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Crustal heat production in the Superior Province, Canadian Shield, and in North America inferred from heat flow data

H. K. C. Perry,[1] C. Jaupart,[1] J.-C. Mareschal,[2] and G. Bienfait[1]

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[1] Measurements of heat flow and U, Th, K concentrations are used to determine the amount of heat generated in various belts of the Superior Province, the largest Archean craton on Earth. These data allow estimates of the average crustal heat production and indicate compositional differences between upper and lower crustal assemblages. The bulk average heat production of the Superior Province crust is 0.64 μW m^{-3} and is almost the same in different belts of slightly different ages, illustrating the remarkable uniformity of crust-building mechanisms. In the wider context of the North American continent, the bulk crustal heat production decreases from 1.0 μW m^{-3} in the oldest Slave Province to a minimum of 0.55 μW m^{-3} in the Paleo-Proterozoic Trans-Hudson Orogen. It increases in younger provinces, culminating with a high value of 1.05 μW m^{-3} in the Phanerozoic Appalachian Province. In all provinces, U and Th enrichment is systematically associated with sedimentary accumulations. A crustal differentiation index is obtained by calculating the ratio between the average values of heat production at the surface and in the bulk crust. The differentiation index is correlated with the bulk average heat production, which suggests that crustal differentiation processes are largely driven by internal radiogenic heat.

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1. Introduction

[2] The compositional and thermal structure of the continental crust remains poorly known despite many years of concerted efforts, and yet these are key constraints for studies of crustal evolution, mantle depletion and the thermal evolution of the Earth. Amongst trace elements, uranium, thorium and potassium have special importance because they generate heat by radioactive decay. Their relative amounts provide the main control on the thermal structure of continents. Obtaining reliable estimates of radiogenic heat production in continental crust therefore serves both geochemical and geophysical purposes. Geological studies are capable of deciphering the complex nature of crustal assemblages and the orogenic processes leading to their formation. Geochemical and petrological studies allow determination of the composition of the upper crust but allow only indirect and incomplete constraints on the whole crust because samples of lower crustal material are rare. Heat flow measurements provide complementary information because they record heat production over the total crustal column, including the lower crust [*Jaupart and Mareschal*, 2003]. For studies of melting regimes and metamorphic conditions, which require accurate temperature predictions, knowledge of the total amount of heat producing elements in the crust is not sufficient, and must be supplemented by constraints on their vertical distribution. In this paper, we deduce both from an analysis of heat flow and heat production data.

[3] We present a detailed study of the Superior Province in the Canadian Shield (Figure 1) where we now have extensive data sets on both surface heat flow and heat production. The Superior Province, the largest Archean craton, is an ideal region for testing theories of crustal formation and geochemical evolution as it juxtaposes belts of varying ages and tectonic origin and has been tectonically inactive for 1000 Myr. Furthermore, it exposes different crustal levels and there is an extensive data set of U, Th, and K concentrations of the major rock types, allowing reconstruction of crustal columns [*Ashwal et al.*, 1987; *Fountain et al.*, 1987]. The Superior Province was welded to smaller Archean blocks in the Early Proterozoic during the Hudsonian orogeny circa 1.8 Ga [*Hoffman*, 1989]. This province (Figure 2) is divided into subprovinces based on geological discontinuities as well as similarities in lithologic assemblages, structural traits and metamorphic grades [*Card and Ciesielski*, 1986]. Rock types vary significantly between the different parts of the province. This variability is shown in the southwestern half of the Superior Province where east-west trending metasedimentary belts are separated by gran-

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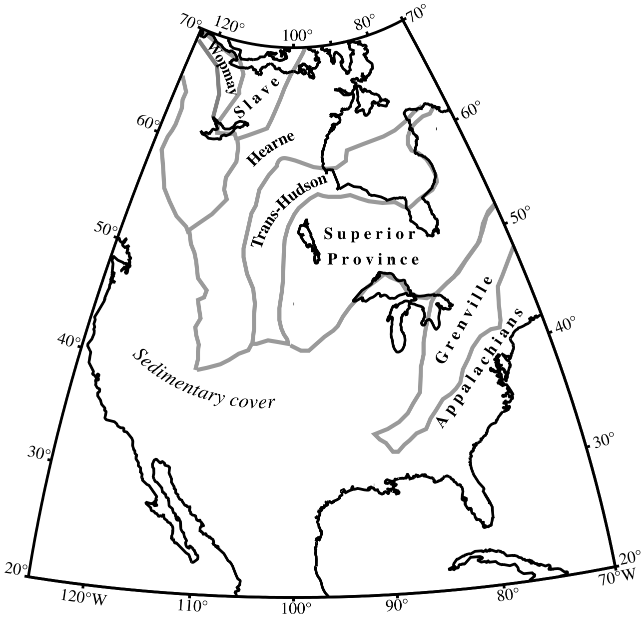

Figure 1. Generalized geological map of North America showing the Archean cratons and Proterozoic and Paleozoic orogens and provinces (modified from *Hoffman* [1989]).

ite-greenstone belts. The alternating pattern of the subprovinces, their characteristic elongated form, and the north-to-south decreasing age trend suggest that the craton was formed by accretion of crustal segments in a convergent margin setting [*Langford and Morin*, 1976; *Blackburn et al.*, 1985; *Corfu et al.*, 1985; *Ludden et al.*, 1986]. Zircon dating shows an uneven but nearly continuous record of magmatism from 3.1 to 2.65 Ga [*Davis*, 1998, 2002]. The major period of arc volcanism and production of tonalite plutons occurred between 2.75 and 2.7 Ga. This was followed by large-scale melting of the crust and mantle between 2.7 and 2.65 Ga as the region underwent regional deformation, thickening and uplift. Rapid erosion and deposition of large volumes of orogenic sediments are recorded in the English River and Quetico subprovinces [*Davis et al.*, 1990]. More detailed information on the structure, composition and age of the various subprovinces may be found in Appendix A.

[4] Previous heat flow studies in the Superior Province focused mostly on the Abitibi subprovince [*Pinet et al.*, 1991; *Mareschal et al.*, 2000a]. In the western Superior Province, there were too few heat flow data to analyze individual subprovinces [*Rolandone et al.*, 2003; *Perry et al.*, 2004] and heat production measurements were absent at many sites. In this paper, we present 10 new heat flow determinations, focusing on the Wawa subprovince, a major greenstone belt which was poorly sampled previously. We also report measurements of U, Th, and K concentrations in samples from the new heat flow sites and from the older sites of *Rolandone et al.* [2003]. We complement this data set with a new compilation of heat flow and heat production data in the Superior Province, some of which come from unpublished technical reports. The large data set now available for the Superior Province allows constraints on bulk crust composition and stratification in four granite-greenstone subprovinces: the Abitibi, Wawa, Wabigoon, and Uchi subprovinces.

[5] The results are compared with those of other major provinces of the Canadian Shield and North America, the early Archean Slave Province, the Proterozoic Trans-Hudson Orogen and Grenville Province, and the Phanerozoic Appalachians (Figure 1). On a continental scale, within North America, radiogenic heat production is significantly higher in the Archean provinces, decreases in the Proterozoic provinces, and increases markedly in the Paleozoic Appalachians. On the local scale, terranes of different origins have different bulk heat production rates. Thus incomplete sampling would likely obscure the global trend. In all provinces, the highest heat flow values, and hence the highest bulk crustal heat production, are systematically observed in

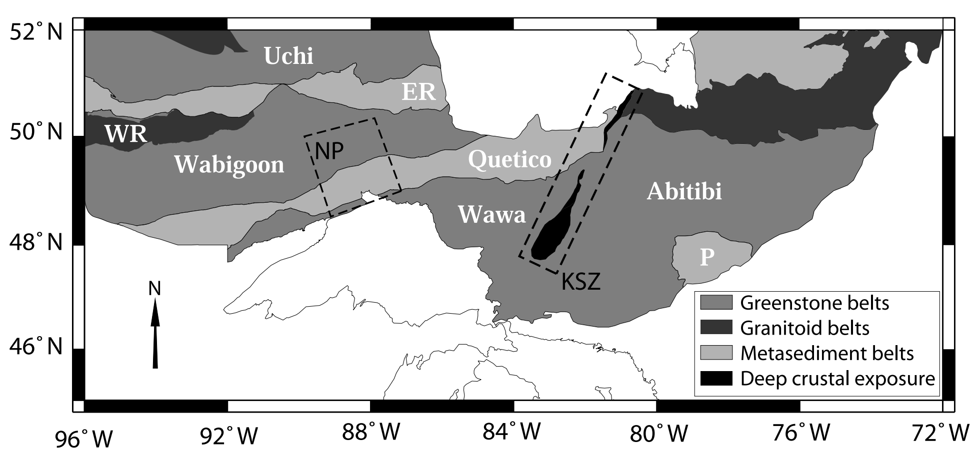

Figure 2. Generalized geological map of the Superior Province of the Canadian Shield showing major subprovinces from *Card and Ciesielski* [1986] and J. Percival (personal communication, 2005). ER is the English River metasedimentary subprovince, WR is the Winnipeg River plutonic subprovince, and P is the Pontiac metasedimentary subprovince. The boxes show the location of the Nipigon Embayment (NP) and the Kapuskasing Structural Zone (KSZ).

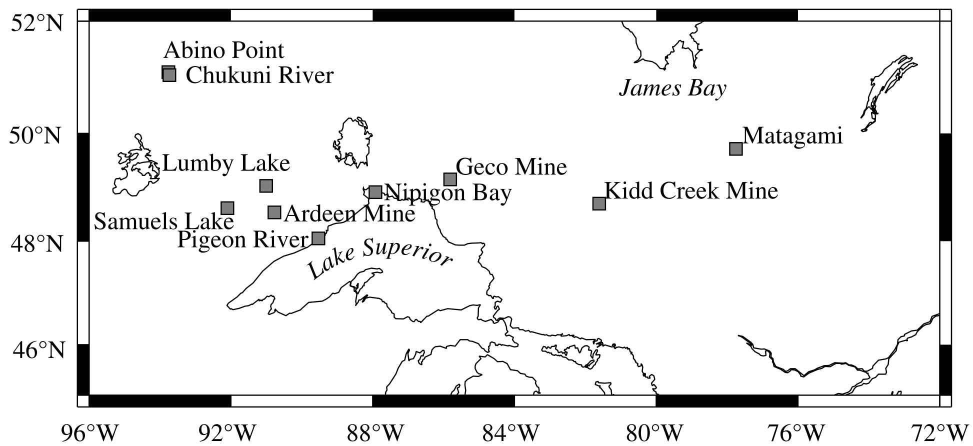

Figure 3. Locations of new heat flow sites in the Superior Province. The heat flow data are tabulated in Table 1.

metasedimentary belts. We introduce a new differentiation index for the crust which provides a simple measure of the amplitude of vertical variations of heat production in the crust.

2. Measurement Techniques

2.1. Heat Flow

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

$$Q = k\frac{\partial T}{\partial z} \tag{1}$$

where k is the thermal conductivity in the vertical direction, T is temperature and z is depth from the surface.

[7] Temperature was determined in mining exploration wells with a thermistor probe calibrated in the laboratory to 0.005 K accuracy. Reliable continental heat flow measurements require deep boreholes since recent climate changes and surface perturbations can affect the temperature profile to ~200 m depth. Measurements were recorded at depth intervals of 10 m. Temperature-depth profiles were obtained in several neighboring wells whenever possible. Figure 3 shows the locations of the heat flow measurement sites. Figure 4 shows the temperature profiles for all the sites in this paper.

