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DIRECT MEASUREMENT OF BASAL WATER PRESSURES: A PILOT STUDY

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ABSTRACT. Bore-hole drilling techniques have been used to connect with the subglacial water system of the temperate South Cascade Glacier. The water level in a connecting bore hole probably represents a direct measurement of the basal water pressure over an area at least 10 m in extent. Fluctuations of up to 40 m in bore-hole water levels occur typically over periods of several days and often peak about 2 d after large changes in water input at the glacier surface. The long-term trend in bore-hole water levels supports the idea of seasonal storage and release of liquid water.

RÉSUMÉ. *Mesure directe des pressions d'eau au fond: une étude temoin.* Les techniques de forages ont été utilisées pour rejoindre le réseau hydrologique sous-glaciaire du glacier tempéré de South Cascade Glacier. Le niveau de l'eau dans le forage atteignant ce réseau, représente probablement une mesure directe de la pression de l'eau au fond, sur une largeur d'au moins 10 m. Des fluctuations de plus de 40 m de ce niveau d'eau dans le forage se produisent de manière caractéristique pendant des périodes de plusieurs jours et présentent souvent des pointes environ plusieurs jours après les grands changements dans les apports en eau à la surface du glacier. La tendance à long terme dans les niveaux d'eau au forage, confirme l'hypothèse de stockage et de lachages saisonniers d'eau liquide.

ZUSAMMENFASSUNG. *Direkte Messung des Wasserdruckes am Untergrund: eine Pilot Study.* Zur Anzapfung des subglaziale Wassersystems im temperierten South Cascade Glacier wurden Bohrloch-Techniken angewandt. Der Wasserspiegel in einem durchgehenden Bohrloch stellt vermutlich eine direkte Messung des Wasserdruckes am Untergrund über ein Gebiet von mindestens 10 m dar. Schwankungen im Wasserspiegel des Bohrlochs bis zu 40 m kommen typisch in Perioden von einigen Tagen vor; sie erreichen ihren Höhepunkt oft etwa 2 Tage nach grösseren Änderungen im Wasserzufluss an der Gletscheroberfläche. Das Langzeit-Verhalten des Wasserspiegels im Bohrloch stützt die Annahme jahreszeitlicher Stauung und Freigabe flüssigen Wassers.

INTRODUCTION

The role of subglacial and englacial water in the hydrology and dynamics of glaciers is important for several reasons. The mechanisms which control both the normal and catastrophic sliding of glaciers are probably affected strongly by subglacial water. Predictions of the run-off from a glacier will be improved significantly when the temporary storage and release of both englacial and subglacial water are understood.

The key variable in these mechanisms is the pressure of water having access to the bed of a glacier, the "basal water pressure". The ability to measure this parameter directly and to monitor its changes with time and location on a glacier is therefore of critical importance.

Some isolated measurements have already been made of water pressure at the bed of a glacier, but most of these have been from holes drilled up to the base of the ice from adventitious man-made tunnels in the bedrock below the glacier. The tunnel under the South Leduc Glacier (Mathews, 1964) was excavated during a mining operation and those under the Glacier d'Argentière (Vivian and Zumstein, 1973) and the Gornergletscher (Bezinge and others, 1973) for hydroelectric developments. Some data have also been obtained on the water pressure in moulins (Iken, 1972; Röthlisberger, 1976) but this method suffers from the complication of an additional dynamic pressure head and from the limited availability of moulins. A technique is thus needed which can be applied to an arbitrary location on any glacier.

It has been known for some time (for example, Raymond, 1971, p. 75) that the level of water in a bore hole drilled into a glacier from the surface often fluctuates, sometimes over a large range. A program was started in 1973 on South Cascade Glacier, Washington, specifically to see if such bore-hole water levels could be related to englacial and subglacial water pressures and the amount of water in temporary storage within the ice. A similar program, employing somewhat different techniques, has also been underway on the Gornergletscher and the Oberaletschgletscher (Röthlisberger, 1976).

Drilling of the bore holes

Accumulation area

In June and August of 1973 five bore holes about 100 m apart were drilled through South Cascade Glacier slightly above the equilibrium line, using 50 mm diameter electro-thermal "hot points" powered with a 3 kW gasoline generator (holes 1–5, Fig. 1). Typical drill rates were 5–6 m h^{-1} using full generator output (1.7–1.8 kW). Any significant drop of drill rate below this was assumed to be caused by the presence of suspended sediments in the ice (referred to as "dirty ice" here).

