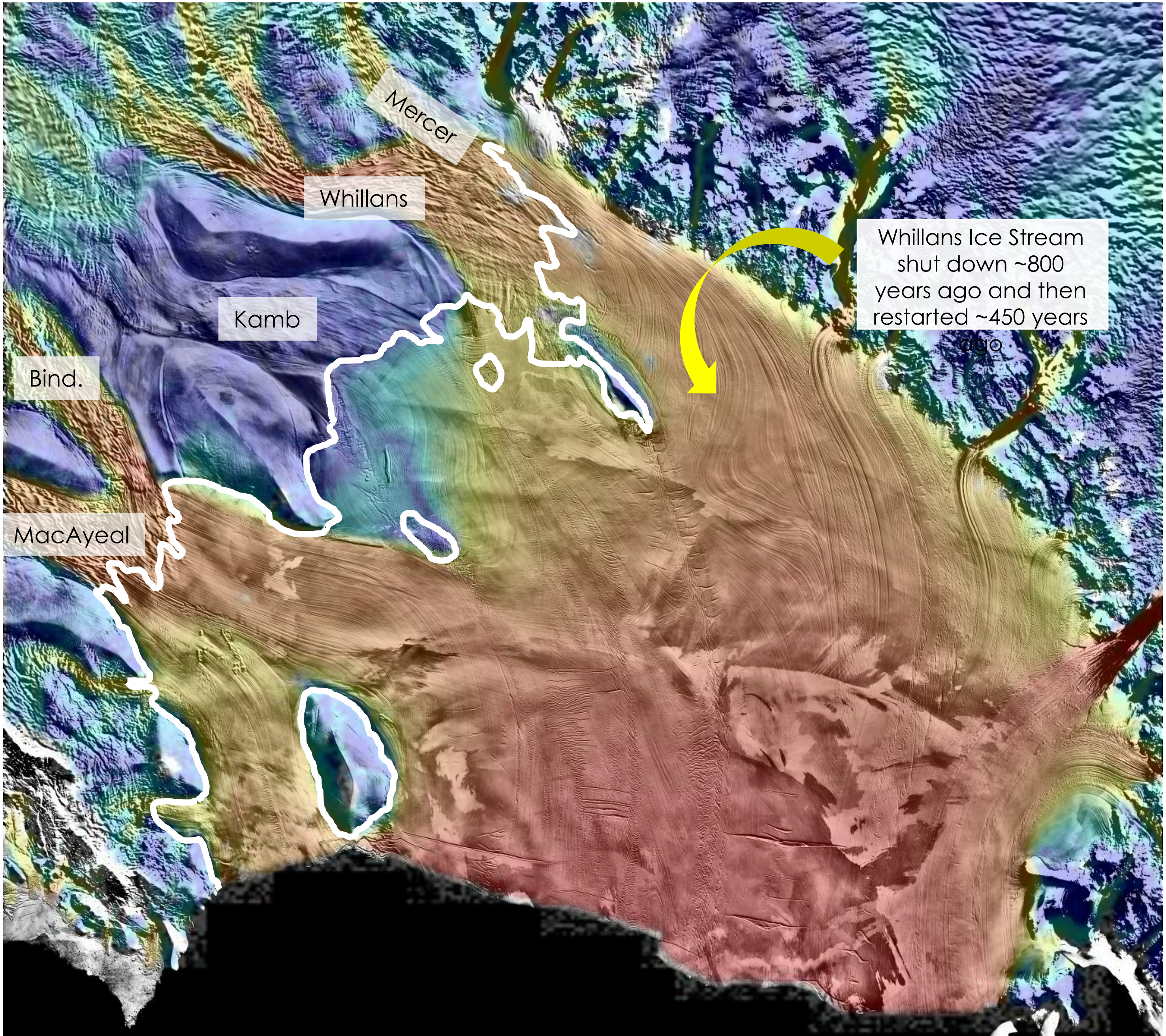
# **Glacier Fundamentals:** ice stream variability



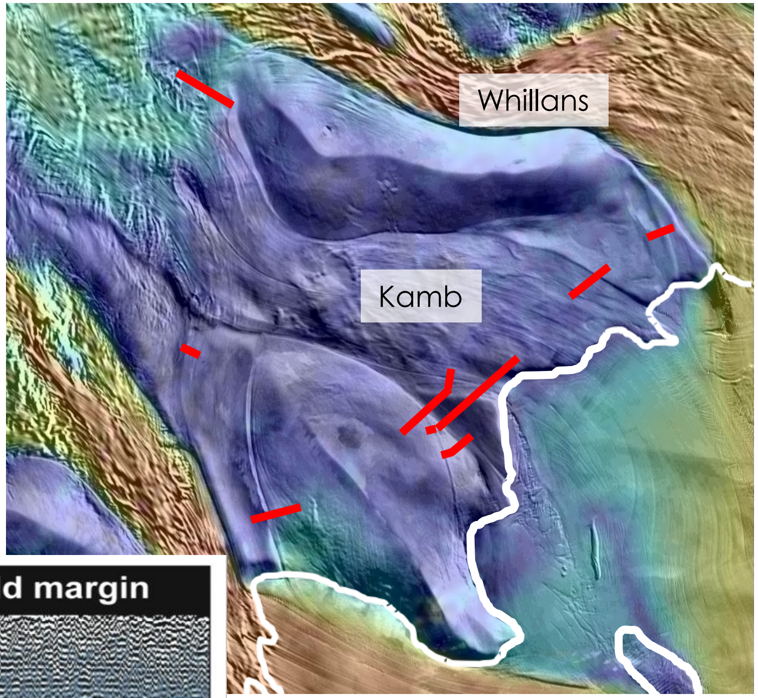
**Glacier Fundamentals:** ice stream variability



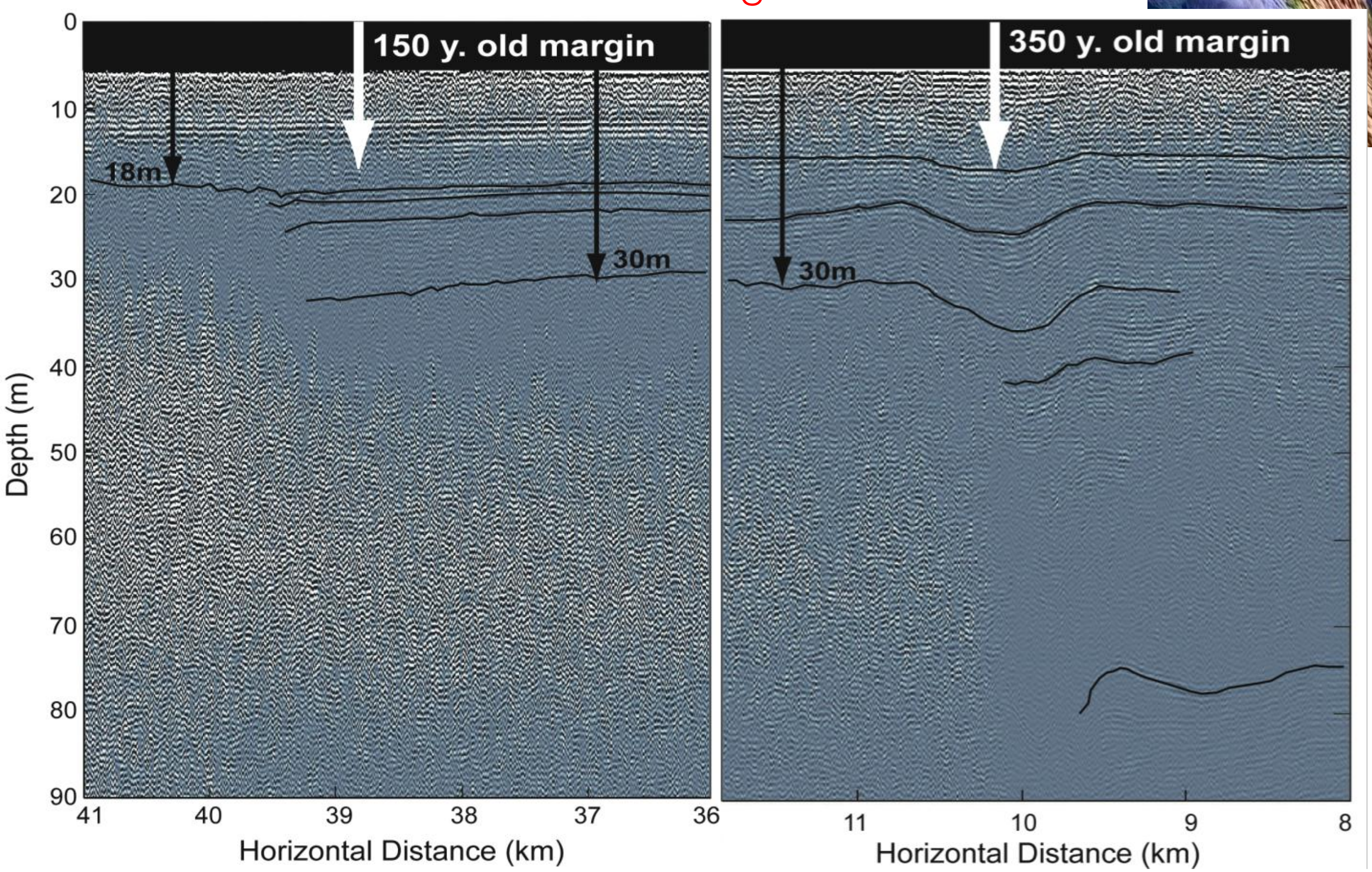
**Glacier Fundamentals:** ice stream variability



