Analysis of Heat-Flow Data—Several Boreholes in a Sedimentary Basin

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For the Western Ontario and Michigan basins, which overlie the Grenville and Central geological provinces, temperature gradients in more than 30 boreholes and thermal conductivities of several hundred specimens from several formations have been determined. It is found that characteristic gradients and conductivities can be assigned to certain formations and to geological periods. There may also be a real variation ($<20\%$) of heat flow between some formations, which is qualitatively correlated with variations in heat producing elements.

With the exception of one value of 1.3 μcal cm^{-2}s^{-1}, which involved extrapolation of data to a great distance, all 'whole borehole' heat-flow values, uncorrected for glaciation effects, lie between 1.0 ± 0.2 μcal cm^{-2}s^{-1}; a correction for the Wisconsin stage of the Pleistocene glaciation would increase these values by 0.3 ± 0.1 μcal cm^{-2}s^{-1}.

On a effectué des gradients de température dans plus de 30 sondages et des conductivités thermales de plusieurs centaines d'échantillons de diverses formations des bassins de l'ouest de l'Ontario et du Michigan. Ces bassins recouvrent les provinces géologiques centrale et grenvillienne. Des gradients et des conductivités caractéristiques peuvent être attribués à certaines formations et périodes géologiques. Il peut se produire aussi une variation réelle ($<20\%$) du flux de chaleur entre certaines formations, ce qu'on attribue à des variations d'éléments qui produisent de la chaleur.

A L'exception d'une donnée de 1.3 μcal cm^{-2} s^{-1} qui comportait une extrapolation de valeurs à une grande distance, toutes les données globales de flux de chaleur, non corrigées pour les effets de la glaciation, donnent des valeurs de 1.0 ± 0.2 μcal cm^{-2} s^{-1}; la correction pour l'étage Wisconsin de la glaciation du Pléistocène augmenterait ces valeurs de 0.3 ± 0.1 μcal cm^{-2} s^{-1}.

[Traduit par le journal]

Introduction

Sedimentary basins cover some 40% of the earth's emergent land surface. The genesis of basins and their persistence are problems which are almost certainly related to the thermal regime of the earth and the solutions may be aided by heat-flow measurements over a wide area; in addition, to obtain a reasonable spatial coverage of heat-flow values for the general global problem, many more values from basin areas are required.

This paper describes the results of a comprehensive series of measurements in several boreholes drilled in the sedimentary basin covering southern Ontario and the southern peninsula of Michigan (Judge 1972); it forms part of a larger project, briefly described by Beck and Judge (1969), to investigate many of the problematical areas in the measurement and interpretation of terrestrial heat flow.

The types of problems likely to be encountered in determining reliable temperature gradients and thermal conductivities have been described in many places in the literature (*e.g.* Beck 1965). The sedimentary basin in which this work was carried out is one with fairly simple structure on the gross scale and of sufficient economic importance that several hundred holes have been drilled in the area. However, because of strict conservation regulations, very few of the holes are available for temperature gradient measurements, although many unreliable (Anglin and Beck 1965; Judge 1972) bottom hole temperatures have been determined; even fewer holes are completely cored and in only one case in southwest Ontario, a specially drilled hole, was such a hole used for temperature gradient measurement.

In these circumstances it is clear that if one of the desired quantities, thermal conductivity and temperature gradient, can be predicted fairly reliably for a given formation, then the possibility of measuring only the other quantity could yield valuable heat-flow data. In some boreholes it is possible to measure both temperature gradient and thermal conductivity, but

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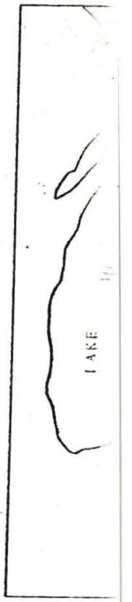

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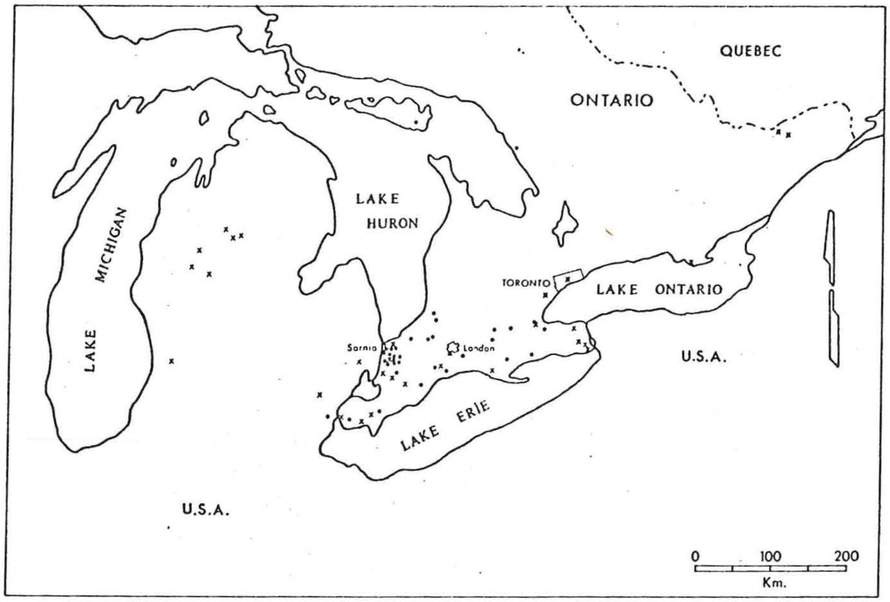

FIG. 1. Approximate location of boreholes used. Dot represents a hole from which core was available, not necessarily from all formations penetrated. Cross represents a hole in which temperature gradients were measured.

only in one formation that happens to have been cored; thus it would be useful to try to relate heat-flow values with specific formations as well.

