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Heat production in an Archean crustal profile and implications for heat flow and mobilization of heat-producing elements

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We have measured concentrations of heat producing elements (Th, U, and K) in 58 samples representative of the main lithologies in a 100 km transect of the Superior Province of the Canadian Shield, from the Michipicoten (Wawa) greenstone belt, near Wawa, Ontario, through a domal gneiss terrane of amphibolite grade, to the granulite belt of the Kapuskasing Structural Zone, near Foleyet. This transect has been interpreted as an oblique cross section through some 25 km of crust, uplifted along a major thrust fault, and thus provides an opportunity to examine in detail a continuous profile into deep continental crust of Archean age. Mean heat production values for these terranes, based on aereal distribution of major rock types and calculated from their Th, U, and K concentrations are: Michipicoten greenstone belt = 0.72 μW m^{-3}; Wawa domal gneiss terrane (amphibolite grade) = 1.37 μW m^{-3}; Kapuskasing granulites = 0.44 μW m^{-3}. Among the silicic plutonic rocks (tonalites, granites, and their derivative gneisses), the relatively large variation in heat production correlates with modal abundances of accessory minerals including allanite, sphene, zircon, and apatite. We interpret these variations as primary (pre-metamorphic). The relatively high weighted mean heat production of the domal gneiss terrane can be accounted for by the larger proportion there of late-stage Th-, U-, and K-rich granitoid plutons. These may have been derived from the underlying Kapuskasing granulite terrane, leaving it slightly depleted in heat producing elements. Transport of Th, U, and K, therefore, could have taken place in silicate melts rather than in aqueous or carbonic metamorphic fluids. This conclusion is supported by the lack of a statistically significant difference in heat production between tonalites, tonalite gneisses and mafic rocks of amphibolite versus granulite grade.

The pre-metamorphic radioactivity profile for this crustal section is likely to have been uniformly low, with a mean heat production value less than 1 μW m^{-3}. This result is distinctly different from measured profiles in more silicic terranes, which show decreasing heat production with depth. This implies fundamental differences in crustal radioactivity distributions between granitic and more mafic terranes, and may be an important factor in selective reactivation of lithologically different terranes, possibly resulting in preferential stabilization of basic terranes in the geological record. Our results indicate that a previously determined apparently linear heat flow–heat production relationship for the Kapuskasing area does not relate to the distribution of heat production with depth. Low, but significant heat production, 0.4–0.5 μW m^{-3}, continues to lower crustal depths with no correlation to the depth parameter from the linear relationship. This low heat production may be a minimum average granulite heat production and suggests that, in general, heat flow through the Moho is 8–10 mW m^{-2} lower than the reduced heat flow calculated from the heat flow–heat production regression.

1. Introduction

Approximately half of the heat flow from the continents comes on average from crustal radiogenic heat production, i.e. heat generated by radiogenic decay of the isotopes ^{232}Th, ^{235}U, ^{238}U, and ^{40}K in the upper crust. Crustal radioactivity is laterally heterogeneous, however, contributing from a few percent to the surface heat flow in basic terranes to over 70% in some granitic terranes [1,2]. Heat production must also be vertically heterogeneous: if the average surface heat production value of 2 μW m^{-3}, is assumed uniform throughout 30 km of continental crust it would produce 60 mW m^{-2} of surface heat flow, approximately the average continental heat flow

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value. This result implies no mantle contribution to the surface heat flow, an unlikely situation [3]. For many granitic terranes, heat production exceeds 2 $\mu W\ m^{-3}$, but surface heat flow is not significantly greater than 60 $mW\ m^{-2}$, yielding the improbable result of a negative mantle heat flux if crustal heat production is vertically uniform. Therefore, crustal heat production must decrease with depth in such terranes. This conclusion is generally consistent with data indicating that most deep crustal rocks have relatively low concentrations of large ion lithophile elements (LILE), including Th, U, and K [4–6].

The form of the decrease in crustal heat production with depth is not known in detail. A possible constraint on the partitioning of mantle heat flow and crustal heat production was given by the discovery by Francis Birch and co-workers of a linear relationship between surface heat flow and surface heat production in major silicic plutons in the same tectonothermal province [7–11]. This relationship requires that heat production at depth follow some systematic distribution from the surface, but the distribution is not defined. A variety of distributions are consistent with the relationship, commonly quoted examples of which include linear or exponential decreases in crustal radioactivity with depth, and step distributions, in which heat production is constant from the surface to an intermediate crustal depth where it decreases to zero [8]. For the relationship to survive in terranes representing different levels of erosion, only an exponential decrease in heat production with depth is theoretically valid [8,9]. A recent discussion of the linear heat flow-heat production relationship has been given by Morgan et al. [12].

It has become common practice in recent years to extend the application and implications of the linear heat flow–heat production relationship to high-grade metamorphic terranes (e.g. [13]). In general the scatter of the data defining the linear relationship is much larger in provinces consisting of both plutonic and metamorphic data sites, or metamorphic sites only, than in provinces defined exclusively by silicic plutonic data sites. This larger scatter in the data could be associated with experimental or sampling error related to the terrane type, or perhaps with greater two- or three-dimensional heat flow effects in the thermally more heterogeneous high-grade terranes. Alternatively, the relationship may only be approximate in high-grade terranes, with the intuitive correlation of higher heat flow and higher crystal heat production, and impose little or no constraint upon heat production as a function of depth [14,15]. This latter possibility has significant implications for the extrapolation of geotherms from surface heat flow measurements.

