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Five Measurements of Heat Flow in Southern Canada[1]

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Five heat flow results from widely separated locations are reported. The results conform to existing heat flow patterns where established, but only very general interpretative comments are possible.

Nous présentons les résultats de cinq mesures de flux thermique. Ces résultats révèlent des flux comparables à ceux qui ont déjà été établis mais leur interprétation ne peut donner lieu qu'à des commentaires généraux.

Terrestrial heat flow has been measured at five widely separated sites in southern Canada. Each site contains a single borehole only, four of which are of approximately 600 m depth, and the other is of 400 m depth. At least three years were allowed for return to equilibrium temperatures in the boreholes. Methods of measurement have been described previously (Jessop 1968), and only variations from routine methods will be mentioned. It might justifiably be argued that all borehole sites have their own individual peculiarities, and that routine measurement of heat flow does not exist. For those interested in the peculiarities of each measurement and the detailed method of measurement and analysis, this information will appear elsewhere.

The locations of the sites are shown in Fig. 1, and the results are given in the top part of Table 1. More detailed data are shown in Table 2.

Oldham

The Oldham borehole was made available for heat flow measurement by the Nova Scotia Department of Mines. The rocks penetrated were quartzites and slates of the pre-Carboniferous Meguma shelf of Nova Scotia. The rocks gave very good conductivity results in the divided bar, the variations between individual discs from any single sample being very low. There was a marked difference between the conductivities of the slates and of the quartzites, and any sampling bias was corrected by means of a series model based on the core log of Townsend and Grimm 1964.

Temperature, conductivities, and heat flow are shown in Fig. 2. The heat flow is shown in

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TABLE 1. Collected results

	Position		Measured (μcal/cm²s)	Corrected for glaciation (μcal/cm²s)	Measured (mW/m²)	Corrected (mW/m²)
	N	W				
Oldham	44°55.4′	63°28.8′	1.35 ± 3%	1.61 ± 4%	57	67
Kelly Cross	46°15.9′	63°26.7′	0.88 ± 2%	1.07 ± 4%	37	45
Ottawa	45°23.7′	75°42.9′	0.80 ± 4%	1.01 ± 5%	33	42
Winnipeg	49°48.7′	97°07.9′	0.70 ± 10%	0.91 ± 10%	29	38
Penticton	49°19.8′	119°37.6′	1.60 ± 8%	1.86 ± 8%	67	79
Halifax	44°38.3′	63°35.5′	1.18 ± 5%	1.41 ± 6%	49	59
Franktown	45°00.5′	76°03.6′	0.99 ± 12%	1.22 ± 12%	41	51
Nielsen I.	55°23.7′	77°41.0′	0.59 ± 5%	0.61 ± 5%	25	26

TABLE 2. Details of measurements

	Collar elevation *m*	Interval of measurement *m*	Conductivity (mcal/cm s°C)		Temperature Gradient (°C/km)		
			No.	Mean	No.	Mean	Corrected
Oldham	117	95–650	31	10.65	26	13.0	
Kelly Cross	52	210–400	36	5.64	11	15.8	
Ottawa	84	330–630	47	5.67	29	14.2	
Winnipeg	232	205–650	56	6.49	20	10.9	
Penticton	552	170–660	118	4.66	53	37.5	34.7

three forms: the measured heat flow calculated in sections, the heat flow corrected for sample bias, and the heat flow corrected for glacial disturbance by means of the model described by Jessop (1971), extended to include variation with depth. The correction for sample bias smooths the heat flow vs. depth profile, but leaves some scatter which might be removed by more closely spaced sampling. The glacial disturbance correction increases the heat flow but reduces the trend of increasing heat flow with depth, which justifies the correction. The scatter in the results prevents any detailed analysis with a view to deriving a climatic model from the measurements. The mean heat flow is 1.35 μcal/cm² s, and the standard deviation of the section results is 3 %, which becomes 1.61 μcal/cm² s ± 4 % when corrected for glaciation.

FIG. 1. Locations of measurement sites. 1. Oldham, N.S. 2. Kelly Cross, P.E.I. 3. Ottawa, Ontario. 4. Winnipeg, Man. 5. Penticton, B.C.