Our principal objectives were therefore to investigate (1) the spatial variation of heat flow in the basin; (2) whether the thermal conductivity, and other physical properties, for particular formations are sufficiently constant over a wide area, or vary systematically with geographical location, depth, or facies, such that an estimate of formation conductivity can be used with gradient measurements to obtain reliable heat-flow values; (3) whether temperature gradients could be similarly categorized so that they could be used to give useful heat-flow values when only core samples are available from given formations or groups; (4) whether there was a heat-flow variation with depth which could be associated with particular formations.

Most, but not all, of the objectives were met.

Borehole Location

While there was no lack of boreholes in terms of numbers, about two thirds of them were blocked and there was little choice in their geographic location. Therefore areas in which we would have liked to obtain information presently remain blank; furthermore, in only one hole in which temperature measurements were made was the complete core available. Apart from this there were 31 other holes available for temperature gradient determinations, of which 25 are based on our own temperature measurements and 6 on industrial temperature logs. Complete cores were available and used from 9 boreholes other than the London hole, and partial cores from a further 50 holes. Temperature and conductivity values determined by other groups were available from 4 more holes in the immediate region (Leney 1956; Misener *et al.* 1951; Jessop 1968; Jessop and Judge 1971). The locations of these holes are shown in Fig. 1, but on the scale used some of the holes overlap; Table 1 gives more details. Where possible and useful, temperature and thermal conductivity from holes outside the main area have been used to fill in the gaps.

Geology of the Area

The southwestern Ontario sedimentary basin forms part of the flanks of both the Appalachian and Michigan Basins (see Fig. 2). Important factors in the deposition of the sedimentary strata have been the two major tectonic features of the basement, the Algonquin

TABLE 1. Boreholes used

	Hole		Heat[3] flow	County	Township	Lot No.	Concession No.	Elev. (m)	Total depth (m)	Coordinates				Fig. 3[4]
	Starts in[1]	Ends in[2]								Lat.		Long.		
										deg.	min.	deg.	min.	
(a) For temperature gradient measurements														
G.S.C. #1 (Picton	Trenton	Precamb	0.9	PCE	ATL	27	1	84	299	43	52	77	14	D
G.S.C. #2 (Russell)	Queenston	Cambrian	1.2	RSL	RSL	24	2	82	753	45	19	75	24	D
M & M—C. Lyons #1	Meaford	Precamb	1.1	PEL	CGC	14	6W	250	710	43	40	79	52	G
Birchfield Oil & Gas #1	Guelph	Precamb	0.9	WLG	PLC	30	7	314	1768	43	27	80	07	G
Consumers Gas #14	Bass Isl.	Cambrian	1.1	WCD	BRT	6	15NR	192	792	42	51	79	05	I
Consumers Gas #466	Bass Isl.	Cambrian	1.1	WLD	BRT	32	BF	188	731	42	56	79	06	I
Consumers Gas #648	Bass Isl.	Cambrian	1.2	WLD	CRD	11	5	200	792	42	59	79	11	I
Consumers Gas #1158	Queenston	Cambrian	1.0	LCL	LTH	4	3	92	792	43	09	79	17	I
J. Brown	Dundee	Trenton	0.9	NFK	SWG	5	B	184	433	42	36	80	31	J
Dom. Obs.-U.W.O. #4	Dundee	Meaford	0.9	MDX	LND	16	3	248	591	43	01	81	16	J
Bluewater IOE. Dunwich 7	Dundee	Cambrian	0.9	ELG	DNC	17	1	214	1000	42	44	81	33	J
Riddell-Hanna-Ewing #4A	Hamilton	Guelph	0.9	KNT	CTM	11	13	177	427	42	34	82	16	C
Imperial East Becher #2	Hamilton	Guelph	1.0	LMB	SBR	20	6	183	579	42	40	82	16	C
Imperial Bickford #16	Hamilton	Guelph	1.0	LMB	SBR	5	11	185	640	42	43	82	25	C
Imperial Kimball #5	Hamilton	Guelph	0.9	LMB	MRE	15	4	191	640	42	50	82	22	C
Dow Farm #13	[5]		—	LMB	SRN	DOW REF		187	488	42	56	82	26	C
Dow Farm #14	[5]		—	LMB	SRN	DOW REF		187	488	42	56	82	26	C
IHS Colchester S #1	[6]		—	ESX	CCS	79	1	182	604	42	01	82	58	A
O.K. West—Gosfield N. #2	Dundee	Trenton	1.0	ESX	GFN	13	9	191	762	42	09	82	44	A
Imp. Calvan Malden #75	Detroit R.	Cambrian	1.2	ESX	MLD	25	3	186	945	42	06	83	01	A
Imp. Calvan Malden #25	Detroit R.	Trenton	1.2	ESX	MLD	25	3	180	792	42	06	83	01	A
Northville #106	Antrim	Trenton	1.2	WSH	SLM	1-15-7E		322	1006	42	26	83	34	D
Muttonville—C. Fawver #2	Antrim	Guelph	0.8	MCB	LNX	13-4N-14E		219	768	43	48	82	44	D
Overisel #150	Coldwater	Guelph	0.9	ALL	OVR	7-4N-14W		217	853	42	44	86	00	B
Overisel #157	Coldwater	Guelph	0.9	ALL	OVR	13-4N-14W		233	823	42	44	86	00	B
Overisel #162	Coldwater	Guelph	0.9	ALL	OVR	28-4N-14W		219	823	42	44	86	00	B
Billingsly #1	Kimmeridgian	Marshall	1.0[7]	NWG	GDW	8-14N-11W		351	305	43	32	85	36	H
Austin Marsh #1	Kimmeridgian	Marshall	1.2[7]	MEC	AHB	23-14N-9W		337	411	43	32	85	16	H
E. Bragg #2	Saginaw	Detroit R.	1.2[7]	OSC	RCH	5-17N-10W		359	1006	43	50	85	35	H
Marion #172	Saginaw	Marshall	1.1[7]	MSK	RCL	24-21N-8W		411	457	44	12	85	11	F
Marion #829	Saginaw	Marshall	1.2[7]	MSK	CLM	23-21N-6W		376	518	44	09	85	00	F
Marion #805	Saginaw	Marshall	1.3[7]	OSC	MAR	28-20N-7W		410	457	44	04	85	05	F