An alternate approach to determining the distribution of heat production with depth is to measure the distribution directly in samples from vertical cross-sections of the crust exposed at the surface by tectonism [16]. Such sections have been measured for a 16 km, originally vertical section of Archean granitic crust exposed in the Vredefort structure, South Africa [17,18], for an unspecified thickness of Archean granodioritic rocks in the upturned collar of the Sudbury structure in the Superior Province of Ontario, Canada [18], and for a 4 km section of late Paleozoic granitic rocks in the Pennine basement of the eastern Alps (Tauern Window) [19]. All three measured sections indicate a general decrease in heat production with depth consistent with (but not proving) the exponential distribution model.

We report here the first measured heat production profile for a more mafic terrane, an Archean greenstone belt exposed by the Kapuskasing structure in the central Superior Province of the Canadian Shield (Fig. 1). This profile represents a cross-section of the crust below a terrane of typically lower heat flow and heat production than the silicic terranes described above. We examine the redistribution of Th, U, and K associated with metamorphism up to granulite facies in this terrane, and the implications of the profile to the heat flow–heat production relationship and the extrapolation of the geotherm to depth in mafic terranes.

2. Geological setting

The area studied is in the central Superior Province of the Canadian Shield, between Wawa and Foleyet, Ontario (Figs. 1, 2). Here, the continuity of east-west trending sedimentary-volcanic belts is interrupted by a major shear zone and structural break (the Ivanhoe Lake Cataclastic Zone), which juxtaposes high-pressure granulite facies rocks of the Kapuskasing Structural Zone

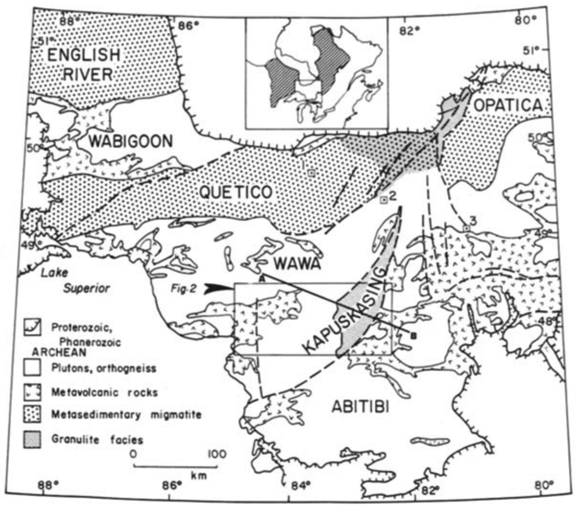

Fig. 1. Generalized geological map of the central Superior Province (modified after [45,46] showing location of study area (outlined) and Superior Province (diagonal ruling in inset). Numbers *1*, *2*, and *3* refer to locations of heat flow measurements of 51, 33 and 43 mW m^{-2}, respectively, with mean site heat production values of 1.8, 0.5 and 1.3 $\mu W\ m^{-3}$, respectively [35]. *A-B* represents line of section to which sample locations were projected in constructing depth profile of Fig. 3.

against greenschist to amphibolite facies volcanics of the Abitibi greenstone belt to the east. Kapuskasing granulites include paragneisses; mafic gneisses, in some cases with associated migmatites; gneissic tonalites, commonly with mafic xenoliths; and a large (750 km^2) anorthosite body (the Shawmere Complex). Peak metamorphic conditions have been estimated at 6–8 kbar and 700–800 °C [20]. To the west there is a complex but apparently continuous gradation over about 100 km through amphibolite facies rocks of the Wawa domal gneiss terrane, and eventually to greenschist and subgreenschist rocks of the Michipicoten greenstone belt. The domal gneiss terrane consists mainly of tonalite to granodiorite gneisses with 5–50% mafic and paragneiss xenoliths, and later granitic intrusions. The Michipicoten greenstone belt consists of mafic and felsic metavolcanics, with intercalated graywacke, conglomerate, iron formation and chert, and may be correlative with the Abitibi greenstone belt to the east [21]. Ages of these rock units range between

