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# THE NATURE OF THE ICE-ROCK INTERFACE: THE RESULTS OF INVESTIGATION ON 20000 m² OF THE ROCK BED OF TEMPERATE GLACIERS*

*By* ROBERT VIVIAN

(Institut de Géographie Alpine, rue Maurice-Gignoux, 38031 Grenoble Cedex, France)

ABSTRACT. This paper reviews the results of 10 years study of the only four subglacial sites which are permanently accessible due to activity by hydro-electrical companies. All the sites occur beneath temperate ice. The first part is devoted to the study of the ice–rock interface as a glaciological phenomenon, and emphasizes the dynamic conditions for separation of the ice from the rock bed. This glaciological cavitation phenomenon occurs when $\tan \alpha > V_i/H_i$. Another phenomenon, "regressive cavitation" refers to the existence up-stream of the large permanent cavities, of a series of small cavities which although they are not permanent are fundamentally important because they control the subglacial water drainage allowing the water to penetrate new routes. The second part analyses the sliding movement of the ice on the rock bed. The deformation of the cavities depends mainly on variations in the velocity of the glacier. The sliding velocity measured at the interface accounts for 60 to 80% of the surface movement of the glacier; 80 to 90% of the surface velocity movement is attained a few metres above the glacier–bed interface. The third part describes the characteristics of subglacial drainage which are necessary to understand the nature of the ice–rock interface. The fourth part is devoted to the precise description of the different types of interface as they appeared in the subglacial sites.

RÉSUMÉ. *La nature de l'interface glace–roche: Résultats de la reconnaissance de 20 000 m² de lit rocheux sous des glaciers de type tempéré.* Cette communication se propose de faire le point sur les renseignements obtenus depuis 10 ans, à la suite de la reconnaissance et de l'étude des quatre seuls sites sous-glaciaires accessibles de façon permanente grâce aux travaux des compagnies hydro-électriques. Tous les sites concernent des glaces tempérées. La première partie est consacrée à l'étude de l'interface glace–roche en taut que phénomène glaciologique. L'accent est mis sur les conditions dynamiques à un décollement de la glace du rocher. Ce phénomène de cavitation glaciaire est réalisé dès lors que $\operatorname{tg} \alpha > V_i/H_i$. Un autre phénomène, la "cavitation régressive" justifie l'existence, à l'amont des grandes cavités permanentes, des séries de cavités de petite taille, non permanentes celles-là, mais fondamentales en ce sens qu'elles conditionnent les écoulements hydrauliques sous-glaciaires en ménageant des passages pour les eaux. La seconde partie analyse le régime des mouvements de la glace sur le lit rocheux. En effet, les déformations des cavités sont largement dépendantes de ces variations de vitesse du glacier. Le glissement mesuré à l'interface explique 60 à 80% du mouvement du glacier; 80 à 90% de ce mouvement étant assurés quelques mètres seulement au-dessus de l'interface. La troisième partie s'attache à décrire et à chiffrer les caractéristiques et les valeurs du drainage sous-glaciaire, éléments décisifs pour une bonne compréhension de l'état de l'interface glace–roche. La quatrième partie est précisément consacrée à la description des différents types d'interface glace–roche.

ZUSAMMENFASSUNG. *Der Charakter der Grenzfläche zwischen Eis und Fels: Ergebnisse von Untersuchungen auf 20 000 m² Felsbett temperierter Gletscher.* Die Arbeit fasst die Ergebnisse 10-jähriger Studien an den vier einzigen subglazialen Stellen zusammen, die dank der Massnahmen von Elektrizitätsgesellschaften ständig zugänglich sind; sie liegen durchwegs unter temperierten Gletschern. Der erste Teil gilt dem Studium der Grenzfläche zwischen Eis und Fels als glaziologisches Phänomen. Die dynamischen Voraussetzungen für eine Trennung des Eises vom Felsbett werden betrachtet. Diese Cavitationserscheinung tritt auf, wenn $\tan \alpha > V_i/H_i$. "Regressive Cavitation" erklärt die Existenz grosser, dauernder Hohlräume gletscheraufwärts und einer Reihe kleiner Hohlräume, die — obwohl nicht dauerhaft — bedeutsam für den subglazialen Wasserabfluss sind. Der zweite Teil analysiert die Gleitbewegung des Eises auf dem Felsbett. Die Verformung der Hohlräume hängt vor allem von den Geschwindigkeitsschwankungen des Gletschers ab. Die Gleitgeschwindigkeit an der Grenzfläche macht 60 bis 80% der Oberflächenbewegung des Gletschers aus. 80 bis 90% der Oberflächengeschwindigkeit werden bereits wenige Meter über dem Felsbett erreicht. Der dritte Teil beschreibt die Charakteristiken des subglazialen Abflusses, die für das Verständnis der Besonderheiten der Grenzfläche zwischen Eis und Fels erforderlich sind. Der vierte Teil gilt der genauen Beschreibung der verschiedenen Grenzflächenarten an den subglazialen Untersuchungsstellen.

