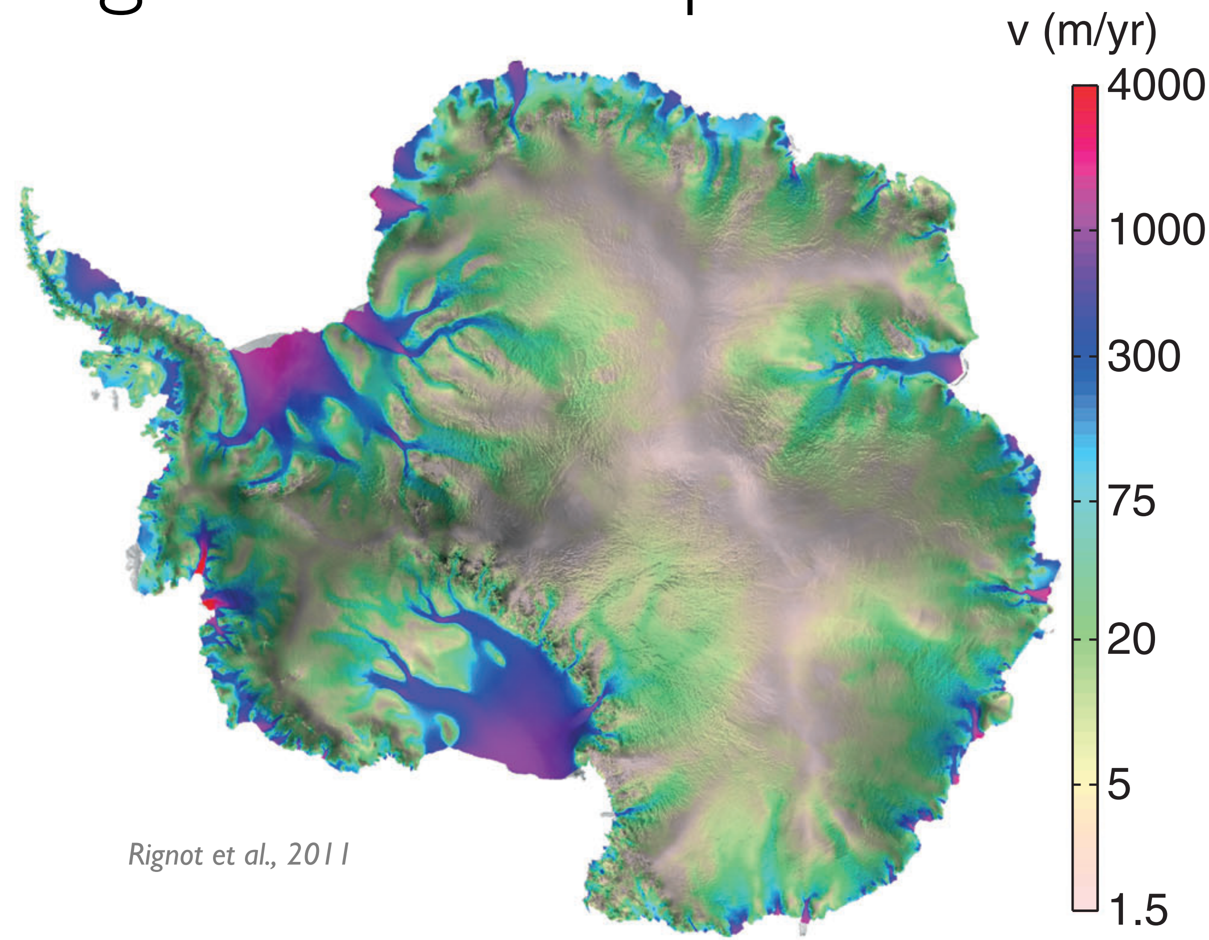
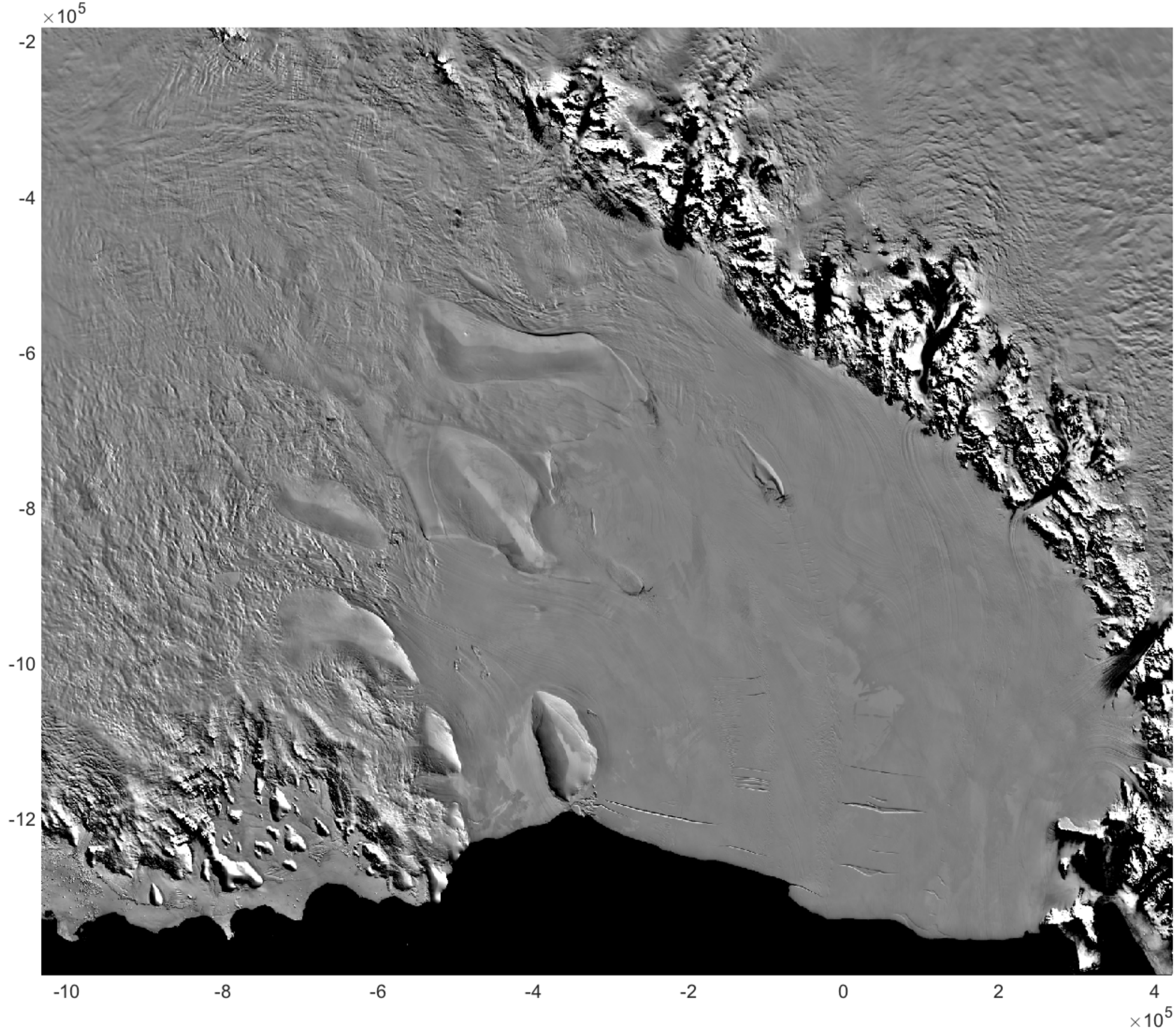
Ice streams, shear margins, and glacier stick-slip motion



Part 1. Background on ice streams



×10^5
-2
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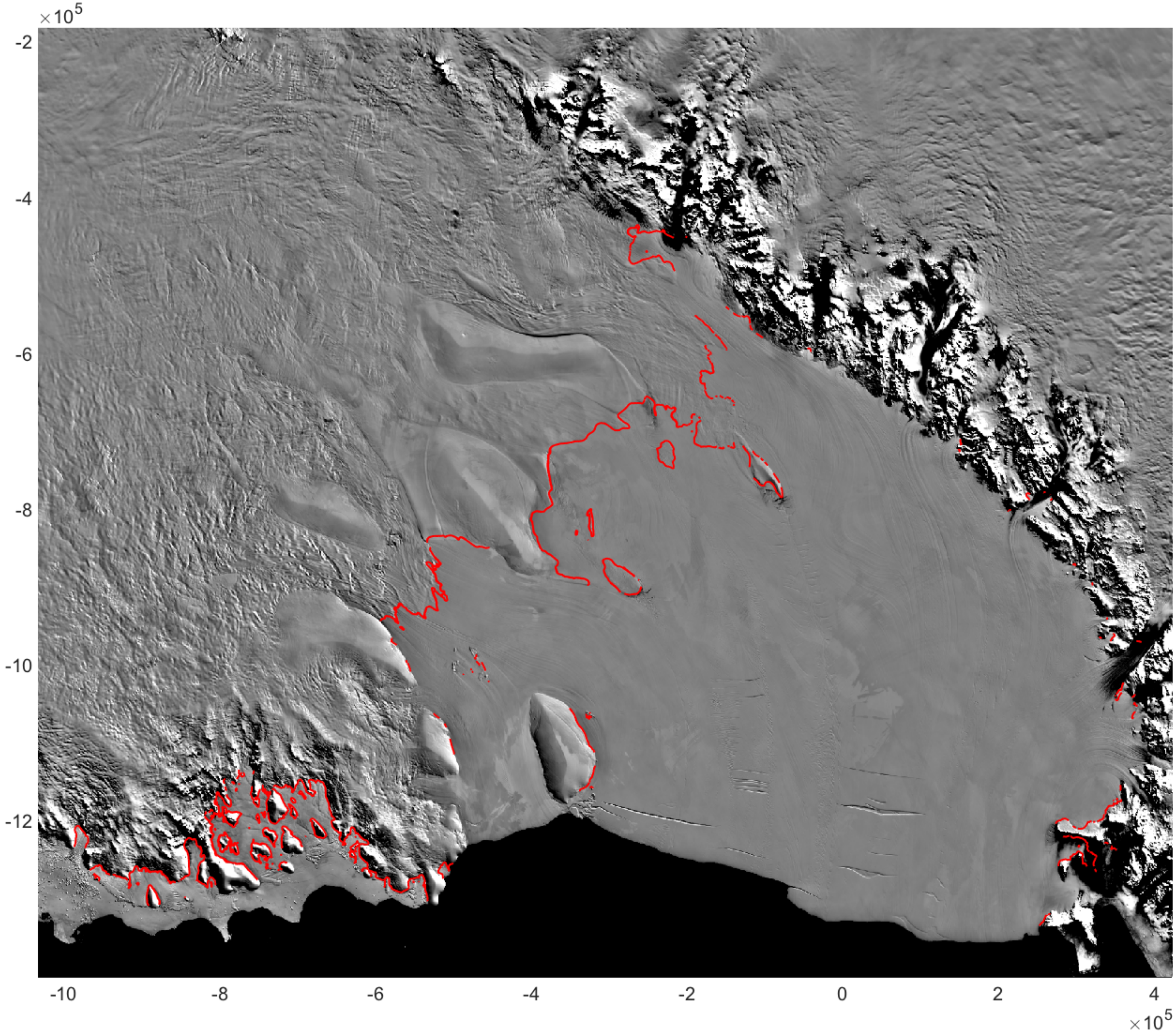
×10^5



×10^5
-2
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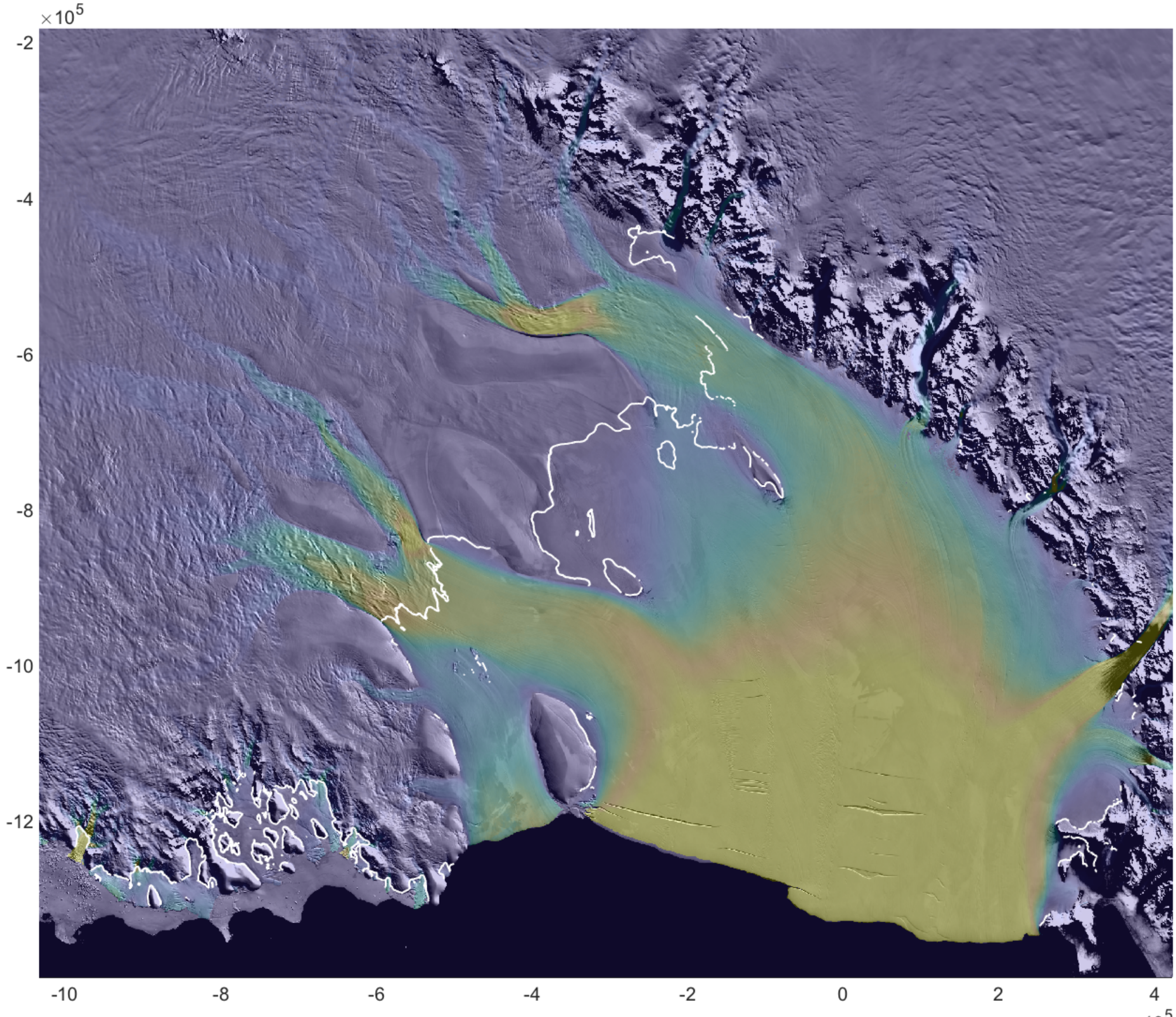

×10^5
-2
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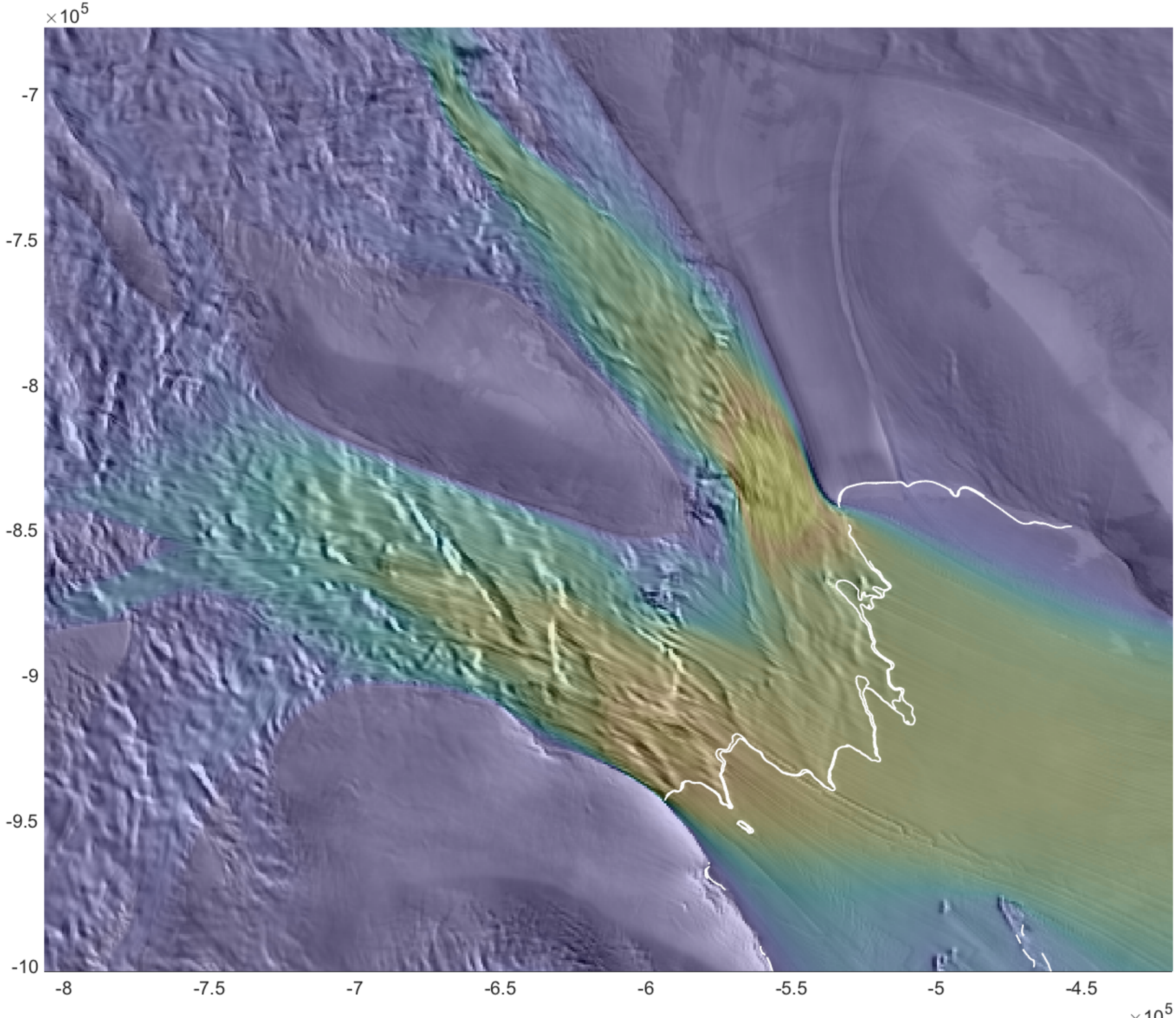