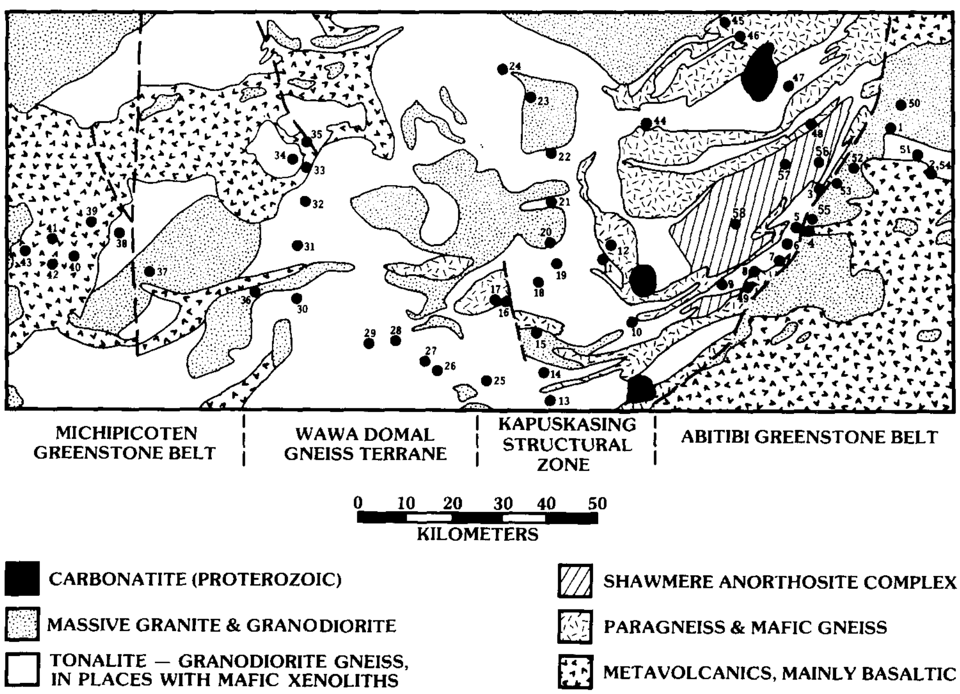

Fig. 2. Geological map of the Wawa Foleyet area showing sample locations. Metamorphic grade increases from greenschist and subgreenschist facies in the Michipicoten belt to granulite facies in the Kapuskasing Structural Zone. The Abitibi belt immediately east of the Ivanhoe Lake Cataclastic Zone is in amphibolite and greenschist facies.

about 2.65 and 2.75 Ga, but the exact timing and sequence of sedimentation, volcanism, plutonism, deformation, and metamorphism have yet to be firmly established [22,23].

The geology and geophysics of the area have been interpreted as an oblique cross-section through some 25 km of crust, uplifted along a major northwest-dipping thrust fault represented by the Ivanhoe Lake Cataclastic Zone [24]. This interpretation is supported by seismic reflection profiling which reveals the presence of a west-dipping reflector in the appropriate position and orientation [25]. The age of this fault is not well constrained, but has been suggested to be mid-Proterozoic on the basis of $^{40}Ar/^{39}Ar$ measurements of cataclastic rocks, and K-Ar ages of possibly associated carbonatite complexes [23,26,27]. This area represents an ideal opportunity for a crustal heat production profile because it is relatively accessible, and is apparently uninterrupted by major faults, thus providing a continuous profile into deep continental crust of Archean age.

3. Sampling and analytical techniques

Fifty eight 1–2 kg-size samples were collected in a 100 km transect across the transition from the low-grade Michipicoten greenstone belt to the granulites of the Kapuskasing Structural Zone and from the Abititi greenstone-granite belt west of the Ivanhoe Lake Cataclastic Zone. Sample locations are plotted in Fig. 2. Representative samples were collected from all major rock units established by the mapping of Percival [27,28]. At localities with complex geological relationships, an attempt was made to sample the more silicic units, i.e., those with higher expected heat production, because we wished to assure that these important lithologies were not undersampled. The sampling bias was removed in calculation of terrane means by weighting according to lithology (see below). Samples were carefully trimmed both in the field and laboratory to remove weathering rinds. Thin sections of all samples were prepared to determine their mineralogy, texture, and extent of weathering and alteration.

The rocks were crushed to fragments less than about 5 mm, and analysed for Th, U, and K concentrations by standard natural gamma techniques, using a shielded NaI crystal, photomultiplier tube, and pulse height analyser [29]. 650 ± 100 g samples were counted for an average of about 1 hour, with calibration using separate Th, U, and K standards and a composite check standard. Data are given in Table 1. Analytical uncertainties are related to counting statistics and least-squares spectral analysis (e.g. [30] and the mean standard deviations and ranges of the individual analyses were as follows: Th $\pm$ 0.41 ppm (0.16–1.15 ppm); U $\pm$ 0.11 ppm (0.04–0.30 ppm); K $\pm$ 0.03% (0.01–0.09%). Repeated analyses of randomly selected samples gave results in agreement with the original analyses to better than $\pm 3\%$. Heat production values, A, were computed from the relationship:

$$A(\mu\text{W m}^{-3}) = \rho(0.097C_U + 0.036C_K + 0.026C_{Th})$$

where ρ is density in g cm^{-3}, and C_U, C_K and C_{Th} are U, K and Th concentrations in ppm, % and ppm, respectively [31,32]. An average density of 2.7 g cm^{-3} was used for all lithologies [35]. The average of standard deviations of individual heat production determinations was 0.06 μW m^{-3} with a range from 0.03 to 0.17 μW m^{-3}.

In addition to the samples collected and analysed here, we also utilized a data base (34 samples) of major and trace element analyses of metavolcanic rocks from the Michipicoten greenstone belt [21].

4. Results

Th, U, and K abundances, calculated heat production values, and Th/U and K/U ratios for individual samples are given in Table 1. Most samples have heat production values less than 3 μW m^{-3}, and the mean heat production of all samples is less than 1 μW m^{-3}. Late-stage granitic rocks show the largest range in Th, U, and K abundances, with heat production values between 0.43 and 6.81 μW m^{-3}. The heat production values of these samples correlate very well with U or Th concentration and to a much lesser degree with K_2O abundance, suggesting that the variation is caused by Th- and U-rich accessory minerals. This is supported by petrographic data, which indicate higher modal abundances of allanite, sphene, zircon, and apatite in samples with higher heat production values. Accessory mineral abundance also appears to be responsible for the more mod-

