Heat flow in the Trans-Hudson orogen of the Canadian Shield: implications for Proterozoic continental growth

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Heat flow in the Trans-Hudson Orogen of the Canadian Shield: Implications for Proterozoic continental growth

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Abstract. Fourteen new heat flow and radiogenic heat production measurements have been obtained in the Paleo-Proterozoic Trans-Hudson Orogen of the Canadian Shield. This orogen, which consists of several distinctive belts, corresponds to a pulse of crustal growth through island arc magmatism between 1.9 and 1.8 Ga. The data now available include 17 previously published measurements. Heat flow variations that are related to the history of magmatism and internal differentiation of the belts provide constraints on the crustal assemblages in the different belts of the orogen. The average and standard deviation of heat flow values for the entire orogen, 42±11 mW m^{-2}, are identical to those of the older Superior Province and of the younger Grenville Province. For the orogen as a whole, heat flow is weakly correlated to the heat production of surface rocks. High heat flow values are found in the Thompson belt, consisting of metasedimentary rocks deposited on the ancient continental margin of the Superior craton. There the accumulation of sediments derived from older and differentiated continental upper crust has resulted in significant concentrations of radioelements in large volumes of rocks. The heat flow is low in the belts that expose juvenile Proterozoic crust consisting mostly of arc-related volcanic rocks. In the Flin Flon-Snow Lake Belt, the average heat flow is the same as the average of the orogen. The low heat production and the lack of correlation between heat flow and heat production suggest that the supracrustal volcanics exposed at the surface are thin and rest on a basement richer in radioelements. In the Lynn Lake belt, the heat flow is significantly lower than the average for the orogen although the surface heat production is not low. The heat flow data require a thin (<10 km) surface layer overlying the mid and lower crust depleted in radioelements. Around the town of Lynn Lake, heat flow is consistently low over a distance of ≈40 km. The coincidence between this "cold spot" and anomalously thick crust suggests that deep crustal roots may be preserved because of the stronger rheology implied by the low temperatures. The evolution of the Trans-Hudson Orogen exemplifies the interplay between the processes generating rocks of evolved composition, which require crustal thickening, and those forming "normal" continental crust with average thickness, which require crustal flow and soft crustal rheology.

1. Introduction

The Paleo-Proterozoic is a key epoch for the evolution of continents, which saw the assembly and welding of continental nuclei into enormous landmasses [*Hoffman*, 1988], as well as the extraction of large amounts of crustal material from the mantle [*Patchett and Arndt*, 1996; *Boher et al.*, 1992; *Arndt and Todt*, 1994]. The present architecture of the North American craton dates from about 1.8 Ga [*Hoffman*, 1989; *Lewry and Collerson*, 1990; *Lewry at al.*, 1990; *Gordon et al.*, 1990; *Ansdell and Norman*, 1995], when oceanic closure brought together the Rae-Hearne and Superior Archean provinces. This final assembly of the North American craton coincides with the formation of the Trans-Hudson Orogen (THO), which extends from North Dakota, across Manitoba and Saskatchewan, across Hudson Bay, into the Cape Smith fold belt in northern Quebec [*Hoffman*, 1988]. Until recently, knowledge of the deep structure

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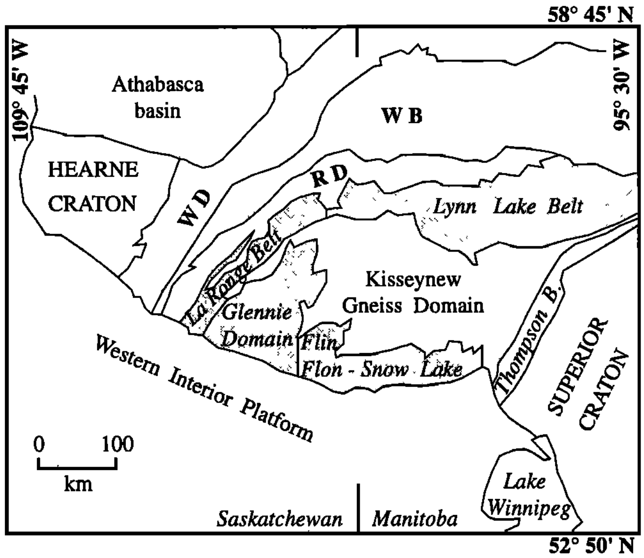

Figure 1. Geological map of the exposed Trans-Hudson Orogen in Manitoba and Saskatchewan, adapted from [*Lucas et al.*, 1996]. RD is the Rotenstone domain, WB is the Wathaman batholith, and WD is the Wollaston fold belt. Juvenile Proterozoic crust is exposed in the Reindeer tectonic zone including the Rotenstone, La Ronge-Lynn Lake, Glennie, Kisseynew, and Flin Flon-Snow Lake domains.

of this part of the North American craton was scanty. This lack has motivated the geological and geophysical studies conducted by the Lithoprobe program.

The THO has been covered by the Paleozoic sediments of the Williston basin in the south and is exposed only in northern Manitoba and Saskatchewan. Farther north, it is covered by the Hudson Bay basin. In the exposed part of the THO, four major tectonic zones have been identified. From east to west they are (Figure 1): (1) The Churchill-Superior boundary, a narrow zone, along the margin of the Superior craton, including the Thompson Nickel Belt, (2) the Reindeer tectonic zone, a ≈400 km wide zone including several belts of arc volcanics and metasediments, (3) the Wathaman batholith, an Andean-type magmatic arc, and (4) a deformed "hinterland" including the Wollaston fold belt and the Cree River zone.

Most of the juvenile Proterozoic crust, newly extracted from the mantle, is found in the ≈400-km-wide Reindeer zone, which consists of several distinctive belts: (1) the Lynn Lake and La Ronge belts to the northwest that are formed of island arc volcanic rocks, (2) the Kisseynew domain and the McLennan belt, made up of gneisses and interpreted as metasediments of a back arc basin, (3) The Glennie domain that contains metavolcanics, and (4) the Flin Flon and Snow Lake belts made up of arc volcanic and plutonic rocks. East of the Reindeer zone, the Thompson belt contains metasedimentary rocks deposited on the Superior Margin. Windows of Archean crust are exposed in the Glennie domain. The seismic studies have suggested that the amount of Archean crust preserved beneath the juvenile crust in the Reindeer zone is limited [*Lucas et al.*, 1993, 1994]. Current models of evolution suggest northwestward underthrusting of the belts of the Reindeer zone during the final assembly of the Sask, Rae-Hearne, and Superior cratons [*Ansdell et al.*, 1995]. The seismic studies have shown that the crustal thickness is variable from < 40 to ≈ 52 km beneath the THO [*Nemeth et al.*, 1996]. In North Dakota and Montana the Consortium for Continental Reflection Profiling (COCORP) studies have also shown a thicker crust under the continuation of the THO beneath the Williston basin [*Nelson et al.*, 1993].

Until recently, only eight heat flow measurements were available from sites sparsely distributed across the THO [*Drury*, 1985, and references there- in]. During the activity of the Lithoprobe transect, new heat flow and heat generation data were collected in the exposed part of the THO, in the Thompson belt, and in the Reindeer tectonic zone. A first series of measurements has confirmed the relatively high heat flow in the Thompson belt, on the former margin of the Superior craton [*Guillou-Frottier et al.*, 1996]. In this paper we present new data from different belts in the Reindeer tectonic zone. In contrast to the Thompson belt, where heat flow values are high for a shield region, the heat flow is very low in the Lynn Lake area, with some of the lowest values yet reported in the Canadian Shield. The heat flow and heat generation data provide solid constraints on crustal composition, on the amount of juvenile Proterozoic crust present in the Trans-Hudson Orogen, and on its composition. We discuss some implications of the thermal regime for the evolution of this part of the Canadian Shield.

2. Heat Flow Measurements

Heat flow and heat production data are presented for 14 new sites in the THO. The heat flow Q is determined from the measurements of the temperature gradient in boreholes and of the conductivity of rock samples:

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

where k is the thermal conductivity, T is temperature, and z is depth. Stable temperature gradients were obtained over several hundreds of meters (Table 1 and Figure 2). For each drill hole, core samples were collected and the thermal conductivity was measured by the divided bar method. A single conductivity determination relies on five measurements on samples of different thicknesses. This procedure allows the detection of local variations of mineralogy unrepresentative of the bulk composition of the geological formation. A correction for the effect of Pleistocene glaciations was applied to the data based on the climatic model of *Jessop* [1971]. This was done for consistency with previously published values, although there is some debate on the

Table 1a. New Heat Flow Data in the Glennie Domain, Kisseynew, and La Ronge and Lynn Lake Belts