×10^5
-7
-7.5
-8
-8.5
-9
-9.5
-10
-8
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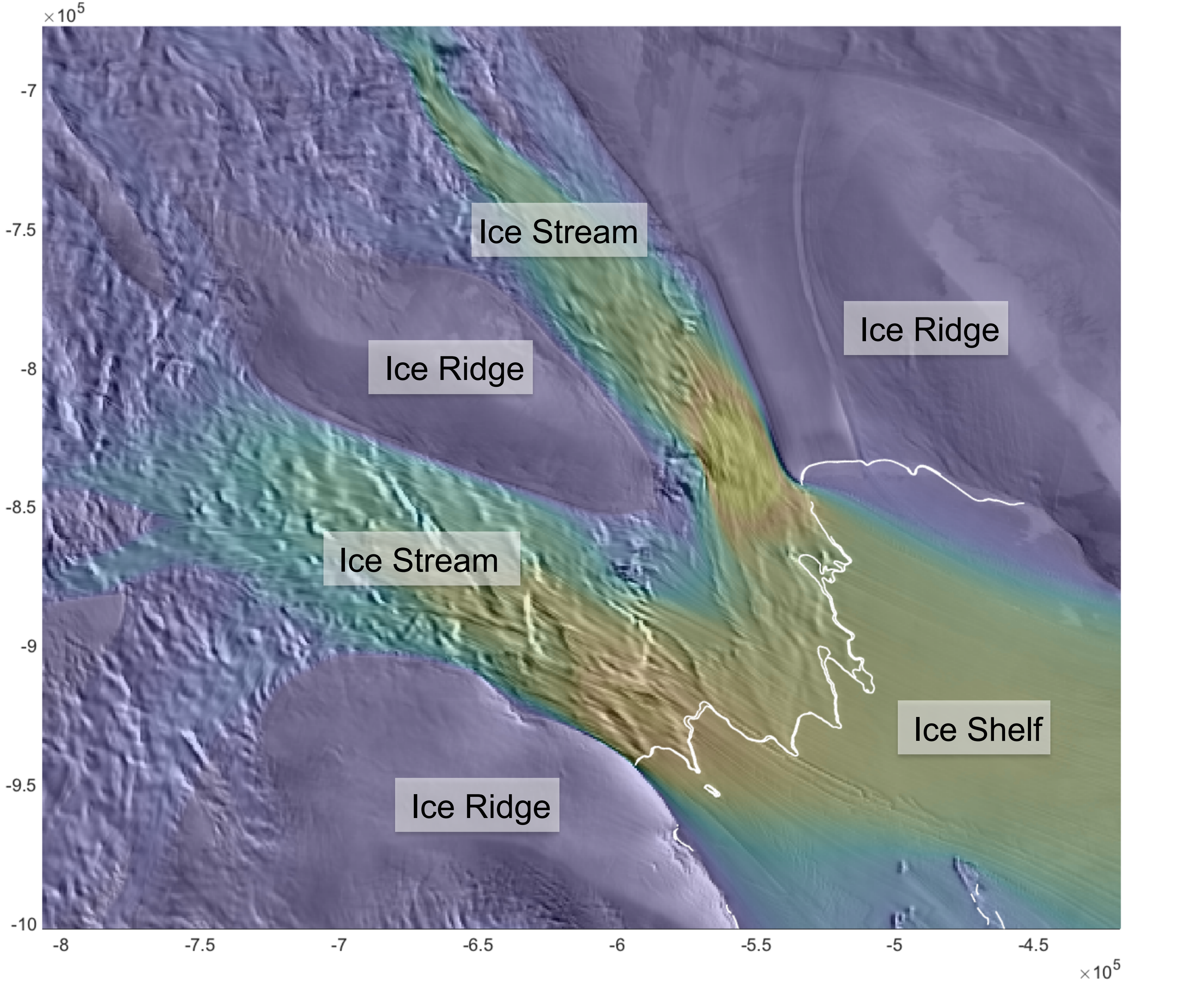
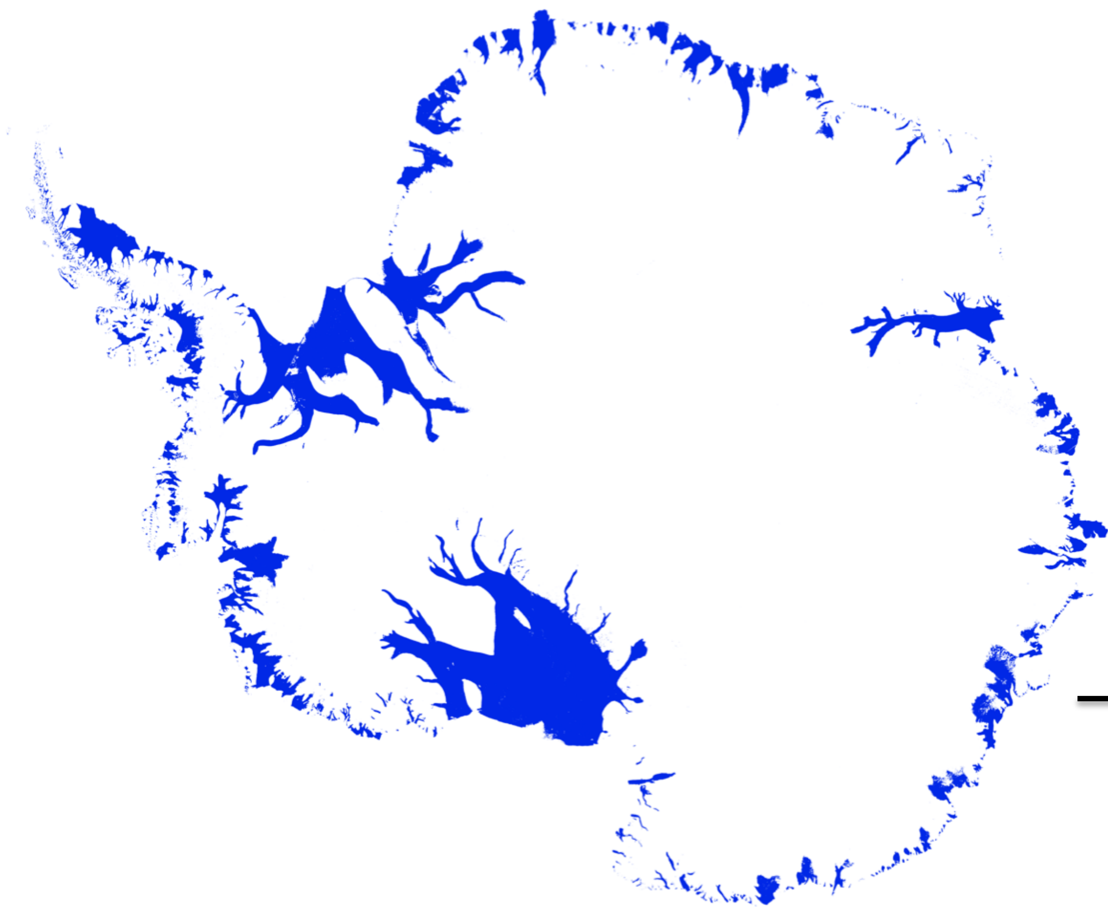
-7
-6.5
-6
-5.5
-5
-4.5
×10^5



Ice Stream
Ice Ridge
Ice Ridge
Ice Stream
Ice Shelf
Ice Ridge
×10^5
-7
-7.5
-8
-8.5
-9
-9.5
-10
-8
-7.5
-7
-6.5
-6
-5.5
-5
-4.5
×10^5

How certain is future Antarctic mass balance?



Mass in

+ 1500 Gt/yr

15 Ice Streams
1 km thickness
50 km width
1 km/yr flow velocity
(other smaller mass fluxes, see Shepherd et al., 2012)

Mass out

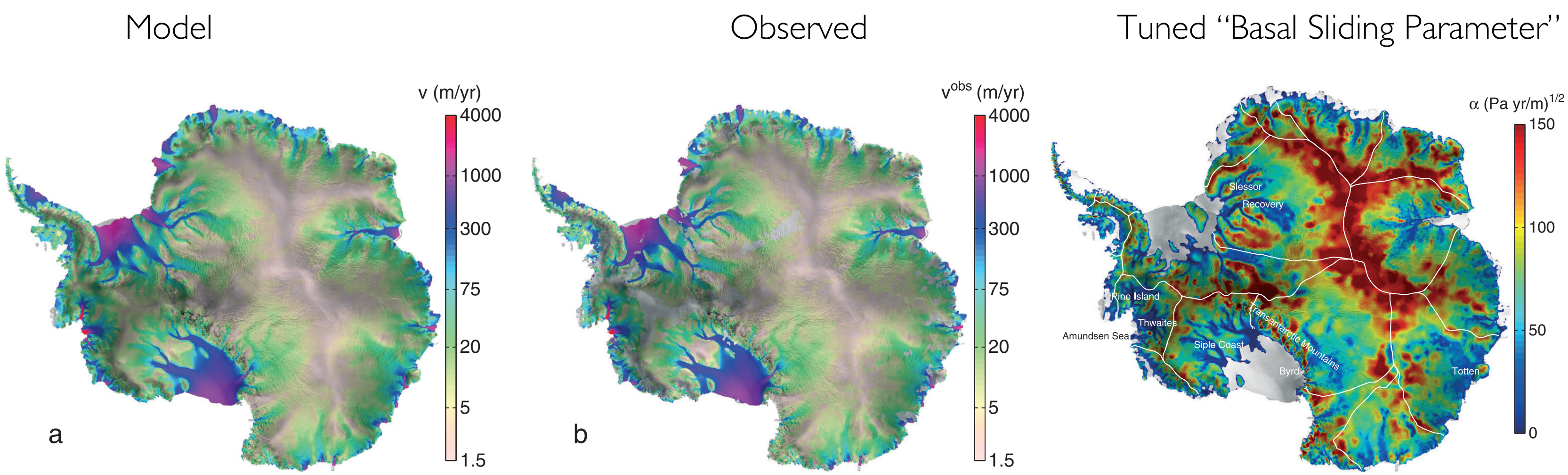
- 1600 Gt/yr

Mass imbalance

- 100 Gt/yr

Imbalance is equal to the discharge of just two ice streams. How sure are we that this calculation will remain the same?

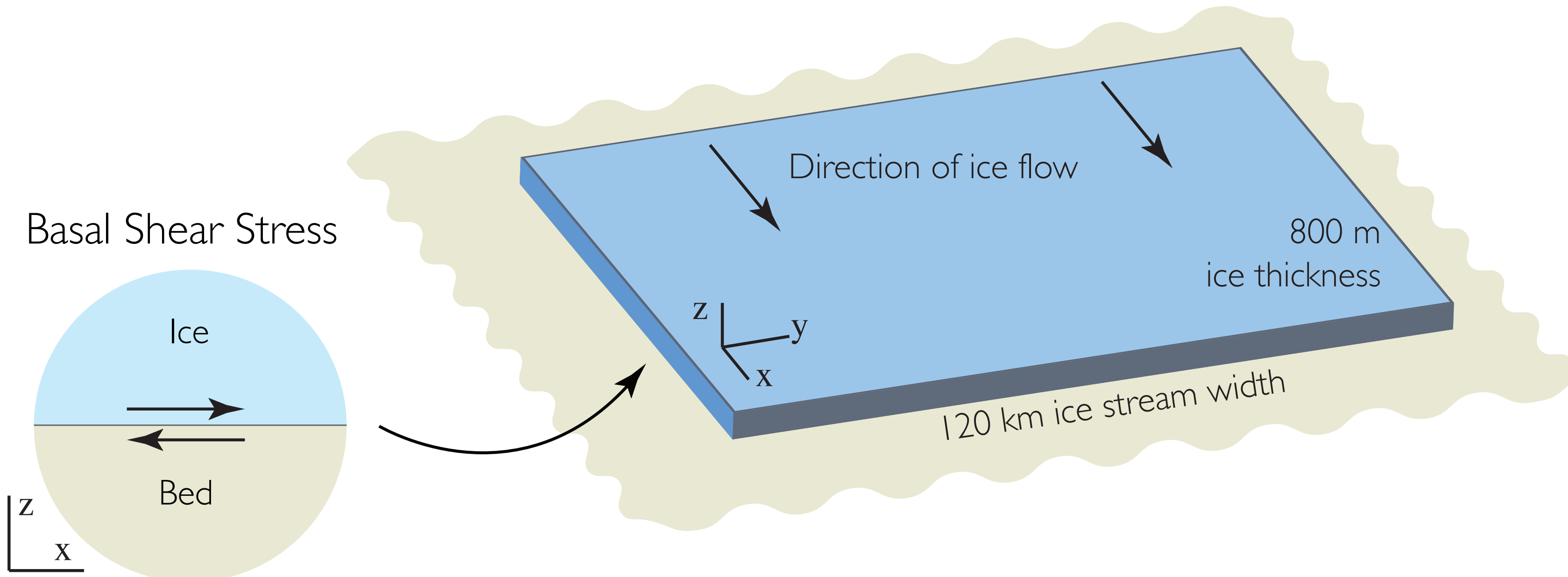
Current state-of-the-art ice sheet models



Morlighem et al. 2013

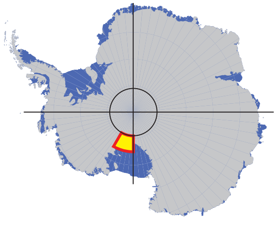
- The simulations shown are 3D, thermo-viscous creeping flow simulations with real bathymetric data.
- **Variation in flow speeds results largely from the tuned basal sliding parameter rather than from actual physical processes.**
- For this reason, such a description may have some utility if interpreted as a linearization about current conditions, but
- it is unlikely that models such as this can forecast complex future changes.

Rapid ice velocities are primarily controlled by subglacial conditions.



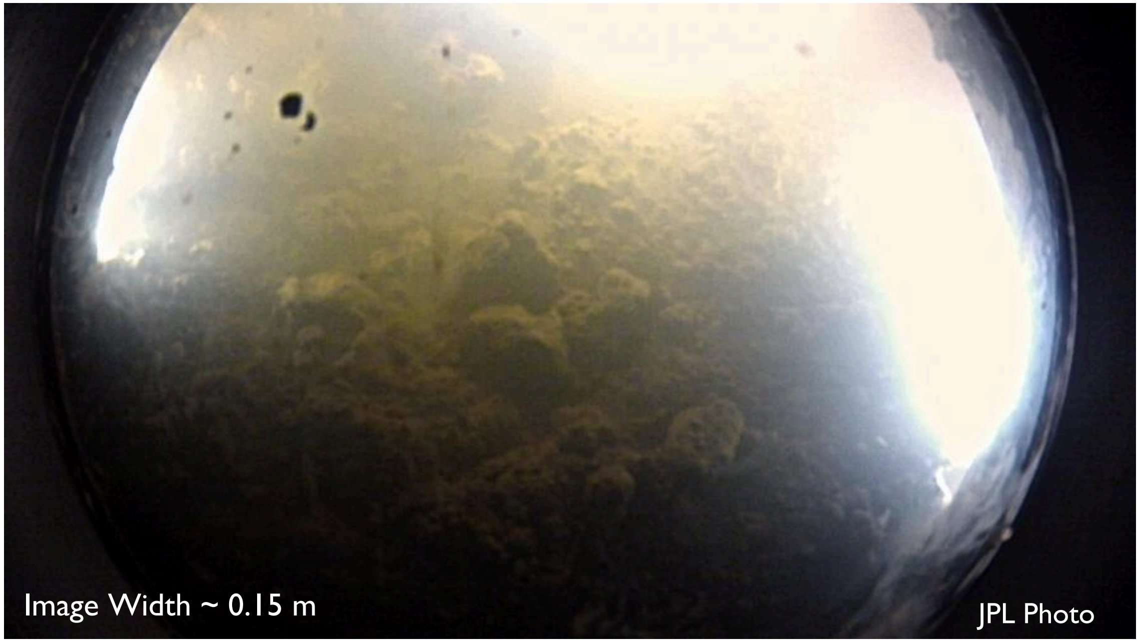
Direct observation of the ice-bed interface: the WISSARD experiment

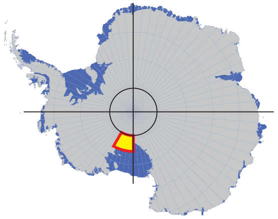
1. **Fast sliding is facilitated by glacial till.**



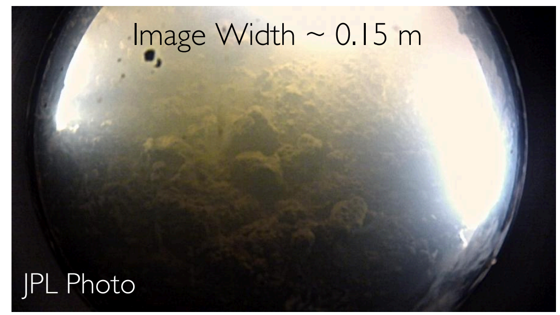
Direct observation of the ice-bed interface: the WISSARD experiment

2. **Subglacial water pressures can be very high.**

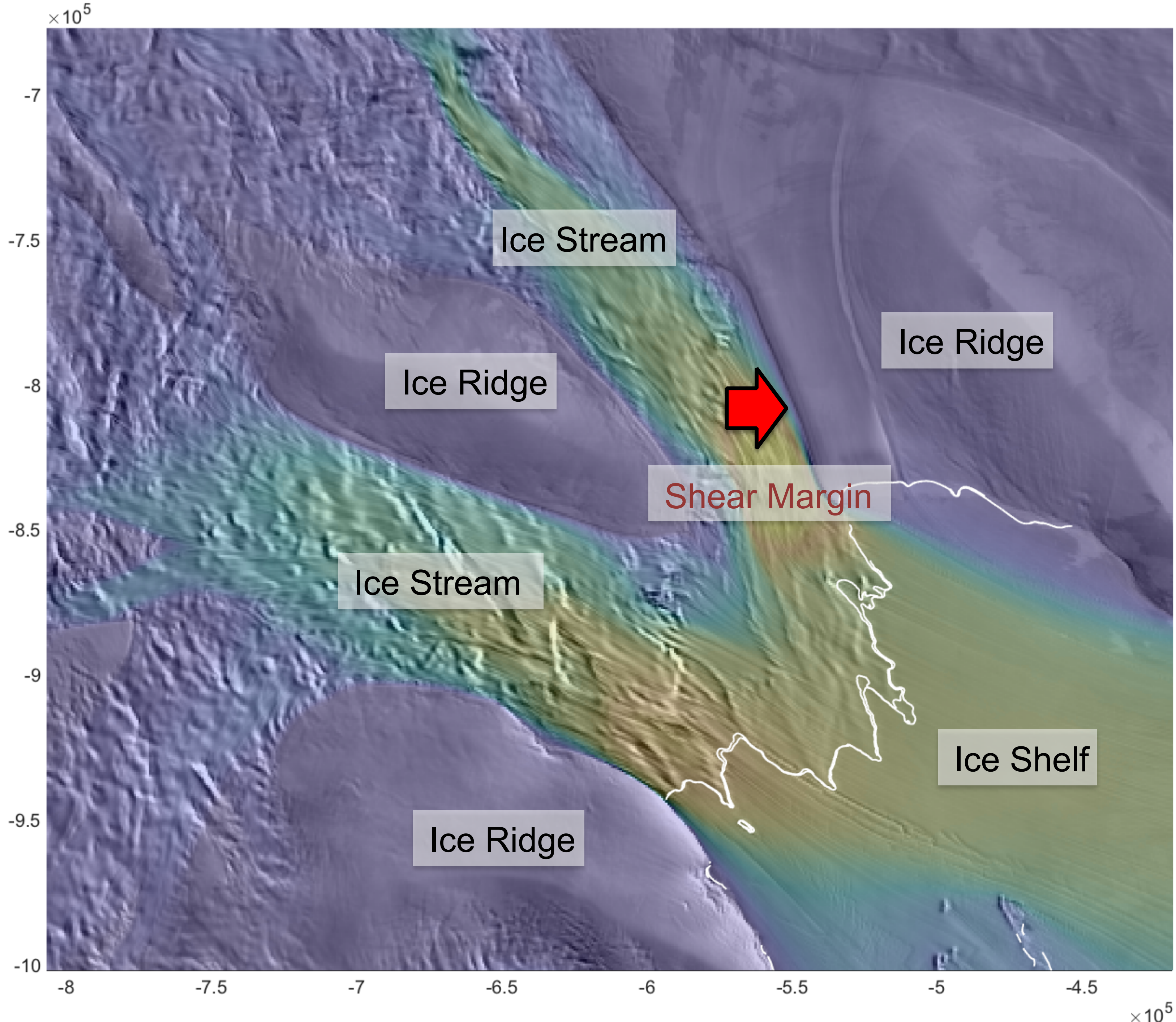




Direct observation of the ice-bed interface: the WISSARD experiment



Fast flowing ice streams exist because of the lubricating effect of a water-saturated subglacial till.



×10^5
-7
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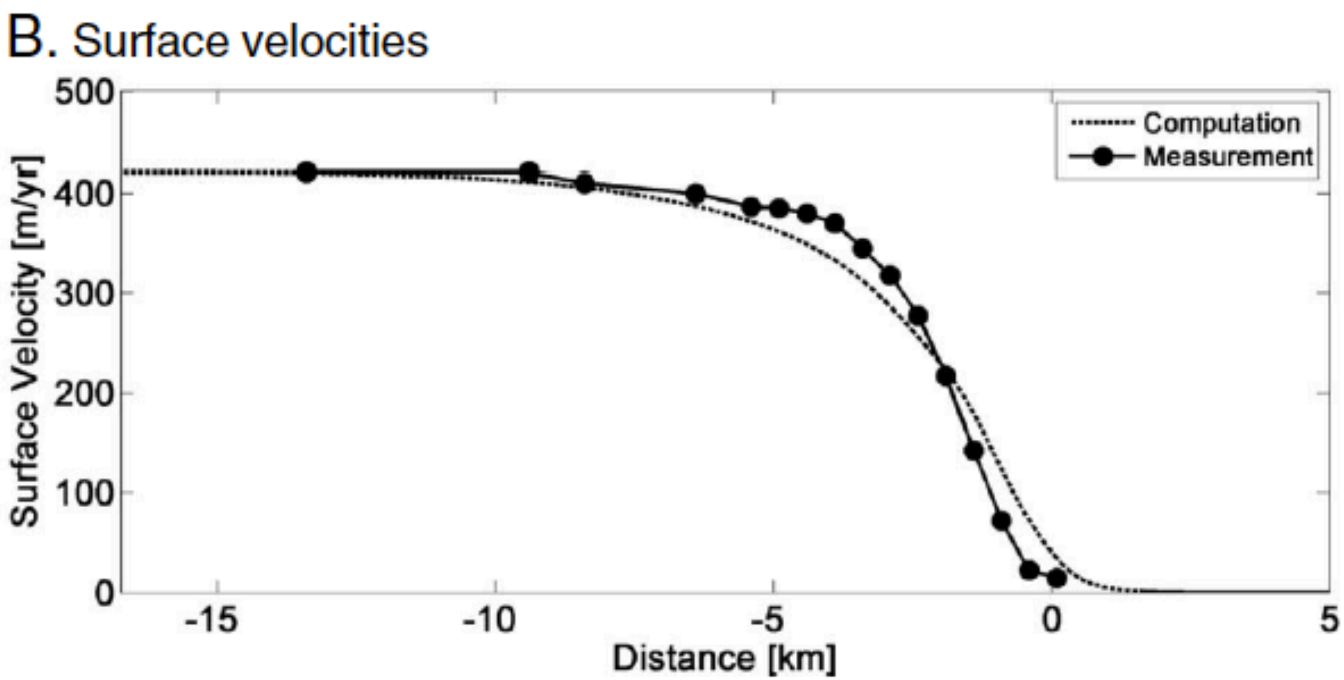
-7
-6.5
-6
-5.5
-5
-4.5
×10^5
Ice Stream
Ice Ridge
Ice Ridge
Shear Margin
Ice Stream
Ice Shelf
Ice Ridge

Ice stream shear margins

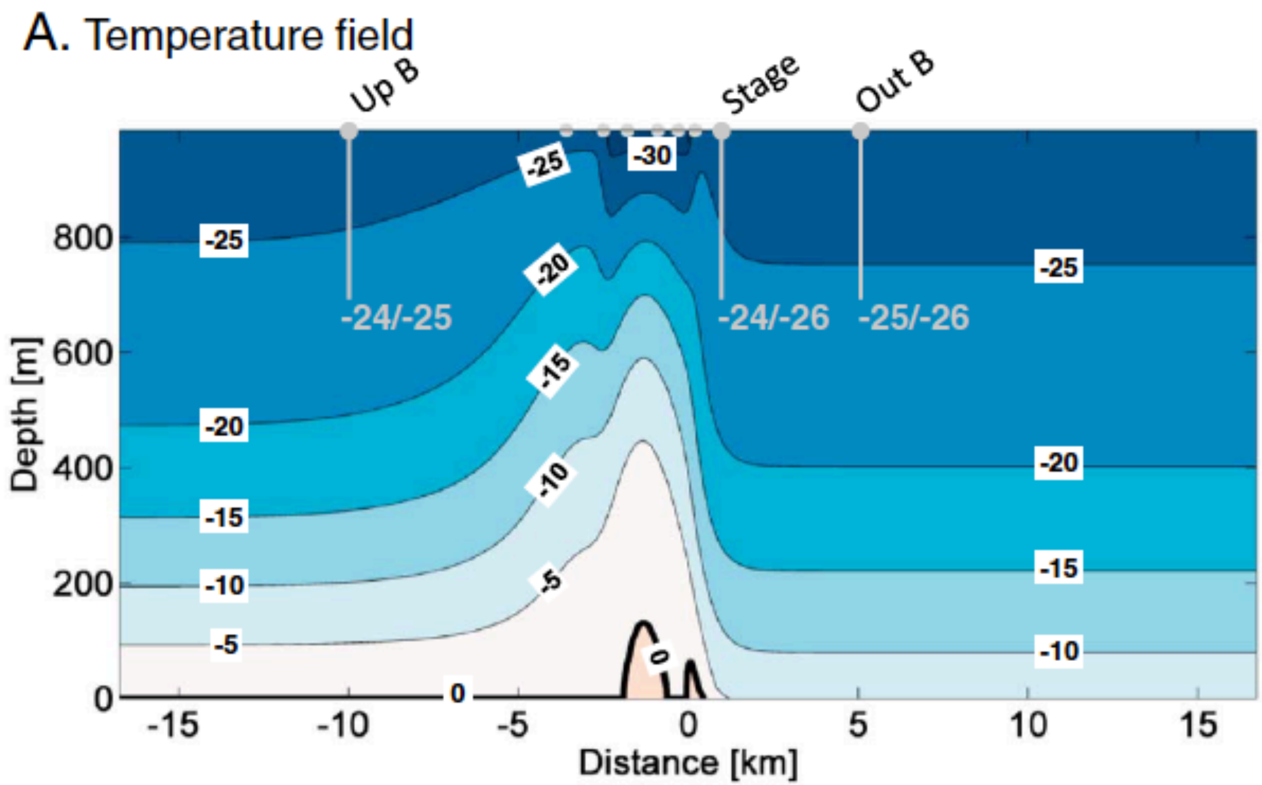
Shear margins are the lateral boundaries of the ice streams. This causes a large velocity gradient.



