WATERWAYS, ICE PERMEABILITY AT DEPTH, AND WATER PRESSURES AT GLACIER D'ARGENTIÈRE, FRENCH ALPS

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ABSTRACT. To clear up the changes which had happened at the subglacial catchment of glacier d'Argentière, an extensive study, with 31 borings and a coring down to the bottom (240 m) was performed in 1979/80, just upstream from the catchment, in an overdeepened area. The behaviour of the water level during boring with a hot water jet, and just after, was different from one bore hole to another, mainly because transient leaks appeared in the walls of bore holes. Next, the water level fluctuated slowly, in the same way in most of the deep bore holes, showing that glacier ice below about 100 m deep is slightly pervious. What is so measured is the pore pressure of water in deep ice. The piezometric gradient between bore holes, and the time lag between fluctuations of water level, which increases with distance from the right bank, shows that there is no waterway at the bottom of the overdeepened area, save at its up-stream end. Most of the melt water must flow between ice and rock along the right bank, its free surface rising by about 150 m during the increased discharge in June. No clear-cut correlation between the bottom pore pressure and the air temperature or the discharge at the subglacial catchment downstream was found.

RÉSUMÉ. *Cheminements de l'eau, perméabilité de la glace en profondeur et pression de l'eau au glacier d'Argentière, Alpes françaises*. Pour éclaircir les changements survenus à la prise d'eau sous-glaciaire du glacier d'Argentière, une étude approfondie a été réalisée en 1979/80, avec 31 forages et un carottage jusqu'au fond (240 m), juste en amont de la prise, dans une zone surcreusée. Le comportement du niveau de l'eau pendant le forage avec un jet d'eau chaude, et juste après, fut différent d'un trou à l'autre, principalement parce que des fuites transitoires apparurent dans les parois des trous de forage. Ensuite le niveau d'eau fluctua lentement, de la même manière dans la plupart des trous profonds, montrant que la glace de glacier en-dessous d'environ 100 m de profondeur est légèrement perméable. Ce que l'on mesure ainsi, c'est la pression interstitielle de l'eau dans la glace profonde. Le gradient piézométrique entre les trous de forage, et le déphasage entre les fluctuations du niveau d'eau, qui augmente lorsqu'on s'éloigne de la rive droite, montrent qu'il n'y a pas de torrent sous-glaciaire au fond du surcreusement, sauf à son extrémité amont. La plupart de l'eau de fonte doit s'écouler entre glace et rocher le long de la rive droite, sa surface libre s'élevant d'environ 150 m au moment de l'engorgement de Juin. On n'a pas trouvé de corrélation nette entre la pression de l'eau interstitielle profonde et la température de l'air, ou le débit à la prise sous-glaciaire en aval.

ZUSAMMENFASSUNG. *Wasserführung, Durchlässigkeit des Eises in der Tiefe und Wasserdruck am Glacier d'Argentière, Französische Alpen*. Zur Erklärung der Veränderungen, die im subglazialen Einzugsgebiet des Glacier d'Argentière aufgetreten waren, wurde 1979/80 eine umfangreiche Untersuchung mit 31 Bohrungen und einer Kernbohrung bis zum Felsuntergrund (240 m) in einem übertieften Gebiet knapp oberhalb des Einzugsgebietes durchgeführt. Das Verhalten des Wasserspiegels während der Bohrung mit einem Heisswasserstrahl und kurz darnach war von Bohrloch zu Bohrloch verschieden, vor allem infolge vorübergehend auftretender Lecks in den Bohrlochwänden. Dann aber wechselte der Wasserspiegel nur langsam und gleichmässig in den meisten der tiefen Bohrlöcher, ein Anzeichen dafür, dass das Gletschereis unterhalb von etwa 100 m leicht durchlässig ist. Was damit gemessen wird, ist der Porendruck von Wasser in tiefem Eis. Der piezometrische Gradient zwischen Bohrlöchern und die zeitliche Verzögerung zwischen Schwankungen des Wasserspiegels, die mit dem Abstand von der rechten Gletscherflanke zunimmt, zeigen, dass am Grunde des übertieften Gebietes keine Wasserführung vorhanden ist, ausser an seinem oberen Ende. Die Masse des Schmelzwassers dürfte zwischen Eis und Fels längs der rechten Flanke fliessen, wobei dessen freie Oberfläche während der Sättigungsperiode im Juni etwa 150 m ansteigt. Zwischen dem Porendruck am Untergrund und der Lufttemperatur oder dem Abfluss unterhalb des subglazialen Einzugsbereiches wurde keine ausgeprägte Korrelation gefunden.