[8] Core samples were collected at an interval of ~80 m, and at major lithological horizons, throughout the depth of the borehole. Thermal conductivity was measured using the divided bar apparatus. Each core sample was cut into five disks of different thicknesses. The thermal resistance of each disk was measured and thermal conductivity calculated by a least squares linear fit to the resistance/thickness data.

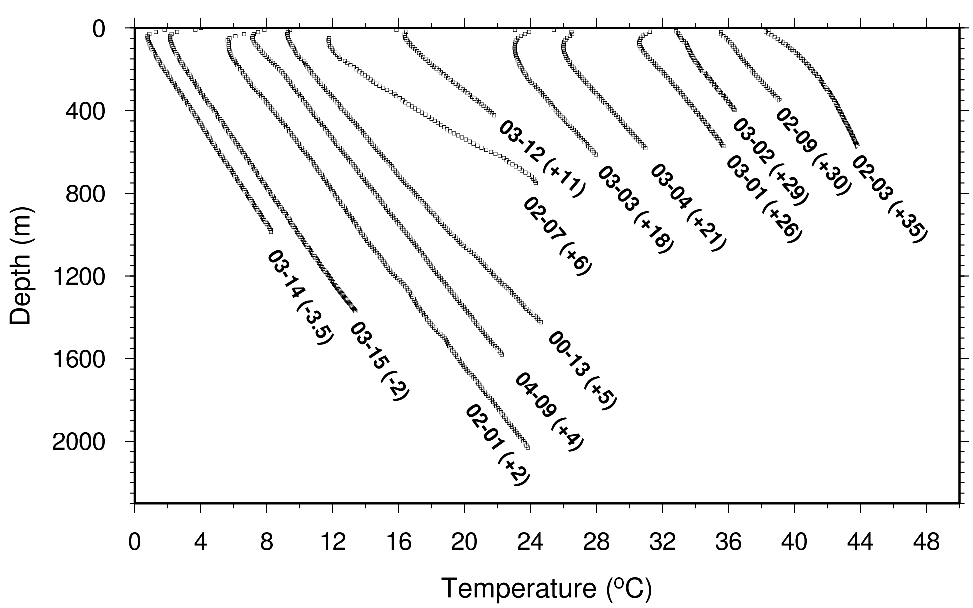

Figure 4. Temperature-depth profiles at the borehole heat flow site locations given in Table 1 (Superior Province). The profiles are shifted horizontally as indicated (in °C) to avoid superposition.

Table 1. New Heat Flow Measurements in the Superior Province[a]

Site Hole	Lat North	Long West	Dip, deg	Δh, m	N_k	$\langle k \rangle$, W m^{-1} K^{-1}	Γ, mK m^{-1}	Q, mW m^{-2}	σ_Q, mW m^{-2}	ΔQ, mW m^{-2}	Q_c, mW m^{-2}
Uchi Subprovince											
Chukuni River											**47** (A)
02-01	51 03 00	93 44 02	90	200-2020	22	4.60	9.5	43.9	5.5	2.7	46.6
Abino Point											**39** (B)
02-03	51 06 16	93 45 35	63	348-663	12	4.76	6.4	30.3	2.5	8.3	38.6
Wabigoon Subprovince											
Lumby Lake											**43** (A)
03-01	49 02 09	91 18 24	72	270-555	7	3.73	10.2	37.9	2.0	5.2	43.1
03-02	49 02 38	91 18 23	55	225-382	7	3.73	10.2	38.0	3.6	4.8	42.8
Quetico Subprovince											
Samuels Lake											**36** (B)
02-09	48 37 15	92 05 43	90	220-360	6	2.71	11.6	31.6	1.6	4.8	36.4
Wawa Subprovince											
Geco Mine											**40** (A)
00-13	49 09 30	85 48 36	89	250-1425	16	3.34	11.0	37.1	3.6	2.8	39.9
Ardeen Mine											**46** (A)
03-03	48 32 24	90 46 10	75	395-603	8	3.65	11.5	41.8	2.3	4.0	45.8
03-04	48 32 35	90 46 04	75	202-571	7	3.65	11.2	40.9	1.6	4.7	45.6
Pigeon River											**59** (A)
02-07	48 03 13	89 31 36	90	210-690	11	2.73	20.5	55.9	9.0	3.2	59.1
Nipigon Bay											**57** (B)
03-12	48 55 11	87 55 12	70	187-368	6	3.28	15.7	51.6	1.4	5.0	56.6
Abitibi Subprovince											
Kidd Creek Mine											**38** (A)
03-14	48 42 18	81 23 39	80	148-963	10	4.10	8.3	34.0	1.3	5.0	39.0
03-15	48 42 13	81 23 22	80	197-1350	17	3.80	8.8	33.5	2.6	3.6	37.1
Matagami											**37** (A)
04-09	49 43 00	77 45 00	90	220-1570	20	3.54	9.7	34.6	1.7	2.8	37.4

[a]Δh is the depth interval over which heat flow is estimated, k is thermal conductivity, N_k is the number of conductivity determinations (total number of samples analyzed is 5 × N_k; see text for details), $\langle k \rangle$ is the average thermal conductivity, Γ is the temperature gradient, Q is heat flow, σ_Q is the standard deviation on the heat flow, ΔQ is the climatic correction for heat flow and Q_c is the corrected heat flow, where boldface indicates the site-averaged corrected heat flow and A and B indicate the quality of the heat flow sites.

This procedure eliminates isolated heterogeneities and yields a truly representative conductivity which characterizes large-scale crustal heat conduction. Thus each conductivity determination relies on five independent samples. For each borehole, the total number of measurements is at least five times the number of conductivity determinations listed in Table 1, and is larger than this when some samples are rejected because of compositional heterogeneities. For inclined wells the thermal conductivity in the vertical direction was determined. Whenever possible, the conductivity was measured in two perpendicular directions, parallel and normal to the visible fabric/foliation. Assuming that these directions correspond to the major and minor principal axes of the conductivity tensor, conductivity in the vertical direction was calculated. The accuracy of the measurement is better than 3%.

[9] Table 1 shows the new heat flow values in the western Superior province. Table 2 provides a geological description of each site. The quality of each heat flow site was rated following *Pinet et al.* [1991]. Sites rated A consist of either several boreholes deeper than 300 m or a single borehole deeper than 600 m where the heat flow is stable over more than 300 m in the bottom part of the hole. Sites where the heat flow is less consistent between neighboring boreholes (but such that the difference is less than two standard deviations) or where the heat flow is obtained from a single borehole less than 600 m are rated B. The heat flow values have been corrected for the thermal effects resulting from the retreat of the Laurentide ice sheet between 12 and 9 ka, depending on the site location, following the model for Pleistocene climate used by *Jessop* [1971].

2.2. Heat Production

[10] The concentrations of U, Th, and K were measured on borehole samples collected at all the heat flow sites following the technique described by *Mareschal et al.* [1989]. At sites where heat flow was measured in more than one borehole, a single average heat production value for all boreholes is reported. Analytical errors on heat production measurements are <5% and are largest for low-radioactivity samples. The concentrations of radioactive elements at the new heat flow sites and those of two earlier reports [*Rolandone et al.*, 2003; *Perry et al.*, 2004] are listed in Table 3. Complementary heat flow and heat production data from the Superior Province are listed in Table 4.

3. Distribution of Heat Flow in the Superior Province

3.1. Heat Flow and Crustal Structure

[11] Caution must be taken when relating variations of heat flow to changes in crustal composition because the crust is heterogeneous at all scales in both horizontal and

Table 2. Site Description of New Heat Flow Measurements

Borehole	Site Name (Depth)	Geological Unit		Site Description
		Subprovince	Local	
02-01	Chukuni River (2000 m)	Uchi		east of Red Lake; mafic volcanics grading to metasedimentary; gradient stable over 2000 m
02-03	Abino Point (660 m)	Uchi		mafic volcanics grading to felsic volcanics at base; gradient stable over 300 m; borehole 30 m from lakeshore, dipping to the lake
03-01	Lumby Lake (550 m)	Wabigoon		mixed felsic and mafic volcanics; gradient stable over 280 m
03-02	Lumby Lake (380 m)	Wabigoon		gradient stable over 160 m
02-09	Samuels Lake (360 m)	Quetico		ultramafic intrusives; gradient stable over 140 m
00-13	Geco Mine (1400 m)	Wawa		tonalite with mafic volcanics between 0–950 m, felsic volcanics between 950–1400 m; iron formations from 1200 m.; gradient stable over 1150 m
03-03	Ardeen Mine (610 m)	Wawa	Ardeen Shear Zone; west of Fisher Lake Zone	mixed mafic/felsic metavolcanics; gradient stable over 200 m
03-04	Ardeen Mine (580 m)	Wawa		gradient stable over 370 m
02-07	Pigeon River (750 m)	Wawa	Duluth Complex; Rove, Gunflint, Kakabeka formations	borehole traverses Osler, Sibley and Animikie Group sediments; Archean basement unconformably overlain by Animikie Group sediments; gradient stable over 480 m
03-12	Nipigon Bay (430 m)	Wawa	south of North Shore Fault; borehole traverses Kama Hill, Rossport, Rove Lake, and Gunflint Formations	granites; Archean basement unconformably overlain by Animikie Group sediments; gradient stable over 180 m
03-14	Kidd Creek (960 m)	Abitibi		mafic volcanics; gradient stable over 800 m
03-15	Kidd Creek (1370 m)	Abitibi		mafic volcanics throughout with sedimentary rock at base (from 1265 m); gradient stable over 1250 m
04-09	Matagami (1600 m)	Abitibi		alternating sequences of gabbro and basalt, increasing occurrence of rhyolite below 900 m; gradient stable over 1390 m

vertical directions. At short wavelengths, horizontal heat conduction smoothes out deep differences in heat production rates, implying that surface heat flow variations depend only on shallow heat production contrasts. For wavelengths longer than the crustal thickness, heat flow records the horizontal average of the depth-integrated crustal heat production [*Jaupart and Mareschal*, 2003].

[12] The mean surface heat flow for the Superior province is 40.9 ± 0.9 mW m^{-2} (standard error on the mean) based on 70 land determinations. The map of surface heat flow is shown in Figure 5. This data set includes measurements in several regions which were modified after the initial phases of crustal growth. In Lake Superior and in the Nipigon Embayment (Figure 2), crustal composition was modified by the Keweenawan rifting event (circa 1000 Ma). In the Kapuskasing structural zone (KSZ), the upper crust was eroded away after deformation and uplift (circa 1800 Ma). These measurements do not affect the global statistics significantly: without them, the mean heat flow value is 41.2 ± 0.9 mW m^{-2}. It is, however, necessary to remove these sites from the average, if we are interested in determining the thermal properties of the crust which reflect its original composition. The map of surface heat flow with these sites removed is shown in Figure 6.

