Stick/Slip Behavior of Ice Streams: Modeling Investigations

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What is similar?

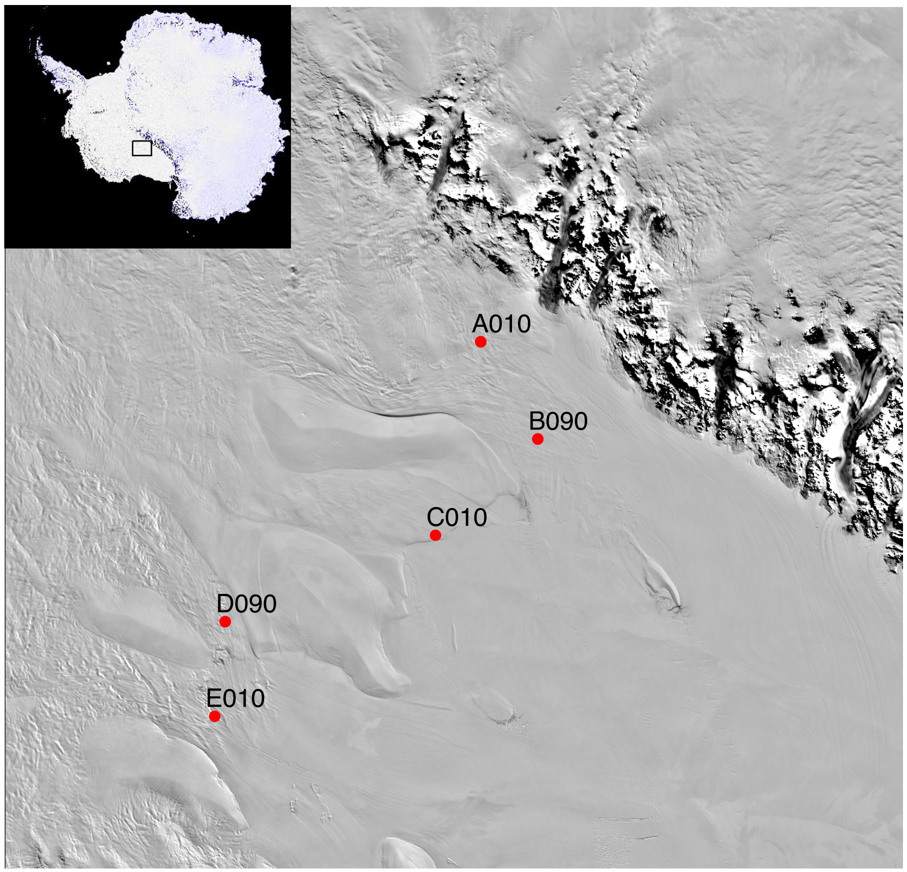
San Andreas Fault

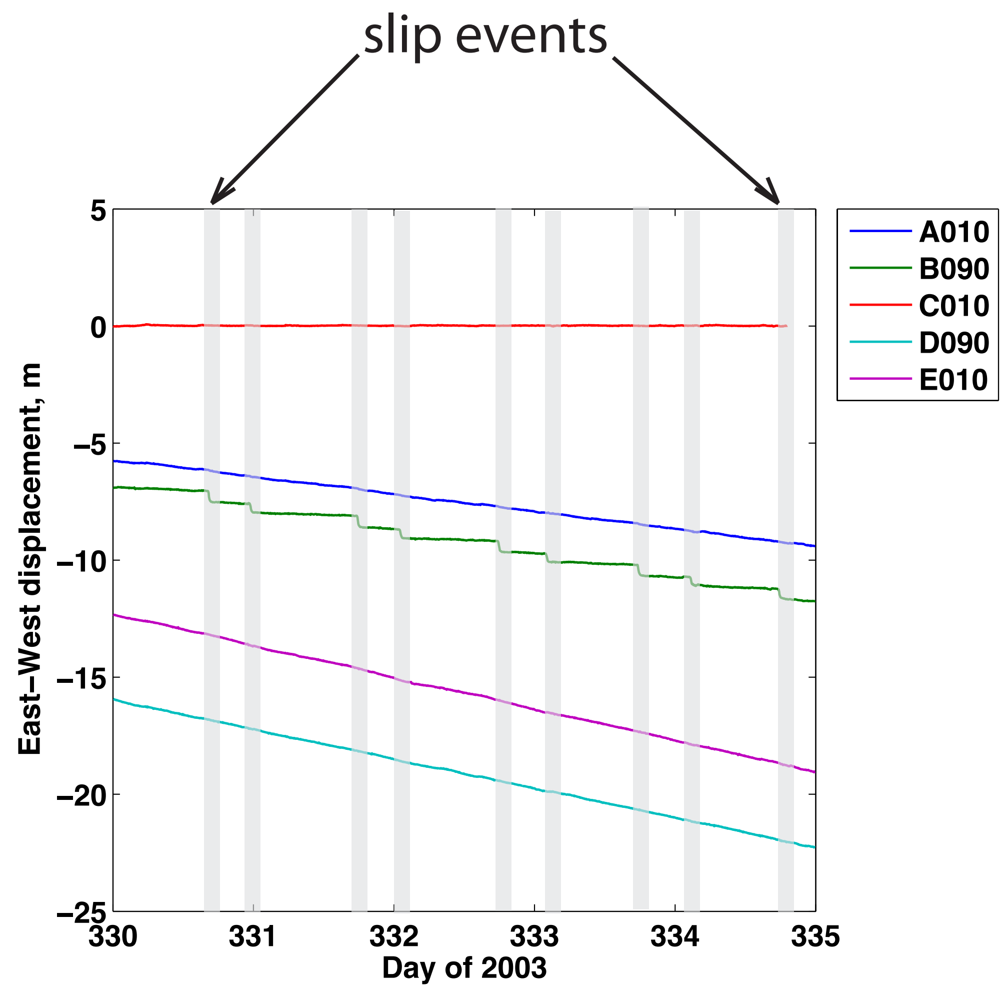
Stick-slip (or "slip-stick")