# **Glacier Fundamentals:** ice stream variability

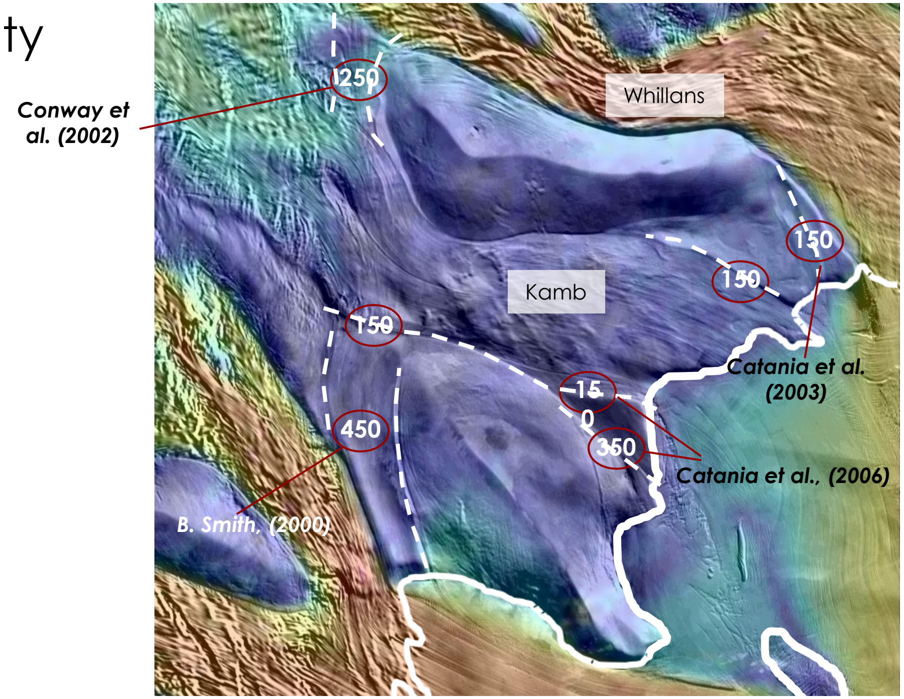



Relict Shear Margins



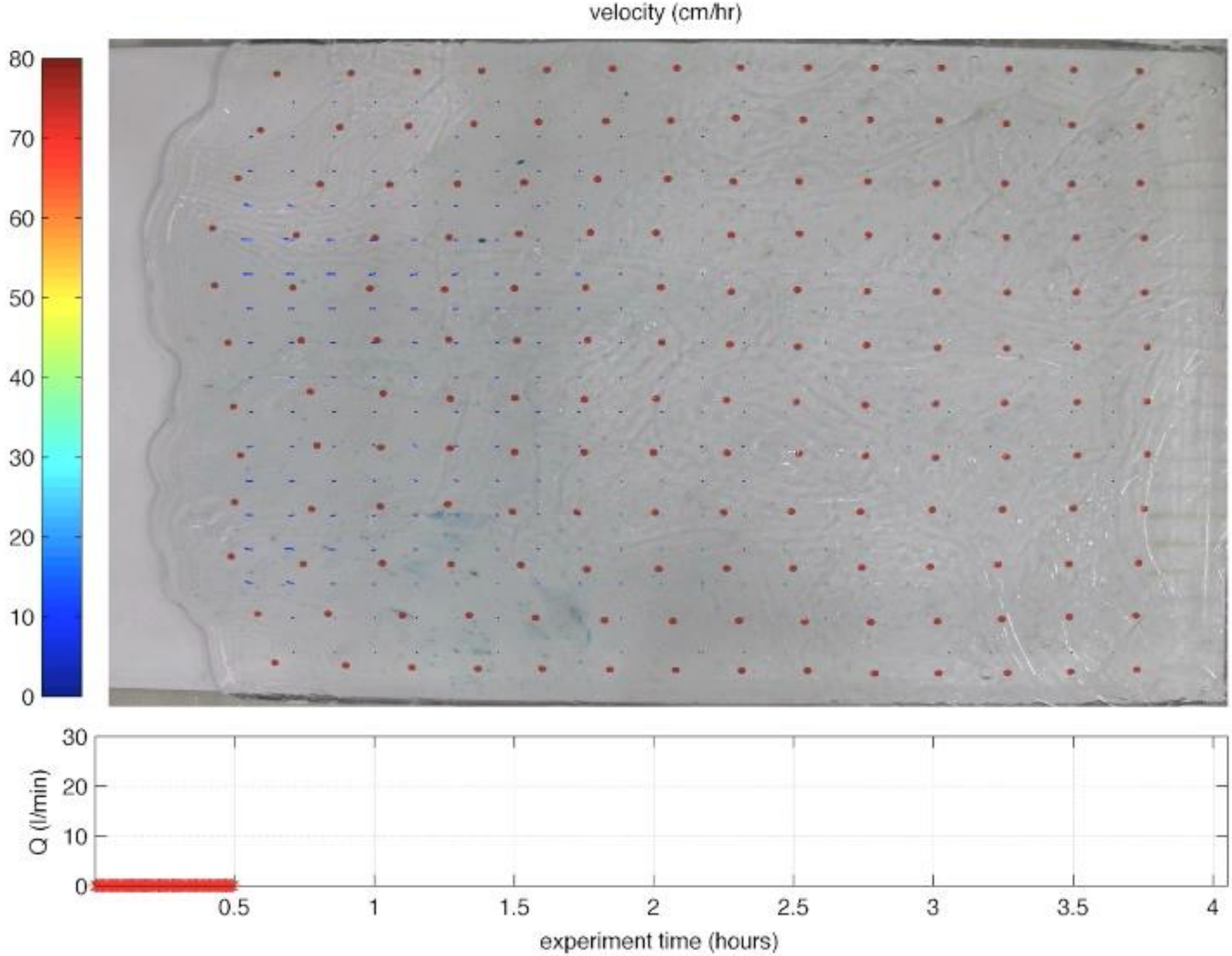

*Catania et al., (2006)*

# **Glacier Fundamentals:** ice stream variability

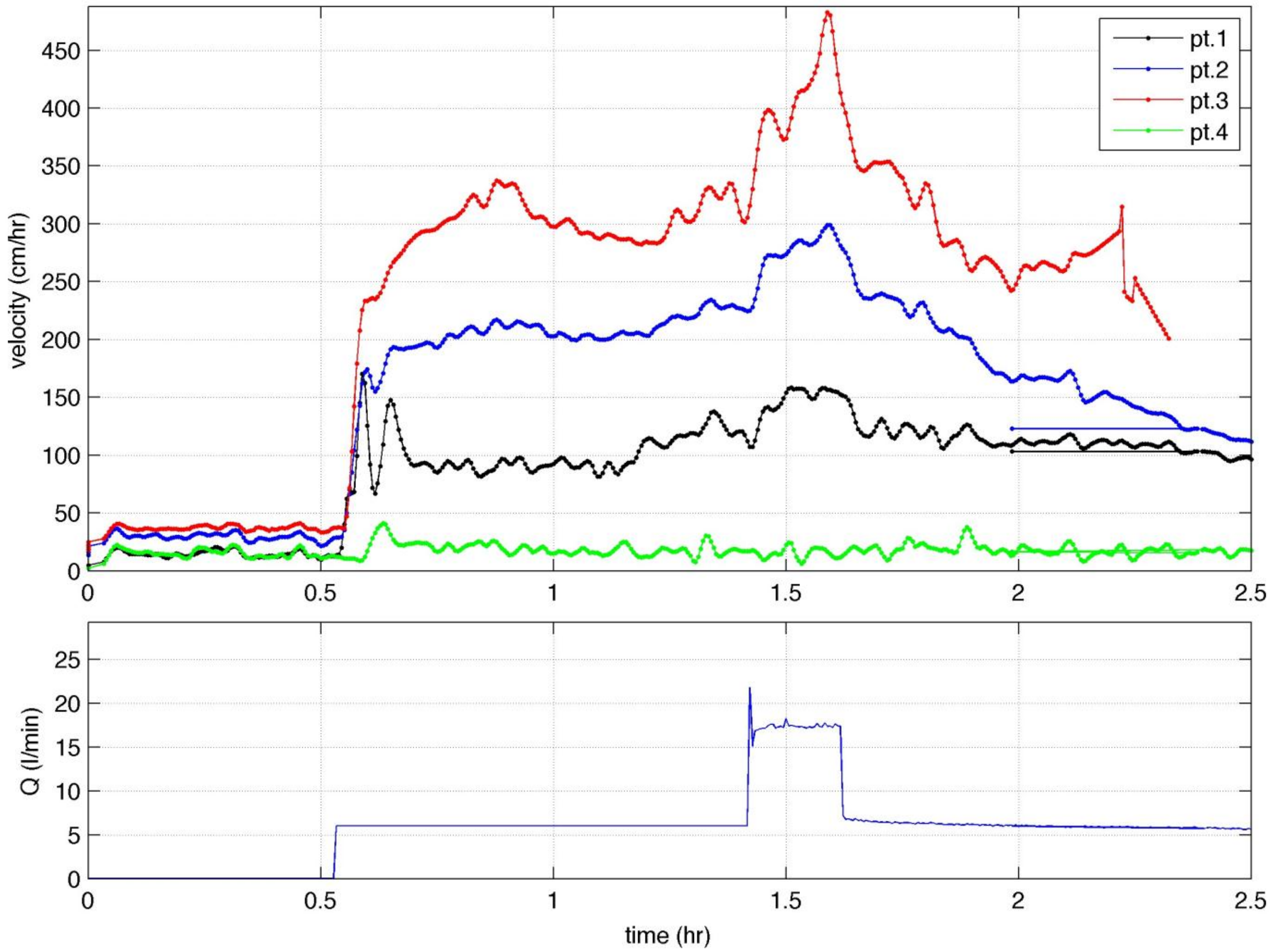


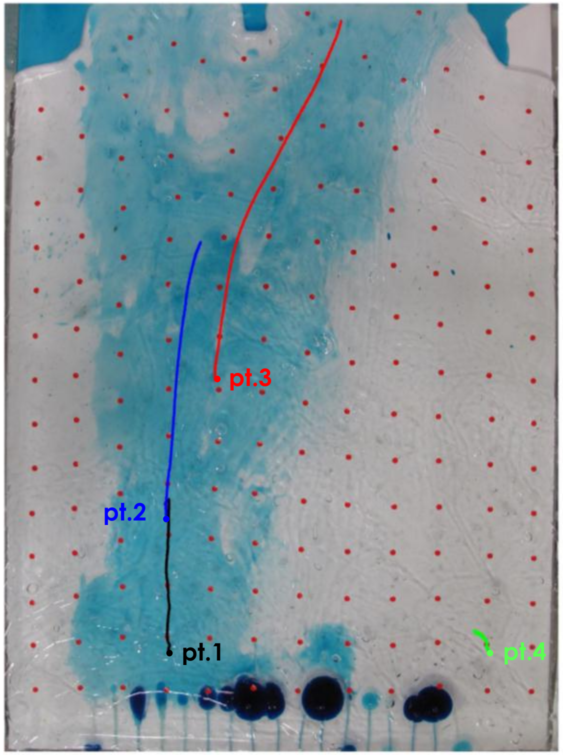

- ice stream system underwent numerous changes in configuration over time

**Physical Model:** ice stream flow variability



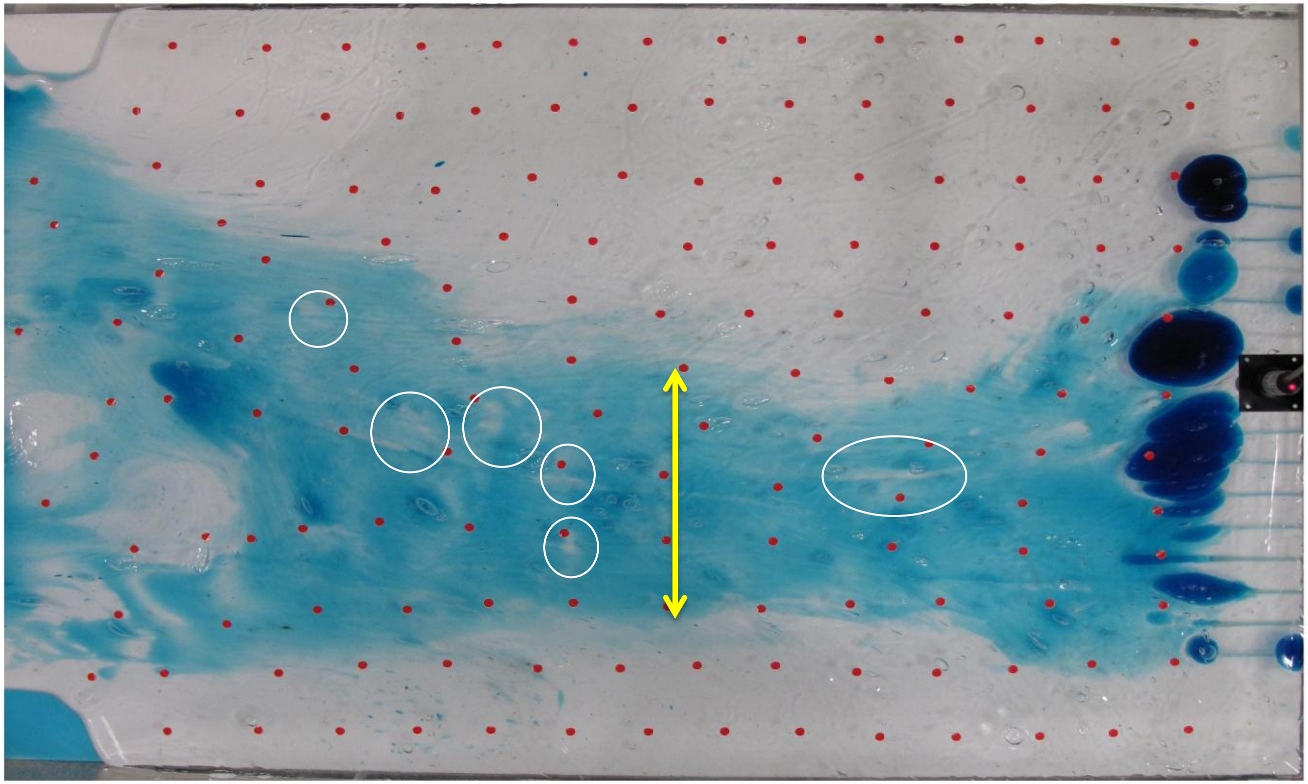
# **Physical Model:** ice stream flow variability

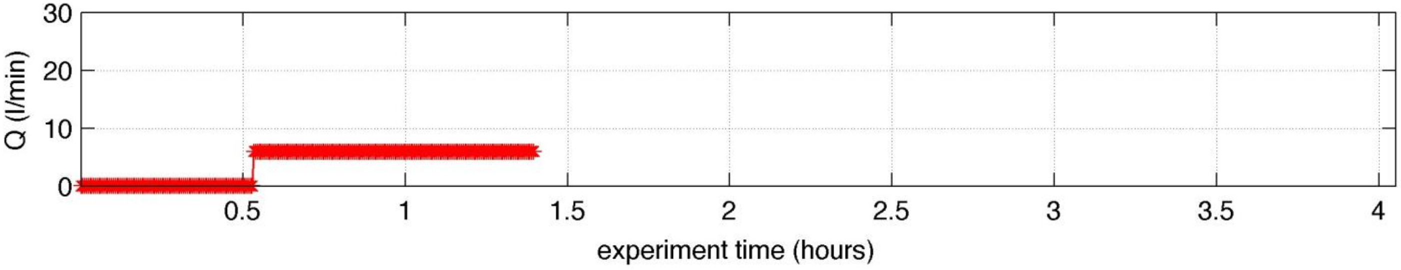


# **Physical Model:** ice stream flow variability

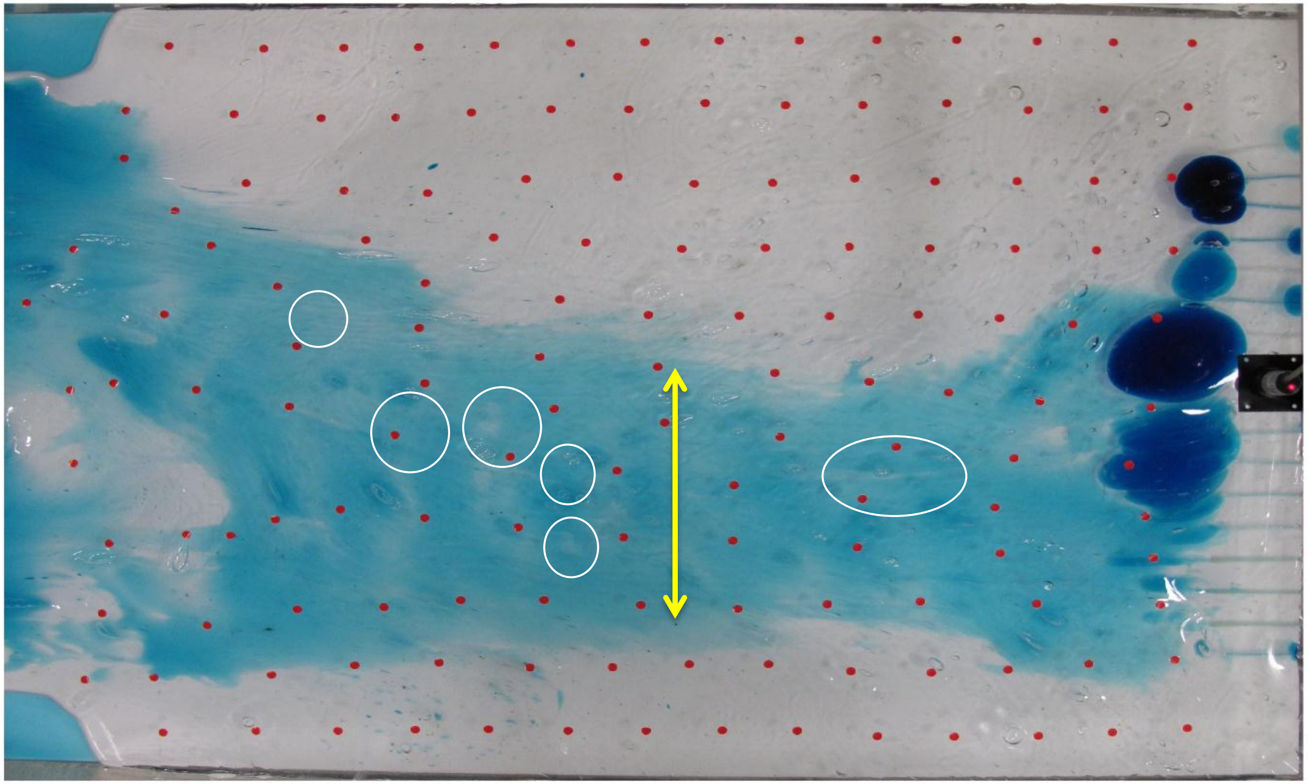
- lighter-coloured areas have a thinner (or absent) water layer due to variations in polymer thickness
- thinner water layer may increase drag of the polymer locally

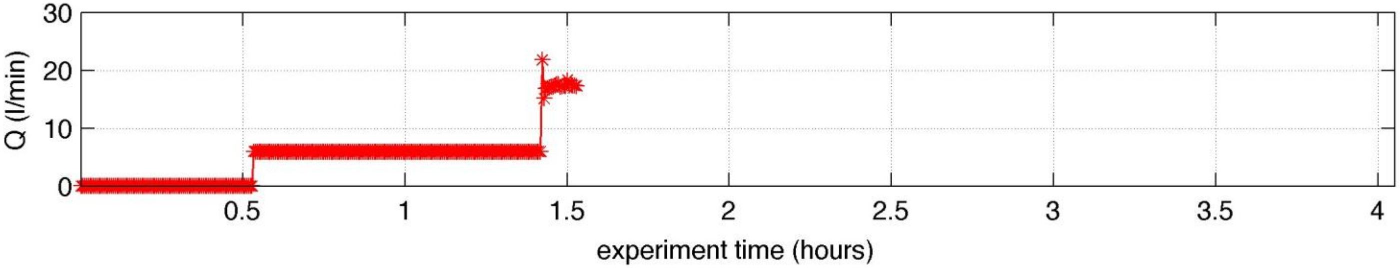




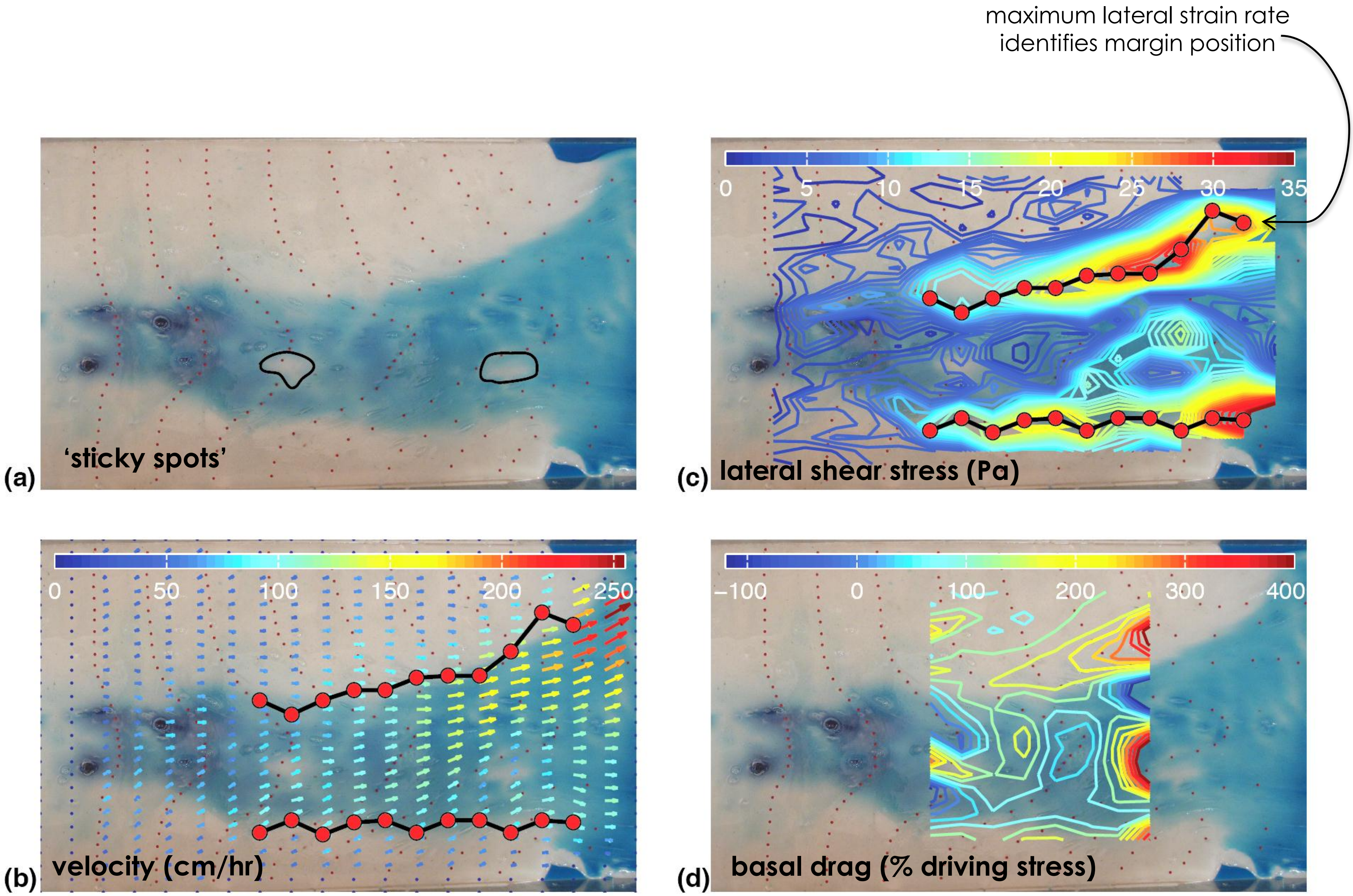
# **Physical Model:** ice stream flow variability

