

Heat flow in the western Superior Province of the Canadian shield

F. Rolandone,^{1,2} J. C. Mareschal,³ C. Jaupart,² C. Gosselin,³ G. Bienfait,²
and R. Lapointe³

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[1] We present new heat flow measurements from deep boreholes at 9 sites, northwest of Lake Superior, in Ontario. The new measurements drastically change the heat flow map in the Western Superior Province of the Canadian Shield. Previous maps relied heavily on shallow (2.5 m) measurements in sediments beneath small lakes and exhibited high heat flow anomalies ($>60 \text{ mW m}^{-2}$). The new heat flow values between 31 and 56 mW m^{-2} are well within the range of values in the eastern part of the Superior and in other Archean provinces. Without the shallow lake data, the mean heat flow from borehole measurements, including 9 previously published values, is $42 \pm 8 \text{ mW m}^{-2}$, which is close to the mean of other provinces in the Canadian Shield. **INDEX TERMS:** 8130 Tectonophysics: Heat generation and transport; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8125 Tectonophysics: Evolution of the Earth. **Citation:** Rolandone, F., J. C. Mareschal, C. Jaupart, C. Gosselin, G. Bienfait, and R. Lapointe, Heat flow in the western Superior Province of the Canadian shield, *Geophys. Res. Lett.*, 30(12), 1637, doi:10.1029/2003GL017386, 2003.

1. Introduction

[2] The Superior Province is a collage of small continental fragments and volcanic arcs. In the western part of the province, several subprovinces elongated in the east–west direction were welded together ca. 2.7 Ga (Figure 1) [Card, 1990; Henry *et al.*, 1998; Tomlinson *et al.*, 2002]. This area records a major episode of late Archean crustal growth and stands east of the Early Proterozoic Trans-Hudson Orogen which saw the final assembly of the cratons forming the Shield of North America.

[3] Heat flow values for this part of the Superior Province are scarce and include data of doubtful reliability. In the compilation by Jessop *et al.* [1984], the Superior Province includes 22 boreholes and 7 shallow lake sites. The latter come exclusively from the Western Superior [Allis and Garland, 1976, 1979]. Jessop *et al.* [1984] noted that the lake data are systematically higher than the deep borehole data. Indeed, the mean value for the lake data is 56.4 ± 9.7 (s.d.) mW m^{-2} , as opposed to 39.1 ± 7.4 (s.d.) mW m^{-2} for the borehole data.

[4] These shallow lake data account for 42 separate entries in the International Heat Flow Commission (IHFC) compilation [Pollack *et al.*, 1993]. Allis and Garland [1979] acknowledged that their very shallow measure-

ments (with less than 2.5 m penetration) were likely to be perturbed and excluded 8 extremely high heat values ($>74 \text{ mW m}^{-2}$). However, as noted by Beck [1980] and Drury [1991], their other heat flow determinations may also be unreliable. Nevertheless, these data are listed in the IHFC archive and have been used in several recent global studies of lithospheric structure. This may lead to inaccurate results in an important part of the Canadian Shield and motivated us to undertake a new heat flow study of the area. In this paper, we report on 9 new heat flow determinations in deep boreholes. Together with 9 previously published borehole data, they allow a reevaluation of the heat flow field of the Western Superior Province.

[5] Our measurements were made in the Uchi, English River and Wabigoon subprovinces (Figure 1).

[6] The Uchi Subprovince is mostly made up of meta-volcanic rocks.

[7] The English River Subprovince, south of the Uchi Subprovince, contains predominantly sedimentary and intrusive rocks similar to those of the Quetico Subprovince.

[8] The Wabigoon Subprovince is a collage of volcano-plutonic belts.

[9] The geographical locations of our new heat flow sites are shown in Figure 2.

2. New Heat Flow Determinations

2.1. Measurement Methods

[10] The heat flow Q is determined from the measurements of the temperature gradient in boreholes and of the conductivity of rock samples:

$$Q = k \frac{\partial T}{\partial z}$$

where k is the thermal conductivity, T is temperature, and z is depth.

[11] Measurement procedures were described by Mareschal *et al.* [1989] and Pinet *et al.* [1991].