Kelly Cross

The Kelly Cross borehole was drilled by the Geological Survey of Canada as a structure test. The rocks penetrated consisted of a series of alternating sandstones, shales, and claystones of Permian age (Howie 1969). Since the rocks had a significant porosity, conductivity measurements of dry rocks were not representative of the true conductivity in the natural condition. Some of the samples, particularly the claystones, could not be soaked in water, owing to a tendency to swell and disintegrate. It was found that all samples could be soaked in a light oil without damage, and conductivities were measured in this condition. A correction was made to account for the difference in conductivity between oil and water. Some of the sandstones could be soaked in water, and these samples were remeasured in the water-saturated condition, giving a check on the correction for fluid conductivity.

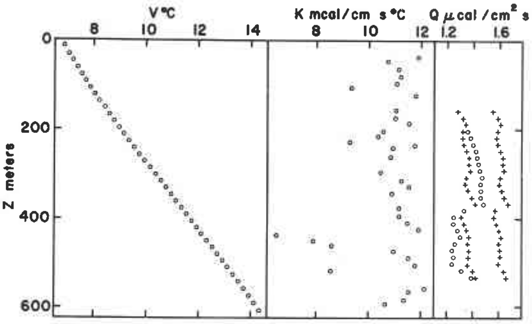

FIG. 2. Temperature, conductivity, and heat flow data from Oldham. Circles denote measured data and uncorrected heat flow, crosses denote heat flow corrected for sample bias and glaciation.

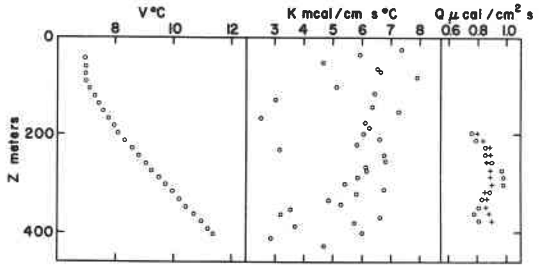

FIG. 3. Temperature, conductivity, and heat flow data from Kelly Cross. Circles denote measured data and uncorrected heat flow, crosses denote heat flow corrected for sample bias.

Temperature, conductivity, and heat flow are shown in Fig. 3. There is considerable scatter in the conductivity, owing to the mixture of rock type, and this is reflected in the heat flow results calculated by normal sectional analysis. A heat flow profile with less scatter has been obtained by separating the rock into sandy and shaley components in each section. The two fractions were credited with the average conductivity for the appropriate rock types, and the overall conductivity of the sections were calculated by means of a series model. In the depth range 244–401 m, both methods give an average heat flow of 0.88 μcal/cm^2 s and the second method gives a standard deviation of 2 %.

Above 200 m in depth heat flow is disturbed. This is believed to be due to ground-water movement and possibly to water temperature changes due to recent climatic changes. P. Carr (1969) cites evidence for ground-water movement to depths of about 150 m on Prince Edward Island. In particular, the region above 100 m depth has a uniform temperature, probably caused by rapid water movement around the hole. Owing to these disturbances, it is not clear what surface or temperature should be used in calculating a glacial correction, but a reasonable compromise yields a correction of 0.19 μcal/cm^2 s $\pm$ 20 %, giving a total heat flow of 1.07 μcal/cm^2 s $\pm$ 4 %.

Wright and Garland (1968) obtained a conductivity measurement of 9.75 mcal/cm s °C, by means of a down-hole heater method, at a depth of 115 m. The closest specimen measured on the divided bar gave a result of 6.43 mcal/cm s °C, and no specimen from the core showed a conductivity higher than 8.0 mcal/cm s °C. Wright and Garland's measurement was made in the zone of suspected water disturbance, and the result is consistent with a small water movement.