- increases in water discharge cause uplift that “drowns out” regions where polymer was dragging on bed
- increased water discharge causes greater wetted area (reduces lateral drag)





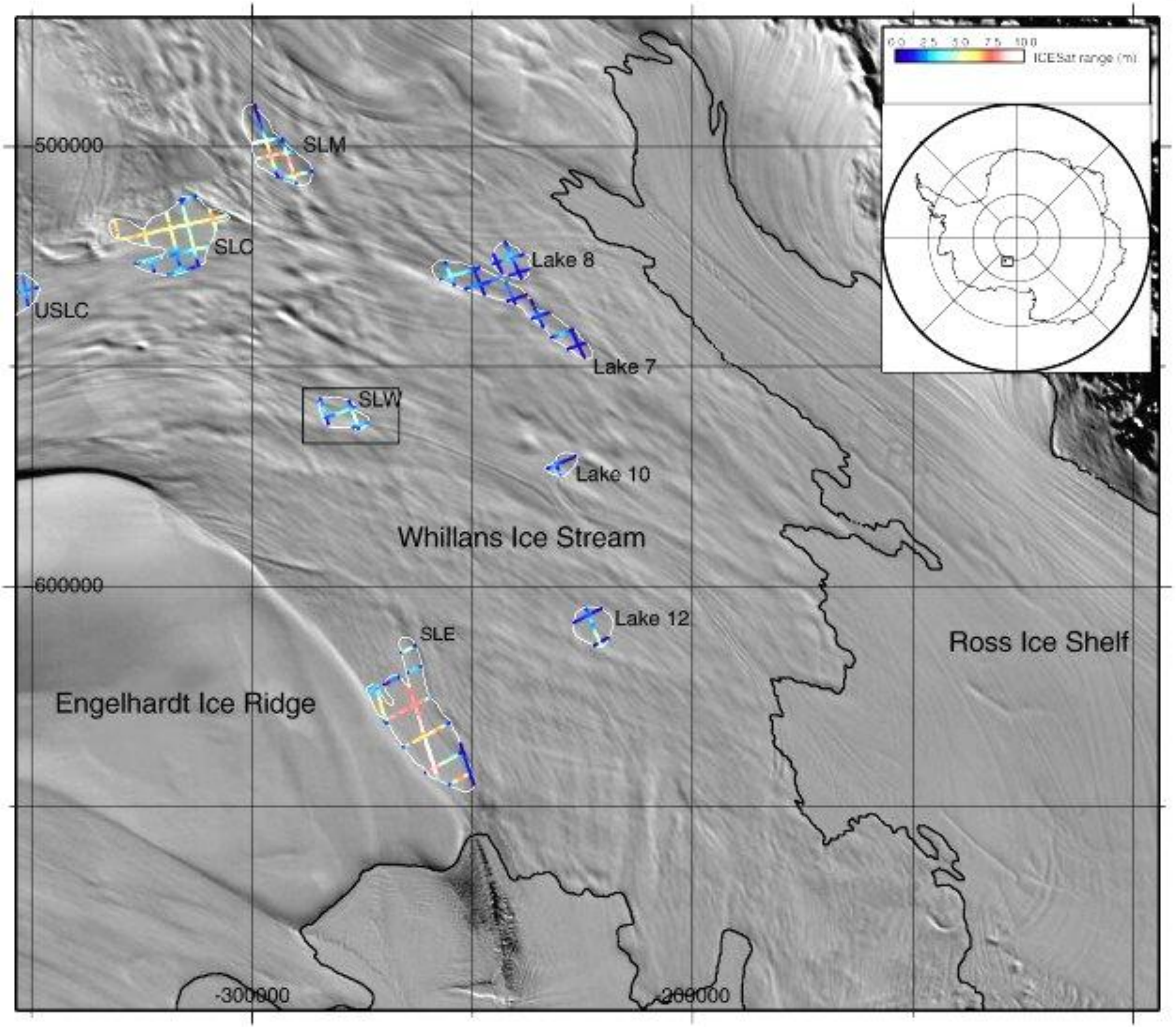
# **Physical Model:** ice stream flow variability

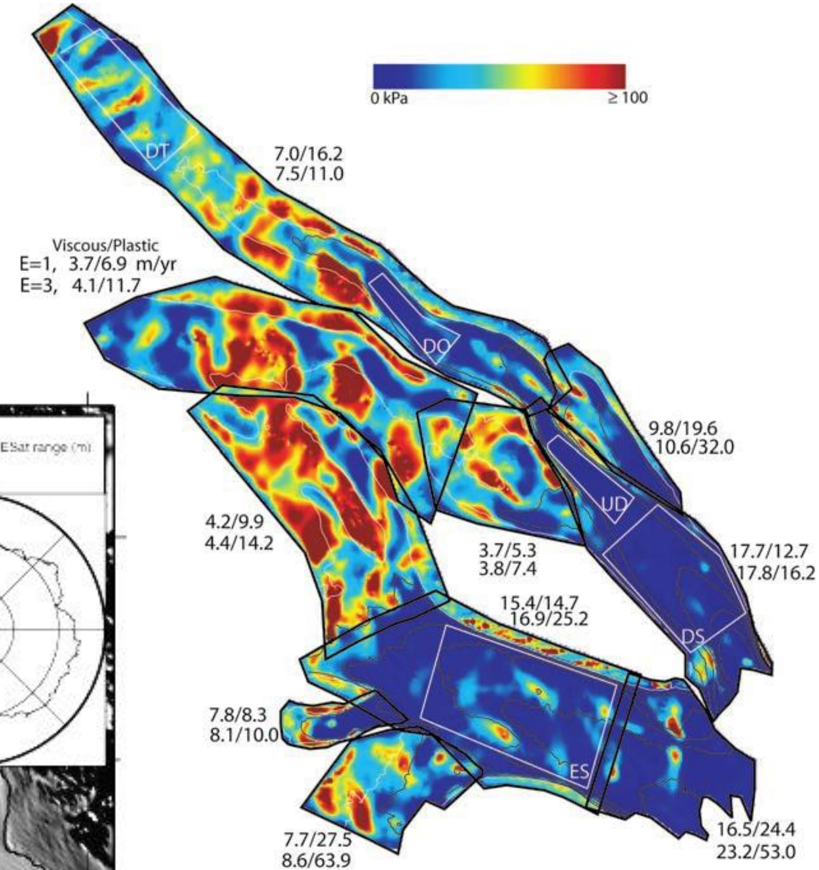



Wagman & Catania (2013)

# **Antarctica:** Ice Stream Variability

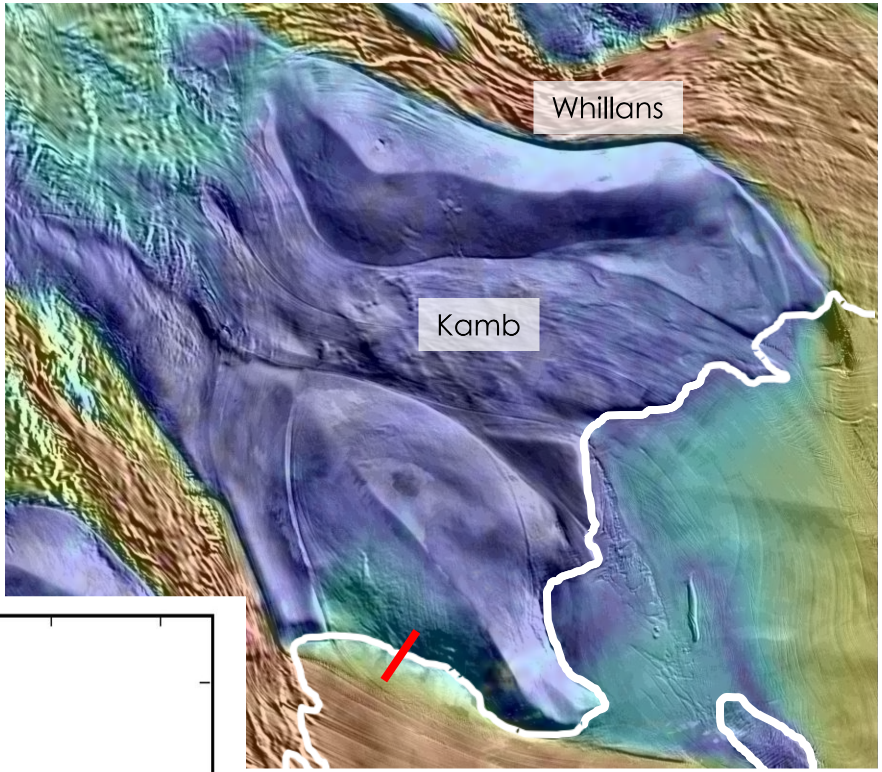
- suggest that some shifts in margin position might result from long-lived sticky spots
- conversely, persistent stationary margins might result from subglacial lakes in close proximity

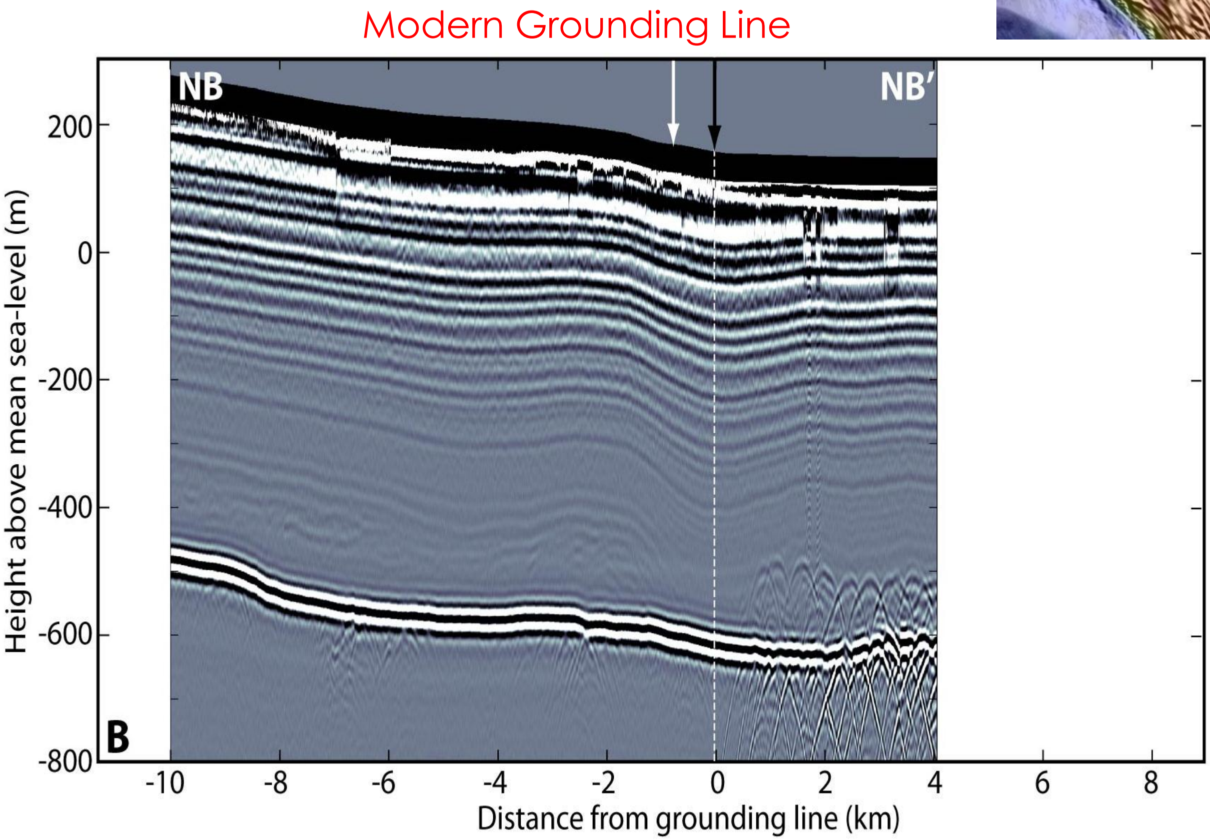



*Joughin et al., (2004); Fricker et al., (2009)*

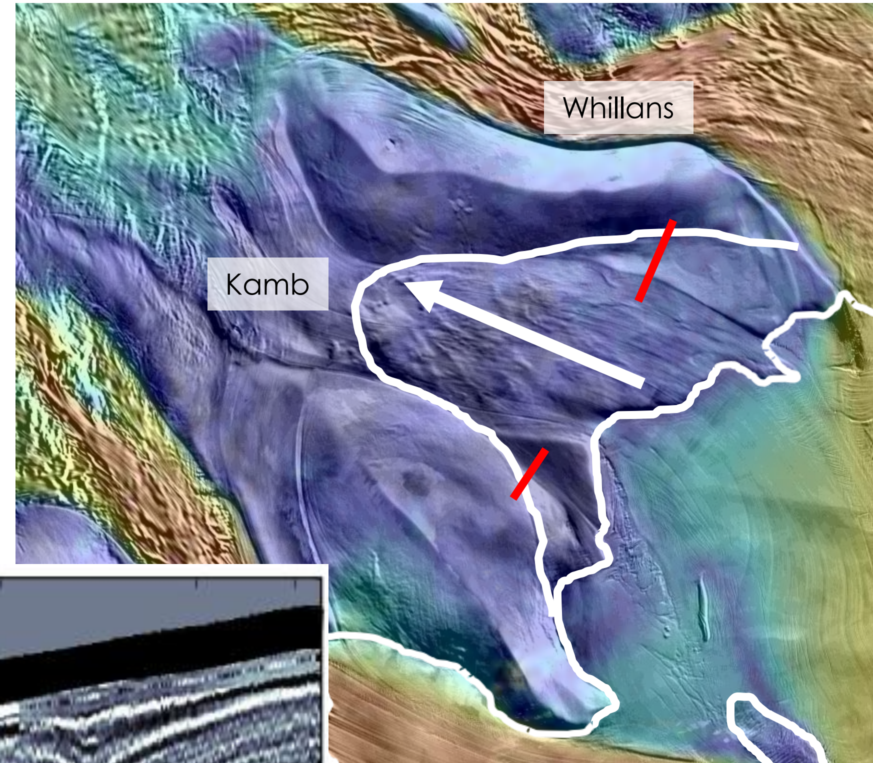
**Glacier Fundamentals:** grounding lines