Austin-Marek #1	Kimmeridgian	Marshall	1.2	MLC	ABS	23-14N-9W	337	411	43	32	85	16	H
E. Bregg #2	Saginaw	Detroit R.	1.2[7]	OSC	RCH	5-17N-10W	359	1006	43	50	85	35	H
Marion #192	Saginaw	Marshall	1.1[7]	MSK	RCL	24-21N-8W	411	457	44	12	85	11	F
Marion #829	Saginaw	Marshall	1.2[7]	MSK	CLM	23-21N-6W	376	518	44	09	85	00	F
Marion #965	Saginaw	Marshall	1.3[7]	OSC	MAR	28-20N-7W	410	457	44	04	85	05	F

TABLE 1. *(Concluded)*

	Hole									Coordinates			
										Lat.		Long.	
	Starts in[1]	Ends in[2]	Heat[3] flow	County	Township	Lot. No.	Concession No.	Elev. (m)	Total depth (m)	deg.	min.	deg.	min
(b) With complete cores used for conductivity determinations[8]													
G.S.C. #1	Trenton	Precamb	0.9	PCE	ATL	27	1	84	299	43	52	77	14
G.S.C. #2	Queenston	Cambrian	1.2	RSL	RSL	24	2	82	753	45	19	75	24
U.S. Steel	Delaware	Cambrian	1.0	NFK	CTL	21	1	215	1711	42	44	80	19
Dom. Obs.—U.W.O. #4	Delaware	Queenston	0.9	MDX	LDN	16	3	248	591	43	01	81	16
Midrim # 3A	Hamilton	Salina A2	0.8	MDX	ADD	9	2NER	230	535	43	01	81	44
Midrim #4	Hamilton	Guelph	1.0	MDX	ADD	10	3NER	230	576	43	02	81	43
Imp. MacGillivray #5-19	Delaware	Guelph	0.9	MDX	MGL	5	19	217	562	43	14	81	37
Imp. Plympton #1-3	Hamilton	Salina A2	0.8	LMB	PLM	1	3	197	673	42	57	82	14
Imp. Enniskillen #20-5	Hamilton	Salina A2	0.8	LMB	ENN	20	5	202	560	42	49	82	06
Argor #1	Pt. Lambton	Guelph	1.0	LMB	MRE	28	2	182	736	42	47	82	26

[1] Does not include drift, which in places exceeds 100 m thickness; in many areas the bedrock is also weathered.
[2] In many cases the hole penetrates only a few feet of the lowest formation.
[3] Heat flow, in μcal $cm^{-2}s^{-1}$, obtained by procedures described in this paper.
[4] Letter refers to figure in which the temperature-depth plot appears.
[5] Data not used because of recorded fluid motion disturbing the temperatures.
[6] Data not used because of suspected fluid motion probably associated with proximity to Lake Erie.
[7] These heat-flow values are probably less reliable than the others—see discussion.
[8] There were numerous other holes from which partial cores were available, usually along very small sections.

Arch with a southwest dip of approximately 6.5 m/km, and the Finlay Arch. These arches seem to have acted as hinges in the basin movement. Between them is a depression known as the Chatham Sag, which is faulted at its northern end against the Algonquin Arch. This may explain the apparent independent movement of the two arches.

The basement is composed of metamorphosed sedimentary rocks of the Grenville Series and is similar in nature to the rocks exposed on the emergent Precambrian Shield in the northern counties of southern Ontario (Stockwell 1965). Overlying this is a sedimentary sequence ranging in age from Late Cambrian to probable Mississippian. The sequence is divided into approximately 30 formations, composed mostly of limestones, dolostones, and shales, ranging in thickness from 1.5 to 460 m. In the eastern area these sediments reach a total thickness of 610 m around Toronto and progressively thicken to 1525 m near Sarnia and beneath Lake Erie with a dip of about 2°. Farther to the west and south of the central parts of the sedimentary basin, the thicknesses reach 4500 m. The sedimentary sequence in Michigan is similar to that of southwestern Ontario, but includes post-Mississippian formations.

The Michigan Basin is roughly circular in shape, with sediment thicknesses ranging from 1200 to 4500 m over the region considered in this work. Data from the very few holes that penetrate to the Precambrian basement indicate that it is probably divided into Grenville and Central Province Series, the Grenville Front striking N.E. to S.W. through the city of Flint (McLauglin 1954; Nwachukwu *et al.* 1965).

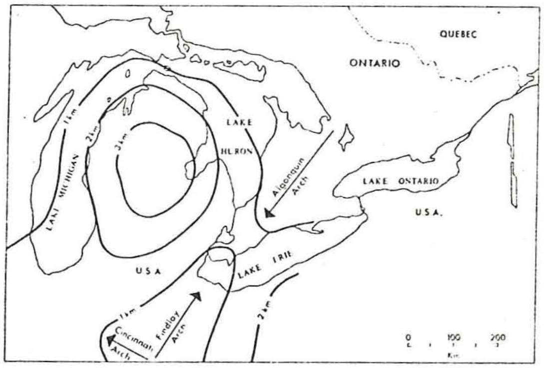

FIG. 2. Depth to Precambrian basement and general structure in the Great Lakes area.

Oil and gas occur in large quantities in southwestern Ontario and are recovered from most of the Paleozoic formations. The Devonian reservoirs are mostly related to the underlying slump structures; the Middle Silurian reservoirs are bioherms and reef structures, except in the Niagara gas fields, whereas the Middle Ordovician production is from dolomitized fracture zones. Salt is also of commercial importance in the area, where it is found in sub-units of the Silurian Salina Formation with thicknesses of up to 215 m. Oil and gas production is also important in Michigan with production horizons, including some of the Mississippian and post-Mississippian formations not found in southwestern Ontario.

Since reservoir material and salt units may have significantly different thermal conductivities from adjacent strata the effect of this relatively small scale structure and thermal conductivity contrast on the heat-flow values has been allowed for where possible and necessary (Judge 1972).