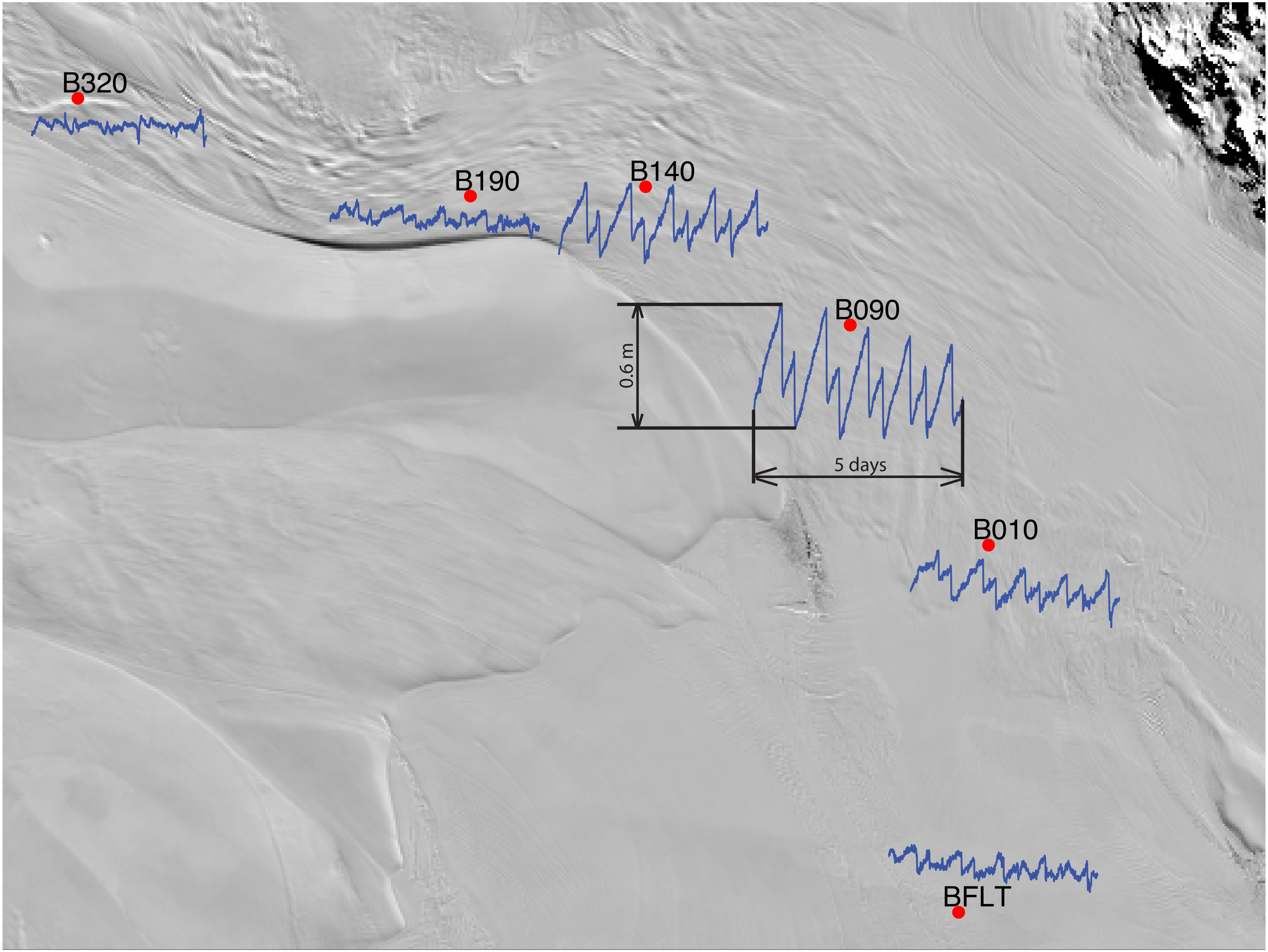
refers to the phenomenon of a spontaneous jerking motion that can occur while two objects are sliding over each other with a corresponding change in the force of friction. Typically, the static friction coefficient between two surfaces is larger than the kinetic friction coefficient.

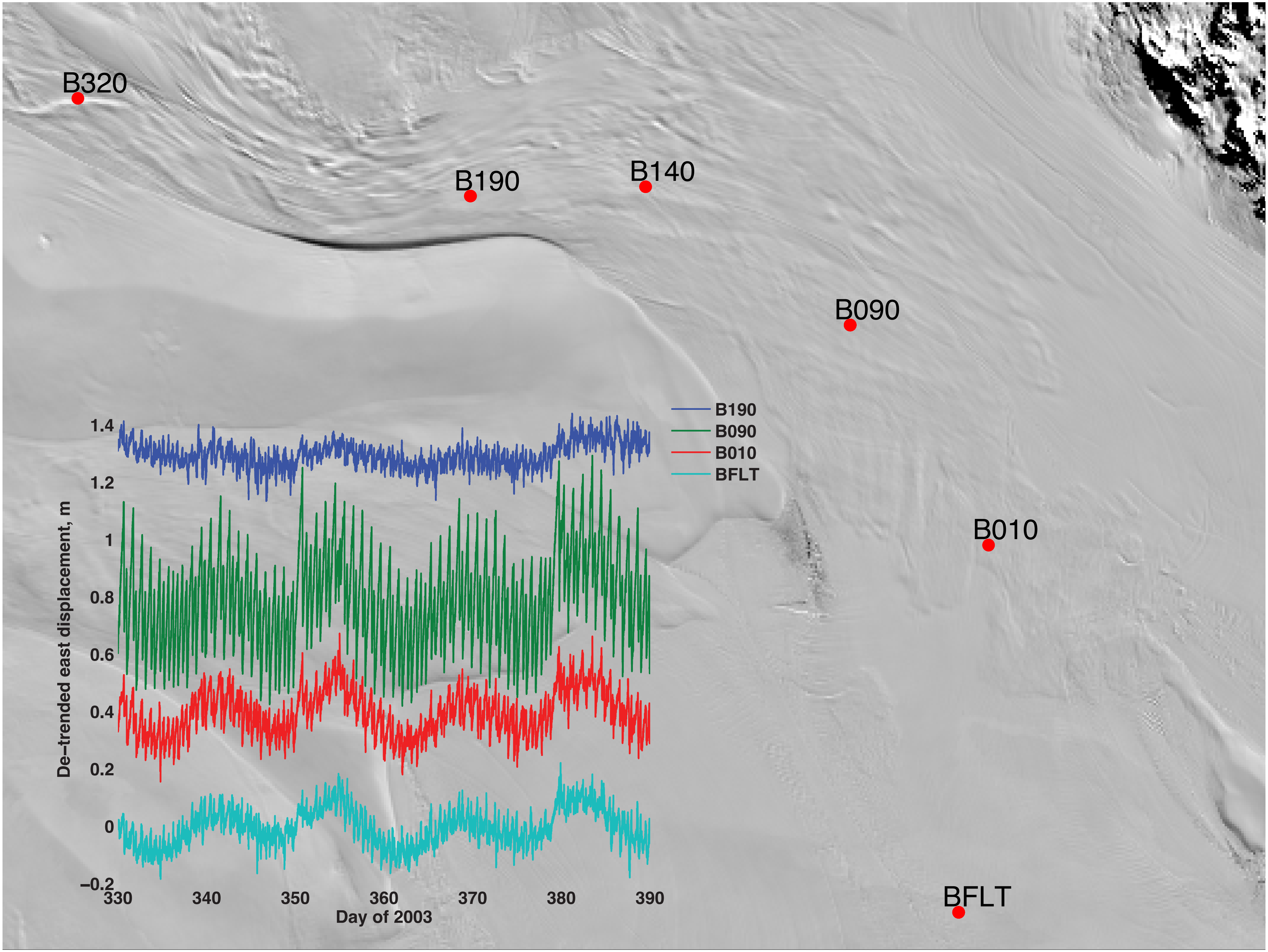
http://en.wikipedia.org/wiki/Stick-slip_phenomenon