THE investigation of a subglacial site is difficult because of the physical environment studied, and also because of the expense involved in reaching the glacier bed which is under at least 100 m of ice. Except in a few cases where access to the glacier bed has been for a scientific purpose (recently for example by LaChapelle (1968), and Schytt and Ekman (1961)), most of the opportunities for subglacial investigations have been provided by hydro-electric companies attempting to capture subglacial water for hydro-electric power.

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The first subglacial excavations were done in 1942–43 when the Société d'Électrochimie et des Aciéries d'Ugine attempted to capture the subglacial waters of glacier de Tré la Tête (Mont Blanc). These results have been described by Waeber in very important and pioneering papers (Waeber, 1943, and in *La Houille Blanche*). From 1955 to 1978 this kind of sub-glacial research was coordinated under glacier d'Argentière by Emosson S.A. In this paper we will describe the results of more than 10 years of systematic observations which have been made at 16 points of access to the ice–rock interface, covering an area of about 15 000 m² (Vivian, 1975).

Between 1969 and 1970 the Grande Dixence company undertook investigations at glacier de Bis in the Pennine Alps, Switzerland. A. Bezinge studied the hydrological and subglacial sedimentation (Bezinge and Peretten, unpublished; Bezinge and Vivian, 1976).

Between 1970 and 1977, the subglacial site under 100 m of ice of Mer de Glace in the Mont Blanc range was explored. Because the ice was constantly in contact with the rock, it was necessary to melt it with hot water, and this allowed us the opportunity to study subglacial topography (Charpentier and others, unpublished).

At the same time, work on the subglacial site of Bondhusbreen in Norway (Folgefonni ice cap) began. In spite of a steep longitudinal slope and a relatively high sliding velocity, the ice adheres to the rock bed dragging boulders of various sizes (Wold and Østrem, 1978).

These are the sites actually investigated (scientifically) and exploited (economically) in the world. They are related to temperate ice, the common denominators of this group are (i) the water which runs between ice and bedrock, (ii) the temperature of the basal ice (near the melting point), (iii) the temperature of the rock bed. At Argentière, in the rock which supports the glacier, we measured a temperature of 1.7°C five metres under the interface, while 40 m below, the temperature had increased to 2.7°C (measurements made in bore holes 4 m long, in rock adjacent to tunnels).

Using these new opportunities for the investigation of the ice–rock interface, it is apparent that each glacier is a special case. It is therefore necessary to be very cautious in making generalizations from these particular cases, even if the examples prove to be closer to the ground truth than many of the theoretical models.

Even though each glacier, and indeed each part of a glacier, may differ from each other, the investigations by various groups of scientists show that there are four principal groups of variables which are important in governing processes at the ice–rock interface:

the geology of the rock bed;
the ice and its physical, physico-chemical, and chemical properties;
the melt water: its discharge and its hydrological regime;
the air in the subglacial cavities, and the penetration of thermal influences.

This environment is not static. It varies in space and time.

## I. THE INTERFACE: A GLACIOLOGICAL PHENOMENON

(a) There are two kinds of ice–rock interface: when the ice is touching the bed, and when glacial cavitation phenomena result in the formation of cavities between rock and ice (Fig. 1). In the first case, there is a good contact between the rock bed and the bottom of the glacier, but the basal ice pressure may vary (Fig. 1a). In the second case, the glacier separates from the rock at an angle $\alpha$ depending on the horizontal and vertical flow components of the glacier and the slope of the rock bed (Fig. 1b).