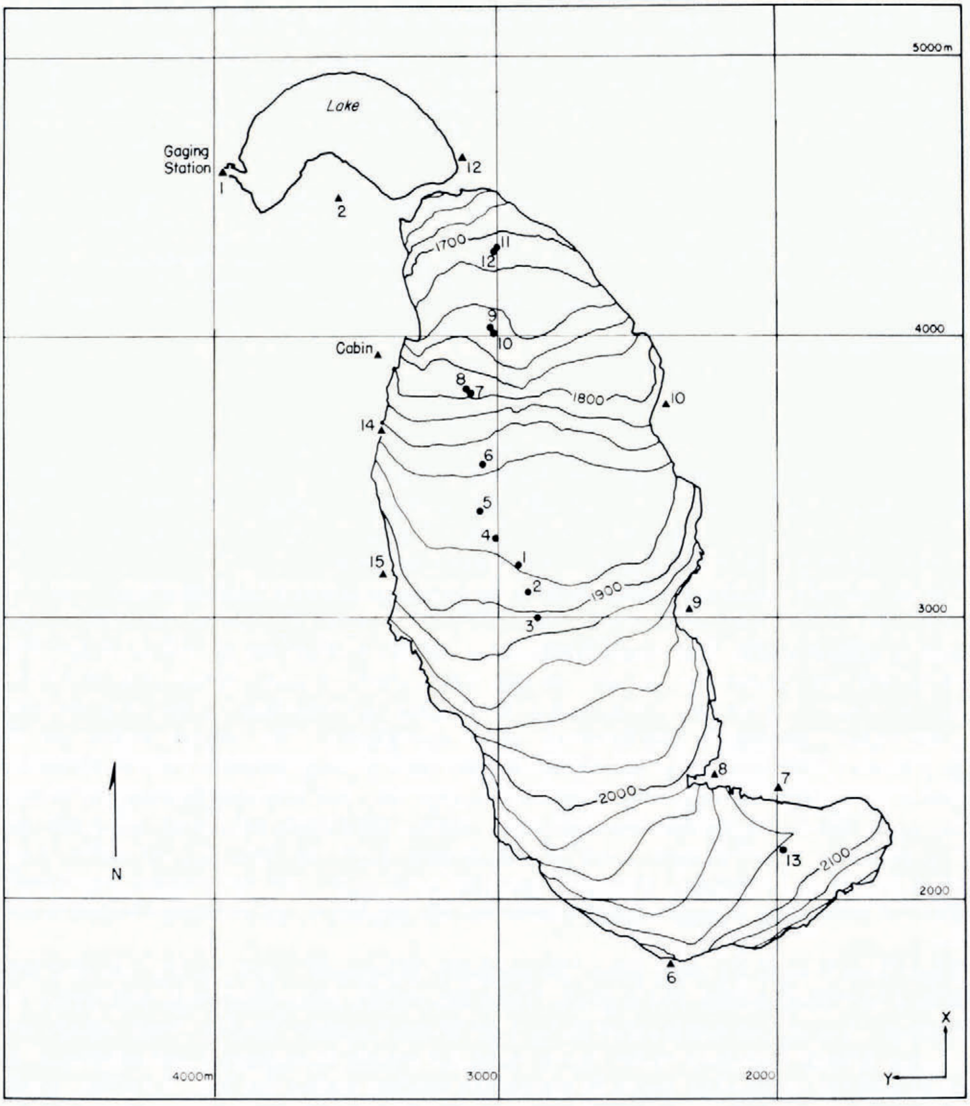

Fig. 1. Map of South Cascade Glacier showing the location of the bore holes. The grid lines have an arbitrary origin and are 1 km apart. The triangles are triangulation stations and the solid dots are the bore holes. The contour interval is 20 m.

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During the drilling the descent of the drill and the water level in the holes were recorded continuously, the water level using a pressure transducer suspended in the bore hole (accuracy of ± 17 mm) and the position of the drill using a potentiometer attached to a pulley axle (accuracy of about ± 10 mm). However, because of problems with maintaining a uniform tension on the cable, only cavities* at least several centimetres high could be detected with any confidence.

The water in all five holes remained at a constant level, equal to that of the water table in the firn layer at the glacier surface, until the bed of the glacier was reached. At that point the water level in three of the five holes dropped abruptly and then started to fluctuate (Fig. 2).

In two of these holes (1 and 2) very persistent drilling in the dirty ice at the bed was required before the water-level drops occurred. In hole 1, for example, the drill had essentially stopped, having advanced only 50 mm in 100 min. Then a small abrupt increase in drill rate

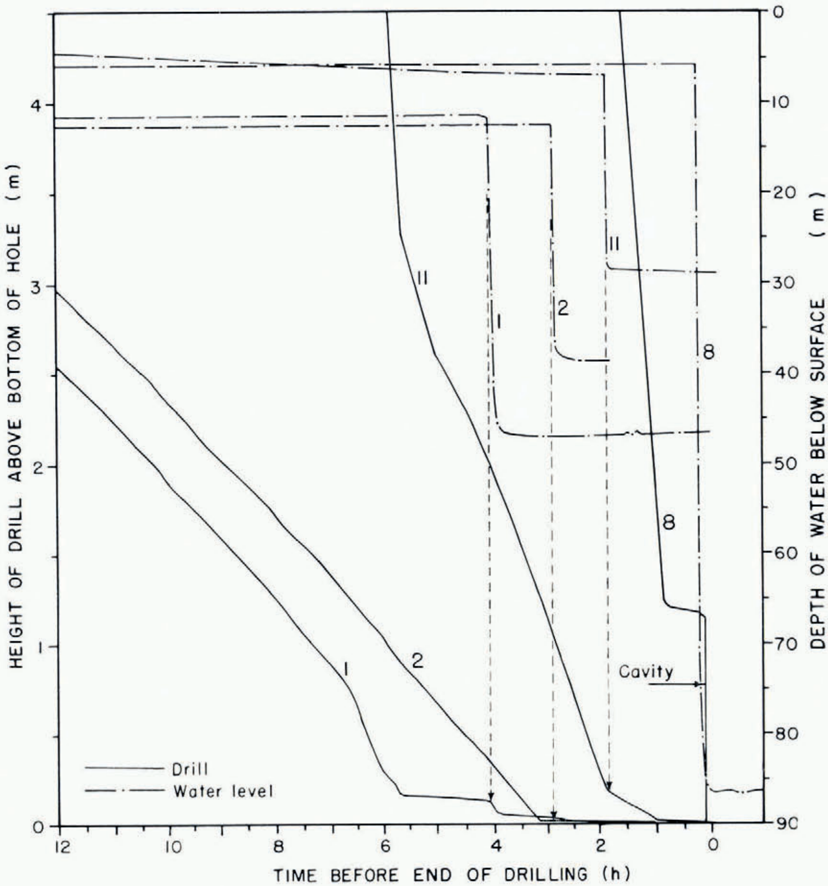

Fig. 2. The water-level drops which occurred at the glacier bed. The hole numbers are indicated beside each line. Hole 5 is not shown because the water-level recorder was in use elsewhere at the time of the drop. Holes 6 and 10, which developed englacial connections, are shown in Figures 4 and 5. The accuracy of the drill curves is about ± 10 mm and the accuracy of the water-level curves is ± 17 mm.

* The word "cavity" is used here to describe any free drop of the drill; the amount of this drop is defined as the "size" of the cavity. The true dimensions of the cavity and whether or not it would be described more correctly as a "conduit" are, of course, unknown.

occurred just as the water dropped. The drill then advanced 70 mm in the next 5 min and came to a stop again. In hole 2, the drill had been advancing very slowly, about 0.35 m h^{-1}, for over 9 h. Then it abruptly stopped and 17 min later the water dropped. Drill power was maintained for the next 3 h but the drill advanced only another 15 mm. In hole 5 a water level drop of 22–27 m occurred at or near the bed, but it is not known exactly where or when because the water-level recorder was being used elsewhere at the time. No water drops were obtained in holes 3 and 4: hole 3 was abandoned after repeated hot-point failures occurred in the dirty ice layer (0.1 m h^{-1} drill rate for over 15 h), and hole 4 was abandoned when no drop in water level occurred despite applying power for almost 9 h after the drill stopped abruptly.