3.2. Short Wavelength Variations

[13] For our present purposes, we define short-wavelength variations as those which occur on length scales less than or equal to the crustal thickness. Such variations in the surface heat flow occur in the granite-greenstone belts of the Wabigoon and Wawa/Abitibi subprovinces. They can be explained by variations in the local crustal geology. The Nipigon Embayment, lying in the Wabigoon subprovince, has an upper crust containing a few kilometers of mafic intrusives [*Musacchio et al.*, 2004; *Perry et al.*, 2004] which decreases heat flow locally. Granitic intrusions in the Wawa subprovince are associated with high heat flow values, indicating that they belong to an enriched crustal segment extending over large lateral and vertical distances. In this

Table 3. Heat Production at New Heat Flow Sites in the Superior Province[a]

Site	Lithology	*U*, ppm	*Th*, ppm	*K*, %	*A*, μW m^{-3}	σ_A, μW m^{-3}	N_A
		Uchi Subprovince					
Red Lake	mixed volcanic and metasedimentary	1.26	4.78	1.04	0.75	0.33	11
Balmertown	mixed volcanic and metasedimentary	2.19	6.86	1.48	1.18	0.69	25
Garnet Lake	granite and meta felsic volcanics	1.61	6.12	0.99	0.93	0.37	13
Chukuni River	mixed volcanic and metasedimentary	0.36	1.31	1.27	0.30	0.25	17
Abino Point	felsic volcanics	1.71	7.22	1.53	1.09	0.07	5
		English River Subprovince					
Big Whopper	amphibolites	0.17	0.18	0.37	0.09	0.03	5
		Wabigoon Subprovince					
Rainy River	greenstones and altered basalts	0.35	1.69	1.30	0.32	0.23	20
Cameron Lake	greenstones and altered basalts	0.18	0.50	0.35	0.11	0.05	10
Thunder Lake	pelitic-graywackes	1.63	6.14	2.05	1.03	0.47	7
Rayleigh Lake	greenstones and altered basalts	0.83	2.92	0.66	0.48	0.61	6
Mattabi Mine	hydrothermally altered mafic volcanics	0.75	3.22	1.12	0.52	0.29	24
Lumby Lake	mixed metavolcanic flows (felsic-mafic)	0.38	1.68	0.75	0.28	0.24	15
Lac des Iles	gabbro	0.17	0.20	0.18	0.07	0.03	24
Gull River	gneiss, metasediments	0.28	0.85	0.43	0.17	0.06	7
Norwood	gneiss, metasediments	0.35	1.36	0.49	0.23	0.07	6
Junior Lake	gabbro	0.17	0.58	0.24	0.11	0.15	10
		Quetico Subprovince					
Samuels Lake	ultramafic intrusives	0.24	0.85	0.69	0.18	0.07	10
Seagull	gneiss, metasediments	1.86	6.89	1.93	1.13	0.19	5
Spruce River	gabbro	0.23	0.90	0.27	0.15	0.04	4
		Wawa Subprovince					
Geco Mine	tonalite	1.36	4.77	1.06	0.78	0.18	8
Ardeen Mine	mixed metavolcanic flows (felsic-mafic)	0.32	1.23	0.83	0.24	0.08	14
Pigeon River	Animikie Group sediments	3.37	5.72	1.42	1.40	0.91	8
Nipigon Bay	granites	2.84	11.20	3.84	1.86	0.27	6
		Abitibi Subprovince					
Kidd Creek Mine	greenstones	0.32	0.95	0.73	0.22	0.23	20

[a]*U*, *Th*, and *K* are uranium, thorium and potassium concentrations, *A* is heat production, σ_A is the standard deviation, and N_A is the number of samples.

subprovince, granitic plutons can be found at all depths down to the Moho and have a mean heat production of 1.6 μW m^{-3} [*Shaw et al.*, 1994].

3.3. Long Wavelength Variations

[14] The average heat flow values in the various belts of the Superior Province are close to one another (Table 5). This result may seem surprising as these belts are characterized by distinct lithologies and metamorphic grades at the surface, and suggests that the bulk crust is extensively reworked. Some subprovinces contain a variety of distinct terranes and the same terrane can be found in several subprovinces. For example, the Wabigoon subprovince contains juvenile Neoarchean greenstone belts in the west, rocks that are isotopically similar to the Winnipeg River subprovince in the north and a terrane similar to the North Caribou block in its south central part [*Tomlinson et al.*, 2003]. All of this suggests that the southern Superior

Table 4. Complementary Heat Flow and Heat Production Values in the Superior Province[a]

Site	Latitude	Longitude	Lithology	*Q*, mW m^{-2}	*A*, μW m^{-3}	σ_A, μW m^{-3}	N_A	References[b]
Wawa	48 18 00	84 26 00	metavolcanics	44.0	0.09	0.10	11	1, 2
Foleyet	47 56 00	82 25 00	metavolcanics	57.0	0.66	0.83	7	1, 2
Matagami	49 47 00	77 39 00	metavolcanics	41.0	0.16	0.08	14	1, 2
Atikokan	48 54 00	91 42 00	granodiorite	46.0	2.03	0.43	12	1, 3
Mariner	50 01 00	84 17 00	Hudson Bay seds	56.0	1.43	0.88	20	1, 3
Lac du Bonnet	50 15 00	95 51 00	granite	50.0	3.60	2.0	23	1, 3
Bernic Lake	50 25 00	95 25 00	basalt volcanics	42.0	0.11	0.11	4	1, 3
East Bull Lake	46 26 00	82 13 00	gabbro-anorthosite	56.0	0.54	0.58	19	1, 3
Hearst	49 41 40	83 32 10	-	52.0	1.80	0.3	1	4

[a]Heat flow values are corrected for the effects of Pleistocene glaciation. Symbols are defined in Tables 1 and 3. Mean heat production at Lac du Bonnet includes all the measurements reported by *Lewis and Bentkowski* [1988].
[b]References are 1, *Lewis and Bentkowski* [1988]; 2, *Drury* [1991]; 3, *Drury and Taylor* [1987]; 4, *Jessop and Lewis* [1978].

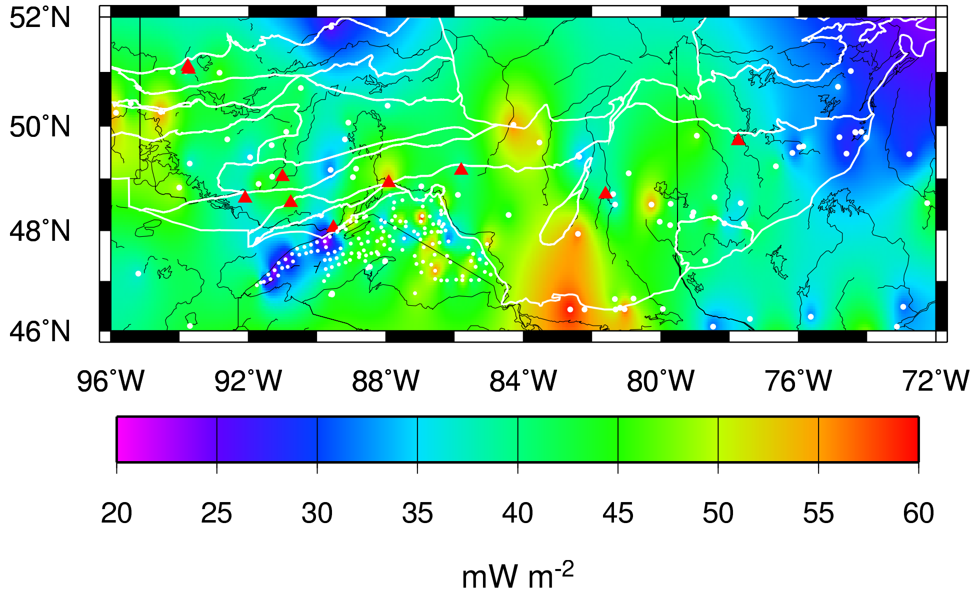

Figure 5. Heat flow in the Superior Province. Red triangles represent the new heat flow sites (summary in Table 1). Large white circles represent previous land measurements, and small circles represent lacustrine data in Lake Superior [*Hart et al.*, 1994]. Thin white lines mark subprovince boundaries.

Province crust has been mixed, leaving subprovinces which resemble one another geochemically. *Davis* [1998] suggested that the belt structure in the southern half of the Superior Province may not have resulted from the sequential accretion of individual belts, but from late differential uplift of a complex layered accretionary complex.

[15] Small heat flow variations do exist amongst subprovinces and follow interesting systematics (Table 5). The average heat flow for the granite-greenstone belts increases from north to south, i.e., going from the Uchi, through to the Wabigoon and Wawa subprovinces. This parallels a trend of decreasing age, with the oldest unit (Uchi) being the poorest in radioelements. This trend is interrupted in the English River and Quetico metasedimentary belts, which are associated with higher heat flow values. As will be argued later, this observation may be highly significant but caution is

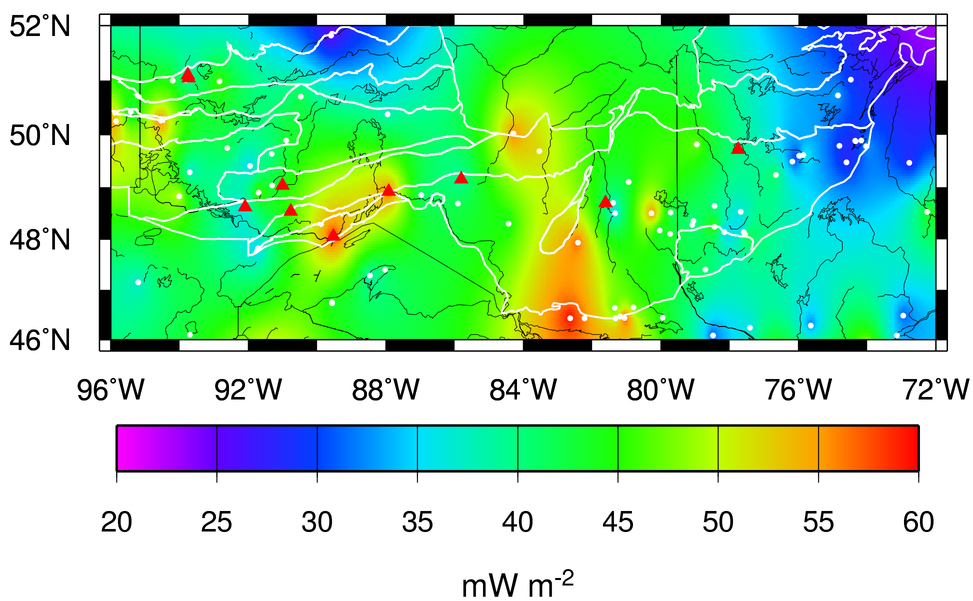

Figure 6. Heat flow in the Superior Province, with sites affected by late stage thermal perturbations removed. These sites include the Nipigon Embayment, where mafic intrusive Logan dikes resulted from the Keweenawan rifting; the Kapuskasing site where the upper crust was eroded following uplift; and the Lake Superior sites which were significantly affected by Keweenawan rifting events. Red triangles represent the new heat flow sites. White circles represent previous land heat flow measurement sites. Thin white lines mark subprovince boundaries.

Table 5. Heat Flow Statistics for the Superior Province[a]

Subprovince	$\overline{Q}$, mW m^{-2}	σ_Q, mW m^{-2}	N_Q	$\overline{Q}$,[b] mW m^{-2}	σ_Q,[b] mW m^{-2}	N_Q[b]	$\overline{A}$, μW m^{-3}	σ_A, μW m^{-3}	N_A	$\overline{A}$[b], μW m^{-3}	σ_A,[b] μW m^{-3}	N_A[b]
Uchi	38.1 ± 3.1	8.3	7	-	-	-	0.75 ± 0.14	0.38	7	-	-	-
English River	48.0 ± 3.4	7.7	5	-	-	-	2.00 ± 0.94	2.1	5	-	-	-
Wabigoon	40.3 ± 1.4	5.1	13	41.6 ± 1.4	4.4	10	0.63 ± 0.19	0.68	13	0.78 ± 0.23	0.72	10
Quetico	46.6 ± 3.4	7.7	5	48.0 ± 6.1	10.6	3	0.95 ± 0.34	0.76	5	1.15 ± 0.50	0.86	3
Wawa	45.1 ± 2.7	8.5	10	46.4 ± 2.6	7.8	9	0.85 ± 0.21	0.59	8	0.90 ± 0.23	0.62	7
Abitibi	38.5 ± 1.4	7.4	30	-	-	-	0.40 ± 0.07	0.32	24	-	-	-
Average Superior												
With Abitibi	40.9 ± 0.9	7.3	70	41.2 ± 0.9	7.3	64	0.72 ± 0.07	0.62	62	0.76 ± 0.08	0.62	56
Without Abitibi	42.8 ± 1.1	7.2	40	43.6 ± 1.2	7.2	34	0.92 ± 0.13	0.80	38	1.03 ± 0.15	0.85	32

[a]Symbols are defined in Tables 1 and 3.
[b]Subprovince statistics excluding areas that were perturbed by late stage magmatism or uplift and erosion. Excluded areas are the Nipigon Embayment (∼1100 Ma) in the Wabigoon subprovince and the Kaspuskasing Uplift Structure (∼1900 Ma) between the Wawa subprovince to the west and the Abitibi subprovince to the east.

warranted because of the relatively small number of heat flow values in these two belts (5 measurements for each belt, Table 5).