Suckale et al 2014

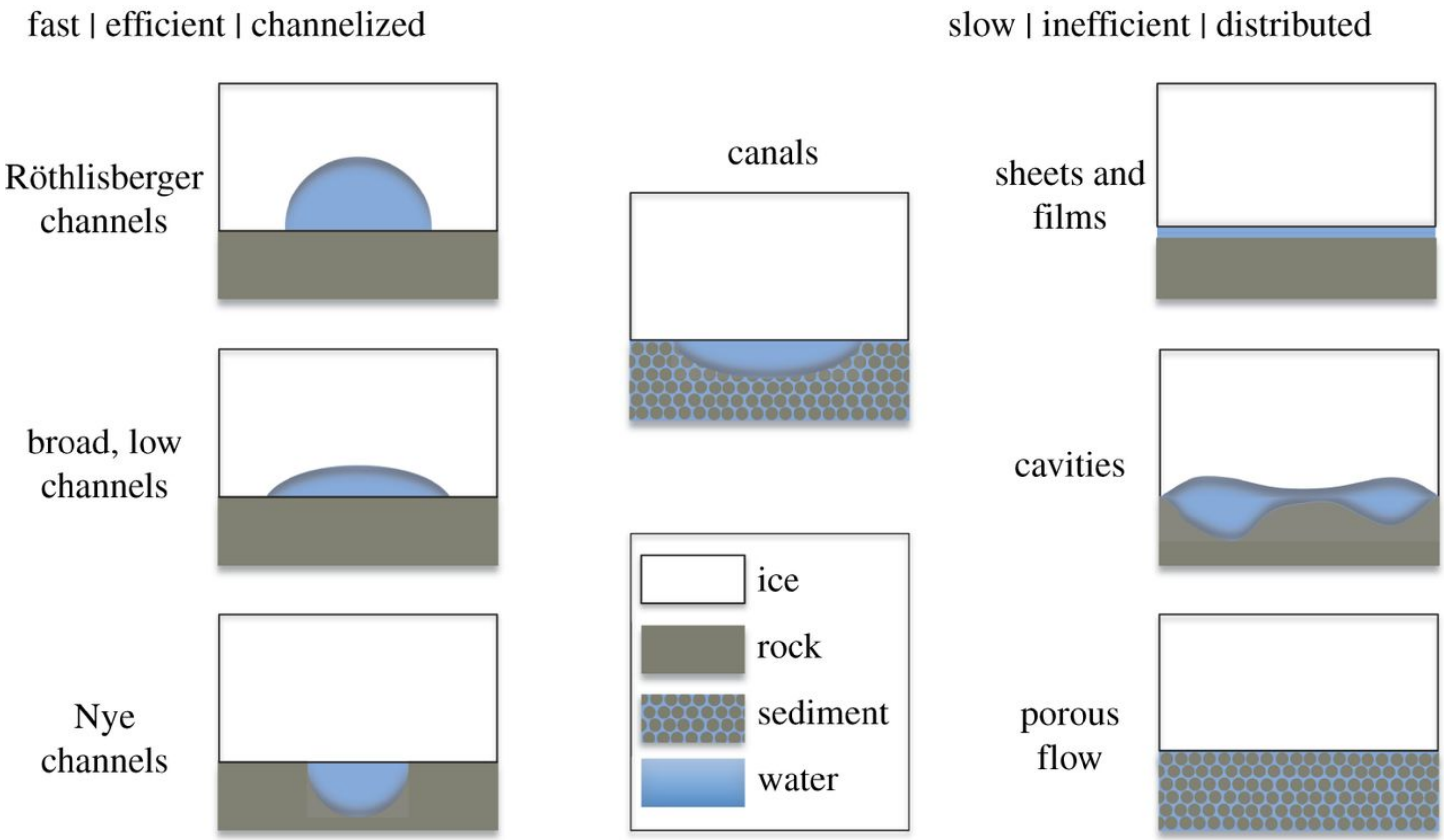
Ice stream shear margins

The shear margin velocity gradient causes shear heating.

