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Flow Mechanism of Glaciers on Soft Beds

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Subhourly measurements of bed deformation, bed shear strength, subglacial water pressure, and surface speed at Storglaciären, a glacier in northern Sweden, showed that the shear-strain rates of the bed decrease during periods of high water pressure and surface speed. High water pressures appear to be accompanied by a reduction in the coupling of ice with the bed that is sufficient to reduce or eliminate shearing. The instability of large ice masses may result from similar decoupling rather than from pervasive bed deformation, as has been commonly thought.

Many glaciers are underlain, at least in part, by unlithified sediment that may deform readily if basal water pressures are near the ice overburden pressure. Such deformation has been invoked to explain the rapid motion and instability of modern and former ice masses (*1–4*). To further study this process, we obtained simultaneous continuous measurements of bed deformation and glacier surface velocity on Storglaciären in northern Sweden. Basal water pressures vary over a wide range of values at Storglaciären; thus, this glacier can be used to study the critical relation between water pressure and bed deformation rate.

Storglaciären is a well-studied, wet-based valley glacier (*5*). Resistivity measurements (*6*), penetration testing, and sampling in boreholes drilled to the bed indicate that much of the ablation area is underlain by a layer of till that is decimeters thick. We studied the deformation of this till in the lower part of the ablation area on the upstream side of a gentle transverse ridge in the bed. The average glacier thickness in this area is ~95 m. We measured bed deformation in boreholes using small dual-axis, leaf-spring tiltmeters (*7*). We also measured the shear strength of the till with a roughened horizontal cylinder with conical ends that was dragged through the till. The force on the cylinder was measured, and geotechnical theory associated with cone-penetration testing was adapted to estimate the shear strength from this force (*8*). We determined surface speed by measuring the down-glacier displacement of a stake at the site every 10 min with an automated distance meter (*9*). Water pressure was measured continuously in boreholes.

During the period of record in 1992 (Fig. 1), a tiltmeter inserted in sediment near the ice-bed interface rotated down-glacier a total of 52°, corresponding to a mean shear-strain rate of 25 year^{-1}. The till thickness at the site, estimated from penetration tests, was 0.33 m. If the full thickness were shearing uniformly, the displacement of the surface of the glacier would have been at least twice what was observed. The observed displacement thus indicates that shearing was not uniform and was instead focused near the glacier sole, as has been both measured (*2*) and predicted from theory (*2, 10, 11*). During two peaks in velocity resulting from rain storms on 15 and 22 July, negative shear-strain rates were recorded (Fig. 1). Such negative values, which have also been observed elsewhere (*7*), imply that the tiltmeter recording the deformation was rotating up-glacier, the opposite of that expected. During acceleration of the glacier toward these peaks, the sediment shear strength tended to decrease; it then increased rapidly during deceleration of the glacier (Fig. 1).

The glacier and till exhibited similar behavior in 1993 (Fig. 2). Diurnal peaks in surface velocity were coeval with maxima in water pressure, which never exceeded the ice overburden pressure (*12*). The velocity peaks occurred during or slightly after till strain-rate minima, which were usually negative. The total down flow rotation of the tiltmeter was 9°, which would account for only 5% of the glacier displacement, even if the full 0.35 m of till were deforming uniformly. The tiltmeter was inserted 0.10 m lower in the till layer in 1993 than in 1992, which may account for the lower mean strain rate.

It appears from these data that the coupling between the ice and the till is reduced during periods of high water pressure and most rapid flow. This decoupling is presumably caused by uplift of the basal ice and reduction of the applied shear stress. A natural conjecture is that the negative strain rates arise because of squeezing of the till into the zone of uplift. This would thicken the till and cause the tiltmeters, which were inclined in the down flow direction, to rotate up-glacier. The up-glacier rotation

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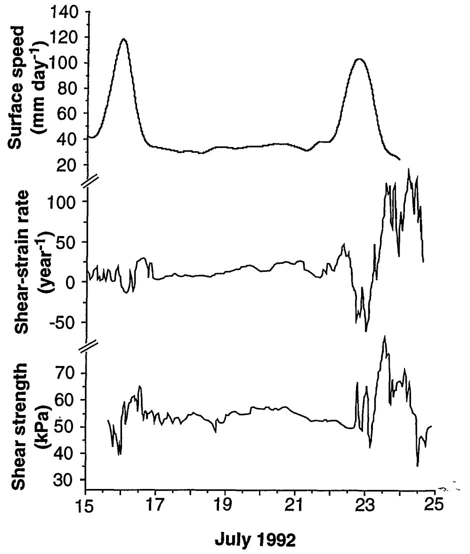