[16] A west-to-east traverse of the heat flow data from the western edge of the Superior Province to the Abitibi subprovince shows that there is no systematic long-wavelength variation in the western Superior Province, i.e., west of the KSZ (Figure 7). A few high heat flow values are recorded over regions of granitic intrusions in the Wawa and Quetico belts. Low heat flow values in the Nipigon Embayment are accounted for by the emplacement of depleted mafic intrusives of the Keweenawan Mid-Continent Rift [*Perry et al.*, 2004]. The heat flow field shows no abrupt change between the Wawa and western Abitibi subprovinces, which seem to belong to a single belt cut by the late Kapuskasing structure. East of the KSZ, heat flow decreases systematically toward the eastern edge of the Abitibi subprovince, where the lowest heat flow values in the Superior Province are found. This long-wavelength trend is due to a change of crustal structure, with larger amounts of tonalite-trondjemite-granodiorite (TTG) in the west and larger amounts of mafic greenstones in the east. The gradual eastward change to more mafic compositions is visible in the gravity field [*Guillou et al.*, 1994; *Jaupart et*

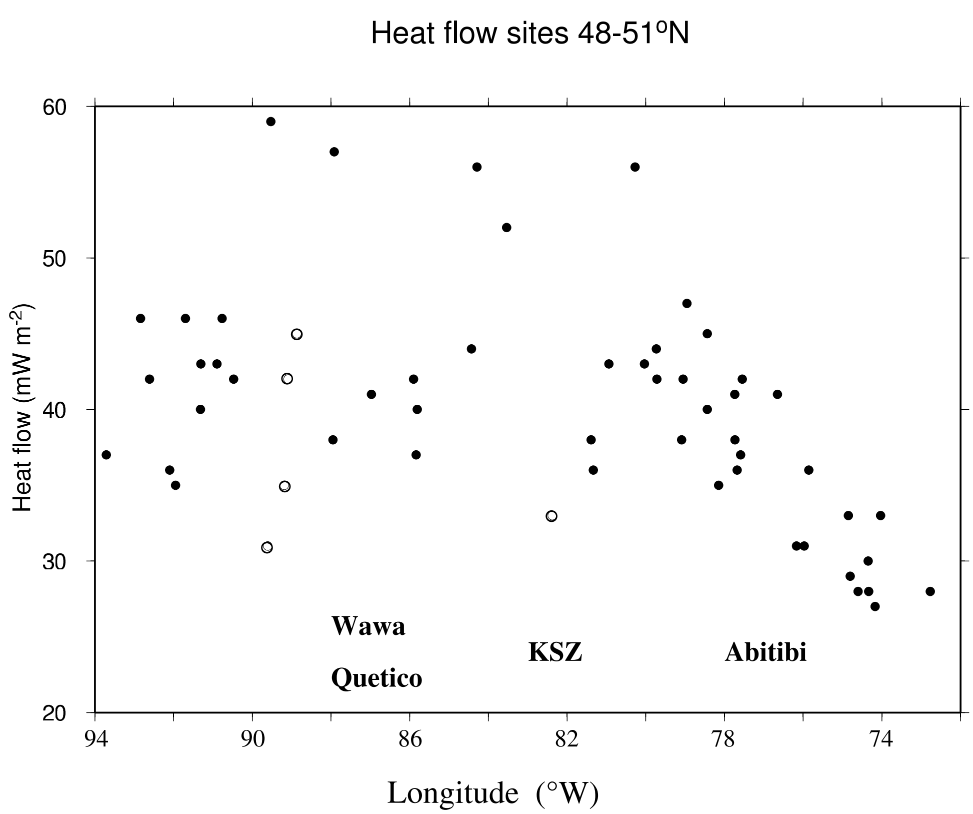

Figure 7. Longitudinal profile of the surface heat flow across the Superior Province. The open circles are heat flow values in the Nipigon Embayment and KSZ.

al., 1998]. The suture of the Abitibi with the Opatica to the north may have resulted in imbrication of the mid and lower crust beneath the Abitibi [*Calvert et al.*, 1995]. The difference between the eastern and western Abitibi might reflect differences in magmatic evolution or in tectonic imbrication of Opatica lower crust.

4. Crustal Heat Production in the Superior Province

[17] Table 3 shows crustal heat production values determined for the heat flow sites reported here and for those of *Rolandone et al.* [2003]. Heat production values for some older heat flow sites in the Superior Province were extracted from *Jessop and Lewis* [1978], *Drury and Taylor* [1987], *Lewis and Bentkowski* [1988], and *Drury* [1991] and are listed in Table 4. The mean surface heat production of the Superior Province is 0.76 ± 0.1 μW m^{-3} (standard error on the mean) based on 56 sites, excluding those in the Nipigon Embayment and the KSZ where mafic intrusions or differential uplift and erosion occurred after crustal stabilization [*Perry et al.*, 2004].

4.1. Vertical Variations of Heat Production

[18] Estimating the chemical composition of a large crustal block through analysis of only upper crustal rocks is challenging, considering the often low proportion of rock outcrop. Estimates of the lower crustal bulk composition may be determined from seismic properties and densities [*Christensen and Mooney*, 1995; *Rudnick and Fountain*, 1995], but they do not provide strong constraints on radiogenic heat production. Uranium and thorium are trace elements which tend to be located in accessory minerals and along grain boundaries, and are thus not sensitive to the major element composition. However, a useful fact is that U and Th concentrations are always small in mafic rocks and can be large only in felsic rocks.

[19] Using heat flow and heat production data, two methods may be used to evaluate how heat production varies with depth. Early work relied on a correlation between local values of heat flow and heat production at the surface:

$$Q_o = Q_r + DA_o \quad (2)$$

where Q_o and A_o stand for the observed heat flow and the local heat production of crystalline basement rocks, respectively. The slope D has the dimension of length and provides a depth scale for enrichment in the upper crust. Q_r is called the reduced heat flow. Comparing D to the crustal thickness h allows an assessment of the vertical variation of heat production. At the scale of individual geological units (10–20 km), this linear relation is valid only over exposed plutons very enriched in radioactive elements [*Birch et al.*, 1968; *Jaupart*, 1983]. Over other rock types, it is weak at best, as demonstrated by data from the large Precambrian provinces of India [*Roy and Rao*, 2000], South Africa [*Jones*, 1987, 1988], and Canada [*Mareschal et al.*, 1999]. The values of D vary little and are $\sim$10 km for almost all the regions where the relationship holds. It can be shown that this depth scale is related also to the degree of horizontal heat conduction [*Jaupart*, 1983; *Vasseur and Singh*, 1986; *Nielsen*, 1987]. Looking for a correlation between local values of heat flow and heat production is useful for comparative purposes only: depth scale D is meaningless for a region with homogeneous crust amongst regions with enriched or depleted upper crusts.

[20] We propose an alternative method which does not rely on the existence of a linear relation at the local scale. This is clearly advantageous in regions where the linear relation does not hold. We compare the surface average and the bulk average of heat production which is the average over the whole crust. In a region with average surface heat flow $\overline{Q}$, the bulk average crustal heat production is

$$A_c = \frac{\overline{Q} - Q_M}{h} \quad (3)$$

where h is the average crustal thickness and Q_M is the Moho heat flow that will be determined independently. The average crustal thickness for each individual geological province of the Canadian Shield presented in this paper was taken from the LITH5.0 crustal model [*Perry et al.*, 2002]. This model at $5^\circ \times 5^\circ$, contains all published LITHOPROBE data from the Canadian Shield, and is the most accurate one available for these regions. A differentiation index can be obtained simply by calculating the ratio between the average surface heat production, $\overline{A}$, and A_c:

$$D_I = \frac{\overline{A}}{A_c} = \frac{\overline{A}h}{\overline{Q} - Q_M} \quad (4)$$

For a homogeneous crust, $D_I = 1$.

[21] For the purposes of comparing h/D and D_I, let us assume that the vertical distribution of heat production averaged in a given region follows an exponential function, i.e., $A(z) = A_o \exp(-z/D)$. This model leads to a linear relation between heat flow and heat production with slope D. It is now abandoned [*Jaupart*, 1983] but allows a useful argument. For this model, if D is much less than h, one has $\overline{A} = A_0$, $A_c \approx A_0 D/h$, and hence $D_I = h/D$. Both approaches lead therefore to identical results. We prefer using the differentiation index D_I as an indicator of vertical stratification in the crust for two reasons: one is that it involves the whole crust, and the other is that its value can be derived, and interpreted, for a single geological province, independently of other provinces.

[22] To summarize, depth scale D provides a (very weak) comparative tool whereas D_I is an absolute index. Furthermore, D_I may be used even when the correlation between local values of heat flow and heat production is poor. By definition, it applies only on the regional scale because it requires averaging representative samples of the surface heat production and heat flow. Usually, we expect $D_I > 1$ because magmatic differentiation results in enrichment of the upper crust in radioelements. Both methods are useful and are complementary in some ways. One caveat is that the surface heat production may correspond to only a very thin cover and hence may not account for a significant part of the crustal column. In this case, it would not affect the heat flow and would be useless for any study on a crustal scale. The various points of this discussion will be illustrated very well by the Superior province data.

4.2. Mantle Heat Flow

[23] To calculate the average crustal heat production and the differentiation index, we must estimate the Moho heat flow Q_M. Two different methods may be used. *Rudnick and Nyblade* [1999] have derived a mantle geotherm from the xenolith suites at Kirkland Lake (located to the east of the KSZ in the Abitibi). With an estimate of thermal conductivity in the mantle, they found a best fit Moho heat flow $\sim$18 mW m^{-2} within a total range of 17–25 mW m^{-2}. Xenolith samples from two kimberlite pipes of the Slave Province lead to a mantle heat flow value of $\sim$15 mW m^{-2} [*Russell et al.*, 2001; *Mareschal et al.*, 2004]. Bounding solutions for the best fitting procedure are 12 and 24 mW m^{-2}. Another method relies on the variations of heat flow and crustal structure combined with heat production data for the various rock types. Mantle heat flow values of 10–15 mW m^{-2} have thus been derived for the Grenville Province, east of the western Superior [*Pinet et al.*, 1991], and for the Trans Hudson Orogen (THO) to the west [*Rolandone et al.*, 2002]. Gravity data can be used to further constrain the crustal models [*Guillou et al.*, 1994]. Crustal models are generated by varying the mantle heat flow, the thicknesses of the lithological units, their densities and heat production rates. Values of heat production are left to vary within reasonable ranges. In the Abitibi, only a limited number of models meet the constraints of both gravity and heat flow data, with values of Q_M lying between 7 and 15 mW m^{-2} [*Guillou et al.*, 1994]. These two methods are associated with different sources of uncertainty. Estimates from xenolith data rely on a steady state vertical conduction model and on values of thermal conductivity at high pressures and temperatures. Estimates from crustal models are sensitive to the proportions of the various rock types. That such independent methods converge to similar results indicates that errors are small.