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INTRODUCTION

There is general agreement today that large sliding velocities, as found in most temperate valley glaciers and in all tidal outlets of large ice sheets, are possible only because there is ice–bedrock separation. The "cavities" so formed should in general be filled with water, mud, and stagnant regelation ice under some pressure. In order to obtain high velocities, and to explain the seasonal fluctuations of sliding velocities, theory shows (Lliboutry, 1979) that most of these cavities cannot be isolated in an autonomous regime, they must be more or less well interconnected, in which case the subglacial water pressures must involve another independent variable, a hydraulic one, which cannot be deduced from the sliding velocity, nor from the normal and shear stresses on the bottom only. Subglacial water pressures are thus a main factor in glacier dynamics. This holds even for cold ice sheets, since their altitude depends on the discharge of tidal outlets which do slide, but the pertinent field studies are far easier on valley glaciers.

The location of intraglacial or subglacial waterways is another problem, although linked with the first one. It is really a problem of applied glaciology, since subglacial streams are often tapped for hydroelectric purposes, and this fact provides research grants and facilities. We do not know of any practical technique to find out directly the precise locations of these waterways. The case we report on here will show how they can be inferred from monitored subglacial water pressures.

Direct observations at depth are scarce and often isolated. Some measurements of water pressure have been made from holes drilled to the bottom of the glacier and from galleries in the bedrock below (Mathews, 1964; Vivian and Zumstein, 1973; Bezinge, unpublished). Some data have also been obtained on the water pressure in moulins (Iken, 1972). However these methods limit the measurements to some isolated and imposed locations where the situation may not be standard. By drilling bore holes into a glacier from the surface a great number of locations can be chosen over a given area. Such drilling projects have been undertaken on several glaciers to measure the water level in bore holes (Hodge, 1976, 1979; Engelhardt and others, 1978; Röthlisberger and others, 1979). Nevertheless the project reported here is the first in which holes were drilled along a cross-profile, at short distances from each other. The behaviour of the water level was found to be quite different from one bore hole to another.

PROBLEMS RAISED BY THE SUBGLACIAL ARGENTIÈRE CATCHMENT

As part of the French–Swiss hydroelectric Emosson project, water is brought from glacier d'Argentière to the Emosson dam by gravity. This vault dam, which can store 225 hm³, rises from 1 785 to 1 930 m a.s.l. Therefore the collecting gallery runs under glacier d'Argentière at 2 060 m, well above its snout (c. 1 480 m). The catchment basin of glacier d'Argentière extends over 26.7 km², and provides about one quarter of the dammed water, which can produce an annually averaged power of 78 MW.

At the prescribed altitude of the intake, glacier d'Argentière pours from an overdeepened area over a transverse *Riegel*, and thus becomes very crevassed. The subglacial topography is quite well known by the many reconnaissance galleries dug within the crystalline *Riegel*, and, up-stream, by seismic exploration and drilling from the surface (Fig. 1). The lowest point of the overdeepening stands at 2 120 m a.s.l. and the lowest point of the transverse *Riegel* at 2 182 m. Over the overdeepening, the glacier is about 700 m wide, and 250 m deep along its axis.

Just down-stream from the lowest part of the *Riegel* there is a furrow in the bedrock, which
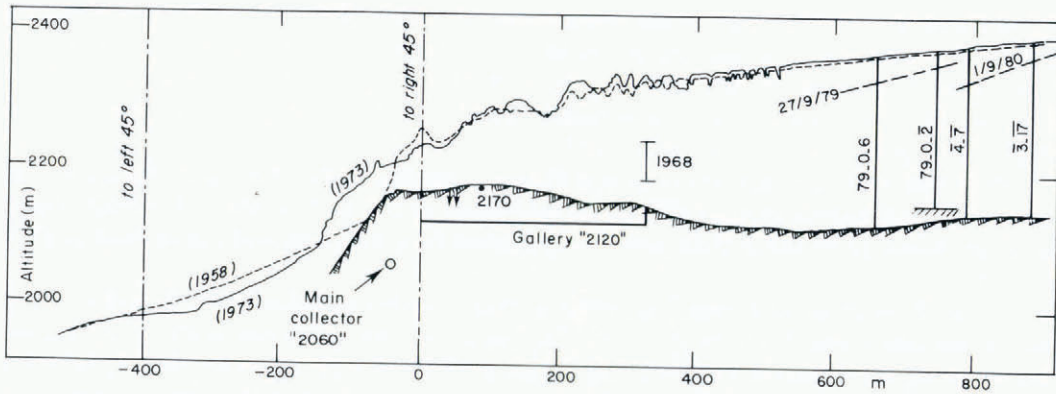
Fig. 1. *Longitudinal section of glacier d'Argentière, showing the transverse* Riegel *with the initial water intakes (vertical arrows), the location of some bore holes, and some observed piezometric heights.*

goes down from 2 175 to 2 120 m. Between 1956 and 1957 almost all the expected water discharge flowed in this furrow, so the underglacial catchment was made there.

According to the account given by Jean-Yves Bernard and Denis Bister during a workshop at Finhaut on 27 April 1979, water disappeared for six weeks in 1967, four weeks in 1969, and several times in 1975, the disappearances following some days of cool weather and reduced discharge. Since April 1976, water has disappeared, definitively it seems, from the central furrow. It was found again almost three years later. Since March 1979 the main subglacial stream has flowed near the right bank, that is 340 m from the furrow. It crosses the *Riegel* at a point at least 25 m higher.

