

EXCESS PRESSURE OBSERVED IN A WATER-FILLED CAVITY IN ATHABASCA GLACIER, CANADA

By W. S. B. PATERSON

(Polar Continental Shelf Project, Department of Energy, Mines and Resources, Ottawa 4, Ontario, Canada)

and J. C. SAVAGE

(Geophysics Laboratory, University of Toronto, Toronto 5, Ontario, Canada)

ABSTRACT. During drilling in the Athabasca Glacier in April 1968, a cavity containing water was punctured at a depth of 9.2 m below the ice surface. Upon removing the drill, water gushed from the bore hole for about 55 s indicating an excess pressure of at least 0.25 bar within the cavity. The surrounding ice was slightly below the pressure melting point, and the excess pressure was apparently generated by the reduction in volume of the cavity caused by freezing of some of the water within it.

RÉSUMÉ. Excès de pression observé dans une cavité pleine d'eau de l'Athabasca Glacier. Durant le forage à l'Athabasca Glacier en avril 1968, on perfora une cavité d'eau à une profondeur de 9,2 m, sous la surface glaciaire. En remontant l'outil, l'eau jaillit du trou de sonde pendant environ 55 s, montrant par là une suppression d'au moins 0,25 bar dans la cavité. La glace environnante était à peine en-dessous du point de fusion à la pression donnée, et le supplément de pression fut apparemment engendré par la réduction en volume causée par le gel d'une partie de l'eau à l'intérieur.

ZUSAMMENFASSUNG. Überdruck, beobachtet in einem wassergefüllten Hohlraum im Athabasca Glacier. Bei Bohrungen auf dem Athabasca Glacier im April 1968 wurde 9,2 m unter der Eisoberfläche ein wassergefüllter Hohlraum angebohrt. Beim Herausziehen des Bohrers ergoss sich etwa 55 s lang Wasser aus dem Bohrloch, was auf einen Überdruck von wenigstens 0,25 bar in dem Hohlraum hinweist. Das umgebende Eis befand sich geringfügig unter dem Druckschmelzpunkt; der Überdruck war offenbar durch eine Verringerung des Höhlenvolumens — verursacht durch Gefrieren von etwas Wasser innerhalb der Höhle — erzeugt worden.

1. INTRODUCTION

It is well-known that cavities containing water can exist within glaciers which are at or near the pressure melting point. For example, Haefeli and Brentani (1955) have described a series of crevasses, closed at the top and containing water, encountered during drilling of the tunnel through the small ice cap at the Jungfrauoch. Fisher (1963) has described "an enormous reservoir of water" punctured during the cutting of a tunnel in ice on the Breithorn. Such descriptions are sufficiently rare, however, that another small example may be worth describing briefly.

We refer readers to a previous paper (Paterson and Savage, 1963) for a description of Athabasca Glacier.

There is indirect evidence for the existence of water-filled cavities in this glacier. Savage and Paterson (1963) found that, during thermal drilling, the casing of the hole would sometimes fall freely for distances of up to 1 m, even at depths of 200 m. Mathews (1964[a]) has examined records of the discharge of the stream that drains the lake at the glacier terminus. He found periods of abnormally high discharge that could not be related to weather conditions and ascribed them to the sudden release of water stored within the glacier.

2. OBSERVATIONS

In late April 1968 we were measuring temperatures to a depth of 10 m in the ablation area. We dug through the snow to the ice surface and then used a mechanical drill. After each meter, we stopped drilling and measured the temperature at the bottom of the hole with a thermistor.

In one place, near the center-line of the glacier and about 3 km from the terminus, an upward force was suddenly felt on the drill when it reached a depth of 9.2 m below the ice surface. On removing the drill, water gushed from the hole for about 55 s. The volume of

water, estimated from the depth to which it filled the snow pit, was roughly 0.09 m^3 . Sounding showed that the cavity was 2.4 m deep; we had no means of determining its lateral dimensions. The water in the cavity had a measured temperature of 0.03°C with a standard error of about 0.05 deg. Table I lists temperatures in the snow and ice above. For comparison, the temperature at 11.5 m below the snow surface, at another point in the same area where the snow was about the same depth, was -0.5°C .