[24] One may derive lower and upper bounds on Q_M using other arguments. *Rolandone et al.* [2002] calculated lower crustal temperatures when the THO and the Abitibi stabilized, which depend on the crustal heat production. Requiring that temperatures were below melting, they found that Q_M could not be less than about 12 mW m^{-2}. Upper bounds on the mantle heat flow can be derived from the smallest heat flow values measured in the Shield. Heat flow values of 22–23 mW m^{-2} are found in the Lynn Lake belt of the THO [*Rolandone et al.*, 2002] and at the eastern edge of the Shield, at Voisey Bay, Labrador [*Mareschal et al.*, 2000b]. Because of horizontal heat diffusion, these values include the contribution of crustal heat production averaged over large crustal volumes [*Mareschal and Jaupart*, 2004]. Using a lower bound on crustal heat production leads to a refined upper bound of 15 mW m^{-2} for Q_M [*Mareschal et al.*, 2000b].

[25] These results provide estimates of the mantle heat flow in specific areas. Horizontal variations of the mantle heat flow are due to differences of heat supply at the base of the lithosphere. For 200 km thick cratonic lithosphere, variations over wavelengths smaller than about 500 km are completely smoothed out by horizontal diffusion [*Jaupart et al.*, 1998]. Thus variations of mantle heat flow within a single province must be small, less than ±2 mW m^{-2} according to *Mareschal and Jaupart* [2004]. We shall show below that heat flow variations in North America can be accounted for entirely by changes in crustal heat production and that variations in mantle heat flow are very small. From the above results, we deduce a conservative range of 12–18 mW m^{-2} for Q_M. Values less than 12 mW m^{-2} are inconsistent with the xenolith data and values higher than 18 mW m^{-2} are inconsistent with heat flow and heat production data.

[26] A common assumption is that lithosphere thickness and mantle heat flow are related, such that a thinner lithosphere implies a higher Q_M. This is not necessarily true. Let us consider for the sake of simplicity that the base of the lithosphere is at a uniform temperature T_B and that there are no heat sources in the mantle part of the lithosphere. By definition, heat is transported through the lithosphere by conduction and hence

$$T_B = T_M + \frac{Q_M}{k_m}(h_L - h_c) \tag{5}$$

where k_m is the mean mantle conductivity, T_M the Moho temperature, h_c the crustal thickness and h_L the lithosphere thickness. Assuming a uniform distribution of heat sources in the crust, the Moho temperature may be written as

$$T_M = \left(\frac{Q_0 + Q_M}{2}\right)\frac{h_c}{k_c} \tag{6}$$

where Q_0 is the surface heat flow and k_C is the mean crustal thermal conductivity. We next assume that k_m = k_c = k and eliminate T_M from these two equations to obtain

$$Q_M = \frac{2kT_B - Q_0 h_c}{2h_L - h_c} \tag{7}$$

This equation shows how the surface heat flow, the lithosphere thickness and the mantle heat flow are related to one another. An increase of surface heat flow and a decrease of lithospheric thickness can compensate one another with little change in mantle heat flow. The following example illustrates this point. Differences of crustal heat production in the Canadian Shield and in the Appalachians induce changes of Moho temperature that are as large as 200 K [*Rolandone et al.*, 2003; *Mareschal and Jaupart*, 2004]. For a mantle heat flow of 12 mW m^{-2}, the temperature gradient in the mantle part of the lithosphere is $\sim$4 K km^{-1}. Thus changing the Moho temperature by 200 K implies a 50 km difference in lithospheric thickness with no change of Moho heat flow.

4.3. Heat Production Heat Flow Relationship

[27] The average heat flow and the average surface heat production in the Uchi, Wabigoon, and Wawa subprovinces are well correlated (Figure 8 and Table 5). This suggests that for these three subprovinces, the bulk crustal heat production is related to the surface value. We may calculate the thickness over which the observed differences of heat production at the surface can account for the heat flow variations. To take one further step, we assume that $Q_r = Q_M$ and use the above estimates for the Moho heat flow. The

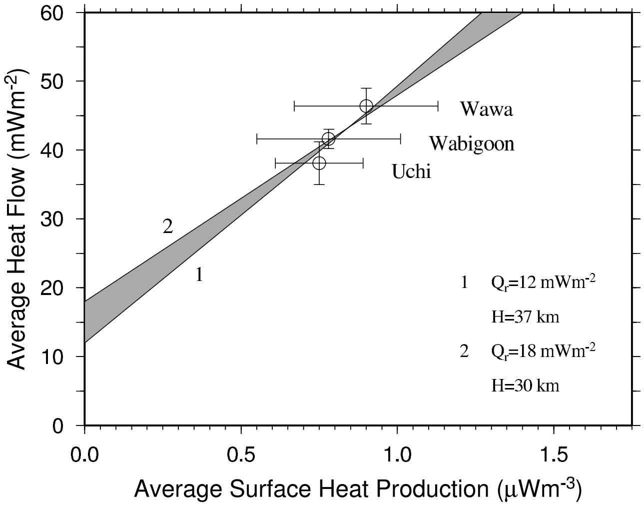

Figure 8. Mean heat flow and surface heat production in the Uchi, Wabigoon, and Wawa subprovinces of the Superior. The averages contain data presented in Table 5 where sites affected by late stage thermal perturbations have been removed. Bars show the standard error on the mean. The grey zone marks the upper and lower limits of the inferred relationship, taking a wide range of estimates for Q_M between $12 \leq Q_M \leq 18$ mW m^{-2}.

average values of heat flow $\overline{Q}$ and surface heat production $\overline{A}$ can be fitted to a linear relationship:

$$\overline{Q} = Q_r + H\overline{A} \quad (8)$$

where H is the thickness of the heat producing layer. The depth scale H lies within a 30–37 km range, and hence is much larger than D values for the (local) linear heat flow heat production relationship (~10 km in continents [*Sclater et al.*, 1980]). The large H value is consistent with the assumed values for Q_r and implies that it is the entire crust that makes the differences between the average surface heat flow in the three granite-greenstone subprovinces. This is reflected in values of about 1 for the differentiation index (Table 6). For these three subprovinces, therefore the depth-averaged heat production is close to the surface average. We thus conclude that the western Superior crust is poorly stratified.

[28] These results are supported by seismic refraction and gravity studies in the western Superior province. *Musacchio et al.* [2004] show that lower crustal chemical compositions estimated from V_P, V_p/V_s, and density are generally intermediate (57–66% SiO_2). This requires the presence of 25–60% granitic rocks in the lower crust, which is significantly higher than estimates for average Archean crust. Thus, on the whole, differentiation between an enriched granitic-rich upper crust and a depleted mafic lower crust is not as well developed in the western Superior crust as elsewhere.

[29] The above arguments and observations indicate that the western Superior province is poorly stratified. Variations amongst the different subprovinces and belts are relatively small, indicating a remarkable uniformity in crust-forming mechanisms at that time. The Wawa subprovince has the most radiogenic crust. Compilations of crustal heat production in the Wawa subprovince have been made by *Sage et al.* [1996] and *Polat and Kerrich* [2000]. An area-weighted average crustal heat production rate by *Shaw et al.* [1994] gives a value nearly identical to our estimate of 0.9 μW m^{-3} (refer to Tables 5 and 7), showing that the heat flow coverage is adequate. According to *Henry et al.* [1998], the TTG and dioritic to granitic plutons of this subprovince have more juvenile isotopic compositions than those of the Quetico and Wabigoon subprovinces. The Quetico and Wabigoon subprovinces have more developed crustal isotopic signatures, indicating extensive reworking of older continental crust.

Table 6. Average Thermal Properties of Juvenile Continental Crust of North America[a]

Province	Age, Ga	$\overline{Q}$, mW m^{-2}	σ_Q, mW m^{-2}	N_Q	$\overline{A}$, μW m^{-3}	σ_A, μW m^{-3}	N_A	h, km	D_I	References[b]
Slave Province	3.1-2.9	51.0 ± 3.5	6.0	3	1.7-2.3			36	2.1 ± 0.5	
Lac de Gras	-	46	6.0	2	1.7		AWA[c]			1
										2
Jericho	-	54		1	2.16		AWA[c]			3
Yellowknife	-	53		1	2.3		AWA[c]			4
Superior Province	2.9-2.6	41.2 ± 0.9	7.3	64	0.76 ± 0.08	0.62	56	41	1.2 ± 0.1	5
Uchi Subprovince	2.9-2.67	38.1 ± 3.1	8.3	7	0.75 ± 0.14	0.38	7		1.3 ± 0.2	
Wabigoon Subprovince[d]	2.9-2.67	41.6 ± 1.4	4.4	10	0.78 ± 0.23	0.72	10		1.2 ± 0.2	
Wawa Subprovince[e]	2.73-2.66	46.4 ± 2.6	7.8	9	0.90 ± 0.23	0.62	7		1.2 ± 0.2	
Abitibi Subprovince	2.73-2.66	38.5 ± 1.4	7.4	30	0.40 ± 0.07	0.32	24		0.7 ± 0.1	
Trans-Hudson Orogen	2.1-1.8	37.0 ± 1.1	7.0	38	0.6 ± 0.08	0.48	36	40	1.1 ± 0.2	6
Wopmay Orogen	1.95-1.8	90.0 ± 1.0	11.0	12	4.8 ± 0.05	1.0	20	36	2.3 ± 0.1	7
Grenville Province	1.3	41.0 ± 2.0	11.0	30	0.80		AWA[c]	40	1.3 ± 0.2	8
Appalachians	0.3	57.0 ± 1.5	13.0	79	2.6 ± 0.27	1.9	50	40	2.5 ± 0.2	9

[a]The ages given correspond to the ages of the major crust-forming events. h is the province-wide average crustal thickness from [*Perry et al.*, 2002] and D_I is the differentiation index. Errors on D_I are calculated assuming a wide range for Q_M between 12 and 18 mW m^{-2}.

[b]References are 1, *Thompson et al.* [1995]; 2, *Mareschal et al.* [2004]; 3, *Russell and Kopylova* [1999]; 4, *Lewis and Wang* [1992]; 5, this paper; 6, *Rolandone et al.* [2003]; 7, *Lewis et al.* [2003]; 8, *Mareschal and Jaupart* [2005]; and 9, [*Jaupart and Mareschal*, 1999].

[c]An area-weighted average.

[d]Nipigon Embayment sites perturbed by late intrusives removed from average.

[e]Kapuskasing site perturbed by late uplift removed from average.

Table 7. Crustal Heat Production in the Wawa Subprovince[a]

Lithology	U, ppm	Th, ppm	K, %	A, $\mu W\ m^{-3}$	N_A	References[b]
Whole Wawa subprovince						
Average Weighted Area	0.90	6.40	2.79	0.94	56	1
TTG Plutons	1.62 ± 1.28	7.61 ± 6.17	[c]	1.12 ± 0.90	8	2
Bimodal volcanic arc sequences	0.83 ± 0.54	3.56 ± 2.35	[c]	0.55 ± 0.36	70	2
Michipicoten granites						
Tonalite-Trondjemite-Granodiorite Plutons						
Hawk Lake	3.0	14.5	3.36	2.09	3	3
Jubilee Stock	1.4	5.8	1.20	0.87	3	3
Gutcher Lake Stock	0.4	2.2	0.82	0.33	3	3
Syenite-Quartz-Monzonite Plutons						
Dickenson Lake Stock	0.4	12.0	3.28	1.24	3	3
Maskinonge Lake Stock	2.5	14.2	3.63	1.96	3	3
Troupe Lake Stock	2.2	10.2	3.12	1.56	3	3

[a]Summary of averaged heat production values of the Wawa subprovince crustal rocks.
[b]References are 1, *Shaw et al.* [1994]; 2, *Polat and Kerrich* [2000]; and 3, *Sage et al.* [1996].
[c]K/U assumed to be 1.2×10^4.