Site Hole	Latitude	Longitude	Altitude, m	Dip, deg	Δh, m	N_k (N_t)	$< k >$, W m^{-1} K^{-1}	G, mK m^{-1}	Q, mW m^{-2}	σ_Q, mW m^{-2}	ΔQ, mW m^{-2}	Q_c, mW m^{-2}
Batty Lake												31 (C)
9804	55°09'52"	100°45'34"	310	75	70-320	6 (6)	3.43	8.28	27	0.04	4.13	31
Brabant												36 (A)
9603	56°07'47"	103°42'24"	370	74	307-553	14 (7)	2.73 †	12.4	34.0	2.3	2.2	36
9604	56°07'54"	103°42'01"	370	69	283-515	14 (5)	2.73 †	12.1	33.1	2.1	2.4	35
9605	56°07'51"	103°42'16"	370	73	277-449	14 (6)	2.73 †	12.2	33.3	2.4	2.4	36
Seabee Mine												32 (A)
9417 *	55°40'52"	103°37'37"	440	51	373-428	8 (8)	2.52 †	11.3	28.4	2.2	3.4	32
9418 *	55°40'52"	103°37'37"	440	58	377-475	8 (8)	2.52 †	11.6	29.2	2.4	3.3	33
9419 *	55°40'52"	103°37'37"	440	64	376-487	8 (8)	2.52 †	10.8	27.2	3.3	3.6	31
Waden Bay												44 (A)
9601	55°17'31"	105°01'11"	370	90	180-870	6 (9)	2.85	14.5	41.2	1.4	3.0	44
McWhirter Lake												39 (B)
9616	56°35'04"	101°39'56"	360	75	190-375	3 (6)	2.90	12.8	37.2	4.5	2.1	39
Fox Mine												32 (B)
9519	56°37'52"	101°38'02"	396	70	221-369	3 (6)	2.58	11.8	30.4	1.6	1.8	32
Wasekwan Lake												27 (B)
9514	56°44'50"	100°57'01"	340	70	102-378	3 (3)	2.48	10.5	26.1	1.1	1.0	27
Frances Lake												34 (B)
9614	56°49'38"	101°06'08"	340	72	196-399	6 (12)	4.03	8.1	32.7	3.1	3.2	36
9615	56°49'29"	101°06'25"	340	68	101-420	6 (11)	3.96	7.3	28.7	3.2	3.8	33
Farley Lake												26 (A)
9516	56°54'34"	100°26'07"	335	74	212-578	7 (6)	3.24 †	7.3	23.6	1.2	1.7	25
9517	56°54'34"	100°26'29"	335	72	331-534	7 (4)	3.24 †	7.7	25.1	1.2	1.4	26
9520	56°54'34"	100°26'18"	335	71	305-559	7 (4)	3.24 †	7.6	24.6	0.9	1.5	26
Ruttan Mine												38 (B)
9513 *	56°29'07"	99°36'21"	572	37	1076-1195	2 (4)	2.96	12.8	37.8	3.4	0.	38

For each borehole the location, altitude, dip at the collar of the drillhole, vertical depth interval used for heat flow determination, number of conductivity samples used (number of 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 are given. The quality of the heat flow value for each site is rated A, B, C, as discussed in text.

* Measurements made from the mine gallery.

† Site-averaged value.

Table 1b. New Heat Flow Data in the Flin Flon-Snow Lake Belt

Site / Hole	Latitude	Longitude	Altitude, m	Dip, deg	Δh, m	N_k (N_t)	$<k>$, W m^{-1} K^{-1}	G, mK m^{-1}	Q, mW m^{-2}	σ_Q, mW m^{-2}	ΔQ, mW m^{-2}	Q_c, mW m^{-2}
West Arm												51 (A)
9501	54°38'13"	101°50'51"	310	85	448-918	11 (14)	3.46	13.9	48.0	1.8	2.5	51
Tartan Mine												34 (A)
9505	54°51'28"	101°44'23"	340	75	203-558	9 (10)	2.95	10.3	30.3	1.7	3.5	34
Denare Beach												37 (A)
9609	54°39'29"	102°03'31"	330	53	364-578	8 (9)	3.1 †	11.2	34.6	1.0	2.9	38
9610	54°39'28"	102°03'27"	330	54	298-533	8 (9)	3.1 †	11.0	34.0	1.5	3.0	37
Snow Lake												41 (A)
9308	54°52'04"	99°58'51"	300	90	266-638	11 (11)	3.05	11.9	36.4	1.5	2.3	39
9309	54°51'16"	99°57'18"	290	65	411-661	10 (10)	3.83	10.4	39.8	3.3	3.0	43

For each borehole the location, altitude, dip at the collar of the drillhole, vertical depth interval used for heat flow determination, number of conductivity samples used (number of 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 are given. The quality of the heat flow value for each site is rated A, B, C, as discussed in text.

† Site-averaged value.

importance of these corrections [*Sass et al.*, 1971; *Mareschal et al.*, 1999b]. In all but one site the climatic correction is <10% of the measured value.

We have established the following criteria to rate the reliability of our heat flow measurements [*Pinet et al.*, 1991]. We divide the temperature profile for each borehole in subintervals within which the heat flow is calculated. The standard deviation is determined for all the heat flow values obtained. The sites rated A consist either of several boreholes deeper than 300 m giving consistent (within one standard deviation) heat flow values or a single borehole deeper than 700 m where the heat flow is stable over >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. Sites where differences between boreholes are larger than two standard deviations or consisting of a single shallow (<300 m) borehole are rated C.

The concentrations of U, Th, and K were measured following the technique described by *Mareschal et al.* [1989] in order to estimate the heat production rates of upper crustal samples. For each borehole, core samples from all the representative lithologies were collected. The heat production is obtained by averaging between these samples. Analytical errors on heat production measurements are <5% and are largest for low-radioactivity samples. For the purposes of interpreting heat flow data the main source of uncertainty is the sampling. Comparison of mean heat production from neighboring boreholes provides an estimate of this uncertainty.

3. New Sites

A summary of the new heat flow data is presented in Tables 1a and 1b. For each site we have measured the radioactive heat generation (Table 2). The temperature profiles used for heat flow determination are displayed in Figure 2. A short description of the sites follows.

3.1. McLean Belt-Kisseynew Domain

3.1.1. Batty Lake (hole 9804). This (320 m) mining exploration hole was drilled in the Kisseynew gneisses a few kilometers north of the Snow Lake belt. Effects of recent ground temperature warming have been detected and analyzed by *Guillou-Frottier et al.* [1998]. The resulting heat flow value is 32 mW m^{-2}. Because this value is based on measurements in a single and shallow drillhole, it is rated C.

3.1.2. Brabant (holes 9603, 9604, and 9605). The Brabant site lies in the McLennan tectonic zone at the boundary between the volcanic LaRonge belt and the McLean gneiss domain. Three boreholes (≈500 m) drilled in 1992 for mining exploration were logged on this site. Felsic and amphibole gneisses are the dominant lithology. The shallow parts (<200 m) of the temperature logs show the effect of recent ground surface temperature warming and possibly of deforesta-

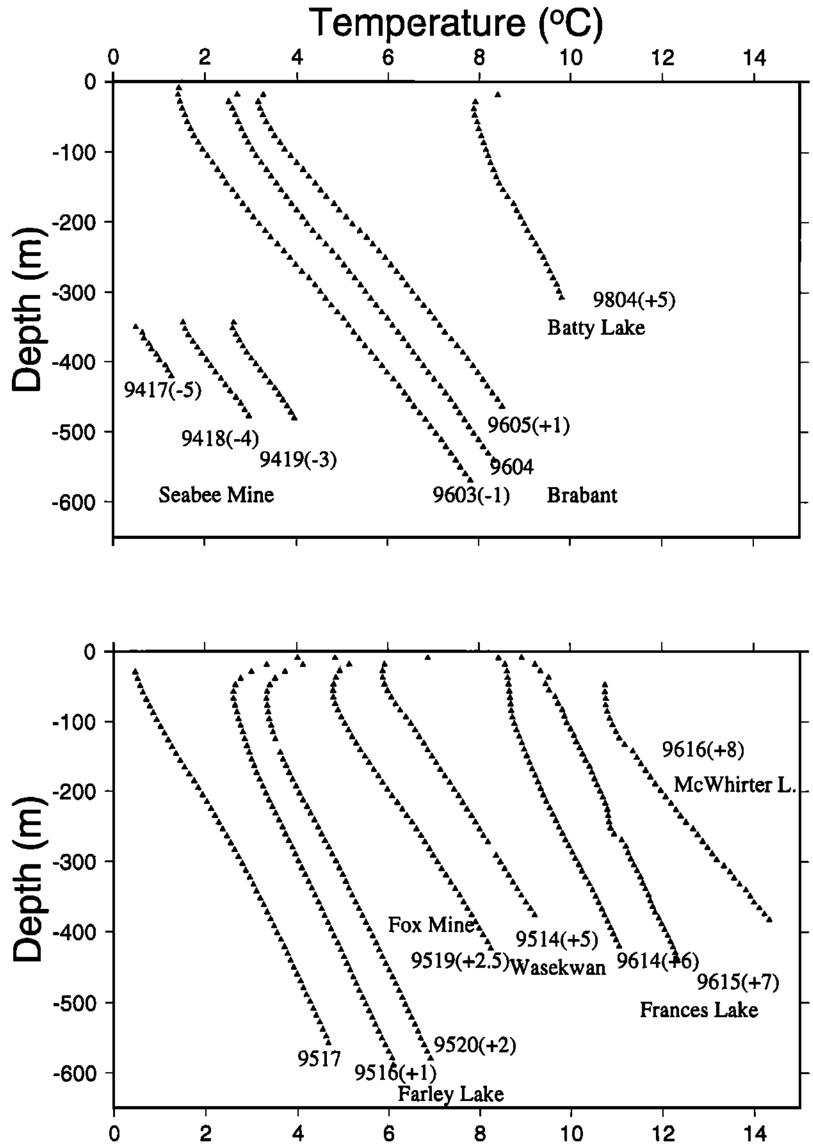

Figure 2. Measured temperature profiles for all the sites. For clarity, temperature profiles are shifted as indicated.

tion following a forest fire [*Guillou-Frottier et al.*, 1998]. At depth, the three boreholes yield consistent temperature profiles and gradients. The resulting value (36 mW m^{-2}) has been rated A.

