A Sliding

The base of a glacier must be wet for it to slide effectively (temperature at the melting point). You can think about cold versus “temperate” ice cube on a board.

Figure 1 shows how a slippery glacier can “hang on” to a mountain. For hard beds the ice flows directly over bedrock. So the glacier is held by: 1) upstream faces of bedrock bumps, 2) friction from the glacier sides, and 3) slowed down by rock friction as rocks (gripped by the basal ice) scrape along the rock bed.

For soft beds the glacier may sit on a layer of gravel and mud (glacial till) made from eroded bedrock. Then it is held by: 1) slow moving ice at the glacier sides, and 2) basal till also forced to deform by the moving ice, acting as a brake (rock friction in the till).

Sliding occurs through regelation (Figure 2), most effective past small (<<1 m) bumps, and enhanced plastic flow, which is more effective for larger bumps. Both these processes are at work at the same time and contribute equally to sliding for obstacles around 10 - 100 mm.
Observations show that basal water pressure is important for sliding. An empirical sliding law,

\[ u = k\tau_p N^{-q}, \]  

(1)

where \( N \) is the effective pressure,

\[ N = P_i - P_w, \]

\( \tau \) is the shear stress, and \( k, p, \) and \( q \) are constants. Figure 3 shows non-dimensionalized velocity as a function of \( N \). Here we have divided with a reference stress \( N_0^2 \) to get \( u(\frac{N_0^q}{\tau p}) = (N_0/N)^q \).

Figure 3: Non-dimensional sliding velocities using Equation 1 with \( p = 1 \), and \( q = 1, 2, 3 \).

The sliding speed of glaciers increases if

- Ice thickness increases (\( \tau \) increases)
- Surface slope increases (\( \tau \) increases)
• Water pressure at the bed increases ($N$ decreases)
  – On a rocky bed, higher pressure "floats" ice, reduces friction with the bedrock.
  – If bed is "rough" high pressure also reduces contact area where sliding friction can occur.
  – On a "soft" bed, high water pressure can make the bed into a softer mud that can then deform and flow faster. For sliding by this deformation of sediments $u \propto N^{-q}$ (see Section B).

When a glacier changes its motion quickly (days, weeks), the cause must be a change in the sliding velocity. The internal deformation cannot be radically altered until the thickness or slope or temperature of the glacier change significantly, and all of these take time to change.

<table>
<thead>
<tr>
<th>Glacier</th>
<th>Sliding speed (m/a)</th>
<th>Deformation speed (m/a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nissqually Glacier, Mt Rainier (S/F)</td>
<td>90</td>
<td>15</td>
</tr>
<tr>
<td>Nissqually Glacier, Mt Rainier (W/Sp)</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Blue Glacier</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td>Variagated Glacier (surging)</td>
<td>10,000</td>
<td>40</td>
</tr>
<tr>
<td>Jakobshavn Isbrae (Greenland)</td>
<td>2,000</td>
<td></td>
</tr>
<tr>
<td>Ice Stream B (Antarctica)</td>
<td>500</td>
<td>5</td>
</tr>
</tbody>
</table>

On average sliding accounts for about half of the surface velocity. 
This applies though only to glaciers where the base is at the melting point. For cold-based glaciers, sliding velocities are $<1$ mm/d.

During sliding over hard beds, Figure 4,

• Pressure opens cavities
• Small bumps are “drowned” by water
• Reduce contact area

This results in faster sliding.
While sliding over soft beds the effects of water (pressure)

• Dilates the till, reducing rock-rock friction
• Deforms till
• Lubricates interface, allowing slip

This results in FASTER SLIDING.
B  Till Deformation

Ice streams are zones of fast moving ice within ice sheets (Bentley, 1987). Of particular interest are the ice streams that discharge from the interior of the West Antarctic Ice Sheet across the Siple Coast into the Ross Ice Shelf and ultimately the Ross Sea (Alley and Whillans, 1991). The high speed (100 to 1000 m a$^{-1}$) of these ice streams is achieved with a very low driving stress ($\sim$10 kPa). Deformation through the thickness of the ice ($\sim$1 km) is expected to contribute less than 1% of the speed at the upper surface. Almost all of the total velocity is produced by motion at the base (Engelhardt and Kamb, 1998). Discovery of a weak layer of dilated till beneath parts of Ice Stream B (Blankenship and others, 1987; Engelhardt and others, 1990) has lead to the notion that lubrication by soft till is responsible for the fast motion at the low driving stress.

