SPATIAL DISTRIBUTION OF ENGLACIAL LAYER SLOPES AS A CONSTRAINT ON ICE SHEET BASAL CONDITIONS

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26th WAIS WORKSHOP - 18 OCTOBER 2019
Can layers be used to constrain present and past ice flow in a systematic way?
Ice Flow, Basal Traction, And Layers

**TRACTION FROM SURFACE DATA...**

**... ANY BETTER WITH LAYERS?**

- **Bed traction** (slipperiness/friction/...) controls ice speed
- For a known geometry, traction is inferred using surface observations
- **Layers** encode information on deformation at depth
- If we could use layers in addition to surface data, perhaps better estimate of traction?

From Sergienko and Hindmarsh, 2014
The Weertman Effect As A Test Case

FROM A MATHEMATICAL MODEL...

\[ C \]

\[ u_b \approx 0 \]

\[ \tau_b = f(u_b, N, \ldots) \]

\[ O(1) \]

\[ x \]

\[ \tau_b = f(u_b, N, \ldots) \]

e.g., Weertman (1976), Leysinger et al. (2007), and many others since
The Weertman Effect As A Test Case

**FROM A MATHEMATICAL MODEL...**

\[ C \]

\[ u_b \approx 0 \]

\[ \tau_b = f(u_b, N, ...) \]

**... TO THE REAL WORLD**

- Can we detect changes in bed friction from their signature in layers?
- What can we learn about the physics of sliding onset?

\[ \tau_b = \text{bed} \]

\[ \text{ocean} \]

\[ \text{air} \]

\[ h \]

\[ b \]

\[ x_{\text{onset}} \]

\[ z \]

\[ x \]

\[ y \]

- e.g., Weertman (1976), Leysinger et al. (2007), and many others since
Step 1: What Are We Looking For?

**THE ICE THICKNESS SCALE PROBLEM**

\[ \varepsilon = \frac{z}{x} \ll 1 \]

- At the ice thickness scale isochrones and streamlines coincide
  \[ \mathbf{u} \cdot \nabla A = 0 \]
- **Downdraw** of streamlines due to speed-up (opposite for slow-down)
- Streamlines become very steep
  \[ \frac{dZ}{dX} \sim X^{-3/2} \]
- So are isochrones

**ANALYTICAL RESULTS**
Numerical Solution Of The Hard Switch Problem

Introduction

Model constraints

The real world

Conclusions
Step 2: How Do We Detect Steep Layers?

**REQUIREMENTS**

- Layer slopes, as opposed to individual layers
- Image the steepest slopes (possibly up to 20-30 deg)
- High accuracy in the detection of small slope changes along track (several deg per ice thickness)
Step 2: How Do We Detect Steep Layers?

**UNFOCUSED SAR**

1400 m

13 km

**Layer-Optimized UNFOCUSED SAR**

**SLOPES**

Castelletti et al., J. Glaciol. (in press)
Step 3: Where Do We Look For Sliding Onset?

**INT. DEFORMATION vs BASAL SLIDING**

Legend

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

- INT. DEFORMATION vs BASAL SLIDING - Map with color legend indicating percentage of flux by internal deformation.
Step 3: Where Do We Look For Sliding Onset?

**INT. DEFORMATION vs BASAL SLIDING**

Legend
- Selected lines
  - C09a
  - C28c
  - C28a
  - C12a
  - BAS Grid
- % Flux from internal deformation
- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

The real world
Sliding Onset In The Real World

- **downwards = speed up**
- **upwards = slow down**

**Introduction**

**Model constraints**

**The real world**

**Conclusions**
Observations Vs. Theory

after bed correction:
slope >0 convergence
slope <0 divergence
Observations Vs. Theory

after bed correction:
slope >0 convergence
slope <0 divergence

The real world

Introduction
Model constraints
The real world
Conclusions
Layer slopes reflect speed-up. But are consistently smaller than an abrupt onset would demand.
All In All, Sliding Onset May Not Be Abrupt...

**HARD SWITCH**

The seminal work by Weertman assumes that sliding starts abruptly when bed temperature reaches the melting point. This corresponds to a discontinuous friction coefficient.
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The seminal work by Weertman assumes that sliding starts abruptly when bed temperature reaches the melting point. This corresponds to a discontinuous friction coefficient.

**TEMPERATURE-DEPENDENT FRICTION**

In reality, the friction coefficient changes continuously with temperature. Since temperature increases slowly, this leads to a spread-out onset.

\[ u_b \approx 0 \]

\[ \tau_b = f(u_b, N, ...) \]

\[ u_b = F(T) \tau_b^\mu, \quad F = \gamma^{-1} \exp(T/\delta) \]
1. The physics of sliding onset

- At IIS, layer architecture suggests sliding onset is spread out.
- An extended onset region is compatible with temperature-dependent friction.
- T-dependent friction is key to ice stream dynamics (Mantelli and Schoof, in press). What else can we do to test the theory?
Implications and Outlook

2. Are layers useful to better constrain basal friction?

- In principle yes, but with some challenges:
  - At the ice thickness scale or shorter: resolving rapidly changing slopes is key. Custom-made processor allows us to do this at unprecedented resolution.
  - At the ice sheet scale: topography, accumulation, and basal speed-up all matter. Inverse ice flow model approach that uses constraints from layer slopes is key.
- If coupled to a higher-order mechanical model, inverse ice flow model using layers could provide information on bed friction at spatial scales much finer than an inversion using surface data only.