The entire area was covered by the Pleistocene ice sheets, the onset and retreat of which can have a significant effect on sub-surface temperature gradients, and the necessary corrections are discussed as appropriate.

Measurement of Temperature

This work was started in 1963, a time when improvements were being made to both the field and laboratory instrumentation; different sets of temperature-measuring equipment have therefore been used, but most of them conformed with the general three or four lead-compensated design (Beck 1963). This equipment, with calibration against a good platinum resistance thermometer, probably gives temperatures accurate to 0.003 °C. However, because of other experimental errors that creep in, such as depth measurement errors, possible convective overturn in large diameter boreholes, etc., the stated temperature at any given depth might be in error by as much as 0.03 °C but most values would be accurate to within 0.01 °C or better. The temperatures, but not necessarily the gradients, obtained from industrial logs may have much larger errors; in the only case, Birchfield O & G #1, where we were able to check the

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data, a systematic difference of 0.25 °C was found, but the temperature gradients were not significantly different. The error in a measured temperature gradient depends on the depth interval over which it is computed and on the conductivity of the surrounding strata.

The upper levels of some holes were dry, the worst example being that of Birchfield O & G #1, which was cased, and dry, to 533 m; data from the dry portion of a hole have not been used. In many sections some formations are either absent, or too thin to give a useful temperature gradient.

Since one of our objectives was to see if a temperature gradient, and conductivity, could be assigned to a given formation, and because the temperature gradient in a single borehole may change by a factor of three or four between formations, we do not give the mean temperature gradient for a borehole; rather we show the complete temperature depth plots for each hole in Fig. 3, the mean heat flow for each hole in Table 1, and in Table 2 we give temperature gradients by formation indicating the number of holes from which the mean gradient for the formation has been calculated and the maximum distance between any two of the holes in the group. In no case is the gradient calculated over a section length that is less than 30 m, commencing at a depth of not less than 100 m and in which not less than three temperature measurements have been made. For those formations in which data were collected over a wide area, no systematic variation with geographic location could be detected.

Although some of the coefficients of variation are as high as 25%, with most in the range of 8 to 16%, it is clear that a characteristic temperature gradient can be assigned to some formations. Furthermore, close to the boundary of a geological period there is a marked change in gradient; in some places this change occurs between the lowest formation of one period and the upper formation of the next, and in other places it appears to be displaced up or down by one formation. This led to an attempt to correlate the gradients with geological series, and recomputed means for these are shown in Table 2. Here again the information indicates that characteristic gradients may be associated with a series. Taking the process one stage further by obtaining means for geological periods, the data indicate that it may be possible to associate characteristic temperature gradients with geological periods as well.

These data have been used in an attempt, Table 3, to rate the reliability of using a characteristic formation gradient to estimate a heat-flow value when bore core is available for conductivity measurements, but the borehole has been blocked; the terms used in the table are explained in the next section.

Since the basic assumption in terrestrial heat-flow work is the constancy of equilibrium heat flow with depth, then clearly the changes in gradients should be accompanied by a corresponding change in thermal conductivity. That this is usually so can be seen in Table 2, although the 'compensation' is not always exact and, unfortunately, not all formations in which temperature measurements were made could be sampled for conductivity measurements.

Thermal Conductivity

For reasons given in the previous section, conductivity measurements were made on a variety of apparatuses. However, all were of the general type described by Beck (1957) with constant end temperatures maintained to within ±0.01 °C by water baths or solid-state heaters and coolers.

Numerous checks on accuracy were made during the work, and the conductivity of individual disks should be accurate to within 2% relative to the Ratcliffe (1959) values for quartz and silica. The principal source of error in assigning a conductivity value to a particular formation or portion of a formation is the usual one associated with adequate sampling of material. One approach to this problem, which can be taken when the complete borehole core is available, was discussed by Beck and Judge (1969).

The type of problem that is encountered is best illustrated by a brief discussion of one of the experiments carried out on the Detroit River Formation, which proved to be one of the formations showing the largest conductivity variations throughout its thickness; the reasons for these variations were not always obvious to the naked eye. A set of 10 contiguous disks, each 1 cm thick, was cut from one core section, together with a second set cut from a similar section offset 30 cm from the original one. The

TABLE 2. Summary of heat-flow data using means for formations, series, and periods

Period	Series	Formation or Group	Formation or Group data														Series means			Period means		
			Gradient (°C/km)						Conductivity													
			Min.	Max.	Mean	Var. (%)	N	Dist. (km)	Min.	Max.	Mean	Var. (%)	N	Dist. (km)	Rock type	H.F.	Grad.	K	H.F.	Grad.	K	H.F.
J		Red Beds	18.7	21.7	20.2	—	2	100									20.2			20.2		
CARB	Pottsville	Saginaw	18.7	25.6	22.3	13	6	100														
	Meramecian	Michigan	18.4	28.9	24.4	13	6	100									24.0			24.0		
	Kinderhookian	Coldwater	20.3	38.0	25.9	28	4	200														
DEVONIAN	Chatauquan	Antrim	26.9	49.2	34.4	24	5	300														
		Hamilton							5.1	6.2	5.7	—	2	100	Sh-L							
	Erian	Traverse	10.2	21.0	14.8	26	5	300														
		Delaware (Dundee)							6.4	7.4	7.2	4	9	200	L		14.8	6.9	1.0	15.9	7.6	1.2
	Ulsterian	Detroit River	7.5	11.5	8.9	18	7	300	7.2	9.4	9.0	12	3	100	D, L	0.8	9.2	8.8	0.8			
		Sylvania	8.1	9.9	9.3	9	3	100														
		Bois Blanc	8.5	10.5	9.7	9	3	100	7.8	9.1	8.5	6	3	100	Ch-L	0.8						
SILURIAN	Cayugan	Bass Island	5.9	12.8	8.9	25	10	400	8.7	13.3	10.7	13	8	200	D	1.0	9.0	10.2	0.9			
		*Salina (upper)	7.9	13.1	9.0	16	12	500	6.5	14.5	9.7	22	7	80	Sh-D	0.9						
	Niagaran	Salina (evap)	6.2	9.2	7.5	16	5	150	6.8	12.0	8.9	20	9	80	L-D	0.7	7.1	9.7	0.7	9.0	9.8	0.9
		Guelph-Lockport	4.9	7.5	6.6	17	4	200	8.1	14.8	10.7	9	8	200	D, L	0.7						
	Alexandrian	Clinton-Cataract	17.0	17.7	17.3	—	2	100	4.9	9.3	7.3	25	3	100	Sh, Ss D	1.3	17.3	7.3	1.3			
ORDO	Cincinnatian	Queenston	15.7	20.7	18.0	11	5	300	—	—	5.3	—	1	—	Sh	1.0	26.8	5.4	1.4			
		Meaford-Dundas	19.7	31.5	26.1	14	7	300	—	—	6.0	—	2	100	Si, Sh-L	1.6						
		Collingwood	30.0	45.0	36.7	12	5	600	—	—	4.4	—	1	—	Sh	1.6				23.3	5.8	1.4
	Mohawkian	Trenton-Black R.	14.8	24.6	18.4	14	12	700	5.0	6.7	6.1	10	6	600	L, Sh-L	1.1	18.4	6.1	1.1			
Ꞓ	St. Croixian	Trempealeau			8.5	—	1	—	11.0	12.1	11.3	4	3	300	Ss	1.0	8.5	11.3	1.0	8.5	11.3	1.0
Pє	Grenville		12.8	15.4	14.1	8	3	400	6.8	7.5	7.1	2	11	200	Gn	1.0	14.1	7.1	1.0	14.1	7.1	1.0

