Glacier Stick-slip Seismicity and Subglacial Conditions
picture. It may well be that a new species of tremor associated with motions in the ice sheet will be recorded by the seismograph stations. It is not surprising that

Caltech Alumni Magazine 1957
• What is stick-slip?
• How do we know it happens under glaciers?
• Why does it happen?
• How can we stick-slip behavior to study glaciers?
Spatial Patterns of Sliding Speed

Joughin et al., 2004

Paul Winberry
Glacier Goes Fast Because of Slippery Bed

They Don’t go faster because of sticky-spots (at many scales)

Sticky-spots can release seismic energy
Sticky-spots as a seismic source

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Joughin et al 2004
Sticky-spots as a seismic source

- **Stick Phase**: Most Strain Accommodated in Ice
- **Slip Phase**: Most Elastic Rebound in Ice
- **Total Motion During Stick-slip Cycle**: Net Displacement

No Net Displacement
Sticky-spots as a seismic source

Negative first motion

Slip Phase

Positive first motion

Most Elastic Rebound in Ice
SEISMIC EVIDENCE FOR GLACIER MOTION

By Douglas VanWormer and Eduard Berg*

(Geophysical Institute of the University of Alaska, Fairbanks, Alaska 99701, U.S.A

Fig. 6. Comparison of signatures of typical events from Harvard Glacier (events 2 and 3) and events not located on Harvard Glacier. All records are from station SCM.
SEISMIC EVIDENCE FOR DISCRETE GLACIER MOTION AT THE ROCK–ICE INTERFACE

By Craig S. Weaver* and Stephen D. Malone

(Geophysics Program, University of Washington, Seattle, Washington 98195, U.S.A.)

Mixed Polarity
Mixed polarity but simple waveforms
How big are the stick-slip patches?
Estimating event size:

Seismic Moment

\[ M_o = \mu A D \]

- \( A \) is derived from the spectral content of the waveform.
- \( \mu \) is the rigidity of the material bounding the fault.
- \( D \) is the fault slip.

Anandakrishnan and Bentley, 1993 J. Glac.
Estimating event size:

Seismic Moment

\[ M_o = \mu AD \]

\( A \) is derived from the spectral content of the waveform.

\( \mu \) is the rigidity of the material bounding the fault.

\( D \) is the fault slip.
The Scales of Glacier Stick-slip

- **Stick Phase**: Most Strain Accomodated in Bed
- **Slip Phase**: Most Elastic Rebound in Bed
- **Total Motion During Stick-slip Cycle**: No Net Displacement

\[ M_o = \mu AD \]

\( \mu \), for sediment, is more appropriate.
The scales of Glacier Stick-slip

\[ M_o = \mu AD \]

\( \mu \) for bedrock is more appropriate
The Scales of Glacier Stick-slip

- ~10 m sticky-spot
  ~1 km away
  ~100 Hz Signal
  Rutford Ice Stream
  (Smith, 2006)

- ~100 m sticky-spot
  ~100 km away
  ~10 Hz Signal
  David Glacier
  (Danesi et al., 2007; Zoet et al., 2012)

- ~10 km sticky-spot
  ~1000 km away
  ~.01 Hz Signal
  Whillans Ice Stream
  (Wiens et al., 2008)
Why Stick-slip Happens

\[ \sigma_e = \frac{Kx}{A} \]
Why Stick-slip Happens

\[ \tau = \sigma'_n c_s \]

\[ \tau = \sigma'_n c_d \]

\[ \sigma'_n \]

\[ \sigma_e = Kx/A \]

\[ \tau \]

Block Displacement

Stress

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Why Stick-slip Happens

\[ \sigma'_n \]

\[ \sigma_e = \frac{Kx}{A} \]

\[ \tau = \sigma'_n c_s \]

\[ \tau = \sigma'_n c_d \]

Block Displacement

\[ \mathcal{L} \]
Why Stick-slip Happens

\[ \sigma_e = \frac{Kx}{A} \]

\[ \tau = \sigma' \cdot c_s \]

\[ \tau = \sigma' \cdot c_d \]

Stress vs. Block Displacement

\[ \text{slope} = -\frac{Kx}{A} \]
\[ \sigma'_e = \frac{Kx}{A} \]

Why Stick-slip Happens

\[ \tau = \sigma'_n c_s \]

\[ \tau = \sigma'_n c_d \]

Paul Winberry
\[ \sigma_e = \frac{Kx}{A} \]

Why Stick-slip Happens

\[ \tau = \sigma_n c_s \]

\[ \tau = \sigma_n c_d \]

\[ \text{slope} = -\frac{kx}{A} \]

Block Displacement
Stick-slip is repetitive

\[ \tau = \sigma' n c_s \]
In the glaciological literature the term stick-slip is used to describe hydraulically forced cycles. This is different to what just described.
Stick-slip is repetitive

\[ \tau = \sigma' n c_s \]
Magnitude 2 events from David Glacier

Paul Winberry

Zoet et al, 2012 Nature Geosci.
2-9 Hz data reveals frequent impulsive arrivals

Zoet et al, 2012 Nature Geosci.
TAM Repeating Earthquakes

Zoet et al, 2012 Nature Geosci.
Identical Waveforms indicate
1) Common Source
2) Common Path
2-9 Hz data reveals frequent impulsive arrivals

Zoet et al, 2012 Nature Geosci.
Small $M < 0$ Repeating Events from the WIS

Winberry et al., 2013, GRL
Time between events is controlled by two factors:

1) Strength of the interface
2) Loading rate of stress

**Inter-event duration** = \( \frac{\text{Strength}}{\text{Loading Rate}} \)
Seismicity as a stress meter

\[ \text{Inter-event Time} = \frac{\Delta \sigma}{\dot{\sigma}} \]
Seismicity as a stress meter

Inter-event Time $= \frac{\Delta \sigma}{\dot{\sigma}}$

Tides modulate the stress budget for David Glacier Events.
Seismicity as a stress meter

Inter-event Time = \frac{\Delta \sigma}{\dot{\sigma}}

Slip rates modulate the stressing rate for WIS slip events

Winberry et al., 2013, GRL
A unique appearance of stick-slip

Tremor from small repeating events during the WIS slip events that scales with sliding velocity
A unique appearance of stick-slip

Tremor from small repeating events during the WIS slip events modeled as small patch ~1m patches

Lipovsky and Dunham, The Cryosphere 2016
Variation in Pacing

Time between events is controlled by two factors

1) Strength of the interface
2) Loading rate of stress

Interevent duration = \( \frac{\text{Strength}}{\text{Loading Rate}} \)

Lower effective normal pressure will lead to smaller more frequent events
Swarms of Repeating Events

Receivers turn on and off

Smith et al., JGR 2015
Swarms of Repeating Events

Fischer and Clarke, 2001

**Sticky-spots migrate due to variable hydrologic conditions**
Variation in Pacing

Time between events is controlled by two factors:

1) Strength of the interface
2) Loading rate of stress

Interevent duration = \textbf{Strength/Loading Rate}

Lower effective normal pressure will lead to smaller more frequent events, perhaps stable sliding.
\[ \sigma'_n \]
\[ \sigma_e = \frac{Kx}{A} \]

Why Stick-slip Happens:

- \(\tau = \sigma'_n c_s\)
- \(\tau = \sigma'_n c_d\)
- \(\tau = \sigma'_{\text{crit}} c_s\)
- \(\tau = \sigma'_{\text{crit}} c_d\)

Slope: \(-\frac{kx}{A}\)

Block Displacement:

- A to B
- B to C
- C to D
- D to E
- E to \(\tau, \sigma'_e\)
Strength depends on waiting time