[12] For each sample, conductivity measurements were made on five disks of different thicknesses in order to detect small-scale variations of mineralogy unrepresentative of the large-scale average rock composition.

[13] Following Pinet *et al.* [1991], we have rated the quality of the heat flow measurements. Sites rated A consist either of several boreholes deeper than 300 m giving consistent heat flow values or a single borehole deeper than 700 m where the heat flow is stable over more than 300 m. Sites where the heat flow is less consistent between boreholes or where the heat flow is obtained from a single borehole shallower than 600 m are rated B.

[14] Sites consisting of shallow boreholes or where differences between boreholes are larger than two standard deviations are rated C.

¹Berkeley Seismological Laboratory, UC Berkeley, USA.

²Laboratoire de Dynamique des Systemes Geologiques, Institut de Physique du Globe de Paris, France.

³GEOTOP, Centre de Recherche en Geochimie et en Geodynamique, Universite du Quebec a Montreal, Canada.

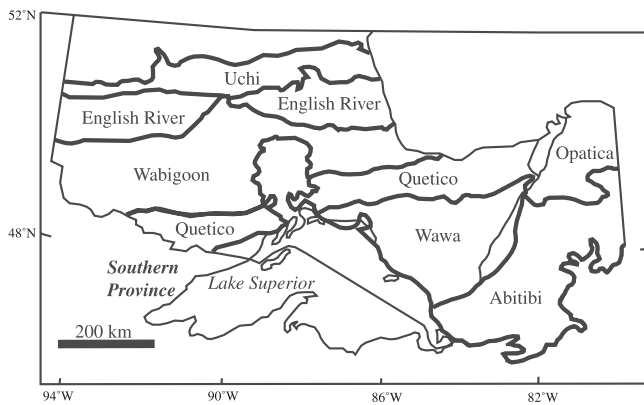


Figure 1. Map of the Superior Province in Ontario, showing the division into distinctive subprovinces from *Card* [1990]. The Southern Province is of Proterozoic age.

[15] The climate model of *Jessop* [1971] was used to adjust for the effect of Pleistocene glaciations.

[16] A summary of the new heat flow data is presented in Table 1, the temperature profiles are shown in Figure 3 and 4, and a description of each site follows.

2.2. Uchi Subprovince

[17] The Uchi Subprovince has been subdivided into the Balmer Assemblage rocks at the core of the Red Lake Greenstone belt and the Confederation Assemblage at the northern and southern flanks of this belt [*Stott and Corfu*, 1991].

2.2.1. Red Lake (Hole 00–01)

[18] This deep borehole (780 m) is located in the Red Lake greenstone belt which is composed of metamorphosed Archean volcanic and minor sedimentary rocks surrounded by younger Archean granitoid batholiths.

[19] The hole penetrates volcanic sequences interlayered with diorite and yields a stable temperature gradient.

2.2.2. Balmertown (Hole 00–02)

[20] This very deep borehole (1720 m), 8 km east of the Red Lake site, was drilled in metasedimentary and volcanic rocks, and yields stable temperature gradient over 1200 m.

2.2.3. Garnet Lake (Hole 00–05)

[21] This deep borehole (925 m), located in the Confederation Lake Greenstone Belt, penetrates quartz-rich felsic rocks. The shallow part of the hole goes through a complex sequence of hydrothermally altered rocks with high and variable thermal conductivity.

[22] In the homogeneous deeper section of the hole, the gradient is stable over 250 m.

[23] We discarded measurements in two other boreholes from the same belt, at the Ben Lake Property 40 km to the southwest, because these shallow boreholes do not reach the deep stable horizon.

2.3. English River

2.3.1. Big Whopper (Holes 01–10, 01–11)

[24] The two shallow boreholes were drilled in a small zone of rare-metal mineralization in the Separation Lake greenstone belt.

[25] This zone contains rare-element-enriched granitic pegmatites which belong to the petalite subtype [*Pan and Breaks*, 1997].

[26] The temperature gradients for these two boreholes are very high ($>17 \text{ mK m}^{-1}$).

[27] The resulting high heat flow value, 56 mW m^{-2} , is probably due to high heat production in the enriched rocks of this small area. U, Th and K measurements are underway to evaluate the relationship between heat flow and heat production.

