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Uniform Heat Flow in a Deep Hole in the Canadian Shield and Its Paleoclimatic Implications[1]

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Precise temperature measurements to 2865 meters in a hole in a granitic pluton near Flin Flon, Manitoba, Canada, showed a systematic increase of temperature gradient with depth. Conductivity determinations at 50-meter intervals revealed a corresponding systematic decrease in conductivity. Over the entire measured depth, no systematic deviation from the mean heat flow of 1.01 ± 0.04 μcal/cm^2 sec is detectable in spite of strong evidence that the ground-surface temperature was at least 3.5°C cooler than at present for long periods during the Pleistocene epoch. These results can be reconciled with plausible paleoclimatic models. Evidently climatic change at this site does not result in a significant correction to the measured heat flow. The observations suggest that generalized estimates of the Pleistocene effect should be assigned a large uncertainty in the absence of an observed variation of heat flow with depth confirming a particular climatic model. The mean heat production is 2.1 × 10^{-13} cal/cm^3 sec. Taken with the observed heat flow of 1.01 μcal/cm^2 sec, it is consistent with other observations of heat flow and heat production in the stable interior of North America.

The transient effects of surface temperature perturbations of only a few degrees can exert a considerable influence on measured underground temperatures after many thousands of years. This fact was recognized by early heat-flow workers, and simple Pleistocene climatic corrections of fairly large magnitude were applied to some of their results [e.g., *Anderson*, 1940; *Benfield*, 1939; *Coster*, 1947].

Birch [1948] took exception to the assumptions about simple step-function 'corrections' and proposed a series of plausible, albeit idealized, models based on a comprehensive survey of the literature of Pleistocene climates. In his models, land-surface temperatures were alternatively colder, the same as, or warmer than present temperatures for various time intervals during the Pleistocene epoch. The total effect of a Birch-type model on present temperatures is not apparent intuitively, but the over-all tendency is for younger events to have relatively strong effects near the surface and for older events to have relatively more influence at greater depths. All Birch's models tended to predict much smaller residual Pleistocene climatic effects than the simple single-step models predicted. Birch concluded that 'the climatic correction may never exceed 3°C/km with a still smaller correction more probable.'

The concept of simple corrections of large magnitude has been revived recently by *Crain* [1968], who applied substantial corrections to measurements in the St. Lawrence lowlands of Quebec. Corrections based on a single-step model have been applied by *Beck and Neophytou* [1969], and corrections based on a two-step model have been applied by *Beck and Judge* [1969], *Lewis* [1969], and *Jessop* [1968]. A major factor in any model of past climate is the amount by which the surface temperature was depressed during the ice age, and some corrections, particularly those made by *Jessop* [1968], may be too large because of overestimation of this factor.

Horai [1969] criticized *Crain*'s [1968] model and calculated possible disturbances for a Pleistocene temperature history based on *Emiliani*'s [1955] calculations for Pleistocene ocean surface

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temperatures. Horai's maximum calculated disturbances to heat flow are lower than those proposed by Crain, and, for reasonable values of thermal diffusivity, his model leads to the same conclusions as those stated earlier by Birch (namely that the upper limit of the temperature-gradient disturbance due to Pleistocene climatic variation is about 3°C/km).

Jessop [1971] prepared a heat-flow correction contour map of Canada based on *Prest's* [1969] map of Wisconsin ice retreat and on *Emiliani's* [1961] glacial chronology. Over most of Canada, the magnitude of this generalized correction is less than 0.2 μcal/cm^2 sec (if a conductivity of 7.5 mcal/cm sec °C is assumed). This value is also in general agreement with Birch's conclusion about temperature gradient.

If the larger Pleistocene corrections that have been suggested are appropriate, heat flow from the Canadian shield and elsewhere might be significantly underestimated. As the actual surface temperature history is uncertain, it is worth considering whether the magnitude of the correction might be constrained by observations of second-order effects related to internal consistency of geothermal data. Two such effects to consider are (1) the variation in correction associated with rocks of contrasting conductivity in a limited region and (2) the variation in the correction with depth in a deep hole. Under very favorable circumstances, these variations might be measured and tested for consistency with predictions from competing climatic models. The first of these variations is difficult to apply. If the gradient correction were the same for a given climatic history, regardless of rock type, the correction to heat flow would be proportional to local conductivity. Such a model has been found to simplify regional heat-flow results in the Appalachians [*Urban and Diment*, 1971]. However, a uniform correction to neither heat flow nor gradient can be justified in a region of locally varying conductivity, and compensating effects relating to corresponding variations in diffusivity make these anomalies difficult to interpret in terms of climatic models. The second method is based on the observation that in the absence of transient disturbances (and departures from one-dimensional conductive heat flow), the heat flow measured in all depth intervals should be the same in a deep hole. If these interval heat flows can be measured with sufficient accuracy in a very deep hole, their limits of variation can significantly limit permissible climatic models and the magnitude of the climatic correction. In this paper we apply this approach to temperature and thermal-conductivity measurements to a depth of 2865 meters in a hole near Flin Flon, Manitoba.

