Geophysics

A paradigm shift in glaciology?

from G.S. Boulton

Two papers on pages 54 and 57 of this issue[1,2] suggest that part of the west Antarctic ice sheet is underlain by a thin layer of deforming water-soaked sediment. In such areas, the rheological properties of the sediment must largely control the dynamic behaviour of the ice sheet. Until now, most models of glacier flow have assumed that the ice moves over a rigid surface, although this was clearly not true for the great mid-latitude ice sheets of the Quaternary era which flowed over strongly deformed and predominantly soft sediment beds. Perhaps we must now revise our view of the sub-glacial processes which control modern ice-sheet flow, and use the new geophysical data that have been gathered from Antarctica to improve our reconstructions of the Quaternary ice sheets.

The great naturalists of the eighteenth and nineteenth centuries established the fact of glacier movement and observed both internal flow and basal sliding. They were impressed by the erosive power of the debris-studded soles of glaciers, which ground over bedrock to produce smoothed and striated surfaces. Similar surfaces in the mid-latitude lowlands of Europe and North America were thought to support the glacial theory, which asserted that in the recent past these areas had been covered by glaciers of continental scale, similar to the modern ice sheets of Greenland and Antarctica.

Subsequent discussions about glacier-bed processes during the early years of this century concentrated on the erosion of rock beds in alpine and highland regions, as the only direct observations of the glacier/bed interface were in natural cavities on the lee-side of bedrock protuberances[3]. Soft sediment-floored glaciers do not permit such observations as sediment is readily squeezed into incipient subglacial cavities. Thus, it is not surprising that sliding over a rigid bed provided the first quantitative analyses of the processes of basal *decollement* of glaciers[4,5], and that glacier movement was generally viewed as consisting of only two possible components, internal flow and basal sliding. As late as 1979, the symposium of the Glaciological Society on glacier beds was subtitled 'the Ice–Rock Interface', as if the two were synonymous.

Such a paradigm should have been quite implausible to geologists; that it survived so long is an indication of how little note the glaciological community took of the views of geologists. A representative measure of the relative importance of different basal processes has until now been accessible only by the study of the exposed beds of the last mid-latitude ice sheets in Europe and North America (where more than 80 per cent of the surface is overlain by soft deformable sediments) and in the areas exposed by recent retreat of valley glaciers, where sediment beds also predominate. A model in which a glacier slides over a smooth, passive, rigid surface seems quite inappropriate for most of these areas. The existence of widespread glacially induced deformation structures in these sediments has long been known[6]; such structures are now being more widely recognized, and are often associated with drumlins[7] (streamlined sediment hills produced beneath glaciers). Recent experiments demonstrate that even relatively coarse-grained subglacial sediments deform readily beneath a glacier and may play a dominant role in glacier movement[8]. It has been further argued[9] that such a mechanism controlled the behaviour of mid-latitude Quaternary ice sheets, with a soft, easily deforming sedimentary substratum permitting high glacier velocities for relatively low driving stresses; rapid responses to changing climate; and fast volumetric growth and decay facilitated by rapid changes in the extent of the ice sheets.

The modern ice sheets of Antarctica and Greenland are thought to be quite different: large, sluggish masses moving by internal flow with fast ice streams radiating through them[10] and discharge (in Antarctica) up to 90 per cent of the mass flux, although they comprise only 13 per cent of the ice-sheet perimeter. It is assumed that sliding over bedrock occurs beneath these ice streams with a lubricating water layer that decouples the glacier from its bed, thereby reducing friction and permitting fast, low-stress sliding[11,12]. A predominantly rock bed could result from progressive stripping of pre-existing sediment during the 15 million years of continuous ice-sheet residence on the Antarctic continent.

The recent exciting results from Antarctica reported in this issue[1,2] suggest that this picture may not be correct. The results are particularly important in demonstrating the relationship between a possibly drumlinized subglacial sediment stratum and a fast ice stream, and illustrate a geophysical technique that could establish the distribution of their physical properties and their relationship to ice-sheet dynamics on a wide scale.

Two important implications should be explored: first, that Pleistocene drumlin fields reflect widespread deformation of soft subglacial sediments, offer little frictional resistance to ice movement and are therefore geological reflections of former fast ice streams; and, second, that soft subglacial sediments are important in regulating the response of the modern Antarctic ice sheet to climate and sea-level changes, a matter of concern even in the short-term future[13]. They may also be important in glacier-surging behaviour.

To explore the implications of subglacial sediment deformation for ice-sheet behaviour we need to understand more about the rapid but sustained deformation of sediments at very low effective stresses, in which dilation is important. Sadly, although such processes are widespread in gravitational flows of many types, adequate flow laws have not been developed and the small strains in most conventional geotechnical experiments make these experiments an inappropriate basis for such laws. Strain rates are strongly affected by water content, so the behaviour of the interstitial water system is of critical importance.

The subglacial zone is different from the *decollement* zone in most other gravity-flow systems, such as gliding nappes and mud flows, in that the glacier sole is a water source, the glacier is an acquiclude and the subglacial water escape pathways are long. Thus, high pore-water pressures need not be transient but can be sustained in a steady state.

The fundamental conceptual difference between analyses of fast low-stress glacier movement over rigid or deformable surfaces is that whereas in the former the surface can be regarded as passive (although it may be temporarily changed by the thickening of a subglacial water film), the strong interaction in the latter requires a coupled analysis of both ice and sediment deformation. Moreover, in coupling the form and structure of the bed with the dynamics of the glacier, such analyses might help to unify glaciology and glacial geology, to the benefit of both disciplines, in a way which until now has been sadly lacking. □

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