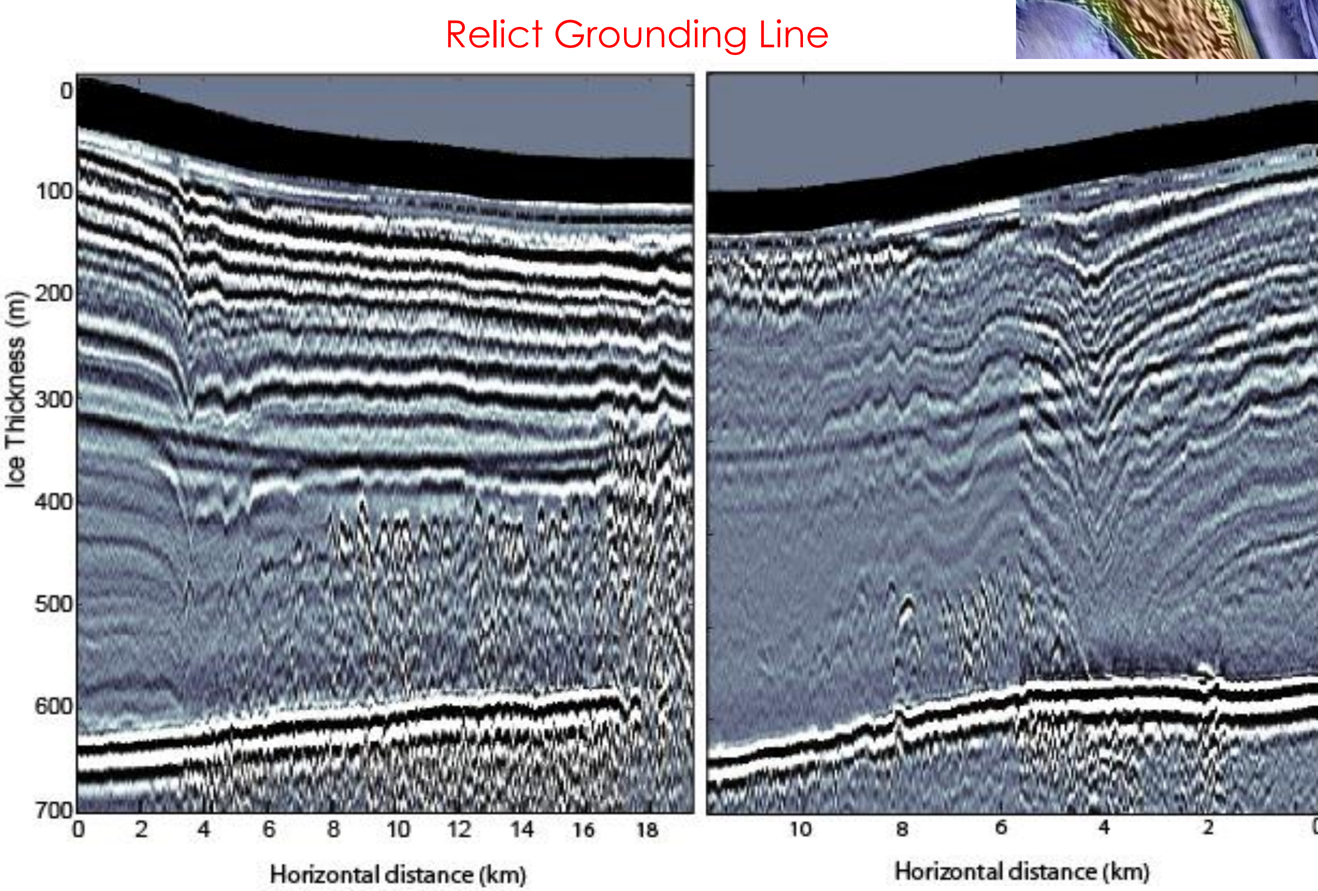



*Catania et al., (2010)*

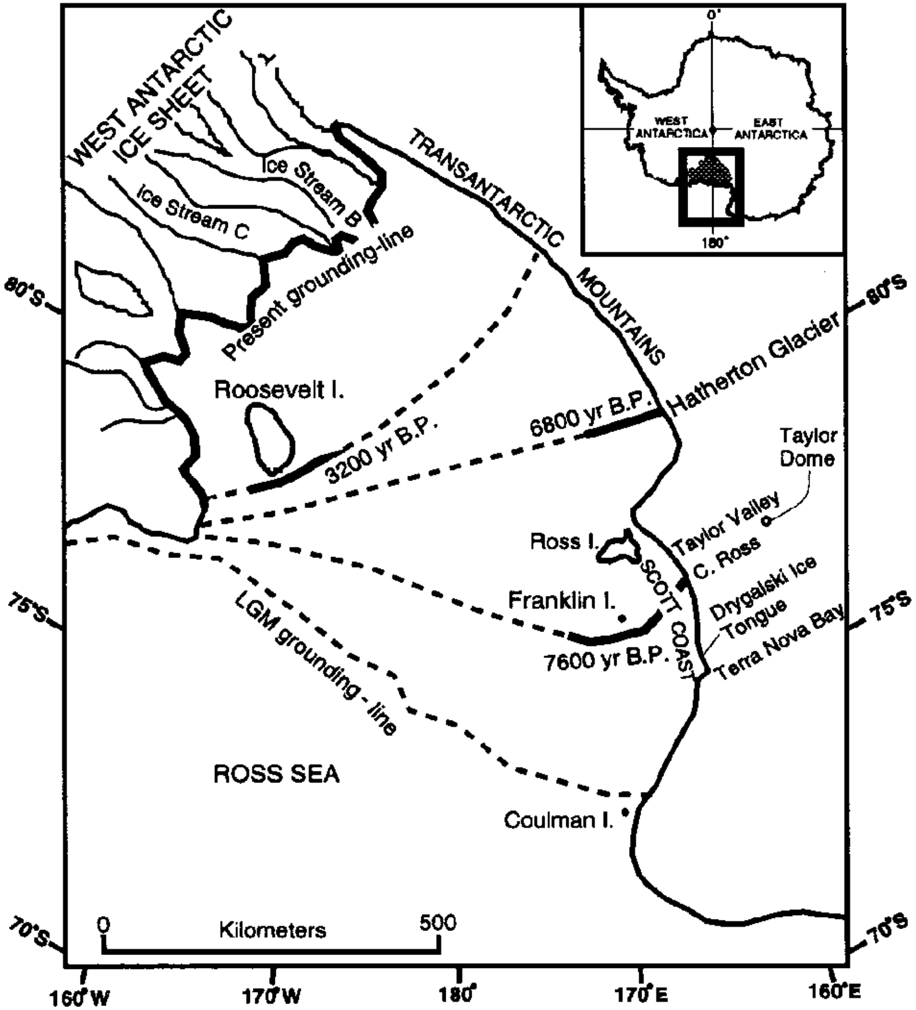
# **Glacier Fundamentals:** grounding lines

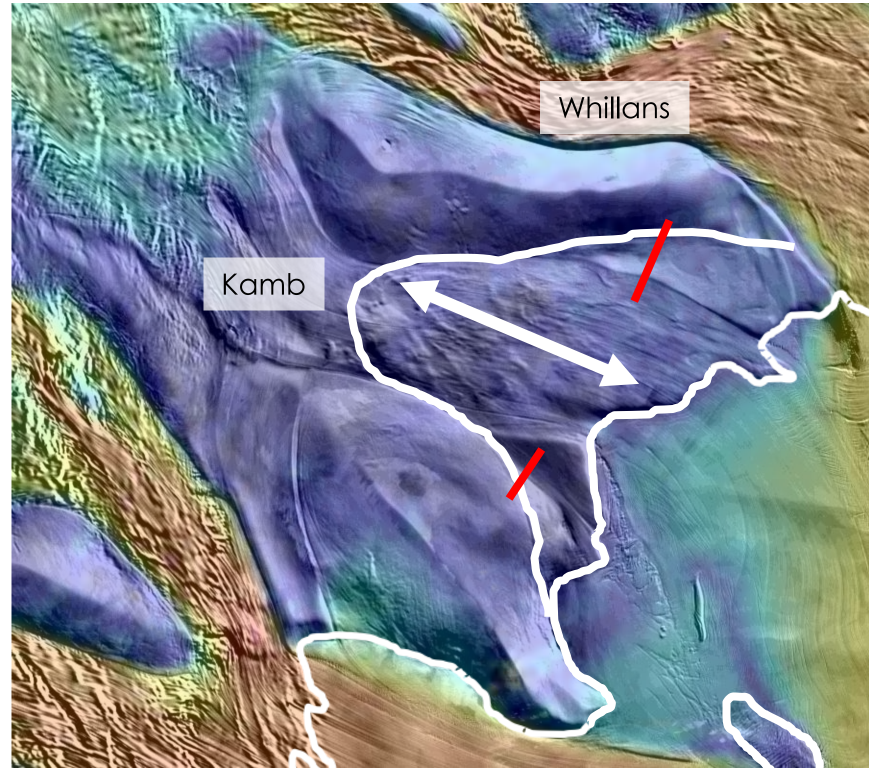



*Catania et al., (2010)*

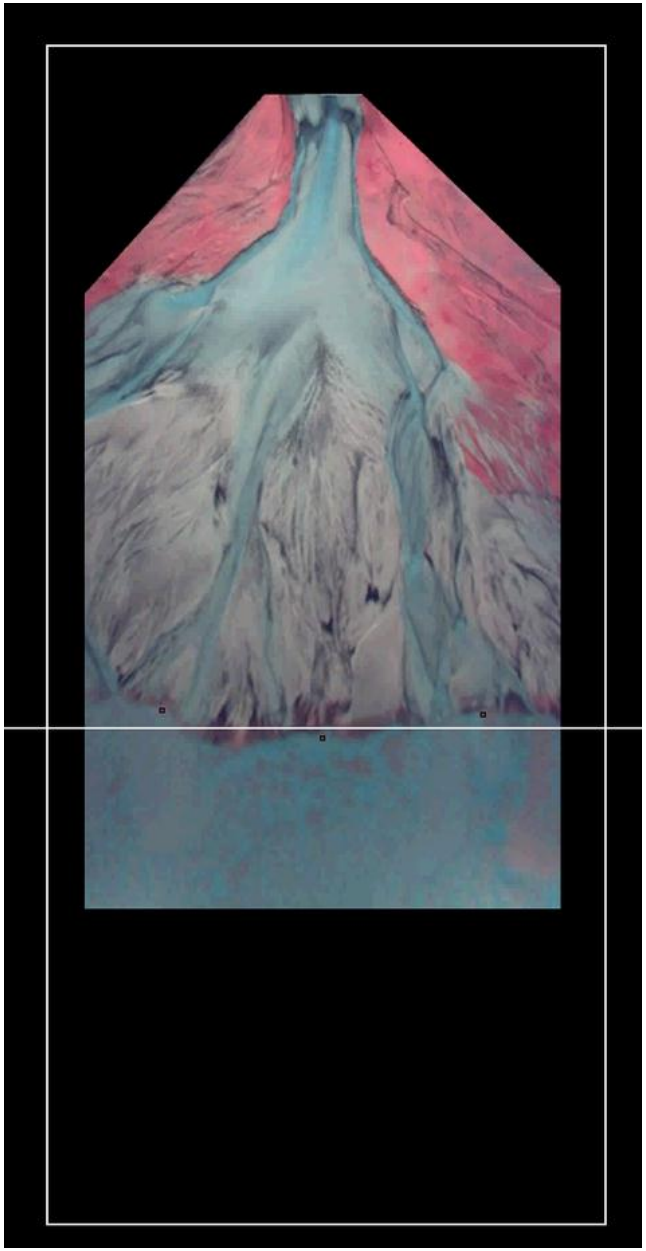
# **Glacier Fundamentals:** grounding lines




Conway et al., (1999)

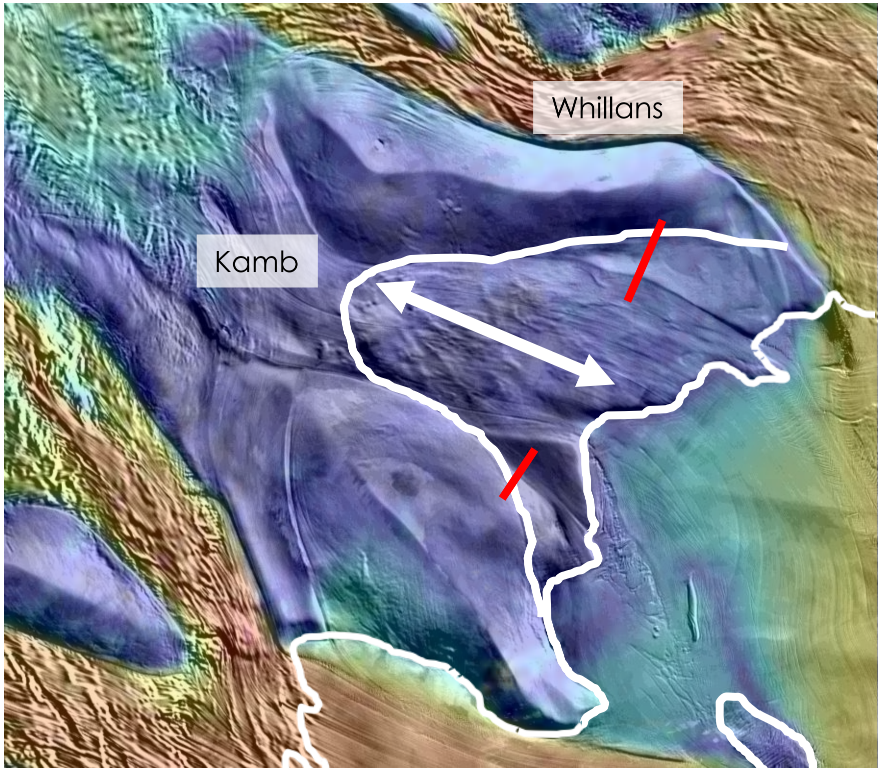
# **Physical Model:** grounding lines



Kim and others (2006)