TABLE I. TEMPERATURE PROFILE IN THE SNOW AND ICE ABOVE THE WATER-FILLED CAVITY IN ATHABASCA GLACIER

| Depth m | Temperature $^\circ\text{C}$ | Material |
|------------|---------------------------------|----------|
| 0 | -3.7 | snow |
| 0.5 | -5.8 | " |
| 1.0 | -5.6 | " |
| 1.5 | -4.8 | " |
| 2.0 | -4.4 | " |
| 2.6 | -3.8 | ice |
| 3.6 | -3.1 | " |
| 4.6 | -2.6 | " |
| 5.6 | -2.4 | " |
| 6.6 | -1.9 | " |
| 7.6 | -1.5 | " |
| 8.6 | -1.1 | " |
| 9.6 | -0.6 | " |
| 10.6 | -0.4 | " |
| 11.6 | -0.2 | " |
| 11.8 | 0 | water |

There are three points to note about these observations:

1. The cavity was in ice slightly colder than the melting point.
2. From the condition of the snow observed in pits we deduced that, as one would expect from climatic conditions in the area, there had been no melt water at the glacier surface since the end of the previous summer.
3. The water was under a pressure sufficient to drive it above the ice surface.

3. DISCUSSION

Water-filled cavities in ice below the melting temperature have been observed before, even at the end of winter. The cavities reported by Haefeli and Brentani (1955) were in ice at a temperature of -2 or -3°C . And Fisher (1963) states that the flow of water from the cavity in the Breithorn tunnel "increased materially in the winter". Again, Mathews (1964[b]) measured the water level from a mine which reached the base of Leduc Glacier. He noted that the water level often remained steady for extended periods and found some evidence for a seasonal cycle in such "base levels". Low base levels seemed to occur in late summer; relatively high levels in winter.

"Water-spouts" have been observed, in summer, in several glaciers; for example by Rucklidge (1956), Wiseman (1963) and Wyllic (1965). These may be either continuous or intermittent; they apparently form part of a system of drainage channels within the ice. However, our observations were made at the end of the winter, and the water only flowed for a short time. These facts suggest that the water was contained in an isolated cavity.

There appear to be two possible explanations of the origin of the cavity:

1. The cavity was originally part of a system of water channels within the ice. Such channels will remain open as long as water flows in them. However, when the supply of surface melt water ceases at the end of the summer, ice flow will start to close the channels and any remaining water will be trapped in isolated cavities.

2. The cavity originated as a water-filled crevasse in the ice fall some 750 m farther up the glacier.

We favour the first explanation because, if we assume that crevasses are 30 m deep (Seligman, 1955), the ice at the base of a crevasse in the ice fall would probably have been removed by ablation before reaching the location where the cavity was formed.

It would appear that a volume of compressed air trapped near the top of the cavity is required to explain the observed discharge from the drill hole after the cavity was punctured. Figure 1 shows the model which we believe explains the discharge. Note that the final water level after discharge was just above the ice-snow interface. Let p and v denote the pressure and volume of the trapped air and let p_0 denote atmospheric pressure (0.76 bar at the glacier

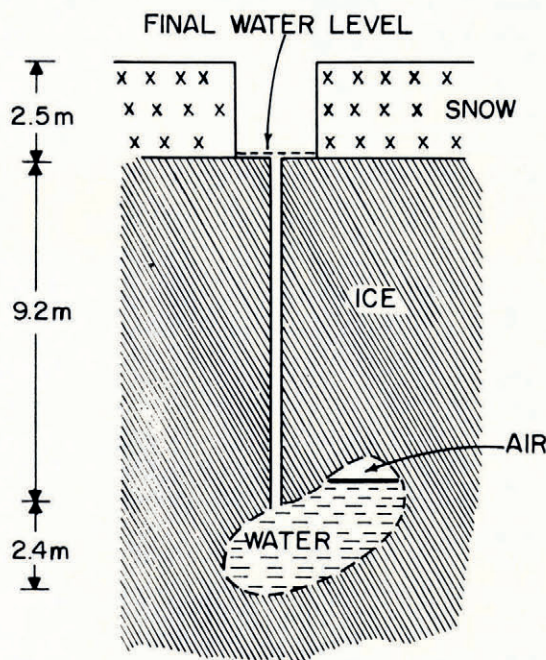


Fig. 1. Model for the observed discharge of water after a drill hole punctured a cavity in the ice of the Athabasca Glacier.

elevation). The subscript 1 indicates the state before the cavity was punctured and the subscript 2 indicates the state when equilibrium had been re-established after discharge. The pressure p_2 must balance p_0 plus the pressure exerted by a column of water reaching from the final water level (just above the ice-snow interface) to the air-water interface in the cavity. The length of this column is not known exactly, but it is very unlikely that it differs significantly from l the length of the bore hole (9.2 m). The value of p_2 is then about 1.66 bar. The expansion of the air in the cavity was apparently a slow adiabatic process, and thus

$$p_2/p = (v/v_2)^\gamma \quad (1)$$

where γ is the ratio of specific heats (c_p/c_v) for air ($\gamma = 1.4$). It will be shown that $\Delta p = p - p_2$ is much less than p_1 or p_2 . Hence Equation (1) may be approximated by