3.2. Glennie Domain-La Ronge Belt

3.2.1. Seabee Mine (holes 9417, 9418, and 9419). The Seabee Mine lies in the Glennie domain. Because of the mine activity, all the surface drill holes had been cemented and could not be logged. Three drill holes were measured from level -370 m in the mine. Away from the perturbation due to the mine gallery, these drill holes yield stable and consistent temperature gradients. Because the thermal perturbations induced by the mine galleries are of short wavelength, they become negligible within <50 m, in contrast with surface measurements where drill holes deeper than a few hundred meters are needed to eliminate the effect of surface perturbations. The resulting value of 32 mW m^{-2} has been rated A.

3.2.2. Waden Bay (hole 9601). This 1000 m deep, vertical exploration borehole was drilled in 1960 at ≈2 km from the now abandoned Anglo-Rouyn mine. The drill hole crosses a granitic intrusion in the LaRonge Belt. The drill hole, located in a peninsula on lake LaRonge, is midway between and ≈500 m from both lake shores. We observed water flow driven by local topography when the cap of the hole was removed. Perturbations, due to water flow and the topography, are marked in the shallowest part of the temperature log but disappear below 250 m. In deeper sections of the borehole, there is no detectable effect of the lake. The stable temperature gradient yields a heat flow value of 44 mW m^{-2}. The value obtained over a wide interval in a deep drill hole has been rated A.

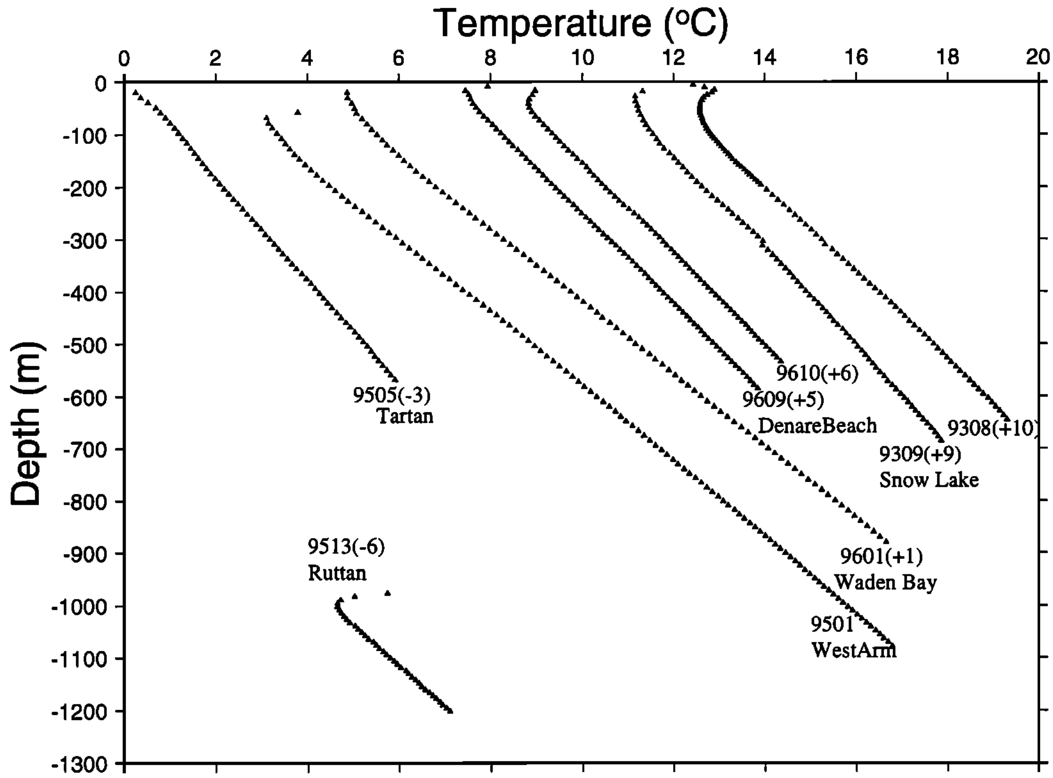

Figure 2. (continued)

3.3. Lynn Lake Belt

3.3.1. McWhirter Lake (hole 9616). This exploration borehole, located ≈20 km south of the Fox Mine site, is drilled in intermediate to mafic volcaniclastic sequences. We experienced some problems with equipment on this site, but the temperature profile appears stable and yields a heat flow value of 39 mW m^{-2}, consistent with those obtained at Fox Mine (32 and 41 mW m^{-2}). This value, based on one drill hole <500 m deep, is rated B.

3.3.2. Fox Mine (hole 9519). One borehole was measured at ≈1000 m from the main shaft of the mine which was abandoned in 1980. The temperature log yields a stable gradient at depth. The heat flow value of 32 mW m^{-2} is close to the 34 mW m^{-2} reported by *Drury* [1985] for one drill hole at the neighboring site of Fox Lake. However, the average value obtained by *Drury* [1985] for the site (41 mW m^{-2}) is higher than ours. The scatter of the heat flow values appears to be due to lateral changes in thermal conductivity. Because our value is based on only one borehole <500 m deep, we have rated this site as B.

3.3.3. Frances Lake (holes 9614 and 9615). These two holes were drilled in felsic volcanic sequences. The two boreholes are located within 20 m of the north shore of Frances Lake, just north of the town of Lynn Lake. No correction was made to account for the effect of the lake, which seems to disappear at depth. The small temperature gradients 7-8 mK m^{-1} are consistent with the measurements of *Drury* [1985] in the Lynn Lake area, but our heat flow value is much higher than the value of 23 mW m^{-2} reported by *Drury* [1985] because of the higher thermal conductivity. To ascertain the value of the thermal conductivity, we returned to the core library to collect additional samples that we measured. We consider that the heat flow value of 34 mW m^{-2} is reliable and rate it as A. Heat production values for the felsic tuffs encountered by the drill holes are variable and reach values as large as 2.2 μW m^{-3}.

3.3.4. Wasekwan Lake (hole 9514). The borehole is located near the BT Mine, southeast of the town of Lynn Lake. The temperature log yields a stable gradient 10.5 mK m^{-1} and a heat flow value of 27 mW m^{-2}. The value, based on a single borehole <400 m deep, is rated B.

3.3.5. Farley Lake (holes 9516, 9517, and 9520). These three boreholes are drilled in a sequence of intermediate metavolcanics and metasediments, including iron formations. The temperature profiles are perturbed by lateral variations in temperature near the surface caused by intermittent permafrost [*Guillou-Frottier et al.*, 1998]. One of the boreholes that we tried to log was blocked by ice at depth of 22 m. At depth, the temperature profiles become identical with a stable gradient. The heat flow value of 26 mW m^{-2} is rated A.

3.3.6. Ruttan Mine (hole 9513). In two deep drill holes that we logged from the surface to >800 m, we observed temperature perturbations probably induced by the mine activity. We logged one borehole from level -970 m in the mine. The borehole yields a stable temperature gradient and a heat flow value of 38 mW m^{-2}, slightly higher than what we obtained from a tentative interpretation of the temperature logs from the surface down. Because the mine is located above a granodiorite intrusive, we have also measured the heat production on granodiorite samples collected in the mine. The heat production of these samples 0.67 μW m^{-3} is not much higher than that of the felsic volcanics from the core samples.

3.4. Flin Flon Snow Lake Belt

3.4.1. West Arm (hole 9501). This drill hole is located near the west arm of Schist Lake and in the vicinity of the West Arm Mine. The borehole intersects andesite flows and mafic intrusives. The gradient, stable below 200 m, is the highest that we have measured in the Flin Flon belt. This site yields a heat flow value of 51 mW m^{-2}, significantly higher than the values of 39 mW m^{-2} measured at the sites of Schist Lake, 8 km to the north, and Denare Beach, 15 km to the west. For this deep drill hole the heat flow determination is rated A.

3.4.2. Tartan Mine (hole 9505). This drill hole, located on the site of the abandonned Tartan Mine, intersects mafic volcanics and gabbros. The gradient is stable at depth, indicating that the effects of the topography and of the nearby lake are negligible at depth. The value of 34 mW m^{-2} is rated A.

3.4.3. Denare Beach (holes 9609 and 9610). Two boreholes were logged at this site. Topographic and climatic perturbations that are marked in the shallow part of the log disppear at depth. The gradient and thermal conductivity values are very consistent between sites and yield a heat flow value of 37 mW m^{-2}, rated A.

3.4.4. Snow Lake (holes 9308 and 9309). The drill holes, $\approx$8 km apart, are located $\approx$1 km away from Anderson Lake. They intersect felsic volcanic sequences. Differences in gradient between the boreholes are partly offset by differences in thermal conductivity, and the two heat flow values stay within one standard deviation. This site is rated A although our resulting value (41 mW m^{-2}) is slightly lower than 46 mW m^{-2} obtained by *Drury* [1985]. The latter value is based on two boreholes shallower than ours. One of these drill holes exhibited a high gradient (17 mK m^{-1}) in the interval 120-185 m. The other hole had a gradient (11 mK m^{-1}) and heat flow value (44 mW m^{-2}) close to those that we obtained.