Ottawa

The Ottawa borehole was drilled at the Dominion Observatory site, and penetrated 14 m of overburden, 220 m of Ordovician sediments, about 100 m of Precambrian schists and weathered gneisses, and gneisses of the Precambrian Shield to a total depth of 602 m. Small temperature fluctuations in time in the upper 200 m indicated water movement in the sediments. Rocks between the depth of 240 m and 300 m were very fragile and porous, and reliable conductivity measurements were not easily obtained. Because of these difficulties, only results from below 300 m depth have been used in the calculation of heat flow. Results are shown in Fig. 4. The heat flow is 0.80 μcal/cm^2 s $\pm$ 4 %. The glacial correction

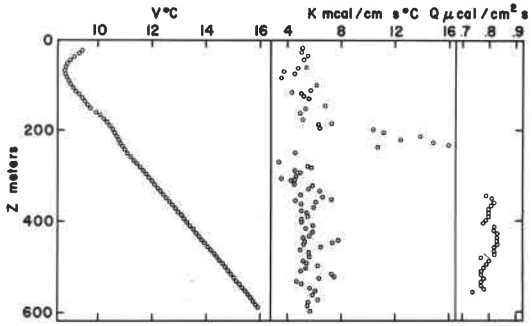

FIG. 4. Temperature, conductivity, and heat flow data from Ottawa.

is 0.21 μcal/cm^2 s $\pm$ 20 %, giving a total heat flow of 1.01 μcal/cm^2 s $\pm$ 5 %.

Winnipeg

The Winnipeg borehole was drilled on the campus of the University of Manitoba by the Dominion Observatory. The rocks penetrated were 18 m of overburden, 115 m of Red River limestone, 57 m of Winnipeg sand, and 420 m of Precambrian gneisses. It was clear from the temperature profile and from the nature of the rocks penetrated that only the part of the hole in Precambrian rock would yield reliable temperature and measurable conductivity, and all heat flow calculations have been restricted to this part, which lies below a depth of 190 m.

Results are shown in Fig. 5. The average heat flow is 0.70 μcal/cm^2 s $\pm$ 5 %. The heat flow is not randomly scattered, but shows a smooth variation from 0.74 μcal/cm^2 s at 260 m to 0.64 μcal/cm^2 s at 540 m. The reason for this variation is not known with certainty, but is believed to be connected with water movement in the loose sand of the Winnipeg formation. Variations of water temperature in the sand, due to climatic change at the surface or due to changes in flow direction, could have caused a non-equilibrium heat flow condition. No adjustments can be made to the result, since any assumptions of water movement changes are only speculations. A heat flow value of 0.70 μcal/cm^2 s has been adopted and instead of using the standard deviation of 5 %, an error limit has been arbitrarily set at 10 %. A glacial correction for an uncomplicated hole

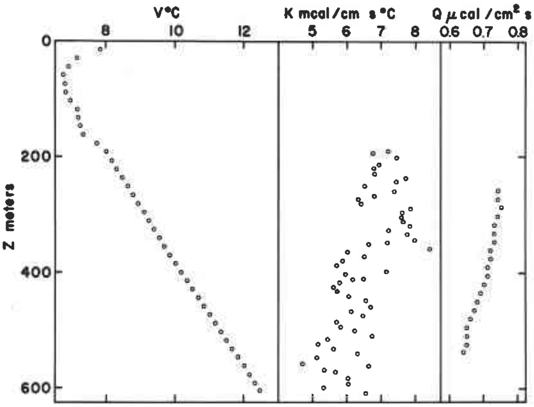

FIG. 5. Temperature, conductivity, and heat flow data from Winnipeg.

in this location, which was submerged beneath Lake Agassiz for a time, is 0.21 μcal/cm^2 s $\pm$ 20 %, giving a total heat flow of 0.91 μcal/cm^2 s $\pm$ 10 %.

Penticton

The Penticton borehole is on the site of the Dominion Radio Astrophysical Observatory. The site is in a valley, with topographic relief of about 800 m within 4 km, and measured temperatures have been corrected for the effects of proximity to elevated land by the method of Jeffreys (1937), giving a reduction in gradient of 7.5 %. The rocks penetrated were tuffs, graywackes, and shales of the White Lake formation to 597 m, and lava of the Marron formation in the lower 14 m.