GPS measurements






B320
B190
B140
B090
0.6 m
5 days
B010
BFLT



B320
B190
B140
B090
B010
BFLT
B190
B090
B010
BFLT
De−trended east displacement, m
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
330
340
350
360
370
380
390
Day of 2003

Tidally Controlled Stick-Slip Discharge of a West Antarctic Ice Stream

Robert A. Bindschadler,[1*] Matt A. King,[2] Richard B. Alley,[3] Sridhar Anandakrishnan,[3] Laurence Padman[4]

A major West Antarctic ice stream discharges by sudden and brief periods of very rapid motion paced by oceanic tidal oscillations of about 1 meter. Acceleration to speeds greater than 1 meter per hour and deceleration back to a stationary state occur in minutes or less. Slip propagates at approximately 88 meters per second, suggestive of a shear wave traveling within the subglacial till. A model of an episodically slipping friction-locked fault reproduces the observed quasi-periodic event timing, demonstrating an ice stream's ability to change speed rapidly and its extreme sensitivity to subglacial conditions and variations in sea level.

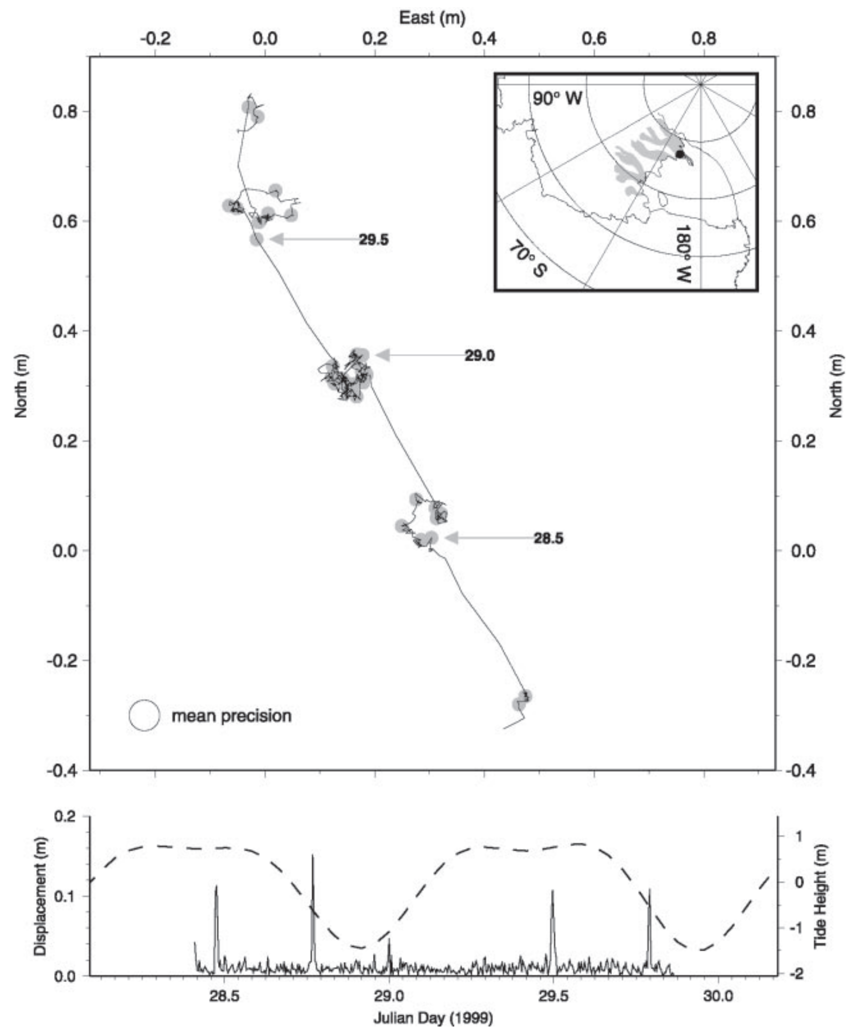


Fig. 1. Motion of site G2. (Top) Horizontal position every 5 min connected by straight lines. Gray dots indicate the beginning of each hour with Julian day indicated by arrows. Inset shows location ofi ce streams (shaded) and site G2 (solid circle). (Bottom) Horizontal displacement (solid line) between successive 5-min positions and modeled ocean tide (dashed line) at a nearby location.

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LETTERS

Simultaneous teleseismic and geodetic observations of the stick–slip motion of an Antarctic ice stream

Douglas A. Wiens[1], Sridhar Anandakrishnan[2], J. Paul Winberry[2] & Matt A. King[3]