4. Heat Flow and Gravity Variations

4.1. Heat Flow

Table 3 summarizes all the heat flow data and heat production data presently available in the Trans-Hudson Orogen. Most of the 31 heat flow values come from the Thompson, Lynn Lake, and Flin Flon belts, where the

Table 2. Heat Production Measurements for the New Heat Flow Sites

Site (Hole)	Main Lithology	Number of Samples	U, ppm	Th, ppm	K, %	Heat Production μW m^{-3}
	Kisseynew-McLean Belt					
Batty Lake (9617)	gneiss	5	0.66	2.5	1.6	0.49
Brabant (9603, 9604, 9605)	gneiss	17	1.1	4.4	1.7	0.72
	Glennie Domain-LaRonge Belt					
Seabee Mine (9417, 9418, 9419)	gabbro	8	0.3	0.6	0.5	0.2
Waden Bay (9601)	granodiorite	5	3.6	4.4	2.2	1.42
	Flin Flon Belt					
Snow Lake (9308-9309)	mixed volcanics	27	0.3	0.6	0.6	0.2
West Arm (9501)	felsic volcanics	10	0.2	0.5	0.8	0.2
Tartan Mine (9505)	mafic and intermediate volcanics	9	0.76	1.2	0.90	0.36
Denare Beach (9609-9610)	basalt	13	0.2	0.2	0.30	0.1
	Lynn Lake Belt					
McWhirter Lake (9616)	intermediate volcanics	5	1.0	3.2	1.0	0.58
Fox Mine (9519)	gneiss	3	2.0	5.5	1.6	1.0
Frances Lake (9514-9515)	felsic tuffs	8	3.0	6.5	3.9	1.6
Wasekwan Lake (9514)	Basalt	5	0.5	0.9	1.3	0.3
Farley Lake (9516, 9517, 9520)	diorite	2	1.4	1.8	2.1	0.69
Ruttan Mine (9513)	felsic volcanics	4	1.3	3.4	1.3	0.69
	granodiorite *	2	1.7	1.9	1.3	0.67

At each site, the dominant lithology, the number of samples used, and the averaged heat production are given.
* Granodiorite samples collected on site

Table 3. Summary of the Geothermal Data in the Trans-Hudson Orogen

Site	Latitude	Longitude	Lithology	Heat Flow, mW m^{-2}	Heat Production, $\mu W\ m^{-3}$	References,
			Thompson Belt			
Birchtree Mine	55°42'15"	97°51'58"	metasediments	64	1.6	2
Birchtree Mine	55°42'05"	97°54'00"	metasediments	50	0.8	2
Moak Lake	55°54'07"	97°40'24"	metasediments	53	1.6	2
Pipe Mine	55°29'15"	98°07'51"	metasediments	49	1.0	2
Thompson	55°44'00"	97°46'00"	metasediments	59	1.0	1
Thompson Station	55°44'36"	97°49'05"	metasediments	81	1.3	2
Wabowden	54°52'54"	98°38'38"	metasediments	45	0.6	2
			Flin Flon-Snow Lake Belt			
Denare Beach	54°39'29"	102°03'29"	basalt	37	0.1	3
Echo Lake	54°39 00"	102°02'00"	mixed volcanics	38	0.1	1
Flin Flon	54°35'00"	102°00'00"	diorite	45	1.0	1
Flin Flon	54°43'00"	101°58'00"	granodiorite	46	*	1
Flin Flon	54°47'09"	101°53'09"	basalt	42	0.3	2
Reed Lake	54°34'17"	100°22'50"	gabbro	40	0.3	2
Schist Lake	54°43'11"	101°49'57"	basalt	39	0.3	2
Snow Lake	54°54'00"	99°58'00"	mixed volcanics	46	0.3	1
Snow Lake 2	54°51'40"	99°58'05"	mixed volcanics	41	0.2	3
Tartan Mine	54°51'28"	101°44'23"	mafic/intermediate volcanics	34	0.4	3
West Arm	54°38'13"	101°50'51"	felsic volcanics	51	0.2	3
			Lynn Lake Belt			
Farley Lake	56°54'34"	100°26'18"	diorite	26	0.7	3
Fox Lake	56°38'00"	101°38'00"	metavolcanics	41	0.9	1
Fox Mine	56°37'52"	101°38'02"	gneiss	32	1.0	3
Frances Lake	56°49'33"	101°06'16"	felsic tuffs	34	1.6	3
Lynn Lake	56°49'00"	101°02'00"	gabbro	23	0.1	1
McWhirter Lake	56°35'04"	101°39'56"	intermediate volcanics	39	0.6	3
Ruttan Mine	56°29'07"	99°36'21"	felsic volcanics	38	0.7	3
Wasekwan L.	56°44'50"	100°57'01"	Basalt	27	0.3	3
			La Ronge Belt-Glennie Domain			
Waden Bay	55°17'31"	105°01'11"	granodiorite	44	1.4	3
Seabee Mine	55°40'52"	103°37'37"	gabbro	32	0.2	3
			McLean Belt-Kisseynew Domain			
Brabant	56°07'50"	103°42'13"	gneiss	36	0.7	3
Batty Lake	55°09'52"	100°45'34"	gneiss	31	0.4	3
			Wollaston Belt			
Rumpel Lake	58°20'	106°33'	sandstones	39	*	1

References are (1) *Drury* [1985]; (2) *Guillou-Frottier et al.* [1996]; and (3) this paper.
* No heat production data.

mining exploration activity has been focused. Nonetheless, these heat flow and heat production data are sufficient to demonstrate major differences between some of the belts in the THO and also to show local variations within each belt. In spite of the uneven distribution of the heat flow values we have constructed a map of the heat flow variations for the Trans-Hudson Orogen region (Plate 1). This map was obtained with data from a region wider than shown, including the Athabasca basin to the northwest, the Alberta and Williston basins to the west and southwest, the Superior Province to the southeast [*Jessop et al.*, 1984; *Majorowicz et al.*, 1986]. There are no data to the east and northeast of the map area. The gridding algorithm interpolates the data on a surface with minimum curvature with a surface tension term to avoid oscillations [*Smith and Wessel*, 1990]. The map exhibits a trend of low heat flow associated with the Lynn Lake and Flin Flon belts, and of relatively higher heat flow in the Thompson belt. The low heat flow area extending across the Kisseynew connects the Batty Lake and Lynn Lake sites where available heat flow values are small and comparable to one another. These sites are separated by a large distance, and there are no data in between, implying that the interpolation is not reliable.

4.2. Long-Wavelength Gravity

Gravity data provide information on crustal structure that is complementary to the heat flow map. In order to reduce the effect of small local structures, we have calculated a filtered Bouguer anomaly map of the region (Plate 2). The Bouguer gravity data were extracted from the database of Geomatics Canada and placed on a 2.5' grid. The data were low pass filtered. All wavelengths shorter than 50 km were eliminated, and wavelengths longer than 80 km were retained. The filtered gravity map exhibits a good correlation with the geological features. The Superior-Churchill boundary is marked by a strong gradient and a negative anomaly in the Thompson belt [*Gibb and Thomas*, 1976; *Gibb et al.*, 1983]. The short-wavelength heat flow high around Thompson coincides with a gravity low. The Kisseynew domain is well outlined and appears as a gravity high. The gravity low on the Lynn Lake belt is consistent with some crustal thickening. The seismic data indicate significant variations (>10 km) of crustal thickness in the area [*Nemeth et al.*, 1996]. For constant average crustal density, such variations would induce Bouguer gravity anomalies >100 mGal. This is much larger than the amplitudes of the observed anomalies (≈50 mGal), which indicates that changes in crustal thickness are compensated by changes in crustal composition and density.

4.3. Heat Flow-Heat Production

Overall, the heat flow and heat production data from the THO seem to be correlated with one another (Figure 3). It is useful to estimate the thickness over which the observed differences of heat production can account for the heat flow variations. The local heat flow Q and heat production A values can be fitted to a linear relationship as defined by *Birch et al.* [1968]:

$$Q = Q_r + AD \tag{2}$$

where Q_r is the reduced heat flow and D is related to the thickness of the surficial heat producing layer. The correlation between heat flow and heat production is marginal when the entire data set is considered (correlation coefficient of 0.51, Table 4). The depth scale (D = 14 km) is larger than the standard values of ≈10 km in continents [*Sclater et al.*, 1980]. As will be discussed later, such a lumped approach for the whole THO glosses over the fundamental geological and geochemical contrasts between the various belts and does not lead to a meaningful interpretation.

4.4. Variations Between Belts

The two extreme heat flow values in the THO (23 and 81 mW m^{-2}) are also the lowest and highest values yet recorded in the Canadian Shield. The average heat flow for all the sites in the Trans-Hudson Orogen, 42 mW m^{-2}, is identical to the average for the Archean Superior Province (42 mW m^{-2}) [*Jaupart et al.*, 1998]. However, the heat flow studies in the Superior Province have shown that there is much variability in heat flow between the different belts of a province. For the THO these differences appear in the heat flow heat production relationships and in the average heat flow and heat production of the various belts (Table 5).