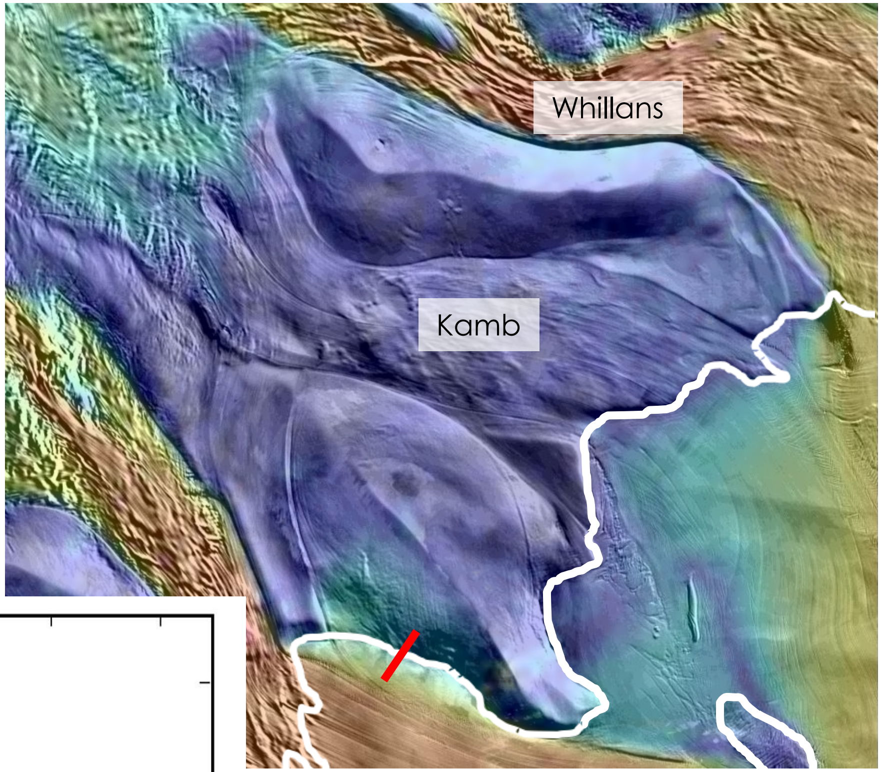
## Variability in Grounding Line

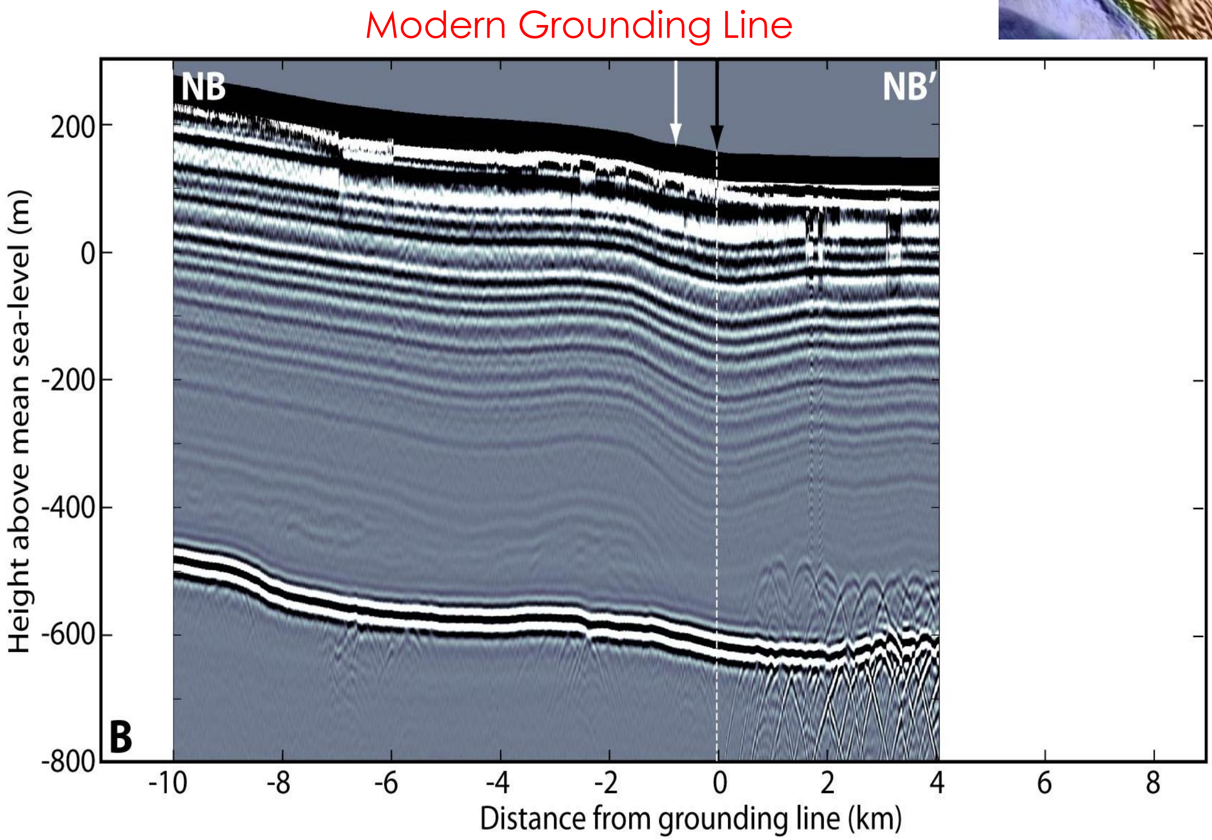
- look to other disciplines where internal variability occurs over **much faster time scales**
- sea-level changes work for/against ice thickness changes and can amplify/diminish changes in the grounding line
- more variability in the grounding line might be expected during periods of sea-level rise




Catania et al., (2012)

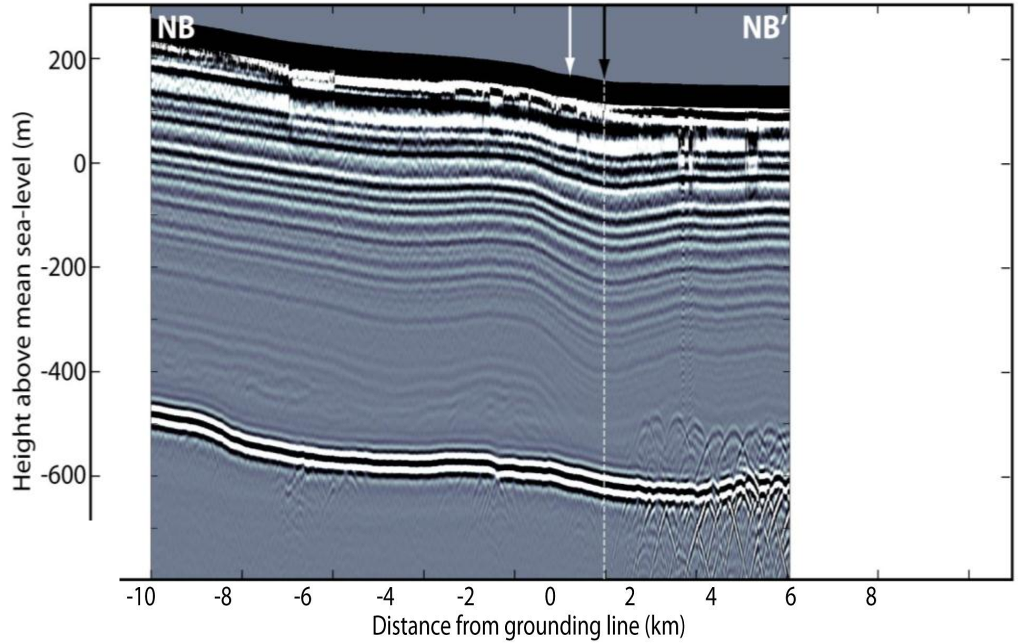
# **Glacier Fundamentals:** grounding lines