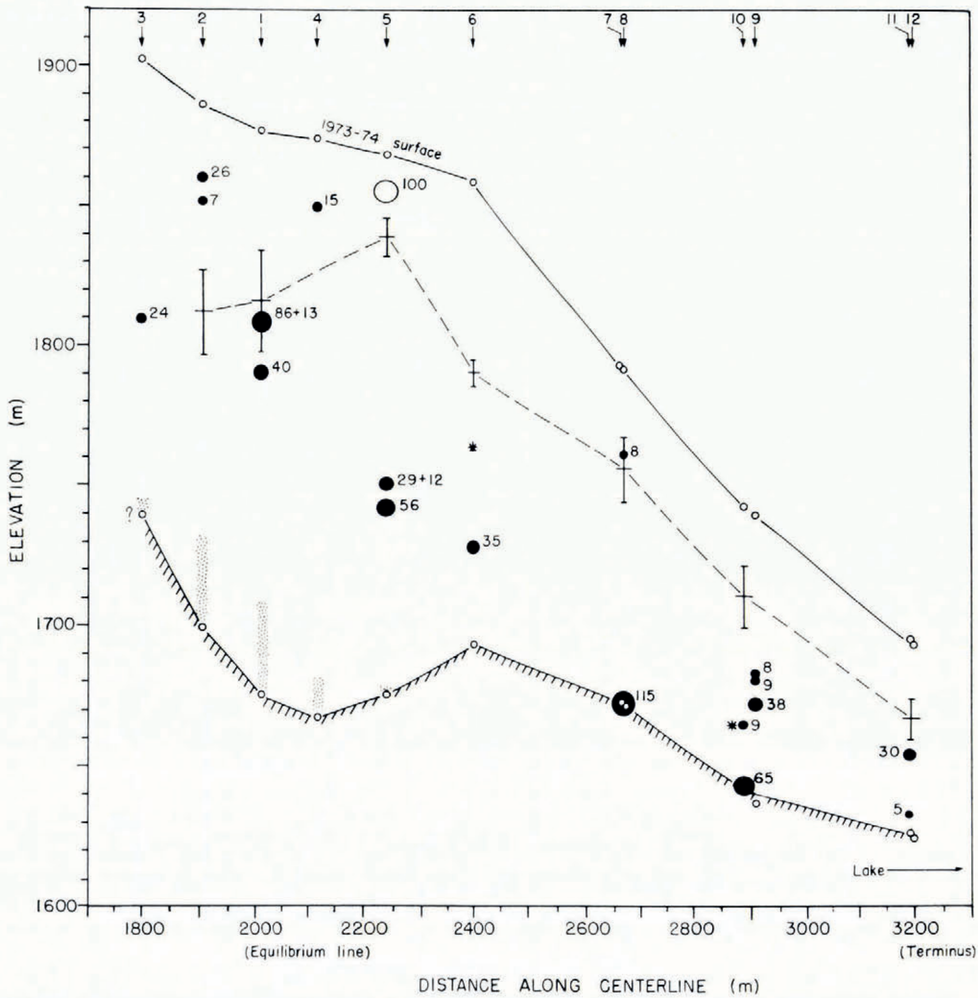

Fig. 3. A longitudinal profile of South Cascade Glacier showing the location of the cavities encountered (solid dots) and the mean summer (July–August) water levels in the bore holes (vertical lines with "error bars"). The hole numbers are shown at the top of the diagram. The number beside each cavity indicates its size in centimetres; a double number (e.g. 86+13) indicates cavities too close together to be distinguished in the diagram. The area of the dots is approximately proportional to the size of the cavity. The circle near the top of hole 5 is probably a crevasse. The stippled columns indicate dirty ice (slow drill rate). The "error bars" show the standard deviation of the water level over the entire observation period. The asterisks on holes 6 and 10 indicate the position of the drill when the englacial connection took place. The question mark on hole 3 means that the real bed of the glacier was probably not reached.

Several cavities were encountered in the drilling of these holes (Fig. 3). No corresponding change in water level occurred in any of these cavities, except possibly in holes 4 and 5 when the water-level recorder was not in use. Conversely, three small changes in water level occurred which could not be identified with any detectable change in drill rate. One (hole 1, at 67.7 m) was a sudden drop of 0.28 m followed by a gradual recovery to the previous level in about 90 min, one (hole 4, at 84.7 m) was a sudden drop of 0.12 m followed by a gradual recovery to 0.03 m below the previous level in about 15 min, and one (hole 4, at 177.8 m) was a gradual drop to 0.21 m below the previous level in about 100 min.

A bore hole near the head of the glacier (13) was drilled in July 1974. No cavities were encountered and the water level remained constant throughout, as expected in a region where there is a firn water table. No water drop occurred at the bed.

Ablation area

In June of 1974, seven bore holes were drilled in the ablation zone (holes 6–12, Fig. 1) and the drill rate and water level monitored as before. All drilling was done before the winter snow layer had been removed by ablation. The results differ in several ways from those of the previous year.