4.4.1. Thompson belt. The heat flow in the Thompson belt is highly variable, ranging from 45 to 81 mW m^{-2}. The average heat flow (57 ± 11 (s.d.) mW m^{-2}) is significantly higher than the average of the THO. *Guillou-Frottier et al.* [1996] have shown that the highest value in Thompson can be explained by refraction effects. Still, after correction for such local effects the heat flow at Thompson remains high compared to the other sites in the THO. A linear relationship was fit to the heat flow and heat generation data in the Thompson belt. When all the data are included, the correlation coefficient is 0.53. The large value of the depth scale (D = 20 km) suggests that enriched crustal rocks extend to large depths in the crust. As shown below, this conclusion is supported by a comparison between the different belts of the orogen.

4.4.2. Lynn Lake belt. In the Lynn Lake belt the heat flow values are consistently lower than the average of the Canadian Shield, and the average heat flow (33 ± 6mW m^{-2}) is significantly lower than the average value for the entire THO. The heat flow values in the Lynn Lake belt range between 23 and 41 mW m^{-2} and include the lowest values for the Canadian Shield (Figure 4). The new measurements confirm the existence of a local negative heat flow anomaly in the vicinity of the town of Lynn Lake. This area is also character-

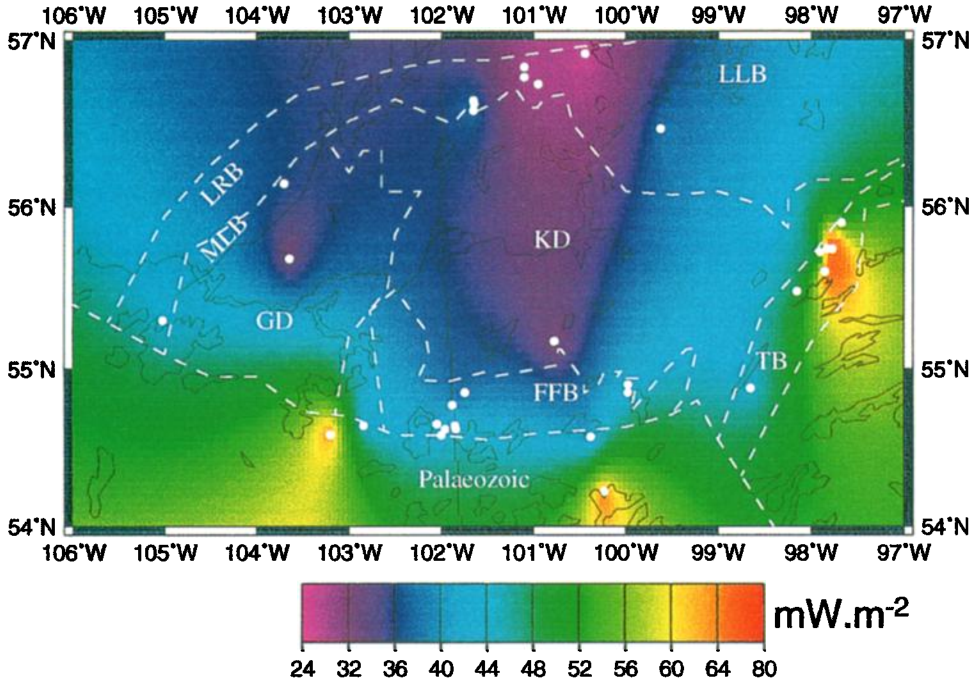

Plate 1. Heat flow map of the Trans-Hudson Orogen. Circles indicate the location of the heat flow values currently available within the area of the map. The map is constrained by data that fall outside the map area, including data from the Athabasca basin to the north, from the Williston and Alberta basins to the west and to the south, and from the Superior Province to the southeast. The main belts of the Reindeer tectonic zone are outlined: GD: Glennie domain, FFB: Flin Flon-Snow Lake belt, KD: Kisseynew domain, LLB: Lynn Lake belt, LRB: La Ronge belt, TB: Thompson belt.

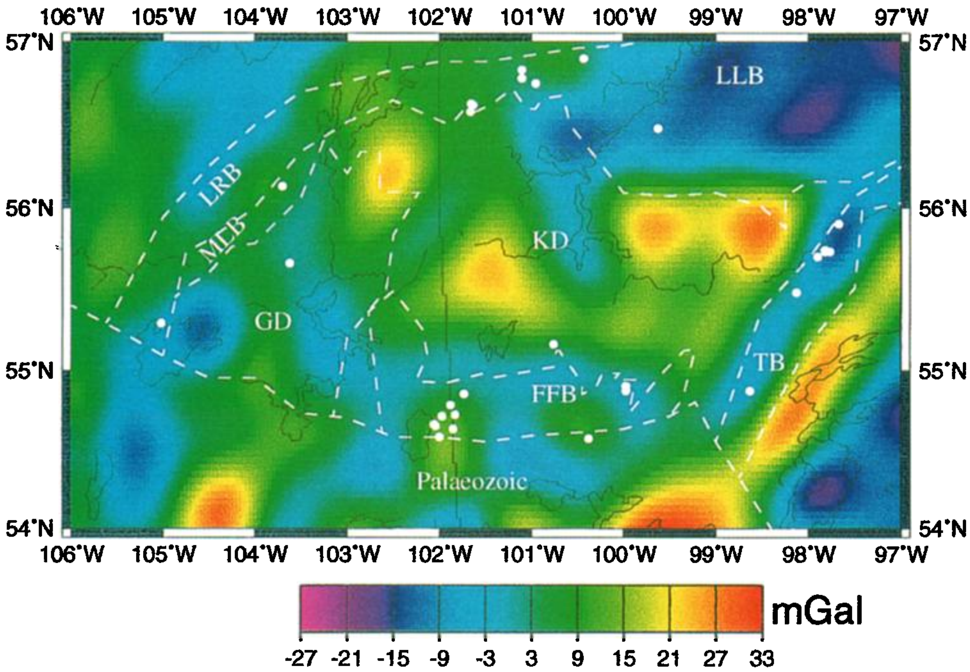

Plate 2. Filtered gravity map of the study area. Wavelengths shorter than 50 km have been eliminated and wavelengths longer than 80 km have not been modified. The main tectonic belts in the Reindeer zone are superposed: GD: Glennie domain, FFB: Flin Flon-Snow Lake belt, KD: Kisseynew domain, LLB: Lynn Lake belt, LRB: La Ronge Belt, TB: Thompson belt. Gravity data are from the Geomatics Canada database. The white circles indicate the location of the heat flow sites.

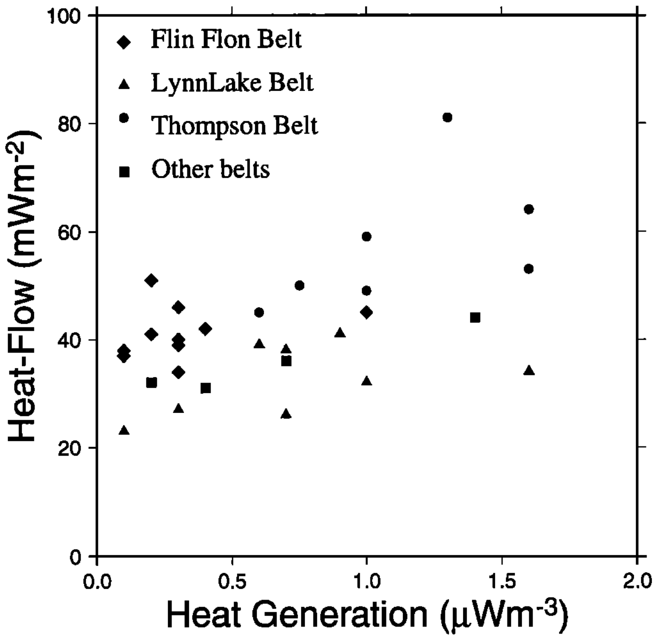

Figure 3. Heat flow and heat production data. The data from the Flin Flon-Snow Lake, Thompson and Lynn Lake belts are identified.

ized by a local gravity high, indicating the presence of large thicknesses of dense rocks, presumably poor in radioelements. The heat flow value at Lynn Lake proper, 23 mW m^{-2}, is obtained through a massive gabbro intrusion with negligible heat production [*Drury*, 1985]. Although short-wavelength variations in heat flow are observed near this site and around Fox Mine, the sampling in the Lynn Lake belt is sufficient to ascertain the regional trends. In this belt, the correlation between heat flow and heat production is even weaker than in the Thompson belt (correlation coefficient of 0.48, Table 4). The values of D and Q_r are about the same as observed in the Superior Province.

The Lynn Lake belt may be separated in two structurally and chemically distinct parts, the southern and northern belts [*Syme*, 1990]. The former is more evolved and older than the latter, which is reflected in their average heat flow values, 37 mW m^{-2} and 28 mW m^{-2}, respectively, and also in their average surface heat production rates.

4.4.3. Flin Flon-Snow Lake belt. The heat flow is less variable in the Flin Flon belt with a standard deviation of 5 mW m^{-2}. In this belt, surface rocks are mostly primitive lavas with very small radioelement concentrations, which cannot account for the average surface heat flow value of 42 mW m^{-2}. Some differences may be noted (Figure 4). The value at West Arm, 51 mW m^{-2}, is the highest observed in the belt and is found within <15 km of two sites with lower heat flow values (39 mW m^{-2}). Tartan Mine yields the lowest heat flow value of the belt (34 mW m^{-2}). Heat flow variations are observed over small distances, indicating that they are due to shallow sources. This is consistent with the model of a relatively thin lava sequence deposited on, or thrusted over, more radiogenic rocks.