The following symbols and units are used in this paper:

N number of thermal-conductivity samples.
K thermal conductivity, mcal/cm sec °C.
α thermal diffusivity, cm^2/sec.
q heat flow; 1 heat-flow unit (hfu) = 1 μcal/cm^2 sec.
A radioactive heat production; 1 heat-generation unit (hgu) = 10^{-13} cal/cm^3 sec.

The plus or minus sign refers to the standard error in all cases.

GEOLOGICAL SETTING

The borehole (hereafter referred to as DH-C) was drilled in Precambrian granitic rocks of the Canadian shield at 54°43′N, 101°58′W at a ground elevation of 336 meters above sea level. The general geology of the area has been summarized by *Froese* [1969] and is shown in Figure 1. The site is about 15 km north of the Coronation mine, where estimates of heat flow were made by *Beck* [1962] and *Beck and Neophytou* [1969].

The local geology around DH-C has been described by D. C. Findlay (unpublished data, 1966), and the following summary is based primarily on his report. The hole is in the Reynard Lake pluton, which has been dated by *Lowden et al.* [1963] at about 1700 m.y. The surface of the pluton varies in composition from quartz monzonite through mafic granodiorite to a contaminated border zone consisting mainly of quartz diorite. The pluton intrudes the Amisk group, a series of Precambrian metavolcanic rocks. Findlay also described the 13 cores and the drill cuttings from the hole. The rocks become more mafic with depth, varying from granodiorite near the surface to mafic quartz diorite in the lowermost kilometer.

MEASUREMENTS

Temperatures were measured with a thermistor thermometer connected to a lead-compensated Wheatstone bridge at the surface. The

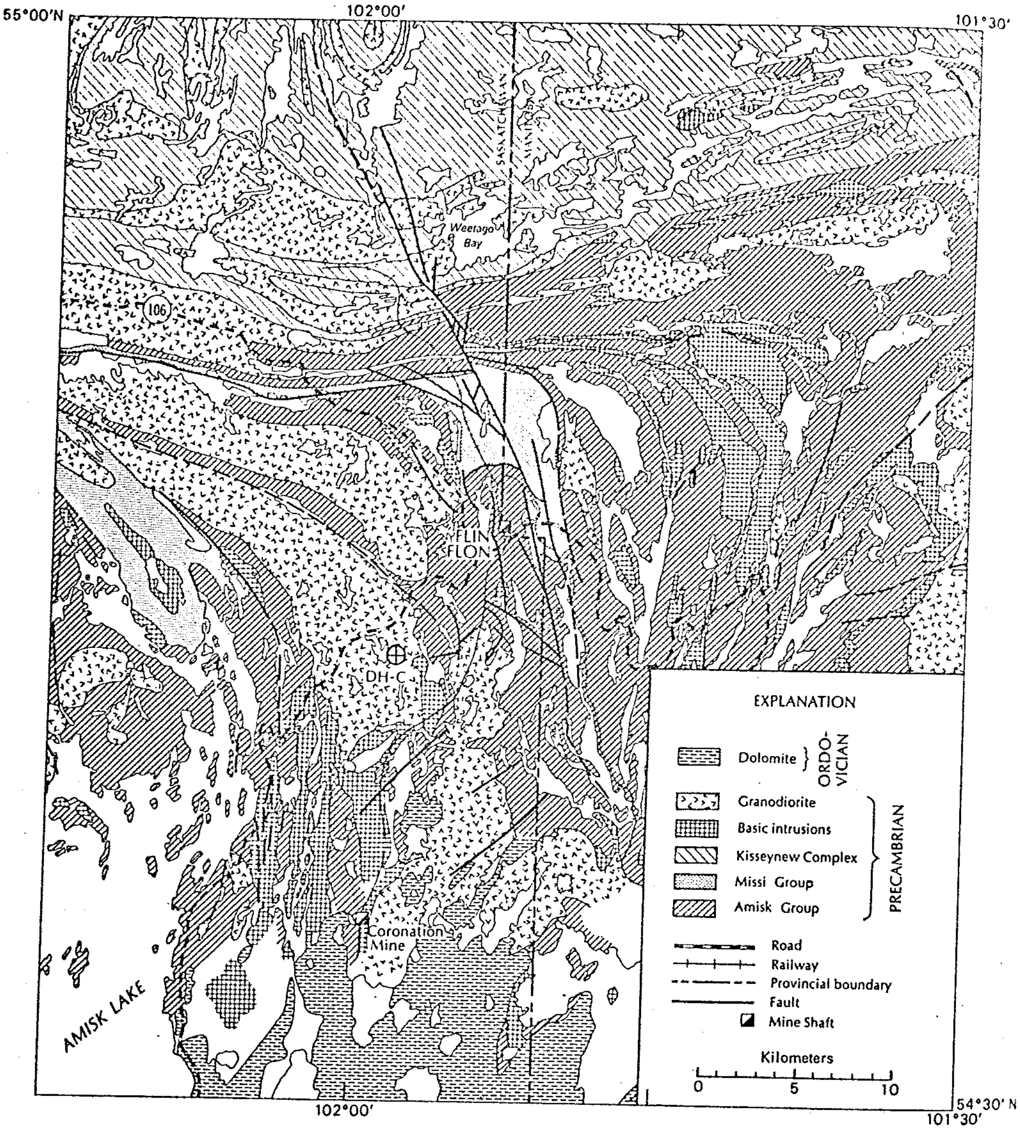
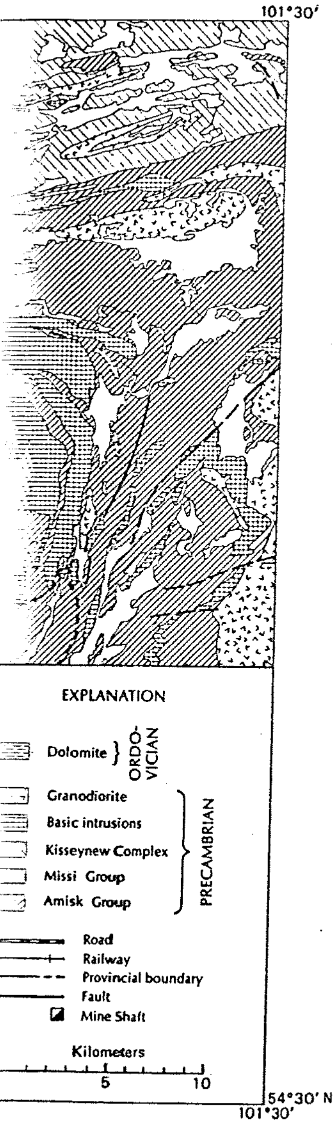


