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Zoet and Iverson, 2018, A healing mechanism for stick-slip of glaciers: Geology, https://doi.org/10.1130/G45099.1.

Supplemental Material

1.1 Devices

A ring-shear device designed for the study of till deformation (Iverson et al., 1997) was used to study healing of till in the absence of ice (Fig. DR1A). This device has an annular sample chamber with an outer diameter of 0.6 m, a width of 0.115 m, and height of up to 0.085 m (Fig. DR1A). The till was gripped on its upper and lower surfaces by roughened, permeable platens. These platens allow water in an internal reservoir under atmospheric pressure to enter or leave the saturated till as porosity changed during shear. The till was sheared by rotating the bottom platen at a constant speed that was recorded using a linear variable differential transformer (LVDT). The upper platen was held rotationally fixed by two diametrically positioned armatures that extended to the load frame where they pressed on load cells that recorded forces used to compute till shearing resistance. Till shear occurs in a lens-shaped zone (Fig. DR1B) with a maximum thickness of ~30 mm (Iverson et al., 1997). A constant vertical stress was applied to the upper platen with weights on a lever arm. Vertical motion of the upper platen was recorded using three LVDTs that were evenly spaced around the sample chamber, so dilation or contraction of the sample could be recorded. Further information about the device can be found in Iverson et al., (1997) and Iverson and Zoet (2015).

A separate ring-shear device (Fig. DR2), designed to slide ice at its pressure-melting temperature over a deformable till bed, was used to study healing of an ice-till interface (Iverson and Petersen 2011). This device has an annular U-shaped sample chamber made from aluminum with an outer diameter of 0.90 m, a width of 0.20 m and a height of up to 0.27 m. A vertical stress is applied to the base of the sample chamber using a servo-controlled hydraulic ram and held steady to within 2% of its set point as the sample chamber expands or contracts. Expansion or contraction is measured with an LVDT. The sample chamber is drained through 12 ports spanning the sample chamber base that drain to atmospheric pressure. Till occupies the lowest 20% of the sample chamber, whereas ice fills the uppermost 80%. The upper surface of the ice is gripped by a toothed upper platen made of Delrin, a plastic of low thermal conductivity that inhibits slip by regelation. The upper platen is rotated at a constant velocity, and shear stress is measured using a torque sensor in the drive shaft, while the sample chamber is rotationally fixed. The device resides in a cold room, and the sample chamber is submerged in a tub of dilute ethylene glycol that has its temperature regulated with an external circulator. This system allows the ice temperature to be regulated to 0.01 C. Importantly, this temperature precision allows ice to be kept at its pressure melting temperature, without melting it prohibitively fast, for the duration of the experiment. Temperature was monitored by 12 thermistors mounted in the interior and exterior walls of the device. Four water pressure sensors were mounted in the sample chamber's walls and were hydraulically connected with the till layer.

1.2 Procedure

A sandy till, the Horicon till of the Green Bay lobe of the Laurentide ice sheet (Mickelson and Syverson and 1997), was used in all experiments because its large hydraulic permeability kept its pore-water pressure steadily close to atmospheric, despite till porosity changes that can accompany shear. The sand content of this till ranges from 50-80% (Mickelson and Syverson and 1997). The till was sieved such that particles larger than 1/10 of the minimum sample dimension (> 6 mm) were removed, in accordance with standard geotechnical testing methods (Head 1989).

In the till-only experiment the sample chamber was filled with a 0.06 m thick layer of dry sieved till. Then the upper platen was placed atop the sample with its rough surface in contact with the upper surface of the till. Water was then added to the internal reservoir, and the sample was allowed to saturate over a few days. A normal stress of 150 kPa was then applied to compact the till. Once compaction was complete shear was initiated through rotation of the bottom platen at a constant velocity while the top was held rotationally fixed. The sample was sheared until a steady (critical-state) porosity and shear stress were achieved. Steady state shear stress was typically recorded within 2 hours of shearing, at which time the slide-hold-slide experiments were initiated.