The water level in the holes usually varied slightly throughout the drilling. In four holes it fell steadily, between 0.22 and 0.34 m h^{-1}, while power was applied to the drill. In two holes (10 and 12) it was variable, rising or falling slowly for periods of several hours, and in one hole (8) it remained more or less constant. The interpretation is that since no firn water

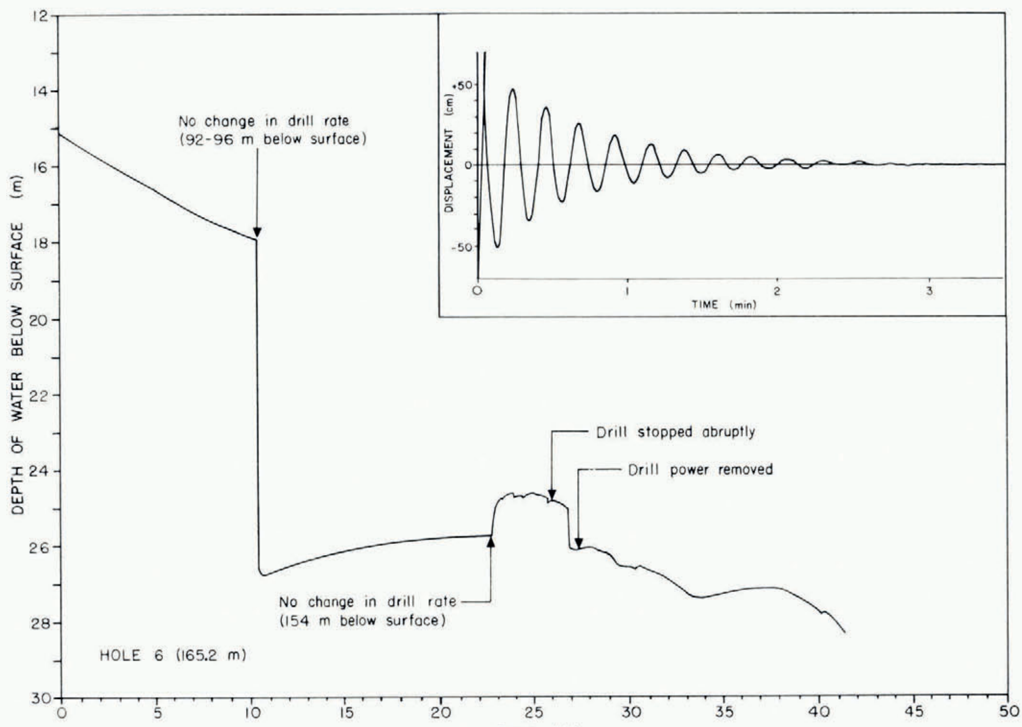

Fig. 4. The water level in hole 6 during drilling. The inset shows an example of damped oscillations which, after the drop at 10.3 h, could be produced by suddenly lowering an object into the water.

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table is present in the ablation zone to replace the ice volume lost by melting, any replenishment must come from melt-water streams running along the snow/ice interface. Such streams will naturally vary in their ability to keep the bore holes full of water.

Cavities were encountered at the glacier bed (Fig. 3). One, at hole 8, was 1.15 m deep and was associated with a water drop of 81 m. The other, at hole 10, was 0.65 m deep and was associated with a water drop of only 0.25 m.

Significant water drops at the glacier bed only occurred at two holes, 8 and 11 (Fig. 2). The one at hole 8 was associated with the cavity just mentioned, but the one at hole 11 occurred after 4 h of drilling through dirty ice at 0.8 m h^{-1}, at a point 0.2 m above the bottom, where the drill slowed to 0.1 m h^{-1}. On the other hand, in two holes (6 and 10) water drops occurred at intermediate depths (Figs 4 and 5). The drop in hole 10 was definitely associated with a 0.09 m cavity 22 m above the bottom, but the one in hole 6, about 70 m above the bottom, was probably not associated with any measurable change in drill rate.* In both cases, after the drop occurred, the water level started to fluctuate in a manner similar to that in holes where water drops had occurred at the bed, but a damped oscillation could be induced by suddenly displacing the water with an object such as the hot point.

Three cavities were encountered which produced small changes in water level. One (0.08 m cavity, 30.3 m below the surface, hole 8) was an abrupt drop of 0.17 m followed by an abrupt recovery to the previous level 2 min later, one (0.08 m cavity, 56.1 m below the

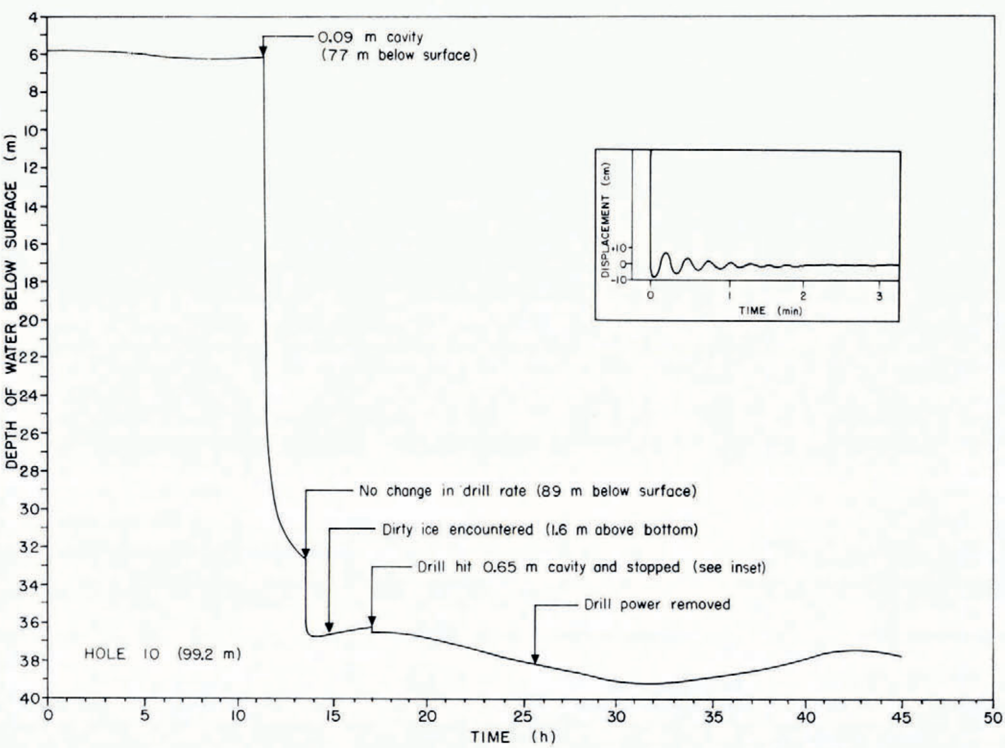

Fig. 5. The water level in hole 10 during drilling. The inset shows an example of damped oscillations, similar to those in hole 6, which could be produced after the water drop at 11.2 h. Such an oscillation took place naturally when the drill hit the 0.65 m cavity at the bed.