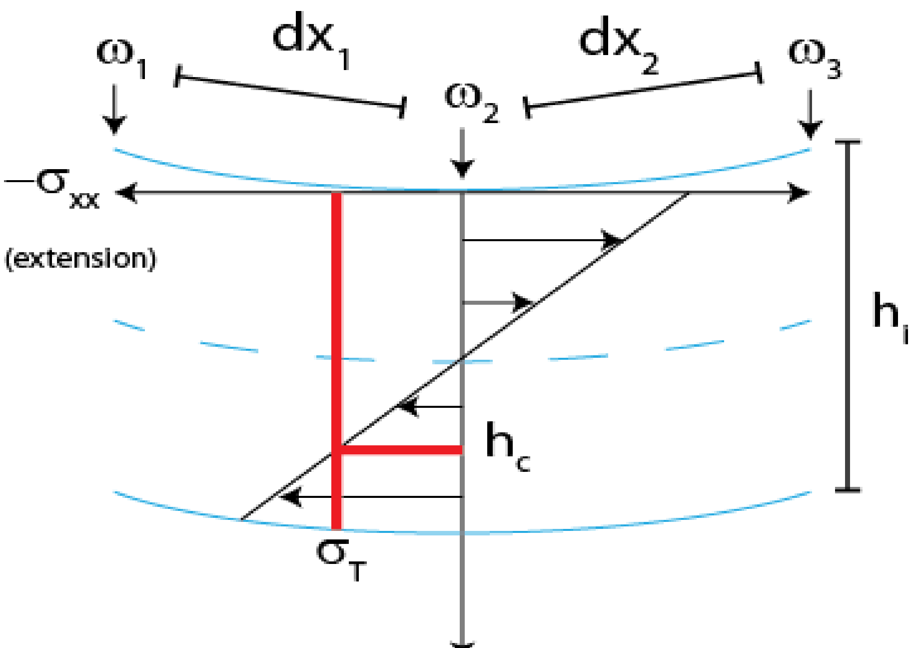


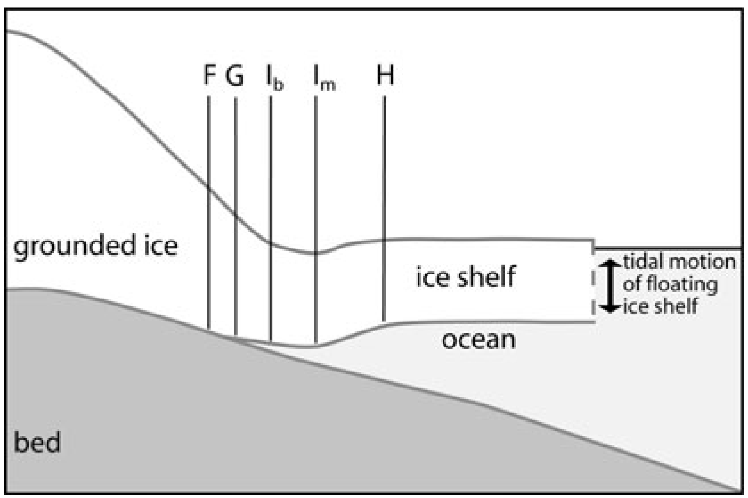

*Catania et al., (2010*

# **Glacier Fundamentals:** grounding lines



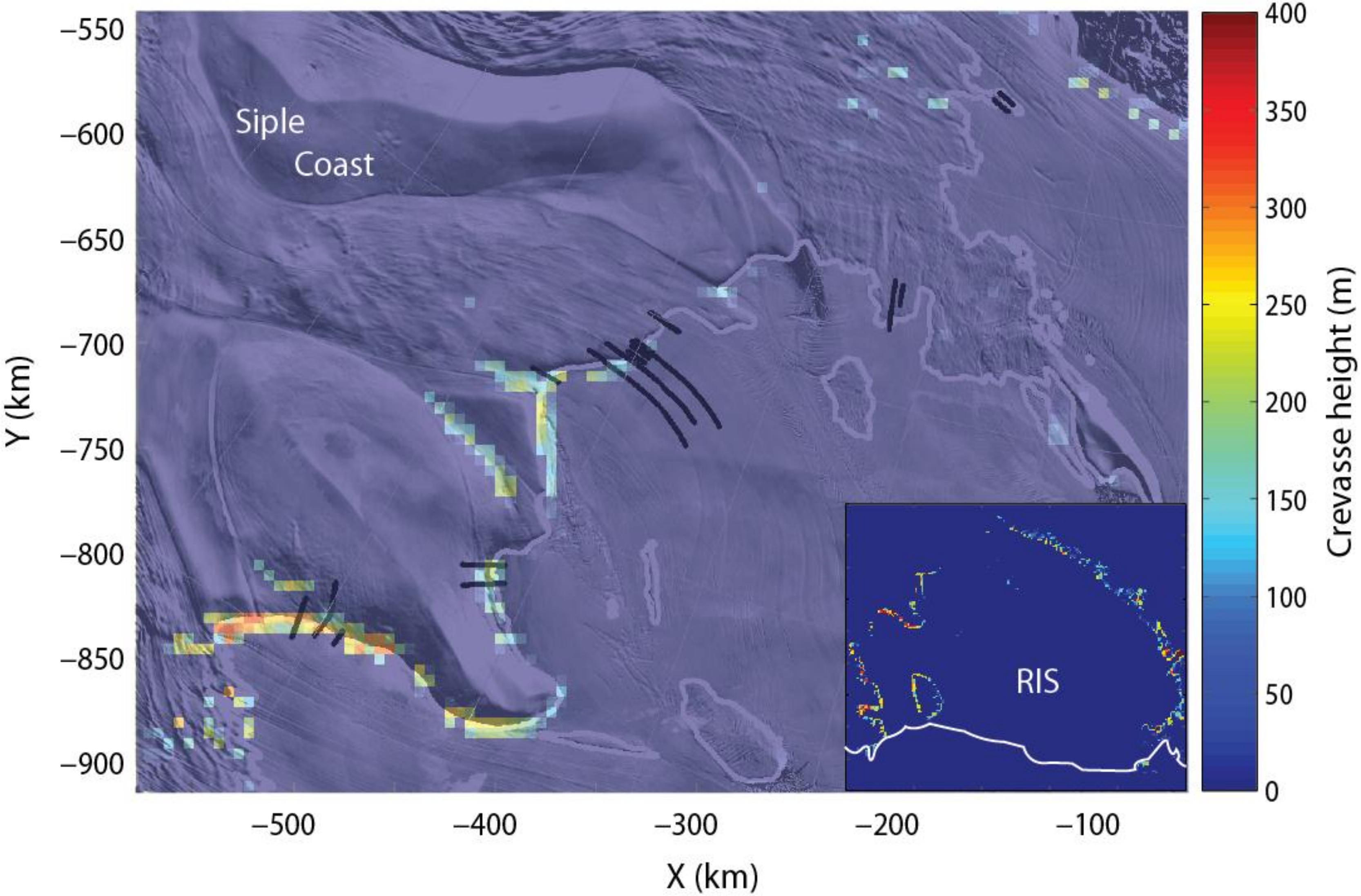




$$\omega''(x) = \frac{\omega_1 - 2\,\omega_2 + \omega_3}{dx_1 dx_2}$$



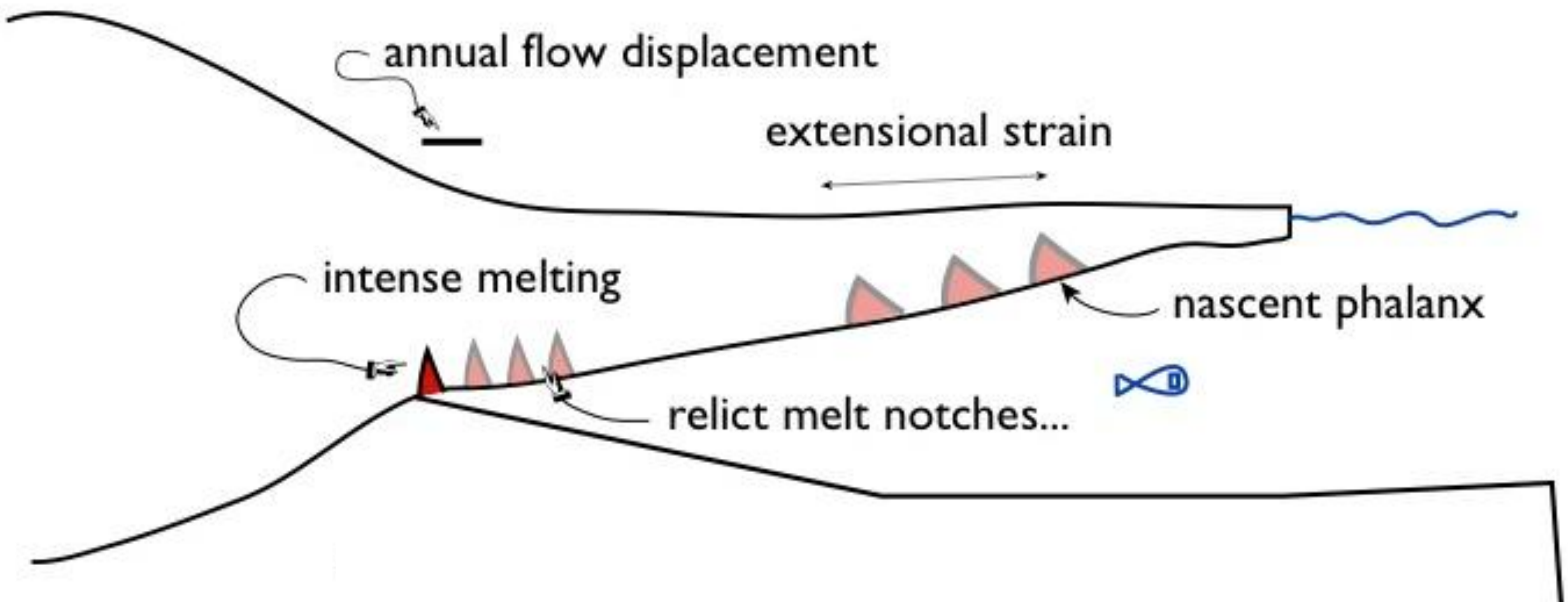

*Logan et al., (in press); Brunt et al., (2010)*

**Glacier Fundamentals:** grounding lines




*Logan et al., (in press)*

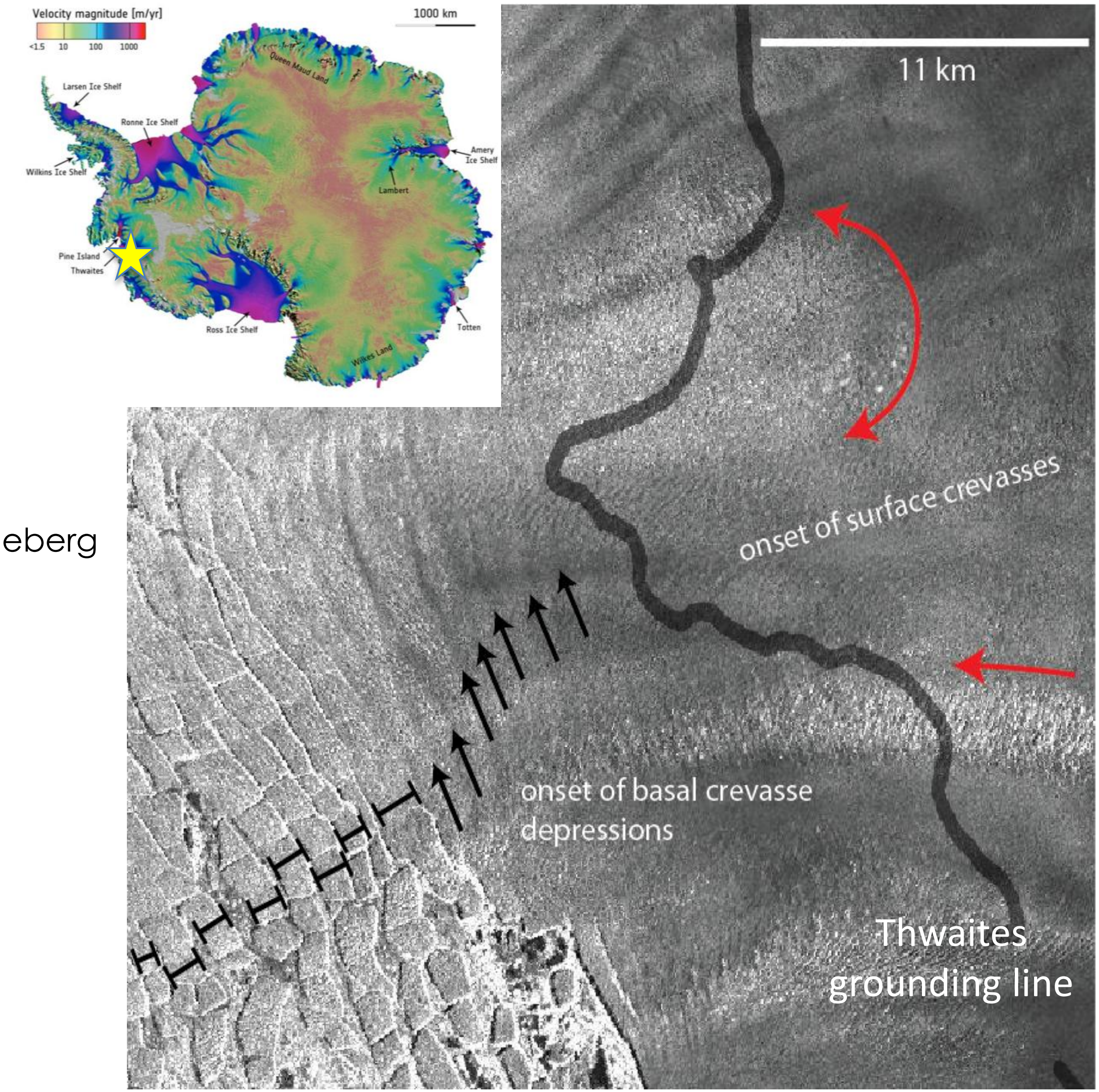
- How to "imprint" a fracture spacing that can allow iceberg capsize:




*ideas borrowed from D. MacAyeal*

# **Glacier Fundamentals:** iceberg calving

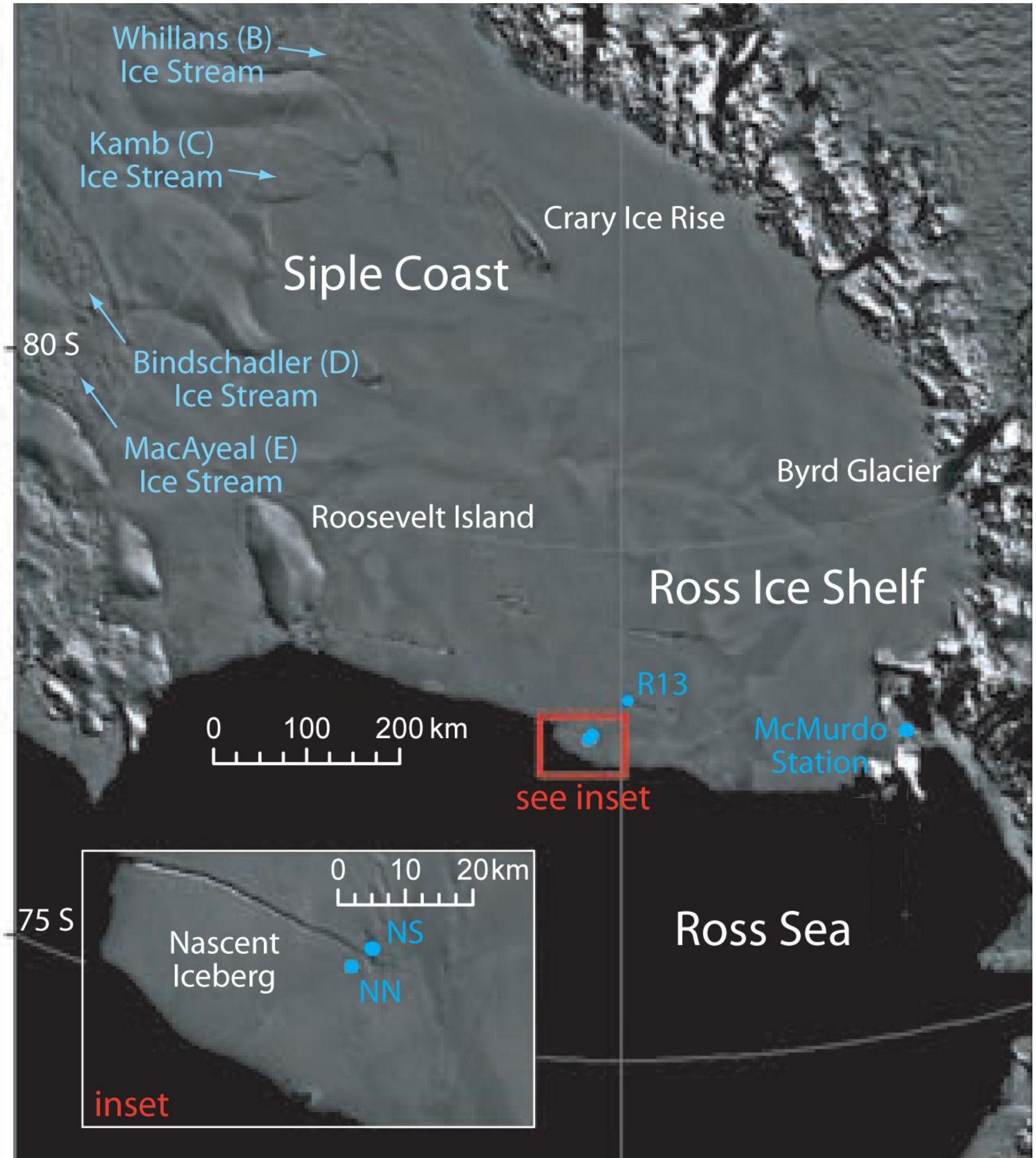
- explains uniformity of iceberg size at the calving front




*Logan et al., (in press)*

# **Glacier Fundamentals:** iceberg calving

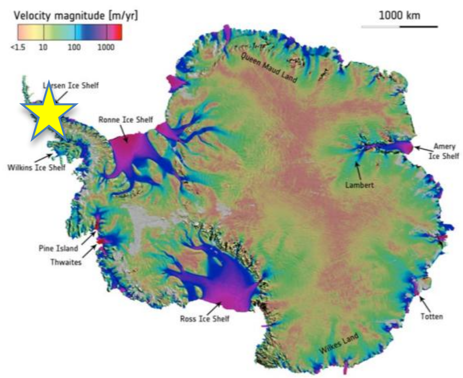
- explains stability of fast-moving ice shelves that periodically produce large tabular icebergs



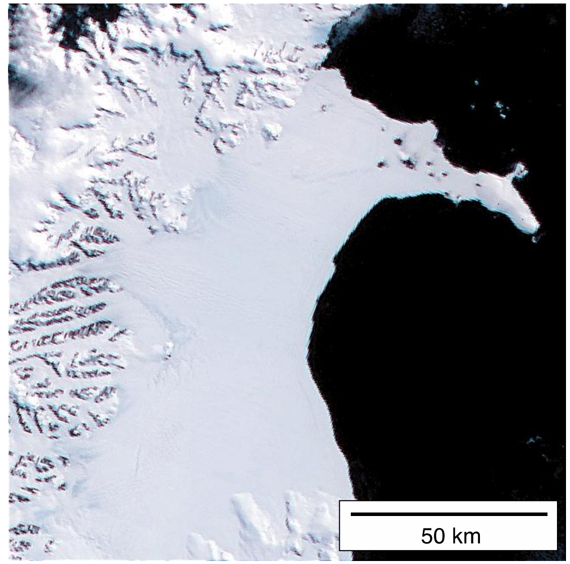

MacAyeal

# **Glacier Fundamentals:** iceberg calving

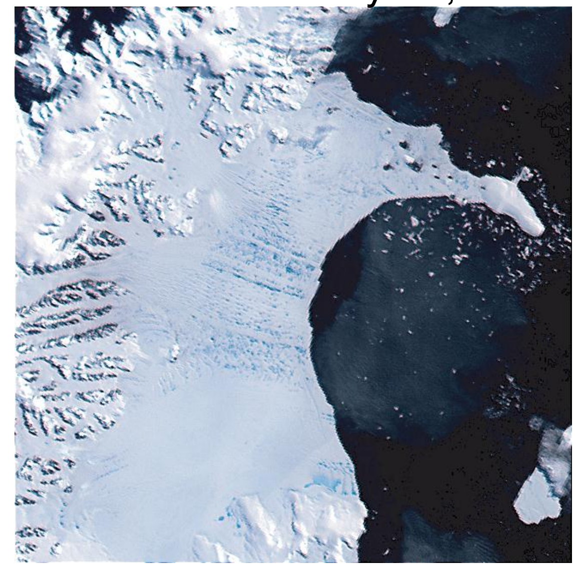
## collapse of Larsen B
## late summer 2002



