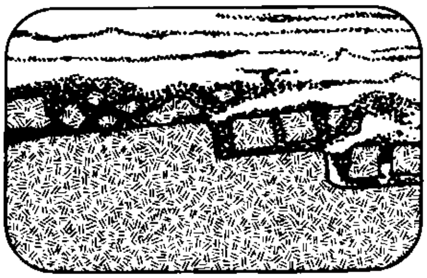

Symposium on Glacier Beds: The Ice-Rock Interface

G.K.C. Clarke
Department of Geophysics and Astronomy
University of British Columbia
Vancouver, B.C. V6T 1W5

R.M. Koerner
Polar Continental Shelf Project
Department of Energy, Mines and Resources
Ottawa, Ontario K1A 0E4

R.J. Rogerson
Department of Geography
Memorial University of Newfoundland
St. John's, Newfoundland A1C 5S7

W.H. Mathews
Department of Geological Sciences
University of British Columbia
Vancouver, B.C. V6T 1W5

C.S.L. Ommanney
Glaciology Division
Environment Canada
Ottawa, Ontario K1A 0E7

Construction of a realistic theory of glacier sliding is still one of the major pieces of unfinished business in glacier research. A significant component of the flow of wet-based glaciers and ice sheets is due to bottom sliding, and until a satisfactory description is found it will be difficult to develop realistic models to describe glacier flow and the growth and decay of ice-age ice sheets. In addition a complete theory of sliding would also lead to a better understanding of erosion and deposition processes at the glacier bed. The "Symposium on Glacier Beds: The Ice-Rock Interface" held in Ottawa, August 15 to 19, 1978, was aimed at bringing together glaciologists and glacial geologists to discuss the intimately connected problems of glacier sliding and erosion.

The existing sliding theories of Weertman, Lliboutry, Nye and Kamb are a good beginning but are obviously incomplete. Weertman's original theory is an idealization which is simple, offers good physical insight into the role of regelation and enhanced creep mechanisms, but is based on an unrealistic model of the glacier bed. The Nye and Kamb theories are based on the same physical ideas but assume a more realistic bed model, although close contact of the ice and bed are assumed. Lliboutry's contributions have been to emphasize the importance of cavitation and subglacial water pressure in allowing sliding to occur at high velocities. Although Lliboutry himself feels his theory is satisfactory for the present, it is clearly not the last word since both cavitation and water flow are introduced in an *ad hoc* fashion.

The invited paper by Lliboutry (CNRS, Grenoble) was an elaboration of his existing theory from which he developed both a global and local friction law for surfaces with different magnitudes of relief, with and without cavitation. Weertman (Northwestern University), in his invited paper, reviewed his contributions to understanding of sliding and water flow. He was also quick to point out that certain parts of his theory are now only of historical interest. His main contribution was to identify what he and many glaciologists consider to be the "Grand Unsolved Problem of Glaciology," a theory of glacier sliding which contains sliding physics, basal water flow and cavitation in some unified treatment. This is obviously a challenging task since the theory envisaged by Weertman contains no preconceptions about the extent of cavitation and the geometry of the subglacial drainage system, whether it be a water sheet, or a communicating network of drainage channels.

One of the major new theoretical contributions to sliding theory was presented by Kamb (Cal. Tech., Pasadena) and his colleagues Engelhardt and Harrison in an invited paper. Inspired by extensive experience in glacier drilling and borehole photography of the bed, Kamb has introduced several new and more realistic components to his theory of sliding. First the bed is not treated as a well-defined contact between ice and rock. A debris layer separates the glacier from its bed. Introduction of subsole drift has two effects on his theory, rock-rock friction becomes an important factor in retarding sliding, and the magnitude of rock-rock friction depends on the "intrusion velocity" of ice into the subsole drift zone. The intrusion velocity depends on how fast ice can move by regelation through the debris: the heat sources which control this regelation process are geothermal heat and frictional heat generated by sliding. Kamb's new sliding theory is the first in which geothermal flux plays a role (apart from its influence in providing meltwater) and it will be interesting to see if this improvement brings new insights on such matters as the geographical distribution of surging glaciers.

A different approach to sliding was taken by Budd (Antarctic Division, Melbourne). Rather than wait for satisfactory theories to evolve, Budd and his colleagues have chosen to dodge the question of sliding physics and instead propose a phenomenological approach based on two parameters which are not directly observable. These parameters are found by fitting the observed response of a particular glacier to a simple flow model. The advantage of this approach is that Budd has successfully devised computer models which imitate large-scale flow behavior in a realistic way. The disadvantage is that sliding physics, cavitation and subglacial water are not explicitly involved in his models, so the fundamental questions remain unanswered.

