

# GEOHERMAL HEAT AND GLACIAL GROWTH \*

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**ABSTRACT.** In a 300 m. deep hole drilled in the 3000 m. thick ice at Byrd Station (lat. 80° S. long. 120° W., 1513 m. above sea-level), the temperature was observed to decline with depth below 45 m. This profile was extended to the bottom of the ice with the aid of heat conduction theory under these assumptions:

- (i) that as the ice was deposited the climate became warmer at the rate of 0.45° C. per 1000 years;
- (ii) The conduction of geothermal heat is 31.6 cal. cm.<sup>-2</sup> yr.<sup>-1</sup>.

It is estimated that the first 2000 years of geothermal heat conducted to this ice, whose annual accumulation is 30 cm., is dissipated to the atmosphere and space. When the ice becomes thicker, it retains all the geothermal heat given to it for a long time.

An alternative, non-climatic change explanation of the decreasing temperature in the Byrd Station hole is based on colder ice from higher elevations moving under the warmer ice accumulated locally. However, an examination of the topography of the Marie Byrd Land ice does not appear to support this explanation.

**ZUSAMMENFASSUNG.** In einem 300 m tiefen Loch, das auf der Station Byrd (80° S, 120° W) 1513 m über dem Meeresspiegel in das 3000 m dicke Eis gebohrt war, war beobachtet worden, dass die Temperatur mit einer Tiefe unter 45 m abnahm. Dieses Profil wurde mit Hilfe der Wärmeleitungstheorie unter den folgenden Voraussetzungen bis auf den Grund des Eises erweitert:

- (1) dass mit der Eisablagerung das Klima im Ausmasse von 0,45° C pro 1000 Jahren wärmer wurde;
- (2) die geothermische Wärmeleitung beträgt 31,6 cal. cm.<sup>-2</sup> Jr.<sup>-1</sup>.

Es wird geschätzt, dass die ersten 2000 Jahre geothermischer Wärme, die zu diesem Eis, das sich jährlich um 30 cm anhäuft, geleitet wird, an Atmosphäre und Raum abgegeben wird. Wenn das Eis dicker wird, so hält es die abgegebene geothermische Wärme für lange Zeit fest.

Eine andere Erklärung für die abnehmende Temperatur im Loch der Station Byrd, die nicht auf klimatischem Wechsel beruht, liegt darin, dass kälteres Eis sich von höheren Erhebungen unter das wärmere lokal angehäuften Eis verschiebt. Eine Überprüfung der Topographie von Marie Byrd Land scheint jedoch diese Erklärung nicht zu unterstützen.

## INTRODUCTION

Since the growth of an inland polar glacier, such as that located in Marie Byrd Land, Antarctica, is quite slow, one might expect that the comparably slow process of geothermal heat conduction might have some influence on the heat exchange within a glacier and between a thin glacier and its atmospheric environment. It is the purpose of this paper to calculate geothermal heat transfer into a growing ice layer of the Marie Byrd Land type and to draw inferences regarding the thermal history of the ice.

## THE MARIE BYRD LAND ICE

The Marie Byrd Land ice has recently been partially surveyed and sounded by a traverse party from the U.S.-I.G.Y. Byrd Station located at lat. 80° S. long. 120° W. The observations were taken along the 1040 km. route from Little America (lat. 78° 11' S. long. 162° 10' W.) to Byrd Station and then on a triangular route of 1980 km. extending north and east of Byrd Station. The seismic observations, which will be published in detail later, revealed a deep basin extending hundreds of meters *below* sea-level and filled with ice so thick that it extended hundreds of meters *above* sea-level. For example, at Byrd Station, elevation 1513 m. above sea-level, the ice thickness is 3000 m.; 90 miles (145 km.) east of Byrd Station the elevation is 1686 m., and the ice thickness is 3970 m. The average annual accumulation as measured in snow pits is about 30 cm. of ice.