$$\Delta p = \gamma p_2 (v_2 - v) / v_2. \quad (2)$$

The drill hole had smooth walls, and the observed flow (0.09 m^3 in 55 s) indicates the appropriate Reynolds Number is of the order of 3×10^4 . Flow through a channel of circular cross-section under such conditions is governed by the Blasius relation (Schlichting, 1955, p. 401)

$$P = \lambda \rho \bar{u}^2 / 2d \quad (3)$$

where

$$\lambda = 0.3164 (\bar{u} d \rho / \eta)^{-1/4}, \quad (4)$$

η/ρ is the kinematic coefficient of viscosity ($1.8 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$), d the diameter of the drill hole (38 mm), ρ the density of water, \bar{u} the velocity of flow averaged over the cross-section, and P is the pressure difference between the ends of the drill hole required to overcome frictional drag. In the absence of friction, the pressure p required to drive the flow should be given approximately by the Bernoulli theorem:

$$p = \frac{1}{2} \rho u^2 + p_0 + \rho g l = \frac{1}{2} \rho u^2 + p_2.$$

An extra pressure drop P is imposed by friction in the bore hole so that

$$\Delta p = p - p_2 = \frac{1}{2} \rho \bar{u}^2 + P = \frac{1}{2} (1 + \lambda l/d) \rho \bar{u}^2.$$

In the flow discussed here $\lambda > 0.02$ so that $\lambda l/d > 5$. In what follows we will replace $(1 + \lambda l/d)$ by $(\lambda l/d)$. The error introduced should be such as to cause the final estimate of $(\Delta p)_1$ to be too small. Thus

$$\Delta p = \lambda \rho \bar{u}^2 / 2d. \quad (5)$$

The volume rate of water discharge through the drill hole must equal dv/dt , the rate of change of the volume of air in the cavity. Thus from Equations (2), (5), and (4) we have

$$dv/dt = \pi d^2 \bar{u} / 4 = A (\Delta p)^{4/7} = A [\gamma p_2 (v_2 - v) / v_2]^{4/7} \quad (6)$$

where

$$A = (\pi d^2 / 4) (2d / 0.3164 \rho)^{4/7} (\rho d / \eta)^{1/7}. \quad (7)$$

The value of A in SI units is 11.3×10^{-6} . Equation (6) may be integrated and solved for v_2 :

$$v_2 = [3A(t_2 - t_1)/7]^{7/4} [\gamma p_2 / (v_2 - v_1)^{3/4}] \quad (8)$$

where $v_2 - v_1 = 0.09 \text{ m}^3$ is the total discharge and $t_2 - t_1 = 55 \text{ s}$ is the time of discharge. It is found from Equation (8) that $v_2 = 0.78 \text{ m}^3$ and from Equation (2) that $(\Delta p)_1 = 0.27 \text{ bar}$. (This confirms the assumption made earlier that Δp is much less than p_1 or p_2 , 1.93 and 1.66 bar, respectively.)

The equilibrium pressure at the depth of the bottom of the drill hole should be 1.68 bar (pressure from 2.5 m of snow (density 450 kg m^{-3}) plus 9.2 m of ice (density 900 kg m^{-3}) plus atmospheric pressure = $0.11 \text{ bar} + 0.81 \text{ bar} + 0.76 \text{ bar}$). On the other hand, the pressure p_1 in the cavity was $p_2 + (\Delta p)_1 = 1.93 \text{ bar}$. Thus the excess pressure in the cavity appears to be about 0.25 bar. The actual excess pressure is probably somewhat larger than this since we have neglected the pressure difference required to accelerate the water from rest in the cavity to the velocity u in the drill hole (see discussion above Equation (5)).

If, as is likely, ice was forming on the walls of the cavity, the expansion of water on freezing could cause this excess pressure. We can in fact estimate the rate of ice formation if we make two dubious assumptions:

1. The temperature profile in Table I represents a steady state.
2. There is no temperature gradient in the water.

In this case the heat flux in the ice must carry away all the latent heat released by freezing. The temperature gradient in the ice immediately above the cavity corresponds to a heat flux of 0.58 W m^{-2} . This gives a rate of ice formation of about $\dot{r} = 0.06 \text{ m a}^{-1}$. Suppose the cavity can be approximated by a sphere of radius $r = 1.5 \text{ m}$. Then the rate of formation of ice will be $4\pi r^2 \dot{r}$, and for each unit volume of ice formed the volume of the trapped air will decrease by 0.1 of a unit volume due to the difference in specific volume between ice and water. To produce the observed excess pressure by an isothermal compression, the air volume change must be 0.126 m^3 rather than the change of 0.09 m^3 observed in adiabatic decompression.

The time required to generate 0.25 bar excess pressure in the model cavity would then be about 9 months. Thus it appears that refreezing of water in the cavity is quantitatively adequate to explain the observed excess pressure. We think that this is the most likely explanation.

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