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A Study on the Reduced Heat Flow

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ABSTRACT : Reduced heat flows in heat flow provinces older than 900 My lie between 22 and 29 $\mathrm{mWm^{-2}}$. In contrast, reduced heat flow for younger terrains varies from 19 $\mathrm{mWm^{-2}}$ to 58 $\mathrm{mWm^{-2}}$, but decreases systematically with $(\mathrm{age})^{1/2}$ to arrive at an equilibrium value at around 450 My.

INTRODUCTION

A linear relationship between surface heat flow and heat production was discovered by Birch et al. (1968) in their heat flow studies of granitic sites in the northeastern United States. Roy et al. (1968) extended this linear relationship from the plutonic rocks in New England to the Central Stable Region, the Sierra Nevada, and the Basin and Range. The relation between surface heat flow (q_o) and surface radiogenic heat production (A_o) within a heat flow province can be written as

$$q_o = q_r + bA_o. \tag{1}$$

For this linear relationship, the intercept (q_r) is referred to as reduced heat flow and the slope (b) is a quantity having dimensions of length. Equation (1) has been used often to define heat flow provinces for which q_r and b values remain constant throughout the region (Lachenbruch, 1970; Jaeger, 1970; Swanberg et al., 1974; Rao and Jessop, 1975; Cermak, 1975; Rao et al., 1976; Chapman and Pollack, 1977; Kutas, 1977; Jessop and Lewis, 1978; Richardson and Oxburgh, 1978; Vitorello, 1978; Sass and Lachenbruch, 1979; Jaupart et al., 1981). Several heat production distributions $A(z)$ as a function of depth (z) satisfy the linear heat flow-heat production relationship. They include the following:

$$\begin{aligned} &A(z)=A_o,\ 0\le z\le b \\ &A(z)=0,\ b<z \end{aligned} \tag{2}$$

$$\begin{aligned} &A(z)=A_o(1-[z/2b]),\ 0\le z\le 2b \\ &A(z)=0,\ 2b\le z \end{aligned} \tag{3}$$

$$A(z)=A_o \exp(-z/b),\ 0\le z \tag{4}$$

Of equations (2), (3), and (4), only (4) allows for the effects of differential erosion. In equation (2), the b-value reflects a constant, uniform distribution of radioactivity. In equation (3), there is a linear decrease of radioactivity. Equation (4) describes an exponential decrease of radioactivity with depth.

The exponential decrease in heat production with increasing depth for heat flow provinces was proposed by Lachenbruch (1970) and later supported by Hawkesworth (1974). The general distribution of radioactive elements in the crust has been a well-investigated subject for several authors (Rogers and Ragland, 1961, Lambert and Heier, 1968; Rogers and Adams, 1969; Lambert and Wyllie, 1970). The relationship between reduced heat flow and age has been studies by Sclater et al. (1980) and Morgan (1983).

Rao et al. (1982) raised questions about the relationship between reduced heat flow and age. The high variations in their results occurred because they divided the huge continents into a few broadly applied heat flow provinces. Another weakness was that they did not take into consideration the unique processes at work in each province.

Drury (1987) questioned the concept after analyzing data from different tectonic environments. By incorporating appropriate uncertainties into heat flow and heat production data, Drury (1987) found that reduced heat flow and b-value for a certain terrain were different from those deduced from data assumed to be free from error. In this paper, reduced heat flow and the slope are studied further, and their implications are discussed because q_r and b-values have some physical meaning.

DATA AND CALCULATIONS

Examination and recalculation of the specific data sets in heat flow provinces are required to refine both heat flow and heat production values, and to

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understand their contribution to continental thermal regimes. There has been distortion of the data because different investigators have followed quite different procedures, using different physiographic boundaries at times, and sometimes using a different number of data for the same province. Also, occasional misinterpretations have crept into the data so that they must be purged. An important phase of my study has been to accomplish this reanalysis.