If we take the basal flow line as the general direction of the flow of the ice on the rock bed, according to Figure 1b the ice will no longer be in contact with the rock bed when the slope of the rock bed on this line satisfies $\tan \alpha > V_i/H_i$.

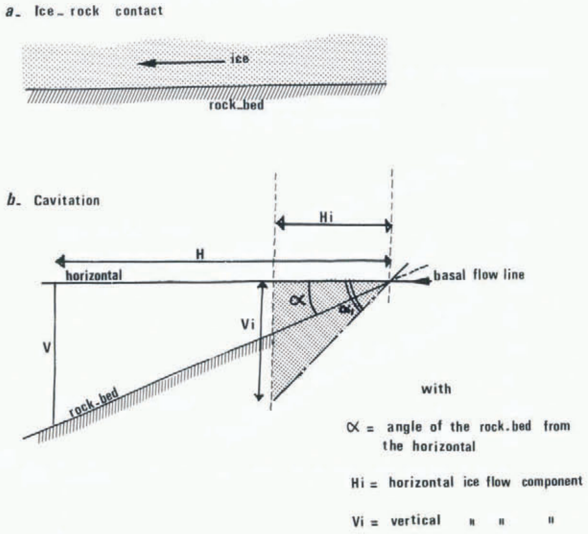

*Fig. 1. Diagrams to indicate the ice–rock interface under conditions of (a) contact and (b) cavitation. Ice contact occurs whenever* $V_i/H_i > V/H$ *or when* $\alpha_1 > \alpha$, *i.e. when* $V_i/H_i > \tan\alpha$ *or* $V_i > H_i \tan\alpha$. *Separation occurs when* $V_i < H_i \tan\alpha$.

The measurement of the horizontal and vertical components of ice movement on the rock bed, under glacier d'Argentière and Mer de Glace, seemed to provide the extreme limits of the range of values between which one can find the various situations of contact or separation of the ice from the bed.

These values are particularly useful in that they permit us to estimate the minimum bed slopes required to create the phenomenon of subglacial cavitation (Figs 2 and 3).

This is a result of great importance for hydroelectric companies which need such an artificial separation of the ice from the rock bed to avoid the penetration of ice into the water intake shafts. Indeed, they are able to produce cavities in such places by building concrete bumps on the bedrock surface.

The minimum slope values required to produce ice–bed separation, under glacier d'Argentière is 10% down-stream of the rock bar, 30 to 50% up-stream of the rock bar, 100% under Bondhusbreen ($H_i = 17$ cm/d) and 100–110% under Mer de Glace.

(b) Observations of subglacial cavities and their evolution in time show that ice velocity is reduced when the ice comes back into contact with the rock, a phenomenon which has been termed regressive cavitation (Fig. 4).

After the separation of the ice from the rock bed, the vault of the cavity, according to the visco-plasticity of the ice (ice being more or less loaded with debris at the level of the sole of the glacier) shows a remarkable concave profile which ends on the rock bed with a variable angle $\beta$. The value of this angle depends, amongst other things, on the slope of the rock bed. As $\beta$ increases, the friction and the stress at the base of the glacier (Boulton and others, 1979), as well as the normal pressure, increase.

In a natural cavity at Argentière, along a single glacier flow line, the horizontal velocities recorded vary in different parts of the cavity (2.9 cm/h at the point of initiation of the cavity, 2.5 cm/h in the central part, and 2.1 cm/h at the point where ice–rock contact is resumed). In the neighbourhood of this contact, internal stresses in the ice increase, precipitating the expulsion of solid material contained in the basal part of the glacier (rejection phenomena). This allows us to understand the observations made under the glacier. The position of the ice–rock contact at the down-stream extremity of the cavity is constant, whereas the point of cavity initiation is locally variable. It is as if the glacier were restrained on the down-stream