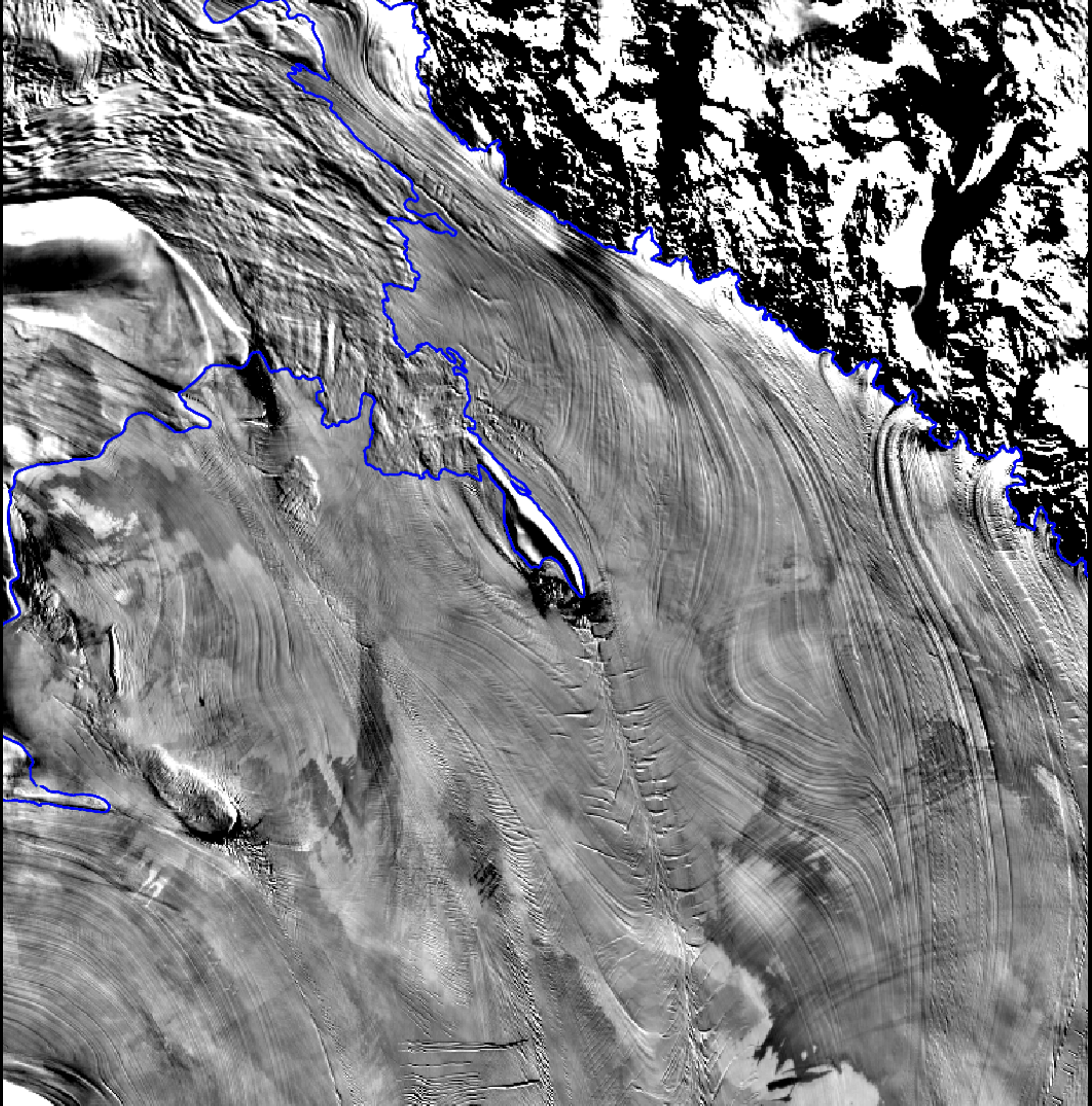


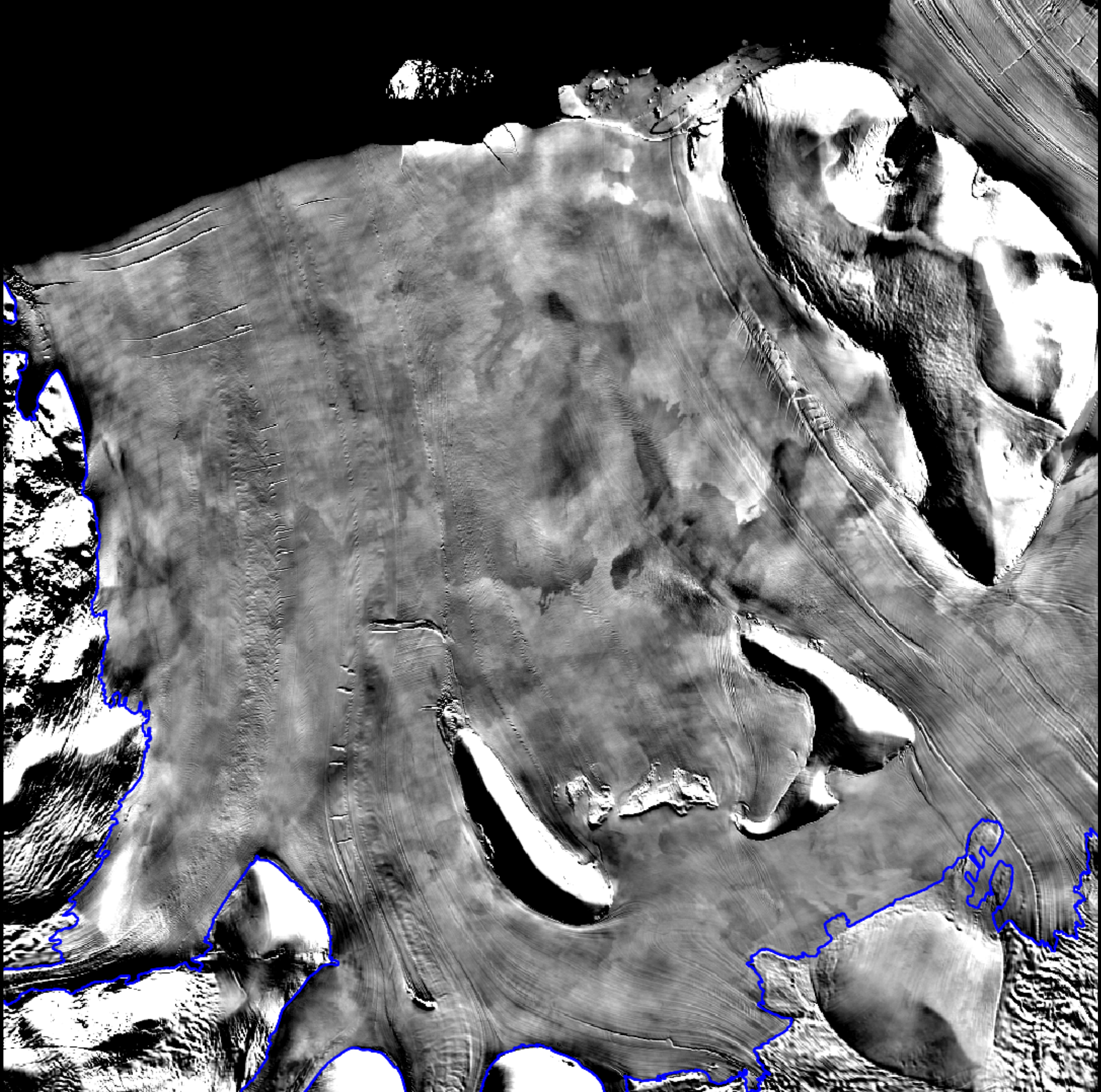
Suckale et al 2014

Subglacial hydrology

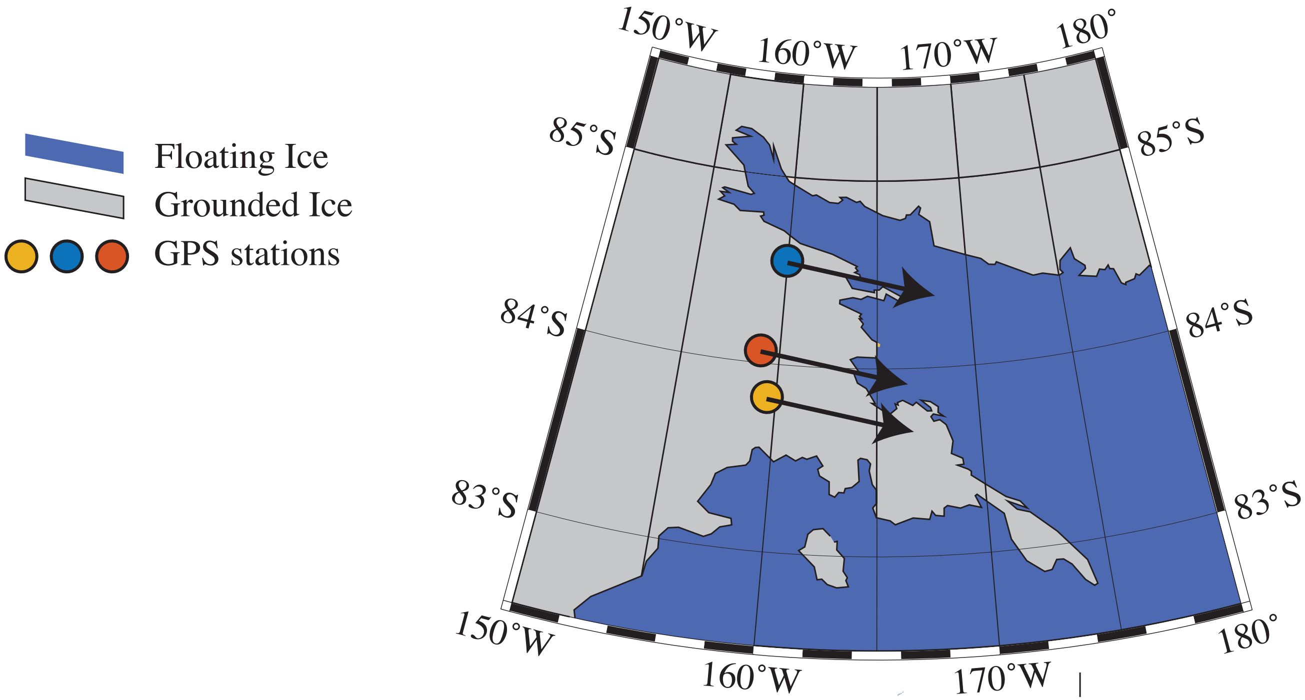


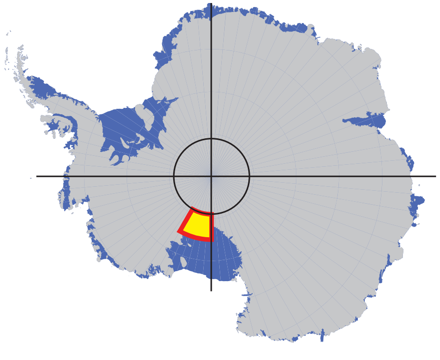
Part 2. Ice stream variability



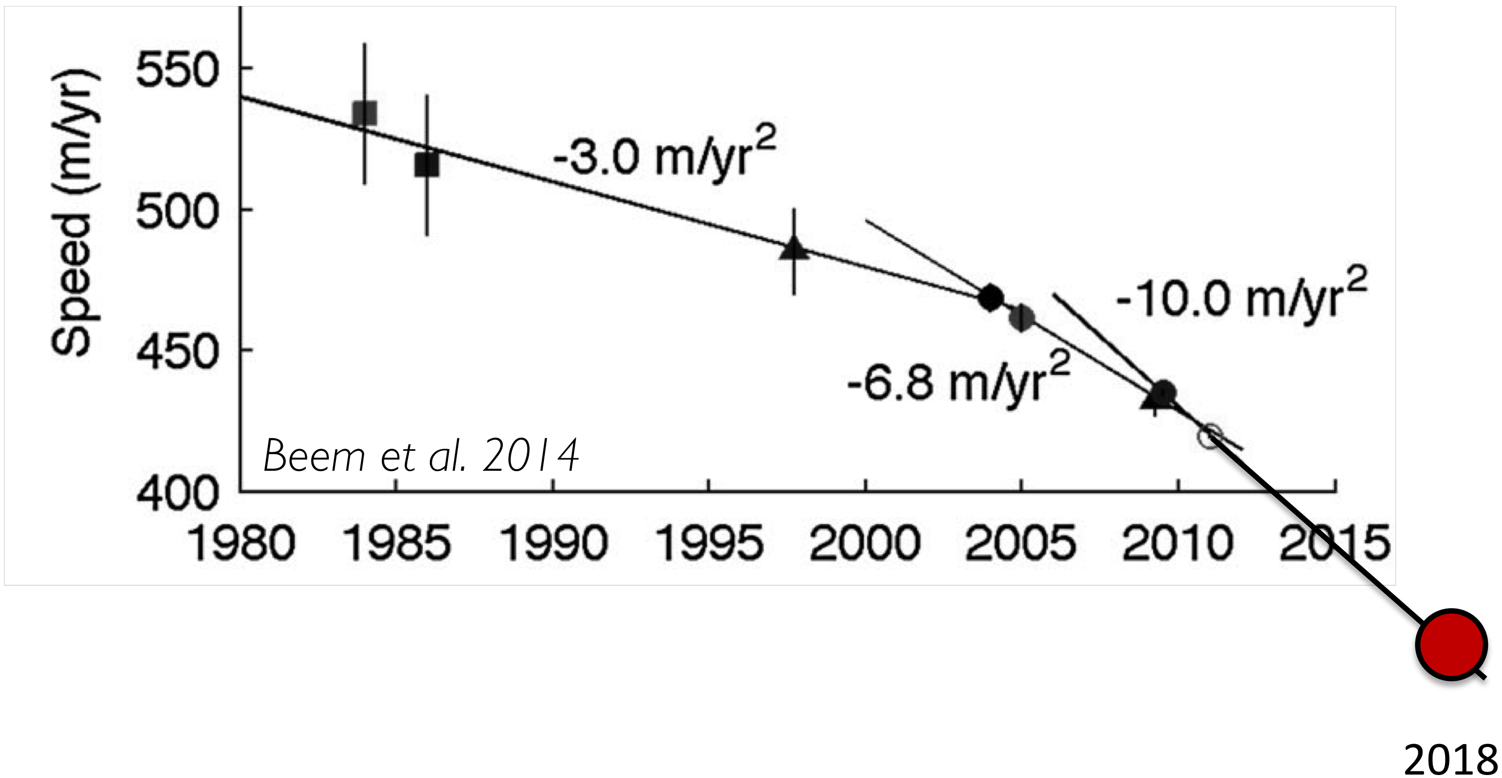


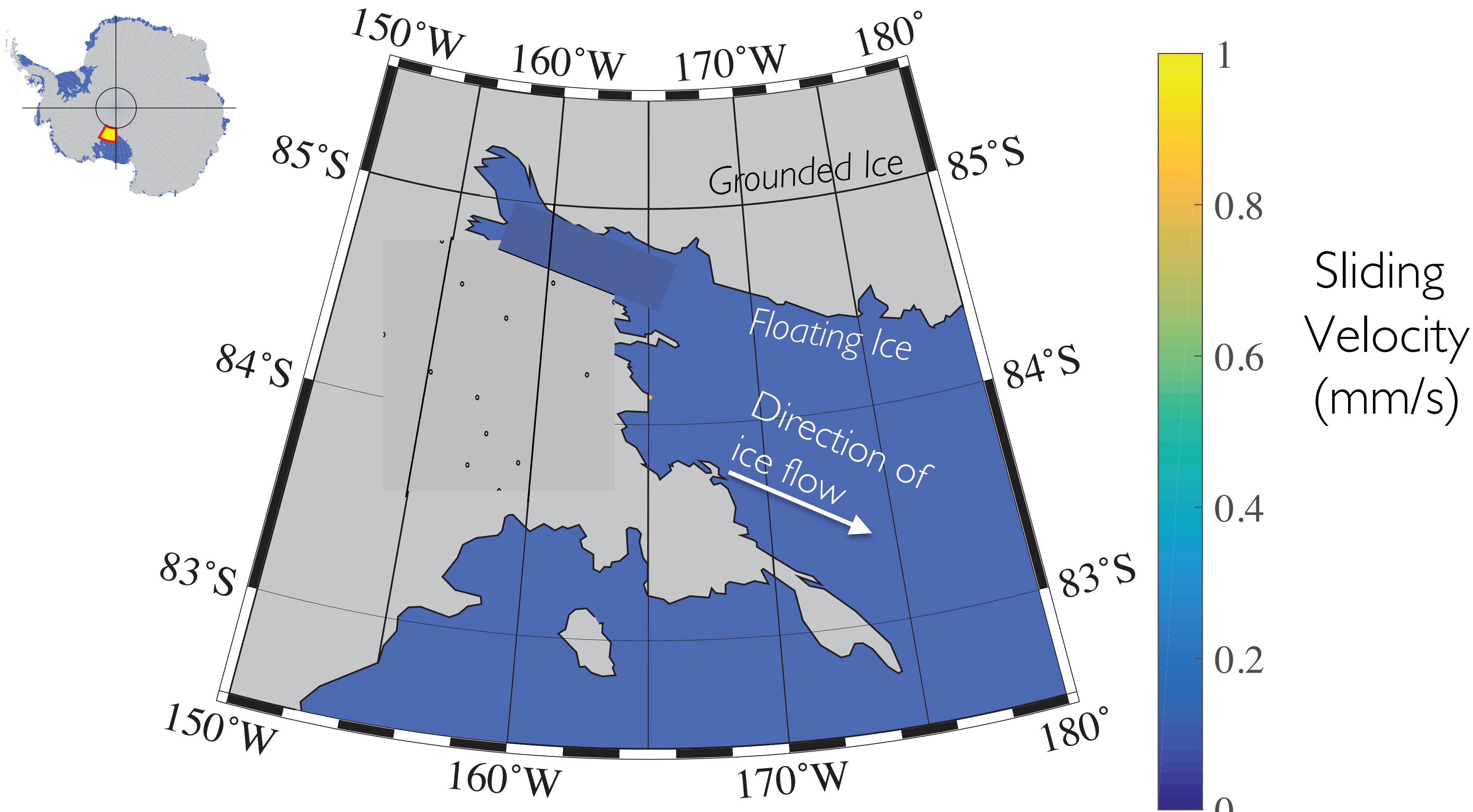
GPS observations





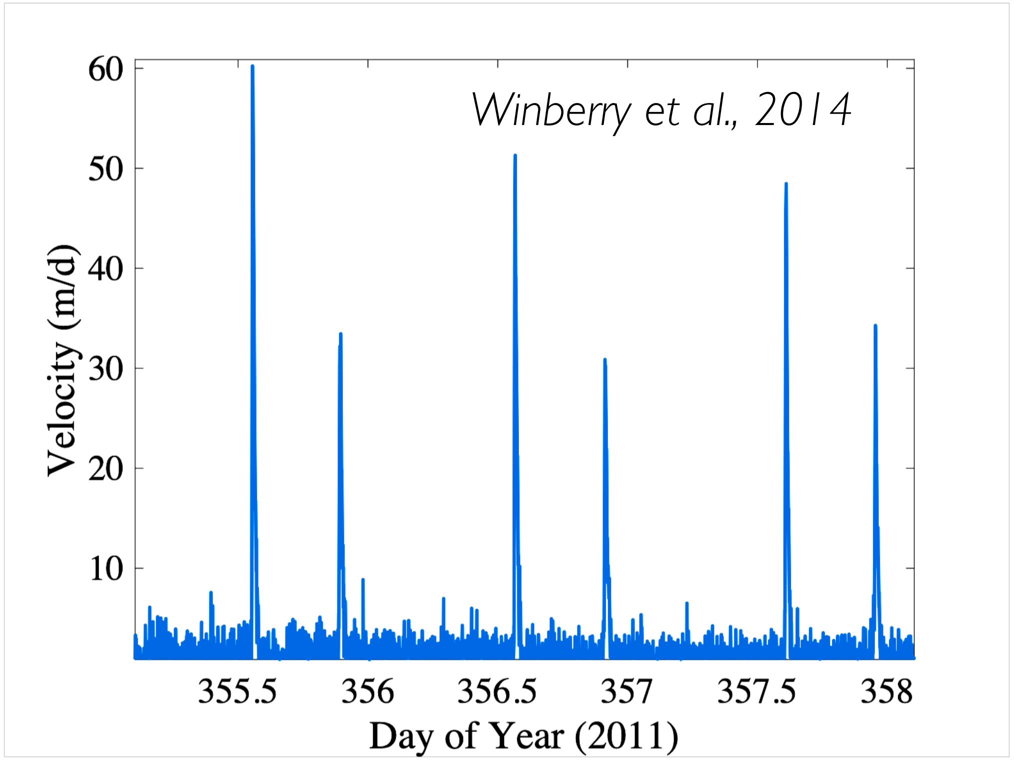
The Whillans Ice Stream is decelerating.



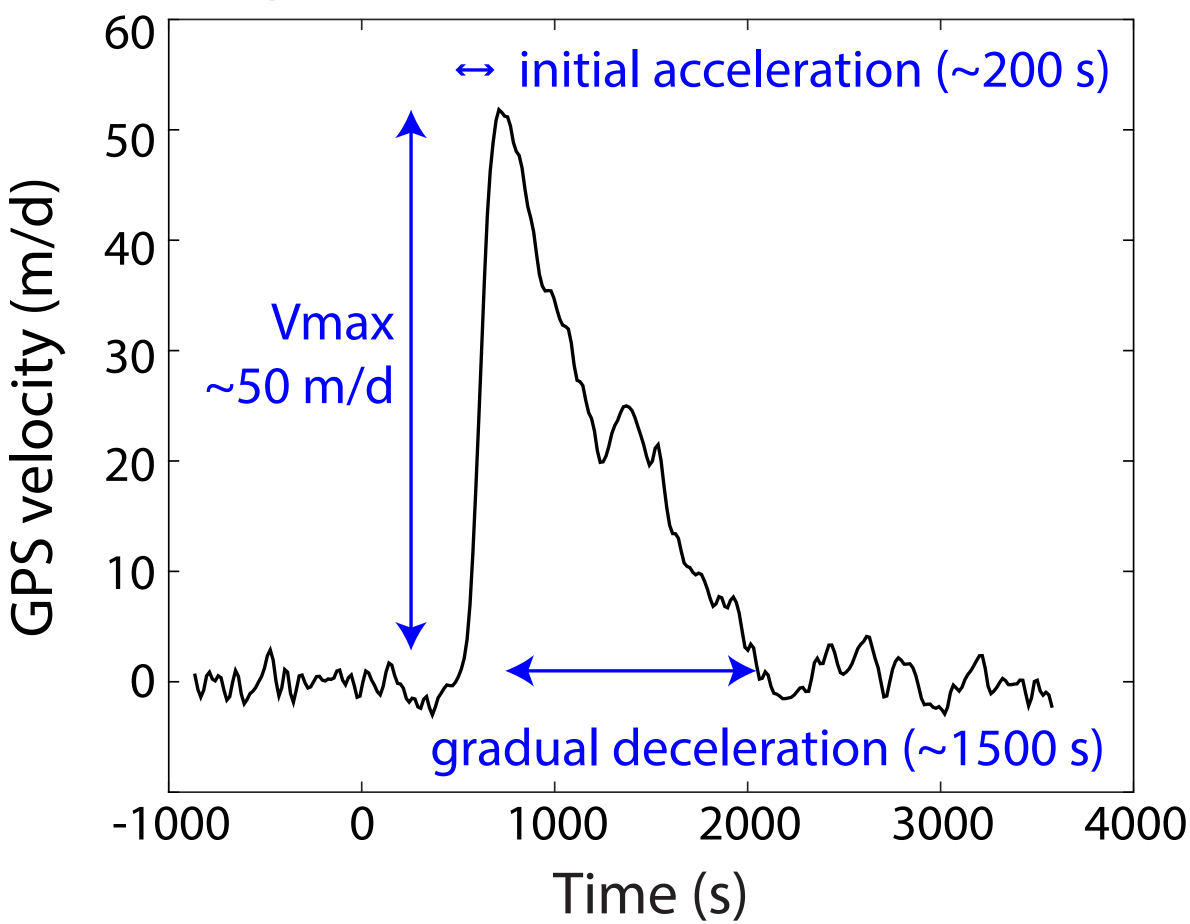


Total duration of sliding is 30 min.

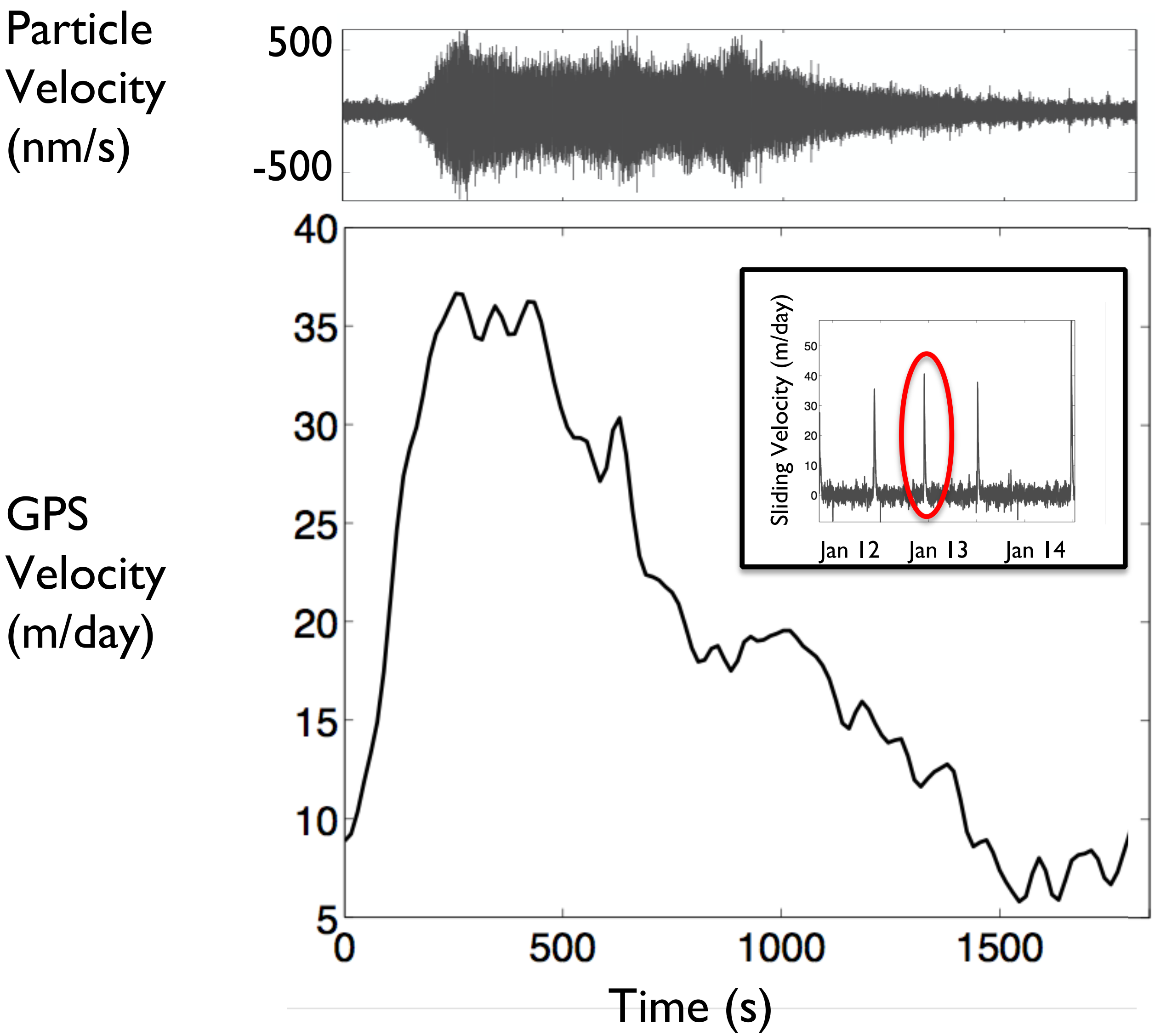
Episodic ice motion



Slip event dynamics



Seismic tremor occurs during sliding.

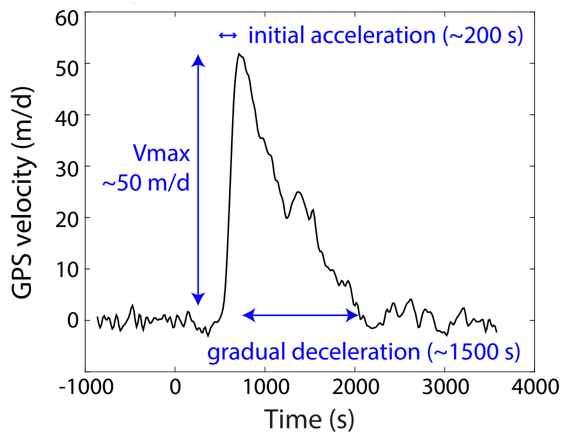


Data from IRIS

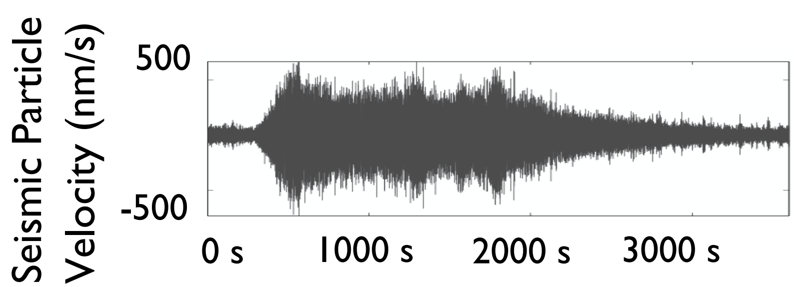
Long term goal: to quantify the processes that determine the strength of the ice-bed interface.

I **validate** an improved glacier sliding law against two observations:

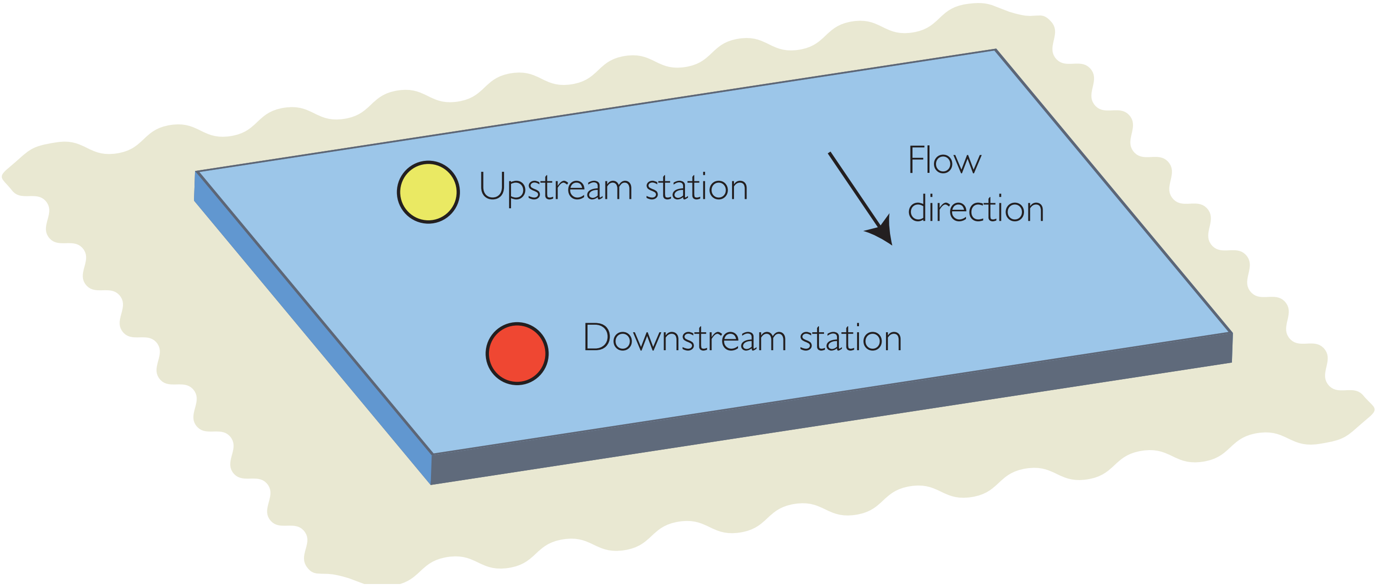
1. Ice stream stick slip motion



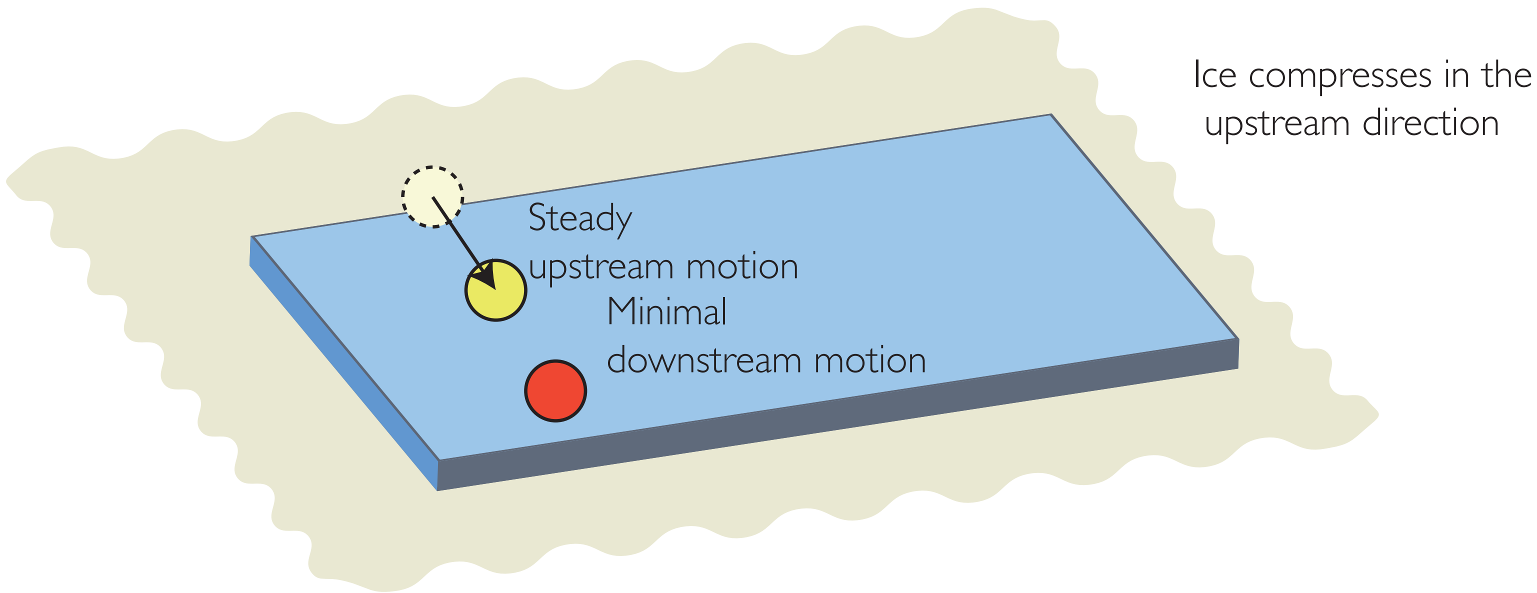
2. Tremor during ice stream slip events



Stick-Slip Cycles: the Sequence of Events

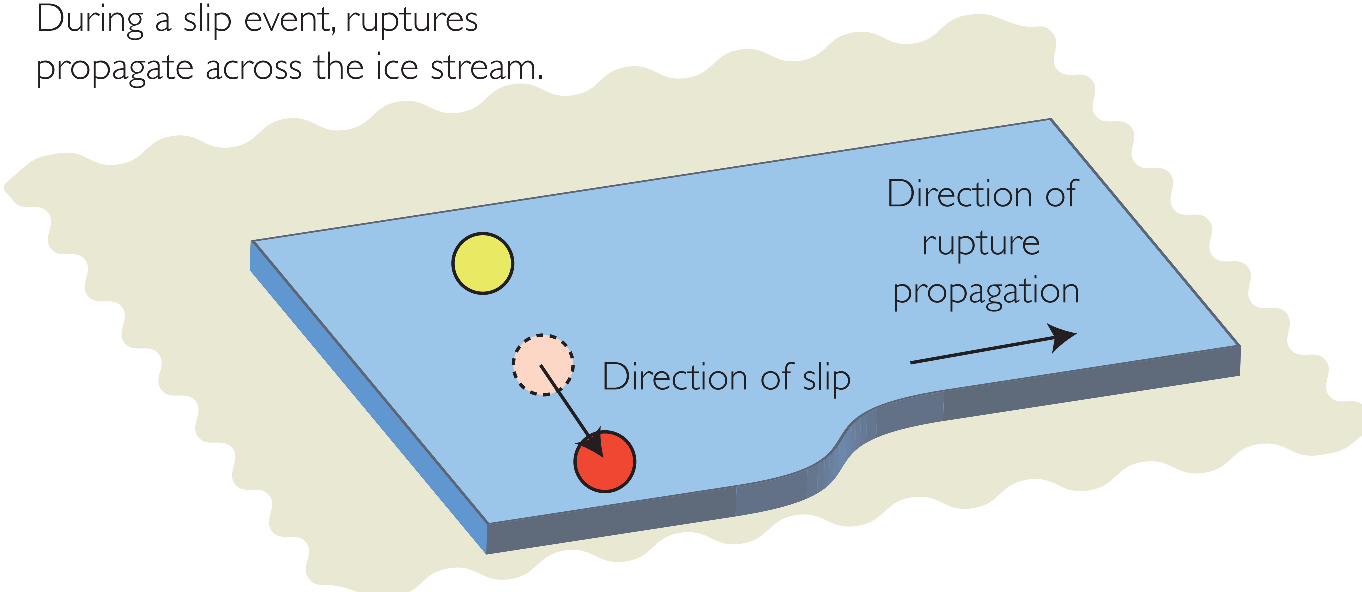


Stick-Slip Cycles: the Sequence of Events



Stick-Slip Cycles: the Sequence of Events

During a slip event, ruptures propagate across the ice stream.



