Modeling the controls on till equilibrium line position beneath a synthetic outlet glacier

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CSDMS COMMUNITY SURFACE DYNAMICS MODELING SYSTEM

Background

- Outlet glaciers convey large quantities of ice, sediment, and water from the interior of ice sheets to the coastal ocean.
- When ice slides over a layer of sediment, buried clasts plough the rest of the till, causing the entire layer to deform.
- In regions where thick sediment layers form and basal sliding velocities are high, till deformation is an extremely efficient process.
- Beneath some Antarctic ice streams, sediment fluxes from till deformation can be as great as 150 $m^3 yr^{-1}$ [1].
- Till deformation also influences ice dynamics, allowing outlet glaciers and ice streams to achieve much higher velocities than otherwise possible on a rigid bed [2, 3].
- Recent research has proposed a new sliding law to account for till deformation when ice velocities exceed a certain threshold [4].
- Here, we use a synthetic model of an outlet glacier to investigate:
  - (1) how ice sliding velocities set the location of a "till equilibrium line,"
  - and (2) how sediment grain size distributions influence till deformation.

Model description

- We consider the sliding law proposed by [4], where the behavior of the ice-bed interface changes at a threshold velocity.
  - Weertman sliding: below the threshold velocity, ice moves by regelation around clasts at the bed.
  - Deformation sliding: above the threshold velocity, clasts plough the till layer based on the till's Coulomb strength.
- The threshold velocity u_t is given by:

$$u_t = \frac{\left(\frac{1}{\eta (Ra)^2 {k_0}^3} + \frac{4C_1}{(Ra)^2 k_0} \right) (N_F N)}{(2 + N_F k)}$$

where:

- η is the ice viscosity,
- R is the clast size of the largest particles at the bed,
- a is the fraction of clasts protruding at the ice-sediment interface,
- k_0 is a geometric correction,
- C_1 is a constant that accounts for regelation,
- N_F and k are constants that depends on the till strength, and
- N is the effective pressure at the bed.

- In the following numerical experiments, we use the *icepack* library [5] to compute steady-state profiles for a synthetic outlet glacier. We then calculate the threshold velocity and use the results to consider sediment transport beneath the outlet glacier.
- We consider two primary cases:
  - (1) When the glacier decelerates below the equilibrium line altitude, deposition occurs at a subsequent "till equilibrium line."
  - (2) When the glacier accelerates through the grounding line, the till equilibrium line marks the onset of deformation and bounds the region contributing to sediment deposition past the terminus.
- We then consider the effects of sediment grain size distributions on till equilibrium line position and overall sediment flux.

Results: Sliding velocity

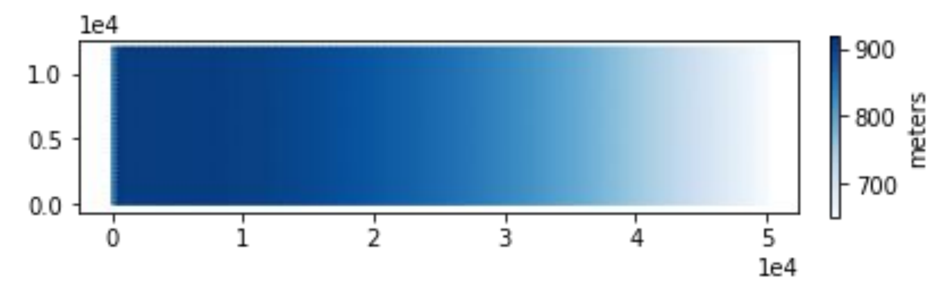

Figure 1a. Ice thickness for the decelerating outlet glacier. The ice sheet boundary is to the left, while the grounding line lies off the figure to the right. Both the x- and y-axes are in meters.