Owing to the large number of thin rock units in the core, a large number of conductivity measurements were necessary. Every third sample was measured as a set of four discs, and the remainder were measured as single discs, all discs being soaked in water.

Results are shown in Fig. 6, and temperature and heat flow are shown both uncorrected and corrected for topography. There is a great deal of scatter in the heat flow results, particularly around 270 m, where the nature of the peak suggests a small groundwater effect. Below 300 m the heat flow seems to follow the conductivity sampling despite the large number of specimens measured. The average heat flow when corrected for topographic effects is 1.60 μcal/cm^2 s $\pm$ 8 %. A correction for Pleistocene glaciation adds a further 0.26 μcal/cm^2 s $\pm$ 20 % to give a heat flow of 1.86 μcal/cm^2 s $\pm$ 8 %.

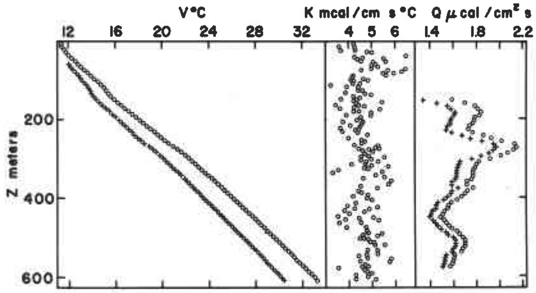

FIG. 6. Temperature, conductivity, and heat flow data from Penticton. Circles denote measured data and uncorrected heat flow, crosses denote temperature and heat flow corrected for topographic distortion.

Discussion of Results

It has been suggested that low values of heat flow may be caused by the measurement of conductivity of low-porosity rocks in an unsaturated state (Walsh and Decker 1966). In the current work, all rocks with significant porosity were measured in a saturated state, but the others were not saturated. Porosity of a random selection from the gneisses of Ottawa and Winnipeg was measured and the greatest porosity found was 0.25 %. The effect on the average conductivity is not likely to exceed 3 % at Winnipeg and $1\frac{1}{2}$ % at Ottawa, and no correction has been made for these small effects.

Since the five measurement sites are so widely separated, it is impossible to draw detailed conclusions from the results, but two of the sites are close to results published previously (Jessop 1968). In the previous work, the glacial corrections were based on a slightly different model, and for the purpose of comparison these corrections have been recalculated to conform with the model used in the present calculations. The recalculated results are shown in the lower part of Table 1. Unfortunately, no data are available concerning heat production by radioactive decay.

The Oldham site is only 33 km north of Halifax, but the heat flow is higher at Oldham by 14 %, which is within the range of significance. The geological environments are similar, but the Oldham site is further inland, so that a thickening, and consequently higher heat production of the crust is a possible explanation. The Kelly Cross site is a further 150 km north of Oldham and is in a sedimentary basin of younger rocks. The heat flow at Kelly Cross is only two-thirds of the flow at Oldham, a difference that cannot be explained on the basis of crustal thickness, since the crust is probably slightly thicker under Prince Edward Island than it is under the Atlantic Coast of Nova Scotia. (Dainty *et al.* 1966.)

The Ottawa site is 50 km northeast of Franktown, where the heat flow is 21 % higher, but owing to uncertainties in the Franktown measurement, the significant difference is much less. The holes are in similar environments, both being in Precambrian rock with a thin cover of Paleozoic sediments, and the lower than average heat flows are normal for the Grenville Province of the Shield. The Winnipeg site is in a similar situation near the exposed edge of the Superior Province of the shield. The heat flow is slightly lower than at Ottawa and Franktown.

The Penticton site is in the interior plateau of British Columbia. There are no other completed Canadian measurements with which to compare it, but there are measurements in the northern U.S.A., where there is a similar value 150 km to the south–southeast, a low value 240 km to the southwest, and several higher values to the southeast (Roy *et al.* 1968, Blackwell 1969). These other measurements have not been corrected for glacial disturbance, and so comparisons are with the uncorrected Penticton figure. Penticton lies within the western side of the northward continuation of Blackwell's (1969) "Cordilleran thermal anomaly zone", and the result is consistent with that concept.

Acknowledgments

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