Fig. 1. Geology of the Flin Flon region (after *Froese* [1969]), showing the location of hole C and the Coronation mine.

configuration was the 'suitcase mode' described by *Sass et al.* [1971*b*]. The temperature measurement system is sensitive to changes of 10^{-4} °C, and temperature differences between successive measurement points were determined to ± 10^{-3} °C. The maximum error in absolute temperature is probably no greater than 0.2°C.

A steady-state divided-bar apparatus was used to measure thermal conductivity on 53 disks from 10 of the 13 cores recovered during drilling. The spacing of 250–300 meters between conductivity determinations on cores was judged inadequate. It was decreased to about 50 meters by measuring conductivities on crushed samples of drill cuttings and adjusting them to solid-rock values by a technique described by *Sass et al.* [1971*a*].

Both temperature and thermal conductivity are plotted as functions of depth in Figure 2. The average conductivity values for disk measurements are plotted as crosses, and individual measurements on chips are shown as solid



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chips are shown as solid circles. Measurements on pulverized core and on disks from the same depth are in good agreement [*Sass et al.*, 1971*a*], even though the disk determinations seem, in general, to yield higher conductivities than the determinations on cuttings. The descriptions of cores and cuttings (D. C. Findlay, unpublished data, 1966) suggest a sampling bias in the core toward rocks of high conductivity, rather than a systematic difference between the two measurement techniques.