* Difficulties with recording at the time prohibit definite conclusions.

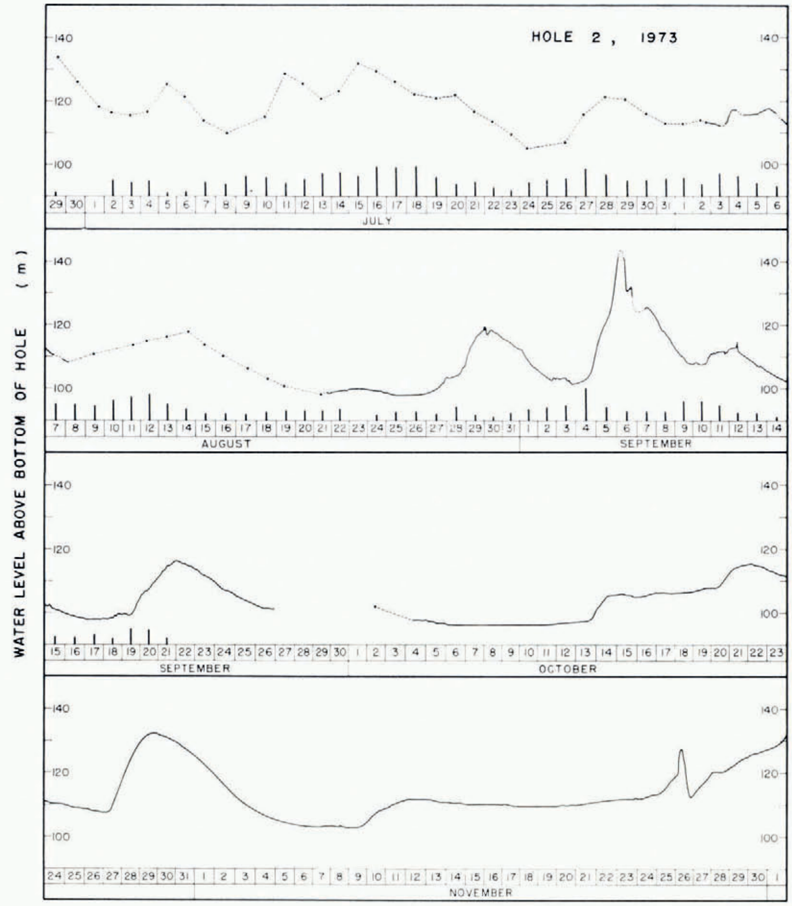

Fig. 6. The water level in hole 2 from 29 June to 1 December 1973. The solid dots represent daily soundings, accurate to abou ±0.2 m, and the solid line indicates continuous recording with a pressure transducer, accurate to ±0.17 m. The vertical bars at the bottom of each section show relative values of daily liquid input to the glacier surface (ablation plus precipitation); these data are unknown after 21 September. After 1 December the water level rose very rapidly, indicating closure of the hole.

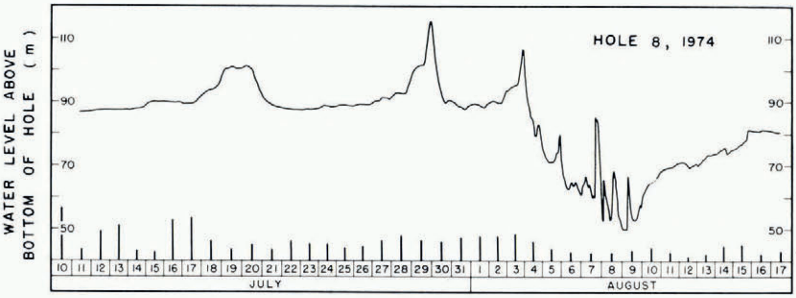

Fig. 7. The water level in hole 8 from 11 July to 17 August 1974, obtained with a pressure transducer accurate to ±0.35 m. The vertical bars show relative values of daily liquid input.

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surface, hole 9) was a permanent drop of 0.14 m over a period of 4 min, and one (0.38 m cavity, 67.1 m below the surface, hole 9) was an abrupt and permanent rise of 0.25 m. In addition, numerous small, rapid changes in water level occurred without any detectable change in drill rate, probably due to changes in surface streams flowing into the holes.

Monitoring the bore-hole water levels

It was apparent that some of the bore holes had connected with a dynamic water system within or at the bed of the glacier. Daily soundings of the water level in these "successful" bore holes were made for various periods of time afterwards and, in two cases, continuous records were obtained using pressure transducers. Hole 2 has the longest record, from 29 June to 1 December 1973 (Fig. 6). A continuous record from hole 8 was obtained between 11 July and 17 August 1974 (Fig. 7), and daily soundings of holes 6, 8, 10, and 11 between June and September 1974, were also made (Fig. 8). Daily values of liquid input per unit area at the glacier surface (ablation plus liquid precipitation) are also indicated.

The major problem with monitoring the water levels is keeping the holes open against the deforming or refreezing ice. In areas where there is a firn water table and the ice is deforming relatively slowly this was only a minor problem during the melt season since sufficient melt water was flowing down the holes to counteract the mechanical or thermal closure. In fact, holes drilled in 1973 *enlarged* over most of their length after they were drilled. Hole 2, for example, required only one brief reaming in August to enlarge a slight constriction about 3 m long about halfway down. However, in early December hole 2 did close off completely, presumably because the supply of melt water had diminished and no one was present to ream the hole.

On the other hand, the 1974 bore holes were in an area where there was no firn water table and the ice was deforming more rapidly. Hole 6 was in an area of strong extending flow and apparently closed off about three weeks after it was drilled. The water level rose steadily thereafter, reaching the surface about two weeks later. After reaming the hole the water dropped approximately to the original level but the hole closed again about 10 d later. Hole 10 closed about 26 July, the water level rising steadily until it was reamed open again on 12 August. Hole 8 was reamed before the hole had closed and no data were lost. Holes 11 and 12 did not require reaming and remained open all summer.