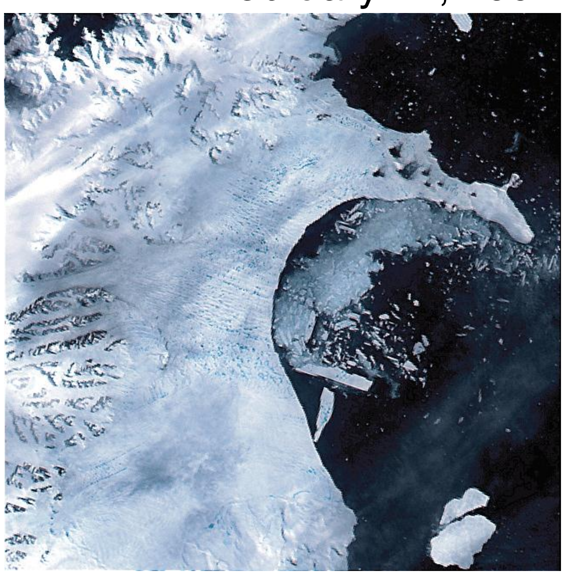

November 22, 2001



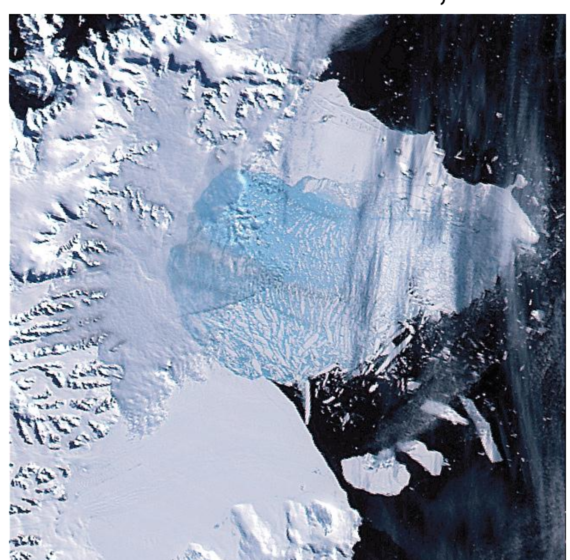

January 31, 2002



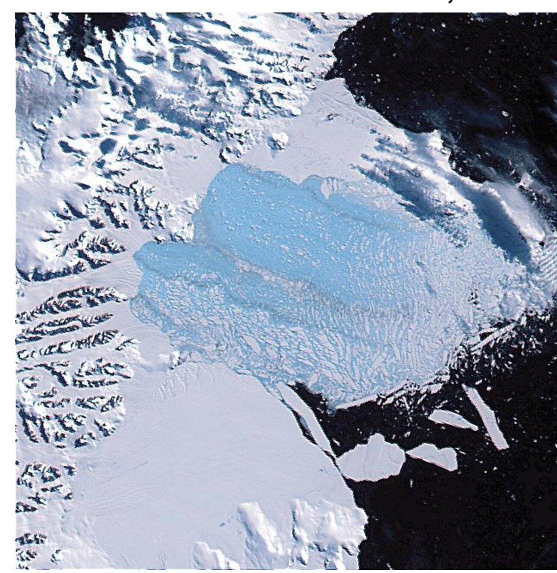
February 17, 2002



March 5, 2002

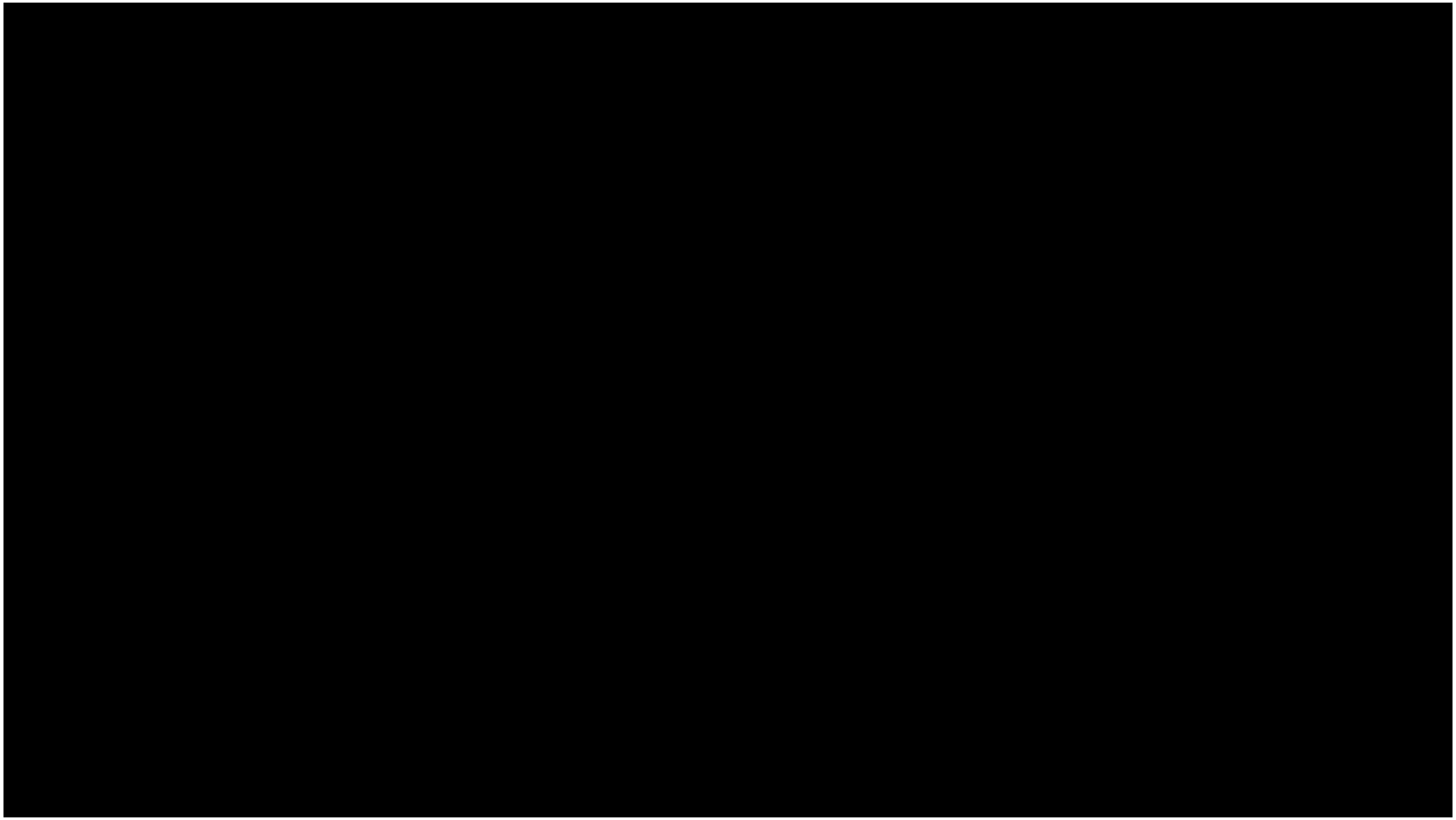


March 7, 2002



MODIS true color from NSIDC, Ted Scambos

**Physical Model:** iceberg behaviour

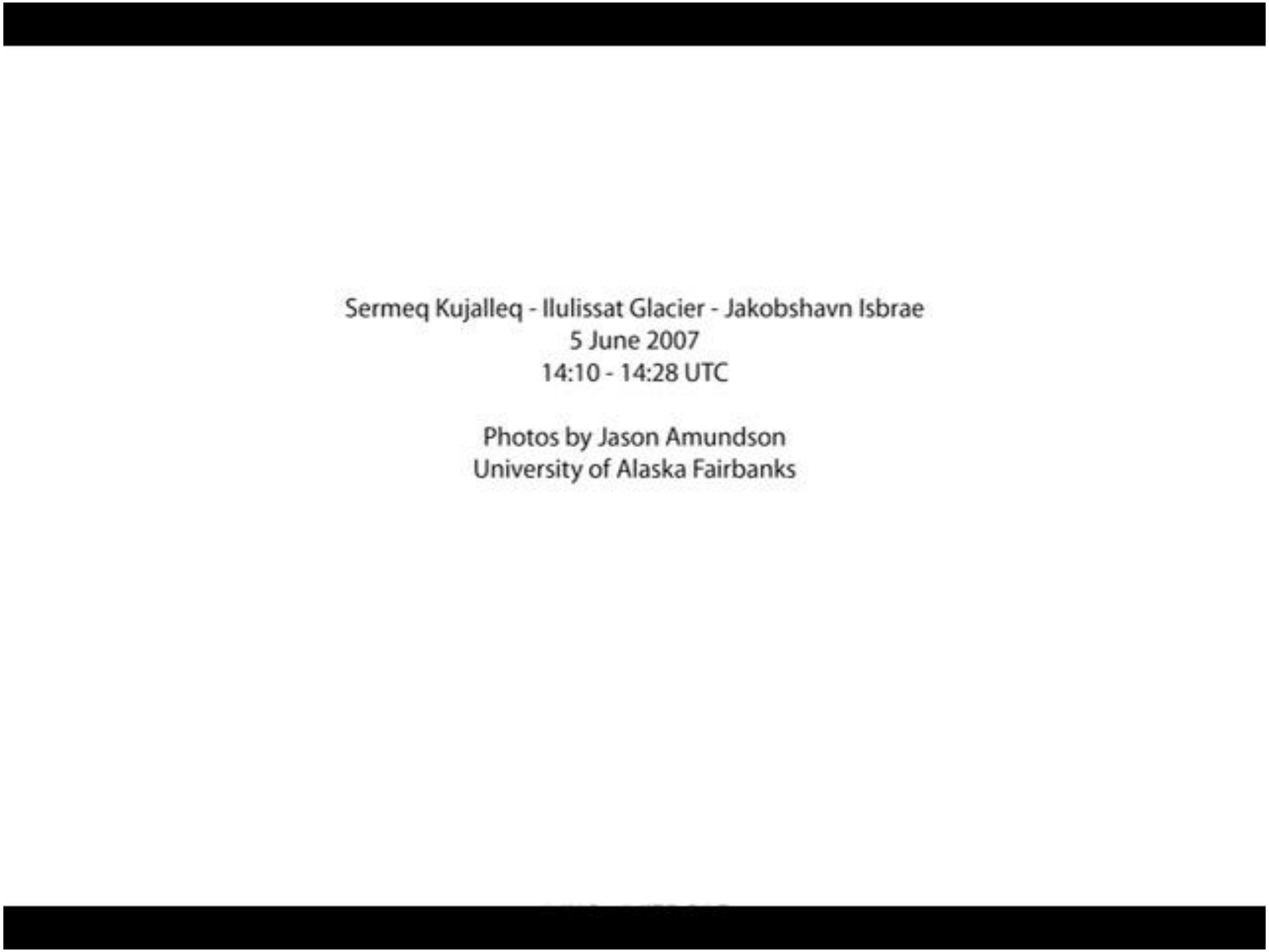


*Burton et al., (2012)*

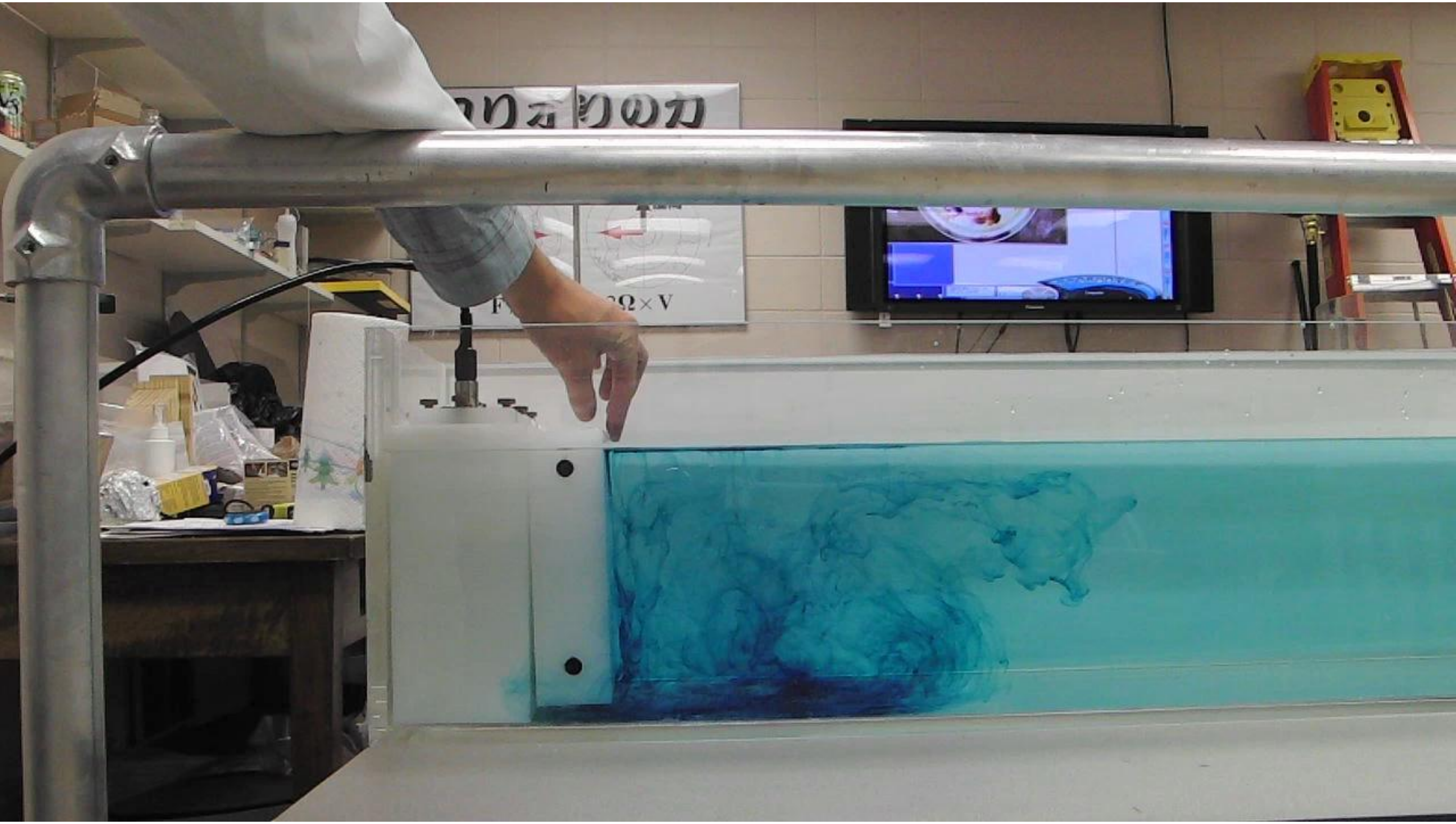
# **Physical Model:** iceberg behaviour


Burton et al., (2012)