The temperature profile in the upper 300 m. of the Byrd ice is shown in Fig. 1. The surface temperature of -28.6° C. is taken as the 1957 average of the surface air temperature, while

\* Paper read before the Symposium on Glaciology, V General Assembly, C.S.A.G.I., Moscow, U.S.S.R., 7 August 1958.

the temperature curve to the 45 m. level is a smoothed line of the snow temperatures measured in deep pits and hand-drilled holes. The temperatures from 50 m. to the bottom were measured by the U.S. Army-S.I.P.R.E. personnel who drilled the 4-inch (10 cm.) hole with a mechanical rig.<sup>1</sup> The outstanding feature of the latter measurements is the sharp decline of temperature from 45 m. to 90 m. followed by a slower, almost linear decline to the bottom of the hole.

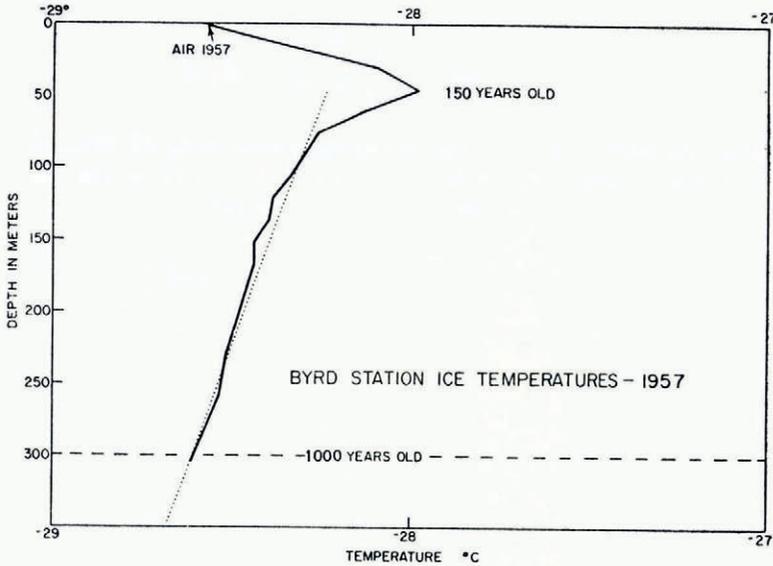


Fig. 1. Ice temperatures at Byrd Station, lat. 80° S., long. 120° W. (The dotted line is the straight-line approximation to the 100 to 300 m. temperatures)

ASSUMPTIONS

In the following calculations these assumptions were made:

- (i) The geothermal heat flux,  $F_0$ , is taken as  $10^{-6}$  cal.  $\text{cm.}^{-2}$   $\text{sec.}^{-1}$  or  $31.6$  cal.  $\text{cm.}^{-2}$   $\text{yr.}^{-1}$ . This is very close to the average value measured in the deep ocean bed as indicated by Bullard, Maxwell and Revelle<sup>2</sup> although in narrow submarine ridges off the coast of South America the value can be ten times larger.<sup>3</sup>
- (ii) In c.g.s. units, thermal conductivity,  $K$ , of ice =  $5.3 \times 10^{-3}$ ; density,  $\rho = 0.92$ ; specific heat,  $c = 0.50$ ; thermal diffusivity,  $\kappa = K/\rho c = 1.15 \times 10^{-2}$ .
- (iii) Although as a convenience the growth of the Marie Byrd Land ice is considered to be constant at 30 cm. per annum the problem could be solved for a variable growth if this were known. The ice is assumed to be contained and motionless as the snow is deposited within the deep basin in Marie Byrd Land.
- (iv) If there were no geothermal heat flow the temperature profile within the Marie Byrd ice would show an increase with height from the bottom to the surface by  $4.5^\circ$  C., that is, it would have the same temperature gradient as that observed in the lower 200 m. of the 300 m. deep hole in Byrd station ice (Fig. 1). This is equivalent to saying that during the time required to lay down the Byrd ice (10,000 years) the climate in that region has warmed by  $4.5^\circ$  C. In making this statement, it is assumed implicitly that the average temperature of the annual accumulation of snow (30 cm.) is equal to the average annual air temperature at the surface. This assumption appears reasonable since the annual accumulation of 30 cm. is much smaller than the wave-length of the annual temperature wave in the snow, approximately 20 m. according to Benfield.<sup>4</sup>