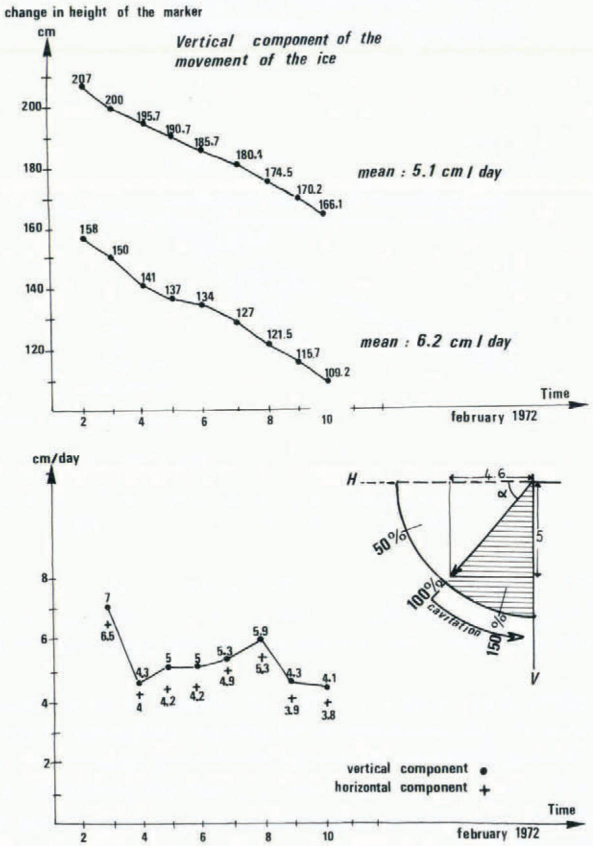

*Fig. 2. Measurements of vertical and horizontal components of the movement of the ice at the base of Mer de Glace (under a cover of 75–80 m of ice at a location where the bedrock slope is 30%) and deduction of corresponding velocities.*

side of the cavity, the resultant longitudinal compressive strain causes the ice to arch up, and the cavity enlarges up-stream (Fig. 4c). We refer to this process as "regressive glacial cavitation".

It is observed that where $\beta$ is large, cavities persist. I believe the reason for this to be that the high normal pressures produced down-stream of the point of cavity closure by high $\beta$ values include a large frictional drag at this point due to rock debris in the ice (cf. Boulton and others, 1979). Thus the down-stream end of the cavity is relatively fixed. The resultant regressive cavitation, working back from the permanent cavity, then causes the development up-stream of small non-permanent cavities (Fig. 4c, 1–2).

In conclusion it is necessary to emphasize three major points:

(1) first, the entrapment and incorporation of debris from the bed material depending on the angle of contact below the ice;

(2) secondly, the importance of a good knowledge of the detailed spacial and temporal variability of the sliding movement of the glacier;

(3) thirdly, the unpredictable effect on water drainage at the interface that reflects the continuing changes in the ice bottom.

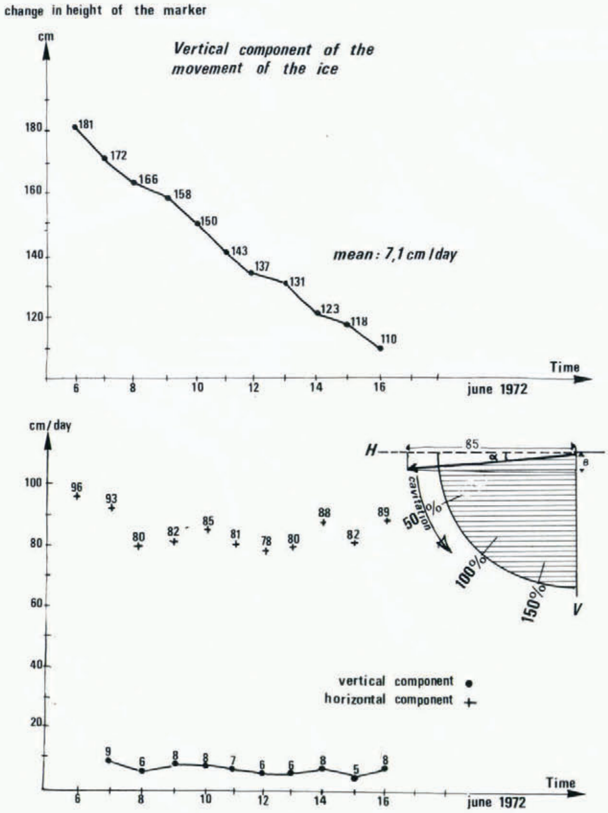

*Fig. 3. Measurements of vertical and horizontal components of the movement of the ice at the base of glacier d'Argentière* (*under a cover of 100 m of ice at a location where the bedrock slope is 120%*) *and deduction of corresponding velocities.*