This change, which had expensive consequences, can be related to a thickening of the glacier which began in 1977. Is it a temporary wandering or a permanent change? Which factors control the location of the subglacial stream? Is it always subglacial, and is there only one?

FIELD WORK

Studies on glacier d'Argentière have been performed by Laboratoire de Glaciologie du CNRS since 1975. In addition to the annual topographic survey of ablation stakes, a seismic exploration was made by M. Vallon in 1976, and important field work was done in 1979–80. In particular, 31 vertical borings were made in the ablation area, up-stream from the *Riegel* (at about 2 400 m a.s.l.), most of them reaching the bedrock.

These borings were made with a hot-water jet, which works much better than a hot-point drill in this glacier ice, which contains some sand and pebbles coming from the steep rocky walls surrounding the accumulation area. A hot-water cleaner for building façades, Kärcher HDS 800 was used; it supplies 750 litres per hour of water at 50–80 °C at a pressure up to 75 bars. Together with a braided flexible tube, 400 m long (in four segments), its winch, the 5 m long rigid hose, and the 4 kVA generator set (for the pump of the HDS 800 and the motor of the winch), the device weighs about 700 kg, fuel (7 litres per hour are needed) excluded. Most of the work was done in June, when there was still 3 m of winter snow on the glacier, allowing the material to be moved by sledge from one point to another (earlier than this there was no running water on the bank to tap for the hot-water jet).
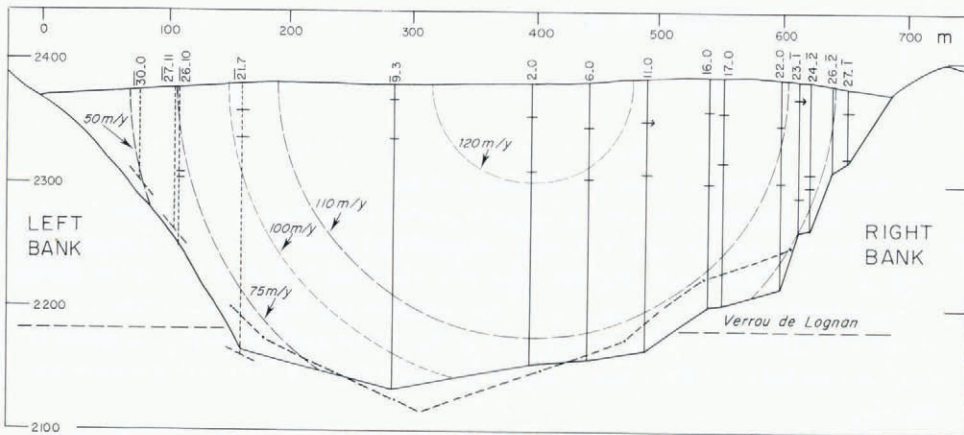
A continuous coring down to the bottom was also made using a hot-point corer. To core 240 m in a temperate, fast-moving glacier without jamming the corer was possible only by working 20 h every day, in two shifts, for eleven days running. As soon as the cores had been removed, their liquid-water content was measured and their petrography studied. (The results so found will be published by Vallon and others).

The location of the bore holes is given in Figure 2, together with the profile of the bedrock, as determined by Swiss borings in 1957/58 and the present work. The bedrock in this overdeepened area was found to be flatter than had been predicted by a Swiss seismic exploration in 1955 (cf. Fig. 3).

The bore holes are designated according to their rounded coordinates, in decametres, in a local Cartesian frame of reference. The Oy axis runs down-stream in the middle of the glacier, exactly along the section of Figure 1. For instance $(15.\bar{6})$ means a bore hole close to the point $x = 150$ m, $y = -60$ m. The borings of 1979 are indicated by 79 at the beginning (for instance 79.13.1). When two bore holes have the same rounded coordinates, they are distinguished by adding a and b.

In September 1979 five holes were bored to test our new hot-water drill, and the water level

Fig 2. Map of the studied area, with subglacial contour lines and location of the borings. The area below 2 182 m is overdeepened. Arrows indicate the displacement of stakes between 11 September 1978 and 13 September 1979. The bore holes are indicated by their rounded coordinates, in decametres, preceded by 79 if drilled in 1979. Borings of 1979 are plotted as surveyed on 29 September 1979. Borings of June 1980 and the coring site were surveyed on 15 June, and borings of August 1980, (30.0) (15.2) and the six up-stream, on 20 September. The straight dashed line joins the bore holes which remained interconnected in June and July.