There is no correlation between heat flow and heat production in the Flin Flon belt, where the correlation coefficient is 0.28 and $D \approx 5$ km (Table 4). The geology shows extreme complexity in the Flin Flon region with imbricated small crustal sheets [*Lucas et al.*, 1996]. The heat flow integrates crustal-scale heat generation and is not sensitive to the small features exposed at the surface.

5. Discussion

5.1. Implications for Crustal Structure

The surface heat flow is the sum of the mantle heat flow and the heat produced in the crust by radioactive decay. It thus depends on bulk crustal composition which varies significantly, even in a province of given age. In the Trans-Hudson Orogen the different belts and domains are characterized by different heat flow distributions (Table 4). A few isolated heat flow measurements are now available in the Kisseynew-McLean gneiss domains (Batty Lake and Brabant, respectively), in the La Ronge volcanic belt (Waden Bay), and in the Glennie domain (Seabee Mine) (Table 3). For these four geological units it is impossible to draw conclusions on crustal structure from such a small number of data. On the other hand, the available data provide no evidence that the average crustal composition of these belts is very different from that of the orogen.

The Thompson belt at the edge of the Superior craton is made of reworked Archean basement and metamorphosed continental margin deposits. The belt is characterized by high heat flow and heat production values and a negative Bouguer anomaly (Plate 2). The present-day exposures of Archean crust immediately next to the Thompson belt are the Pikwitonei granulite terranes, which represent crustal material from mid to lower crustal levels [*Fountain et al.*, 1987]. A likely interpretation is that the missing upper crust now resides in the Thompson belt. A representative sample of upper crustal levels in this part of the Superior can be found in the Sachigo subprovince, east of the Pikwitonei, where rocks are in the amphibolite facies. Indeed, the mean heat production for these rocks is 1.0 μW m^{-3} [*Fountain et al.*, 1987], which is almost iden-

Table 4. Heat Flow Heat Production Relationship

	Q_r, mW m^{-2}	D, km	N	Correlation
Lynn Lake	27±4	7±5	8	0.48
Flin Flon	40±3	5±6	10	0.28
Thompson	39±11	20±8	6	0.53
Trans-Hudson	33±3	14±4	29	0.51

Q_r is the reduced heat flow (± one standard error), D is the depth scale, and N is the number of data.

Table 5. Mean Heat Flow and Heat Production in the Different Belts of the Trans Hudson Orogen and in the Canadian Shield

	$< Q >$, mW m^{-2}	σ_Q	N_Q,	$< A >$ μW m^{-3}	σ_A,	N_A
Lynn Lake Belt	33± 2	6	8	0.74 ± 0.15	0.43	8
FlinFlon Belt	42± 1.5	5	11	0.3 ± 0.06	0.2	10
Thompson Belt	57± 4	11	7	1.1 ± 0.15	0.4	7
TransHudson (1.8 Ga) (juvenile crust only)	37± 1.4	7	24			
TransHudson (whole data set)	42± 2	11	31			
Superior (>2.5 Ga)	42 ± 1	10	57	0.95 ± 0.15	1	44
Grenville (1.1 Ga)	41 ± 2	11	30			

$< Q >$ is the mean heat flow ± one standard error, σ_Q is the standard deviation on the heat flow distribution, N_Q is the number of sites, $< A >$ is the mean heat production ± one standard error, σ_A is the standard deviation on heat production, and N_A is the number of heat production values. Each value is based on many samples.

tical to the average heat production in the Thompson belt, 1.1 μW m^{-3} (Table 5). According to this interpretation the Thompson belt crust is on average less dense than than the granulite facies terranes of the Pikwitonei to the east and the mafic gneisses and volcanic sediments of the Kisseynew to the west, which is consistent with the gravity data.

The Flin Flon-Snow Lake belt is a fossil island arc with a few kilometers thick volcanic deposits underlain by arc-derived gneisses. The interpretation of the seismic data has remained ambiguous. Some have suggested a continuous sequence of arc-related rocks almost down to the Moho, with little older protolith beneath [*Clowes*, 1997, pp. 3.67-3.69]. Reprocessing of the data [*Pandit et al.*, 1998] now suggests that the lowermost crust beneath the Flin Flon belt is Archean. This is not inconsistent with the heat flow data. The average heat flow for this belt (42±5 mW m^{-2}; Table 5) is identical to the average heat flow in the Archean Superior Province [*Mareschal et al.*, 1999a].

The Lynn Lake belt is the oldest in the orogen. It is interpreted as a mature island arc which erupted magmas of evolved compositions, implying that the residues had been depleted in radioactive elements. Lithoprobe data suggest that the belt is underthrust by crust from the Kisseynew domain, which represents an ancient marginal basin. It is instructive to compare this belt to slightly younger and less evolved Flin Flon belt. Its evolved character is reflected in the surface values of heat production which are slightly larger than in the Flin Flon belt (Table 5) [*Syme*, 1990; *Thom et al.*, 1990]. In contrast, its heat flow values are smaller than in the Flin Flon belt. This negative correlation implies that the mid and lower crust must be poorer in radioelements beneath Lynn Lake than beneath Flin Flon.

The intricate superposition and imbrication of different lithological units in the Trans-Hudson Orogen imply that one cannot characterize the whole THO with a single representative crustal column. Using the information available, one may propose tentative crustal models for the Flin Flon, Lynn Lake, and Thompson belts. These models are not meant to be unique but to illustrate in a quantitative manner the constraints brought by heat flow data (Figure 5). Uncertainties in the Moho depths in these three crusts type preclude accurate results. The Flin Flon crust has a thin layer of low-radioactivity lavas above rocks which, in the mean, are identical to average Precambrian crust [*Jaupart et al.*, 1998]. Such crust may either be remnant of an Archean craton underthrust beneath the belt or juvenile crust from the island arc. The Lynn Lake crust has an upper layer of evolved rocks, whose heat production values are close to average Precambrian values, and depleted lower crust. One interpretation is that the Lynn Lake supracrustals have been derived by partial melting of arc material, whose residue now make up the lower crust. An alternative explanation is that the Lynn Lake volcanic belt was thrust over rocks with low heat production. Current interpretation of the Lithoprobe data has a slab of Kisseynew crust thrust below an island arc sequence. In this study we have measured the heat production of Kisseynew metasedimentary gneisses at only one site (Batty Lake, Table 2). Our measurements at Brabant (Table 2) in McLean-McLennan belt gneisses to the west of the Kissenew domain indicate high heat production. The McLean-McLennan formations have been extensively studied by *Yang et al.* [1998], who confirm their relatively large U and Th concentrations and who state that they have been made with evolved felsic volcanics from distant sources. This precludes lumping the two gneissic domains. If the McLean heat production rates are representative of Kisseynew crust, the heat flow data imply that only a small thickness of such material may be present beneath the Lynn Lake belt. On the other hand, if the average Kisseynew crust is similar to the Batty Lake samples, with a heat production rate of 0.49 μW m^{-3}, it may make up most of the crust below the surficial volcanic material. Unfortunately, there is no information on the intermediate crustal levels, below the volcanic supracrustals and above the underthrust Kisseynew unit. Average values of heat production in mid-lower crustal terranes world wide are all remarkably close to 0.40 μW m^{-3} [*Pinet et al.*, 1991], and we have selected this value for the Lynn Lake crust below the volcanic supracrustals.