## II. The movement of the ice on the rock bed

(1) Time-lapse photography at glacier d'Argentière with a speed of one frame per minute shows the glacier as a mass sliding homogeneously on its bed. Here, as in many other temperate glaciers, the sliding on the rock bed accounts for 60 to 80% of the glacier movement.

(2) At Argentière the surface velocity increases toward the end of the spring, and then maintains this maximum value during the summer before decreasing in the autumn.

However, the basal velocity is highest in spring, and decreases noticeably in summer. This ratio of surface to basal velocity varies, depending on the location within the transverse profile between 1.7 and 1.3 (1.2 m/d and 0.7 m/d; 2.0 m/d and 1.5 m/d). Compared to the spring this ratio tends to increase during each year.

(3) At the surface, much more than at depth where the influence of the rock bed is strong, one can see changes in the direction of the velocity vectors from season to season (Desperrier, unpublished) although exceptions do exist. The faster the glacier flows, the more the surface velocity vectors are controlled by the topography of the glacial valley, and the more the glacier tends to ignore the influence of the subglacial topography.

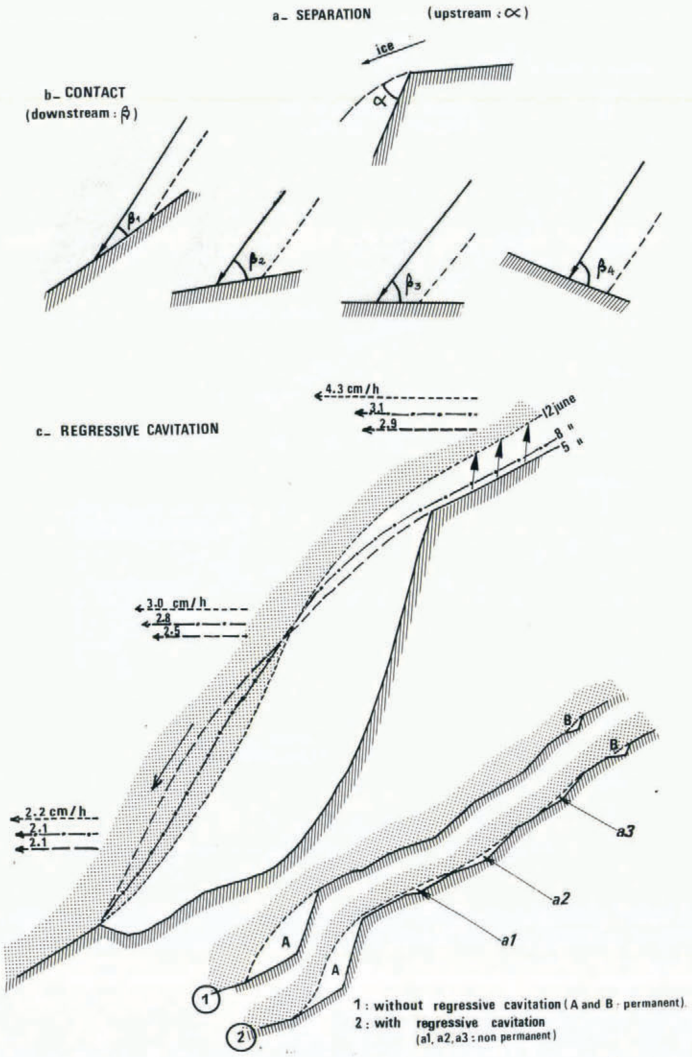

*Fig. 4. Diagrams to indicate the separation of ice from rock giving cavitation and the subsequent contact and the regressive cavitation that can result.*

(4) Even though the mean sliding velocities are roughly comparable, they are far from being identical from one point to another in the same transverse section (Vivian and Bocquet, 1973). Furthermore, the speeds are very different at the ice–rock contact and one or two metres above the interface. These values can vary by a ratio of 2 to 3, demonstrating the influence of friction at the ice–rock interface. If 70% of the movement of the glacier is explained by the sliding movement, up to 80 to 90% of the total movement is attained a few metres above the rock bed.