Ch — Chert
D — Dolostones
Gn — Gneisses
L — Limestones
Sh — Shales
Si — Siltstones
Ss — Sandstones
* — Very complex
N = Number of holes
Var = Coeff. of variation
Dist = Maximum distance between holes
K = Thermal conductivity in mcal cm^{-1}s^{-1} °C^{-1}
Grad = Temperature gradient in °C km^{-1}
H.F. = Heat flow in μcal cm^{-2}s^{-1}

TABLE 3. Estimates of reliability of formation conductivities and gradients

Formation	Main rock types	Mean Conductivity mcal cm^{-1} s^{-1} °C^{-1}	Reliability	Mean gradient °C km^{-1}	Reliability
Red Beds	Shales, sandstones			20.2	Fair
Saginaw	Sandstones, shales			22.3	Fair
Michigan	Sandstones, shales			24.4	Fair
Coldwater	Shales, siltstones			25.9	Poor
Hamilton	Shales, limestones	5.7	Fair	—	—
Antrim	Shales			34.4	Poor
Traverse	Dolostones, limestones			14.8	Poor
Delaware	Limestones	7.2	Good	—	—
Detroit River	Dolostones, limestones	9.0	Good	8.9	Fair
Sylvania	Sandstones, dolostones			9.3	Fair
Bois Blanc	Cherty limestones	8.5	Good	9.7	Good
Bass Island	Dolostones	10.7	Good	8.9	Poor
Salina	Very complex	9.3	Poor	8.8	Poor
Guelph-Lockport	Dolostones, limestones	10.7	Fair	6.6	Fair
Clinton-Cataract	Mixed	7.3	Poor	17.3	Fair
Queenston	Red shales	5.3	Fair	18.0	Good
Meaford-Dundas	Mixed	6.0	Poor	26.1	Fair
Collingwood	Shales	4.4	Poor	36.7	Good
Trenton-Black River	Limestones, shales	6.1	Good	18.4	Fair
Eau Claire	Sandstones	11.3	Good	8.5	Poor
Grenville	Gneisses	7.1	Good	14.1	Good

measured conductivities of individual disks in each section varied by up to 50%, but the means for the sets were 7.8 for set 1 and 7.9 mcal cm^{-1}s^{-1} °C^{-1} for set 2, each set having a coefficient of variation of 13%.

In many of the sections variations of conductivity could be correlated with changes in core seen with the unaided eye or with the aid of easily performed staining techniques. For instance, the red and gray-green shales in the Queenston Formation have significantly different thermal conductivities, but the two can readily be distinguished by eye and hence appropriate weighting factors given to each section without detailed conductivity measurements (Johnson 1968).

In general we believe that our sampling technique, together with a geological log and a reasonably careful selection of cores based on visual observations of core variations, gives errors that are no greater than 10% for the mean conductivity of a section, and that in most cases these are probably better than 5%.

Because the number of holes available for temperature measurements far exceeds those in which the complete core is available, we have attempted to determine whether the formation conductivities are relatively uniform or vary systematically in space, or whether they are simply highly variable and therefore unreliable.

The mean conductivity values for each formation are shown in Table 2, the same table in which the temperature gradients are given. Similarly, mean conductivities are shown for the series and periods.

In Table 3 we list the formations again, with comments as to whether temperature measurements in the formations would give a useful heat-flow value in the absence of core samples from the same area. Where a formation has been classified as 'good' it indicates that the formation occurs in reasonable thicknesses over a wide area and that the thermal conductivity has been found to be either reasonably constant or that sufficient data have been accumulated on systematic spatial variations that corrections can be applied with some confidence. Where a formation is classified as 'fair' it has either been found to be less widely distributed in reasonably thick sections than the 'good' formations or/and the thermal conductivity data indicate a reasonable constancy of thermal conductivity, but are insufficient to make a positive statement; further work will be required on these. Where a formation is classified as 'poor' either it occurs in such short sections in many areas