Fig. 1. Surface speed, down-flow shear-strain rate of till, and till shear strength during 10 days in July 1992. Shear strain was measured with a tiltmeter inserted in the till with a hammer and insertion tube (7). The tiltmeter was 85 mm long and had a precision of 2.0° at 0° of tilt and 5° at 60° of tilt. The relative error between successive measurements was near zero as indicated by the smoothness of the raw tilt data (not shown). As in earlier work (7), it was assumed that the principal direction of tilt was in the down-flow direction. During the period shown, the down-flow rotation of the tiltmeter was from 20° to 72°. The till shear strain and strength were measured in boreholes that were 10 m apart and within 20 m of the velocity measurements.

events measured in 1993 did not exceed 1.0°. This value corresponds to a minimum increase in till thickness of 0.7 mm, if the thickening were confined to a zone equal in thickness to the length of the tiltmeter (0.085 m). The corresponding minimum thickness increases in 1992 were 3 and 16 mm during the two high-velocity events. This difference may reflect the closer placement of the tiltmeter to the glacier sole in 1992 than in 1993 (till nearer the ice is probably more mobile).

The changes in shear strength during high-velocity events (Fig. 1) are also consistent with uplift and reduced coupling of ice with the bed. Uplift during glacier acceleration would reduce the effective pressure on the till, and the till thus would be weakened as a result of a reduction in intergranular friction. As velocity decreases and the ice again firmly couples to the till surface, the effective pressure and the till strength would be expected to increase. The shear strength increases transiently to values that are higher than the average strength at high strains (Fig. 1). This increase may reflect the increase in stress required to rearrange sediment grains as simple shear is reinitiated, a common phenomenon when sediment is sheared in the laboratory (*13*).

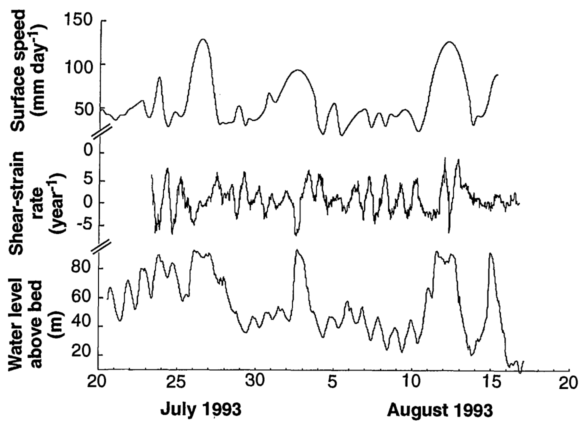
The reduction in coupling at the sites of our tiltmeters, and by extension over the entire deforming till layer, indicates that stresses resisting glacier motion must be concentrated elsewhere, perhaps at places where the till is absent. Evidence from some larger valley glaciers and ice streams (*14*) suggests, similarly, that deformable beds may not provide the principal resistance to motion. Perhaps movement of these ice masses is also concentrated at the glacier sole, rather than within the bed. For example, effective pressures beneath Ice Stream B (*15*) are less than those indicated by our water pressure data; thus the tendency for reduction in coupling may be even stronger there.

The extent to which the coupling is influenced by unsteady water pressure is uncertain, however. Water pressures beneath Ice Stream B, although high, are also relatively steady. Perhaps fluctuations in water pressure are an essential element of the reduction in coupling that we observed, although it is not obvious why this should be the case.

The instability of ice sheets moving over unlithified beds may have led to diverse phenomena, including the deposition of massive volumes of ice-rafted sediment in the North Atlantic (*3*), nonsynchronous glacier-margin fluctuations in North America, and abrupt climate change (*4*). Although the presence of an extensive soft bed may be necessary for such instability, interpretations of the geologic record differ with respect to the actual mechanism of glacier motion. Both pervasive bed deformation and motion confined to the ice-bed interface have been advocated on the basis of characteristics of basal tills. At present, there is no means of determining unequivocally whether such tills have undergone the very high cumulative strains indicative of the deforming-bed mechanism.

Our measurements do not support the notion that instability results from pervasive deformation of the bed. Rather, they suggest that, where water pressures are sufficiently close to the ice overburden pressure, the shear strength of the ice-sediment interface may be reduced more than that of the underlying sediment. Sediment deformation may be important primarily because it results in a smooth surface over which the glacier can slide. Smoothing is expected because irregularities on the sediment surface would not support concentrated shear stresses. Sediment deformation may also be important, albeit locally, because it allows clasts that protrude from the glacier sole to plow through the bed (*10*, *16*).

Fig. 2. Surface speed, down flow shear-strain rate, and borehole water level during late July and early August 1993. Shear strain was measured with a tiltmeter identical to that used in 1992. The total down flow rotation of the tiltmeter was from 5° to 14°. The borehole water level was measured with a model PX176 Omega pressure transducer with an accuracy of ±1.4 m.



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