[30] Over the rather small horizontal distances that separate the three subprovinces, variations in the Moho heat flow are necessarily small, as explained above. This is consistent with the data shown in Figure 8. If there were variations of the mantle heat flow, they would need to be proportional to those of the average surface heat production. To our knowledge, no physical mechanism can explain how these independent variables could be linked to one another.

5. Large-Scale Variations of Crustal Heat Production in North American Provinces

[31] We now develop a broader perspective of crustal evolution on the scale of the whole North American continent using heat flow and heat production data from five major geological provinces: the early Archean Slave Province, the Neo-Archean Superior Province, the Paleo-Proterozoic Trans-Hudson Orogen, the late Proterozoic Grenville Province and the Phanerozoic Appalachian Province (Figure 1). For each province, we list values of two important parameters, the surface average crustal heat production and the differentiation index, which allow calculation of the bulk average heat production (Table 6). These parameters can only be interpreted within a geological framework, which is briefly reviewed below. Together, these five provinces make up a representative sample of the continental crust and cover the major episodes of crustal growth in North America. With the exception of the missing Rae-Hearne craton, the five provinces allow a continuous NE-SW profile across stable North America. They document different types of crust and different mechanisms of crustal growth.

5.1. Other Major Geological Provinces of North America

5.1.1. Slave Province

[32] Compared to the Superior, the Slave Province is characterized by a greater abundance of felsic volcanic rocks and by large volumes of sedimentary rocks and granitic basement. The 2.9–2.6 Ga volcanic and sedimentary rocks overlie older sialic basement [*Bowring et al.*, 1990; *Isachsen and Bowring*, 1994].

[33] Three standard heat flow measurements and estimates based on geothermobarometry on xenoliths give an average surface heat flow of 51 ± 3 mW m^{-2} [*Mareschal et al.*, 2004]. With such a small data set, it is impossible to properly evaluate the error on the average value. We note that the xenolith data, which record temperatures at great depths in the lithosphere, are consistent with the heat flow data [*Mareschal et al.*, 2004]. Temperatures at such depths are sensitive to the average crustal heat production over large horizontal distances, and hence indicate that the heat flow values are truly representative of the bulk crust. All heat flow sites for the Slave Province intersect the older metamorphosed crystalline basement, which is very enriched in radioactive elements: its average heat production of 2.01 ± 0.28(σ) $\mu W\ m^{-3}$ [*Thompson et al.*, 1995] is more than double that of the average Archean crust [*Jaupart and Mareschal*, 2003]. Numerous granite intrusions post-date the major magmatic and tectonic events (2.62–2.58 Ga) [*Henderson*, 1985; *Yamashita et al.*, 1999] and dot the whole province with high heat production rates (8–15 $\mu W\ m^{-3}$) [*Thompson et al.*, 1995]. Table 6 lists values of the average surface heat production in three different areas encompassing the heat flow sites, which rely on extensive sampling of all rock types present. All three values are elevated.

[34] Because of the sparsity of heat flow measurements in the Slave Province, values of the bulk average heat production and of the differentiation index must be regarded as preliminary.

5.1.2. Wopmay Orogen

[35] West of the Slave Province, the Wopmay orogen has very high surface heat production and heat flow, with average values of 4.8 $\mu W\ m^{-3}$ and 90 mW m^{-2}, respectively [*Lewis et al.*, 2003]. Most of these heat flow values were obtained from bottomhole temperature measurements in oil wells with limited control on thermal conductivity and may not be as reliable as those of the other provinces. U, Th and K concentrations were measured on drill cuttings from the crystalline basement at the base of the sedimentary cover. These were taken from within of few meters of the major erosional unconformity at the top of the basement and were once exposed to weathering. *Lewis et al.* [2003] found

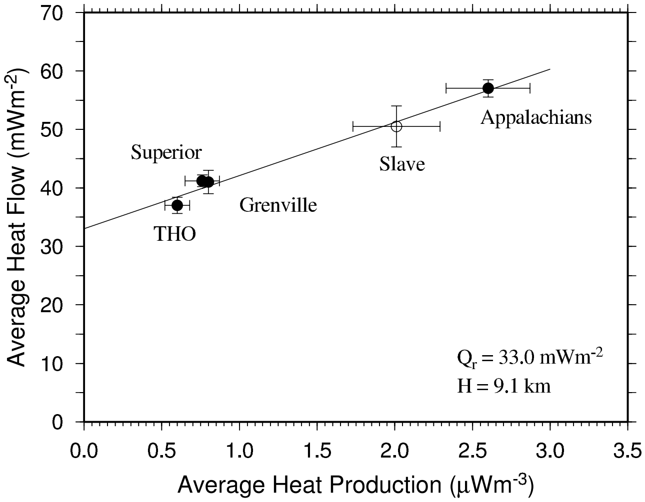

Figure 9. Mean heat flow and surface heat production in the Canadian Shield comprising averages for the Archean Slave and Superior provinces, the juvenile THO (excluding the Thompson Belt), the Grenville, and the Appalachians. The Slave Province data are represented by an open circle since the heat flow data set is small compared to those in the other provinces. Bars show the standard error on the mean. The line is the best fit to the data.

that they were depleted in radioelements by alteration processes and attempted a correction. The reliability of the heat flow and heat production data in this orogen is difficult to assess and we have excluded them from our analysis. These data do demonstrate, however, that high heat flow values can be accounted for by elevated heat production in the upper crust [*Lewis et al.*, 2003]. These data are consistent with the Wopmay orogen being made up of metasediments derived from the Slave Province.

5.1.3. Trans-Hudson Orogen (THO)

[36] In this 1.8 Ga orogen, four belts with different origins and crustal structures can be defined: the northern and southern volcanic belts, the Central Gneiss Domain composed of metasedimentary rocks, and the Thompson belt at the easternmost edge of the province [*Rolandone et al.*, 2002]. Juvenile rocks account for a large fraction of surface rocks in all belts except the Thompson belt, which is exclusively made up of reworked and metamorphosed Archean sediments. In this belt, heat flow is high (53 mW m^{-2}) due to the highly radiogenic metasediments. Juvenile THO crustal material is poor in radioelements [*Mareschal et al.*, 1999]. In the southern volcanic belt, surface heat production is low ($0.3 \pm 0.2(\sigma)$ μW m^{-3}), but the heat flow is average (42 ± 1.8 mW m^{-2}) [*Rolandone et al.*, 2002]. This belt is underlain by highly radiogenic Archean basement rocks of the Sask craton [*Lucas et al.*, 1993; *Lewry et al.*, 1994; *Rolandone et al.*, 2002]. In this province, high heat flow and heat production areas are those with the oldest rocks: the Archean Sask basement or the Thompson belt.

[37] The northern volcanic belt is made of island arc volcanics and abuts against an Andean-type continental magmatic arc. This belt therefore allows an interesting comparison with the older arcs of the Superior province, the Uchi, Wabigoon and Wawa belts. Present-day values of the average surface heat production in all these belts are very close, ~0.8 μW m^{-3} (see *Rolandone et al.* [2002] and Table 6). Corrected for age, however, the THO northern volcanics are slightly less enriched than those of the Superior.

5.1.4. Grenville Province

[38] The Grenville Province is a heterogeneous mosaic of terranes with different origins, compositions and tectonic/magmatic histories which were imbricated against one another during several orogenic events terminating with the Grenville orogeny at circa 1.0 Ga [*Rivers et al.*, 1989]. Most of the rocks had a long history of prior orogenic and magmatic events and were not made of material newly extracted from the mantle. One exception is the relatively small Allochthonous Monocyclic Belt, which has arc volcanics and plutonic rocks mixed in with metasediments. This belt includes many enriched granites and has an average heat flow of 44 mW m^{-2}, higher than the average value of 37 mW m^{-2} in the rest of the province [*Pinet et al.*, 1991; *Jaupart and Mareschal*, 1999].

5.1.5. Appalachians Province

[39] This narrow (~200–500 km wide) belt at the edge of the North American continent exhibits high-grade metasedimentary rocks with island arc volcanics and a large number of granitic plutons. In a succession of collisional events between about 470 Ma and 350 Ma, granites were generated from the metasedimentary formations with little mantle input [*Lathrop et al.*, 1996]. Anorogenic granites of the White Mountain series were emplaced between ~240 and 100 Ma, probably above a hot spot [*Foland and Allen*, 1991]. These alkaline granites were produced from mantle-derived mafic magmas but bear a considerable crustal imprint [*Foland and Allen*, 1991]. Seismic and geochemical data indicate the presence of older Grenville basement beneath the upper crustal units [*Spencer et al.*, 1987]. U and Th concentrations are high in both the metasediments and the granites [*Jaupart et al.*, 1982; *Chamberlain and Sonder*, 1990]. Heat flow is very high over enriched granites (with a maximum of 97 mW m^{-2} over the White Mountain batholith itself) and much lower elsewhere [*Jaupart et al.*, 1982].

5.2. Heat Flow Systematics

[40] On the continental scale and from a time evolution perspective, the average heat flow decreases from about 51 mW m^{-2} in the oldest province (the Slave) to a minimum of 37 mW m^{-2} in the THO and then increases again in younger provinces reaching a high of 57 mW m^{-2} in the youngest province, the Appalachians (see Table 6). The average heat production follows exactly the same trend, which suggests that the heat flow variations can be attributed largely to changes in crustal heat production.

[41] Figure 9 compares average values of heat flow and surface heat production for these five provinces. The remarkable correlation between heat flow and heat production demonstrates that heat flow variations in North America are controlled by changes of crustal heat production. A linear regression through the data points yields a slope of 9.1 km, indicating further that most of the heat flow variations originate in the upper crust. This relationship cannot be interpreted literally as indicating an upper layer of

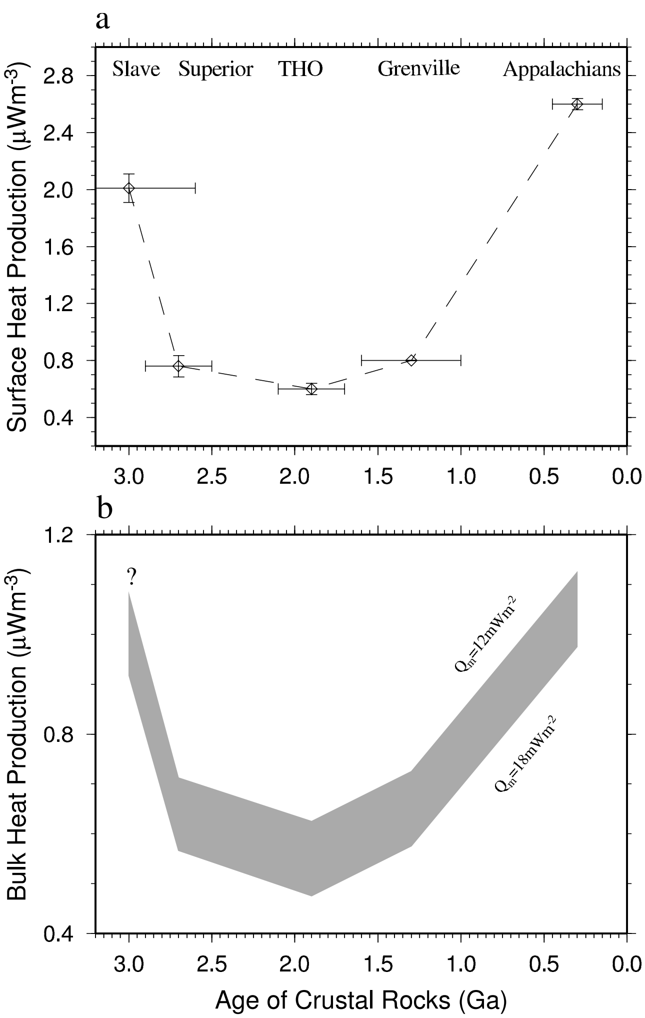

Figure 10. (a) Average surface crustal heat production as a function of ages of crustal accretion events in the Archean Slave and Superior provinces, in the Proterozoic THO and Grenville provinces, and the Paleozoic Appalachians. Error bars in y show the standard error on the mean. Bars in x are the uncertainties in the ages of major crustal accretion events. (b) Average bulk crustal heat production as a function of ages of crustal accretion events. Average bulk crustal heat production is calculated based on a large range for Moho heat flow between $12 \leq Q_M \leq 18$ mW m^{-2}. Crustal thickness, used in the calculation is based on the mean value for each region according to *Perry et al.* [2002]. The Slave Province bulk heat production is poorly constrained since only three heat flow sites are available.

uniform thickness throughout North America because the average heat flow values lump together different kinds of crustal structures and stratifications. We have demonstrated above that the western Superior crust is poorly stratified. The linear relationship does show that in the lower crust, horizontal variations of average heat production are small and/or of short wavelength [*Mareschal and Jaupart*, 2004].