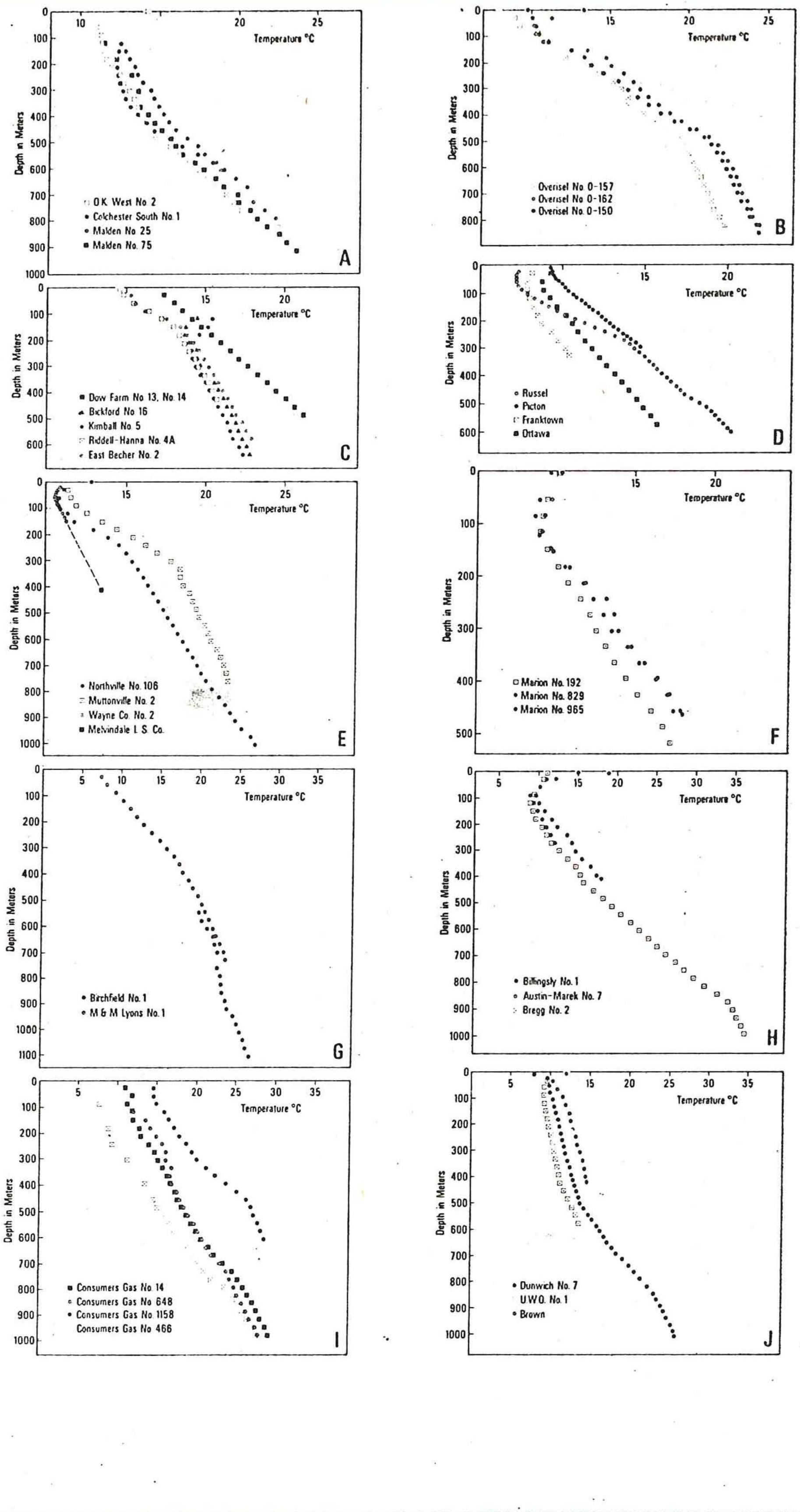

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TABLE 4. Derivatio
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(a) Bass Island Form

Borehole
U.W.O.—Dom. Obs.
Enniskillen #20-5
Plympton #1-3
MacGillivray #5-19
Midrim #3A
Midrim #4
Argor #1
U.S. Steel
Wayne Co. (Leney 19
Mean for all holes

(b) Trenton–Black Ri

Borehole
Colchester-2
U.S. Steel
C.N.E. (Misener *et al.* 1951)
Russell—GSC #2
Ottawa—Dom. Obs.
Picton—GSC #1
Mean for all holes

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that it is not useful, or the thermal conductivity data indicate that this property varies widely and it would therefore be unreliable as a base on which to produce a heat-flow value; in some cases these variations can be attributed to specific mixes of, for example, dolostone and shale, and further work is in progress to determine whether a reliable correlation can be made between the variation in the mixes and the variation of thermal conductivity.

It is emphasized that the mean conductivities shown are the average values obtained from the means of the number of boreholes indicated in Table 2. For instance, the means for the Bass Island Formation are shown in Table 4*a*, from which the mean value from 9 holes is found to be 10.7; similar data are given for the Trenton–Black River conductivities in Table 4*b*, which exhibited a systematic spatial variation.

TABLE 4. Derivation of formation mean conductivity (mcal cm^{-1}s^{-1} °C^{-1}) for use in Table 2

(a) Bass Island Formation

Borehole	Conductivity	Coeff. of variation (%)
U.W.O.—Dom. Obs. #4	10.0	25
Enniskillen #20-5	9.9	5
Plympton #1-3	11.5	—
MacGillivray #5-19	9.7	—
Midrim #3A	10.0	10
Midrim #4	13.3	11
Argor #1	12.4	10
U.S. Steel	8.7	18
Wayne Co. (Leney 1956)	11.1	—
Mean for all holes	10.7	5

(b) Trenton–Black River Group

Borehole	Conductivity	Coeff. of variation (%)	Position
Colchester-2	6.7	10	S.W.
U.S. Steel	6.4	9	↓
C.N.E. (Misener *et al.* 1951)	6.1	13	
Russell—GSC #2	6.6	9	
Ottawa—Dom. Obs. #1	5.8	10	
Picton—GSC #1	5.0	10	N.E.
Mean for all holes	6.1	10	

The Trenton–Black River Group was the only one where there were a sufficient number of samples over a wide enough area to establish what appeared to be a systematic spatial variation of conductivity in the group. The group consists of limestones, shaly limestones, and dolostones, with the thermal conductivity decreasing from Colchester in the southwest to Picton in the northeast, the decrease being attributed to an increasing shaliness of the cores in the same direction. The occurrence of dolostones in the samples obtained was limited to some of the Colchester holes.