All available heat flow and heat production data are given in Table 1 and plotted for each of 14 heat flow provinces. Each heat flow and heat production data point in the heat flow provinces was scrutinized and replotted. The reduced heat flow (q_r) and depth parameter (b) in the linear relationship $q_o = q_r + bA_o$ together with their statistical errors were recalculated. Reduced heat flow (q_r), b-value, and standard deviation of q_r and b are calculated by the following procedure, using the standard equation (Reddik and Miller , 1947). For the best calculation on a straight line, equation (1) was applied. The desired values of q_r and b are obtained by using the following equations:

$$q_r = \frac{\Sigma A_i^2 \Sigma q_{oi} - \Sigma A_i \Sigma A_i q_{oi}}{k \Sigma A_i^2 - (\Sigma A_i)^2} \tag{5}$$

where k is the total number of pairs of values, and

$$b = \frac{k \Sigma A_i q_{oi} - \Sigma A_i \Sigma q_{oi}}{k \Sigma A_i^2 - (\Sigma A_i)^2} \tag{6}$$

The standard deviation, S, is computed by the equation

$$S = \frac{\sum_{i=1}^{k} (\delta\, q_{oi})^2}{k-1} \tag{7}$$

where $\delta q_{oi} = q_{oi} - (q_r + bA_i)$.

The standard deviation of q_r is as follows:

$$S_{qr} = S\sqrt{\frac{k \Sigma A_i^2}{(k-1)\ [k \Sigma A_i^2 - (\Sigma A_i^2)]}} \tag{8}$$

In a similar manner, the standard deviation of the slope, S_b, is calculated

$$S_b = S\sqrt{\frac{k^2}{(k-1)\ [k \Sigma A_i^2 - (\Sigma A_i^2)]}} \tag{9}$$

The summary of the results of recalculations for reduced heat flow (q_r), b-values, and standard deviations in selected heat flow provinces is listed in Table 2. The compilation of geologic age data for the heat flow provinces is given in Table 3.

In my examination of geologic age in the provinces, it was necessary to reconsider some of the conclusions previously held. As has been noted, the data sometimes proved unreliable and contradictions were found between the conclusions of different investigators. When confronted with contradictory conclusions, I had to reinvestigate the entire question.

INTERPRETATION

Reduced Heat Flow

In an attempt to find the heat flow provinces which yield reasonably good estimates of reduced heat flow, I have analyzed statistically the heat flow and heat production pairs for 14 provinces. Heat flow and heat procution data subsets are recalculated from the original data sets. Results show that the new values for slope (b) and intercept (q_r) are different from the earlier reported values.

Individual heat flow-heat production pairs from heat flow provinces are plotted. Fourteen heat flow provinces (Sierra Nevada, Basin and Range, Central Stable Region, New England, Maritime Canada, two from the Canadian Shield, Southern Norway, England and Wales, Indian Shield, Brazilian Shield, Central Australia, Eastern Australia, and Western Australia) yield interesting results. The provinces with low heat production and heat flow are Central Stable Region, Canadian Shield, and Southern Norway. The provinces with high heat production are Brazilian Shield and Central Australia. Table 2 lists reduced heat flow, b-value, and ages for various heat flow provinces. Table 3 is similar to ones discussed by previous studies, but some differences for reduced heat flow are presented for comparison with previous works in Table 4.

The Basin and Range Province has the highest reduced heat flow of all provinces reported in Table 2. Lachenbruch and Sass (1977) first studied this problem and suggested that the linear heat flow and heat production relation does not hold true for the Cenozoic Basin and Range. Their data however were contaminated by extremely variable heat flow associated with young tectonism.

Working only with granitic areas, Blackwell (1978) showed that a good linear relation for the Basin and Range can be observed for the province in sites where the age of regional volcanism is more than 17 My. The intercept value I found, 58 $\mathrm{mWm^{-2}}$, is close to Pollack and Chapman's (1977) result and Vitorello and Pollack's (1980).