2.4. Wabigoon Subprovince

2.4.1. Rainy River (Holes 01–02, 01–06)

[28] Two deep boreholes in the Rainy River greenstone belt penetrate sequences of mafic tuff interlayered with dacites and basalts.

[29] They yield stable and consistent temperature gradients.

2.4.2. Cameron Lake (Hole 01–04)

[30] One deep borehole was drilled through a sequence of basaltic lavas and intrusives.

[31] The temperature gradient is stable over 450 m.

2.4.3. Thunder Lake (Holes 01–07, 01–08)

[32] These two deep boreholes intersect gneisses, schists, and quartz-porphyrines of the Wabigoon greenstone belt.

[33] They yield stable and consistent temperature gradients.

2.4.4. Raleigh Lake (Holes 02–04, 02–05)

[34] Two shallow boreholes were logged in the Raleigh Lake greenstone belt.

[35] They penetrate a series of intermediate to mafic volcanic rocks.

[36] Variations of thermal conductivity lead to complex temperature logs and only the deepest borehole was retained.

2.4.5. Mattabi Mine (Holes 00–06, 00–07)

[37] These two deep holes are drilled in sequences of felsic and mafic volcanics.

[38] Significant variations of the temperature gradient in hole 00–06 do not allow an independent and reliable heat flow determination.

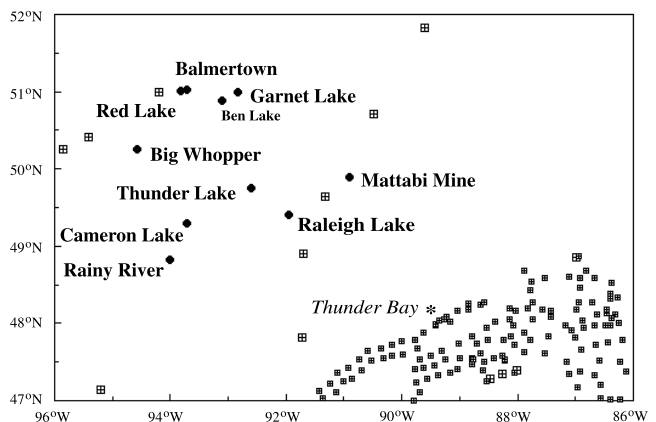


Figure 2. Heat flow sites in the Western Superior. The new sites are shown by dots. Large squares stand for older borehole data, including sites in the Proterozoic Southern Province. The small squares show the locations of marine heat flow sites in Lake Superior from *Hart et al.* [1994].

Table 1. New Heat Flow Data

Site Hole #	Lat north	Long west	Dip deg	Δh , m	N_k	$\langle k \rangle$ W m ⁻¹ K ⁻¹	G, mK m ⁻¹	Q , mW m ⁻²	σ_Q , mW m ⁻²	ΔQ , mW m ⁻²	Q_c , W m ⁻²
<i>Uchi Subprovince</i>											
Red Lake 00-01	51 00 47	93 48 50	77	430-772	11	3.05	9.0	27.4	0.8	3.9	31 (A) 31.3
Balmertown 00-02	51 01 59	93 42 56	88	450-1715	25	3.37	9.6	32.4	3.3	2.5	35 (A) 34.9
Garnet Lake 00-05	50 59 49	92 49 27	78	606-859	15	4.22	9.8	41.5	1.7	4.0	46 (B) 46.0
<i>English River Subprovince</i>											
Big Whopper 01-10	50 15 48	94 33 54	67	74-230	5	2.94	17.6	51.8	1.8	5.2	56 (C) 57.0
01-11	50 15 49	94 33 57	67	83-295	6	2.94	17.1	50.2	1.8	5.0	55.2
<i>Wabigoon Subprovince</i>											
Rainy River 01-02	48 49 54	94 00 46	90	220-709	9	3.97	11.0	43.8	2.0	5.5	50 (A) 49.3
01-06	48 49 44	94 00 54	90	277-450	11	3.97	11.2	44.3	2.5	5.7	50.0
Cameron Lake 01-04	49 17 35	93 43 11	73	176-634	8	3.39	9.2	31.1	1.4	5.6	37 (B) 36.7
Thunder Lake 01-07	49 45 24	92 36 53	90	300-715	8	3.23	11.9	38.3	1.8	3.7	42 (A) 42.0
01-08	49 45 27	92 36 36	83	285-750	10	3.23	12.0	38.8	1.0	3.6	42.4
Raleigh Lake 02-04	49 24 29	91 56 54	70	205-262	6	2.59	12.2	31.7	0.8	3.5	35 (C) 35.2
Mattabi Mine 00-06	49 52 36	90 59 45	65	252-635	12	3.48					43 (A)
00-07	49 53 39	90 53 51	87	209-648	16	3.85	1.1	4.0	43.2	10.2	39.2