Fig. 3. *Cross-section of glacier d'Argentière along most of bore holes, on 15 June 1980. The bedrock forecast by Swiss seismic exploration is dashed. Cross bars at each bore hole indicate the highest and lowest water level observed in June 1980. (Two small horizontal arrows indicate a very constant water level.) The altitude of the lowest point of the Riegel down-stream (verrou de Lognan) is plotted. The curves of equal velocity are assumed to be semicircles, as suggested by a numerical treatment of the inverse problem (Hantz and Lliboutry, 1981).*

was sounded only once, just after drilling. In June 1980 a cross-profile of 14 holes ($\overline{\overline{27}}$.11) to (27.$\overline{1}$), was bored. Three other borings had to be stopped before the bed was reached because of pebbles in the ice, and a fourth was useless because it was impossible to insert any sensor into it. In these cases another hole was drilled nearby at a point 1–2 m away. Lastly, in August 1980, eight borings were made, namely ($\overline{3}$.1$\overline{7}$) (6.1$\overline{7}$) (15.1$\overline{7}$); ($\overline{4}$.$\overline{7}$) (8.$\overline{7}$) (15.$\overline{6}$); (15.2) and (30.0). (The objective was nine borings forming the surface of a square 200 m × 200 m, to be surveyed with an inclinometer, as a start for a new project.)

In 1980 pressure gauges had been purchased to monitor water pressure but they were not watertight enough. Their failure constrained one of us (D.H.) to remain on the glacier all summer, to sound the water level several times a day. (An audible signal indicates when the lead reaches water.) One night, the shelter where the observer was sleeping was blown down by a squall; he was only slightly injured, but two weeks of records were lost. Moreover the closure and deformation of the bore holes progressively made them unserviceable. Field observations were stopped on 1 September.

In spite of the project not being entirely successful, it is worthwhile to give our results: they show how oversimplified were our previous ideas about water in glaciers, the problems to be investigated, and the pitfalls to avoid.

INITIAL DROP OF THE WATER LEVEL

In no hole has the water always remained at the surface or close to it. Let us examine first what happened during boring, when hot water was continually injected into the bore hole, and just after. The following observations were made during the borings of 21–27 September 1979.

Bore hole (79.0.6.a): Bottom not reached; water drop on reaching 37 m.

Bore hole (79.0.6.b): Bottom reached at about 250 m; water drop on reaching 52 m; water level just after boring at 36 m from the surface.

Bore hole (79.0.$\bar{2}$): Bottom reached at about 230 m; water drop on reaching 70 m; final water level at 22.5 m.

Bore hole (79.13.1): Bottom reached at 220.5 m; water drop on reaching 65 m; final water level at 28.5 m.

Bore hole (79.23.3), at 80 m from the right bank: Bottom reached at 126.5 m; water drop when 5 m from the bottom; the bore hole remained empty.

In June 1980, interesting observations were made in the bore holes drilled 1–2 m apart. Holes (11.0.a) and (6.0.a) 84 and 99 m deep respectively) when boring was stopped remained water-filled at first. Water levels dropped only after the drop had occurred in the deeper hole nearby. In bore hole (11.0.a), the water level rose again to the surface, and there was a second drop. In hole (2.0.a) (151 m deep), during boring, the water level dropped to a depth of 31 m. Next, when boring hole (2.0.b), water dropped in (2.0.b) less than half an hour after this depth was reached.

Among the holes drilled in June 1980, only bore hole (27.$\bar{1}$) and perhaps bore hole ($\overline{27.11}$), the nearest from the banks which reached the bottom, did empty. Before emptying (27.$\bar{1}$) remained infilled with water for three or four days. Eleven days later, the water level was found at a depth of 19 m, and rose progressively (Fig. 4).

Among the seven bore holes drilled on 23–31 August 1980 (Fig. 5), the ones nearest to the bank emptied. Bore hole (15.2) emptied progressively in about one day. In bore holes (15.$\bar{6}$) and (15.$\overline{17}$) the water level first dropped at a depth of 25 or 45 m, remained one day at this level, and then dropped again: the first bore hole emptied totally, and maybe the second one. We do not know what happened after 3 d in bore holes (15.2) and (15.$\bar{6}$); in bore hole (15.$\overline{17}$) the water level rose back progressively to 22 m below the surface. In the four other bore holes the water level progressively reached its "stable" situation, 23 to 74 m below the surface.

The observations of September 1979 show that at some variable depth between 37 and 125 m, a leak appeared in the wall of the bore hole. In the case of neighbouring holes, water flowed by such leaks from the more water-filled one to the other. Since the rate of these initial drops was several metres per hour at least, and they started suddenly, we must attribute them to
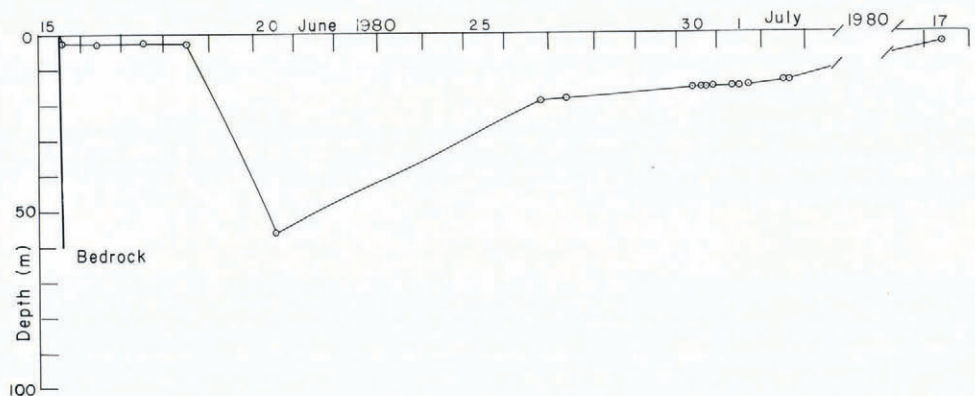