The linear relation in the Sierra Nevada has been

Table 1. Heat flow (q_o) and heat production (A_o) information in heat flow provinces.

Province	Number Site	q_o(mWm^{-2})	A_o(μWm^{-3})	Rock Type	Reference
Sierra Nevada	1. Helms Creek	54	3.68	granite	Roy et al. (1968)
	2. Loons Lake	52	1.67	〃	
	3. 〃	52	4.02	〃	
	4. Blodgett	44	2.68	〃	
	5. Wright's Lake	35	1.97	〃	
	6. Grass Valley	31	1.34	〃	
	7. Loomis	26	0.75	〃	
	8. San Joaquin	25	0.92	〃	
Basin and Range	1. Site>17 My	59	0.63	granitic rock	Blackwell (1978)*
	2. 〃	72	0.96	〃	
	3. 〃	68	1.34	〃	
	4. 〃	75	1.57	〃	
	5. 〃	76	1.84	〃	
	6. 〃	85	2.05	〃	
	7. 〃	35	1.88	〃	
	8. 〃	88	2.26	〃	
	9. 〃	79	2.22	〃	
	10. 〃	80	2.39	〃	
	11. 〃	77	2.34	〃	
	12. 〃	65	2.51	〃	
	13. 〃	67	2.76	〃	
	14. 〃	80	2.93	〃	
	15. 〃	85	3.22	〃	
	16. 〃	77	3.18	〃	
	17. 〃	89	3.60	〃	
Central Stable Region	1. Picher	61	3.2	granite	Roy et al. (1968)
	2. Riverview	51	2.4	〃	
	3. Levasy	49	2.3	〃	
	4. Ely	34	0.6	〃	
	5. Saranac	34	<0.2	〃	
	6. Wadhams	33	<0.2	〃	
	7. Elizabethtown	34	<0.2	〃	
New England	1. Kancamagus	95	8.6	granite	Roy et al. (1968)
	2. Waterville	90	8.9	〃	
	3. North Conway	79	7.4	〃	
	4. Casco	75	5.4	〃	
	5. Chelmsford	68	4.8	〃	
	6. Fitzwilliam	68	4.0	〃	
	7. North Haverhill	56	3.3	〃	
	8. Durham	45	1.6	〃	
Maritime, Canada	1. Baie Verte	42	0.8	grandiorite	Hyndman et al. (1979); Wright et al. (1980)
	2. Buchans	37	0.7	volcano-sedimentary rock	
	3. St. Lawrence	74	4.9	granite	
	4. Cand Lake	72	3.2	granitic rocks	
	5. Oldham	53	1.9	quartzite and slate	
	6. Antigonish	47	0.9	sedimentary rock	
	7. Chocolate Lake	55	2.1	granitic rock	
	8. Halifax	47	2.1	〃	
	9. Wallace	39	0.4	sedimentary rock	
	10. Kelly's Cross	33	0.4	〃	
Kapuskasing	1. Cochrane	43	1.3	gneiss complex	Cermak and Jessop (1971)
	2. Kapuskasing	33	0.5	〃 〃	
	3. Hearst	52	1.8	〃 〃	
Superior Province	1. Jackfish	35	1.01	gneiss complex	Jessop and Lewis (1978)
	2. Sudbury Basin	43	1.43	〃 〃	
	3. Manitouwadge	31	1.31	gneiss complex	

Table 1. Continued.