TABLE 1

Heat production in Kapuskasing samples

Sample No.	Description	Metamorphic grade	Th (ppm)	U (ppm)	K_2O (wt.%)	Th/U	K/U ($\times 10^{-4}$)	Heat production ($\mu W\ m^{-3}$)
1	Leucogranite, Oswald L. Pluton, E of ILCZ	"granitic"	63.45	4.76	3.86	13.3	0.67	6.09 ± 0.14
			59.94	4.87	4.00	12.3	0.68	5.89 ± 0.16
		avg. =	61.70	4.82	3.93	12.8	0.68	5.99 ± 0.15
2	Flaser tonalite, Abitibi Belt	amphibolite	3.65	0.58	1.66	6.29	2.38	0.57 ± 0.06
3	Paragneiss, graphite-bearing	granulite	4.94	0.55	1.71	8.98	2.58	0.66 ± 0.05b
4	Mafic volcanic, Abitibi belt, E of ILCZ	amphibolite	0.31	0.21	0.38	1.48	1.46	0.12 ± 0.04
5	Mafic gneiss	granulite	2.47	0	2.08	–	–	0.36 ± 0.06
6A	Mafic tonalite gneiss, garnet-rich	granulite	0.41	0.45	0.97	0.91	1.80	0.24 ± 0.05
6B	Mafic tonalite gneiss garnet-free	granulite	5.27	0.48	0.99	11.0	1.72	0.59 ± 0.04
7	Paragneiss	granulite	8.44	0.99	1.74	8.53	1.46	1.02 ± 0.05
7A	Mafic gneiss	granulite	0.47	0.20	0.23	2.35	0.95	0.11 ± 0.03
8	Mafic gneiss with leucosome	granulite	3.92	0.56	0.62	7.00	0.90	0.48 ± 0.04
9	Banded gneiss	granulite	2.03	0.50	0.67	4.16	1.11	0.34 ± 0.05
10	Xenolithic tonalite gneiss	amphibolite	2.06	0.51	0.73	4.14	1.17	0.35 ± 0.04
11	Diorite-monzonite, Floranna Complex	"granitic"	6.55	0.84	3.60	7.80	3.55	1.03 ± 0.08
12	Mafic granulite gneiss, garnet bearing	granulite	0.65	0.09	0.20	7.22	1.91	0.09 ± 0.03
13	Xenolithic tonalite	amphibolite	5.18	0.23	0.94	22.5	3.46	0.52 ± 0.05
			5.22	0.23	1.00	22.7	3.66	0.53 ± 0.05
		avg. =	5.20	0.23	0.97	22.6	3.50	0.53 ± 0.05
14	Tonalite gneiss	amphibolite	21.09	0.45	0.92	46.9	1.72	1.70 ± 0.07
			21.38	0.59	0.80	36.2	1.12	1.74 ± 0.08
		avg. =	21.24	0.52	0.86	40.8	1.37	1.72 ± 0.08
15A	Granite	"granitic"	42.31	4.38	3.97	9.66	0.75	4.51 ± 0.15
15B	Tonalite gneiss (inclusion in 15A)	amphibolite	0.69	0.29	0.77	2.38	2.17	0.20 ± 0.05
16	Paragneiss (minus leucosome)	amphibolite	10.23	1.02	2.29	10.0	1.87	1.21 ± 0.07
17	Leucosome of paragneiss	"granitic"	25.71	0.70	2.09	36.7	2.46	2.20 ± 0.08
			22.08	1.63	2.04	13.6	1.03	2.18 ± 0.08
		avg. =	23.90	1.17	2.07	20.4	1.46	2.19 ± 0.08
18	Tonalite gneiss	amphibolite	8.58	0.69	0.81	12.4	0.97	0.87 ± 0.06
19	Xenolithic tonalite	amphibolite	0.85	0.35	0.85	2.43	2.02	0.23 ± 0.05
20	Chaplin Lake granodiorite	"granitic"	6.24	0.69	1.19	9.04	1.43	0.74 ± 0.05
21	Mafic xenolith from xenolithic tonalite	amphibolite	1.26	0.27	0.56	4.67	1.75	0.21 ± 0.03
22	Tonalite gneiss (layered)	amphibolite	2.34	0.58	0.82	4.03	1.17	0.40 ± 0.05
23	Massive granite	"granitic"	15.74	0.73	2.74	21.6	3.12	1.57 ± 0.08
			13.99	1.34	2.55	10.4	1.58	1.58 ± 0.08
		avg. =	14.87	1.04	2.65	14.3	2.12	1.58 ± 0.08
24	Xenolithic tonalite	amphibolite	10.13	2.85	0.61	3.55	0.17	1.51 ± 0.06
			9.56	2.58	0.65	3.71	0.21	1.41 ± 0.06
		avg. =	9.85	2.72	0.63	3.62	0.19	1.46 ± 0.06
25	Flat banded gneiss	amphibolite	3.38	0.34	1.00	9.94	2.43	0.43 ± 0.05
26	Pegmatite, sphene-bearing	"granitic"	30.37	4.39	3.25	6.92	0.61	3.59 ± 0.12

TABLE 1 (continued)