The second major theme of the symposium, and one which is closely related to glacier sliding, was that of erosion and deposition processes at the bed. Boulton (University of East Anglia) opened the proceedings with a review of the glacier erosion problem, suggested cold-based glaciers could erode their beds, and presented evidence of soft sediments deforming with the glacier. Subsequent papers, in particular that of Hughes (University of Maine) and an abstract of an unread paper by Baranowski, emphasized the idea that ice sheets can have basal conditions that vary in both time and space from frozen to melting. While this possibility complicates ice sheet modelling, it simplifies interpretation of glacial features left behind by ice sheets of the past. Hallet (Stanford University), drawing from Nye's sliding theory, presented a model of glacier abrasion, which suggested that ice thickness has no significant influence on abrasion rates (in contrast to some of Boulton's results). According to Hallet, abrasion always tends to smooth the bed: thus other processes are required if surface roughness is to be maintained. Papers by Mathews (University of British Columbia), Brepson, CNRS, Grenoble), and an Australian group led by Budd presented laboratory simulations of glacial abrasion and sliding. Brepson's work was the most sophisticated and has already produced qualitative results, the most important of which may be that the impurity content of the ice is an important variable in the ice-bed interaction. Laboratory simulations will surely contribute much to understanding this interaction although it is often difficult to judge how well such experiments match conditions beneath glaciers. In the final paper of the session Rogerson and Eyles (Memorial University) assessed the relative importance of subaerial and subglacial processes in the erosion of glacial basins.

Remarkable advances were reported in the direct observation of processes at the ice-rock interface. An invited paper by Vivian (Institut de Geographie Alpine, Grenoble) opened the session on the nature of the ice-rock interface. The tunnel beneath Glacier d'Argentiere (French Alps) has given Vivian and his colleagues a unique opportunity to make direct observations of sliding, cavitation and erosion and the bed. His work is the most ambitious and extensive of those using the tunnelling approach. Benoist (CNRS, Grenoble) presented spectral analysis results from deglaciated beds and from these calculated roughness sectra and shadowing functions. these are required inputs for various sliding theories. Laverdiere (Université de Montréal) and Guimont closed the session with a beautifully illustrated review of the forms of glacier erosion and their classification.

Ice cores contain a wealth of information about past climates and conditions at the base of ice sheets. Three papers were devoted to discussion of cores from the base of present-day ice sheets in Antarctica, Greenland and Devon Island. At Byrd Station, Antarctica, the basal ice is now at the melting point; Gow (CRREL, Hanover), Epstein and Sheehy attributed the 12 to 16 per cent (by weight) of debris in the bottom 4.83 m of the 2164 m core to the freezing-on debris at the base. Herron and Langway (University of Buffalo) found much lower debris concentrations (0.24% by weight) in the bottom 15.7 m of the 1375 m Camp Century, Greenland, core and attributed this to freezing-on at some time in the past. The present basal ice at Camp Century is well below the melting temperature so the ice sheet may have experienced a major change in bottom conditions. Analysis by Koerner and Fisher (Polar Continental Shelf Project, Ottawa) of the debris in the 298 m core from Devon Island ice cap indicates that it is windblown – not derived from the bed – and that the ice cap has always been frozen to its bed.

Most processes which occur at the glacier bed are extremely difficult to observe in a realistic setting. For this reason the studies of Souchez, Lemmens, Lorrain and Tison (Université Libre de Bruxelles) on the chemistry of regelation ice have proved rewarding. They have shown by analysis of Na+K/Ca+Mg values in basal ice that a heat-pump mechanism predicted by Robin does indeed act in the basal ice. Robin (Scott Polar Research Institute, Cambridge) reported new support for this mechanism coming from laboratory studies and observation of stick-slip strain events recorded in the Glacier d'Argentiere tunnel. Metcalf (University of Washington) used chemical analyses of the Nisqually Glacier runoff to estimate the erosional energy of the glacier. Experimental work by Tusima (University of Hokkaido) and Tozuka on ice regelation – the melting-refreezing process which contributes to glacier sliding – was splendidly elucidated by a time-lapse film; many in the audience were perplexed to observe that the physics of regelation is much more complex than simple theory would suggest. That something important is missing from present regelation theory was also hinted at by a mathematical paradox described by Morris (Institute of Hydrology, Wallingford, U.K.) in a theoretical paper. Such paradoxes often arise when the underlying physical model is deficient in some important respect.

A planned session on remote sensing of the ice-rock interface was reduced to a single paper by Woodruff and Doake (British Antarctic Survey) on the use of depolarisation of radio waves to distinguish between floating and grounded ice. Remote sensing of the characteristics of the glacier bed has seemed an attractive goal to glaciologists and it was disappointing that no other groups had successes to report.