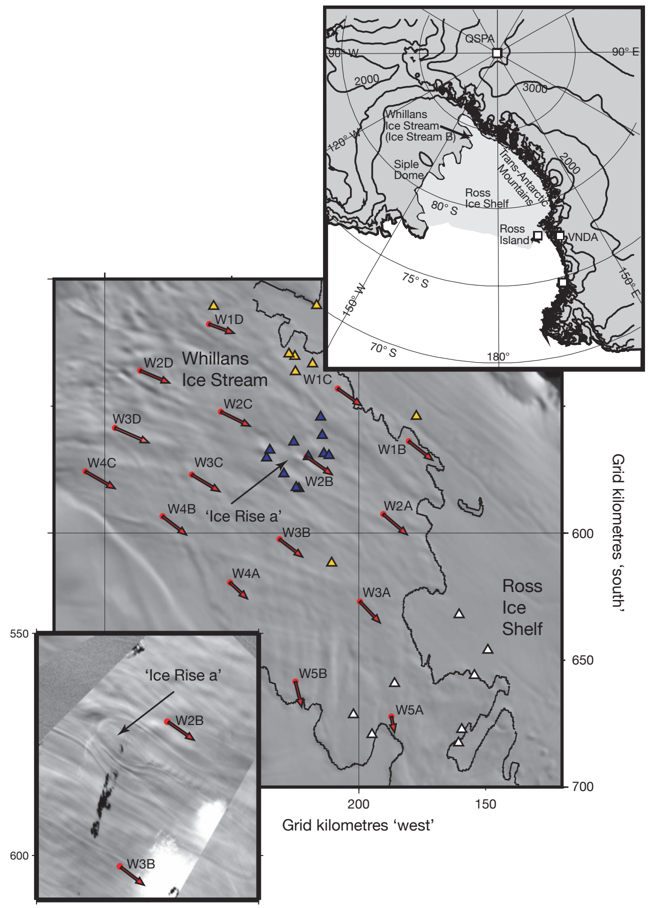
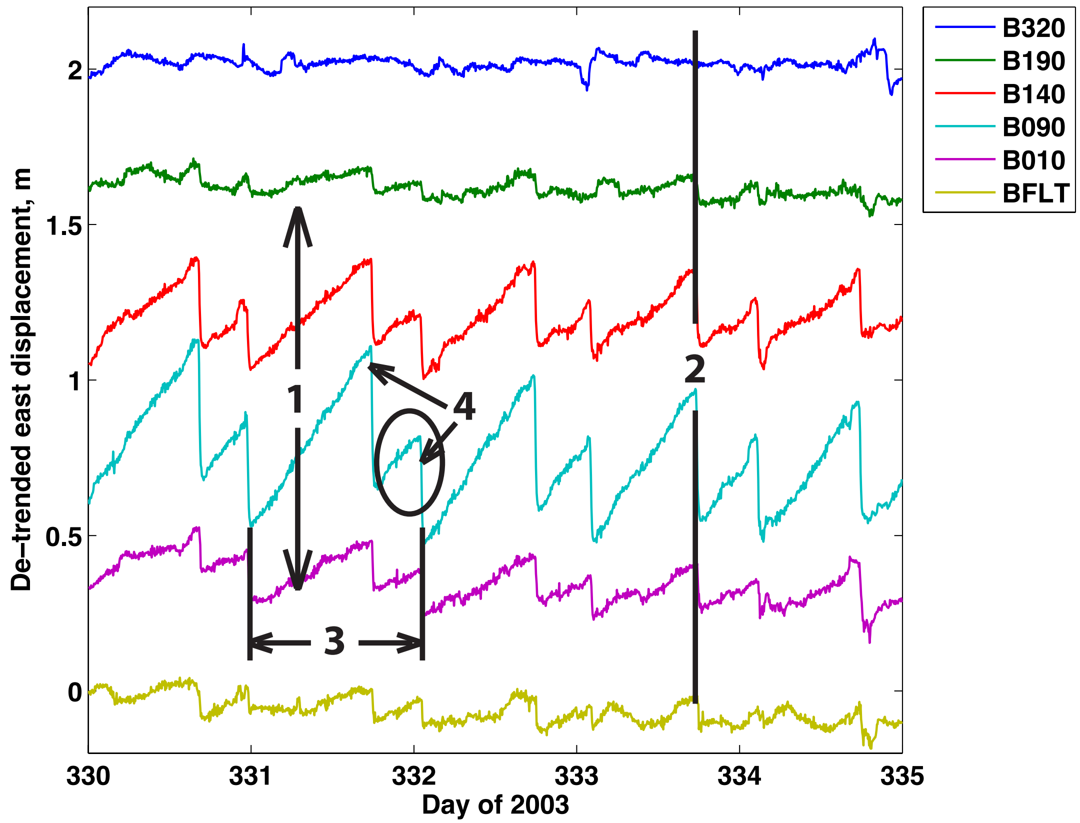


Figure 1 | The Whillans Ice Stream, the positions of the sensors and the positions of the slip nucleation and seismic source locations. TIDES GPS receivers (red circles), the slip nucleation points determined from GPS (blue triangles) and the approximate source regions for the second (orange triangles) and third (white triangles) seismic surface-wave arrivals, calculated from the seismic arrival times and the average rupture velocity for nine slip events from 16–20 November 2004 are shown on a Moderate Resolution Imaging Spectroradiometer mosaic map. The grounding line is marked with a black line[24]. Red arrows indicate the direction of ice flow determined from GPS, with arrow length proportional to speed (for scale, the red arrow at W2B represents 392.4 m yr^{-1}). Coordinates are given in a grid system with the origin at the South Pole, the 'south' axis oriented along longitude 180°, and the 'west' axis along longitude 90° W. The upper inset shows the location of the Whillans Ice Stream and the QSPA and VNDA seismic stations, among other permanent seismic stations (open squares). Contours indicate surface elevation in meters. The lower inset, which has the same axes as the main panel, is an enlarged SPOT image showing ice flow features in the region of the rupture nucleation points and 'Ice Rise a', which is thought to represent a region of reduced subglacial water and higher basal friction.

Specific features of stick/slip events



1. Amplitude decays up- and down-stream from B090

2. Slip occurs almost simultaneously, ~ within 10-20 min

3. Slip phase onset seems to be phased with the ocean tide in the neighboring Ross Sea...

4. ... but curiously, a second complete stick-slip cycle follows shortly after the first tidally-phased cycle for no apparent reason...