COMPUTED TEMPERATURE PROFILES

According to Carslaw and Jaeger,<sup>5</sup> the temperature,  $T$ , within a semi-infinite solid of uniform thermal diffusivity,  $\kappa$ , and conductivity,  $K$ , whose uniform temperature initially is zero and one face of which ( $x=0$ ) is subjected to a constant heat flux,  $F_0$ , is

$$T = \frac{2F_0}{K} \left[ \left( \frac{\kappa t}{\pi} \right)^{\frac{1}{2}} \exp \left( -\frac{x^2}{4\kappa t} \right) - \frac{x}{2} \operatorname{erfc} \left( \frac{x}{2\sqrt{\kappa t}} \right) \right], \tag{1}$$

where

$$\operatorname{erfc} x = 1 - \operatorname{erf} x = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-\beta^2) d\beta.$$

If the semi-infinite solid is taken as the Marie Byrd ice resting on bedrock,  $x=0$ , whose bottom temperature is  $T_0$  and whose temperature at a distance  $x$  above the bottom initially is

$$T = T_0 + ax, \quad a = \text{const.}, \tag{2}$$

then

$$T = T_0 + ax + 2 \left( \frac{F_0}{K} + a \right) \left[ \left( \frac{\kappa t}{\pi} \right)^{\frac{1}{2}} \exp \left( -\frac{x^2}{4\kappa t} \right) - \frac{x}{2} \operatorname{erfc} \left( \frac{x}{2\sqrt{\kappa t}} \right) \right] \tag{3}$$

is the solution of the heat conduction problem whose boundary conditions are

$$\begin{aligned} T &= T_0 + ax, & \text{for } t = 0, \\ F_0 &= -K \frac{\partial T}{\partial x}, & \text{for } x = 0, t > 0. \end{aligned}$$

Equation (3) has been used to compute a family of temperature curves for various durations of geothermal heat flux and the results are shown in Fig. 2. Here the initial temperature profile in the Byrd ice is shown extending from  $-28.17^\circ$  at the surface to  $-32.67^\circ$  C. at the bottom of 3000 m. of ice, and  $a = 1.5 \times 10^{-5}$  C. cm.<sup>-1</sup>.

If the geothermal heat begins to flow into the ice at the prescribed rate, the new temperature profiles, computed from equation (3) are shown in Fig. 2. after 1000, 1500, 2500, 3500, 5000, 8000, 10,000 and 15,000 years. Although equation (3) is derived for a semi-infinite solid it can be applied to an ice layer of finite thickness provided the layer is so thick that within the time-scale considered the geothermal heat does not penetrate to the top layer. In this model this condition is fulfilled beyond the first few thousand years. For shorter periods and thinner layers an approximate method of estimating the loss of geothermal heat from the ice is described below.

LOSS OF GEOTHERMAL HEAT FROM THE ICE

The curves shown in Fig. 2 are based on the assumption that the ice retains all of the geothermal heat given to it from the underlying earth. When the snow mantle is thin the yearly accumulation of 30 cm. does not keep pace with the upward conduction of geothermal heat, which penetrates to the snow surface and is lost to the atmosphere and space. For example, as may be seen in Fig. 2, after 1000 years the snow mantle is 300 m. thick but in that interval of time, geothermal heat would have spread to that level and 300 m. higher, if there had been snow that thick. Obviously, therefore, there must have been a loss of geothermal heat from the 300 m. thick mantle to such an extent that at no place within the mantle (except perhaps a thin bottom layer) could the temperature have been higher than that of the snow surface. The geothermal heat loss is represented by the area ABCD (area between the initial temperature line, RS, the full curve marked "1000", the vertical dashed line marked "(1000)" and the abscissa). Similarly for the 2500 year period of geothermal heat flux into the mantle.

The process of heat loss is of course a continuous one—while the first year's accumulation of 30 cm. is being deposited, practically all of the geothermal heat conducted to the layer is

being dissipated to the atmosphere and space. This loss of geothermal heat would continue until the mantle becomes so thick that all the geothermal heat liberated is used in warming the ice deep below the surface layer. According to the curves shown in Fig. 2, this would occur at about 2500 years from the time the ice began its growth. Beyond this time (until approximately 17,000 years) all the transmitted geothermal heat would be preserved within the ice. Thus 1000 years later, or 3500 years from time zero, the temperature profile would be that labeled (3500) which is nearly identical to a curve marked "1500" computed from equation (3).