Discussion

This pilot study demonstrated that it is possible for bore holes to connect with a water system, or systems, within or at the bed of a glacier. Out of 13 holes drilled, eight were successful. Five of these (1, 2, 5, 8, and 11) penetrated to a dynamic water system at the glacier bed and two others (6 and 10) did so at intermediate depths. The eighth one (12) connected by itself 6 d after drilling was terminated. During 1974 it was planned to see if explosives could be used to establish a link to a water system in those holes where drilling alone was unsuccessful; such tests were never carried out but they apparently have been successful elsewhere (H. Röthlisberger, written communication to M. F. Meier, 1975).

Cavities

In these 13 bore holes, 18 englacial and 2 subglacial cavities were encountered. The average englacial cavity size was 0.25 ± 0.21 m, ranging from the limit of detection (about 0.05 m) to a maximum of 0.86 m. The subglacial cavities were larger, 0.65 and 1.15 m. When cavities were encountered there was usually no change in water level; if there was it was usually small and temporary. In only two cases did connection with a dynamic water system occur when a cavity was known to have been encountered, once at the bed and once internally. The englacial cavities have a tendency to cluster around a line (Fig. 3). A definite conclusion on this interesting point must await more extensive and more accurate data but it may indicate there is a layer where conduits are more likely, as suggested by Röthlisberger (1972).

The cavity sizes measured on South Cascade Glacier are comparable to those noted on the Athabasca Glacier (Savage and Paterson, 1963, p. 4522) and the Blue Glacier (Shreve and Sharp, 1970, p. 68). However, fewer and less dramatic water-level changes seem to

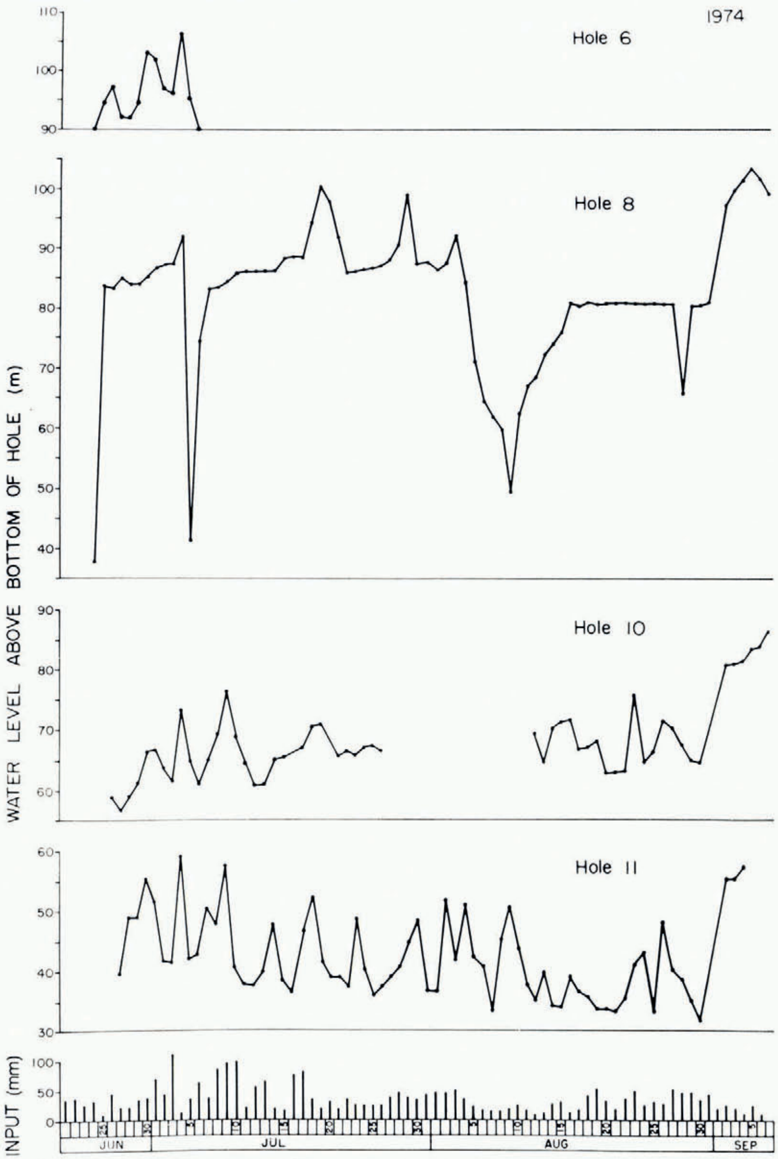

Fig. 8. Daily soundings of the water level in holes 6, 8, 10, and 11 from late June to early September 1974. Relative values of daily liquid input are shown at the bottom. The data are approximately simultaneous and are accurate to about ±0.1 m. Hole 6 was in a region of strong extending flow and closed after 6 July. Hole 10 closed on 26 July and no data were obtained until it was reamed open on 12 August.

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occur on South Cascade Glacier when cavities are encountered. For example, water has not (yet) overflowed out of a bore hole.

Since water drops occurred at the glacier bed both with and without detectable cavities it may be that water flows along the bed both in conduits and thin layers. A drop of the drill of a centimetre or less cannot be detected with the existing apparatus.

Water levels

If connection was established at the glacier bed, it is reasonable to suppose that the bore hole resembles a large manometer and that the water level in the bore hole is a direct measure of the basal water pressure. Further experiments are required to verify or deny this assumption, which is equivalent to assuming that the presence of the bore hole has not significantly altered the basal water pressure. However, the present data do contain several pieces of information which, at the very least, do not contradict this basic point.

All the water drops took place very rapidly. The water system was able to absorb the extra water in the bore hole (100–200 l) within a few minutes, suggesting that the basal water system is the dominant factor rather than the bore hole.