In the ice-till experiment an ice ring was constructed on top of a till layer. A 0.06 m layer dry sieved till was placed at the base of the sample chamber. Four vertical bead strings that were 60 mm tall and composed of beads 5 mm in diameter were placed in the till at positions evenly spaced along the centerline circumference for use as passive strain indicators. The till was then compacted with weights for approximately a day. The till surface was then repeatedly misted with deionized water, with the till at -5 ^{o}C, to seal the top of the till with ice during the ice-ring construction phase. The ice barrier prevented liquid water from entering the till pore space and freezing during the construction of the ice ring. Once the barrier was sufficiently impermeable the ice ring was constructed on the till by adding millimeter scale crushed deionized ice particles in successive layers (~15 mm) that were then flooded with deionized water near 0 ^{o}C and allowed to freeze. This process was repeated until the ice ring filled the remainder of the sample chamber. Plastic beads strings were frozen into the ice vertically to track the displacement of ice and its internal deformation during the experiment.

Once the ice ring was completed, the upper platen was frozen into contact with the upper surface of the ice ring. After the upper platen was attached, the vertical ram supplied a normal stress of 150 kPa as in the experiments with only till. The temperature of the cold room was then raised to +1 ^{o}C and the temperature the fluid surrounding the ice chamber was raised to a fraction of a degree above the pressure melting point. After ca. 7 days the temperature of the ice ring reached the pressure melting point as indicated by temperature sensors and the measured melt rate. Meltwater produced during the warming phase entered the pore spaces of the till. In addition to meltwater filling pore spaces, chilled deionized water was injected into the till through ports located at the base of the sample chamber to ensure that the till was fully water-saturated during deformation. A valve was left open to the chamber, so that air in pore spaces could evacuate the otherwise sealed sample chamber. Once gages that were hydraulically connected to the till recorded a spike in water pressure coincident with water injections, the till was assumed to be saturated. When the till was saturated and the ice was at its pressure melting temperature, sliding was initiated by rotating the upper platen at a constant velocity. The ice was slid until a steady shear stress was reached after ca. 24 hours, and then the slide-hold-slide experiments were started.

2.0 Correcting shear stress to account for till-wall friction

In the till-only experiment, drag between shearing till and the walls was measured directly. Drag between ice and the walls in the ice-till experiment was isolated and measured in a separate experiment with a smooth, flat rigid bed. Additional friction between shearing till and the walls in the ice-till experiments was estimated independently and added to the ice-wall drag to correct friction coefficients. Slip resistance measured in the ice-till experiment needed to be corrected to account for friction between shearing till and the lateral walls of the ice chamber. The shear-zone thickness was known from the relative displacements of beads arranged in initially vertical columns within the till. From the measured shear zone thickness, the total area of contact, At, between the shear zone and the inner and outer later walls was calculated and used to determine the shear force, F, supported by the walls:

$$F = A_t N \, tan\phi, \qquad \text{(S1)}$$

where, N is the effective stress and ϕ is the angle of internal friction of the till measured in direct-shear experiments (Lambe and Whitman 1979). In applying this relation, we assume that effective stress is isotropic and that wall drag is limited by the Coulomb strength of the till. As noted in the text, a separate experiment with temperate ice and a smooth, flat, rigid bed was used to measure drag between ice and the walls of the device. The sum of this drag and *F* was then subtracted from the force associated with the measured torque on the upper platen to compute the desired shear stress associated with slip over the bed.

Supplemental Figure Captions

Figure DR1: Till-only ring shear device. (A) Cross-sectional view. The yoke is connected to a torque sensor that allows friction on the walls to be measured independently from the shear stress on the upper platen. (B) Oblique view of the sample chamber that contains the till sample. The till shear is focused in a lens in the center of the sample chamber (from Iverson and Zoet, 2015).

Figure DR2: Cutaway of the Iowa State University sliding simulator, configured for ice-till experiments. The base of the sample chamber is filled with a till layer 6 cm thick. The outer diameter of the sample chamber is 0.90 m with a width of 0.20 cm. The upper platen grips the upper surface of the ice ring and slides the temperate ice over the till layer. The sample chamber is drained through ports in the walls and base of the chamber.

Figure DR3: Final displacement of beads that were originally inserted as a vertical column into the till of the ice-till experiment. No till deformation was observed in the bottom 80% of the till layer. The dots indicate mean bead displacement at a given depth with the error bars representing one standard deviation. Total upper surface displacement of the ice ring was 600 cm.