Sample No.	Description	Metamorphic grade	Th (ppm)	U (ppm)	K_2O (wt.%)	Th/U	K/U ($\times 10^{-4}$)	Heat production ($\mu W\ m^{-3}$)
27	Tonalite gneiss	amphibolite	6.21	0.54	1.01	11.5	1.54	0.68 ± 0.05
28	Xenolithic tonalite	amphibolite	2.81	0.64	0.76	4.39	0.98	0.44 ± 0.05
29	Tonalite gneiss	amphibolite	2.52	0.97	0.68	2.60	0.58	0.50 ± 0.05
30	Tonalite gneiss with crosscutting granite dike	amphibolite	10.15	5.33	1.79	1.90	0.28	2.27 ± 0.08
31A	Granitic gneiss (cataclastic)	"granitic"	19.99	3.65	3.87	5.48	0.58	2.73 ± 0.08
31B	Tonalite gneiss	amphibolite	29.73	17.5	3.84	1.70	0.18	6.99 ± 0.17
			30.65	16.4	3.85	1.87	0.19	6.78 ± 0.14
		avg. =	30.19	16.9	3.85	1.79	0.19	6.89 ± 0.16
32	Mafic gneiss	amphibolite	0.53	0.01	0.34	53.0	28.2	0.08 ± 0.04
32A	Tonalite gneiss	amphibolite	1.73	0.04	0.99	43.3	20.5	0.23 ± 0.05
33	Mafic volcanic	amphibolite	0.78	0	0.28	–	–	0.08 ± 0.03
34	Massive granite	"granitic"	3.49	0.24	1.30	14.5	4.50	0.43 ± 0.05
			1.56	0.69	1.36	2.26	1.64	0.42 ± 0.05
		avg. =	2.52	0.47	1.33	5.36	2.35	0.43 ± 0.05
35	Mafic volcanic	greenschist	0.48	0.02	0.12	24.0	3.96	0.05 ± 0.03
36	Lineated tonalite	amphibolite	6.09	0.71	0.93	8.58	1.08	0.71 ± 0.06
	(mafic sample +		6.38	0.71	0.96	8.98	1.12	0.73 ± 0.05
	felsic sample)	avg. =	6.24	0.71	0.95	8.79	1.11	0.72 ± 0.06
37	Massive granodiorite	"granitic"	4.29	0.52	1.30	8.25	2.07	0.56 ± 0.05
38	Tonalite	greenschist	7.53	2.06	1.33	3.66	0.54	1.20 ± 0.06
			6.72	2.02	1.42	3.33	0.58	1.14 ± 0.06
		avg. =	7.13	2.04	1.38	3.50	0.56	1.17 ± 0.06
39	Pillowed basalt, Sir James Mine	greenschist	0.58	0.09	0.27	6.44	2.61	0.09 ± 0.03
40	Felsic volcanic, Sir James Mine	greenschist	20.74	3.87	3.15	5.36	0.67	2.77 ± 0.10
41	Felsic volcanic	greenschist	18.94	2.47	2.33	7.67	0.78	2.20 ± 0.08
42A	Felsic volcanic,	greenschist	15.75	1.36	1.27	11.6	0.78	1.59 ± 0.06
	McLeod Mine		14.51	1.62	1.29	8.96	0.80	1.57 ± 0.06
		avg. =	15.12	1.49	1.28	10.15	0.71	1.58 ± 0.06
42B	Iron formation, McLeod Mine	greenschist	0.08	0.08	0.03	1.00	0.31	0.03 ± 0.02
43	Dore conglomerate	greenschist	10.13	1.70	2.25	5.96	1.10	1.37 ± 0.08
44	Mafic tonalite to diorite	granulite	8.32	0.83	0.93	10.02	0.93	0.90 ± 0.06
45	Paragneiss	granulite	0.63	0	0.68	–	–	0.11 ± 0.05
46	Flaser diorite to mafic tonalite	granulite	1.54	0.07	1.83	22.0	21.7	0.31 ± 0.05
47	Mafic tonalite to diorite	granulite	7.84	0.62	1.58	12.6	2.12	0.87 ± 0.09
48	Paragneiss	granulite	8.28	0.63	1.65	13.1	2.17	0.91 ± 0.07
49	Paragneiss	granulite	8.17	0	1.43	–	–	0.71 ± 0.06
50	Leucogranite assoc. with aplite and pegmatite	"granitic"	3.20	0.72	1.72	4.44	1.98	0.58 ± 0.12
51	Foliated mafic tonalite	amphibolite	6.12	0.73	1.40	8.38	1.59	0.76 ± 0.08
52	Unfoliated granodiorite	"granitic"	13.61	1.93	2.43	7.05	1.05	1.70 ± 0.18
53	Diorite-monzonite	"granitic"	3.82	1.07	3.71	3.57	2.88	0.90 ± 0.09
54	Tonalite	greenschist	2.05	0.37	1.57	5.54	3.52	0.39 ± 0.05
55	Foliated granodiorite	amphibolite	4.28	0.84	1.71	5.09	1.69	0.69 ± 0.06
56	Anorthosite	granulite	0.30	0.04	0.05	7.5	1.04	0.04 ± 0.03
57	Anorthosite	granulite	0.68	0.01	0.07	68.0	5.81	0.06 ± 0.03
58	Anorthosite	granulite	0.29	0.05	0.06	5.8	1.00	0.04 ± 0.03

est variation in heat production among tonalites and tonalite gneisses (0.20–1.72 μW m^{-3}). The textural relationships of these accessory minerals in deformed as well as undeformed silicic plutonic rocks suggest that their variations in abundances are a primary igneous feature rather than one produced by metamorphic processes. There are no correlations between Th, U, or K abundances (or heat production values calculated therefrom), Th/U, or K/U ratios and extent of alteration or retrogression, as determined petrographically.

Relative abundances of the lithologic types in the Kapuskasing cross-section and their average heat production values are given in Table 2, grouped according to metamorphic grade. For the amphibolite and granulite terranes, the relative abundances of rock types were determined from the aereal distribution of lithologies shown in Fig. 2. Relative abundances of lithologies in the Michipicoten greenstone belt were provided by P.J. Sylvester (personal communication, 1986).

