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Experimental evidence for healing during stick-slip at the bases of ice streams

Lucas K. Zoet (1) and Neal R. Iverson (2)

(1) Department of Geoscience, University of Wisconsin-Madison, Madison, WI, USA, (2) Department of Geological and Atmospheric Science, Iowa State University, Ames, IA, USA

The Whillians Ice Stream has twice daily stick-slip events of ca. 50 cm with a maximum inter-event time of ca. 60,000 s. In order for stick-slip phenomena to occur under rate and state friction, two conditions need to be met: 1) A rate-weakening material at the interface, so that a nucleated slip perturbance can be propagated and 2) a material capable of healing (i.e., becoming stronger) when stationary, so that stress can be recharged during hold periods between ruptures. Although rate weakening has been experimentally demonstrated for some basal tills, experimental data relevant to glacier slip that bear on healing have been absent. Without an understanding of the healing mechanisms active at the beds of ice streams, models of the mechanics of ice stream stick-slip or ice stream shut-down will be inadequately informed.

We investigated healing mechanisms with slide-hold-slide experiments, a technique common in rock mechanics, using two different ring shear apparatuses. In one set of experiments till alone was sheared, while in another set ice at its melting temperature was slid over till. These two kinds of experiments allowed for the isolation of mechanisms active at ice-till interface from those within the till. In all experiments sliding velocity was ca. 345 m/yr, and effective stress was ca. 150 kPa. Once steady-state sliding friction, μ_{ss}, was attained, sliding was stopped and the materials were held in stationary contact for a given duration. When sliding was reinitiated, slip resistance initially rose above the previous μ_{ss} value to a peak friction, μ_{peak}, before returning to μ_{ss}. The difference between μ_{ss} and μ_{peak}, $\Delta\mu$, was then calculated. For each subsequent hold, the duration of stationary contact was increased logarithmically (100, 1,000, 10,000 and 100,000 s) until the maximum hold duration was attained. From the relationship between hold time and $\Delta\mu$, a healing rate was calculated.

Results from both sets of experiment indicate that $\Delta\mu$ increases with the logarithm of hold time but that in experiments with the ice healing rate is significantly faster than in experiments with till alone at hold times greater than $\sim$1000 s. This result indicates that some strengthening is the result of ice-till interactions. Mechanisms postulated previously to explain strengthening at the ice-bed interface are insufficient for characterizing the amount and form of strengthening observed over realistically brief hold times. A new model was generated to relate healing rate to changes in the real area of contact, A_r, between the ice and bed. The model attributes growth of A_r to the closure of micro-cavities formed in the lee of grains that span the ice-bed interface. In the model, A_r increases with the square root of the hold time, owing to cavity shrinkage that begins when sliding stops. This model yields a reasonably good fit to strengthening observed in the experiments and provides the first empirical justification for strengthening between slip events at the bases of soft-bedded ice streams.