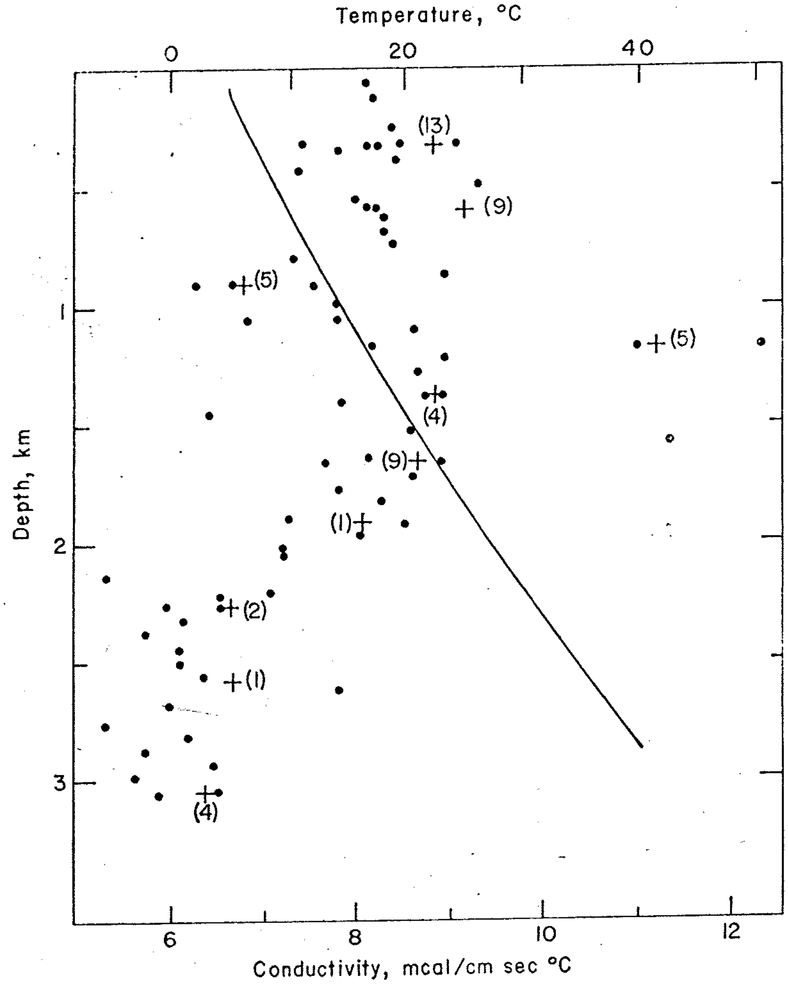

Fig. 2. Temperatures and thermal conductivities for DH-C. Temperatures are shown as a continuous curve. The average conductivity of each core is shown as a cross. The values in parentheses refer to the number of disks measured from each core. Conductivities of samples of drill cuttings are represented by solid circles.

Two sizes of disks were cut to test for evidence of a grain-size effect [e.g., *Birch and Clark*, 1940; *Beck and Beck*, 1958]. The mean K of 8.80 ± 0.28 mcal/cm sec °C for 26 disks about 1.2-cm thick agrees perfectly with that of 8.80 ± 0.38 mcal/cm sec °C for 22 2.5-cm thick disks. Since the latter disks were between 10 and 20 times the thickness of the average grain size, we can rule out any significant parallel component of heat conduction in these samples.

DH-C was completed on April 19, 1966, after a drilling period of 152 days, and the temperatures were measured in July 1968. With this time lapse between drilling and measurement, the disturbance to the temperature gradients should have subsided to a negligible level [e.g., *Lachenbruch and Brewer*, 1959].

HEAT FLOW

Examination of Figure 2 shows a systematic increase in temperature gradient with depth and corresponding systematic decrease in thermal conductivity. The latter is not surprising in view of the descriptions of cores and cutting by D. C. Findlay (unpublished data, 1966). Modal analyses of core samples show a progressive decrease in the proportions of quartz and K feldspars and an increase in plagioclase and biotite with depth. All these changes in proportions of constituent minerals result in decreased thermal conductivity.

The temperature gradients over 5 intervals of roughly 500 meters each were determined by linear least-squares fits to the measured temperatures. These gradients were combined with average conductivities over the same intervals to give independent estimates of heat flow. These data are summarized under the column headed q_1 in Table 1. Small corrections for in situ temperature were made to the conductivity measurements by using the temperature coefficients of conductivity determined by *Birch and Clark* [1940] for granitic rocks of similar mineralogy. Heat-flow values corrected for this effect are presented under q_2 in Table 1.

The mean of 155 determinations of heat production of systematically sampled drill cuttings is 2.11 ± 0.05 × 10^{-13} cal/cm^3 sec. (The heat-production values and their variation with depth were discussed by *Lachenbruch* [1971] and *Lachenbruch and Bunker* [1971].) The effect of this heat production on the component heat flows calls for an additional small correction which is included in the values listed under q_3 in Table 1. The mean of the 5 component heat flows is 1.01 ± 0.02 hfu. With this value of q and a mean heat production of 2.1 hgu, data for this station fall close to the heat flow–heat production curve determined by *Roy et al.* [1968] for the stable interior of the continent.

The discrepancy between the heat flow from DH-C and the mean value of 0.7 hfu adopted by *Beck and Neophytou* [1969] at the Coronation mine 15 km away deserves some discussion. The geologic structure at the mine is very complicated, and the conductivity sample there contained only 7 specimens, which showed a large range in values. The heat flow at DH-C lies within the possible range reported for the Coronation mine, and the gradients at the two sites are about the same. It is likely that the discrepancy in means results from problems in characterizing the conductivity at the mine. However, a real lateral gradient in heat flow of up to 0.3 hfu in 15 km is not out of the question, particulary in view of the fact that the near-surface rocks at the mine are mafic.

DISCUSSION

The most striking features of the 5 independent heat-flow determinations (Table 1) are their uniformity and their constancy with depth. A formal regression analysis of heat flow versus the midpoint of the depth interval results in a

TABLE 1. Heat-Flow Summary, Hole C, Flin Flon

Depth, meters	N*	Mean Conduct., mcal/cm sec °C		Temp. Grad., °C/km	Heat Flow,‡ μcal/cm^2 sec		
		Meas.	Corr.†		q_1	q_2	q_3
152–610	11	8.01 ± 0.34	8.24	11.79 ± 0.02	0.94 ± 0.04	0.97	0.98
610–1356	13	8.26 ± 0.34	8.41	11.44 ± 0.02	0.94 ± 0.04	0.96	0.98
1356–1920	14	8.38 ± 0.30	8.35	12.43 ± 0.03	1.04 ± 0.04	1.04	1.07
1920–2301	7	6.80 ± 0.32	6.78	14.21 ± 0.06	0.97 ± 0.05	0.96	1.01
2301–2865	11	6.17 ± 0.19	6.11	15.59 ± 0.02	0.96 ± 0.03	0.95	1.00

* Number of discrete depths at which thermal conductivities are measured. Several determinations at a given depth are averaged and counted as one value in the average for the interval.