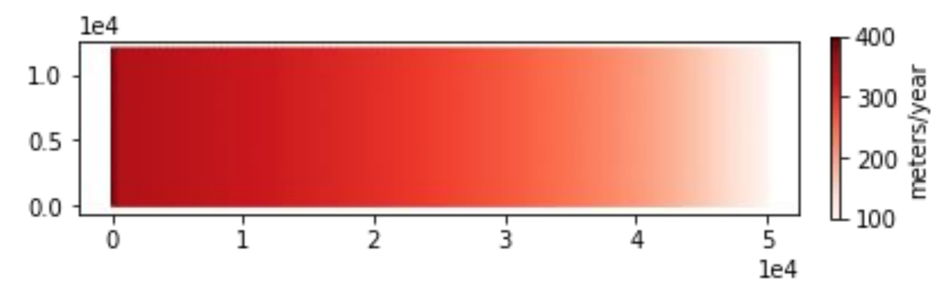

Figure 1b. Ice surface velocity for the decelerating outlet glacier. We assume that the sliding velocity may be approximated as a linear function of surface velocity.

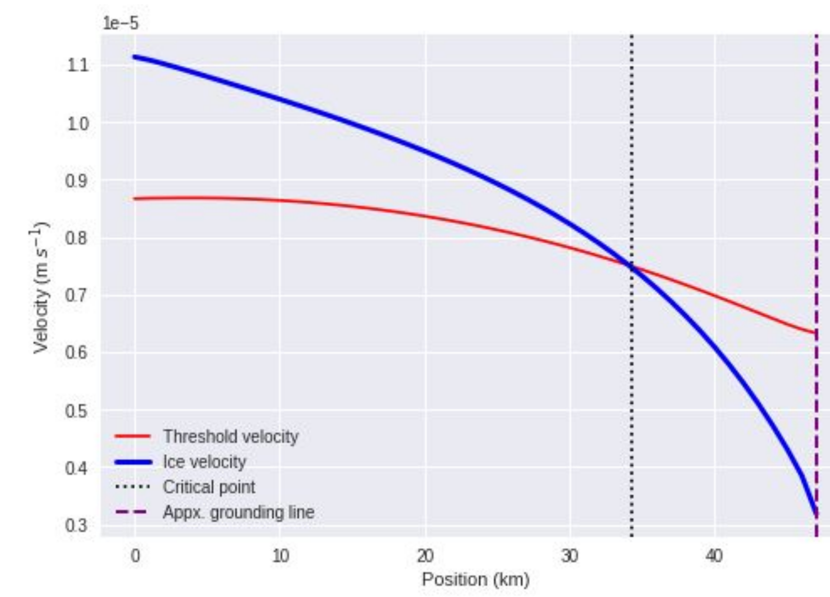

Figure 2. Results from modeling the till equilibrium line for a decelerating glacier. The ice velocity is in blue, the threshold velocity in red, and their intersection is plotted with a dotted vertical line. The till layer upstream from the critical point undergoes deformation from sliding ice, and deposition is concentrated at the till equilibrium line. Downstream from that point, the glacier follows a Weertman-style sliding law.

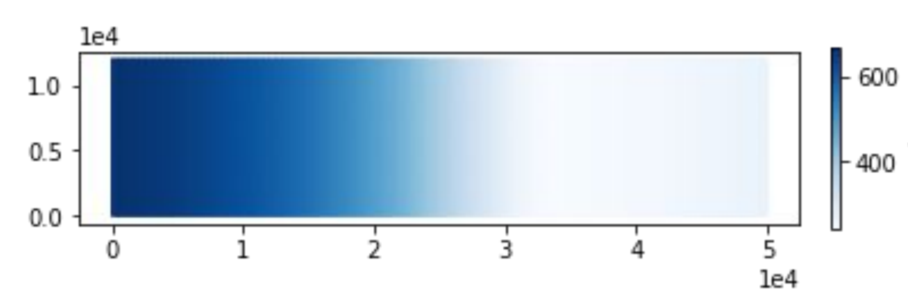

Figure 3a. Ice thickness for the accelerating outlet glacier. The ice sheet boundary is to the left, while the grounding line lies near 30 km. Beyond 30 km, the outlet forms a floating shelf.