Stick-Slip Cycles: the Sequence of Events

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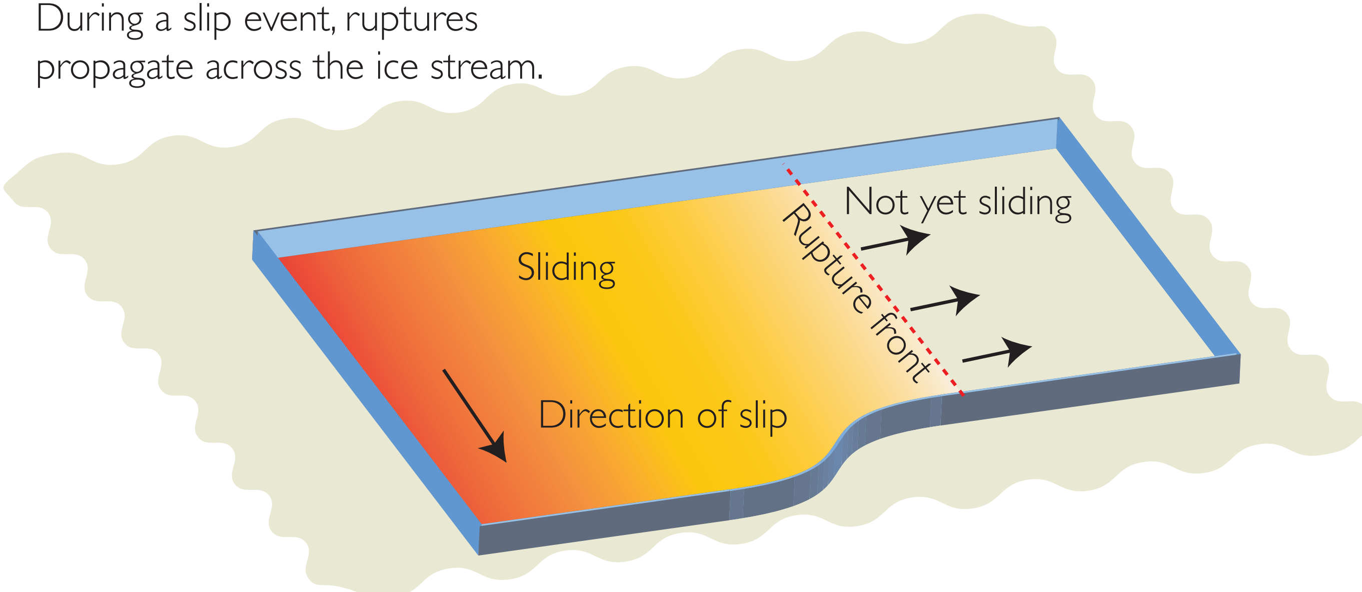
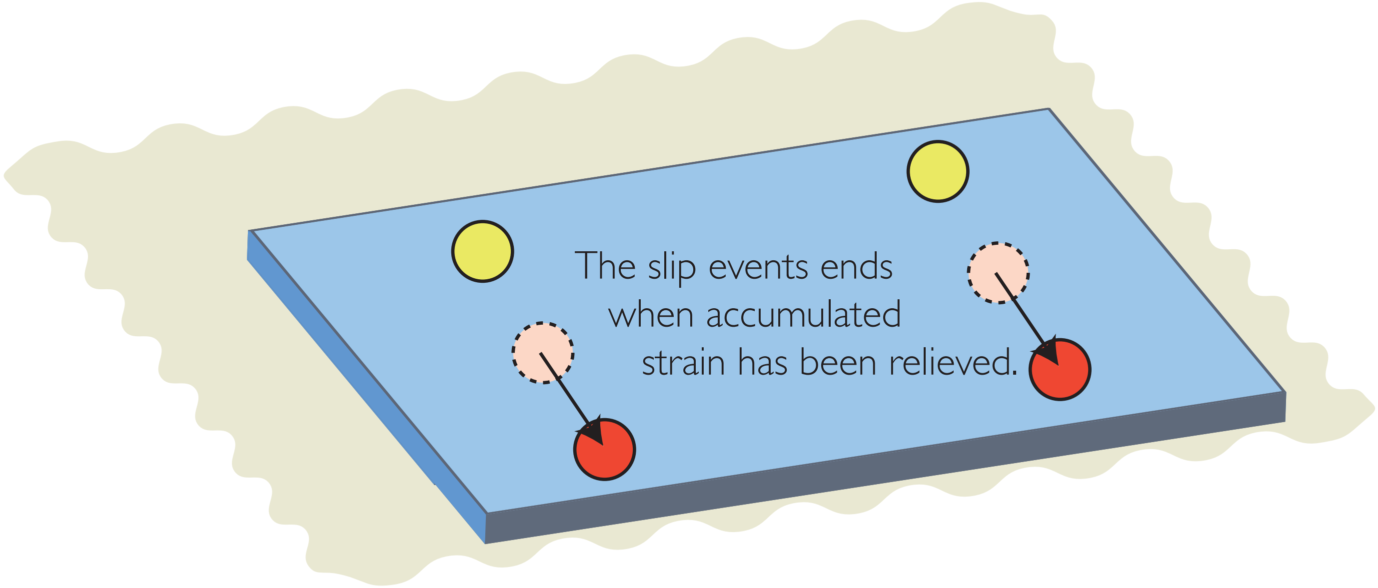
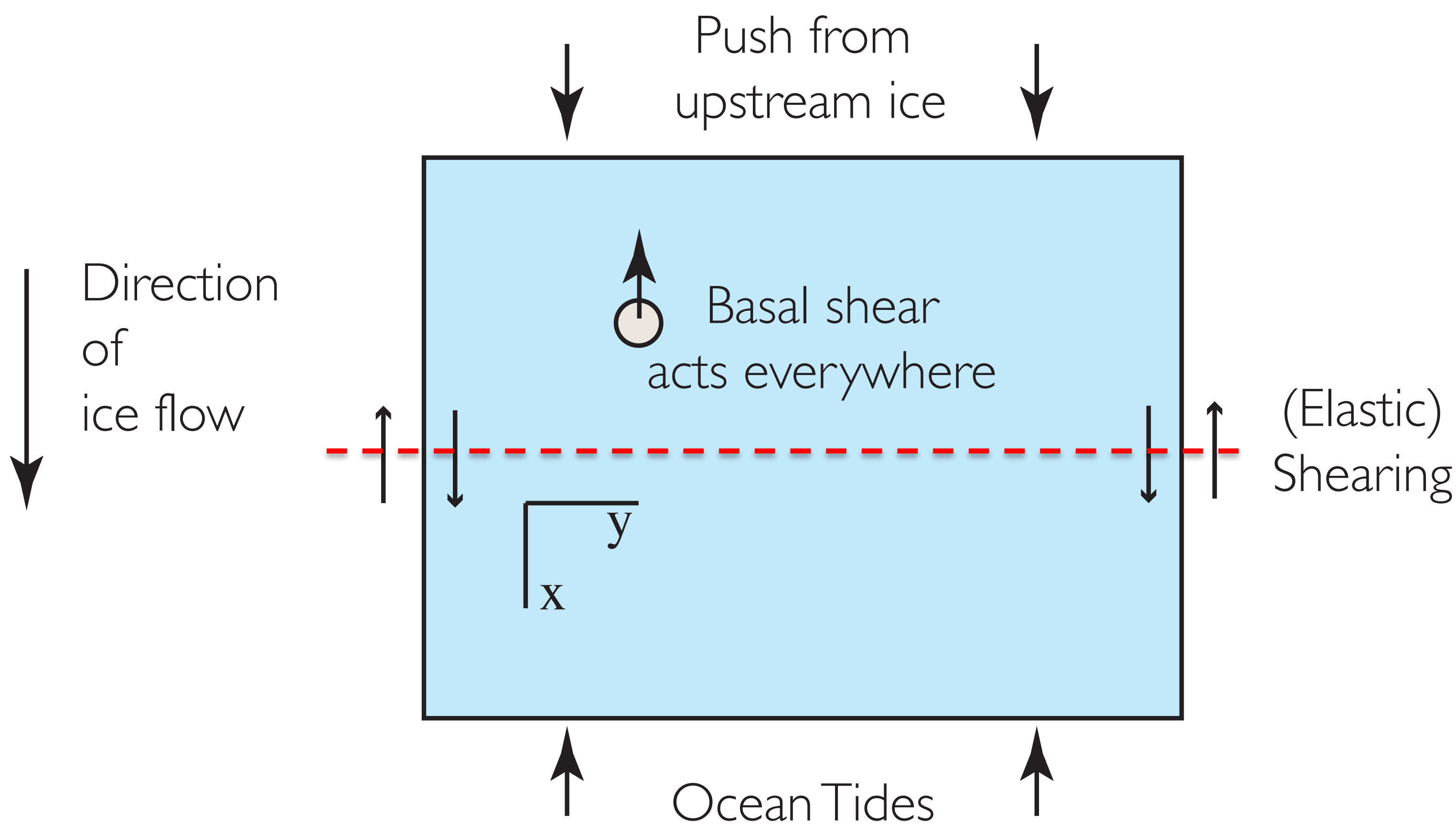


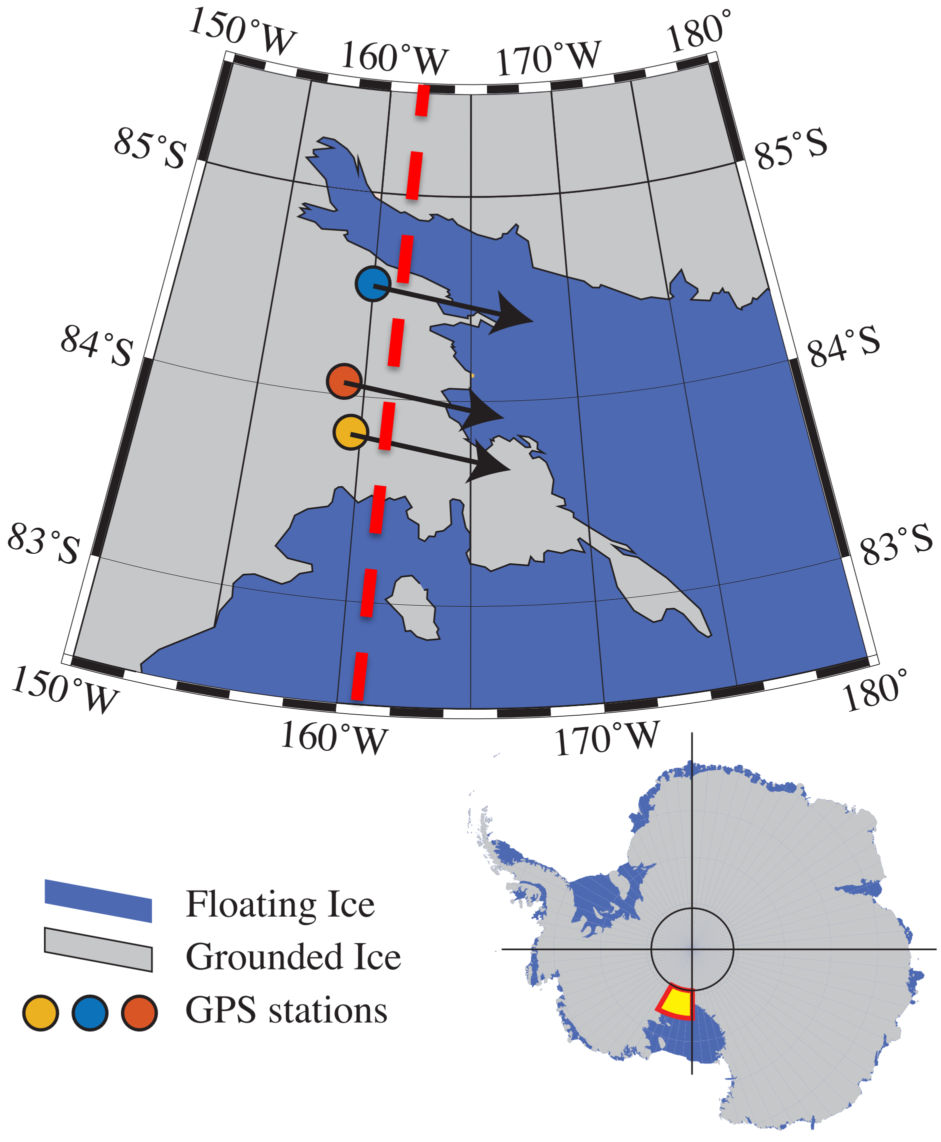
Stick-Slip Cycles: the Sequence of Events



The balance of forces



The balance of forces



The balance of forces

$$\rho \frac{\partial^2 u}{\partial t^2} = \frac{\sigma_{xx}}{L} + G \frac{\partial^2 u}{\partial y^2} - \frac{\tau}{H}$$

Inertia

Longitudinal driving stresses

Vertical elastic shear

Basal shear

Our simplified ice sheet model represents a **depth integrated**, **cross-stream** profile of an ice stream.

Inertia plays only a limited role in our simulations, but including it serves as a check on our predictions.

Most of the interesting dynamics come from the **basal shear stress** term.

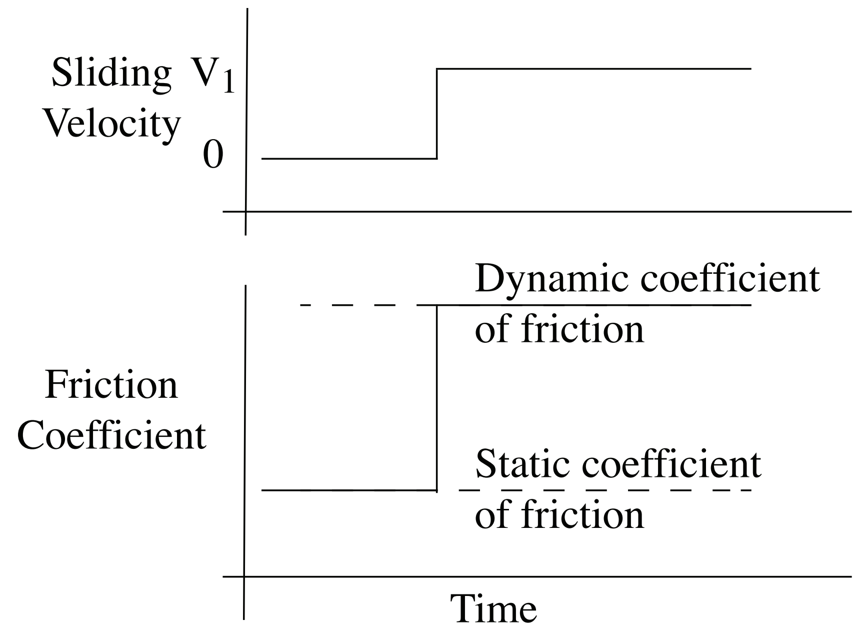
Designing a stick-slip sliding law

During sliding with **Coulomb Friction**, the frictional coefficient instantaneously jumps from a static to a dynamic value.

$$\tau = f\,\sigma$$

Coulomb Friction cannot explain the re-strengthening that causes repeatable slip events

and leads to numerical ill-posedness due to the infinitely sharp transition in strength.

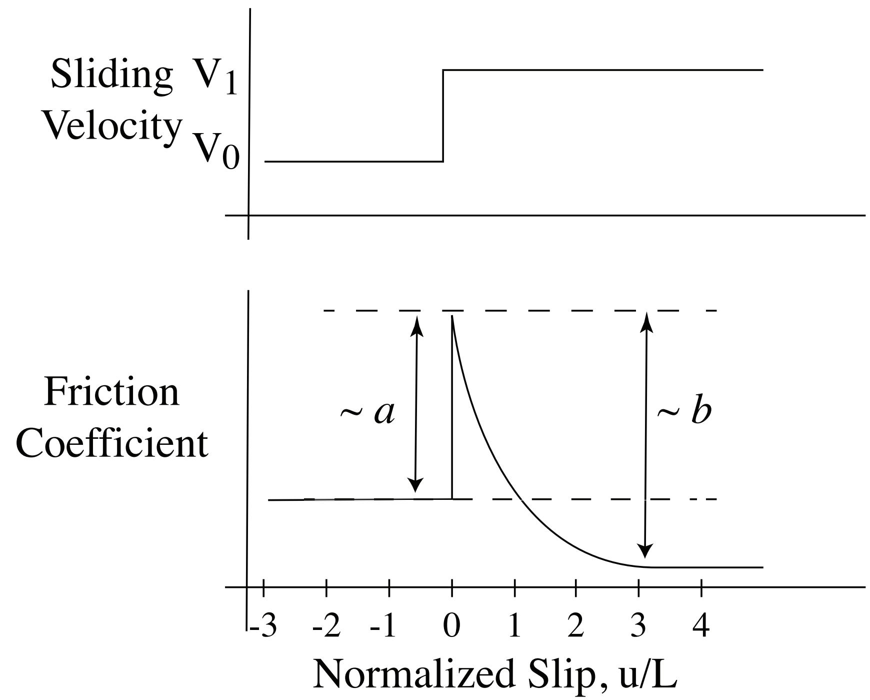


Designing a stick-slip sliding law

We use a **Rate- and State-Dependent Frictional** sliding law. Important properties:

1. An instantaneous strength increase during acceleration (a stabilizing feature),

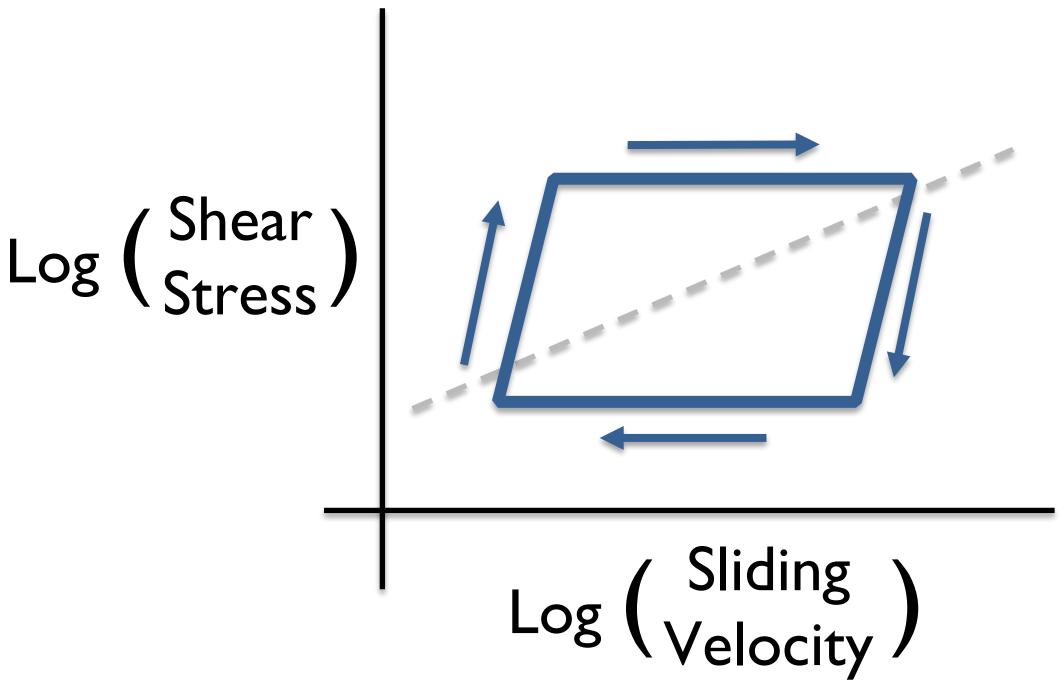
2. Evolution to a steady state value over a slip scale L. Sliding is said to be rate weakening if b>a.