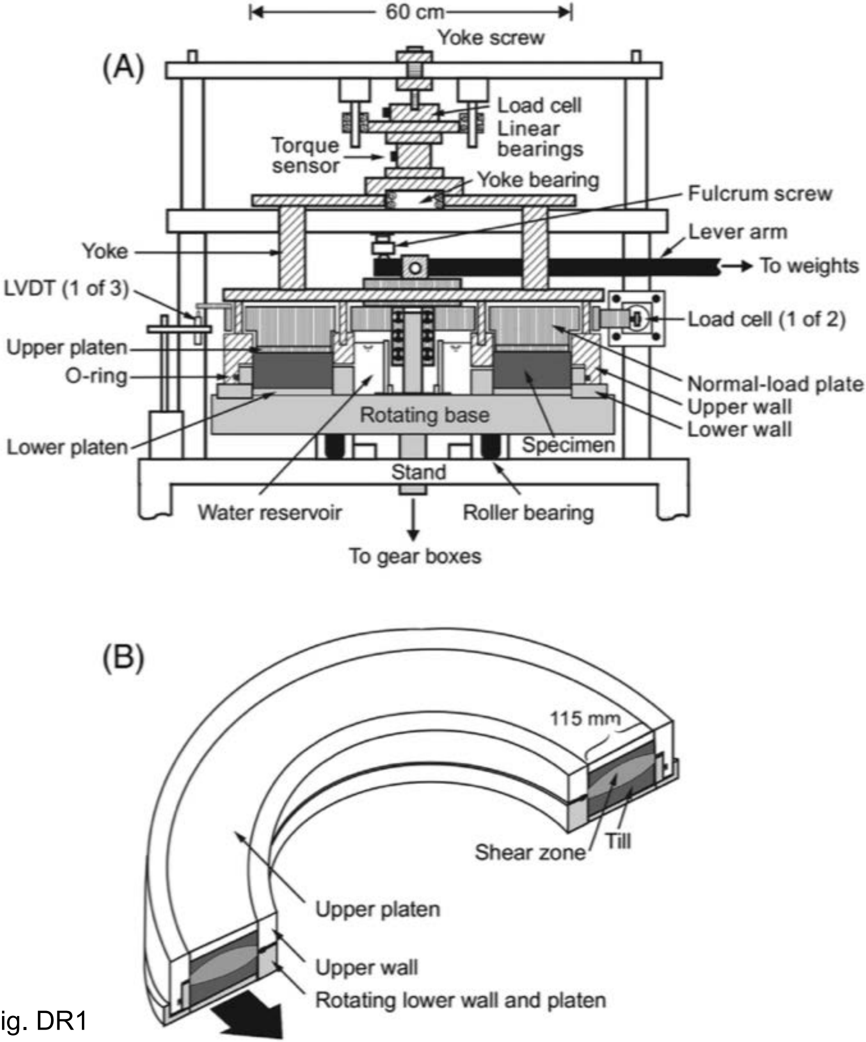
Figure DR4: Contraction in both experiments during the first ~14 hours following the initiation of a hold period.

Supplemental References

Head, K. H., 1989, Soil Technician's Handbook. John Wiley and Sons, New York.

Iverson, N. R., & Zoet, L. K., 2015, Experiments on the dynamics and sedimentary products of glacier slip. Geomorphology, 244, 121-134.

Mickelson, D. M., & Syverson, K. M., 1997, Quaternary geology of Ozaukee and Washington Counties, Wisconsin (Vol. 91). University of Wisconsin--Extension, Wisconsin Geological and Natural History Survey.



60 cm
Yoke screw
(A)
Load cell
Linear bearings
Torque sensor
Yoke bearing
Fulcrum screw
Lever arm
Yoke
To weights
LVDT (1 of 3)
Load cell (1 of 2)
Upper platen
O-ring
Normal-load plate
Upper wall
Lower wall
Rotating base
Lower platen
Specimen
Stand
Water reservoir
Roller bearing
To gear boxes
(B)
115 mm
Shear zone
Till
Upper platen
Upper wall
Rotating lower wall and platen