Fig. 4. *Water level in bore hole (27.$\bar{1}$), close to the right bank. It emptied temporarily 3–4 days after boring. We suggest that this is a consequence of glacier sliding, shallow ice being impermeable. This behaviour is that predicted by the classical theory.*
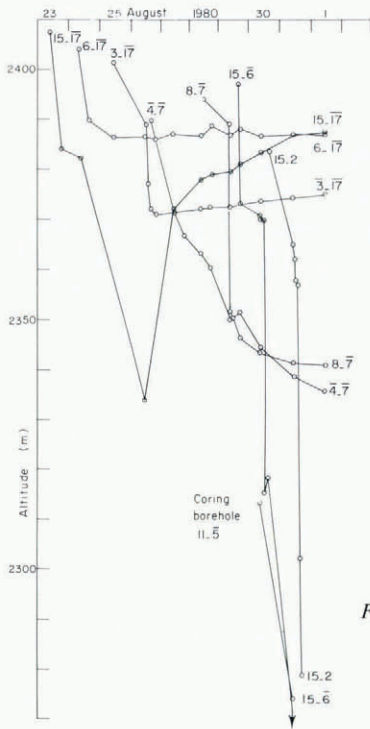
Fig. 5. *Water level in the bore holes of August 1980. At 60–70 m up-stream from the main profile, the piezometric gradient is directed towards the right bank, between (8.7̄) and (15.6̄). At 170 m up-stream it is the reverse: the piezometric gradient is directed from (6.17̄) towards (3.17̄), i.e. towards the centre of the valley.*

some internal crack rather than to a capillary network. Some closed, air-infilled cavity seems to be excluded, because in this case the water level would have again risen to the surface (in fact this phenomenon was also observed, once, at shallow depth). The subsequent progressive rises show that the draining off by a leak is a transient phenomenon, probably due to the input of hot water, and favoured by the proximity of a less water-filled hole.

SUBSEQUENT FLUCTUATIONS OF THE WATER LEVEL

No diurnal fluctuation of the water levels was observed. They only changed at rates of some decimetres per hour (exceptionally up to 3 m/h).

In September 1979 the final water level in four bore holes was more or less that corresponding to the water equivalent of the glacier thickness. Thus probably the small amount of water continuously entering into the hole (the ice very near the surface is permeable and soaked with water) did drain off at the ice–bedrock interface. Bore hole (79.23.3) near the right bank, which remained empty, must be connected with some subglacial waterway at atmospheric pressure.

Among the bore holes of June 1980, there was a main set (2.0.b) (6.0.b) (11.0.b) (17.0) (22.0) which had the same fluctuations (Fig. 6). There was nevertheless a piezometric gradient from (2.0.b) to (22.0) and a progressive lag from (22.0) to (2.0.b). Thus they were linked, with some head loss between them, to some waterway controlling the pressure which was situated still further to the right than (22.0).
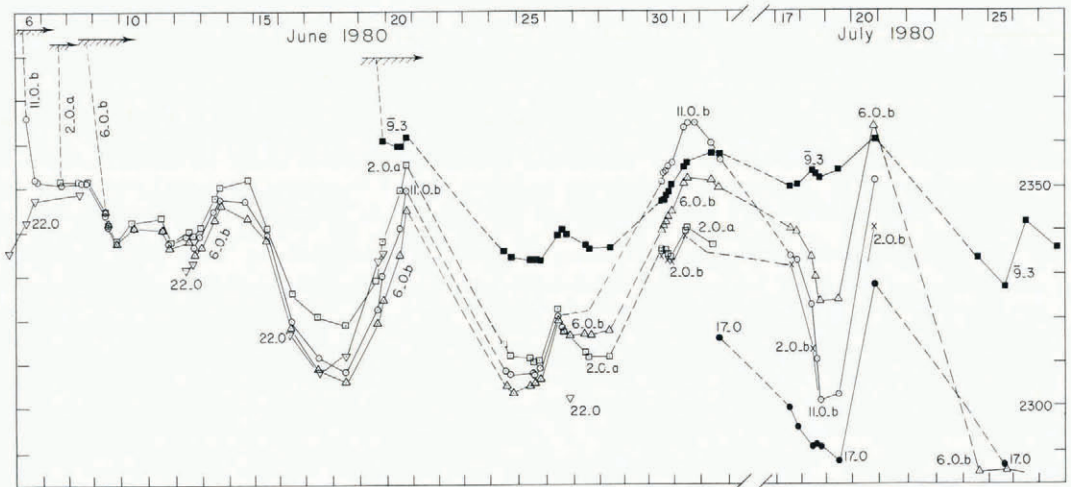
Fig. 6. Water levels in several bore holes of the transverse profile (cross-section Fig. 3), which are called the "main set" in the text. They have the same fluctuation (although strongly damped for (9.3), in the middle of the glacier). No diurnal fluctuation seems to happen. The piezometric gradient between them may be important. On 30 June, with rising water levels, it was directed towards the middle of the glacier. On 17–18 July, with sinking water levels, the piezometric gradient was directed towards the bank. Thus in spite of some exceptions to this scheme, a control by some subglacial waterway near the right bank is suggested.