[42] Formally, the data in Figure 9 do not rule out variations of mantle heat flow between the five provinces. They require, however, that such variations are exactly balanced by variations of heat production in the lower crust. It is hard to explain how this might be achieved. The simplest hypothesis is that the mantle heat flow is approximately the same beneath the five provinces, which, as shown above, is supported by independent arguments. For further confirmation, we briefly examine alternative causes for the heat flow variations: changes of crustal thickness and/or lithospheric thickness.

[43] The regional averages of crustal thickness vary only slightly from about 36 km in the Slave to 41 km in the Superior [*Perry et al.*, 2002]. To account for the difference in heat flow, crustal thickness should vary in the opposite direction. From seismic tomography studies, the lithospheric thickness is 250 ± 50 km in the Slave Province [*Bostock*, 1998], about 270–300 km in the Superior [*Sol et al.*, 2002], and about 270 km in the THO [*Bank et al.*, 1998]. These estimates refer to the total vertical extent of seismic velocity anomalies, which lumps together the purely conductive upper region and the underlying convective boundary layer [*Jaupart et al.*, 1998]. By definition, the seismically defined thickness is larger than the intersection of the conductive geotherm extrapolated downward with the isentropic temperature profile for well-mixed mantle. Petrological determinations of (P,T) equilibrium conditions for Slave Province xenoliths lead to low values of mantle heat flux which are comparable to those of the Superior Province [*Russell et al.*, 2001]. They also show that at the same depth, temperatures are lower beneath the Slave Province than beneath the Superior craton [*Rudnick and Nyblade*, 1999, and that the intersection of the conductive geotherm with the 1300°C adiabat, which defines the base of the lithosphere, may be ∼30 km deeper beneath the Slave than the Superior [*Mareschal et al.*, 2004]. Such differences in crustal or lithospheric thickness cannot account for the observed heat flow variations [*Mareschal and Jaupart*, 2004].

5.3. Time Evolution of Crustal Composition

[44] The rocks exposed today in the Canadian Shield correspond to different metamorphic grades (see Appendix A). It would be useless, however, to try to link observed differences of heat production to changes in the erosion level. It is now well established that there is no universal distribution of heat production with depth in the crust and that in many regions, upper crustal layers are depleted with respect to the middle and lower crust [*Jaupart and Mareschal*, 2003]. This is exemplified by the Abitibi subprovince with its thick cover of depleted greenstones and by the southern volcanic belt of the THO. Within a single province, there is no relationship between metamorphic grade and heat production. For example, in the western Superior, high-grade metasedimentary rocks of the Quetico and English River belts are enriched compared to the lower-grade volcanic and plutonic rocks of the Wabigoon and Uchi belts. The low grade rocks of the THO are also poor in radioelements compared to deep crustal exposures of the Grenville. As explained above, crustal thickness does not vary much between the provinces of this study.

[45] For our present purposes, it is important to recognize that the data record the time evolution of crustal-building episodes on the same continental block. The surface and depth-average heat production follow similar trends (Figure 10). Both decrease through the Archean, reach a

Table 8. Heat Flow and Heat Production Data in Australian Cratons[a]

Craton	Age, Ga	$\overline{Q}$, mW m^{-2}	N_Q	$\overline{A}$, μW m^{-3}	N_A
Pilbara	3.4-2.9	43 ± 1.5	4		
Yilgarn	3.0-2.6	39 ± 1.5	23	3.3	540
Western Gawler	2.7-2.0	54 ± 2	3		
Eastern Gawler	1.8-1.5	94 ± 3	6	3.6	90

[a]Average heat flow $\overline{Q}$ and standard error and average heat production $\overline{A}$ [from *Neumann et al.*, 2000; *Jaupart and Mareschal*, 2003; *Sass and Lachenbruch*, 1979]. Because of the large number of samples, the standard error on heat production is small, although the standard deviation is as large as the mean.

minimum in the Paleo-Proterozoic (THO) and show a marked increase in the Phanerozoic. On a global scale for all continental areas, when collected in only the three age groups of Archean, Proterozoic and Phanerozoic, average heat flow values, and hence average crustal heat production rates, increase with time (i.e., with decreasing age) [*Sclater et al.*, 1980; *Pollack et al.*, 1993; *Nyblade and Pollack*, 1993]. Such a global trend obscures the large heterogeneity of each age group and is not relevant to any specific continent, for example, North America.

[46] Carrying out the same analysis in other continents requires an extensive database of heat flow and heat production, which is not available. Tables 8 and 9 list heat flow and heat production data for several Precambrian provinces in Australia and South Africa. Although it is not possible to determine the mantle heat flow with the same precision than in the Superior Province, it is clear that heat flow variations can be attributed to changes of crustal heat production. In Australia, this was shown a long time ago by *Sass and Lachenbruch* [1979], who noted that heat flow values over low heat production rocks were almost identical in Archean and Proterozoic provinces.

[47] The Australian heat flow data suggest that the bulk crustal heat production decreased during the Archean and reached a minimum just prior to the Archean-Proterozoic boundary. The Yilgarn has very high surface heat production with a differentiation index >3.5, larger than that of the Slave Province. In Australia, crustal heat production increased in the Proterozoic. The high surface and bulk crustal heat production in the eastern Gawler craton are due to the large volume of metasediments. From our perspective, the Gawler craton may be similar to the Wopmay orogen (Figure 1).

[48] In South Africa, heat flow values in the Archean Zimbabwe and Kaapvaal cratons are close to those of the Superior Province. Heat flow is higher in the Limpopo belt which separates these two cratons. The small width of the belt (≈120 km) suggests that the heat flow variation has a crustal origin. Interestingly, rocks from this belt were derived from the margins of the craton and hence may be analogous to those of the Thompson belt in the THO. Heat flow and heat production are both high in the mid-Proterozoic Namaqua-Natal belt, with values that are close to those of the Appalachians province.

[49] Differences in crustal heat production between provinces thus illustrate that the processes of crustal formation and stabilization rather than age determine crustal heat production.

5.4. Crust-Building Mechanisms

[50] The Slave and Superior provinces were shaped by volcanic processes with little evidence for continental collision and crustal thickening, save for the very last episode marking their amalgamation into the craton. For these early continental blocks, reworking and imbrication of earlier crust is necessarily limited. Geochemical studies confirm this [*Henry et al.*, 1998, 2000]. The metasedimentary belts of the Superior (English River, Quetico) dip beneath adjacent greenstone belts (Uchi, Wabigoon, Wawa) [*Davis*, 1998; *Musacchio et al.*, 2004], but all these units are similar in age and bulk composition. In such early times, there was not much geochemical variety in crustal rocks. The THO offers a different case, with thrusting of older cratonic crust beneath juvenile volcanic arcs and marginal basins. In this province, the juvenile crust is poor in radioelements and the bulk of the crustal heat production is provided by ancient cratonic crust. The Grenville province represents a major compression event and is shaped by thrusting and thickening, with little addition of juvenile crust. The Appalachians record several episodes of continental collision, with island arcs, accretionary sedimentary prisms and abundant plutonic activity with little addition of juvenile material. One highly significant feature common to all the provinces is that the metasedimentary belts are systematically enriched in radioelements and associated with high heat flow anomalies. This is conspicuous in the Superior Province, with the English River and Quetico belts standing out amongst their adjacent volcano-plutonic belts. This is also exemplified by the Thompson belt in the THO and by the Allochtonous Monocyclic Belt in the Grenville. The most enriched province, the Appalachians, has large volumes of metasedimentary rocks.

[51] With the trend shown in Figure 10 and with the large variations of surface heat production within each province, it is clear that age is not a control parameter for crustal heat production. The Earth has been cooling down over geologic time, leading to systematic changes in crustal and lithospheric melting conditions. The nonmonotonous variation of average crustal heat production with age suggests that more than one mechanism is at work. The size of cratons and their geometry provide a tentative framework for understanding this trend. The THO marks the final welding of the different Archean cratons which now make the core

Table 9. Heat Flow and Heat Production Data in Southern African Cratons and Belts[a]

Tectonic Unit	Age, Ga	$\overline{Q}$, mW m^{-2}	N_Q	$\overline{A}$, μW m^{-3}
Zimbabwe Craton	3.4–2.6	47 ± 3.5	10	1.34
Kaapvaal Craton	3.3–2.6			
Basement to Witwatersrand Basin[b]		∼44	81	1.8
Limpopo Belt	3.2–2.6	53 ± 1.5	4	
Namaqua-Natal Belt	2.0–1.1	61 ± 2.2	21	2.3

[a]Average heat flow $\overline{Q}$ and standard error and average heat production $\overline{A}$ [from *Nicolaysen et al.*, 1981; *Jones*, 1987; *Jones*, 1998; *Kramers et al.*, 2001].
[b]heat flow from beneath the stratified sedimentary rocks.

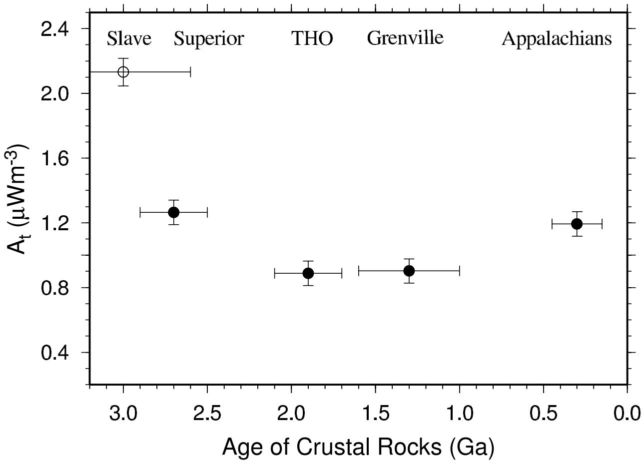

Figure 11. Average bulk crustal heat production back calculated to its value at the time of accretionary events in the given geological provinces. The Slave Province calculation is represented by an open circle since the heat flow data set is small compared to those in the other provinces. Error bars on A_t were calculated assuming a wide range for Moho heat flow between $12 \leq Q_M \leq 18$ mW m^{-2}. Error bars in x are the uncertainties in the ages of major crustal accretion events.

of the North American continent. Prior to 2.0 Ga, continents were smaller than today and probably more mobile. As a consequence, active margins accounted for a larger fraction of continental area and volume than today [see *Allègre and Jaupart*, 1985]. During the Proterozoic, two mechanisms were at work, accretion of juvenile crust and reworking of old crust, resulting in large differences in heat production between Proterozoic provinces, such as the Wopmay and the THO in North America, or the eastern and western parts of the Gawler craton of Australia. Between 2.0 and 1.0 Ga, the amalgamation of cratons into large blocks restricted magmatic activity in both volume and area. Reworking became the dominant process with little addition of juvenile material. In such circumstances, the total amount of crustal heat production did not change significantly. Production of enriched crust takes specific settings where volcanic activity and sedimentation can be sustained over long periods of time in the same region, as in the Appalachians. The counterexample is nicely provided by the THO, where short-lived island arc activity did not produce enriched crust.