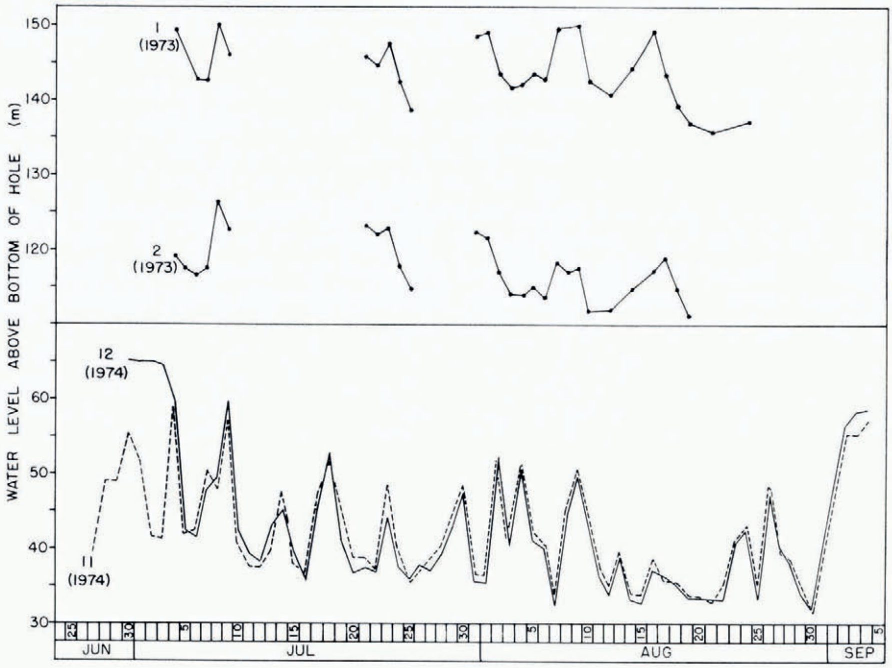
The mean summer (July–August) water level in all the bore holes* (Fig. 3) was 66.5% of the ice thickness, with a hole-to-hole variance of only $\pm 8.6\%$. The time variations of water level within each hole, during the same period, average about $\pm 8.3\%$, a comparable figure. The water level in the lowermost three holes (8, 10, and 11) almost perfectly parallels the glacier surface. Thus the surface defined by the bore-hole water levels during the summer was consistently about two-thirds of the ice thickness.

Holes which were close together exhibited time variations which were well correlated (Fig. 9). Holes 11 and 12 were only 10 m apart; thus when the water in hole 12 started to follow that in hole 11 six days after it was drilled, a new result emerged: the water level in a single bore hole appears to be representative over an area at least 10 m in extent. It is possible that hole 12 established an englacial connection to hole 11 but the fact that the correlation between the two holes is *not* perfectly synchronous suggests that the connection with the basal water system was at two distinct points rather than a single one. Furthermore, since hole 12 was initially filled with water to the ice surface, connection is most likely at the bed because this is where the difference in hydrostatic pressure between water and ice is the greatest. In 1973 some soundings were also made simultaneously in holes 1 and 2 (Fig. 9). These holes were 105 m apart and both are known to have connected at the bed. The day-to-day variations in water level correlate remarkably well also, both in phase and magnitude, but the mean water levels have different values.

Large variations in water level in the bore holes usually correlate with large *changes* in the amount of water input to the glacier surface. Peaks in water level often occur roughly 2 d after a large increase in water input (Fig. 6). This suggests a transit time of about 2 d from snow surface to glacier bed, a result which agrees with the dye experiments of Krimmel and others (1973). The large fluctuations occur typically over time spans of a few days to a week, indicating that it takes this long for the glacier's conduit system to adjust to changes in input, as suggested by Shreve (1972). The magnitude of the fluctuations ranges from a few metres up to 40 m, a smaller range than the 100 m or more found by Röthlisberger (1976).

The flow of water down the bore hole does not appear to affect the bore-hole water levels since no consistent diurnal variations in water level occur, despite such variations in the firn water table and ablation rate. Slight diurnal fluctuations occurred occasionally in hole 8 between 30 July and 9 August (Fig. 7), but this was the only such occurrence. Other workers (Vivian and Zumstein, 1973; Röthlisberger, 1976) have found large diurnal variations to be

* From now on only bore holes where connection with the basal water system took place are referred to.



9. Daily soundings of holes 1 and 2, 105 m apart, in 1973 and of holes 11 and 12, 10 m apart, in 1974. The data are approximately simultaneous and are accurate to about ±0.2 m for 1973 and ±0.1 m for 1974. After 4 July, the water level in holes 11 and 12 was almost perfectly synchronous. In fact, much of the discrepancy shown has been exaggerated for clarity; for the same reason no dots are shown.

the rule rather than the exception. However, Mathews (1964) found "moderately steady conditions, at times showing slight diurnal fluctuations, interrupted by irregular and catastrophic surges, particularly during periods of rapid snow melt and heavy rains". South Cascade Glacier fits this description quite well also. The fact that diurnal fluctuations may or may not be found in subglacial water pressures could be a reflection of how directly the particular point on the bed connects with the glacier surface. Moulins, for example, probably connect with the bed very rapidly and may therefore give atypical results. Bore holes drilled at random should give data which are more representative of the average conditions at the bed.

There are some instances, particularly on a small scale, of waves of water pressure passing along the glacier bed. Some of these resemble a shock wave, the water level changes often occurring discontinuously. A large-scale example of this can be seen on 27 October in hole 2 (Fig. 6).

None of these points proves or disproves the assumption that bore-hole water levels are a direct measurement of basal water pressure; for this reason the term "bore-hole water level" has been used rather than "basal water pressure". It is simply that the overall picture suggests that this assumption is indeed correct.

Similarly, even though holes 6 and 10 made an englacial connection with a water system, the pattern of water-level variations which occurred in them resembles that in the other holes and so it assumed that this englacial connection was linked directly with the glacier bed and thus the water level still represents the basal water pressure. The fact that damped oscillations

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could be induced in them suggests the presence of a partially air-filled cavity. Such a cavity could be created if the drill penetrated a water-filled conduit which extended from a point above the drill and above the static head down to the bed and which was nowhere connected to the atmosphere.

The overall trend of the water level in hole 2 from the end of June to the end of November is shown by the 11 d running average in Figure 10. There is a net decrease in water level throughout the summer until about the end of the ablation season. Then the trend reverses and the water level rises during October and November. This agrees with the observations of Mathews (1964) and Vivian and Zumstein (1973) and supports the concept of seasonal storage and release of liquid water (Tangborn and others, in press). The englacial water definitely does not drain out of the glacier once ablation stops. In fact, in mid-January 1974, hole 5 was found to have water in it about 22 m below the surface, approximately the same level as the previous summer.