3. Supports both steady and unstable sliding

4. The weakening length scale L is thought to scale with the grain size of the sheared material.

Designing a stick-slip sliding law



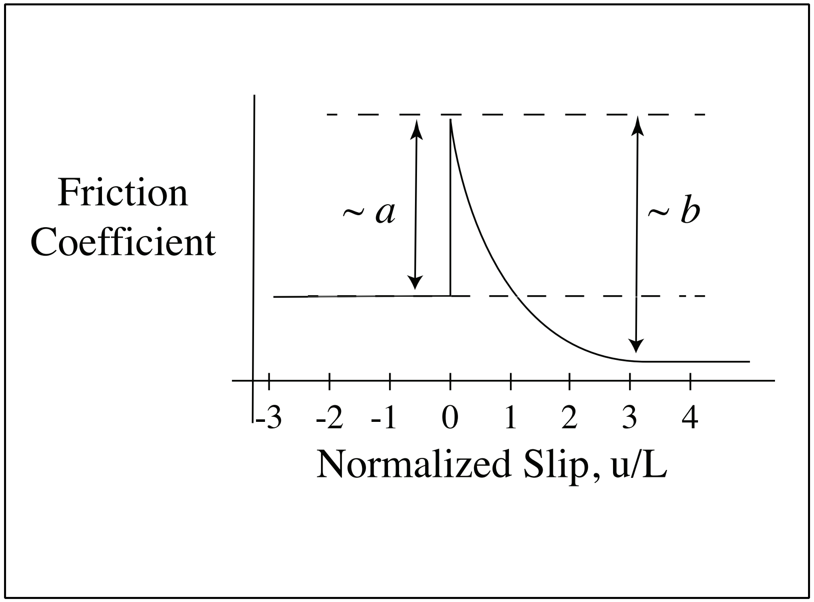
Traditional glacier sliding laws (i.e., Weertman, 1957) are inconsistent with stick slip cycles.

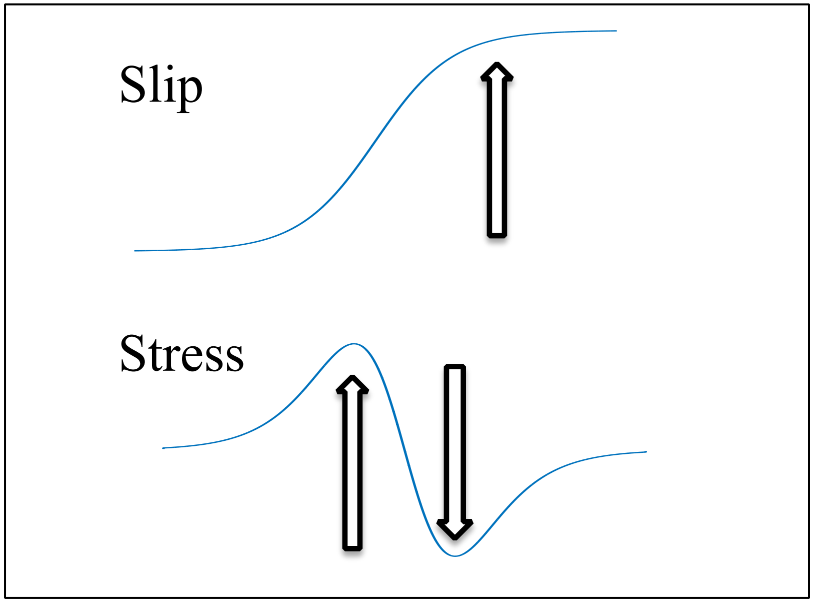
Stick-slip in the presence of steady loading requires a basal sliding law that results in cyclic acceleration and deceleration.

Importantly, traditional glacier sliding laws exhibit unrealistic **unbounded strength** and may therefore overestimate the resistance to forces that favore ice acceleration.

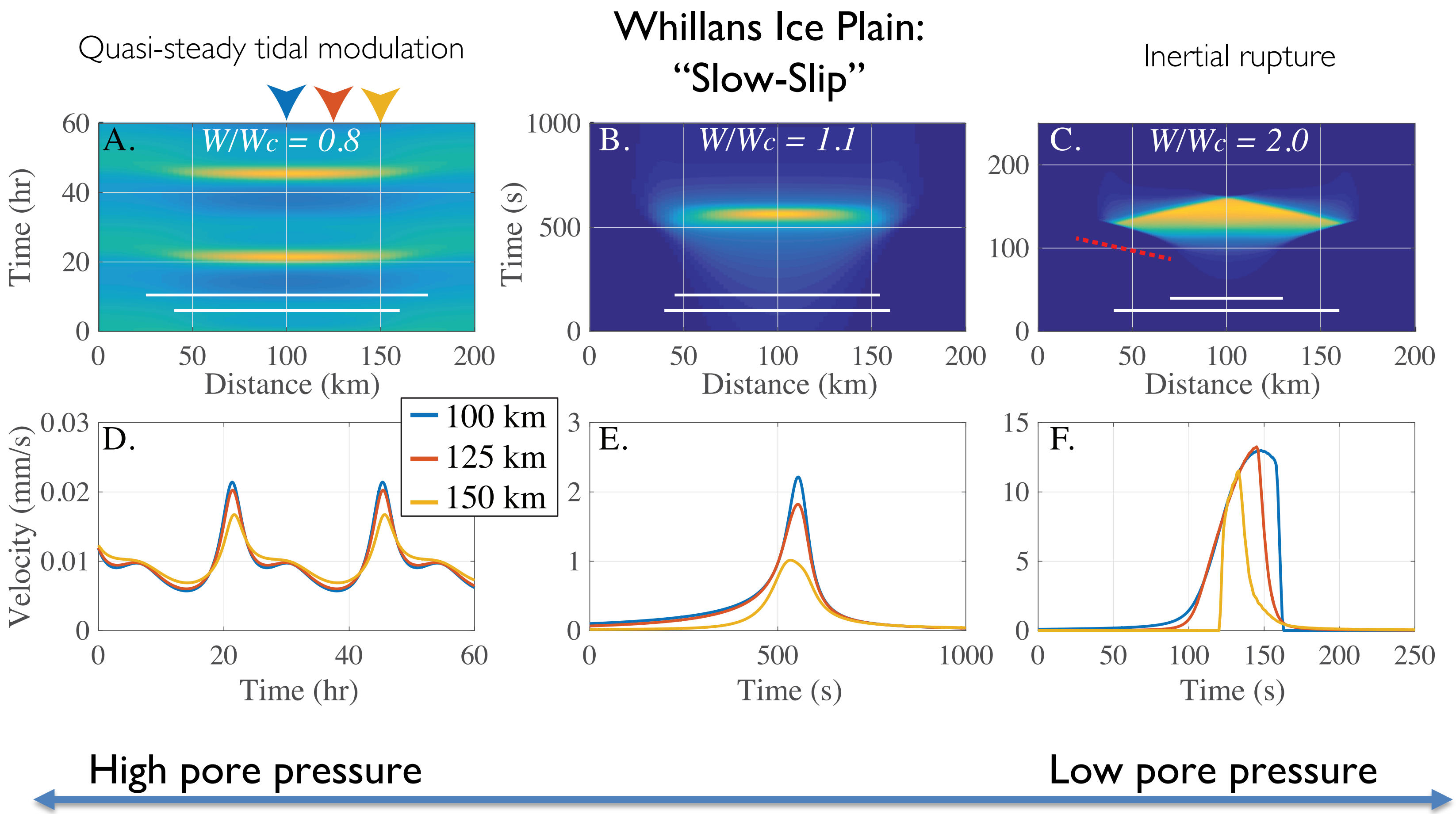
One sliding law, two behaviors

The transition between steady sliding and stick-slip occurs because of a balance between **frictional weakening** and **elastic restoring force**:





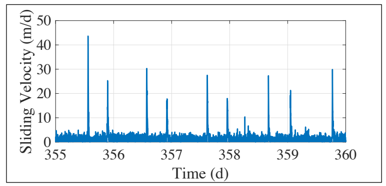
Fast slip and Slow Slip



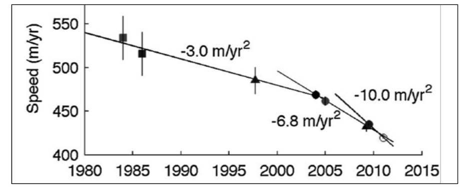
Slow slip events happen in a unique range of parameter space:

- Pore pressures are low enough to cause stick—slip cycles, yet
- Pore pressures are high enough to avoid inertial ruptures.

Stick-slip cycles are consistent stagnation



$\overset{?}{\sim}$



1. Low water pressure causes stick-slip cycles:

frictional weakening due to sliding $>$ elastic resistance to slip

depends on water pressure

2. Lower water pressure increases the absolute level of resistive shear stress

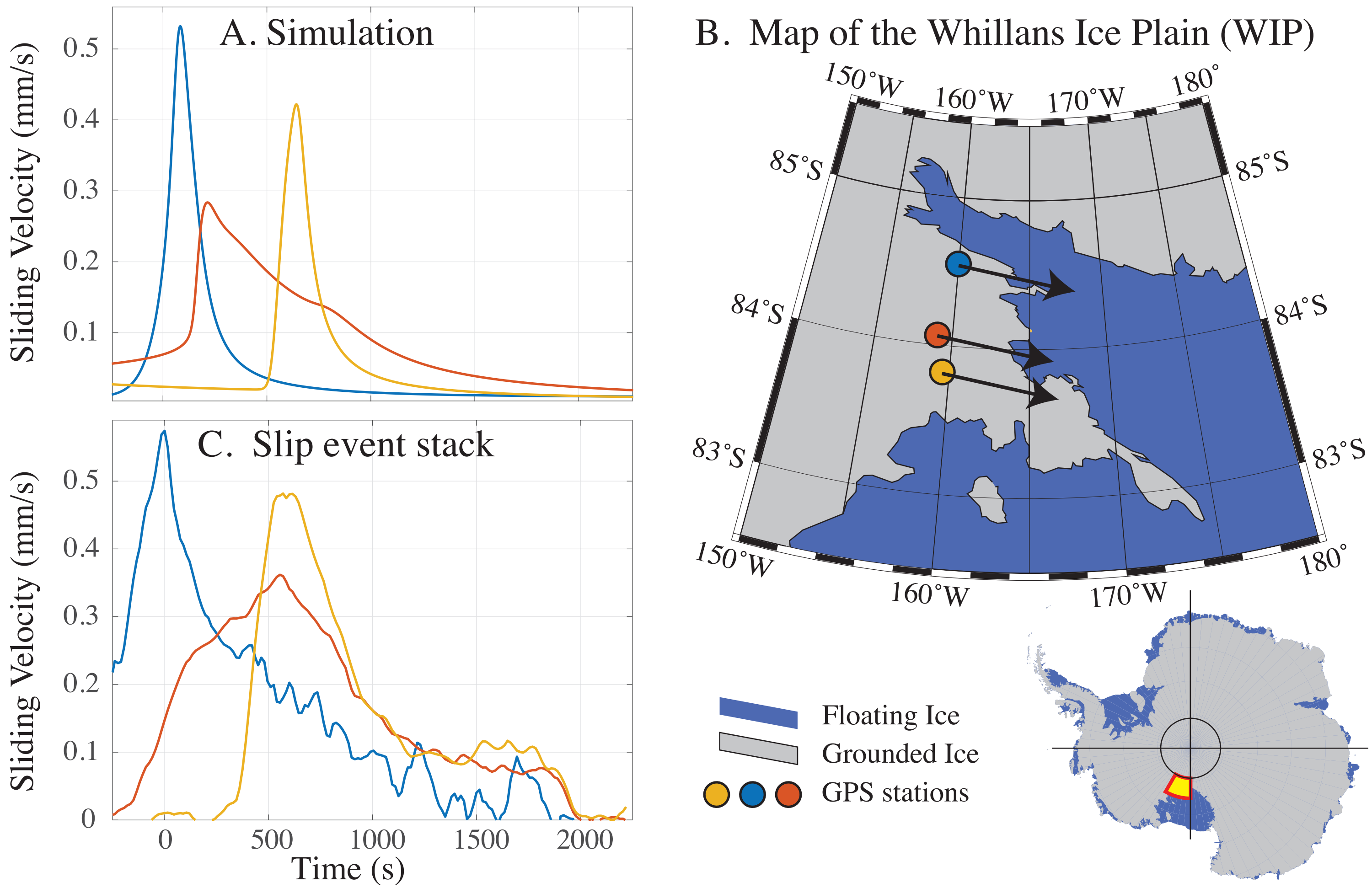
Basal Resistive Stress $>$ Driving Stresses

Also depends on water pressure

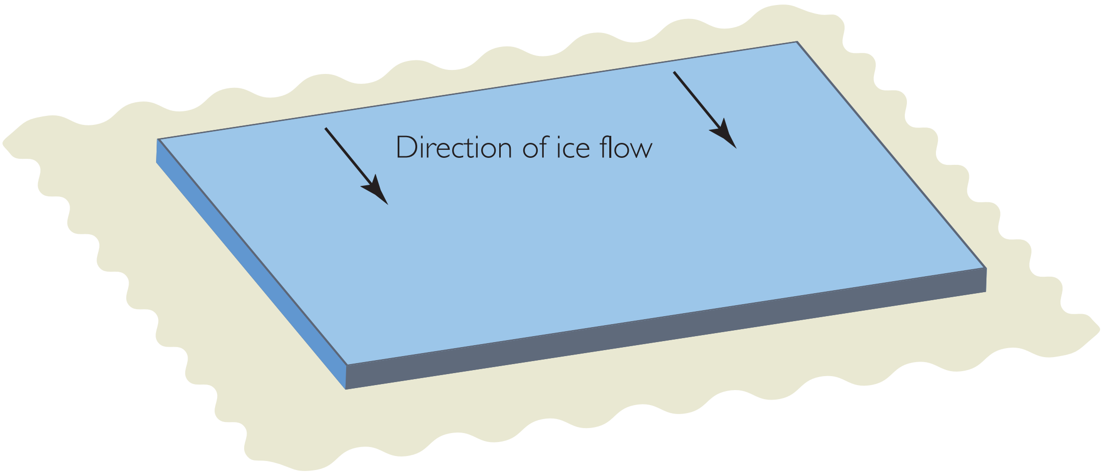
***Absolute strength* and *weakening rate* both depend on effective pressure.**

Details: The critical pore pressure p_* results from a linear stability analysis of perturbations to steady frictional sliding with rate and state friction (see, for example Rice et al., 2001; Lipovsky and Dunham, 2016).

Rupture Dynamics

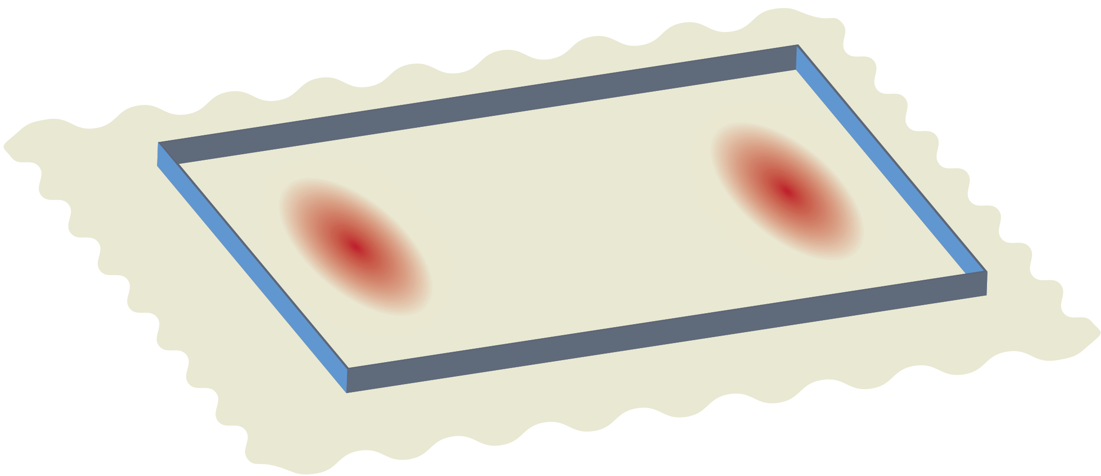


A picture of conditions at the bed



A picture of conditions at the bed

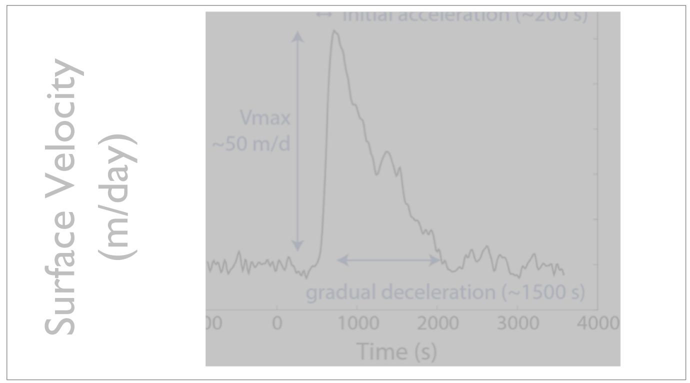
Rupture propagation occurs as the onset of slip moves from one weakening zone to another.



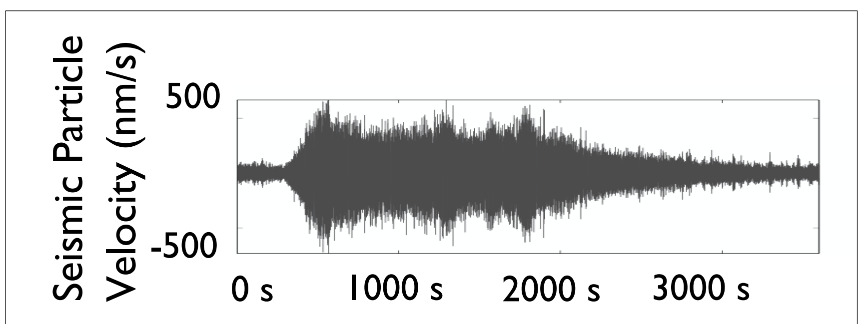
We still have not addressed the details of the weakening zones…