[52] Back calculation of the average crustal heat production at the time of accretionary processes shows an age-heat production trend (Figure 11). The highest concentration of heat production occurred in the oldest Slave Province, and decreased through the Archean and Proterozoic. The calculated radioelement enrichment suggested in the Phanerozoic Appalachians, following cratonic stabilization, is less marked than presently observed (Figure 10). The differentiation index (D_I) for the North American provinces shows no relationship with age (Figure 12). It shows a marked trend of increased differentiation with average crustal heat production. This strongly supports the suggestion that the heat producing elements must be brought to shallow levels for a very enriched crust to become stable [*Mareschal and Jaupart*, 2006]. This is discussed below.

5.5. Crustal Differentiation

[53] *Kemp and Hawkesworth* [2003] have recently assessed the secular evolution of the continental crustal chemistry and the role of granites in crustal generation. They show that Archean calc-alkaline granites have significantly higher U and Th than their Paleozoic analogs, and show evidence for progressive differentiation over geologic time, from the generation of basaltic protoliths to subsequent intracrustal and supracrustal recycling processes.

[54] One interesting clue is provided by the differentiation index, i.e., the contrast between the average crust and the enriched upper layers. Where the average crustal heat production is large, differentiation is also pronounced, as shown by the Slave and the Appalachians. In these regions, an enriched upper crust is due to granite emplacement which usually marks the end of geological activity. The association of an enriched upper crustal layer with a large average crustal heat production (A_c) suggests that this late plutonic phase is due to, or facilitated by, in situ radiogenic heat production leading to high temperatures in the lower crust. In the Appalachians, for example, isotope systematics demonstrate that granites were later generated by anatexis of metasedimentary rocks [*Lathrop et al.*, 1996]. From a thermal standpoint, this final, purely internal, melting episode allows thermal stabilization: redistributing the radioelements through extraction and upward migration of evolved enriched melts ultimately acts to lower crustal temperatures.

6. Conclusions

[55] Heat flow studies allow the determination of the total amount of heat produced by radioactive decay in continental

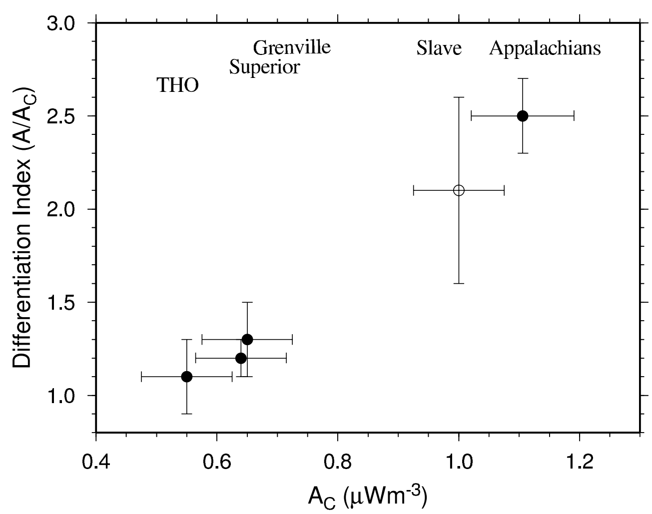

Figure 12. Differentiation index of crustal rocks ($\overline{A}/A_C$), where $\overline{A}$ is the surface-averaged heat production and A_C is the bulk average heat production, as a function of the bulk average heat production. The Slave Province calculation is represented by an open circle since the heat flow data set is small compared to those in the other provinces. Error bars associated with D_I and A_C were calculated assuming a wide range for Moho heat flow between $12 \leq Q_M \leq 18$ mW m^{-2}.

crust, including the lower crust which can seldom be sampled. In this paper, we have presented a detailed heat flow–heat production data set for the Superior Province of the Canadian Shield. The average surface heat flow is 41.2 ± 7.3(σ) mW m^{-2}, based on 64 high-quality measurements. This value is similar to that of the surrounding Grenville Province and the THO. The average surface heat production in the Superior Province is 0.76 ± 0.62(σ) μW m^{-3} based on data from 56 sites. Sites affected by late stage thermal perturbations were removed from the heat flow and heat production averages. Such perturbations generally lead to lower heat production and heat flow values owing to intrusions of mafic composition, which do not reflect the original crustal composition. The crust of the southwestern belts of the Superior Province is largely unstratified. The similarity in the heat flow and heat production values between three different granite-greenstone belts suggests a remarkable uniformity in crust-building mechanisms. Average heat flow and heat production values depend on the geology of the subprovince, e.g., volcano-plutonic or metasedimentary, and on the amount of reworking of juvenile crust.

[56] On a continental-scale, the bulk crustal heat production in five major geological provinces of North America varies significantly. The data define a peculiar evolution through time, with high heat flow and heat production in the oldest province, the Archean Slave craton, and lower heat flow and heat production through the Proterozoic, followed by even higher heat flow and heat production values in the Paleozoic provinces. On a local scale, high heat flow and heat production subprovinces are systematically characterized by large accumulations of metasedimentary rocks. Thus the average heat flow and heat production of a province reflect more the proportion of metasedimentary terranes than other petrological or geochemical characteristics. We have shown that differences in crustal heat production between Proterozoic provinces in North America, Australia and South Africa suggest that the crustal formation and stabilization processes, not age, determine crustal heat production.

[57] The large data set available for North America allows calculation of a simple differentiation index for the crust. This index provides a measure of the segregation of enriched rocks in the upper crust. It is correlated with the bulk average crustal heat production, suggesting that crustal differentiation is largely driven by internal crustal heat production.

Appendix A: Study Area and Tectonic Setting: Geology of the Superior Province

[58] The subprovinces covered in this study are presented in order from north to south.

A1. Uchi (2.9–2.72 Ga)

[59] The Uchi Subprovince is characterized by narrow, sinuous, partly interconnected greenstone belts surrounded and intruded by voluminous granitoid rocks [*Card*, 1990]. Metasedimentary rocks are also present. In the greenstone assemblages, basalts are oceanic tholeiites, whereas andesites and fractionated felsic volcanics bear the signature of sialic crust assimilated in mafic magmas [*Thurston and Fryer*, 1983]. Volcanic rocks belong to two age groups spanning 2.9–2.8 Ga and 2.75–2.73 Ga, respectively.

A2. English River (2.71 Ga)

[60] This metasedimentary subprovince probably represents a major suture zone with gneisses and migmatites accounting for approximately 65% of the bedrock [*Card*, 1990]. The metasediments are derived from volcanic and plutonic protoliths [*Breaks et al.*, 1978; *van de Kamp and Beakhouse*, 1979]. S-type granites with metasedimentary inclusions occur throughout the migmatitic complexes. Across the belt, the pattern of metamorphism is symmetrical with respect to the axis, with greenschist facies in marginal zones increasing to granulite facies in the interior.

A3. Wabigoon (3.0–2.70 Ga)

[61] In this volcano-plutonic subprovince, the surface geology consists of about 2/3 plutonic and 1/3 supracrustal rocks. Supracrustals include small amounts of metasediments and are dominated by tholeiitic-komatiitic volcanics (60%) and calc-alkalic-shoshonitic volcanics (30%) [*Card*, 1990]. Western and eastern greenstone domains are separated by a central plutonic region [*Edwards and Sutcliffe*, 1985]. The western domain consists mainly of juvenile ≈2.7 Ga greenstones and granites, in contrast to the eastern part made of older volcanic and intrusives [*Blackburn et al.*, 1991; *Henry et al.*, 1998]. The central region contains vestiges of 2.93–3.07 Ga crust, and is postulated to be the basement to the bordering greenstone domains on either side [*Thurston and Davis*, 1985].

A4. Quetico (2.70–2.69 Ga)

[62] Extending for at least 1200 km with large width variations (10 to 100 km), the Quetico subprovince consists almost exclusively of metasedimentary and plutonic rocks, with most of the plutons in the axial zone. The metamorphic grade follows the same pattern as the English River subprovince, increasing from greenschist facies at the margins to amphibolite facies in the axial regions. Late orogenic sedimentation at ≈2.7 Ga was short-lived and lasted for about 10 Myr. Most of the supracrustals are younger than the igneous rocks of the adjacent Wabigoon and Wawa belts [*Davis*, 1998].

A5. Wawa (2.9–2.67 Ga)

[63] This volcano-plutonic terrane lies at the southern edge of the Superior province. It hosts a number of large granitic intrusives and four greenstone belts (Vermilion, Shebandowan, Hemlo and Michipicoten) which together account for 35% of the exposures. These greenstone belts consist of approximately 60% tholeiitic and komatiitic volcanics, 20–25% calc-alkaline volcanics and 15–20% metasediments [*Card*, 1990]. In the Michipicoten greenstone belt, plutons occur over an area of ∼1400 km^2 and span over 200 Ma of evolution [*Sage et al.*, 1996].

A6. Abitibi (2.77–2.67 Ga)

[64] This province consists of 40% supracrustal rocks and 60% granitic rocks. Supracrustals consist of bimodal (mafic/felsic) volcanic series and coeval sediments intruded by numerous K-poor plutons of tonalite-trondhjemite affinity [*Ludden et al.*, 1986]. The bulk of the igneous, tectonic and metamorphic events were concentrated in a relatively short

time span between 2.74 and 2.69 Ga [*Ludden et al.*, 1986; *Corfu et al.*, 1989]. This was followed by the intrusion of granodioritic plutons which account for a small fraction of the exposures. The volcanic units form a layer of several kilometers in thickness, and are underlain by intraplated tonalites and layered mafic/felsic gneisses and anorthosites [*Percival and Card*, 1983; *Green et al.*, 1990; *Percival and West*, 1994]. Seismic images provide convincing evidence for lateral convergence, with the accretion of immature Abitibi supracrustal material onto an older microcontinent that today comprises the Opatica plutonic belt, which bounds the Abitibi to the north.

A7. Kapuskasing Structural Zone (2.75–2.5 Ga and 1.9 Ga)

[65] In the central part of the Superior Province, the Kapuskasing structural zone (KSZ), the Wawa domal gneiss terrane and the Michipicoten greenstone belt form part of the Kapuskasing uplift structure, which extends eastward from Lake Superior for about 120 km and terminates against the Abitibi Subprovince along a fault zone. The KSZ is made of east-northeast trending belts of various types of gneisses. The central and eastern parts of the uplift are underlain by rocks in upper amphibolite to granulite metamorphic grades, unlike the greenschist assemblages of the Abitibi. The KSZ is interpreted as an oblique cross section through about 20 km of Archean crust thrust southeastward 1.9 Ga, exposing parts of the lower continental crust [*Percival*, 1983; *Percival and Card*, 1983].

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