Province	Number Site	q_o(mWm^{-2})	A_o(μWm^{-3})	Rock Type	Reference
Superior Province	4. Merrill Island	23	0.07	〃 〃	
	5. Minchin Lake	35	0.86	〃 〃	
	6. English River	34	2.01	〃 〃	
	7. Otoskwin River	20	0.18	〃 〃	
	8. Red Lake	37	0.83	〃 〃	
	9. Nielson Island	25	1.25	〃 〃	
	10. Lake Dufault	36	0.55	〃 〃	
	11. Elliot Lake	50	1.76	〃 〃	
Southern Norway	1. Knaben	48	3.32	granitic gneiss	Swanberg et al. (1974)
	2. Tellenes	21	0.10	anorthosite	
	3. Lier	52	3.50	granite	
	4. Hurum	47	3.50	〃	
	5. Hurdal	35	2.23	syenite	
England and Wales	1. Croft Quarry	37	0.85	quartz-monzonite	Richardson and Oxburgh (1978)
	2. Raydale	65	2.91	granite	
	3. Rookhope	95	4.65	〃	
	4. Bryn Teg	41	0.63	〃	
	5. Coed-y-Brenin	42	1.29	〃	
	6. Glanfred	59	1.95	〃	
	7. Thorpe-by-Water	56	1.94	〃	
	8. Withycombe Farm	60	1.53	〃	
	9. Geevor	128	6.53	〃	
	10. South Crofty	129	5.27	〃	
Indian Shield	1. Singhbhum	54	1.15	granite	Rao et al. (1976)
	2. Khetri	74	2.19	phyllite	
	3. Agnigundale	75	2.62	phyllite and argillite	
	4. Jharia	80	2.80	sedimentary rock	
Brazilian Shield	1. Currais Novos	69	3.30	paragneiss	Vitorello et al. (1980); Vitorello and Pollack (1980)
	2. Caraiba-Poco de Fora	37	0.80	granulite	
	3. Jacubina	51	1.60	gneiss	
	4. Sao Paulo	66	2.70	mica schist	
Central Australia	1. Bendigo Sta.	64	3.80	granite	Sass et al. (1976); Sass and Lachenbruch (1979)
	2. Broken Hill	81	4.60	gneiss	
	3. Mootooroo	67	3.10	〃	
	4. Parabarana	126	7.86	granite	
	5. Radium Hill	75	3.80	paragneiss	
	6. Tarcoola	50	2.65	granite	
	7. Rum Jungle	84	6.27	〃	
	8. Wuddina	58	4.93	〃	
	9. Mount Isa	84	3.89	〃	
	10. Tennant Creek	84	3.89	〃	
	11. Whyalla	92	8.36	〃	
	12. Blockade	75	3.14	〃	
	13. Iron Knob	109	7.52	〃	
Eastern Australia	1. Apsley	63	2.47	schist	Sass et al. (1976); Sass and Lachenbruch (1979)
	2. Moruya	54	1.45	granodiorite	
	3. Dromedary	45	1.13	〃	
	4. Canberra	88	2.72	〃	
	5. Captain's Flat	100	2.17	〃	
	6. Snowy Mountains (N)	75	2.63	granite	
	7. Snowy Mountains (S)	88	2.61	〃	
	8. Castlematine	121	3.43	〃	
	9. Stawell	117	3.14	〃	
Western Australia	1. Kambalda	35	1.29	granite	Sass et al. (1976); Sass and Lachenbruch (1979)
	2. Mount Windarra	37	1.17	geneissic granite	
	3. Widgiemooltha	32	1.15	granite	

Table 1. Continued.

Province	Number Site	q_o(mWm^{-2})	A_o(μWm^{-3})	Rock Type	Reference
Western Australia	4. Fraser Range	29	0.54	pyroxene granulite	
	5. Doodlakine	54	8.90	granitic gneiss	
	6. Mount Magnet	54	6.82	granite	
	7. Northam	36	2.13	gneiss	
	8. Woolganie	41	3.18	gneissic granite	
	9. Yakabindie	34	1.93	granodiorite	

* Blackwell (1978) indicates granitic rocks for areas where principal volcanism is greater than 17 My old (Fig. 8-7, p. 195).

Table 2. Reduced heat flow (q_r) and b-value.