In a session devoted to conditions at the base of the Pleistocene ice sheets, Moran (Alberta Research Council, Edmonton), with Clayton, Fenton, Andriashek, and Hooke discussed the problem of longitudinal-streamlined and transverse-thrust features. They attributed streamlined features to basal sliding in the thawed zone and transverse thrust features to the freezing zone of the glacier bed and to regions of locally elevated pore pressure. Broster, Dreimanis and White (University of Western Ontario) traced the sequence of erosional and depositional phases of the glaciation of an area in British Columbia. Goldthwait (University of Ohio) presented evidence for the mechanical abrasion of the deep glacial grooves of Kelleys Island, Lake Erie, and was followed by his colleague Whillans who preferred an origin by solution erosion in subglacial meltwater channels. Hughes (University of Maine) gave results from the CLIMAP model for the last ice sheet. It incorporated melting, freezing and melt-freeze transitional zones. The melting zone is where crushing occurs while quarrying takes place in the transitional zone. Freezing-on occurs at the edges of the melting and freezing zones. He related the present topography of glaciated areas to his various zones.

In the final session nine papers were given on subglacial hydrology. They pointed to water as the key to glacier-sliding. When we finally understand how water moves through the glacier and how it affects glacier flow, solution of most of the other problems concerning abrasion, sedimentation and plucking may follow. The various papers gave the impression that we are indeed progressing toward this goal. Hodge (USGS, Tacoma) showed that there is a strongly-preferred channelling of water flow under temperate glaciers whereas Rothlisberger, Iken and Spring (ETH, Zurich) stressed the importance of sheet-flow at the bed in effecting maximum early summer ice-flow rates Iken, Rothlisberger, Flotron and Haeberli then suggested that the water storage system of the Unteraar Glacier fully connected with the main subglacial water channels only when the water temperature was high, in their case in early summer. Two papers (Hallet; Walder and Hallet, of Stanford University) described studies of the micro- and meso-relief of deglaciated areas to emphasize the presence and varying thickness (from microns to tens of microns) of a continuous water film at the bed and related abraded areas to "through-flow" of water and areas with CaC03 deposits to local "thin-film" water flow associated with regelation sliding Collins (University of Manchester) illustrated and quantified the role of englacial and subglacial water flow. Ostrem's paper on the tunnels excavated, through rock, to the base of a Norwegian glacier for hydro-electric power presented qualitative observations on water-flow through a glacier. In this glacier he showed that debris transport was by the water rather than by the ice However, his results also illustrated the almost insurmountable problem that tunnelling (or boreholes for that matter) immediately creates a unique local condition which may bear little relevance to the natural situation

There has been a striking renewal of interest in glacier seismicity The original contributions to this field were by Neave and Savage in the 1960s, and their conclusions were mainly negative the events they found were associated with ice crack propagation in crevasse fields and did not originate from near the bed Weaver and Malone (University of Washington) presented a paper on their measurements on Mt. St. Helens and reported englacial seismic sources. The glacier they investigated is thin so it remains possible that their deepest sources are nevertheless associated with crevasses. Deichmann (ETH, Zurich) presented convincing evidence that some of the seismicity of Unteraar Glacier, Switzerland, originates from near the bed and appears to be associated with the growth of the subglacial drainage network. St. Lawrence and Qamar described a new mechanism, "water hammering", a sort of subglacial organ pipe, which could explain monochromatic seismic events recorded from within glaciers.

Looking back on the symposium, it is clear that the geomorphologists and glacial geologists displayed a more catholic knowledge of glaciology than glaciologists did of glacial geology We hope this aberration is temporary. There is no question that the glaciologists' view of the ice-rock interface must become more complex if it is to encompass the observations of glacial geologists as well as the tunnel and borehole measurements. At the same time, the glacial geologists have managed well with the simple sliding theories and would not necessarily welcome the encumbrance of the more realistic, but highly complicated, theory which glaciologists are striving to build

The Symposium on Glacier Beds was originally conceived by the National Research Council Sub-Committee on Glaciers, and is the fourth major glaciological conference initiated by that group in the past 12 years. The meeting was sponsored by the Royal Society of Canada and Carleton University and received financial support from the National Research Council, Department of Fisheries and Environment and Department of Energy, Mines and Resources. With 145 registrants from 12 countries, the conference had a distinct international flavour. That the conference was conceived and organized in Canada is encouraging: although the Canadian glaciological community is small and widely-dispersed, it has enjoyed its role as a catalyst for international research interest. Symposium proceedings will appear as Vol. 23, No. 89 of the *Journal of Glaciology* and should prove a cornerstone for future research on the ice-rock interface.

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