For each borehole we give the latitude, longitude, dip at the collar of the drillhole, vertical depth interval used for heat flow determination, number of conductivity samples measured, average thermal conductivity, average temperature gradient over the depth interval, mean heat flow, standard deviation, correction for postglacial warming, and adjusted heat flow. The quality of the heat flow value for each site is rated A, B, C.

[39] Hole 00-07 yields a stable temperature gradient over 400 m.

3. Discussion: Distribution of Heat Flow in the Western Superior

[40] Including 9 previous borehole determinations [Jesop *et al.*, 1984; Drury and Taylor, 1987], there are now 18

reliable heat flow values in the Western Superior Province, west of the 88 W meridian.

[41] This data set yields a mean and standard deviation of 42 ± 8 mW m⁻². We have compared this data set with that in the IHFC archive, which does not include 3 values from Drury and Taylor [1987] but contains 7 shallow lake determinations from Allis and Garland [1979]. The IHFC archive lists 13 values, with a mean and standard deviation

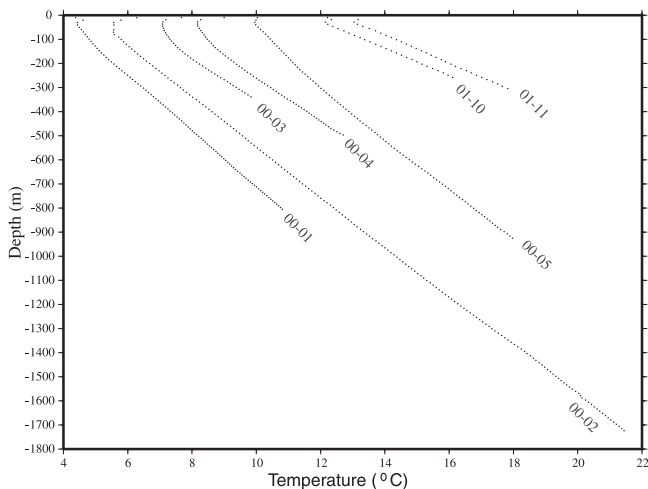


Figure 3. Temperature-depth profile for the Uchi and English River Subprovinces. For clarity, the profiles are shifted horizontally as indicated.

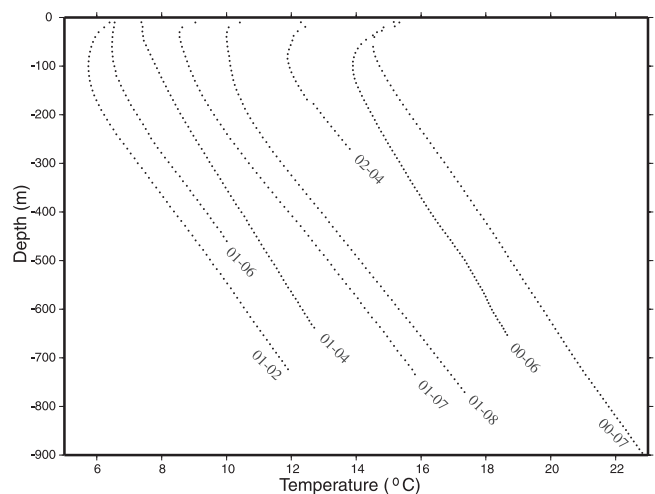


Figure 4. Temperature-depth profile for the Wabigoon Subprovince.