TABLE 2

Average heat production values (in μW m^{-3}) of main lithologic units in the Kapuskasing crustal cross section subdivided by metamorphic grade

Michipicoten greenstone belt	
Iron Formation (3%)	0.03
Conglomerate (12%)	1.37
Granitoid stocks (20%)	0.73
Volcanics (65%):	
LREE-enriched basalt (3%)	0.50
HREE-depleted dacite (1%)	0.77
Rhyolite MV 1 (3%)	2.01
LREE-depleted basalt (40%)	0.10
Rhyolite FV 1 (10%)	1.65
Dacite (3%)	1.08
Rhyolite FV 3 (5%)	1.67
Weighted mean	0.72 μW m^{-3}
Amphibolite terrane	
Paragneiss (5%)	1.21
Mafic gneiss (8%)	0.12
Granites (24%)	2.85
Tonalites (63%)	0.84
Weighted mean	1.37 μW m^{-3}
Granulite terrane	
Tonalite (40%)	0.54
Paragneiss and mafic gneiss (43%)	0.49
Anorthosite (17%)	0.05
Weighted mean	0.44 μW m^{-3}

When considered on the broad scale, the highest weighted mean heat production (1.37 μW m^{-3}) is present in the Wawa domal gneiss terrane (amphibolite grade) (Table 2). This may be explained by the large proportion there of late-stage granitoid plutons, which have relatively high concentrations of Th, U, and K (Table 1). By contrast, the overlying Michipicoten greenstone belt has a weighted mean average heat production of 0.72 μW m^{-3}, or about half the value of the amphibolite terrane, and the underlying granulite terrane has yet a lower weighted mean value of 0.44 μW m^{-3}.

In order to understand this distribution in more detail, we plotted the heat production data for individual samples as a crude function of apparent depth by projecting the sample locations to a line of section (shown in Fig. 1) constructed approximately perpendicular to the Ivanhoe Lake Cataclastic Zone (Fig. 3). The following observations are of significance:

(1) Tonalites and tonalite gneisses show a relatively restricted range of heat production regardless of metamorphic grade or position within the crustal section. Although the mean heat production value of granulite facies tonalitic rocks is lower than those of amphibolite grade (0.54 vs. 0.84 μW m^{-3}), we do not consider this difference to be statistically significant, considering both analytical uncertainty and the variations among individual samples.

(2) The mafic rocks (and anorthosites) have very low heat production values (0.05–0.60 μW m^{-3}) which also exhibit no variations as a function of metamorphic grade. We lack sufficient heat production data for paragneisses to make any conclusions about their correlation with metamorphic grade.

(3) Late-stage granitoids, many of which are undeformed, show a large variation in heat production (0.2–6.8 μW m^{-3}). This, we believe is produced by the variable abundances in these rocks of U- or Th-bearing accessory minerals including allanite, sphene, zircon, and apatite. The igneous textures of these minerals supports this variation as a primary rather than a metamorphic feature, although we cannot rigorously constrain how these variations were produced.

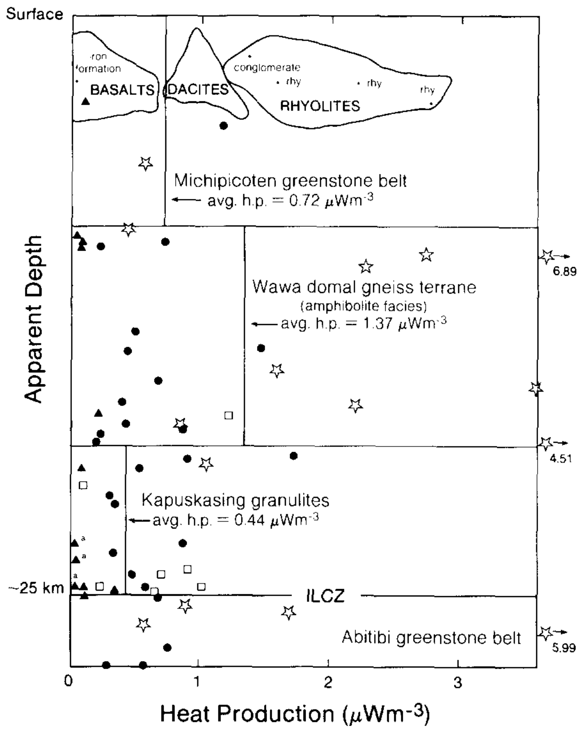

Fig. 3. Plot of heat production in individual samples vs. apparent depth as determined by projecting sample locations to line of section *A-B* (shown in Fig. 1). Fields for Michipicoten metavolcanic rocks are data from [21]. Lithologies are distinguished as follows: stars = late-stage granitoids; closed circles = tonalites and tonalite gneisses; triangles = mafic metavolcanics and anorthosites (a); squares = paragneisses; others as indicated.

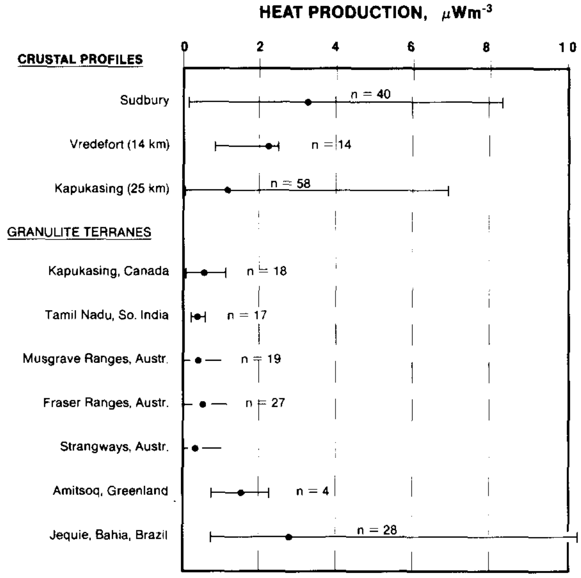

Fig. 4. Means and ranges of heat production measurements for the Kapuskasing transect compared with data for other crustal profiles and granulite terranes. Data sources: Sudbury [18]; Vredefort [17]; Kapuskasing (this study); Tamil Nadu [47]; Musgrave, Fraser, Strangways [48]; Amitsoq [49]; Jequie [50]. n = number of samples. For Vredefort, n = number of depth averages given in [17].