Part 3. Glacier microseismicity

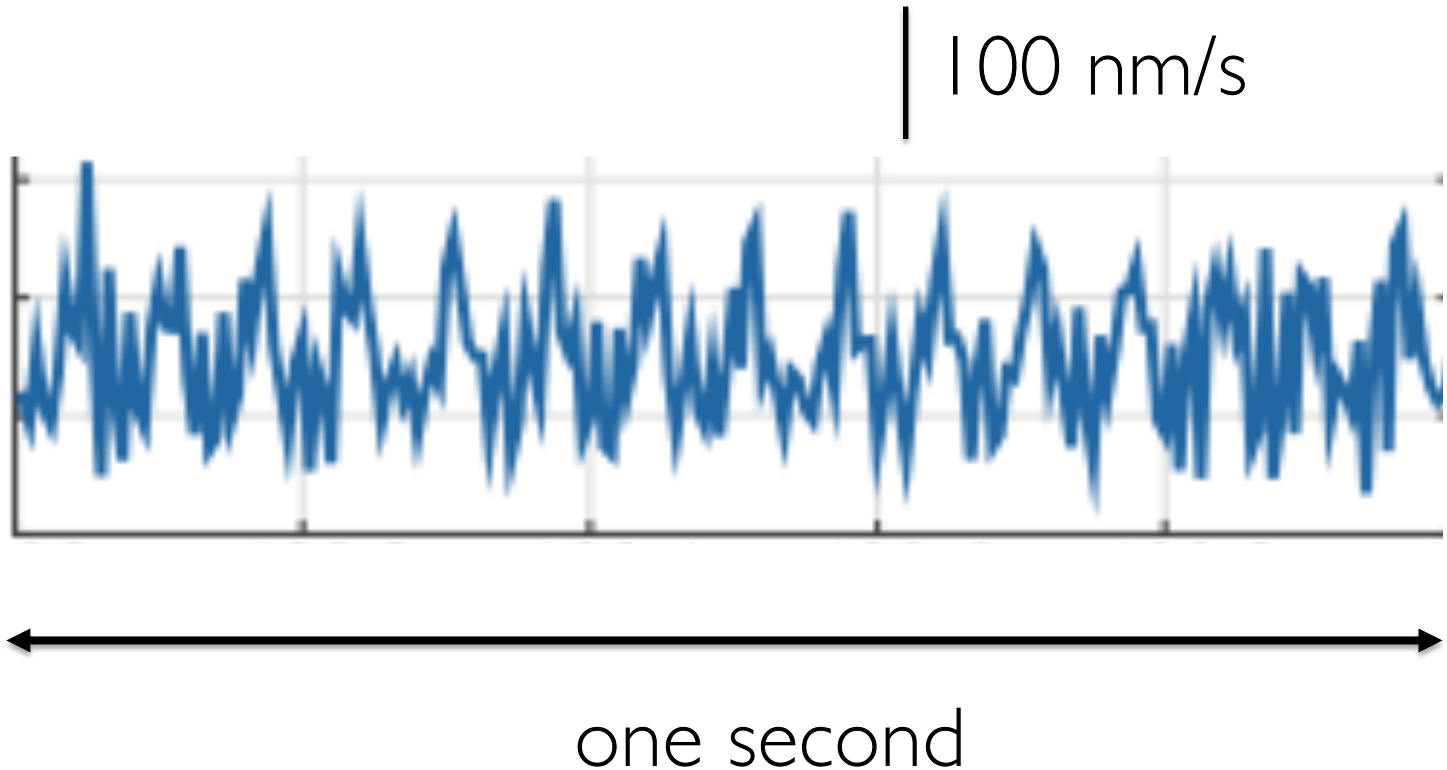
1. Ice stream stick slip motion



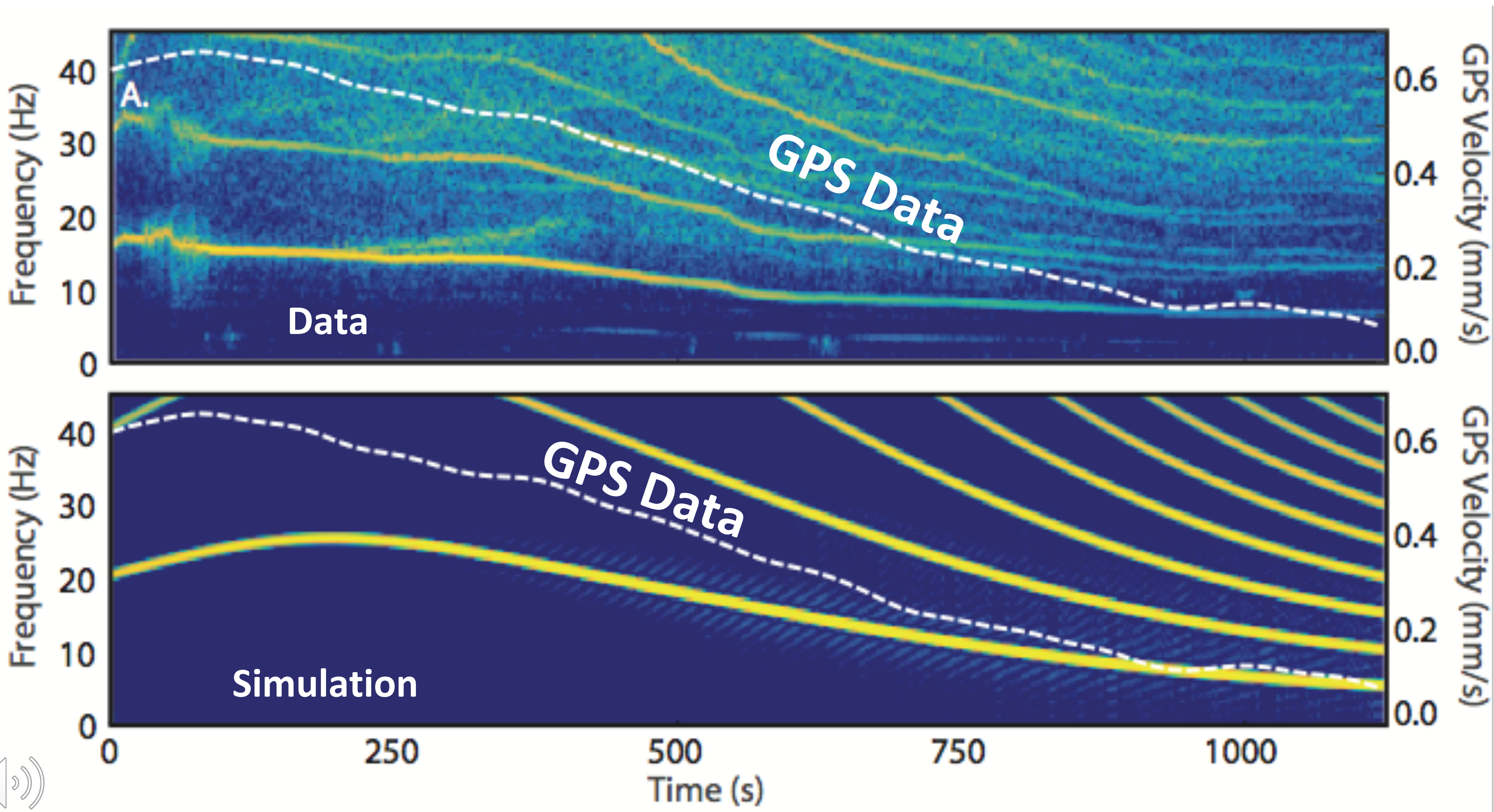
2. Tremor during ice stream slip events



Seismic tremor occurs during slip events.

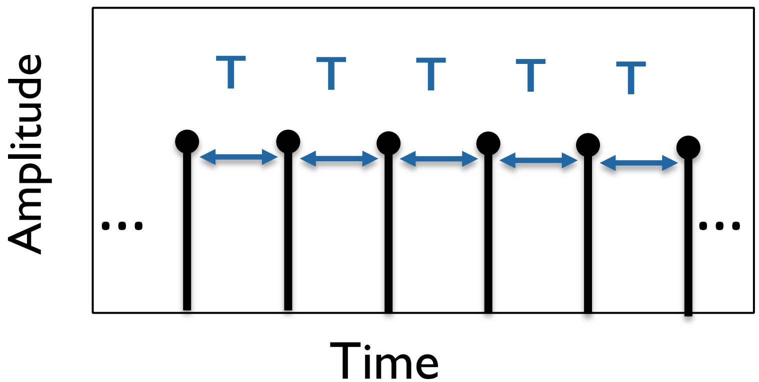


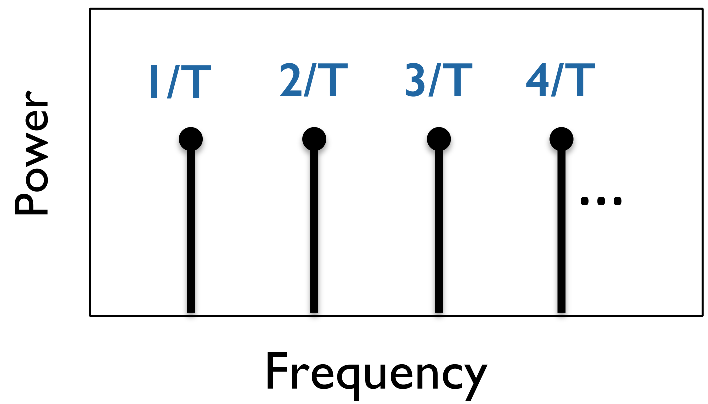
This shows 20 earthquakes per second.



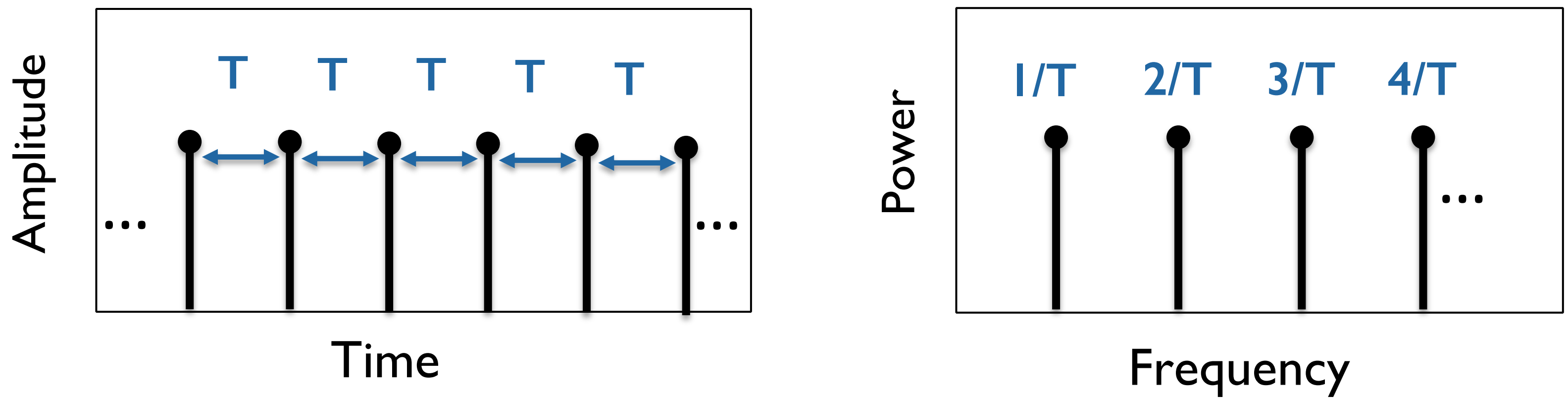
Same log-power color-scale in both figures

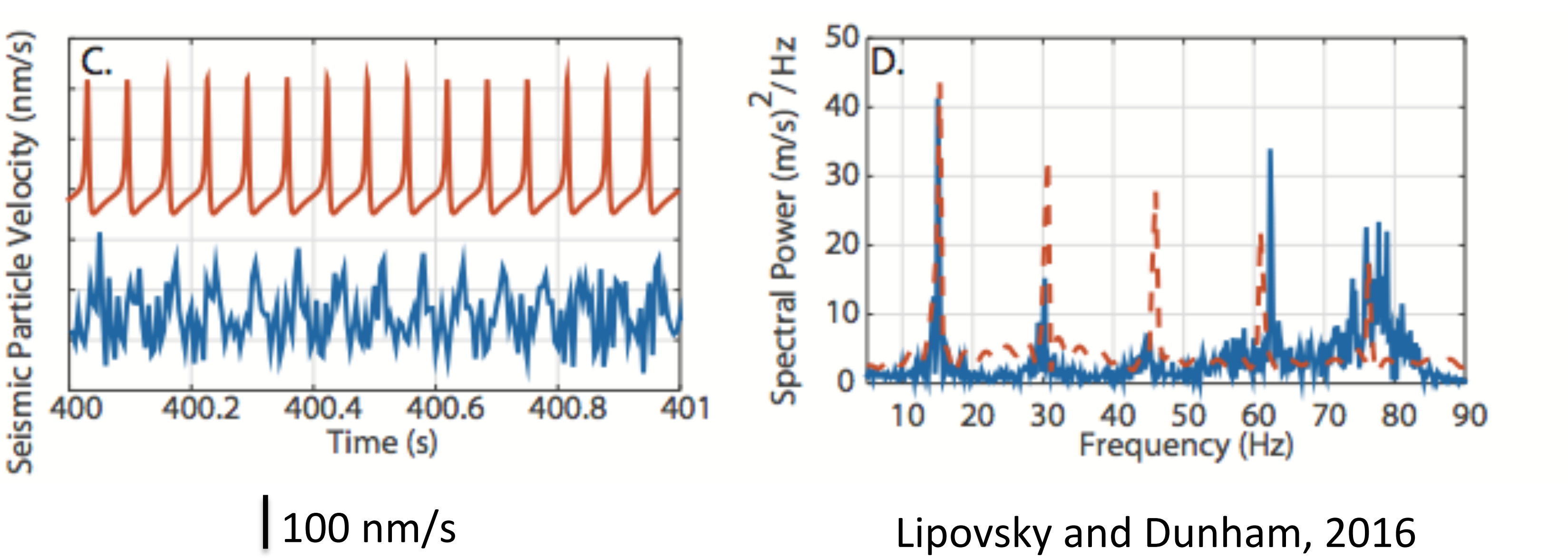
Periodic earthquakes have periodic spectra.



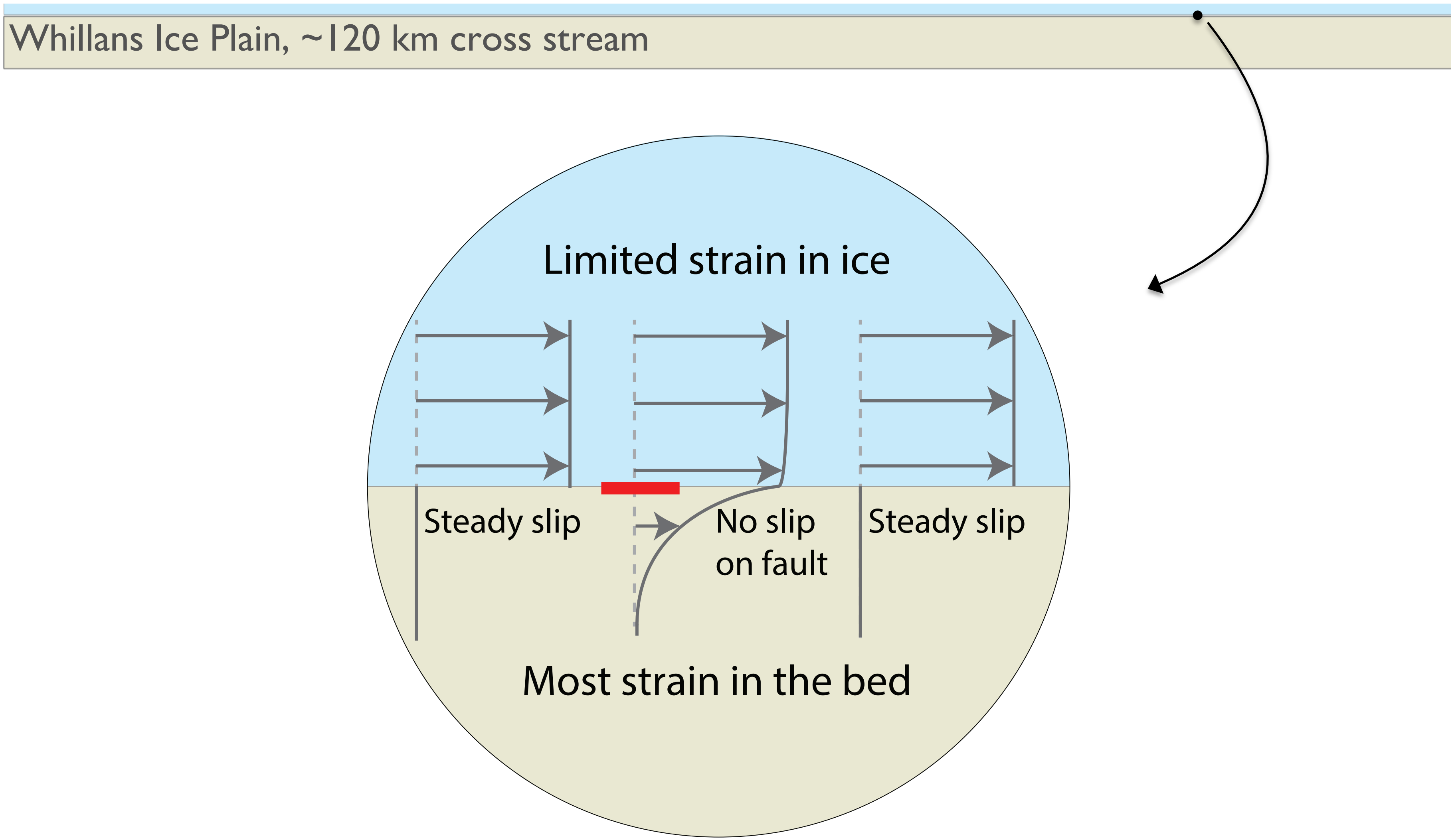


Periodic earthquakes have periodic spectra.