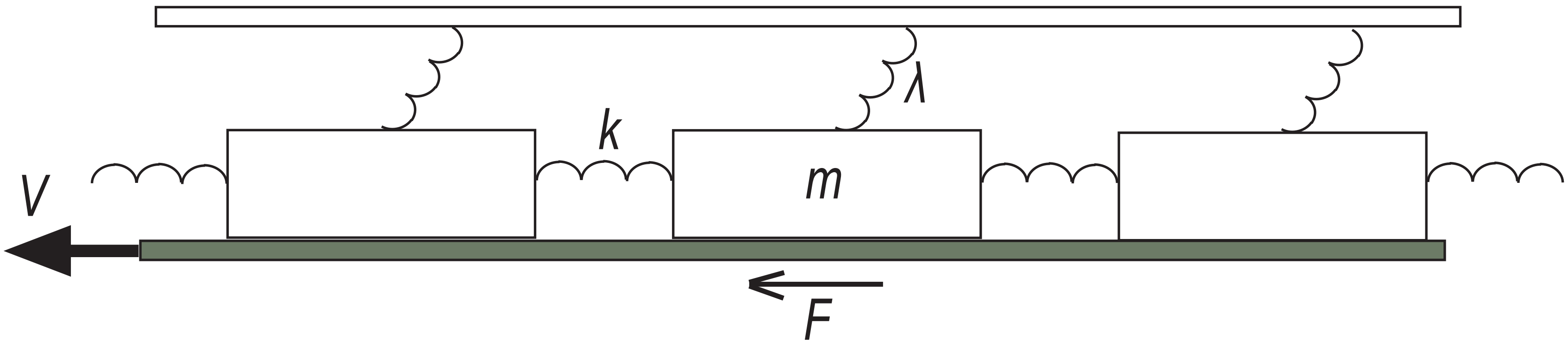
Questions:

— Is WIS a typical stick/slip system?

— Can we model it with an idealized stick/slip model?

— Why does WIS have stick/slip and other ice streams do not?

Burridge and Knopoff (1967)



$$\underbrace{m\ddot{X}_j}_{\text{block acceleration}} = \underbrace{- k(X_{j+1} - 2X_j + X_{j-1}) - \lambda X_j}_{\text{spring force}} + \underbrace{F\,\mathrm{sgn}(\dot{X}_j - V)}_{\text{friction force}}$$

$$F(v) = \begin{cases} F_s, & v = 0 \\ F_k, & v \neq 0 \end{cases}$$

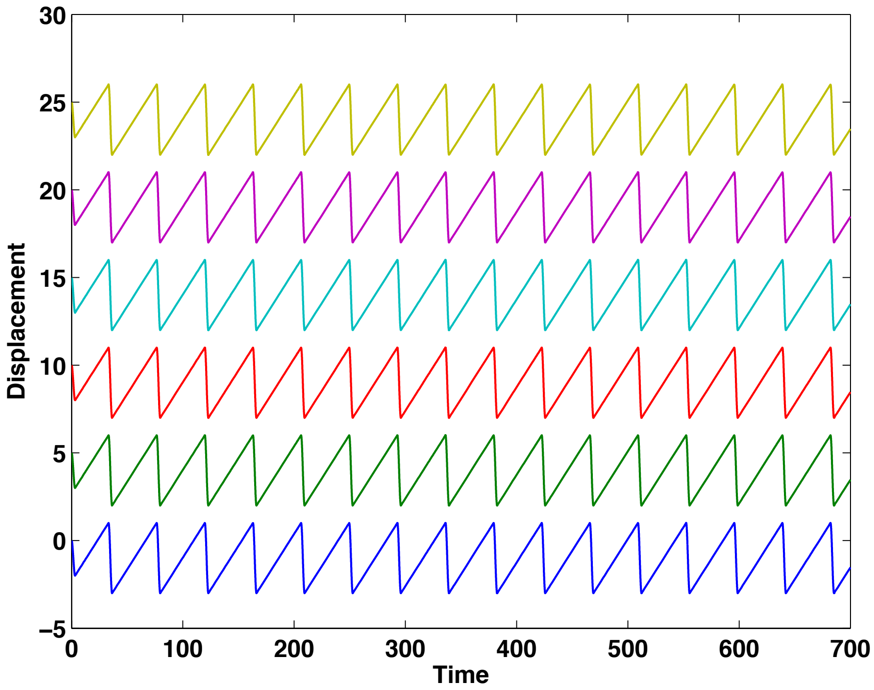
Experiments

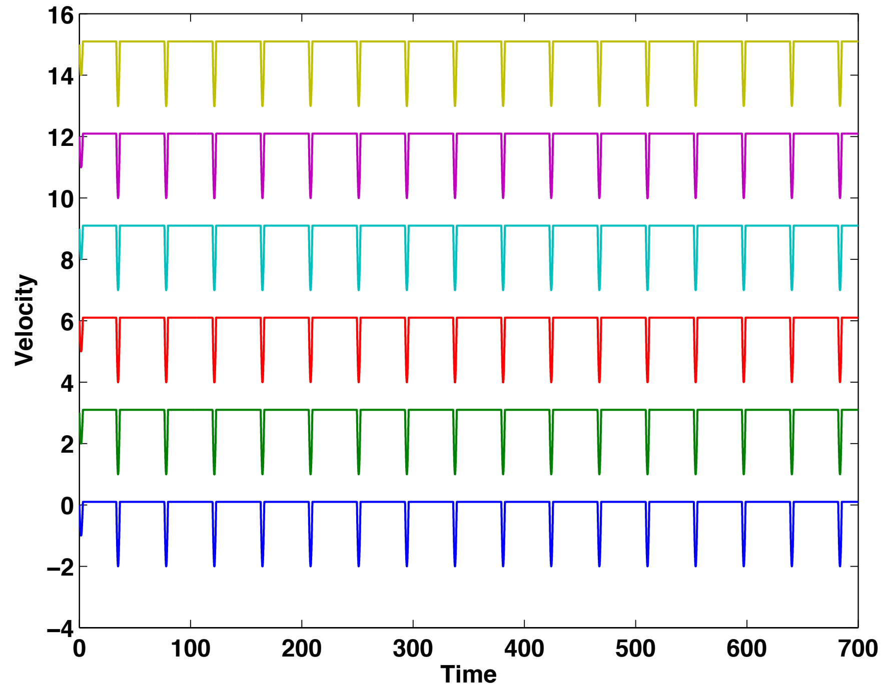
1. Homogeneous system

2. Heterogeneous system
    2.1 Increased friction force (”sticky spot”)
    2.2 Periodic forcing (”tides”)

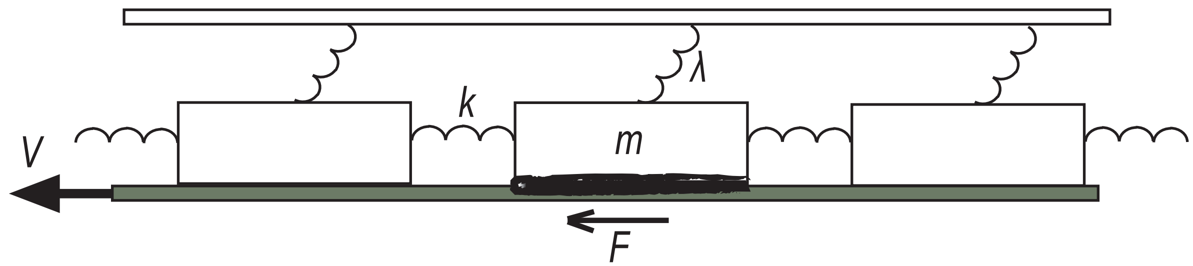
3. Transition from slip to stick/slip motion