Fig. DR1

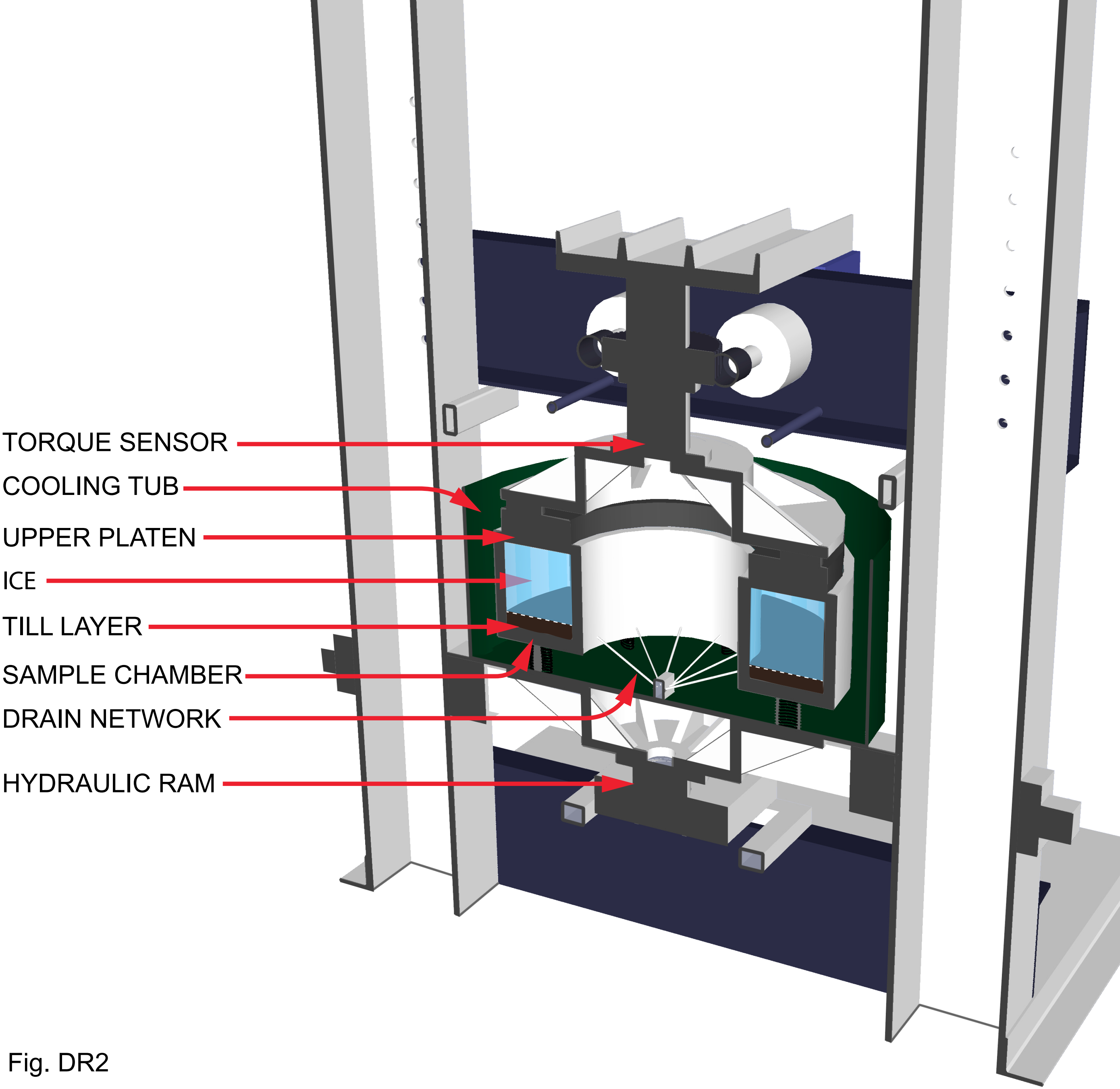
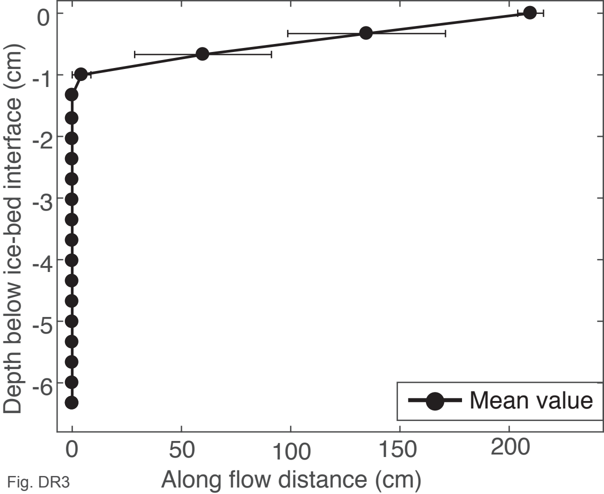
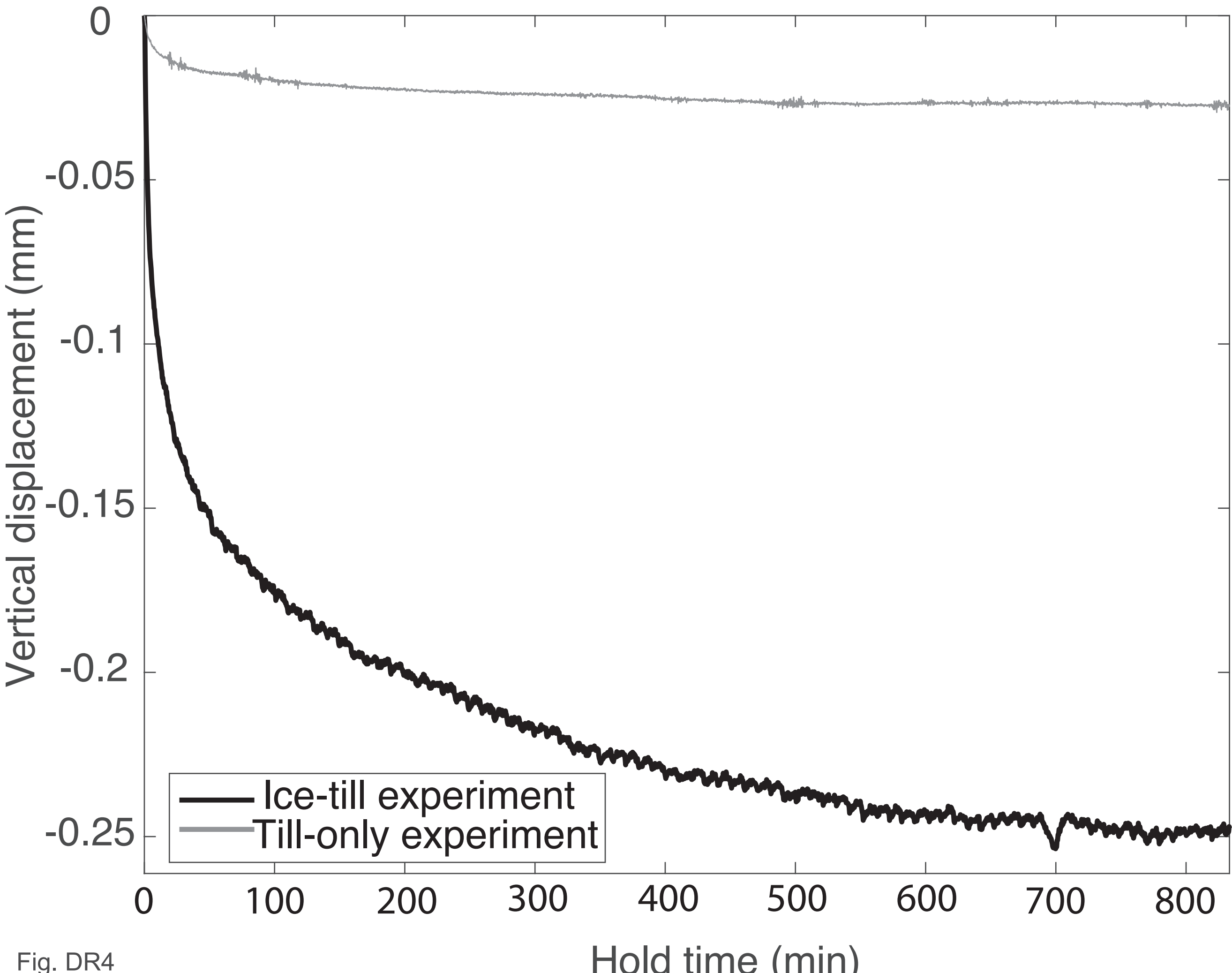

TORQUE SENSOR
COOLING TUB
UPPER PLATEN
ICE
TILL LAYER
SAMPLE CHAMBER
DRAIN NETWORK
HYDRAULIC RAM

Fig. DR2



0
-1
-2
-3
-4
-5
-6
Depth below ice-bed interface (cm)
0
50
100
150
200
Along flow distance (cm)
Mean value

Fig. DR3



0
-0.05
-0.1
-0.15
-0.2
-0.25
Vertical displacement (mm)
0
100
200
300
400
500
600
700
800
Hold time (min)
Ice-till experiment
Till-only experiment

Fig. DR4