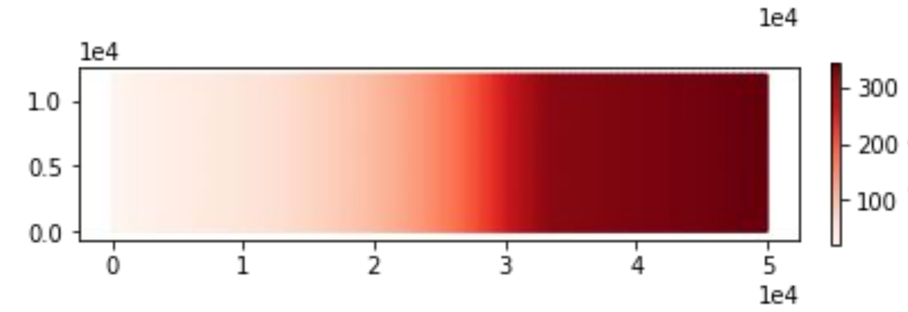

Figure 3b. Ice surface velocity for the accelerating outlet glacier. We again assume that the sliding velocity may be approximated as a linear function of surface velocity.

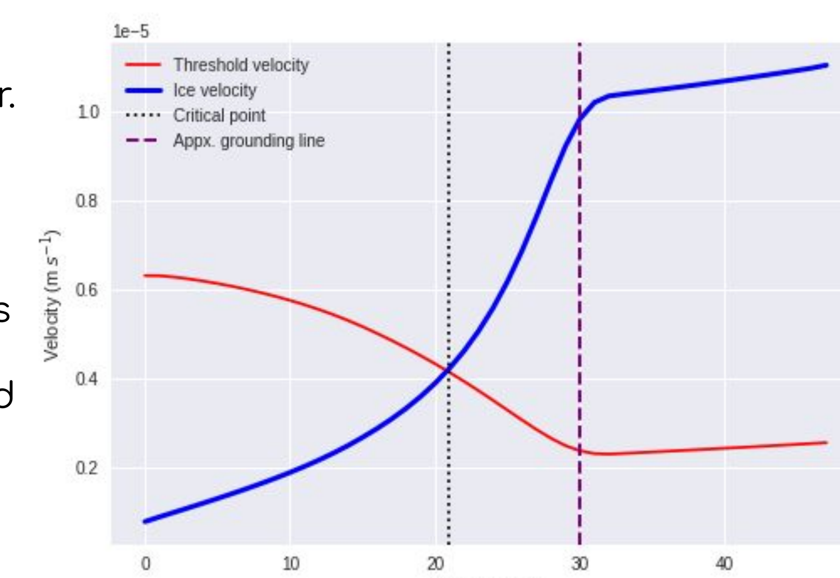

Figure 4. Results from modeling the till equilibrium line for an accelerating glacier. The ice velocity is in blue, the threshold velocity in red, and their intersection is plotted with a dotted vertical line. In this scenario, the till layer does not deform until the critical point, but then undergoes rapid deformation until it reaches the grounding line. Deposition is concentrated at the grounding line. The ice switches from regelation-based sliding upstream from the till equilibrium line to deformation-based sliding downstream.

References

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Results: Grain size distribution