With these crustal models, mantle heat flow values

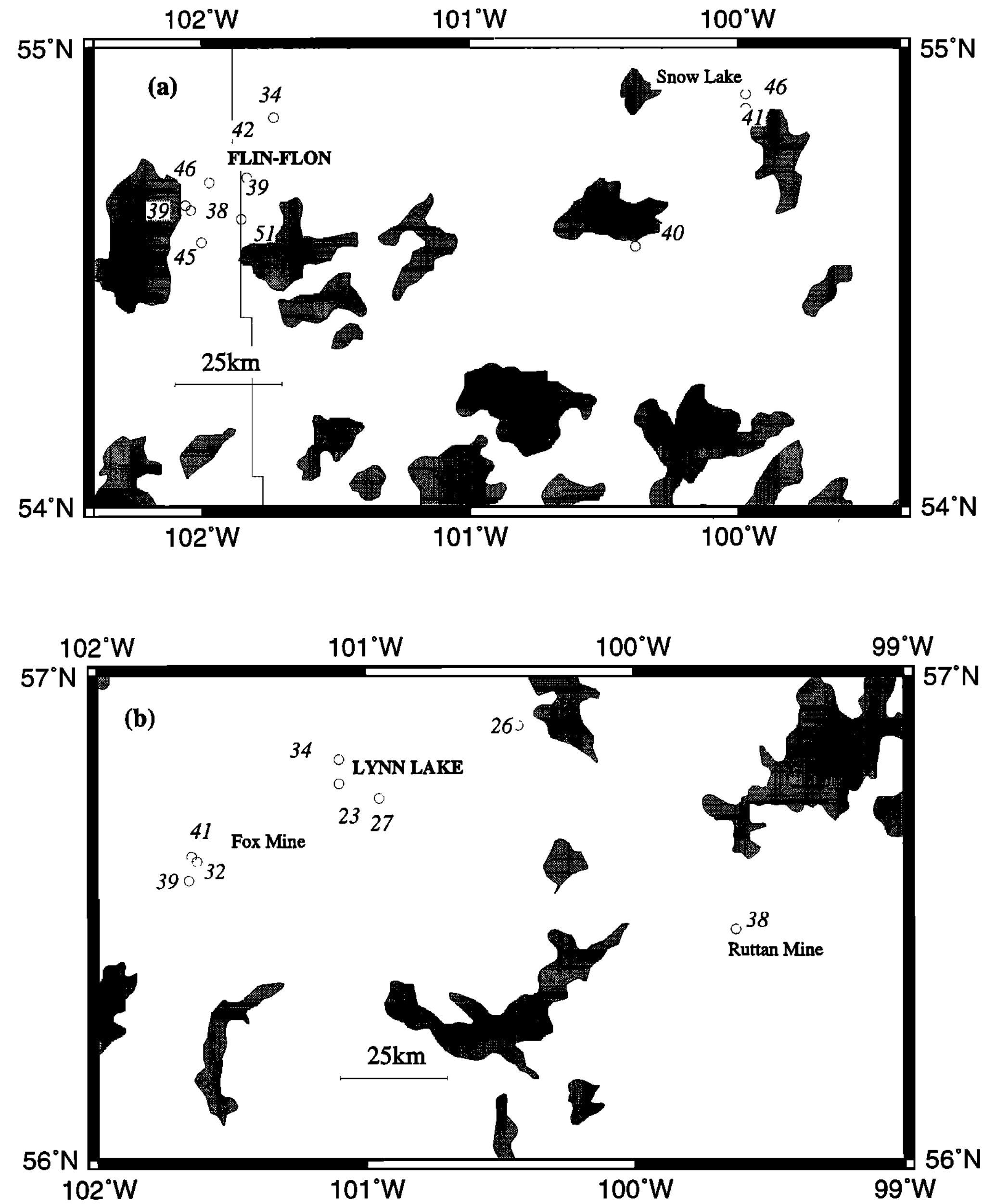

Figure 4. Local variations in heat flow values: (a) in the Flin Flon-Snow Lake belt, and (b) in the Lynn Lake belt. Heat flow values are in mW m^{-2}.

are almost identical (12 versus 11 mW m^{-2}) for both the Flin Flon and Lynn Lake belts. The Thompson belt has a radiogenic upper crust, with heat production values similar to Archean mid crustal material, as sampled in amphibolite facies terranes [*Pinet et al.*, 1991]. The small wavelength of heat flow variations along and across the belt rules out variations in mantle heat flow as a source of these variations. If one uses the same value of mantle heat flow for the three belts, the average heat production of the Thompson lower crust is almost identical to that of the upper crust.

5.2. Global Trends of Heat Flow

The continental lithosphere is probably significantly thicker than its oceanic counterpart and hence may have a large thermal relaxation time. For this reason, many authors have attempted to detect a systematic dependence between heat flow and age [*Vitorello and Pollack*, 1981; *Nyblade and Pollack*, 1993]. The new data allow reliable statistics for the Proterozoic of North America. Table 5 summarizes the heat flow data for the Precambrian provinces of North America. Average values and standard deviations of heat flow for the Archean (>2.7 Ga), Paleo-Proterozoic (2.0-1.8 Ga), and mid-Proterozoic (1.8-1.0 Ga) are 42$\pm$11 mW m^{-2}, 42$\pm$11 mW m^{-2}, and 41$\pm$11 mW m^{-2}, respectively. For these data sets, the errors on the mean values are <2 mW m^{-2}, which can be considered as negligible. It is therefore clear that there is no age dependence. The standard deviations of the heat flow distributions in

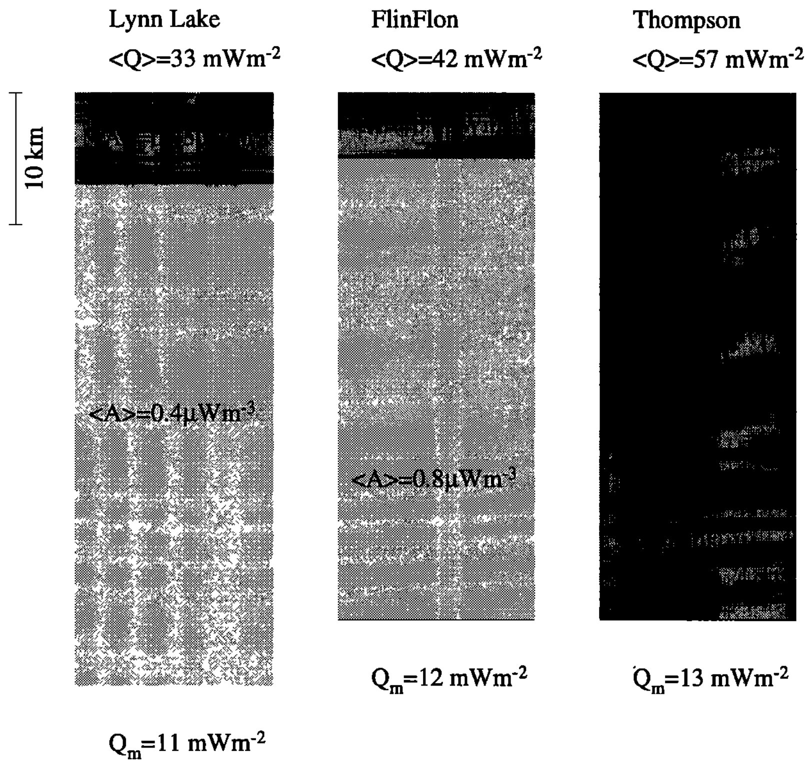

Figure 5. Average crustal column for the Lynn Lake, Flin Flon, and Thompson belts. Crustal thickness for Flin Flon and Lynn Lake is constrained by seismic data. Beneath the surficial layer, the crust is depleted for Lynn Lake, average for Flin Flon-Snow Lake, and enriched for Thompson.

these three age groups are also identical (11 mW m^{-2}) and quite large, which indicates that internal variations of crustal structure and composition remain large regardless of age. From this distribution of the data, one may not establish any variation of continental heat flow for ages between 3.0 and 1.0 Ga. On closer scrutiny, one may argue that the Thompson belt should not be assigned a Proterozoic age because it is exclusively made of Archean protoliths. It has anomalously large heat flow values and represents a small crustal volume at the edge of the Superior. Thus it is not representative of average Proterozoic crust and may bias the heat flow statistics. Excluding it from the data set, the mean value for the Paleo-Proterozoic drops to 37 mW m^{-2}, which is significantly less than the mean Archean value of 42 mW m^{-2}. Indeed, for each province the error on the mean is <1.5 mW m^{-2} (Table 5). This reasoning illustrates the difficulties of a global approach for the world wide heat flow data. Assigning a single age to a geological province implies lumping together different belts in proportions which may vary among provinces. An average heat flow value may therefore not be compared to a specific geochemical model without due consideration for the complexity of Precambrian crustal assemblages.

The position of the Trans-Hudson Orogen in the middle of the Canadian Shield also demonstrates that there is no large-scale systematic variation across the shield: as regards the surface heat flow field, the center is identical to the edge. The average heat flow from the juvenile part of the THO, 37±7 mW m^{-2}, near the center of the North American craton, is smaller than in most provinces of the shield, but it is due to the depleted character of the crust and hence cannot be attributed to an anomalously low value of the mantle heat flow. One should also note that it is identical to the average heat flow value in the Archean Abitibi province 2000 km to the east, which is 37±7 mW m^{-2} [*Mareschal et al.*, 1999a]. There are some long-wavelength trends in the Canadian Shield, most notably in the Abitibi province, where heat flow increases from ≈28 to 59 mW m^{-2} over a distance of ≈800 km [*Pinet et al.*, 1991; *Guillou et al.*, 1994]. This large-scale variation occurs from the east to the west, i.e., inward from the craton edge, and is associated with a gradual change of crustal composition and structure [*Pinet et al.*, 1991; *Guillou et al.*, 1994]. For the North American continent a significant change is only found at the very eastern margin where the heat flow increases markedly over a small horizontal distance at the boundary between the Grenville and the Appalachians. However, it has been suggested that this increase is due to a change of upper crustal composition and does not reflect a change of heat supply to the base of the lithosphere [*Birch et al.*, 1968; *Roy et al.*, 1968; *Jaupart et al.*, 1982; *Mareschal et al.*, 1999a].

Southwest of the THO, the Precambrian crystalline rocks are covered by the Paleozoic sediments of the western platform, including the Alberta foreland and the Williston basin. Heat flow on the platform was estimated from bottom hole temperature (BHT) measurements in oil exploration wells [*Majorowicz et al.*, 1985]. The apparent trend of increasing heat flow should be considered with caution. The problems of estimating the heat flow from BHT are notorious: (1) The temperature measurements are not made in equilibrium conditions and large corrections are required; and (2) core samples are not available, and the thermal conductivity is often estimated from the lithological logs. In addition, the heat flow pattern in sedimentary basins is often perturbed by hydrological phenomena [*Jessop*, 1989]. This is indeed the case in the western platform of Canada, as shown by *Majorowicz et al.* [1986]. Finally, a meaningful interpretation and comparison with the heat flow data from the exposed Shield requires proper sampling of the heat production of the crystalline rocks. The drill holes of the platform did not penetrate at all or not sufficiently deep into the basement. However, the available geochemical data suggest that the heat production of basement rocks in the western platform is twice the average of the shield [*Burwash & Cumming*, 1976]. The western platform of North America has also been recently uplifted and affected by tectonic events, implying that the lithospheric thermal structure is not in equilibrium. Such transient effects are not relevant to our discussion of the heat supply at the base of the lithosphere. For all these reasons, we prefer to exclude the platform heat flow data.