(4) Granulite facies rocks have low, but significant heat production (weighted mean heat production = 0.44 μW m^{-3}). This is similar to measurements of many other granulite terranes, although some unusual examples (e.g. Greenland, Brazil) have abnormally high heat production (Fig. 4).

5. Interpretation and discussion

5.1. Selective leaching during weathering?

It has been shown (e.g. [33]) that selective leaching of one or more of the heat producing isotopes may occur during weathering even in apparently fresh samples. This problem is especially acute with uranium, the most soluble of the heat producing elements at low temperatures. Our sample suite shows a large range in Th/U (0.91–68.0, Table 1), with a (mean Th)/(mean U) of 6.54, slightly higher than the expected global mean Th/U ratio of 3.8–4 [34]. This could be interpreted to indicate that some of our samples were affected by U mobilization. However, the (mean K)/(mean U) of our samples is 0.96×10^4, insignificantly lower than the "global" K/U ratio of 1×10^4 [34]. Furthermore, if U was selectively leached from our samples, we might expect a negative correlation between Th/U and heat production. No such trend is apparent (Fig. 5). We believe, therefore, that U leaching has not substantially affected our samples, although the evidence is inconclusive.

In any event, recalculation of the heat production of our samples, assuming Th/U = 4 increases the mean heat production only by 15%. In addition, there is no evidence in the Kapuskasing profile for selective U leaching at different apparent crustal depths, so even in the event that we have underestimated heat production due to possible U loss, the general shape of the Kapuskasing radioactivity profile as determined in our study is valid.

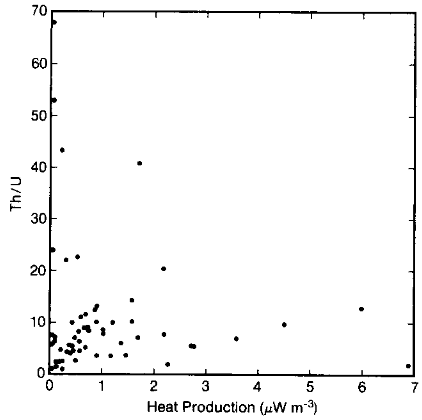

Fig. 5. Plot of heat production vs. Th/U for samples in this study. The lack of a negative correlation argues against selective removal of U from the samples during weathering.

5.2. Redistribution of crustal radioactivity

A currently popular model for Archean crustal genesis involves transport of materials rich in heat-producing and other large-ion lithophile elements (LILE) to repositories in the middle and upper crust, by processes associated with high-grade metamorphism, partial melting, metasomatism, and fluid migration [34]. For the Kapuskasing crustal profile, the heat production data are consistent with the granitoid intrusives in the Wawa domal gneiss terrane as having been derived from the sampled Kapuskasing granulite terrane, thereby enriching the middle parts of the section and slightly depleting the lower parts in heat producing elements. This implies that transfer of heat producing elements in this case may have taken place by means of silicate melts rather than by aqueous or carbonic fluids. The lack of substantial depletion of heat production in granulite facies tonalites and tonalitic gneisses compared with those of presumably shallower depth supports the lack of LILE transfer by metamorphic fluids. The Kapuskasing profile thus differs from other terranes showing distinct enrichments of LILE in amphibolite grade zones relative to lithologically equivalent, adjacent granulites (e.g. [36]).

It seems likely therefore, that prior to melt segregation, the Kapuskasing crustal section was characterized by an approximately uniformly low heat production profile, with no significant enrichments or depletions in heat producing elements at least to a depth of about 25 km. Although it has been argued (e.g. [37]) that low heat production in some Archean terranes such as the Superior Province is the result of removal of upper crustal enriched zones by erosion, this seems a highly unlikely explanation for the Kapuskasing profile inasmuch as quite shallow levels are preserved in the Michipicoten greenstone belt.

5.3. Comparison to other measured radioactivity profiles

The uniformly low radioactivity profile at Kapuskasing clearly differs from the pronounced decrease in heat production with depth measured at Sudbury, Vredefort, and the Eastern Alps [17–19]. A possible implication of this result is that there are fundamental differences in crustal radioactivity profiles between "granitic" (decreasing heat production with depth) and more basic (constant, low heat production with depth) terranes. If this is the case, then low heat production terranes may be less susceptible to reactivation than high heat production crust. Geothermal gradients and crustal strength profiles are controlled by upper crustal heat production, among other things, and may result in stabilization and preservation of basic terranes in the geological record [2]. Intrinsically low heat production, therefore, may account for the relative abundance of greenstone terranes in Archean cratons.