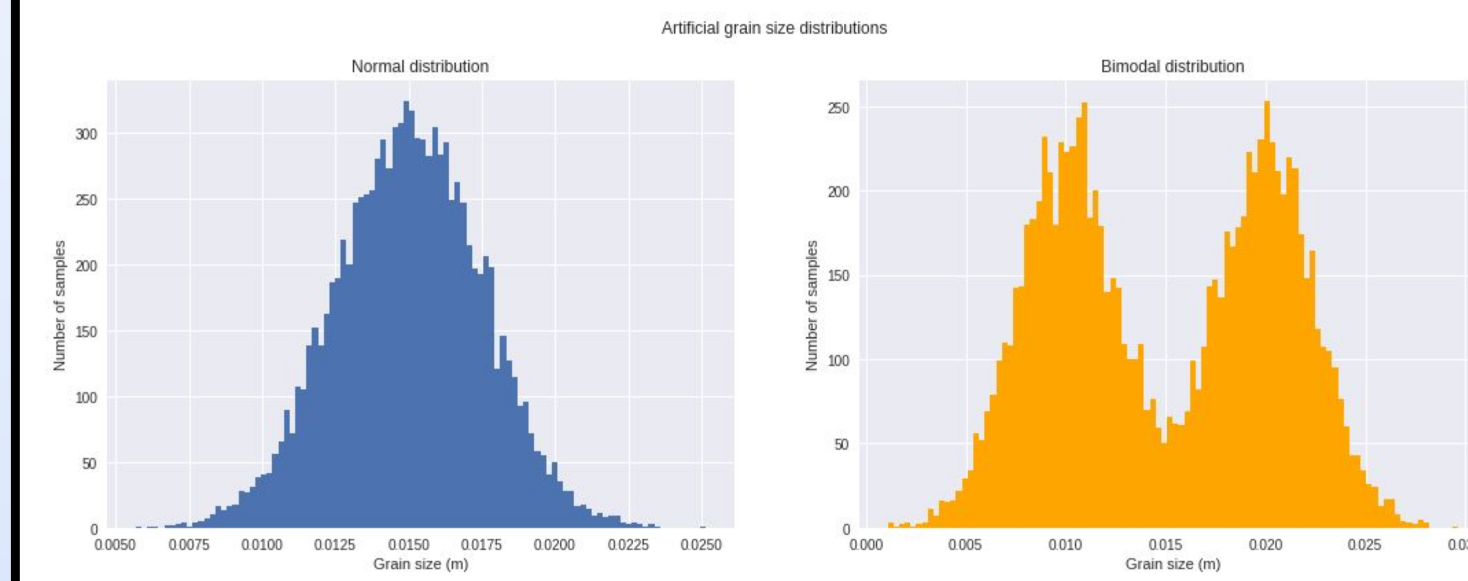

Figure 5. We use two synthetic grain size distributions to investigate the effects of sediment properties on till deformation.

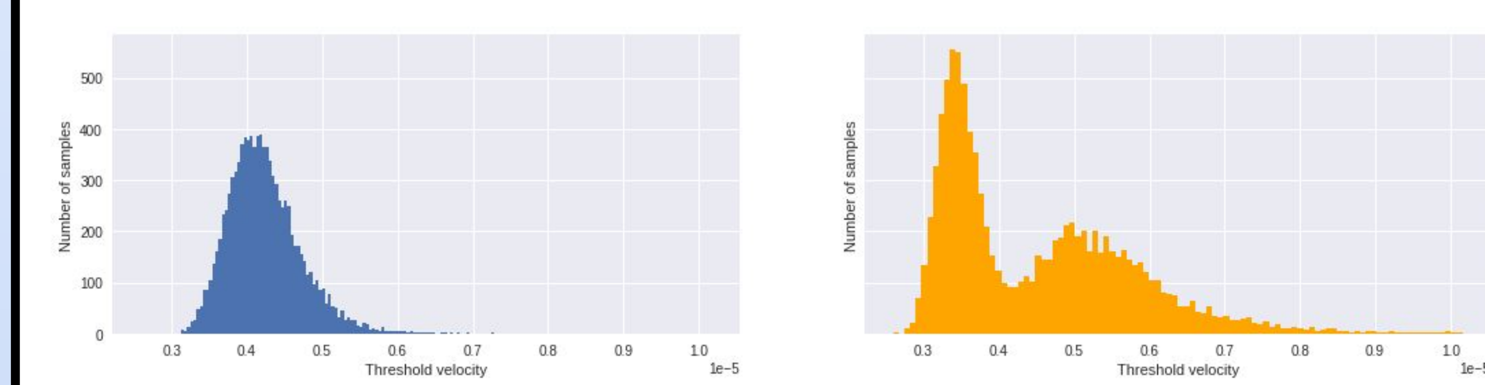

Figure 6. Threshold velocity results for each grain size distribution (normal at left in blue, bimodal at right in orange). The bimodal distribution leads to a wider range of threshold velocities, despite the approximately equal spread in the grain size distributions.