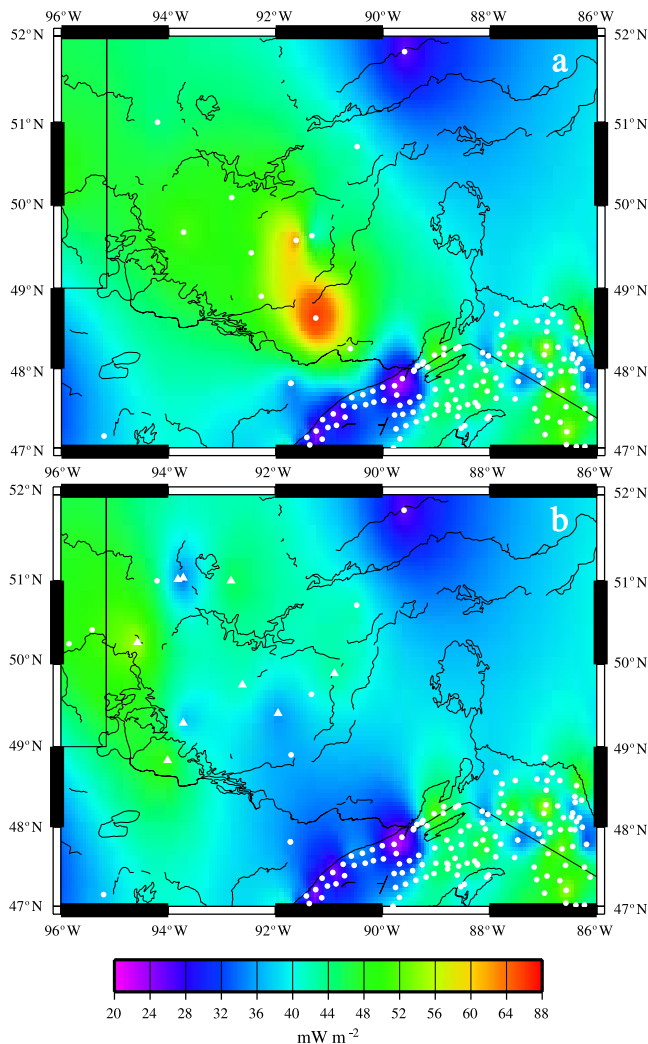


Figure 5. Heat flow map of the Western Superior Province. (a) Data from the IHFC compilation [Pollack *et al.*, 1993]. (b) New data set including 9 older sites (dots) and 9 new sites (triangles). Both maps were drawn using data from the southern Province and Lake Superior.

of $49 \pm 12 \text{ mW m}^{-2}$. The new mean heat flow value is thus significantly lowered and is almost identical to values for other parts of the Canadian Shield [Mareschal *et al.*, 2000]. Note also that the standard deviation is reduced. The two data sets lead to very different heat flow maps (Figure 5). Both maps were constrained with data from outside the area, including a large number of marine data from Lake Superior [Hart *et al.*, 1994].

[42] With the new data set, the Western Superior Province no longer stands out as a heat flow high in the Canadian Shield.

[43] The remarkable uniformity of the mean heat flow in the major North American Precambrian provinces confirms that, on a large-scale, there are no significant variations of crustal heat production for ages between 2.7 Ga and 1.0 Ga [Mareschal *et al.*, 2000; Rolandone *et al.*, 2002]. Only the younger Appalachians Province at the edge of the continent stands out with higher heat production and higher heat flow. On the scale of individual subprovinces with distinctive

tectonic and magmatic origins, however, there are significant differences. As regards the Western Superior Province, the present data set suggests that the English River subprovince is slightly more radiogenic than the Uchi and Wabigoon subprovinces. However, more data are required to confirm these trends.

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- F. Rolandone, Seismological Laboratory, UC Berkeley, 215 McCone Hall, Berkeley, CA 94720, USA. (frede@seismo.berkeley.edu)
- G. Bienfait and C. Jaupart, Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris cedex 05, France. (cj@ccr.jussieu.fr)
- C. Gosselin, R. Lapointe, and J. C. Mareschal, GEOTOP, UQAM, C.P. 8888, Succ. Centre-Ville, Montréal, H3C 3P8, Canada. (jcm@volcan.geotop.uqam.ca)