5.4. Implications for the heat flow–heat production relationship and geotherm extrapolation

Data for the Archean mafic crustal section exposed by the Kapuskasing Structural Zone do not indicate a systematic distribution of heat production with depth. Sites in the low-grade greenstone terrane would result in an underestimation of the mean thermal contribution in the underlying amphibolites. Sites in the amphibolite terrane would probably yield a positive correlation trend between surface heat flow and heat production, but variable geometries of the granitic bodies would produce scatter in the correlation. Sites in the granulite terrane would probably be uniformly low, plotting as group of uncorrelated points near the heat flow axis of the heat flow–heat production plot. Combined with data from high heat production "granitic" terranes, these more mafic terrane data may appear consistent with a linear heat flow–heat production relationship, as the mafic terrane data would plot near the heat flow axis with values close to the reduced heat flow (zero heat production). However, this apparent consistency with the relationship is insensitive to the distribution of heat production in the mafic crust, and our data indicate heat flow and heat production may be only weakly correlated in mafic terranes.

Low, but significant heat production in the granulites of the Kapuskasing zone has important implications for extrapolation of the geotherm to lower crustal and upper mantle depth. The concentrations of Th, U, and K in refractory accessory minerals suggest that a small, but significant heat production may be common in the deep crust unless depleted by major crustal melting events. It is interesting that 0.4–0.5 $\mu W\ m^{-3}$ seems to be a minimum heat production value for granulite terranes (Fig. 4), suggesting an immobile component of Th, U, and K during metamorphism (see also [38–41]), and perhaps a minimum heat production for the lower crust. It must be kept in mind, however, that most granulite terranes, including Kapuskasing, represent crustal depths of 25–30 km, and true lower crust of 30–40 km depth is rarely, if ever available for study. Nonetheless, whatever the terrane, deep crustal heat production may not decrease below 0.4–0.5 $\mu W\ m^{-3}$, and may make a significant contribution to heat flow. In the heat flow–heat production relation separation of the upper crustal heat generation and reduced heat flow components of surface heat flow, lower crustal heat production would be represented in the reduced heat flow component, and heat flux through the Moho could be significantly lower than reduced heat flow. For example, in stable regions the average reduced heat flow is 27 $mW\ m^{-2}$ [1]: a 20 km thick "lower crust" would contribute 8–10 $mW\ m^{-2}$ to this value yielding a 17–19 $mW\ m^{-2}$ heat flux through the Moho. Similar values have been estimated from empirical heat production–seismic velocity measurements (e.g. [42]), and have been included in some geotherm models (e.g. [11,43,44]): The granulite heat production measurements potentially place a significant constraint upon this important component of reduced heat flow.

Cermak and Jessop [35] reported three heat flow–heat production data pairs crossing north of the Kapuskasing study area (Fig. 1) from which they calculated a reduced heat flow (heat flow from below the zone of upper crustal radiogenic element enrichment) of 26 $mW\ m^{-2}$ with a depth parameter (exponential scaling length for exponential distribution or thickness for step distribution) of 13.5 km. Our data indicate that the approximate linear heat flow–heat production reported by [35] is fortuitous, and does not result from a systematic distribution of heat production with depth. Heat flow and heat production at the Kapuskasing site (site 2, Fig. 1) were 33 $mW\ m^{-2}$ and 0.46 $\mu W\ m^{-3}$, respectively, the heat production being very similar to the mean value of 0.44 $\mu W\ m^{-3}$ determined in this study for the Kapuskasing granulites. A 30 km thick crust with this heat production would produce 13 $mW\ m^{-2}$, suggesting a heat flow at the Moho of about 20 $mW\ m^{-2}$, similar to the value deduced by Cermak and Jessop [35], but from very different reasoning (Cermak and Jessop assumed a basaltic lower crust underlying an upper crustal layer defined by the apparent linear heat flow–heat production relationship). Similar values of heat flow through the Moho have been deduced for other stable areas (see above), and thus it is likely that heat production is approximately uniform through the entire crustal section in this area.

6. Concluding remarks

In contrast to the previously reported granitic crustal sections in which heat production appears to decrease roughly exponentially with depth, heat production in the 25 km Archean crustal section in the Kapuskasing area shows no systematic trend with depth. Th, U and K abundances in samples from this section show no distinct correlation with lithology, metamorphic grade, extent of alteration or retrogression, K/U, or Th/U ratios. Variations in modal abundances of accessory minerals, including allanite, sphene, zircon, and apatite appear to be responsible for modest variations in heat production in the more silicic rocks in the section: this may be a primary feature. The mean heat production for the section of about 1 $\mu W\ m^{-3}$ (or less, depending upon the weighted mean of exposed rocks types) is similar to that of many granulite terranes, and there appears to be a minimum heat production of 0.4–0.5 $\mu W\ m^{-3}$ in these granulites that may represent a minimum deep crustal heat production. We emphasize, however, that crust deeper than about 25–30 km is not exposed in the Kapuskasing profile, and we cannot make direct statements about heat production in true lower crust from this data set.

The relatively uniform and low heat production profile measured in the Kapuskasing area may be a primary feature since there is no evidence for large-scale mobilization or removal of LILE within the exposed portion of the crustal profile. This implies fundamental differences in the radioactivity profiles beneath "granitic" and "mafic" terranes, and may be an important factor in the selective preservation of crust with low heat production in the geologic record [2].

Our data suggest that apparently linear heat flow-heat production relationships in "mafic" terranes, such as characterized by the Kapuskasing area, have no meaning in terms of a systematic distribution of heat production with depth characterized by the slope of the relationship. In these regions crustal thickness may be a more important parameter controlling crustal heat production than the slope of the apparently linear relationship.

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