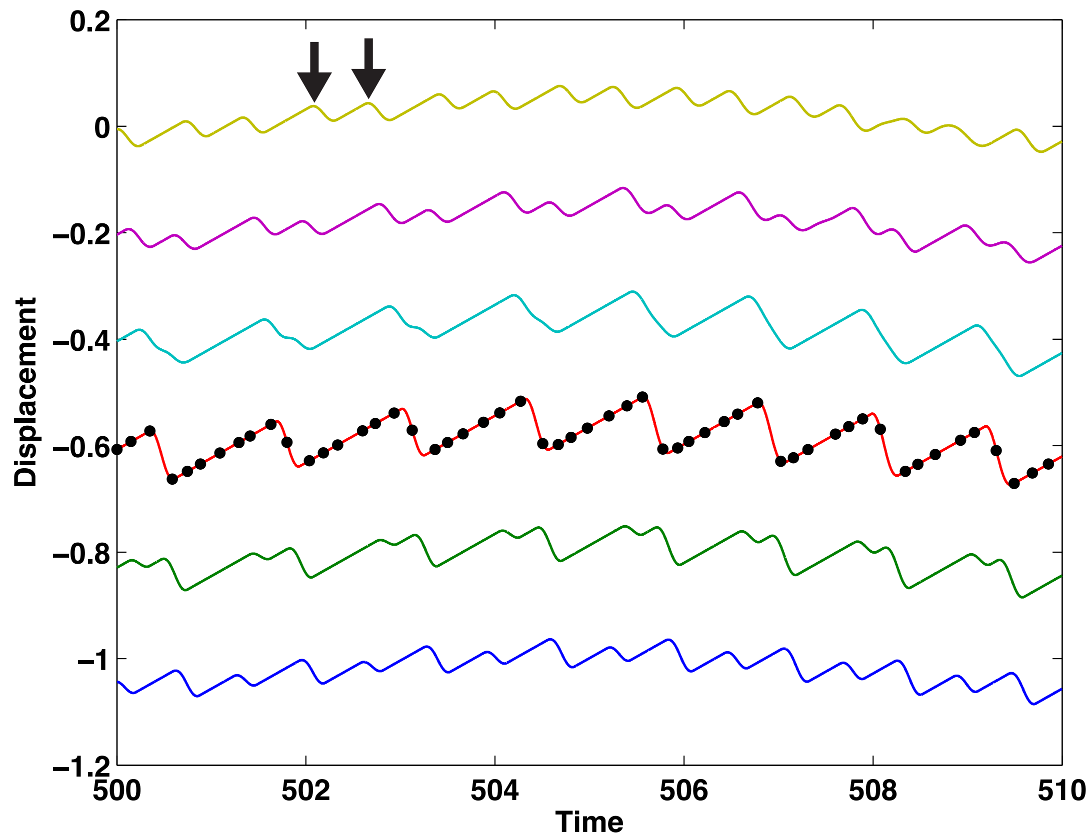
1. Homogeneous system



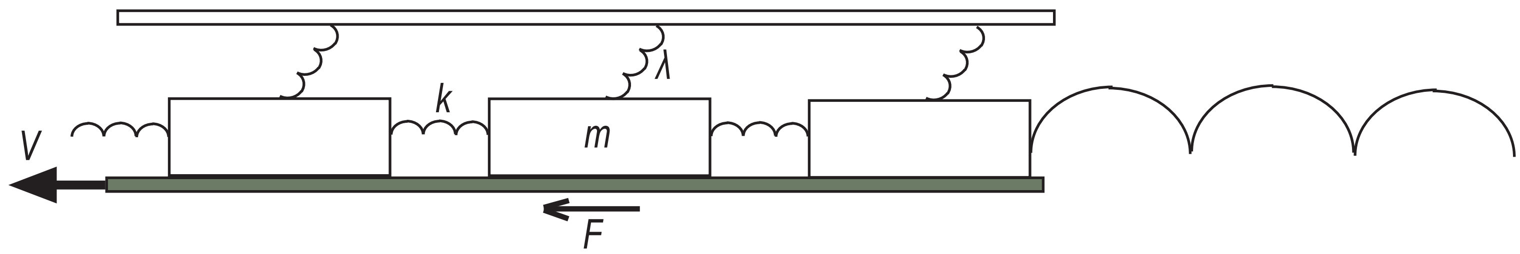


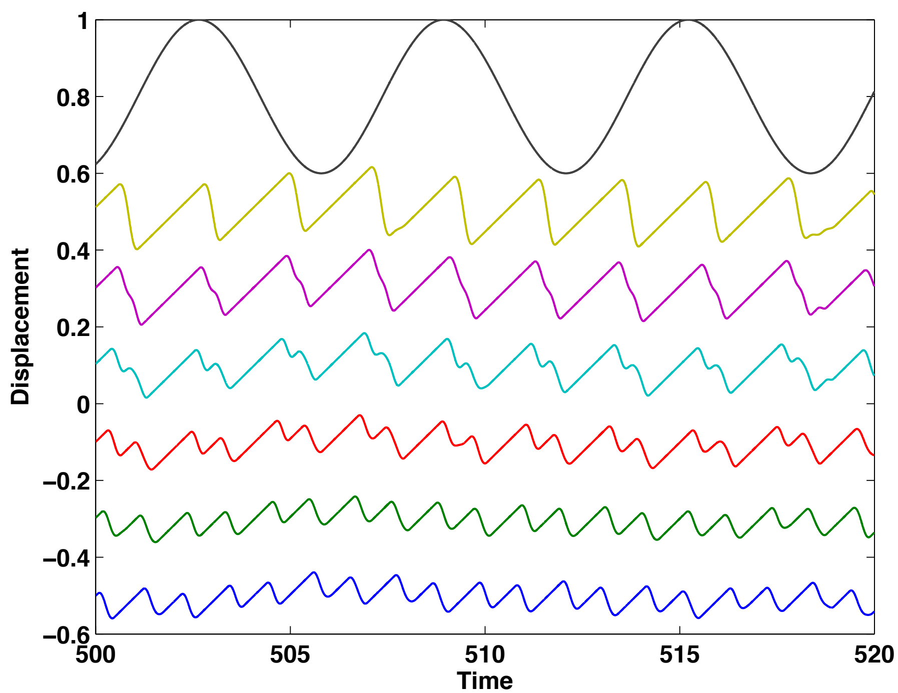
2.1 Increased friction force (Sticky spot)