The high speed could be achieved by some combination of distributed deformation within the till layer, or slip on discrete interfaces, such as the ice-till interface, within the till or at the till base (Alley, 1989; Engelhardt and Kamb, 1998; Truffer and others, 1999). Pervasive deformation of the till and slip at the ice-till interface have been the focus of most previous investigations relevant to the West Antarctic Ice Streams. There is observational evidence for both of these processes, but no conclusive evidence regarding which processes is most important (Engelhardt and Kamb, 1997). This open question represents a major gap in fundamental understanding of fast ice-stream motion and related geomorphic issues concerning till transport, erosion required to replace till carried away and till discharge to deltas deposited at the grounding line of ice streams.

Thorsteinsson and Raymond (2000) explored the partitioning of the basal motion between till deformation and slip at the ice base. The primary assumption is that till-ice boundary is a sharp, well-lubricated interface, which may be expected under conditions in which there is net heat flow to the base of the ice (Engelhardt and others, 1990), melting of the ice and lack of adhesion of till components to it. In this circumstance, stress is transmitted between the ice and till by roughness elements of the ice-till interface. The resulting mean shear stress can cause deformation through the thickness of the till.

Slip in the presence of the roughness elements can occur by local deformations in the till, which is analyzed using the classic theory of ice sliding (Nye, 1969) with the primary modification that the ice is assumed to be rigid and the till to deform like an incompressible viscous fluid, thus reversing the role of ice and bed.
In this regard, both the shearing through the till thickness and the slip at the ice till interface are mediated by deformation in the till. Both mean till deformation and slip increase with increasing softness of the till. The primary control variables affecting the relative amount of sliding and till deformation are the interface roughness and the vertical thickness of the till that can deform. We explore how the ratio of sliding to till deformation depends on these two variables and examine some implications concerning motions in the till imposed by the sliding.

Particles in the till smaller than 10-1 mm are 75% of mass (Tulaczyk and others, 1998). As long as wavelength of the roughness elements $\lambda > 0.03$ m the single continuum assumption should hold.

Figure 5 shows the percentage of sliding to total speed ($100 \times U_s/(U_s + U_d)$), where $s$ denotes sliding and $d$ deformation, for a range of roughness ($Ak$), scale height ($h$) and wavelength ($\lambda = 2\pi/k$) for sinusoidal ice-till interface $f(x) = A\sin(kx)$, with $Ak << 1$ and $A << h$. Note that we have plotted the ratio as the percentage contribution of sliding and till deformation to the total ice velocity. The contribution from sliding increases as the roughness decreases. The contribution from till deformation increases as the thickness of the till layer increases. This is the qualitative behavior that one would expect.

The wavelength at which sliding contributes more to the ice motion ($U_s/U_d > 1$) depends on roughness $Ak$, and till thickness $h$. Examples are: $h = 5$ m, $Ak = 0.1$, then $\lambda$ must be larger than 0.3 m; $h = 5$ m, $Ak = 0.05$, $\lambda > 75$ mm; $h = 5$ m, $Ak = 0.001$, $\lambda > 3$ mm (Fig. 5).

Our conclusion is that sliding dominates till shearing when the thickness of till is order 10 m or less, unless there is substantial roughness on the ice-till interface at scale of order $10^{-1}$ m or less.

The resulting heating will be located where strain rate is maximum. For the sliding induced motion that occurs beneath the locations of maximum slope deviation of the interface. The heating induced by the mean shearing will be maximum under the deepest protrusions of the ice, where the differential shearing motion is accommodated over a shorter vertical distance. Examples of the instantaneous total heat production rate per unit volume for the total motions (sliding induced...
and mean shearing) are shown in Figure 6.

Figure 6: Heat generated in the till by its deformation. Here $\lambda = 30$ cm and the amplitude of the roughness, $A$, about 0.5 cm.