It is possible to divide both the Trenton and the Black River Formations into a number of units. There is some evidence, from one hole only, that the Trenton may have a more uniform and 15% lower conductivity than the Black River Formation, the lower conductivity being attributed to the increased shaliness of the Trenton limestones compared with the dolomitic limestones of the Black River. However, on a regional basis it is felt that there are so few samples in some of the units that results beyond a Trenton–Black River grouping are not reliable.

Heat-Flow Values

The temperature gradients and thermal conductivities in each borehole have been combined to give the heat-flow values in Table 1. The relatively uniform heat flow for the whole area is obvious from Fig. 4, which also includes some previously published results in the same general region for comparison. None of the data has been corrected for the effects of Pleistocene glaciation. Such corrections would increase the heat-flow values by about 30% depending upon which theory of the onset and retreat is believed and, more importantly, on the change of surface temperature that occurs during these onsets and retreats (Beck and Judge 1969). However, since the Pleistocene history of the whole area is, in general, a common factor for all of the boreholes, the appli-

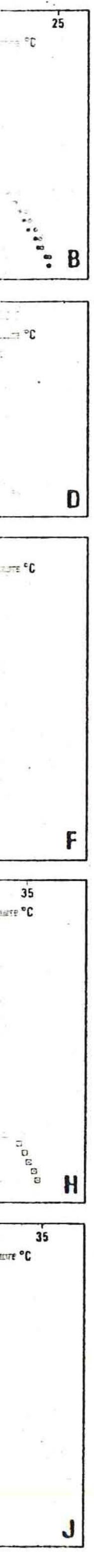

FIG. 3. Temperature-depth plots; holes are divided into groups for clarity of presentation (see also Table 1). 3D—Franktown from Jessop (1968), Ottawa from Jessop and Judge (1971); 3E—Wayne Co. No. 2 from Leney (1956), Melvindale from industrial measurements in a nearby salt mine.

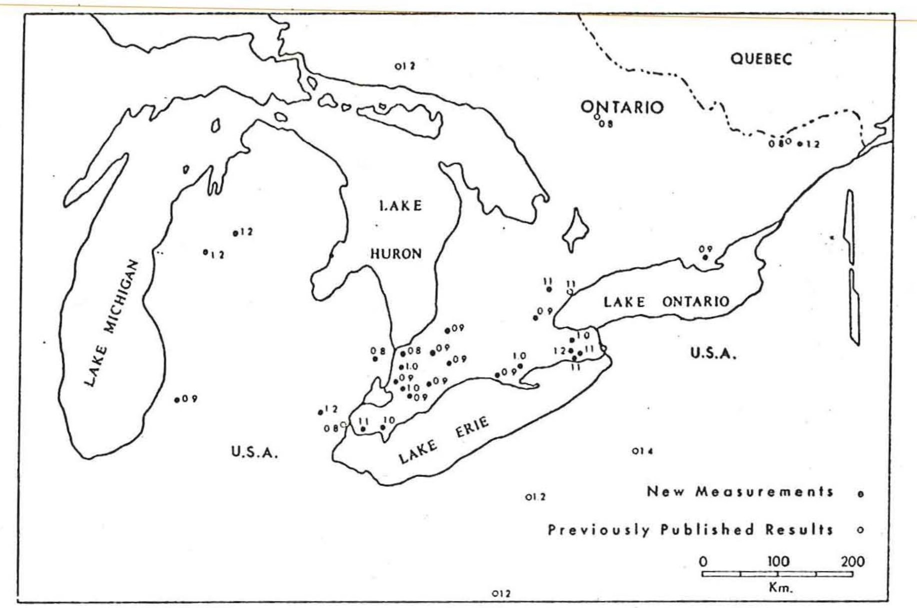

FIG. 4. Heat-flow values (in microcalories cm^{-2}s^{-1}) in the field area. None of the values has been corrected for effects of onset and retreat of ice sheets. Some holes are too close together to be separable on this scale; in such cases the mean of the group is shown. For reasons given in the discussion only the mean values are shown for the two groups of holes in northern Michigan.

cation of such a correction would simply raise all heat-flow values by roughly the same amount in formations of the same lithology.

Therefore, the general picture of a relatively uniform terrestrial heat flow over the whole of the basin area will hold whether or not the Pleistocene correction is applied. There might well be minor variations from one borehole to the next, particularly if the overall effects of the Pleistocene glaciation vary slightly because of variations in borehole depths (Crain 1968) or lithology for which there is some but no conclusive evidence.

Such uniformity over a large area is rather gratifying in view of the fact that in another and far smaller region, but admittedly structurally complex, variations of nearly 100% have been found (Mustonen and Beck 1967).

Table 2 shows the heat-flow values that result from combining the mean gradients and conductivities for formations, series, and periods. The series and period mean gradients and conductivities were obtained by combining the formation means weighted according to the number of boreholes used; if the data are combined giving each formation mean a weight of one, the only change in heat-flow value is that of the Cincinnatian, which decreases to 1.4 from 1.5 μcal cm^{-2}s^{-1}.

Because of insufficient thermal conductivity data for some of the formations it is not possible, at a significant level, to correlate a specific heat-flow value with a particular formation or series. However, the heat-flow value in the middle Devonian to middle Silurian formations does appear to be significantly lower than that in the adjacent Ordovician formations.

These differences are not attributed to the period as such, but to the predominance of low conductivity shales in one span of geological time; therefore a formation or series in a particular epoch or period may contain a significantly higher proportion of shale than a neighboring formation or series. Because of the nature of these measurements, and the wide area over which they were made, the association of high heat flows with low conductivity shales cannot be due to structural refraction, as sug-

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TABLE 5.