Bore hole $(\bar{9}.3)$, which reaches the deepest part of the cross-section, also belongs to this set, but the bottom pressure there is noticeably higher, and its oscillations are somewhat damped. Its draining towards the right should involve an important head loss. Later, in July, it probably closed at some depth.

The case of bore hole (16.0.b), situated among the main set, is aberrant (Fig. 7). Between 9 and 26 June its water level can be compared with the other ones. Twice, during four days each time, the bottom pressure became definitely higher than for its neighbours.

As for the bore holes not reaching the bottom, (11.0.a) (84 m deep) behaves quite differently from (11.0.b) (220 m deep) nearby, and (6.0.a) (99 m deep) behaves quite differently from (6.0.b) (220–230 m deep) nearby (Fig. 7). On the other hand (2.0.a) (151 m deep) fluctuated exactly in the same way as (2.0.b) (232 m deep) nearby, i.e. like all the main set. Thus an intraglacial connection existed between (2.0.a) and (2.0.b), although it must have been a small one since the head loss between, over the 1–2 m in distance reached as much as 3 m of water on some days.

We have not enough data to study water pressures under the left part of the glacier. On 20 June, the water level in bore hole $(\overline{21}.7)$ was found to be 2 333 m a.s.l., and the following day in bore hole $(\overline{26}.10)$ it was found to be 2 299 m. A very steep piezometric gradient (34 m over 57 m in distance) towards the left bank may be tentatively inferred.

The few measurements made in August 1980, up-stream from the main cross-profile, afford yet another picture. The water level was about the same in bore holes $(6.\overline{17})$ and $(15.\overline{17})$, 12 m lower at bore hole $(\overline{3}.\overline{17})$, and 46 m lower at bore holes $(\overline{4}.\overline{7})$ and $(8.\overline{7})$. Thus in this area up-stream the piezometric gradient was directed towards the central, deepest part of the valley, while at the main cross-section, it had been the reverse in June (and probably this situation was still maintained in August, since bore hole (15.2) emptied).
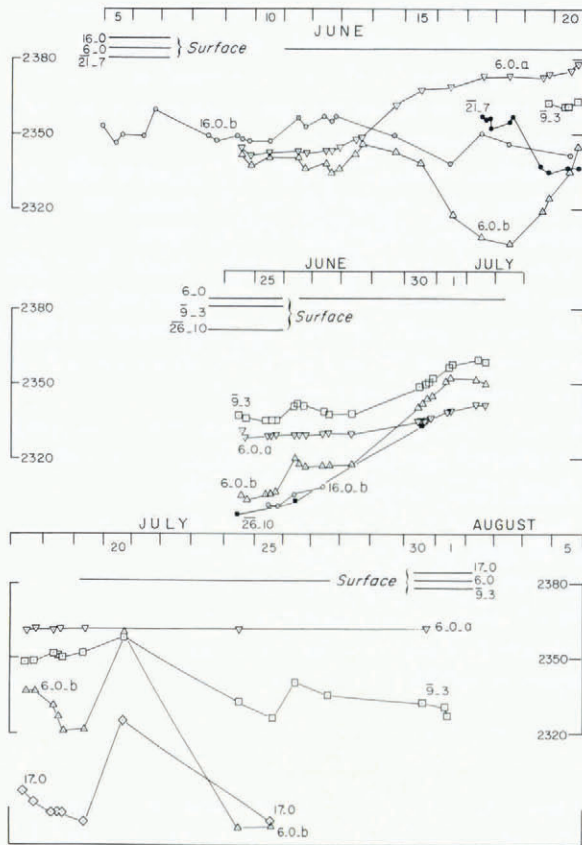
Fig. 7. *Water levels with an erratic behaviour. The water level in bore hole (6.0.b), from the main set, is plotted for comparison.*

DISCUSSION: WHICH PRESSURE WAS MEASURED?

In sliding theory, glacier ice has hitherto been considered as an impervious body. The melting–refreezing process leads to the existence of a water film of micrometric thickness on the up-stream face of any bump to drain the melt water which is produced. On the down-stream side the water film should, for large sliding velocities, be replaced by a flat pocket of stagnant water, regelation ice, and drift rather improperly called a "cavity". The water pressure in the water film or the cavity equals the normal pressure of ice: it is larger on the up-stream face and lower on the down-stream face than its mean value. With this model, the water level in a bore hole would indicate the pressure in the water film or in the cavity. This pressure should be different for each up-stream film, for each down-stream film or autonomous cavity, and the same in all the down-stream interconnected cavities.