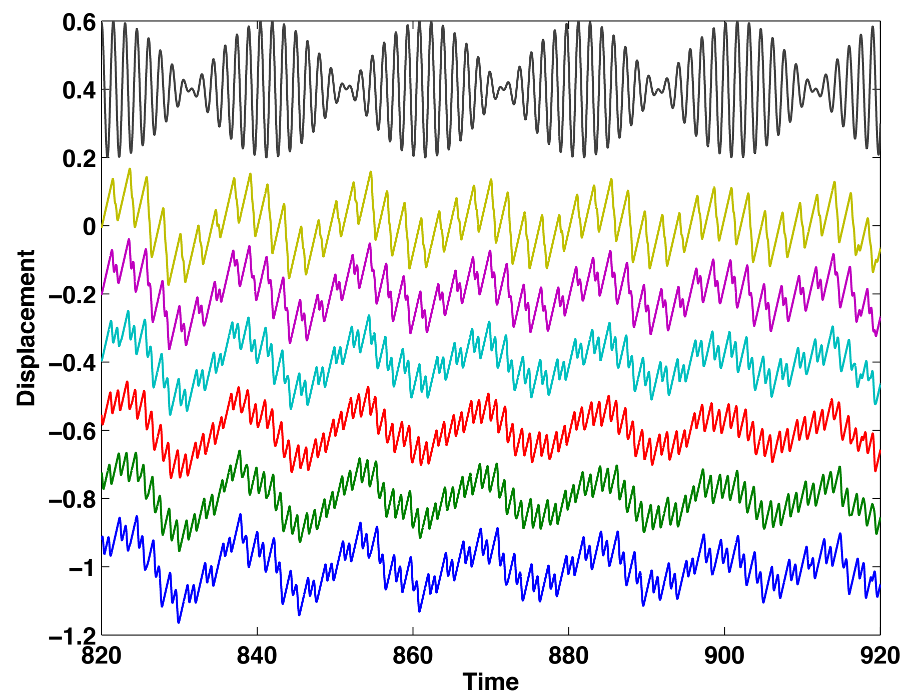


2.2 Periodic forcing (tides)



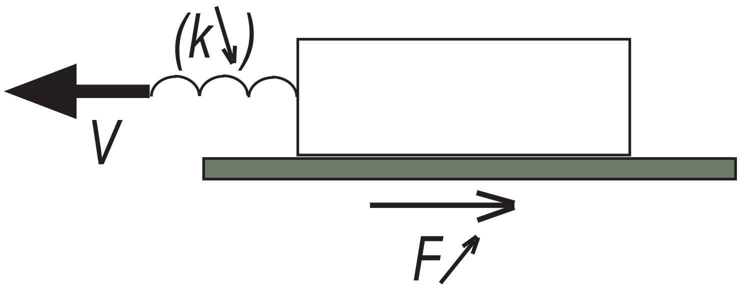


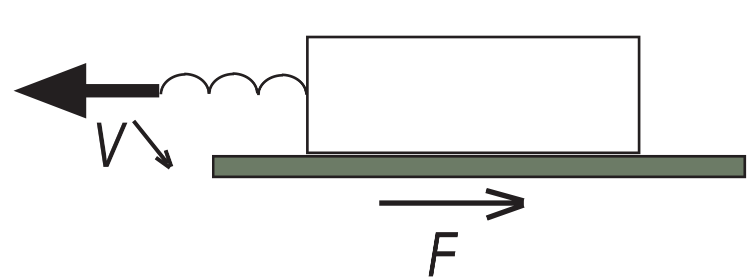
“Diurnal”