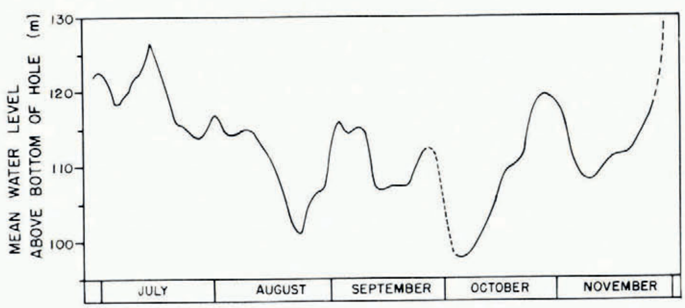

Fig. 10. An 11 d running average of the water level in hole 2, 1973. The overall trend decreases through the summer until the end of the melt season in early October and then increases through the fall. The dashed line at the end indicates the approaching closure of the hole in early December.

Summary

The purpose of the bore-hole drilling on South Cascade Glacier has been to see if the technique can be used to study englacial and subglacial water. To this end the work has been successful. The bore holes had a probability slightly better than 50% of connecting with the subglacial water system. Persistent drilling in the dirty ice at the bed is often required, so the use of supplemental techniques, such as explosives or pumps, should increase this probability. The resulting water level probably represents a direct measurement of the basal water pressure over some significant area of the glacier bed.

Further work is in progress to try and resolve the important and complex question of exactly what the bore-hole water levels represent. Continuous recording for at least one year of the water level in an array of bore holes covering the entire glacier, and accurate measurements of surface and sliding velocities and water input and output, are also planned.

Acknowledgements

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DISCUSSION

L. LLIBOUTRY: I question whether you did not modify the subglacial conditions by applying a large head of water at the interface when the drill reached it.

You found very similar pressures in all the holes. In Gillet's holes, under Glacier de Saint-Sorlin, they differed widely.

S. M. HODGE: Yes, in some situations this may be an unavoidable problem. Hopefully, however, the glacier will soon adjust to the changed situation and so measurements obtained over an extended period of time may become meaningful. In some cases, such as encountering the large cavity at the bed in hole 8, the brief application of a large head of water doubtless had little effect.

G. DE Q. ROBIN: Although it is clear that the pressures will be representative of any relatively thick, low pressure, water layer at the base of a glacier, it seems unlikely that this will be the case if the bore holes hit a very thin, high-pressure zone at the base of the ice. For example, there will scarcely be enough water to let it form a geyser shooting up above the glacier surface if the pressure is locally higher than the mean loading due to the weight of ice. Do you agree?

HODGE: Yes, at least for pressures greater than that of a head of water equal to the glacier thickness. For pressures less than this, however, the bore-hole water levels should still represent the basal water pressure. Initially the bore hole is full of water and it can be filled with surface water if necessary; thus the amount of water available in the film is of little consequence in this case.

The region over which a single bore-hole measurement is applicable may well be a function of the pressure, with relatively low pressures being representative of a larger area than higher ones.

W. H. MATHEWS: Was the water level in the hole constant throughout the period of drilling, and if so does this not imply there was a water input into the upper part of the hole?

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HODGE: In the accumulation area, the water level remained constant because of water input from the firn water table near the surface.

MATHEWS: Could you inject a dye into the bottom of the hole and monitor flow velocity to the glacier terminus to obtain a mean figure for the thickness of the water layer under the glacier?

HODGE: Yes, we are currently building a dye injector to do that.

J. F. NYE: The time taken for the water level to drop in a hole could give information on the size of the connection to the subglacial water system (for example, in the way Weertman used for the "Byrd" station hole). Have you tried to use the observed relaxation time of the water level in this way?

HODGE: No.

NYE: When doing the calculation one should not forget the possible thermal effects—for example, melting by heat of friction, and the fact that the change of water pressure will change the melting point and so cause local freezing at the outlet point at the bottom of the hole.

HODGE: Agreed.

R. H. GOODMAN: On the Athabasca Glacier, radio reflections were observed which varied rapidly with time. These were not correlated with diurnal variation or regional water production. I believe these reflections are a result of the filling of internal structures by a fluctuating water table. This may be an alternative technique.

HODGE: Hopefully, remote-sensing techniques such as radio-echo sounding can be used eventually to replace laborious bore-hole drilling and investigate englacial and subglacial water, but the "ground truth" must be established first. However, it is conceivable that remote-sensing techniques will *not* be able to measure numerical values of basal water pressure since the "water table" defined by the bore-hole water levels may not exist as a real, detectable physical structure when no bore holes are present.

In our future work we intend to record the characteristics of the radio reflection, as a function of time, at a fixed location on the glacier where the bore-hole water levels are also being recorded. We will use a relatively low frequency mono-pulse technique, however, so the necessary resolution may not be attained.

F. MÜLLER: Water-table fluctuations measured in moulins on the White Glacier on Axel Heiberg Island showed fluctuations of short duration linked to surface velocity fluctuations. Did you also find such a relationship?

HODGE: No, we did not measure any velocities. However, we intend to do so this season.

K. PHILBERTH: Would it be possible to pump in or out a constant flow rate of water, measure its influence on the water-level in the bore hole and in this way calculate the thickness of the basal water layer?

HODGE: In theory this is possible, and we have already done similar tests in the firn water table. Initially, however, the water level drops rapidly and so a very large pumping rate would be required. It might not be possible to get a strong enough submersible pump down a bore hole 5 cm in diameter. On the other hand, we could probably pump water into the bore hole, provided an adequate supply of water were available.

M. M. MILLER: Although you have found no apparent relationship with diurnal fluctuations in the firn water table, have you looked into the possibility of an aperiodic correlation between your sudden changes in bore-hole pressure and any unusual fluctuations in water stage level in the pro-glacial lake at the glacier's terminus?

HODGE: Not yet, but we intend to do so this season.