Now, in the area studied, sliding is important. Sliding velocities can be inferred from the curves of equal velocity drawn on Figure 3. These curves are based on measured annual surface velocities, and on a numerical computation, which shows that these curves are approximately semicircles (Hantz and Lliboutry, 1981). Since in the computation the bedrock is assumed to be

a cylindrical channel, which it is not, stresses and the rate of deformation of the body of the glacier are underestimated. On the other hand, velocities are high in June. Thus the sliding velocity at the bottom of the main set $(\bar{9}.3)$ to (17.0) should be 1.5–2 metres per week, and they should have found several bumps of about the controlling size (which afford the widest pressure fluctuations) during the time of observation.

Only the water levels at bore holes $(27.\bar{1})$ and $(16.0.b)$ agree with this model. The six other ones of the main set which were monitored would always have to have debouched into interconnected down-stream cavities, which cannot be the case.

Thus our model must be changed for deep bore holes. At depth glacier ice becomes permeable, and the water level corresponds to the *pore pressure of water in the bottom layers*, which is not the pressure of ice against the bedrock. The water produced by pressure melting must diffuse within the permeable ice, instead of flowing as a very thin film at the interface. This new model agrees with old observations by Carol (1947).

The fact that bore hole (2.0.a), 151 m deep, was connected with its neighbour, while boreholes (6.0.a) and (11.0.a) 99 and 84 m deep, were not, shows that ice becomes permeable below about 100 m in depth. This is consistent with the fact that, down to 107 m, only 10 to 20% of blue ice was found in the cores, the remaining being white. Below 107 m the amount of blue ice increases, reaching 90–95% between 180 m and the bottom (237 m at the site of coring) (Vallon and others, in preparation). Blue ice contains 0.8–3.2 cm³/kg of air under normal conditions, white ice 24–68 cm³/kg. Now air bubbles can interrupt the capillary channels at the junction of three crystals which make ice slightly permeable (Lliboutry, 1971; Nye and Frank, 1973; Raymond and Harrison, 1975).

FINAL EVOLUTION

With time, several bore holes closed at shallow depth, and became full of water. Bore holes $(24.\bar{2})$, (17.0), and $(2.0.a)$ were so found on 16 June, 26 June, and 17 July respectively, the closures being at depths of 1.6, 3 and 1 m. On 17 July, bore holes $(\overline{27}.11)$ and $(\overline{26}.10)$ were found closed at 9 and 19 m, the lead not finding water; on 26 July, they were found full of water. On 30 July bore hole $(\overline{21}.7)$ was closed at 33 m, and it was found full of water on 30 August.

Two reasons can be put forward for such closures. First at shallow depth there is no water counter-pressure to impede plastic shrinking. Second, faults starting from the surface, more or less along planes of maximum shear stress, may form (Lliboutry, 1964–65, Tom. 2, p. 607–09).

Nevertheless in moderately deep closed bore holes (6.0.a), (11.0.a), (16.0.a), $(23.\bar{1})$ after some date the water level became perfectly constant at 13.5, 24, 35 and 20 m from the surface respectively. Permanent outlets have appeared at these depths, probably in relation with old, closed crevasses. The same kind of leaks could explain the initial drop of water level in bore holes $(15.\bar{6})$ and $(15.\overline{17})$.

LOCATION OF THE WATERWAYS, AND CORRELATION BETWEEN THE BOTTOM PORE PRESSURE AND THE DISCHARGE

The slight permeability of bottom ice does not allow any significant discharge. The measurement of the bottom pore pressure showed, in June 1980, a main drainage towards some waterway against the right bank, and a minor one towards the left one. In September 1979 at least the right waterway was at atmospheric pressure (emptying of bore hole 79.23.3). In June, it

should be flooded, and the free surface much higher. The start of the melting season is sudden, and a more or less circular "gradient conduit" as modelled by Röthlisberger cannot have enough time to form.

It must be noted that, on glacier d'Argentière, most melting takes place on the right half of the glacier, and the ice-free slopes to the right, the left side being in the shadow of rock walls 1 000 m or more high.

Up-stream from the main cross-profile, at the start of the overdeepening, the drainage in August 1980 was towards the lowest area of the bedrock. This agrees with the theoretical considerations of Lliboutry (1983). In temperate valley glaciers, normally, water should flow at atmospheric pressure along the lowest part of the bedrock. Some floods from time to time, especially in June, broaden the conduit and impede its closure by plasticity. But, when entering an overdeepening, this situation becomes unstable and sooner or later water migrates towards the banks.