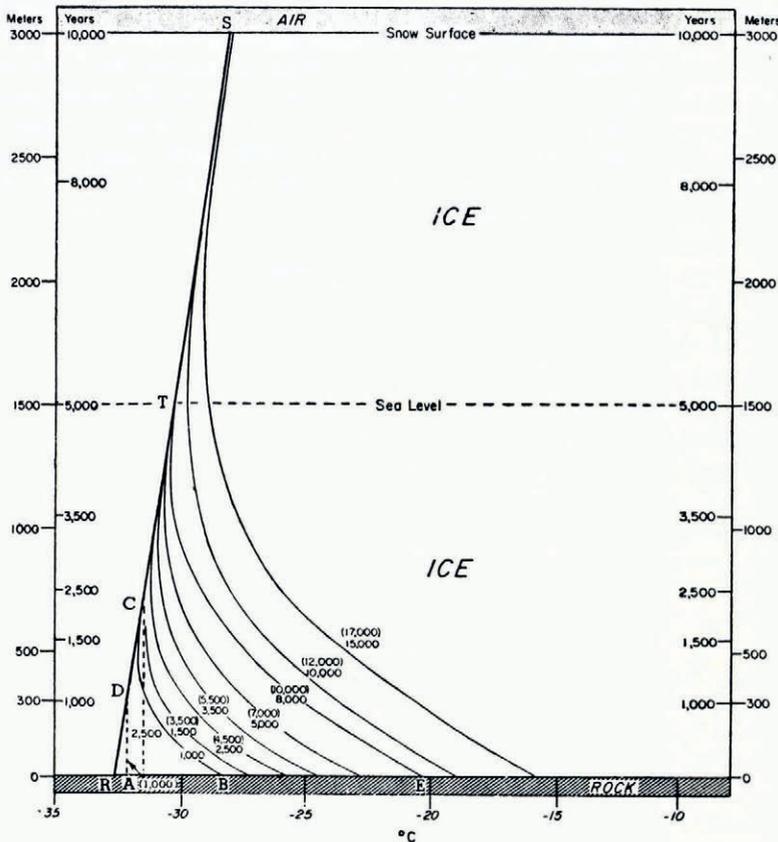


Fig. 2. Computed temperature profiles in the Byrd ice after various periods of geothermal heat flow. RS is the assumed initial temperature in the ice with no geothermal heat transfer. Figures in parentheses are based on loss of first 2000 years of geothermal heat

Thus it may be said that in the initial 3500 years of growth of the ice at an annual rate of 30 cm., the first 2000 years of geothermal heat is lost and is not available to heat the ice. But later the ice is so thick that all the geothermal heat is preserved and is available to heat the ice. Therefore in Fig. 2, all curves beginning with "1500" years have had 2000 years added to them and their larger numbers are shown in parentheses.

It must be stressed that the above conclusions apply to ice accumulating at the assumed rate of 30 cm. per annum. A higher rate of accumulation would decrease the loss of geothermal heat from the ice while a lower accumulation rate would increase it.

## INTERPRETATION IN TERMS OF CLIMATIC CHANGE

Turning again to Fig. 2 we see that the curve marked "(10,000)" years merges with the line "RS" at about 1500 m. below the surface or near sea-level. Under the assumptions underlying the construction of the curves shown in Fig. 2, this means that if a future observed deep temperature profile in Marie Byrd Land should be approximately that given by the curve STE, it might be said that the climate of this region has warmed by  $4.5^{\circ}$  C. in the past 10,000 years.

There are, of course, other possibilities for hypothetical "initial" temperature profiles "RS". One would be an increase in temperature with depth which would indicate a climate colder now than formerly. However, after 10,000 years of flow of geothermal heat, the temperature would still increase with depth—in disagreement with the observed temperature profile below 45 m. in the Marie Byrd Land ice. As another alternative the initial temperature may decrease with depth to 1500 m. say, and then increase by the same amount to the bottom, indicating a colder period followed by warmer. Although temperature profiles for this case have not been computed, these curves would differ from those shown in Fig. 2 by having much thicker intermediate layers of constant temperature. Under the assumptions underlying the calculations, it should therefore be possible to distinguish between three of the simplest possible thermal histories once a complete temperature profile of the ice is available. A more complicated climatic history would be most difficult to interpret.