† All measurements were made at about 25°C and were corrected to the ambient temperature by using the data of *Birch and Clark* [1940] for rocks of similar mineralogy.

‡ q_1 is the uncorrected heat flow; q_2 is the heat flow calculated by using the corrected thermal conductivity. q_3 is q_2 plus a correction for radioactive heat generation above the midpoint of the interval.

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	Heat Flow,‡ μcal/cm² sec		
	q_1	q_2	q_3
2	**0.94** ± 0.04	0.97	0.98
2	**0.94** ± 0.04	0.96	0.98
3	**1.04** ± 0.04	1.04	1.07
6	**0.97** ± 0.05	0.96	1.01
2	**0.96** ± 0.03	0.95	1.00

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coefficient of correlation of only 0.34 and a very small slope (0.01 ± 0.02 hfu/km.) This observation places severe constraints on the possible Pleistocene glaciation effects.

Figure 3 is based on a map by *Bryson et al.* [1969] showing the dates of retreat of the Laurentide ice. For this map, DH-C lies on the 8000-year isochrone.

Another recent map by *Prest* [1969] places the retreat at 10,500 years ago. Although the discrepancy in these dates does not seriously affect the calculations that follow, the fact that two authoritative presentations can differ so greatly emphasizes the uncertainty that still prevails about Pleistocene climatic history.

In Figure 4, we show two simple climatic models for the Flin Flon area. Model 1, the type of correction suggested by *Crain* [1968], is simply a 5°C step 10,000 years ago, the correction applied by *Beck and Neophytou* [1969] to their heat-flow estimate at the Coronation mine. Model 2 is similar to one of *Birch*'s [1948] more conservative models (model 2B, Table 4, p. 747). It differs from model 2B only in that the cooling during glacial periods is 3.5°C (equivalent to an ice-base temperature of 0°C) rather than 5°C.

Theoretical heat flows (normalized to 1 hfu for a K of 7 mcal/cm sec °C and $\alpha = 0.015$ cm^2/sec) are shown as functions of depth in