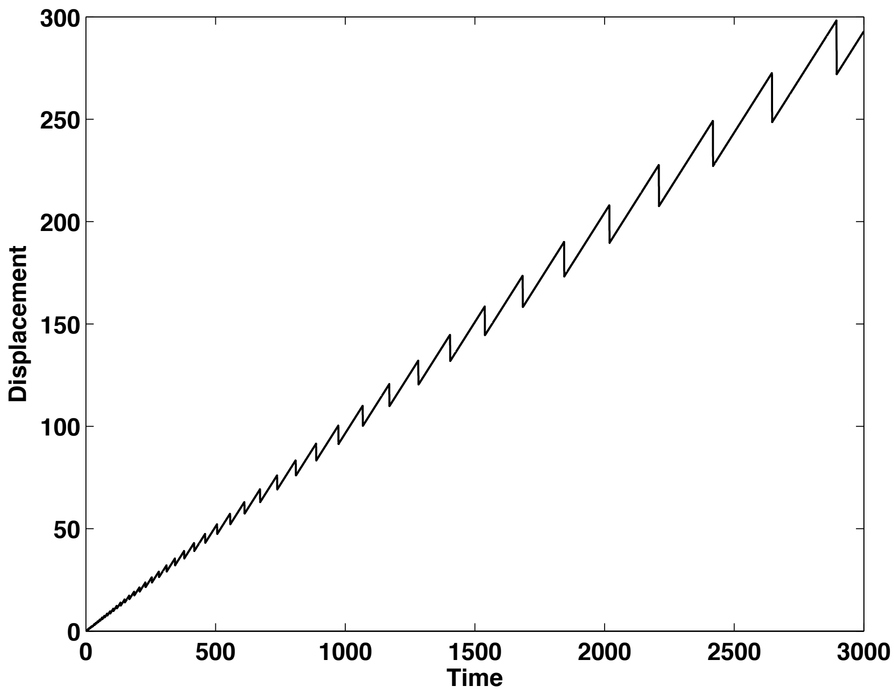


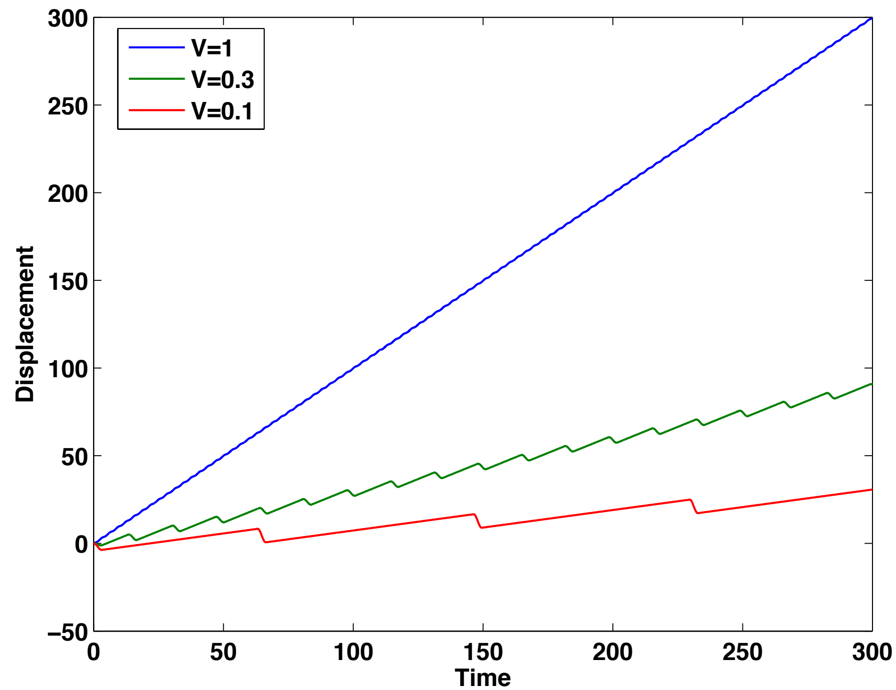
“Spring-to-neap”

3. Transition from slip to stick/slip









$$\tau = \frac{F}{kV}$$

$\tau \to 0$ permanent slip

$\tau \to \infty$ permanent stick

WIS is slowing down

www.sciencemag.org SCIENCE VOL. 279 30 JANUARY 1998

Changes in the West Antarctic Ice Sheet Since 1963 from Declassified Satellite Photography

Robert Bindschadler* and Patricia Vornberger

Comparison of declassified satellite photography taken in 1963 with more recent satellite imagery reveals that large changes have occurred in the region where an active ice stream enters the Ross Ice Shelf. Ice stream B has widened by 4 kilometers, at a rate much faster than suggested by models, and has decreased in speed by 50 percent. The ice ridge between ice streams B and C has eroded 14 kilometers. These changes, along with changes in the crevassing around Crary Ice Rise, imply that this region's velocity field shifted during this century.

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22501, doi:10.1029/2005GL024319, 2005

Continued deceleration of Whillans Ice Stream, West Antarctica

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S. Anandakrishnan,[4] H. Horgan,[4] L. Peters,[4] P. Winberry,[4] S. B. Das,[5] and G. Catania[6]

Answers:

Is WIS a typical stick/slip system?

Yes

Can we model it with an idealized stick/slip model?

Probably yes, its specific features could be explained by such a model

Most likely, stick/slip events are controlled by a "sticky spot", and triggered by tides.
Periodicity and amplitudes of stick/slip events are determined by internal properties of the ice stream.

Why does WIS have stick/slip?

It is slowing down

Other ice streams are either in permanent slip (Mercer, Bindschadler, MacAyeal) or in permanent stick phase (Kamb).
A state of an ice stream - permanent slip, permanent stick or stick/slip is determined by a ratio of the driving force to the basal friction force.

More questions

– What are blocks and springs in the “ice-stream notation”?

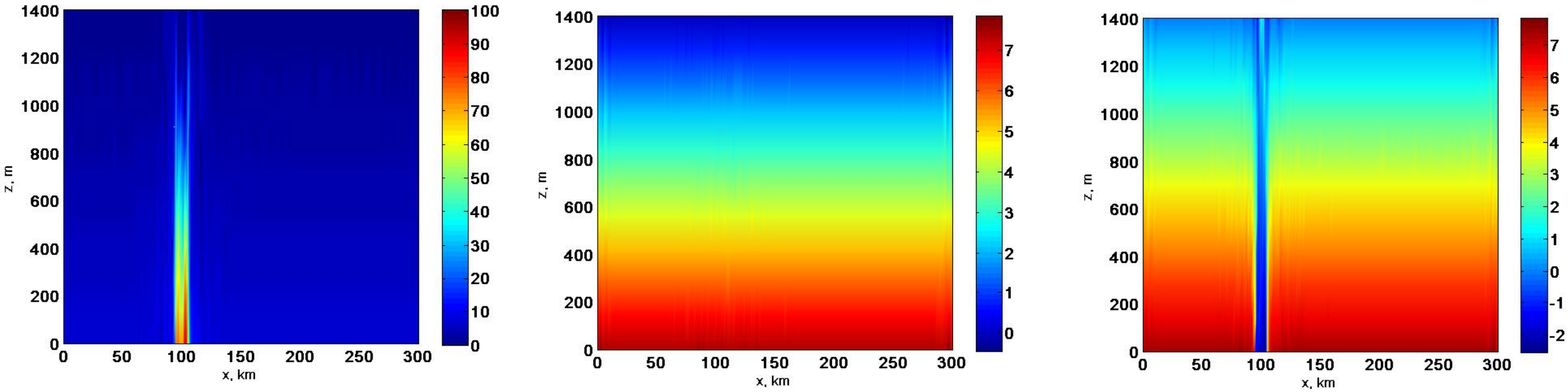
– What are stick/slip effects for long-term ice-stream flow?

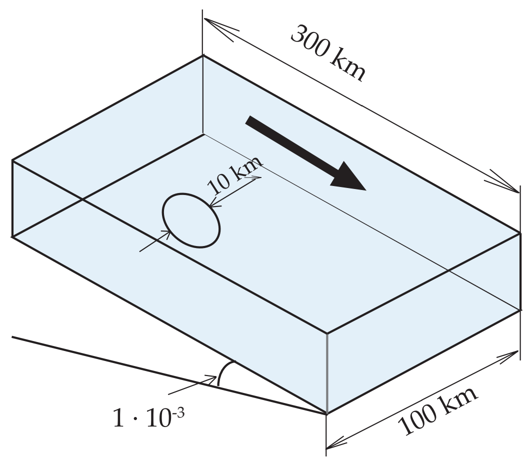
– Is Glen’s flow law valid for such ice behavior?

– How is stick/slip affected by subglacial water movement?

•••

σ'_{xz}, kPa





σ'_{xx} kPa