(5) The intensity to the friction forces, and hence the different sliding regimes of the glacier, are also dependent on the state of the subglacial drainage system. There is in fact a direct relationship between the sliding velocity and subglacial hydrology. (This does not contradict my initial statement, but implies that while the ice bottom influences the water regime, the water regime also influences the ice bottom).

(6) Subglacial hydrology appears to be a major control on the sliding movement (Table I).

TABLE I

| *Season* | *Discharge* | *Shape of the drainage* | *Relationship of channel capacity to discharge* | *Sliding movement* |
|---|---|---|---|---|
| Winter | 0.1–0.4 $m^3/s$ | undefined with subglacial water pockets | channel capacity $<$ discharge | slow and regular sliding |
| Spring | several $m^3/s$ | water sheet | channel capacity $>$ discharge | very irregular and slow sliding |
| | | | spreading | regular and quick sliding |
| Summer | $>10$ $m^3/s$ | defined channels | discharge $=$ channel capacity ($\leqslant$ or $\geqslant$) | very irregular slower flow |
| Autumn | about 1 $m^3/s$ | defined channels | discharge $<$ channel capacity | fairly regular and moderate sliding |

With regard to sliding, the hydrological regime can be divided into five periods, the most efficient for the movement being the late spring–early summer. One can note that with each period of irregular sliding*, the mean velocity of the glacier decreases. Melt-water discharge is closely related to the daily variations of sliding movement. A detailed study made under glacier d'Argentière emphasizes the increase of the discharge, and of the sliding velocities at the end of the day (late afternoon). Every cooling period in summer was followed by a reduction in speed, while every warming period (in summer) saw the speed increase (Vivian, 1975).

In theoretical models, much emphasis has been placed on the water pressure at the bed of the glacier, and on the resulting uplift with a reduction of friction forces on the bed. Water certainly is important, but field experience does not support the ubiquity of this mechanism for such types of glaciers. Our experience shows that the variations in subglacial water discharge are accompanied by variations in the sliding velocity, and yet cavities, both large and small, never fill up with water. Other processes can achieve the same effect as water pressure, amongst them a gradual reduction of friction through the elimination of the contact points between the glacier and the bed by thermal and mechanical erosion of subglacial waters, and the removal (by water) of the subglacial debris which inhibits basal sliding.

As for the uplift movement, it is well documented (Vivian, 1975) that the increase of the sliding velocities in spring favours the rise of the ice ceiling of the cavities by several decimetres (maximum in one day: 80 cm; absolute maximum in ten years: 1.5 m; measurements done in the central cavity of Argentière). This deformation correlates with uplift of the surface of the glacier.

## III. SUBGLACIAL DRAINAGE CHARACTERISTICS

Subglacial drainage characteristics are vital elements in the explanation and understanding of the ice–rock interface. Water has a major effect directly and indirectly on erosion and sedimentation at the glacier bed.

(1) The primary characteristic of subglacial drainage is its two-dimensional variability: laterally (or up-stream–down-stream), and vertically (with intraglacial flow of several hundred litres per second).

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* The field observations of Goodman (Goodman and others, 1979) suggest that the jerking movement of the glacier seems to be responsible for the strain variations observed and measured in the rock a few metres under the interface.

A third dimension, time, can be added, because the behaviour of a glacier at one point can be quite variable. With reference to the question within the main drainage system, it is important to mention that under a temperate glacier, there is not usually only one, but several alternative systems of subglacial water drainage.

Thus under glacier de Bis over a period of one year, Bezinge documented the variability of the water intake related to the snow and ice melt. Similar observations have been made at Mer de Glace by Charpentier.

At Argentière over a period of 12 years, we have noticed, on a much larger scale, that the greatest discharge has occurred successively in the middle, on the left side, and then on the right side of the glacier.