## ANOTHER INTERPRETATION?

It is possible that the decrease in temperature noted in the lower 255 m. of the Byrd hole does not support an interpretation in terms of climatic change. Robin<sup>6</sup> has discussed the observed decrease in temperature in the Greenland Ice Sheet where a hole drilled in the ice at Station Centrale, elevation 2994 m. above sea-level, showed a temperature decrease of  $0.8^{\circ}$  C. from 20 m. depth to 120 m. and then remained constant at  $-27.8^{\circ}$  C. to the bottom of the hole at 150 m. Taking into account geothermal heat conduction, Robin concluded that "for a moderate rate of accumulation [*i.e.*, 16 cm. or more annually] a substantial fraction of the total thickness of ice at the centre of a large ice sheet may be isothermal at the prevailing surface ice temperature. Under these conditions at some distance from the centre, the change in the surface ice temperature with elevation may produce a temperature gradient opposite to normal, that is the temperature falls with increasing depth below the surface, due to the outward movement of the ice."

For the case of Station Centrale, which is located west of the highest portion of the Ice Sheet, the vertical temperature gradient computed by this effect is only  $\frac{1}{10}$  to  $\frac{1}{5}$  of that observed, so that Robin concludes (i) that climatic change can play an important role, and (ii) that the existence of "ice streams" in the main ice sheet, as proposed by Bauer,<sup>7</sup> means a greater outward velocity in some locations, with steeper temperature gradients as a result.

With regard to the ice flow explanation it would be of interest to compute how far from Byrd Station the center of the Ice Cap would have to be to account for the vertical temperature gradient of  $1.5 \times 10^{-3}$  C. m.<sup>-1</sup> observed below 45 m. in the ice at Byrd Station.

According to Robin,<sup>6</sup> the vertical temperature gradient in a non-heat-conducting ice at a distance  $r$ , from the center of an ice dome of radius  $R$ , and constant accumulation is

$$\frac{d\theta}{dh} = -\frac{r}{2(R-r)} \times 0.9^{\circ} \text{ C./100 m.},$$

where  $\theta$  is temperature and  $h$  is depth of ice (positive downward).

For the observed gradient between 45 and 300 m. at Byrd Station,

$$\frac{d\theta}{dh} = -1.5 \times 10^{-3} \text{ C./m.}, \quad \frac{r}{R} = \frac{1}{4},$$

suggesting that Byrd Station is located one-fourth of the distance between the center of the Marie Byrd Land Ice Cap and its terminus. Since the coast is about 500 km. to the north of the station and the junction of the inland ice with the Ross Ice Shelf about the same distance to the west, this result means that the center of the ice cap would be about 170 km. to the south-east. The elevation at that spot is not known, but the highest elevation observed during the recent Byrd traverse was 2196 m. above sea-level at lat.  $80^{\circ}3' S.$ , long.  $95^{\circ} W.$  or 460 km. east of Byrd Station. Furthermore, the elevation *drops* from 1787 m. at a point 180 km. north-east of the Byrd Station to 1513 m. at the station itself.

Therefore it does not appear likely that the highest elevation of the ice cap would be found 170 km. south-east of Byrd Station, as called for by the ice-flow explanation. We are thus left with the climatic change hypothesis as the likely one.

Additional observations taken on traverses out of Byrd and Ellsworth I.G.Y. Stations in the 1958-59 season should add much to the knowledge of the topography and depth of the ice in the unknown area south-east, south and south-west of the Byrd Station. Although there are no immediate plans to drill to the bottom of the ice at Byrd Station it is hoped that the U.S. Army-S.I.P.R.E. engineers can develop a means for doing so in the next few years. To settle the question of the ice-flow hypothesis a deep hole should be drilled at the top point of the ice cap. Then if it is found that the temperature decreases with depth this would reinforce the climatic change hypothesis.

*MS. received 28 July 1958*

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