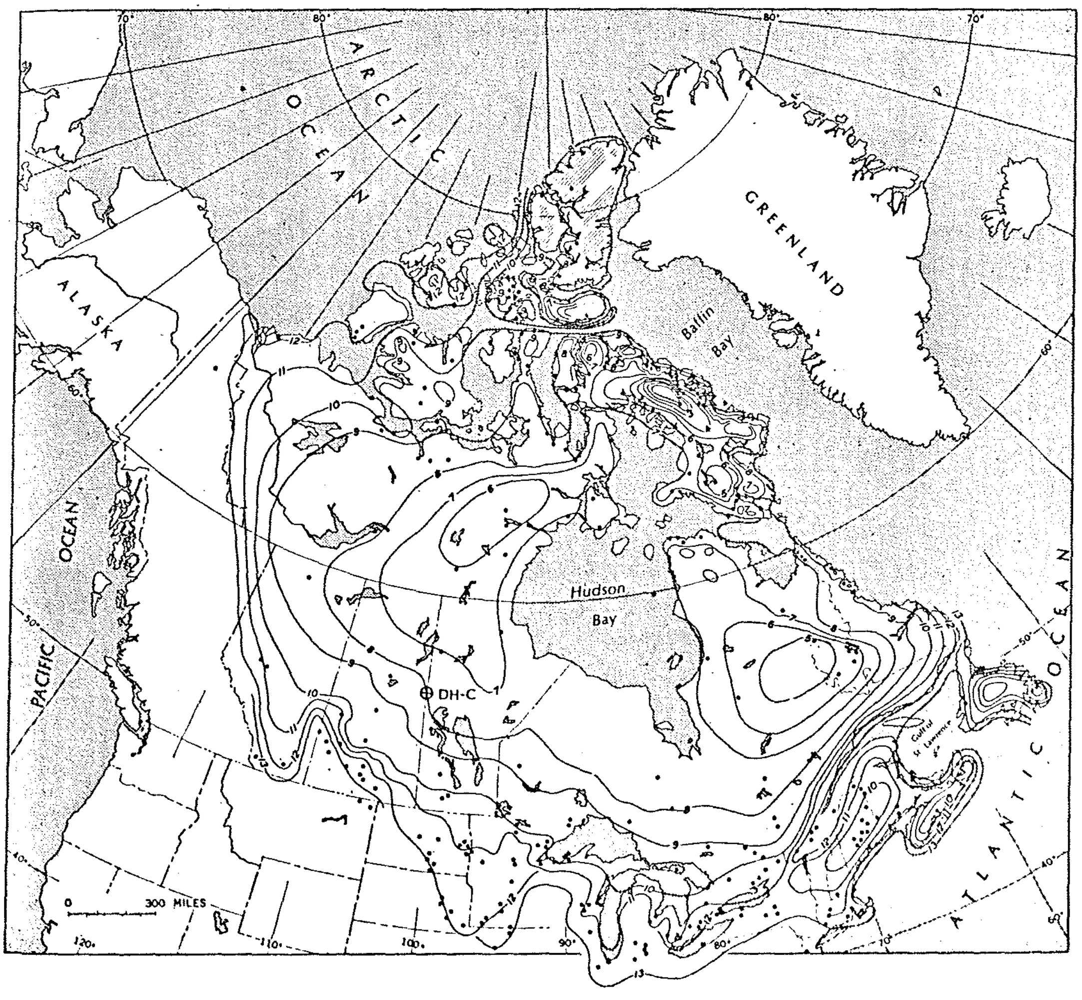


Fig. 3. Radiocarbon isochrones of the retreat of the Laurentide. Isochrone locations based on carbon 14 dates, coastline location, moraine orientation, and other field evidence (from *Bryson et al.* [1969, Figure 2]).

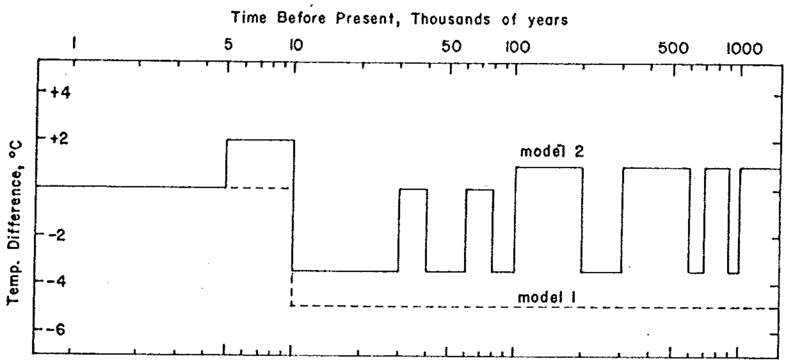


Fig. 4. Simplified models for the Quaternary climatic history of the Flin Flon area. Curve 1 refers to a 5°C increase in surface temperature 10,000 years ago. Curve 2 is based on model 2B of *Birch* [1948].

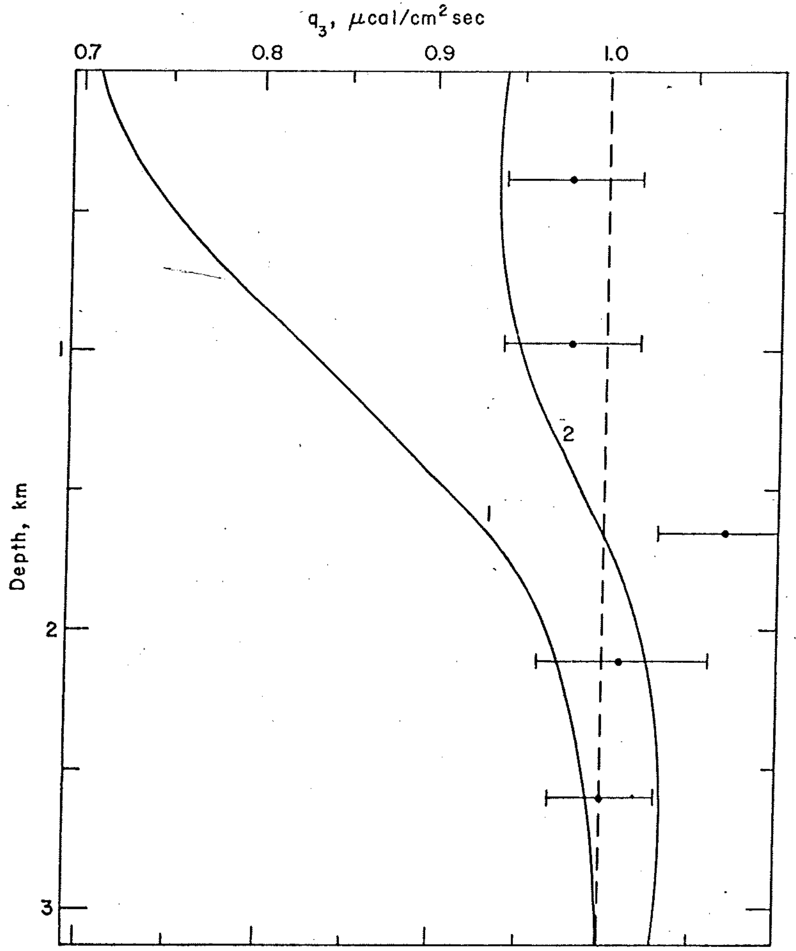
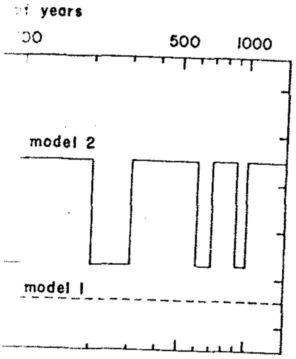


Fig. 5. Calculated heat flows (normalized to an equilibrium heat flux of 1 μcal/cm² sec with a conductivity of 7 mcal/cm sec °C and diffusivity of 0.015 cm²/sec) for the two models shown in Figure 4. The observed heat flows from DH-C are plotted (with bars representing the standard error of the determination) as a function of the mean depth of the interval over which the heat flow was calculated.