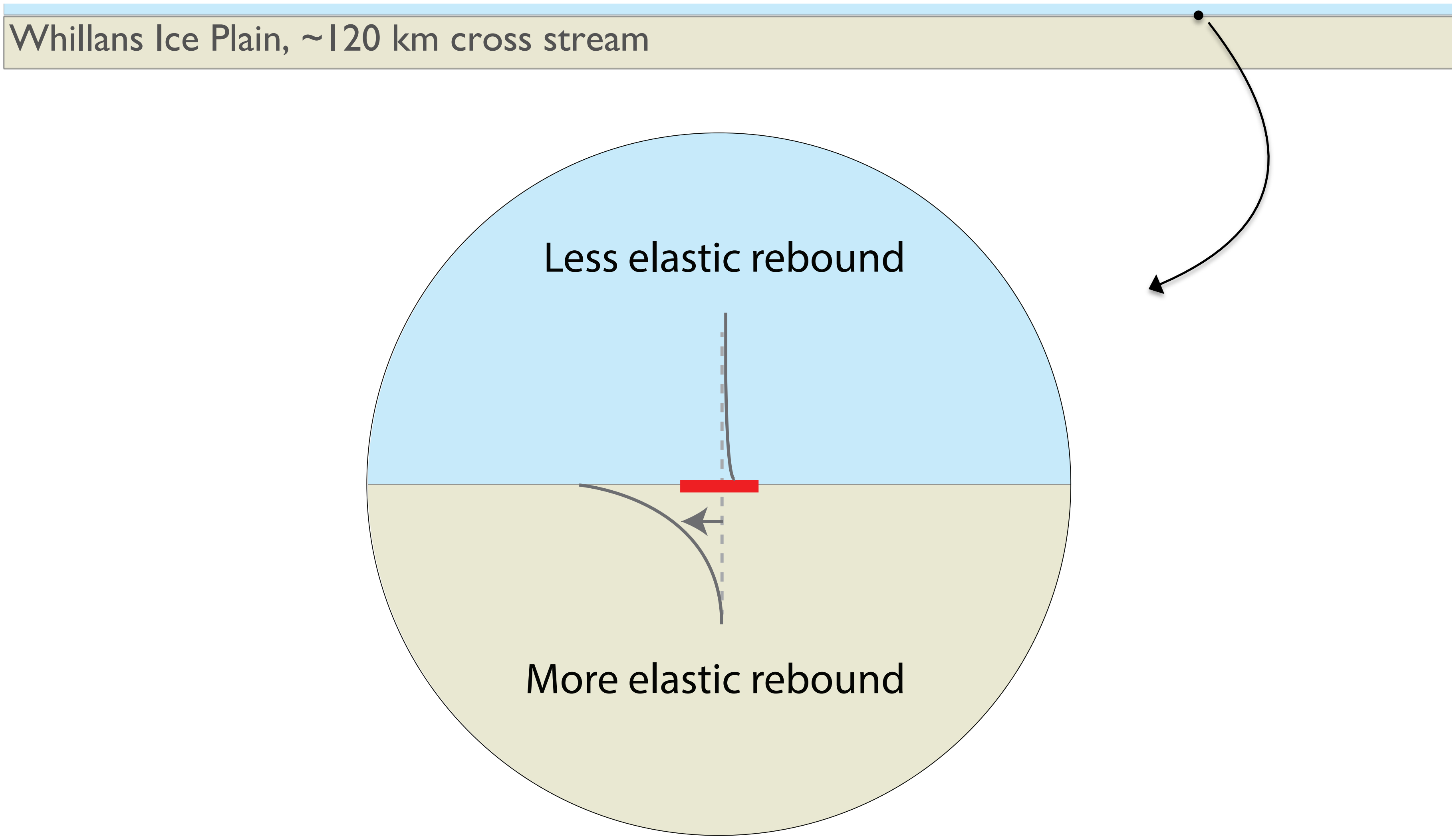




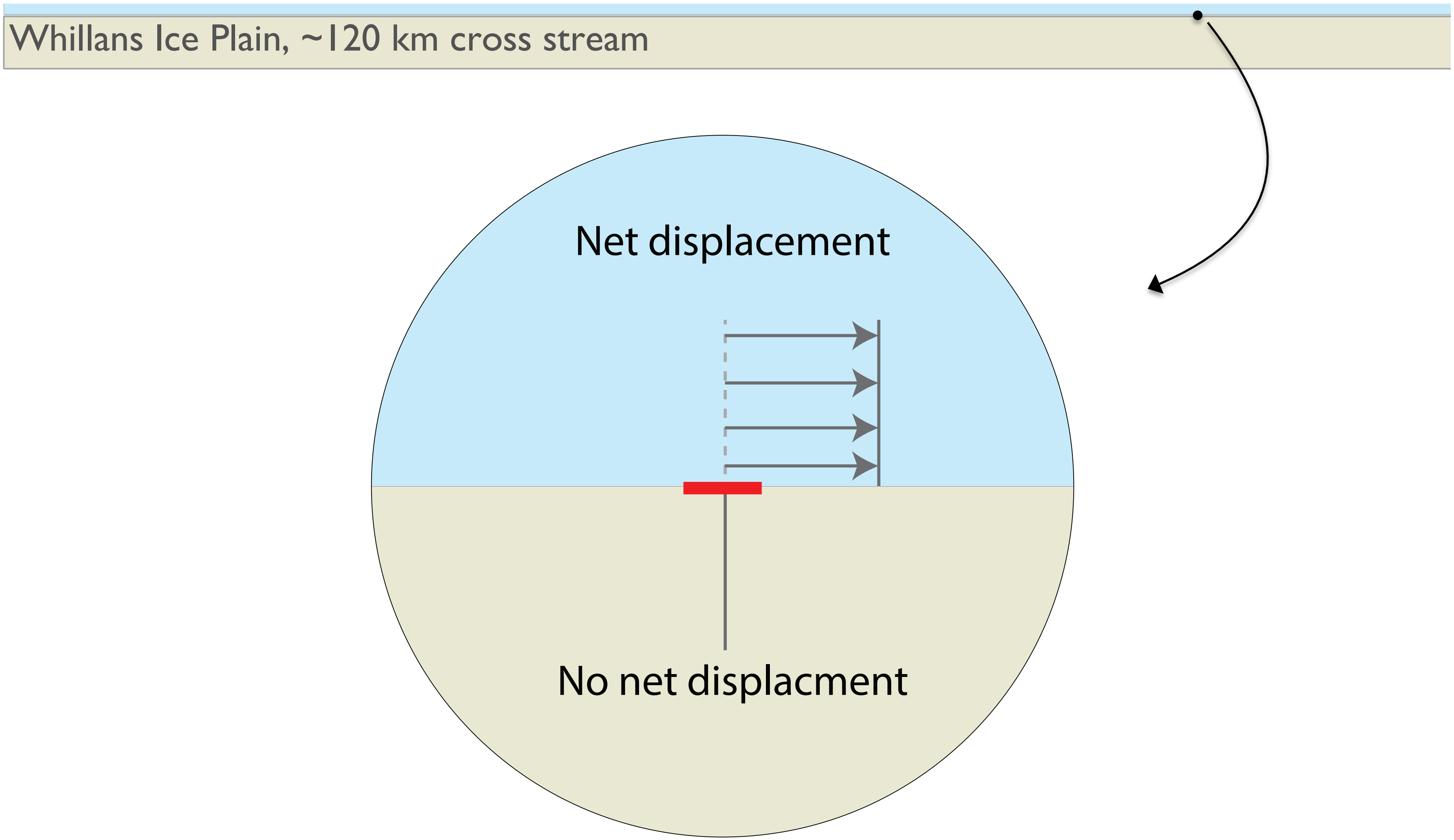
Lipovsky and Dunham, 2016



Lipovsky and Dunham, 2016

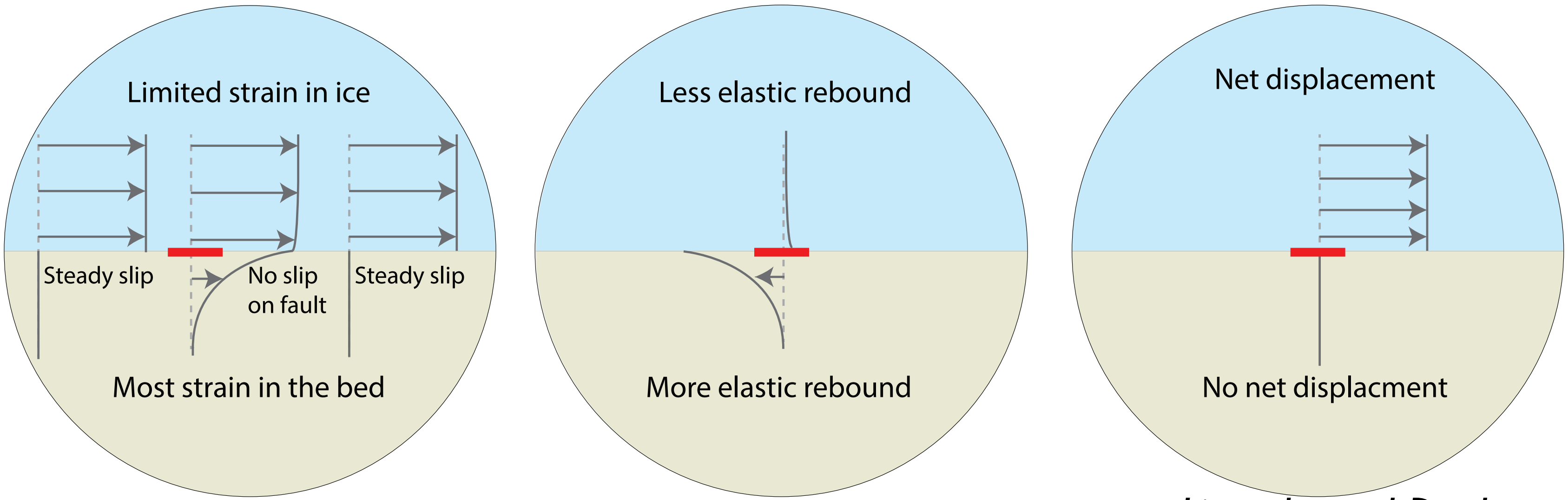


Lipovsky and Dunham, 2016



Lipovsky and Dunham, 2016

Tremor and slow slip: Both modeled with same sliding law

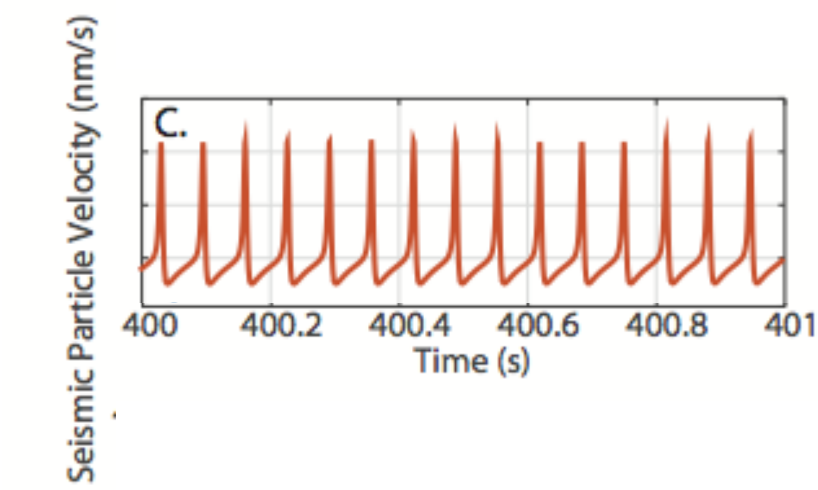


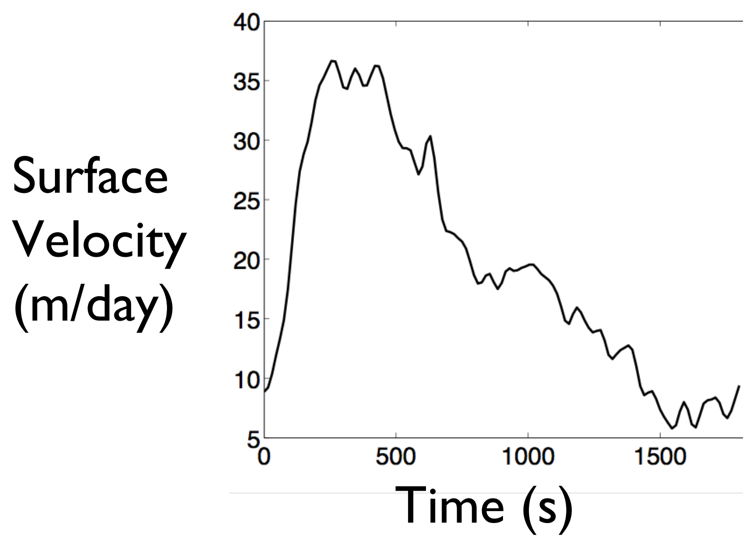
Lipovsky and Dunham, 2016

Models of tremor episodes reveal a tremendous amount of information about subglacial conditions:

- **Seismic parameters: slip, rupture velocity, fault dimension**
- **Till properties: elastic modulus, grain size, water pressure**
- ***The temporal variation of these properties.***

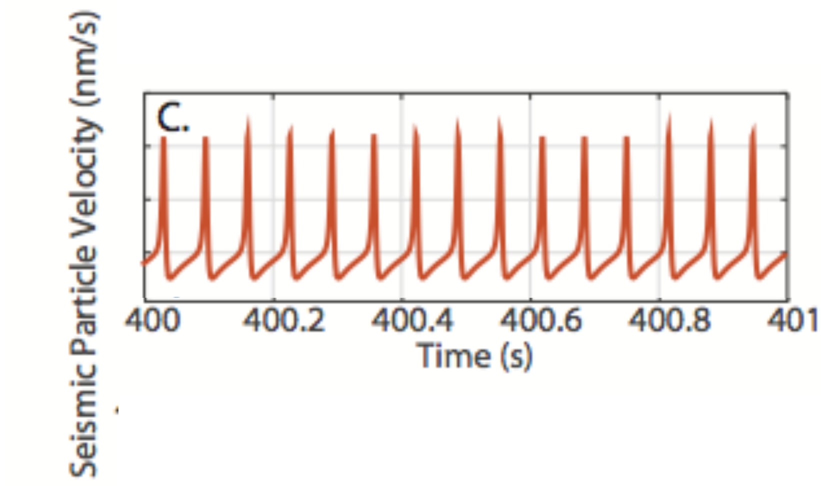
Seismic parameters: slip, rupture velocity, fault size

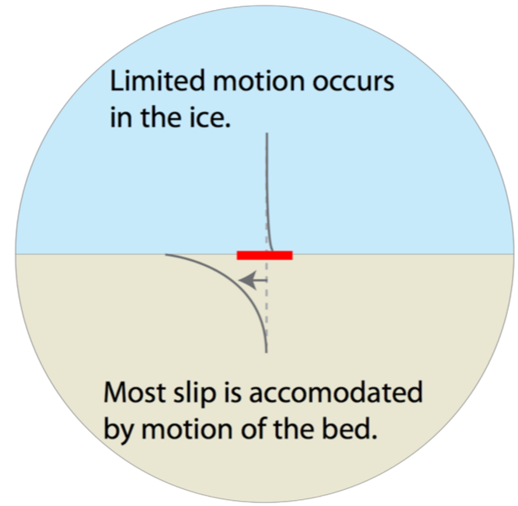




Slip = Velocity x Recurrence Time **~ 50 microns**

Seismic parameters: slip, fault size, seismic velocity amplitudes





Elastic Whole Space

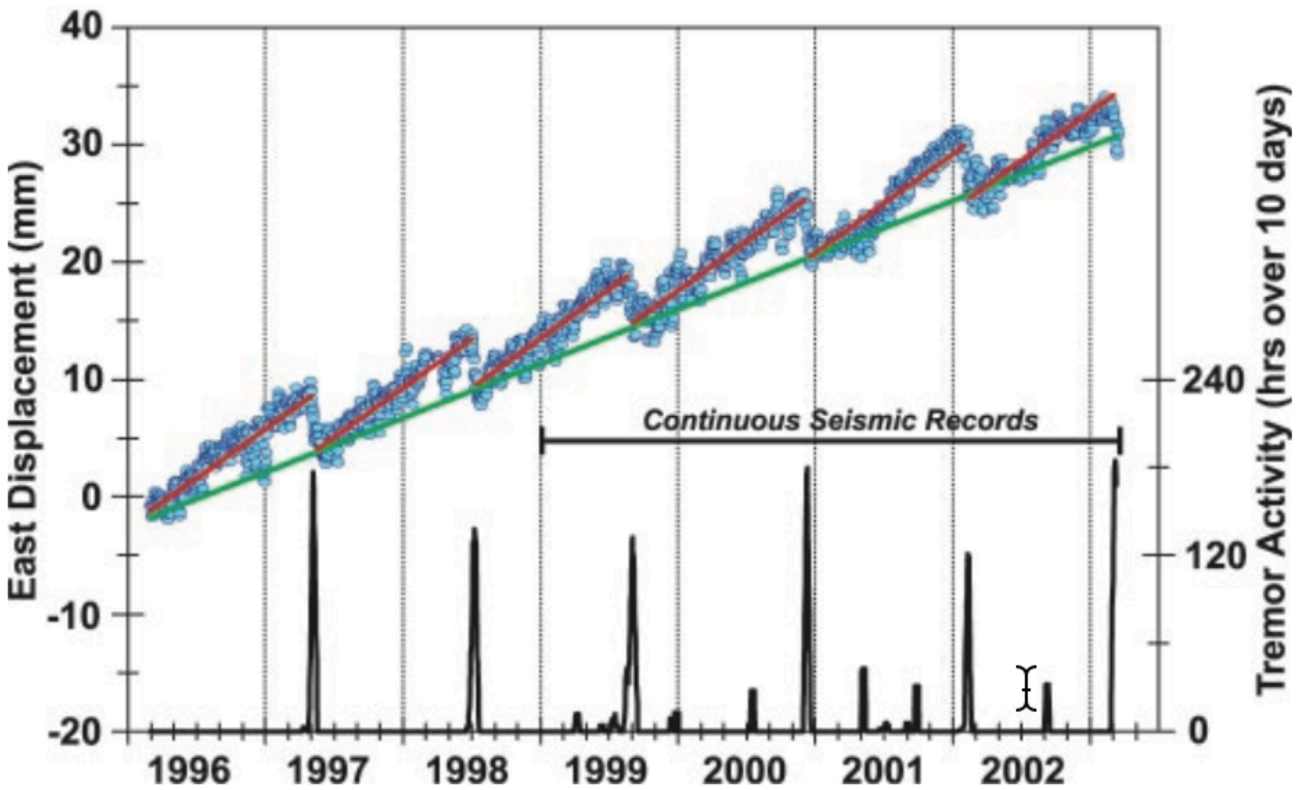
$$M_0 \equiv \pi R^2 G D$$

$$V(t) = \frac{\ddot{M}(t - H/c_i)}{4\pi \rho_i c_i^3 H}$$

Bimaterial Interface

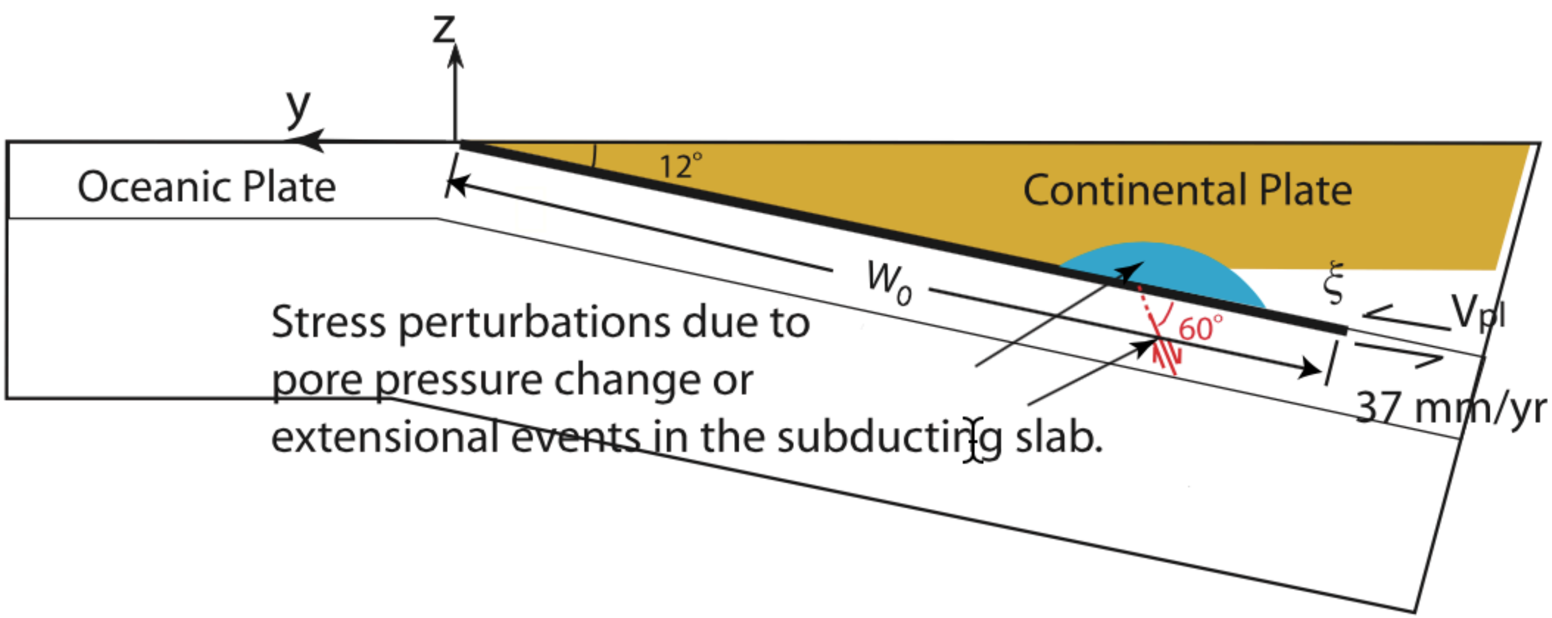
$$V \sim \frac{z_b}{z_i + z_b} \frac{\pi R^2 D}{T^2 c_i H}$$

Subduction zone tremor and slow slip



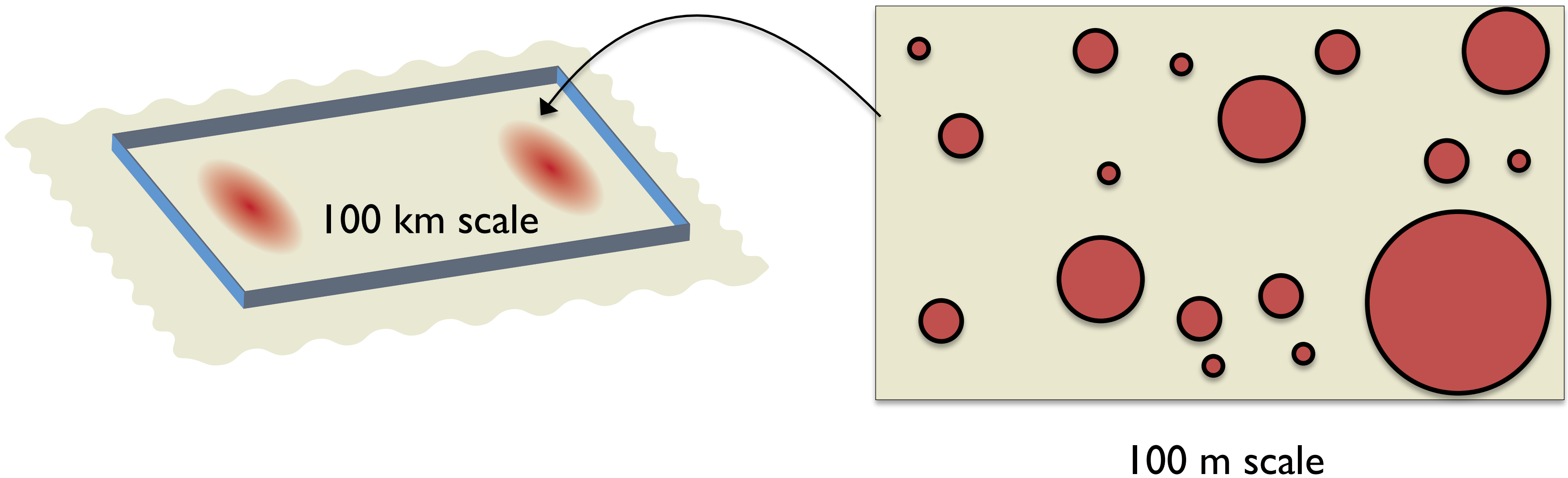
Rogers and Dragert (2003)

Subduction zone tremor and slow slip

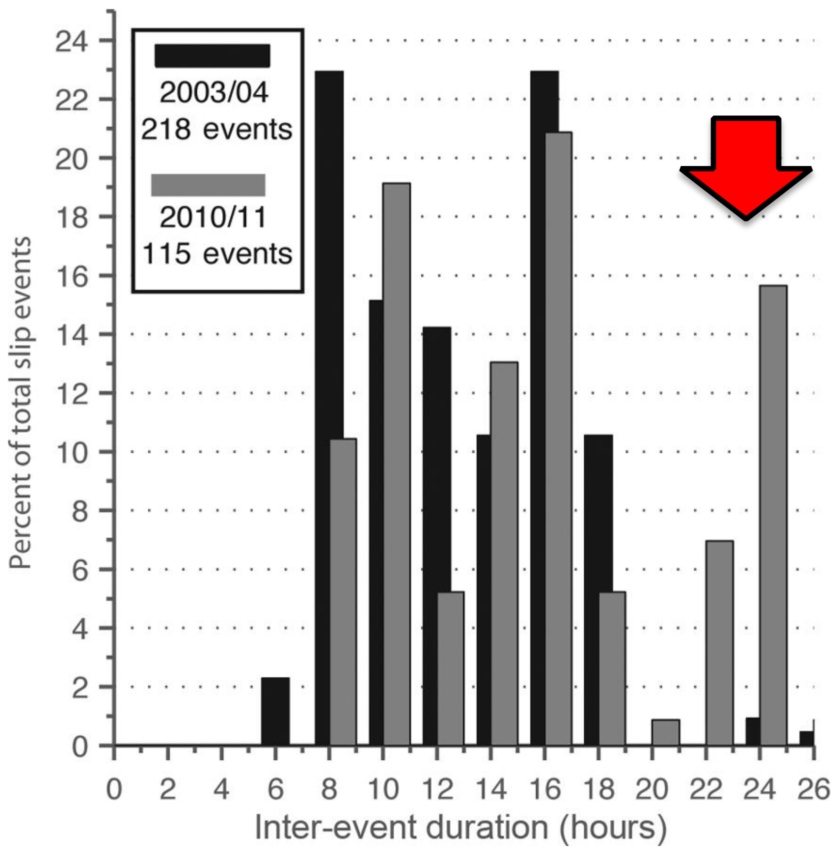


Liu and Rice (2008)

A picture of conditions at the bed



Interevent time is increasing.



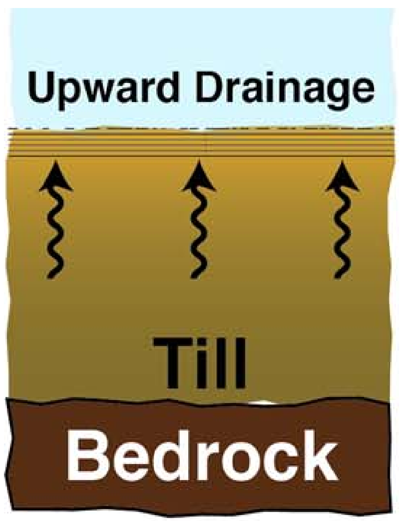
Winberry et al., 2014

Temporal variation in bed rigidity

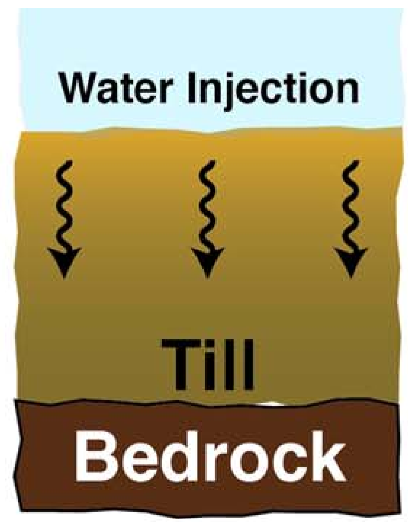
Mechanical and hydrologic properties of Whillans Ice Stream till: Implications for basal strength and stick-slip failure

J. R. Leeman[1], R. D. Valdez[1], R. B. Alley[1], S. Anandakrishnan[1], and D. M. Saffer[1]

Compaction during stick-phase



Dilatancy during rapidly sliding phase



Details: The change in the bed effective shear modulus can be computed through an effective medium (e.g.., Voight-Reuss) description. The shear modulus is inversely related to the porosity because bulk averge shear modulus decreases when there is a higher water fraction.

The ice sheet bed is stiffening

Shear modulus inferred from models of small, repeating earthquakes (Lipovsky and Dunham, 2016)