**Physical Model:** iceberg behaviour

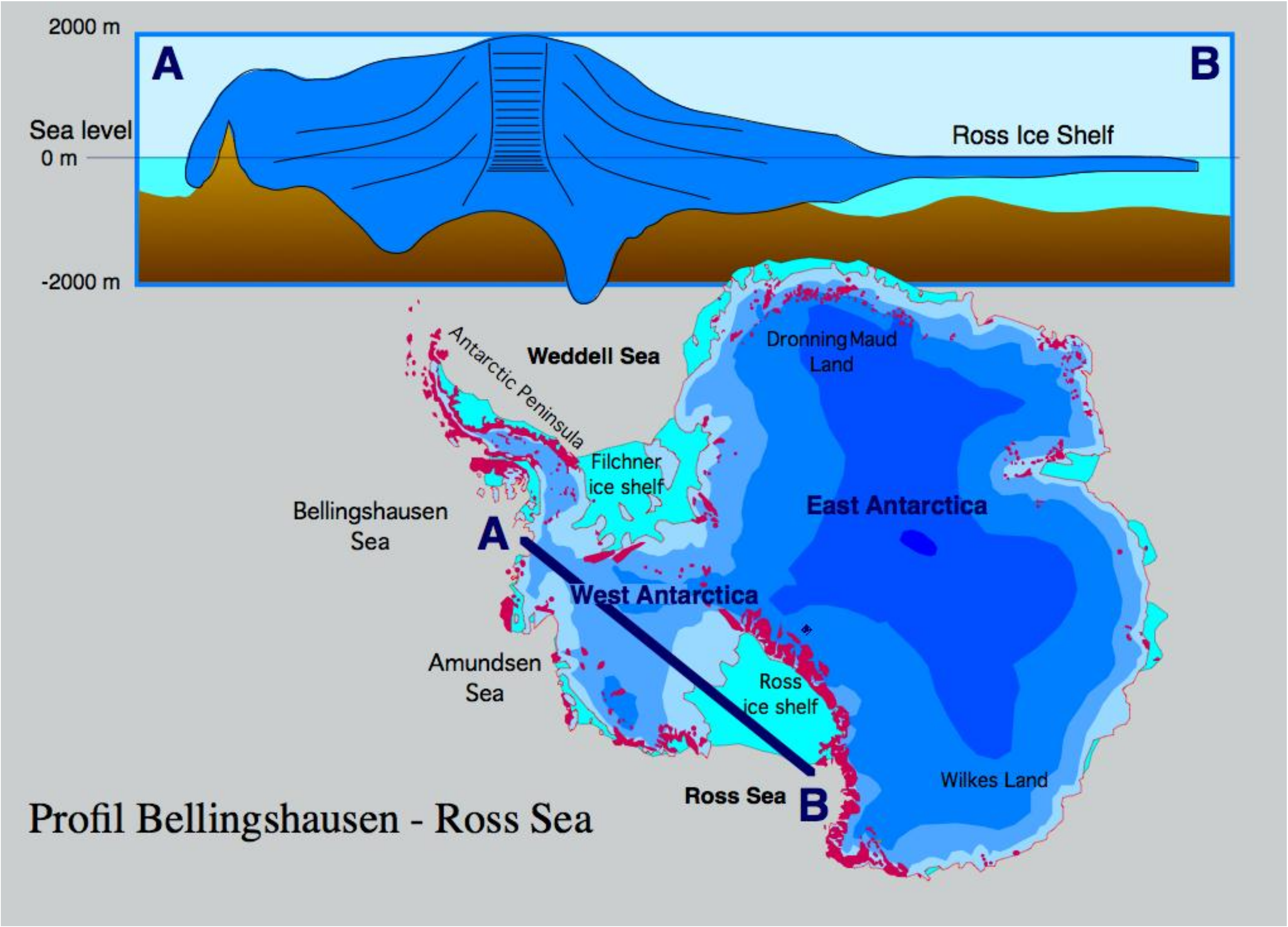


**Physical Model:** iceberg behaviour

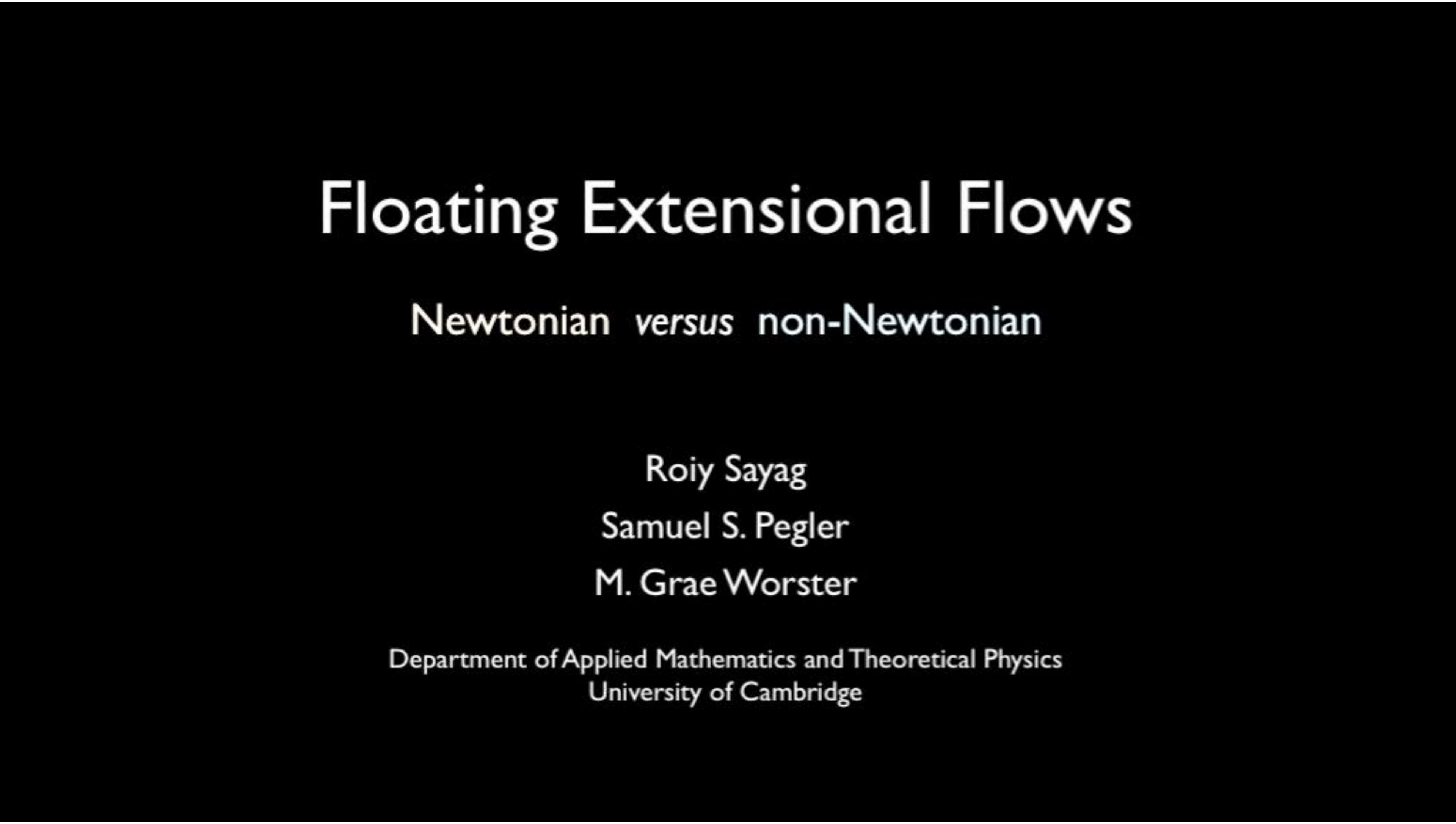


*Burton et al., (2013)*

**Physical Model:** ice shelves



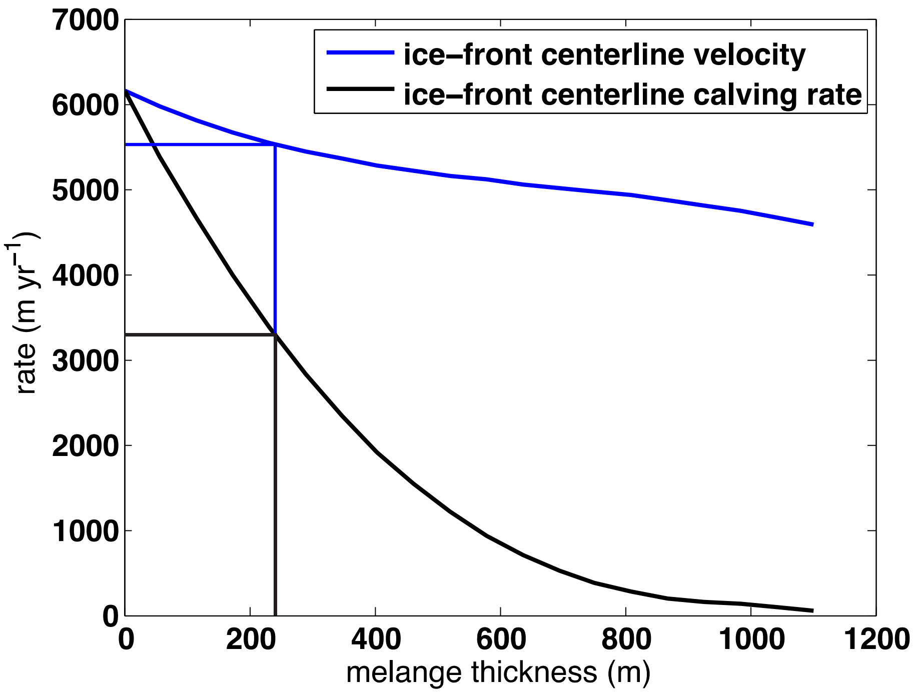
**Physical Model:** ice shelves

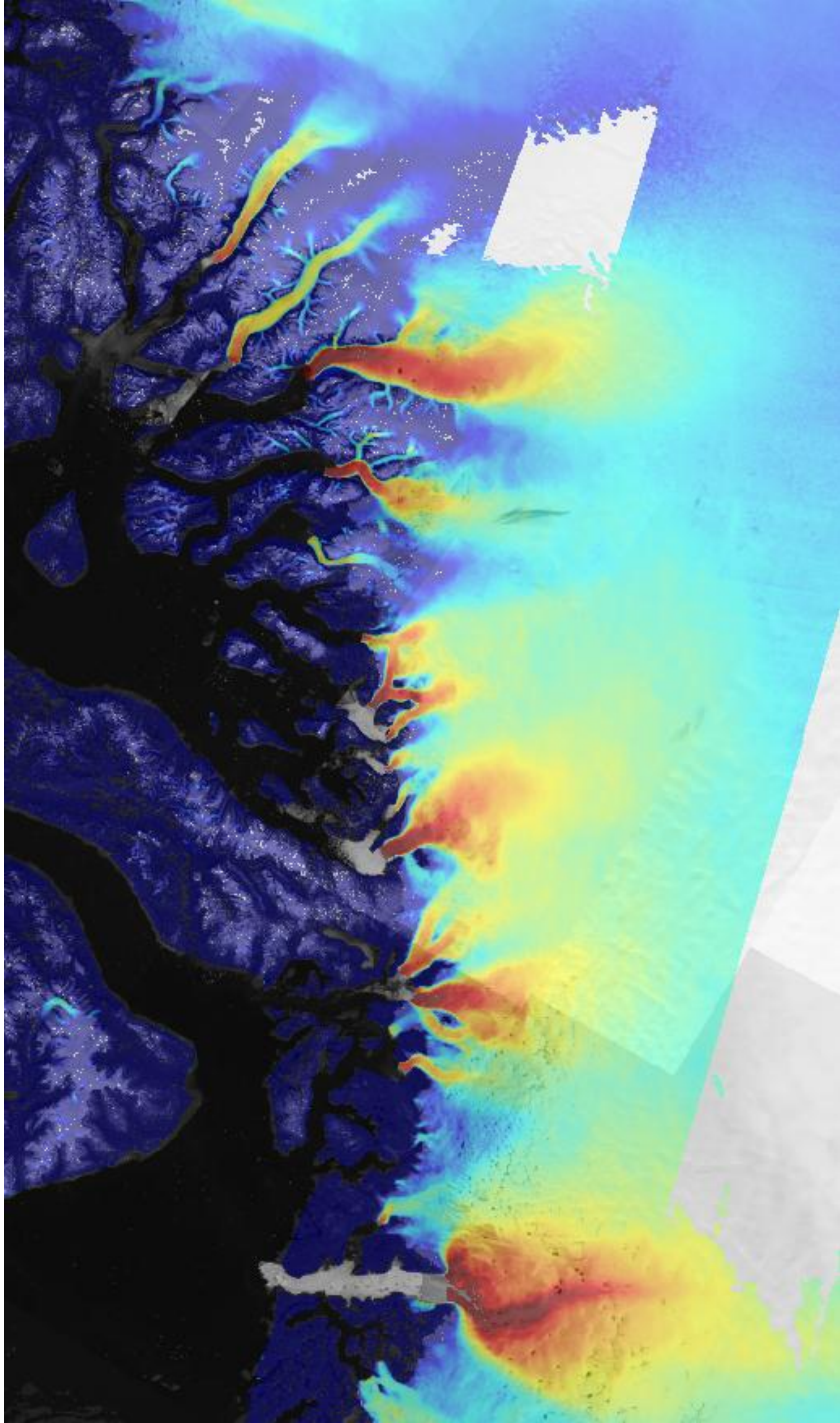


# **Physical Model:** future directions?

***melange***: mixture of icebergs, sea ice in outlet glacier fjord

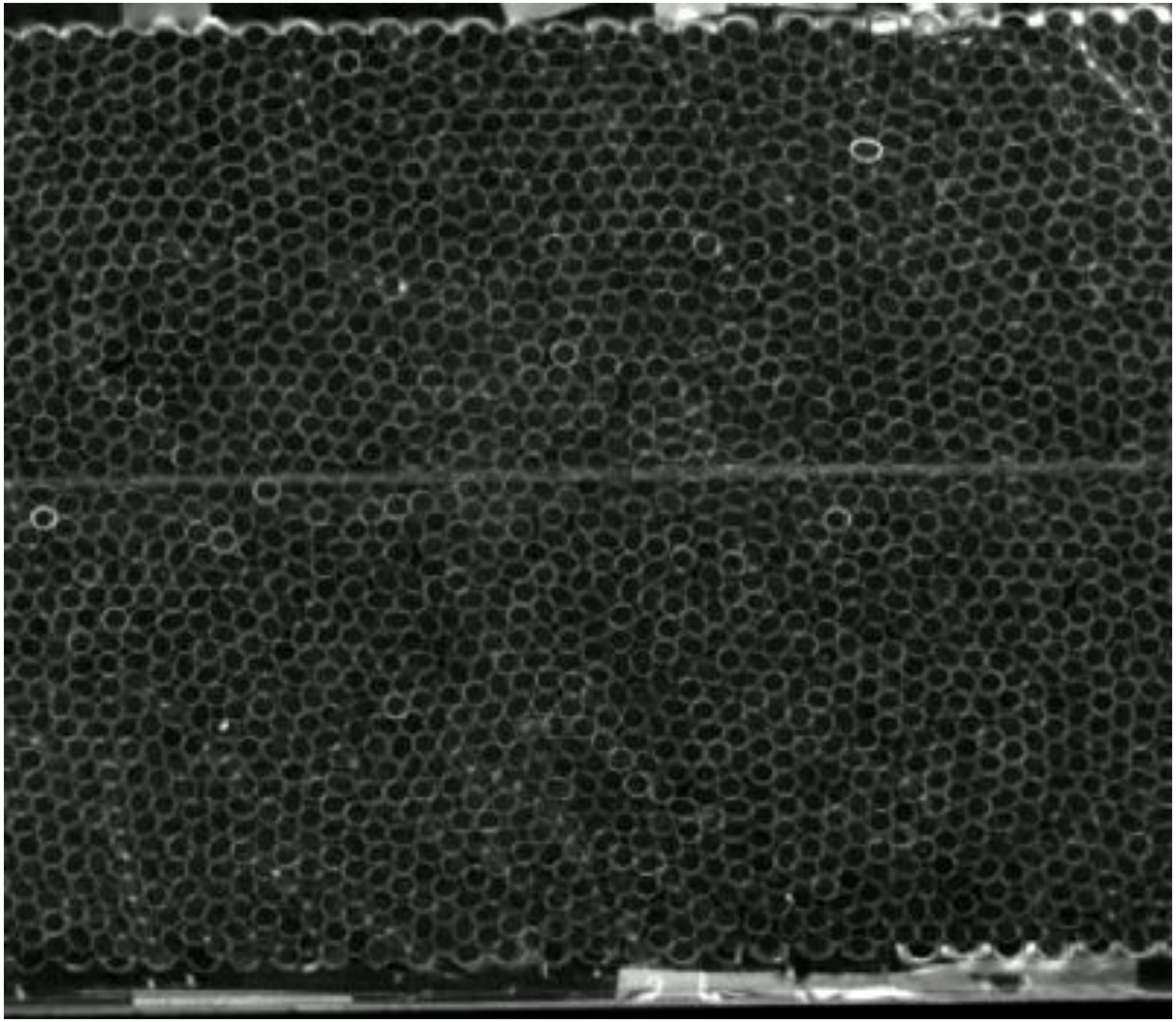
- influences calving rate and glacier velocity



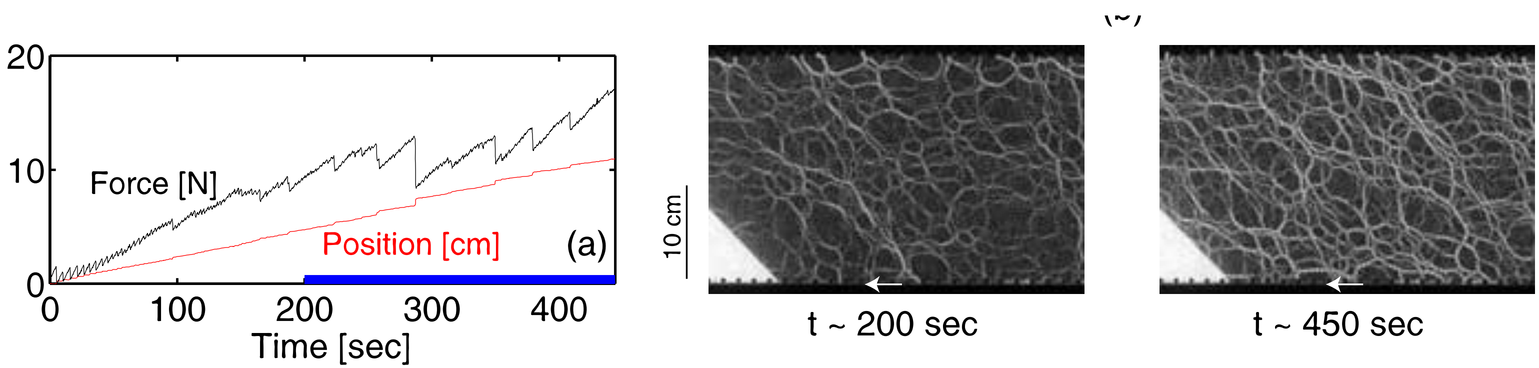
*Lindsay and Dupont, (2013)*

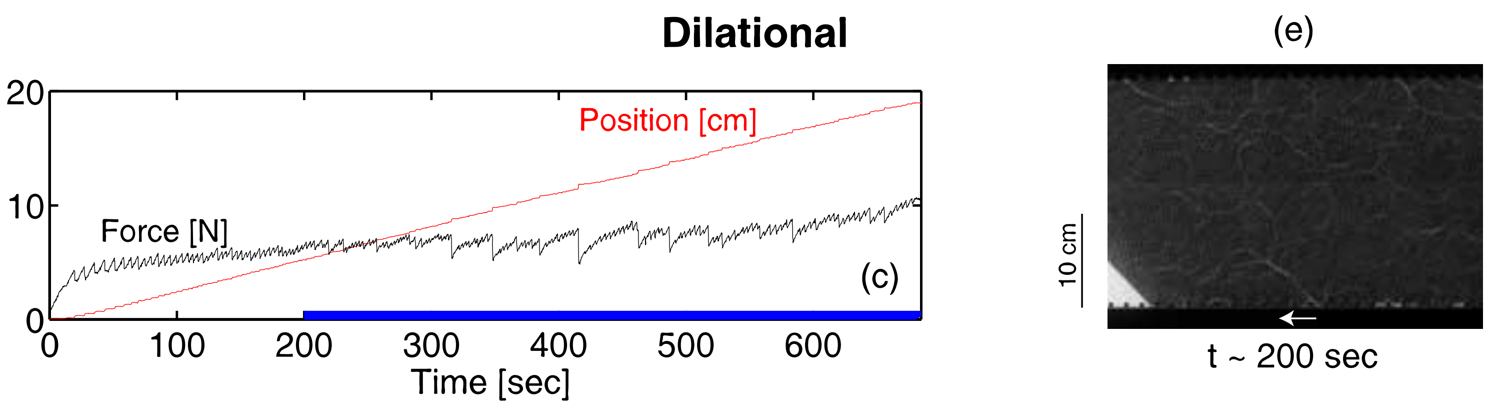
**Physical Model:** future directions?



*Hayman et al., (2011)*

# **Physical Model:** future directions?




*Daniels and Hayman, (2008)*

# **Physical Models:** conclusions

Earth-Science Reviews 97 (2009) 1–43

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ELSEVIER


The “unreasonable effectiveness” of stratigraphic and geomorphic experiments

Chris Paola [a,*], Kyle Straub [a,b], David Mohrig [c], Liam Reinhardt [d]

- We can easily be convinced of the utility of physical experiments
  - evolve under controlled conditions
  - can examine the independent control from changing a single variable
  - can provide a greater degree of measurement not possible in the field
  - can speed up time

# **Physical Models:** conclusions


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The "unreasonable effectiveness" of stratigraphic and geomorphic experiments

Chris Paola [a,*], Kyle Straub [a,b], David Mohrig [c], Liam Reinhardt [d]

- Skepticism arises from concerns about how representative these systems are (i.e. scaling)
  - most experiments fall short of full dynamic scaling – but still capture the essence of many important processes in natural systems

# **Physical Models:** conclusions

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The "unreasonable effectiveness" of stratigraphic and geomorphic experiments

Chris Paola [a,*], Kyle Straub [a,b], David Mohrig [c], Liam Reinhardt [d]

- Paola and others argue for a broader view including the idea of natural similarity
  - argues for abandonment of the term 'physical model' or 'analogue model' since a model is an idealization or theory about how nature works.
  - these experiments are a part of nature, however simplified or reduced in scale they may be