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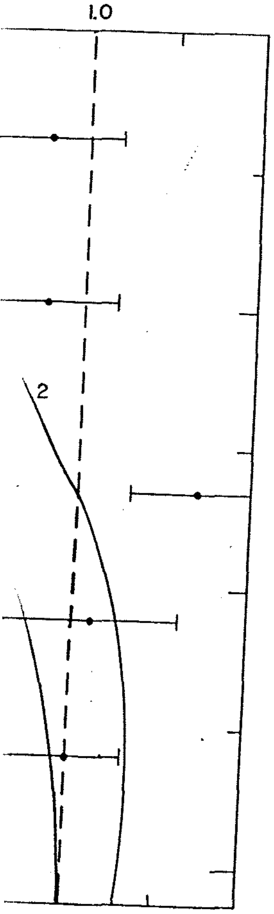

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Figure 5. Curves 1 and 2 refer to the corresponding models in Figure 4. The observed heat flows (q_3) are plotted as a function of the midpoint of the depth interval.

The simple step model is clearly inadequate to explain the observed heat flow. Had we applied model 1 to the upper 600 meters of DH-C, we would have predicted an equilibrium heat flow some 40% higher than the heat flow measured between 2301 and 2865 meters.

The variation with depth indicated by model 2 (Figure 5) can probably be considered to lie within the uncertainty of the present observations, as it is well within 2 standard errors of each of the 5 component heat flows. However, the data suggest that climatic histories leading to more extreme effects are highly improbable.

Another reduction method that should reveal systematic trends with depth is the resistance integral method first proposed by *Bullard* [1939]. This analysis was carried out over 100-meter intervals, most of which contained two determinations of conductivity. (Temperature values were obtained by linear interpolation between the adjacent points that bracketed the even 100-meter depths.)

If we assume a steady-state vertical one-dimensional conductive thermal regime, a plot of temperature as a function of integrated thermal resistance $\Sigma_i \Delta z_i/K_i$ (where Δz_i is the length of the ith depth interval, and K_i is the effective conductivity within that interval) should be a straight line whose slope is the heat flow q_2 [*Bullard*, 1939]. Thus deviations from linearity should indicate disturbances to the thermal regime.

The Bullard calculation gives the same heat flow (0.98) as the mean q_2 from Table 1. The effect of heat generation raises this flux to 1.01, as in the previous analysis. Examination of the detailed analysis (Table 2 and Figure 6) indicates a quasi-periodic deviation from linearity

TABLE 2. Bullard Calculation at 100-Meter Intervals, DH-C

Depth, meters	$\sum \Delta Z/K$, cm² sec °C/μcal	Temperature, °C Obs.	Calc.	(Obs. − Calc.)
100	1.20	4.77	4.39	+0.38
200	2.67	5.74	5.83	−0.09
300	3.82	6.96	6.96	0.0
400	4.99	8.14	8.11	+0.03
500	6.16	9.31	9.26	+0.05
600	7.31	10.43	10.39	+0.04
700	8.49	11.57	11.55	+0.02
800	9.73	12.68	12.77	−0.09
900	11.01	13.78	14.03	−0.25
1000	12.30	14.96	15.30	−0.34
1100	13.57	16.13	16.54	−0.41
1200	14.44	17.23	17.40	−0.17
1300	15.56	18.44	18.50	−0.06
1400	16.69	19.61	19.61	0.0
1500	18.09	20.82	20.99	−0.17
1600	19.09	22.02	21.97	+0.05
1700	20.29	23.27	23.15	+0.12
1800	21.51	24.56	24.35	+0.21
1900	22.80	25.81	25.62	+0.19
2000	24.03	27.18	26.83	+0.35
2100	25.42	28.55	28.19	+0.36
2200	27.05	29.99	29.79	+0.20
2300	28.61	31.49	31.33	+0.16
2400	30.31	33.01	33.00	+0.01
2500	31.97	34.54	34.63	−0.09
2600	33.54	36.11	36.17	−0.06
2700	35.00	37.69	37.61	+0.08
2800	36.90	39.25	39.48	−0.23
2865	38.01	40.28	40.57	−0.29