Combs and Simmons (1973)		This work	
Marion	1.10 (972)	Marion	1.2 (192, 829, 965)
Northville	1.39 (N-203)	Northville	1.2 (106)
Burnips	1.07 (S-503-E)	Overisel	0.9 (150, 157, 162)

gested by Horai and Nur (1970); the explanation may be similar to another of their suggestions and is discussed in the next section.

Discussion

The validity of our approach is confirmed by both internal and external evidence.

The internal evidence comes from detailed temperature and thermal conductivity measurements in holes U.W.O. #1 (London), G.S.C. #1 (Picton), and G.S.C. #2 (Russell), the work on the latter two holes being completed after the data collection for this paper. The heat-flow values obtained from analysis of the detailed observations are 0.8 μcal cm^{-2}s^{-1} for the London hole (Beck and Judge 1969), 1.3 for the Russell hole, and 1.0 for the Picton hole (A. M. Jessop, private communication, 1972) compared with the figures for the present work of 0.9, 1.2, and 0.9 respectively.

The external evidence comes from recently published values of Combs and Simmons (1973); their paper, received after completion of our original manuscript, includes three results from the Michigan Basin, all in regions close to some of ours. They were fortunate to find holes with at least some core available for conductivity measurements, whereas our heat-flow values (Fig. 4) were obtained by extrapolating the conductivity values in particular formations from S.W. Ontario into the Michigan Basin. Details of the geology of each area are given in Judge (1972).

The two sets of values are compared in Table 5, the figure in brackets being the borehole number in which temperature gradients were measured.

The closeness of the heat-flow values at Marion may be fortuitous, since the values from Marion #192, #829, and #965, together with those from Billingsley #1, Austen-Marek #1, and E. Bregg #2 are probably less reliable than our other values.

Useful temperature gradients in these six holes could only be obtained in formations that were not encountered elsewhere in southern Ontario. However, the holes at Overisel and Northville passed through some of the same formations and also through formations that were encountered in southern Ontario; the mean heat flow for these two regions was used to infer conductivities for the formations intersected commonly in these areas and in northern Michigan. These conductivities were then used to obtain the heat-flow values shown in Table 1 but, because of the uncertainties involved in such extreme extrapolations, only the mean heat-flow value for each area is shown in Fig. 4.

The mean of all heat-flow values shown in Table 1 is 1.01 μcal cm^{-2}s^{-1}, with a coefficient of variation of 14%. A histogram of the values, Fig. 5, suggests that the distribution may be bimodal, with modes at 0.9 and 1.2. The concentration of higher values from the six northern Michigan holes contributes significantly to the higher mode; if the six values from these holes are omitted the mean changes to 0.98 with a coefficient of variation of 13%. These means may be compared with the mean of 0.9 ob-

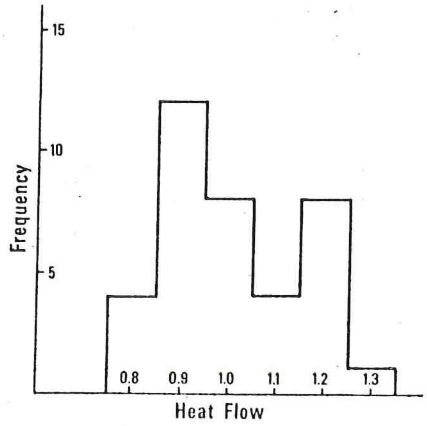

FIG. 5. Histogram of heat-flow values (in microcalories cm^{-2}s^{-1}) obtained in this work.

tained from published values for the exposed shield around the basin.

Although the heat flow over the whole area is fairly uniform, some formations have characteristic temperature gradients and thermal conductivities, the product of which gives heat-flow values significantly higher than adjacent formations; the formations having the higher heat-flow values also have a higher proportion of low conductivity shales.

The regional nature of the measurements eliminates the possibility that the differences are caused by refraction due to conductivity differences between structural units. The possibility that the differences are due to systematically high conductivity values determined in the laboratory can also be eliminated. In sampling the cores we selected representative material and not just that which was most competent. If the conductivity values of the more fragile material are incorrect, the laboratory value would be lower than the *in situ* value, since the layered structure of a shale sample would cause it to expand when pressure is removed; this is supported by laboratory and *in situ* measurements of the Queenston shales (Beck *et al.* 1971) where the *in situ* values were found to be slightly, but not significantly, higher than the laboratory values.

The basin is composed largely of shales, limestones, dolostones, and sandstones. Of these the shales usually contain much more K, Th, and U than the other rocks. The higher heat flows are therefore associated with larger quantities of heat-producing elements (Beck 1970; Hamza and Beck 1971) and the low conductivity of shales is presumably related to the way potassium is located in the lattice of the clay minerals. Unfortunately, the heat flow – heat production relationship is not an obvious one, since the variations in the abundances of the heat-producing elements are too small to account directly for the change in heat flow (Hamza 1973). The higher heat flows in the shaly formations are therefore only partly attributed to higher heat production at this stage. It is possible that an exothermic geochemical process contributes to the higher heat flow of these formations.

Whatever the cause of the apparently high heat flows in the shaly formations, it seems clear that even where it is possible to make detailed conductivity measurements on core from a borehole in which temperature measurements have been made, to confine these measurements to only one formation may give a heat-flow value that is not representative of the whole section. If the formation used is composed mainly of shales while the whole section is dominantly limestone or dolostone, the heat-flow value will be too high, and if the formation is mainly dolostone or limestone while the section as a whole is composed of shales, the heat-flow value may be too low.

Summary

Detailed measurements in sedimentary sections have shown that some formations have predictable thermal conductivities or temperature gradients over several thousand square kilometers; when only one of these parameters can be measured in a borehole within the study area, use of the predicted value of the other parameter can give a useful heat-flow value with an error estimated to be less than 20%, and possibly as small as 10% when there is sufficient control.

Use of this approach indicates that the heat flow over the whole of the Western Ontario and Michigan basins is relatively uniform, the mean being 1.01 μcal cm^{-2}s^{-1}, with a coefficient of variation of 14%.

It has also been found that there is a high probability that shale formations will give higher heat-flow values than dolostone or limestone formations.

Acknowledgments

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