Water flow is about 10 to 30 m per minute for slopes of 25 to 50% (Vivian, 1975). Bezinge measured velocities of 10–15 m/min at glacier de Bis for slopes of 8 to 10%. Forel (1899) gave values of 12 to 13 m/min (for slopes of 25–30) for glacier du Rhône. That is, rates of 6 to 10 times less than those rates measured in front of the glaciers (80 to 100 m/min for slopes of 8 to 10%).

(2) More important in their effects are the sudden releases of water caused by the high pressures exerted on subglacial water pockets by the glacier itself. Over several metres, the cold water (0.3 to 0.6°C) can reach velocities estimated at 20–30 m/s. The higher viscosity due to lower temperatures, and the potential for greater transport of debris (sand, gravel), together with higher speeds, explains the erosive capability of subglacial water. The effect of erosion can be seen in the shape of the blocks and stones carried, in the destruction of the sedimentation areas, and also in linear erosion at the level of bedrock (cf. Vivian and Bocquet, 1973).

(3) We must also include glacial phreatic water sheets. They are the result of ponding behind bedrock or detrital dams. The upper surface of glacial phreatic water is a water table with a down-glacier slope which results in a downward flow. It is karstic in form, distinguished by its discontinuity in three dimensions, its instability, and its morphometric variability. Such a phreatic sheet reduces the glacier–bedrock contact area and is likely to facilitate basal slip. The resulting increase in velocities heightens the effects of abrasion. The natural consequence is a sensitive shaping of the rock bed.

One can see that the interplay between the geology, the hydrology, and the glaciology is complex. Thus we have only touched certain problems and have ignored others (like the effect of chemical processes on sliding: Ricq-de Bouard, 1973; Souchez and Lorrain, 1975; Hallet, 1976) which are fundamental on one level, but which are less crucial for understanding the general problem.

## IV. Different types of interface

The main characteristic and the beauty of glacier ice is its purity; but the glacier drags under its body a variable amount of debris. The amount of debris is a function of the geology, the rate of removal of debris, i.e. the rate of sliding, the water drainage and its flushing effects, the location of the debris on the transverse section of the glacier (larger debris on the margins), the slope of the valley, and the mean longitudinal slope of the glacier. The type of ice–rock interface is naturally controlled by these parameters.

### (1) *Areas where ice is in contact with rock (e.g. Bondhusbreen, Mer de Glace, glacier d'Argentière)*

(a) The areas where the ice is in contact with rock have virtually no debris. There is, however, a very thin water film. We indirectly obtained an estimate of the thickness of this film from the granulometric study of sand collected from the bottom of the ice and from the interface. All the particles less than 0.2 mm were missing. They had been washed out by water diffusing under the ice. Only the largest particles remained and contributed to the polishing of the rock.

This measured thickness is larger than the usual calculated thickness of the water film (between 1 μm and 100 μm). It is possible to explain the difference either by the role of the channels between ice crystals (oral comment by L. A. Lliboutry), or by the grooves resulting from the abrasive effect on the bedrock, which allow the transportation of particles up to 0.2 mm.

(b) The areas with debris are those where it is possible to find at the bottom of the ice, blocks of variable size dragged by the glacier. Usually these blocks are never completely in the ice but are always in contact with the rock bed or other blocks.

This ice layer loaded with these boulders has a behaviour completely different from the upper ice. Shear stress appears to be a function of the volume concentration of debris in the ice. The result is a very spectacular differential sliding movement of the two layers. Measurements made on some of these blocks under Mer de Glace show that their rate of movement was on the average seven times less than the speed of the ice above (5 cm/week as opposed to 5 cm/d). The exception which confirms the rule has been a block which had been drilled from a lower gallery in the rock and which after melting of the ice six months later, was recovered exactly in the same position, completely unchanged.

(c) The areas with a "basal ice layer" have been observed under Mer de Glace, glacier d'Argentière (Vivian, 1975), and Bondhusbreen (Wold and Østrem, 1979). Near the bottom of the glacier, the deep ice is sometimes stratified. Bands of pure ice alternating with bands of ice containing solid debris are visible in sections on the walls, as well as in ice cores extracted from the base of the glacier. These strata have a mean thickness of 8 to 10 cm. Stratification is not general, but constitutes a discontinuous phenomenon. It seems that it must be connected with the classical phenomena of freeze–thaw related to the overcoming of obstacles on the rock bed, but even more to temperature differences (some tenths of a degree is sufficient) existing from time to time at the level of the beginning of the cavities.