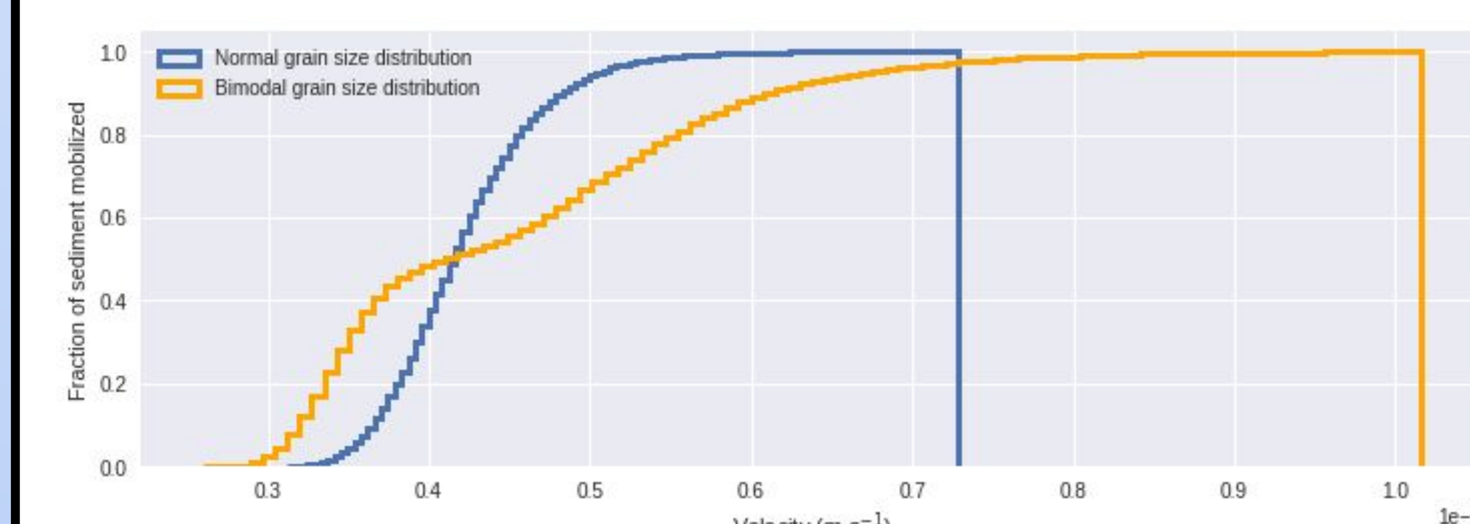

Figure 7. Cumulative sediment mobilized under each scenario. Note that larger clasts begin ploughing at lower velocities than smaller clasts, so the increase in fine fraction in the bimodal distribution causes the longer tail at high velocities in this analysis.

Sediment fluxes

If we assume that sediment velocities follow an exponential decay function from the ice-sediment interface to some critical depth [6], we can use this till deformation model to calculate bulk sediment fluxes from deformation.

- Consider characteristic depths equal to the largest clast size (here, 15 mm). Then:
  - At the till equilibrium line of Figure 1, the sediment flux is 3.95 $m^3 yr^{-1}$.
  - At the grounding line of Figure 2, the sediment flux is 4.34 $m^3 yr^{-1}$.
- If, instead, we take a characteristic depth of 0.5 m:
  - At the till equilibrium line of Figure 1, the sediment flux is 113.77 $m^3 yr^{-1}$.
  - At the grounding line of Figure 2, the sediment flux is 125.08 $m^3 yr^{-1}$.