One must not conclude from this discussion that there are no variations of deep thermal structure in the mantle part of the thick North American lithosphere. For small values of the mantle heat flow, differences of crustal composition induce large variations of temperatures in the crust and in the mantle below. For the Canadian Shield, geotherms obtained with the mantle heat flow set to 12 mW m^{-2} lead to variations of Moho temperature of ≈150 K and variations of lithosphere thickness as large as 50 km [*Pinet et al.*, 1991; *Jaupart and Mareschal*, 1999]. Several authors have recently used thermobarometry on mantle xenoliths to determine the mantle heat flow [*Rudnick and Nyblade*, 1999; *Nyblade*, 1999; *Russell and Kopylova*, 1999]. The downward extrapolation of geotherms is prone to many errors. In particular, we have shown that no simple "synthetic" crustal model can be considered valid for the whole Archean and Proterozoic. Supposing that the total amount of crustal heat in a province is well-known, one additional source of uncertainty is the vertical distribution of heat sources. For given values of the surface and mantle heat flow, predictions for two end-member vertical distributions may differ by as much as 50 K at the Moho [*Mareschal et al.*, 1999a; *Jaupart and Mareschal*, 1999]. Using only heat flow and heat production data, one may not rule out small variations of the mantle heat flow. The mantle heat flow estimate is a small residual difference and hence is affected by a significant error. Allowing for uncertainties in the values of heat production and heat flow, as well as in crustal structure, *Guillou et al.* [1994] obtained a total range of 10-15 mW m^{-2} for the mantle heat flow beneath the eastern part of the Canadian Shield. The uncertainty on the mantle heat flow value is likely to remain for some time. However, two important points must be emphasized. One is that, at given pressure, the overall range of xenolith temperatures for the kimberlite pipes of the Canadian Shield is ≈200 K [*Russell and Kopylova*, 1999], which is comparable to our predicted range of 150 K for a fixed mantle heat flow value. The other point is that differences of crustal composition are well-established and that they imply significant variations of deep thermal structure.

5.3. Crustal Growth in the Proterozoic

The metavolcanic belts of the THO are almost identical to Cenozoic island arc magmatic sequences in terms of lithology, deposition environment and chemical composition [*Baldwin et al.*, 1987; *Syme*, 1990]. We are aware of only one study of heat production through the whole crust of an island arc, in the Hidaka belt in Hokkaido, Japan [*Furukawa and Uyeda*, 1989; *Furukawa and Shinjoe*, 1997]. There it has been possible to reconstruct a full vertical crustal sequence over a total thickness of 30 km, including high-grade metamorphic rocks representative of lower crustal material. The total rate of crustal heat generation in this arc is 25 mW m^{-2} [*Furukawa and Shinjoe*, 1997]. For comparison with our data we exclude the Thompson belt, which is not an island arc, and retain all the other heat flow data. The average heat flow for the THO volcanic belts is 37±7 mW m^{-2} (Table 5). For a crude estimate we take a mantle heat flow value of 12 mW m^{-2} (Figure 5) and obtain a value of 25 mW m^{-2} for the total rate of crustal heat production in the juvenile THO crust. This is identical to the Hidaka belt value. Obviously, this comparison is uncertain but serves to demonstrate that the island arc rocks of the THO are not anomalous with respect to heat production.

The Trans-Hudson Orogen represents a significant addition of continental crust in Proterozoic times to the North American craton, which has not been subsequently modified [*Arndt and Todt*, 1994; *Lucas et al.*, 1996]. One key problem is the genesis of typical felsic continental crust with significant volumes of chemically evolved, and hence radiogenic, rocks [*Rudnick*, 1995]. Heat flow data provide constraints on the composition of the whole crust, which is useful in areas where lower crustal samples are absent. In the THO the average heat flow is identical to that for the older Archean crust, which indicates that the new crust is not enriched in radioelements relative to older continental crust. Truly juvenile crust, exemplified by the Flin Flon, Snow Lake, and Lynn Lake metavolcanic belts, is lower in radioelements [*Thom et al.*, 1990]. Variations in the degree of internal crustal differentiation among these different belts and within these belts are reflected in the compositions of surface rocks. However, radioelement concentrations in individual rocks never reach large values. Making large volumes of radiogenic crustal material did not occur in the oceanic arcs and basins of the THO. This shows that the formation of "typical" continental crust requires an additional magmatic event to produce evolved granitic melts. From this perspective the Lynn Lake belt is particularly interesting. It has the most evolved volcanics and the thickest crust, with Moho depths exceeding 50 km [*Nemeth et al.*, 1996]. It is the most ancient belt in the orogen and went through two phases of magmatism: an initial phase of oceanic arc volcanism at about 1.91 Ga, and a later phase of internal differentiation with the emplacement of tonalite and diorite plutons at about 1.88 Ga [*Baldwin et al.*, 1987; *Gordon et al.*, 1990]. Heat flow data demonstrate that below these supracrustal units, the crust is depleted in radioelements. To generate "average" continental crust, a third event must take place with the elimination of depleted mafic/ultramafic lower crust, as required by isotopic and trace element data [*Rudnick*, 1995]. This third event can be seen as a return to "normal" crustal thickness involving some form of delamination through crustal and mantle flow. The large crustal thickness in the Lynn Lake belt indicates that this event did not take place for reasons that are discussed below.

In contrast, heat flow is significantly higher in the Thompson belt at the edge of the Superior craton. This small crustal segment was formed in part by sediment accumulation from the adjacent Archean crust and hence is not representative of new continental crust of Proterozoic age. The large values of radiogenic heat production found there are typical of well-differentiated crust.

5.4. The "Cold Spot" of Lynn Lake

The Lynn Lake site has the lowest heat flow value yet measured in the Canadian Shield, 23 mW m^{-2} (Table 3). This value, obtained by *Drury* [1985], is confirmed by our measurements at the neighboring site of Wasekwan Lake (Figure 4). This is not an isolated low heat flow value: the Farley Lake site, at ≈50 km NE of Lynn Lake, has similar low heat flow values (Figure 4). Individual heat flow values in the Lynn Lake belt vary over distances of a few kilometers, indicating that they record superficial heat production differences. The heat flow differences can be accounted by the known heat production differences over a thickness of ≈7 km. It is therefore more appropriate to consider the local average heat flow value for the Lynn Lake area, which is 28 mW m^{-2} (Plate 1). This is identical to the value in another "cold spot" of the shield, the eastern part of the Grenville Front, at the boundary between the Archean Abitibi and the mid-Proterozoic Grenville provinces [*Guillou et al.*, 1994; *Guillou-Frottier et al.*, 1995]. It is significant that the area seems to be characterized by anomalously thick crust, as in the eastern part of the Grenville Front. These variations of crustal thickness are not compensated by crustal density changes, as shown by gravity data, and imply significant horizontal stress gradients which should induce flow in the crust and in the mantle below. However, low heat flow values imply low crustal temperatures, which in turn imply strong lower crust and upper mantle. Also, the low heat flow values suggest a mafic composition for the crust which implies a stronger rheology than that of felsic rocks [*Carter and Tsenn*, 1987]. *Mareschal et al.* [1999a] have compared the geotherms and the yield stress envelopes for different regions in the eastern Canadian Shield. They suggested that the strength of the lower crust in the regions with low heat flow explains the preservation of thick crustal roots. They calculated that in the regions with low heat flow (< 32 mW m^{-2}), the lower crustal temperatures are ≈400°C. The lower crust will not flow at a geologically significant rate. For the rheology of mafic granulites [*Carter and Tsenn*, 1987] it requires a deviatoric stress in excess of 1000 MPa to maintain a strain rate of 0.3×10^{-16} s^{-1} corresponding to a relaxation time of 1 Gyr.

6. Conclusions

The THO offers an exceptional example of how new continental crust is created and accreted to older continents. The heat flow and heat generation data provide strong constraints on the nature of the new crust and on the processes that have controlled the evolution of this orogen.

1. The average heat flow for the THO, 42 mW m^{-2}, is identical to that of the Archean Superior Province and to that of the Grenville Province. For the Canadian Shield, there is no trend of decreasing heat flow with age. The western platform has been affected by recent tectonic activity and seems to be underlain by very radiogenic basement. There is no geographic trend of increasing heat flow toward the eastern edge of the craton.

2. Heat flow varies markedly between the different belts of the THO. These variations reveal differences in crustal composition. The amplitude of the heat flow variations and the poor correlation with surface heat production imply that the differences in crustal composition involve the entire crust.

3. The belts where juvenile Proterozoic crust is found are characterized by low heat flow. The low heat flow is due to the low radioactivity of the juvenile crust formed by island arc magmatism.

4. The low heat flow in the THO might explain the preservation of important (≈10 km) differences in crustal thickness over 1.8 Gyr.

5.The evolution of the THO demonstrates the complex interplay between the processes generating rocks of evolved composition, which require crustal thickening, and those forming "normal" crust with average thickness, which require crustal flow and soft crustal rheology. These processes are controlled by the thermal structure of the crust and the distribution of radioelements.

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