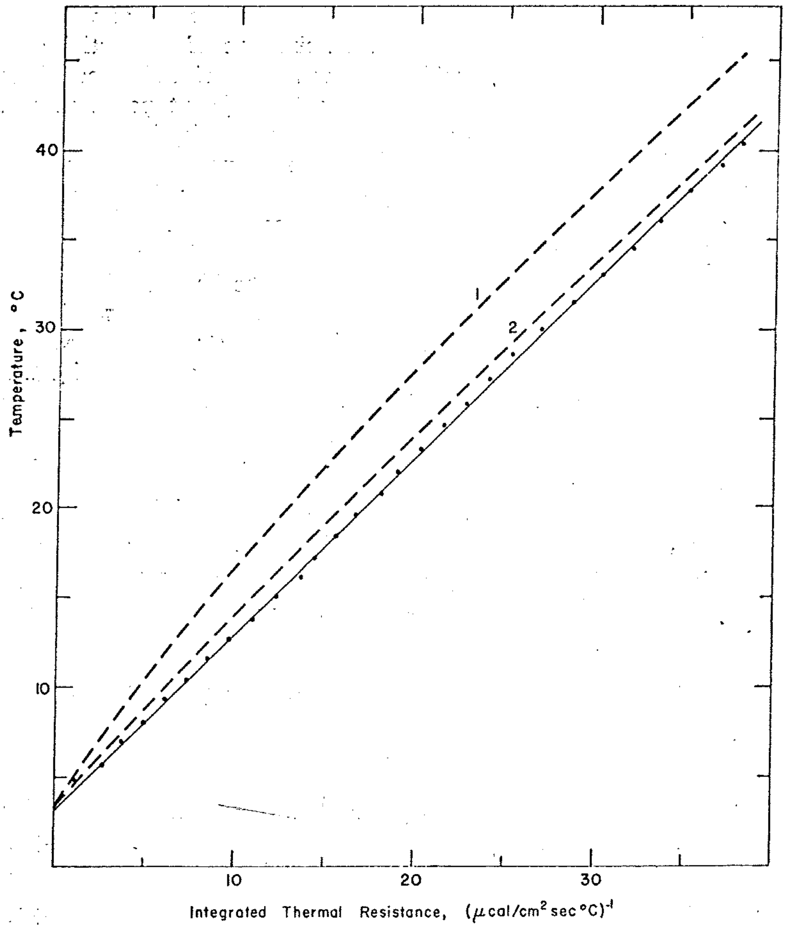
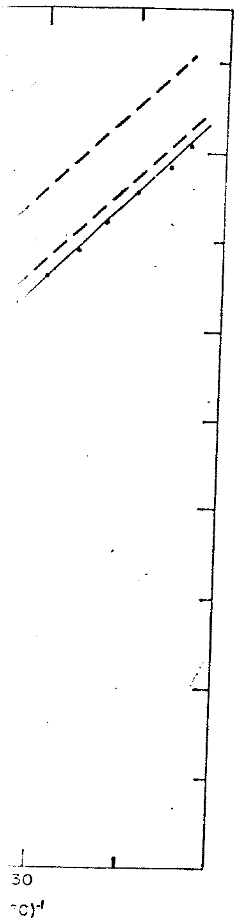


Fig. 6. Temperature versus integrated thermal resistance for DH-C. The solid line represents the least-squares linear fit to observed temperatures; the dashed lines indicate theoretical temperatures based on the observed surface heat flow and climatic models 1 and 2, Figure 4.

with amplitude of 0.4°C and wavelength on the order of a kilometer. By contrast, model 1 predicts a temperature disturbance increasing from zero at the surface to about +5°C at depth; model 2 predicts a maximum disturbance of +1.1°C at about 1.5 km. By adjusting the temperature intercept (Figure 6), a plausible fit of the temperature data to model 2 could be contrived, but because of the small amplitude of the observed temperature disturbance (some of which must be attributed to the scatter in conductivity), such an adjustment would be difficult to justify.

The extrapolated surface temperature of 3.5°C at DH-C is in reasonable agreement with that found for the Coronation mine by *Beck and Neophytou* [1969]. Temperatures in the upper 100 meters at both sites can be interpreted as indicating a temperature increase of 1° or 2°C during the past century [e.g., *Lachenbruch and Marshall*, 1969]. This increase, in turn, implies a present-day ground-surface temperature near +5°C. The mean annual air temperature in this region is about −1°C [*Thomas*, 1953, p. 31]. The difference of about 6°C between the two temperatures is consistent with the findings of *Brown* [1966] for areas of comparable seasonal snow cover.

Thus the value of 3.5°C used in the calculation for model 2 (Figure 4) represents a lower limit for the temperature depression that must have occurred at this site during much of the Quaternary period. However, calculations using this low value and a conservative climatic model



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predict disturbances that are, if anything, higher than those observed.

There are at least two possible explanations for the uniformity of heat flow with depth at DH-C:

1. The Pleistocene climatic effect near Flin Flon has been masked by some coincidental disturbance of comparable magnitude and opposite sign.
2. Generalized models commonly used to approximate Pleistocene climatic history are inadequate to describe the observed present-day temperature–depth distribution. (The local disagreement between *Prest* [1969] and *Bryson et al.* [1969] as to the time of glacial retreat lends support to this alternative.)

Whether one accepts explanation 1 or 2 or some other explanation for the apparently small residual climatic effect at DH-C, it seems clear that any estimate of the Pleistocene climatic effect is subject to considerable uncertainty. In the absence of an observed variation in heat flow with depth corresponding to a particular model, the 'correction' calculated from the model should be assigned an uncertainty, which, unfortunately, seems to approach the magnitude of the correction itself in the present state of knowledge.

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Publication authorized by the Director, U.S. Geological Survey.

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