The water level in bore hole (6.0.a) was found between 9 and 13 June at about 40 m from the surface, higher between 15 and 20 June, lower between 25 June and 2 July. These fluctuations are qualitatively similar to the discharges measured at the subglacial water catchment of Lognan (cf. Fig. 8). So we tentatively suggest that a connection did exist at very shallow depth, within the firn and the superficial, permeable ice, between this hole and the flooded waterway of the right bank. This assumption leads to a free surface of the waterway at 2 315–2 380 m a.s.l. during the June flood, whereas in September 1979 it should have been at about 2 235 m a.s.l., and in August 1980, probably at about the same altitude as the lowest point of the *Riegel*, 2 182 m (since holes (15.2), (15.6̄), (15.1̄7) emptied during boring).

On Figure 8 the air temperatures in the Chamonix valley nearby, at 1 050 m, are also plotted. The four peaks in water discharge occurred roughly two days after large increases in air temperature or rainfalls (12–14 June: föhn; 5–6 July: warm weather and rain; 15–16 July: big
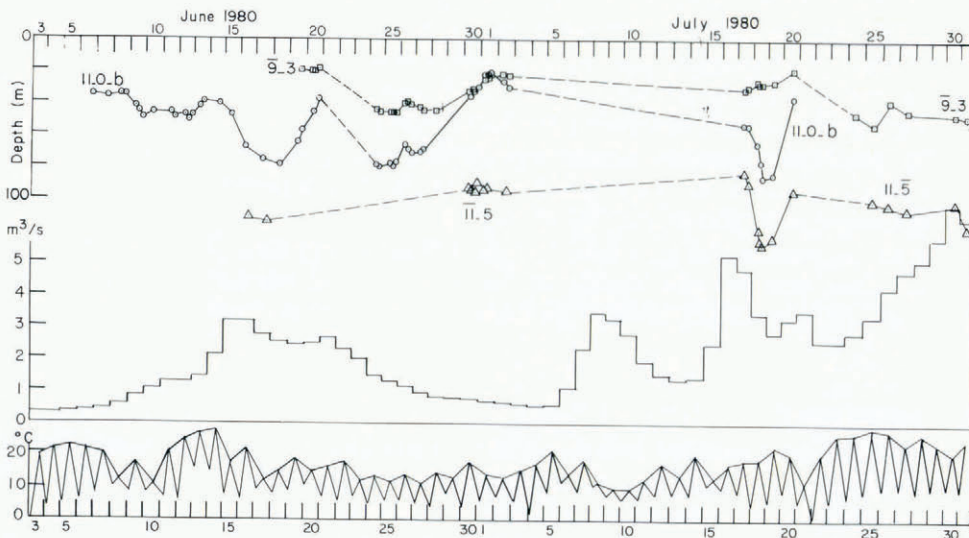

Fig. 8. Water levels in (11.0.b), from the main set, in (9̄.3), and in the coring bore hole (11.5̄), compared with the discharge at the catchment down-stream, and the temperatures (diurnal maxima and minima) in the Chamonix valley. No significant correlation seems to exist.

rainfall; 23–25 July: beginning of the warm summer conditions). Two days is longer than the transit time within the glacial waterway as measured with dyes (Vivian and Zumstein, 1973). The lag should come from the overall transit time within the snow cover.

Nevertheless in July there is a general rising trend which remains unexplained. A subglacial storage of water at the beginning of the melting season has been proved (Hodge, 1974; Collins, 1979; Iken and others, 1979). There is also water retention in the snow-pack by capillarity. But the extra discharge in July alone, about 4 hm^3, must be one order of magnitude higher. Thus, in our opinion, local meteorological factors prevail.

Anyway, no clear correlation, with or without some time lag, appears between the bottom pore pressure, as measured in bore hole (11.0.b), and either the discharge or the air temperature. This point deserves further study.

CONCLUSIONS

(1) The boring of holes with a jet of hot water perturbs the natural conditions, as does the proximity of a less water-filled hole. Leaks may temporarily appear. The bore hole can be considered as giving bottom water pressures only after some days.

(2) Above a depth of 35 m, leaks can also appear with time. Below, down to about 100 m deep, glacier ice is completely impervious, probably as a consequence of air bubbles.

(3) Below about 100 m, deep ice has a small permeability. What is measured with bore holes is then the pore pressure of water in bottom ice. It fluctuates in an unclear way.

(4) There is no need at large depths for a water film at the interface to evacuate the water formed by pressure-melting against the obstacles of the bedrock. The overpressure of ice against these obstacles cannot be reached.

(5) The water pressure in the down-stream cavities p which enters sliding theory is the pore pressure. Thus, at large depths, cavities are always interconnected. But head losses between cavities are much larger than assumed by Lliboutry (1979).

(6) Periods of flood excepted, waterways should be at atmospheric pressure. Thus pressure p comes from the head loss between the cavity and the waterway, a fact which explains why its variations are moderate, and consequently the fluctuations of the drag are also moderate.

(7) The piezometric gradient of interstitial bottom water gives the direction in which the waterway must be sought. At the overdeepening of glacier d'Argentière, it is along the right bank, in agreement with Lliboutry's (1983) theory.

(8) Since the emptying of bore holes during boring or some days after indicates that the bottom is higher than the free surface of the waterway, the altitude of the latter can be approximately deduced. During the June flood, it may rise by 150 m or more.

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