The recent age and origin of these intraglacial formations is attested to by the sands in the basal ice which are associated with the bacteria "psychrophiles" (pseudomonas) which one usually finds in subglacial or periglacial deposits.

(d) The areas of stagnant ice where the amount of debris can be unusually high are similar to the margin of the glacier where we can note high densities of blocks, this feature resulting from the penetration by ice into lateral morainic deposits. In this region, ice takes up great amounts of debris which subsequently will contribute to the creation of the subglacial alluvium described in (b).

### (2) *An intermediate type between cavities and contact is the subglacial gorge*

We have good descriptions of this from Waeber (1943). These are the gorges where water is channelled (in principle if not in fact!), and which gathers blocks and boulders carried by the water and by the ice. In these gorges ice penetrates, leaving at the bottom a channel maintained by water and air circulation.

Ice usually shows steep longitudinal foliations like those observed previously at glacier de Tré le Tête (Mont Blanc) by Waeber, or visible today at the intake shaft No. 1 of glacier de Bis (Bezinge and Vivian, 1976).

This penetration of the ice into the narrow gorge is sometimes simultaneous with an up-hill movement evidenced by striations initially vertical, and then curving upwards (Waeber, 1943).

However, it can be noted that the largest channels dug in the rock by subglacial waters or having a tectonic origin, are often filled by ice; thus water is not necessarily found at the lowest points of the subglacial bed.

### (3) *Areas with subglacial cavities (e.g. glacier d'Argentière)*

A detailed description of these cavities has been provided by Vivian and Bocquet (1973).

(a) The construction work undertaken by the hydro-electric company d'Emosson S.A. on glacier d'Argentière has allowed access to a number of natural cavities elongated in the longitudinal direction between the rock bed and the base of the glacier. These cavities are situated on the downhill slope of a rock bar. The flòor is formed by the rock bed (crystalline schists). Despite an ambient temperature which is highly positive and which varies somewhat (around +0.50°C), the rock is sometimes covered discontinuously by a coating of ice. This ice, 2–8 cm thick, contains a little solid matter and is sometimes loaded with sand which has fallen from the ice ceiling. Where ice is absent one can find juxtaposed, glacial abrasion forms (striae, grooves) and water erosional forms (solution cups, scallops, pot-holes), a juxtaposition which underlines that in time various types of interface can succeed each other in the same place.

(b) The subglacial cavities at Argentière are continuous from one side to the other side beneath the glacier. As a result, thermal influences can easily penetrate and spread into the cavities from the margins.

Thus, in the middle of the glacier, it is possible to have an average reduction of temperature of 0.5 deg, allowing melting of the sole of the glacier. Consequently thawed slabs of sandy material fall from the ice ceiling, thus giving locally the basal debris content.

Sometimes at the point where the ice–rock contact is renewed, pockets of water in subglacial positions can form efficiently washing the rock bed. As we saw before, they are more frequent in the cold season than in summer when the sliding velocities are high. In June, the non-permanent small cavities (a few decimetres to some metres long, 5 to 20 cm high) contribute to the emptying of these storages. Their influence is important, because they often control the subglacial drainage, their instability being responsible for the frequent changes in water flow direction. The small permanent cavities resulting directly from the glacial cavitation behave in the same way.

As there exists in fluvial hydrology the concept of a "wetted perimeter", in glaciology we must admit the concept of an "englaciated perimeter". The ice–rock interface is simultaneously at the bottom of the glacier, but also on the slopes of the valley up to the ice limit. One can consider a whole range of erosion processes juxtaposed or in succession which can explain at any one point the particular features of the glacial valley as modified by a temperate glacier.

The ice–rock interface is not only a line, but a complex and very active band. A good knowledge of this interface, an area which requires the integration of many different parameters, confirms the complexity of the studies. This also serves to show even more the essential role of sliding in the movement of the glacier, a vital element in the calculation of glacier flow.

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