Heat Flow Province	N	Age (My)	q_r± s.d. (mWm^{-2})	b± s.d. (km)
Sierra Nevada	8	135-1 (65)	22± 5	8.4± 2.3
Basin and Range	17	65-1 (25)	58± 8	7.4± 3.7
Central Stable Region	7	1100-225 (400)	31+1	8.7± 0.6
New England	8	440-135 (270)	38± 3	6.2± 1.0
Maritime, Canada	10	395-345 (370)	34± 2	9.1± 1.1
Canadian Shield				
Kapuskasing	3	3500-2000(2800)	23± 2	15.8± 2.0
Superior	4	3550-1460(2000)	22± 5	11.4± 4.7
Southern Norway	5	1100-270 (600)	19± 3	8.8± 1.0
England and Wales	10	1100-270 (600)	26± 8	16.5± 1.3
Indian Shield	4	850-530 (700)	38± 4	14.9± 1.8
Brazilian Shield	4	2600-1800(2200)	29± 3	13.0± 1.0
Central Australia	10	1700-510 (1200)	29± 13	10.7± 2.8
Eastern Australia				
Lachlan Fold Belt	2	500-2 (225)	41± 10	8.8± 0
Western Australia				
Fraser Range	4	2981-600 (1000)	24± 5	8.5± 4.3

N is number of heat flow-heat production pairs. Age in parentheses is representative age of province used for plotting.

confirmed by further studies (Lachenbruch and Sass, 1977). However, the reduced heat flow is conspicuously low. The factor that makes the Sierra Nevada unique is that this province was associated with subduction, with low surface heat flow and reduced heat flow resulting from the cooling effect of a subducting slab on the overlying lithosphere.

Each heat flow province in Australia includes several geologic provinces and shows complex tectonic activities, particularly those activities in Eastern Australia. Therefore, according to tectonic activity and geologic age, heat flow provinces in Australia should be redefined because heat production and heat flow values cannot satisfactorily define a heat flow province when dealing with such a huge area in which tectonic activities and geologic age are so varied.

Data from the Albany-Fraser Province (Gee, 1979) are used for the Western Australia province. A number of features including faults, intrusion of Proterozoic granites, and the occurrence of variably metamorphosed sediments help to define the regional extent of this province.

From the recalculations of the 14 heat flow provinces, the following inferences can be drawn: reduced heat flows for three Precambrian provinces (Superior, Kapuskasing, and Western Australia) are tightly grouped in a range of 22~24 mWm^{-2}; for the England Wales (Paleozoic) and Brazilian Provinces (Precambrian), the values (26 and 29 mWm^{-2}, respectively) are not much different; for two provinces in North America (New England, Maritime Canada), the reduced heat flow is little higher, ranging from 34 to 38 mWm^{-2}.

Geochemical signals for several geologic provinces are listed in Table 5. Abnormally high or low reduced heat flow provinces such as the Southern Indian Shield or Southern Norway might be

Table 3. Geologic age information in heat flow provinces.

Province	Age (My)						
	a	b	c	d	e	f	g
Sierra Nevada	–	–	–	135–1	94–74	–	–
Basin and Range	–	–	35–1	65–1	–	–	–
Central Stable Region	–	–	1100–800	–	–	–	225
New England	–	–	200–190	–	440–135	–	–
Maritime, Canada	–	–	395–345	–	–	–	–
Canadian Shield							
Kapuskasing	–	–	3000–2600	–	–	–	2000, 3500
Superior	–	–	3000–2600	–	–	2480	1460, 3550
Southern Norway	–	–	416–345	–	325–270	–	1100
England and Wales	500–400	410	300–270	–	–	–	1100
Indian Shield	–	590–530	850	–	850–580	–	–
Brazilian Shield	–	–	–	–	–	1811	1800, 2600
Central Australia	–	–	1400–900	–	1400–1200	–	510, 1700
Eastern Australia	–	–	–	70–2	85–2	–	500
Western Australia	2981–1725	–	1900–1600	–	1328–1100	1000–600	1100, 1900

a=Rb-Sr age; b=K-Ar age; c=orogeny; d=volcanism; e=thermal events (intrusion, rifting, thrust, complex); f=isotope age (unspecified); g=unknown method.

explained on the basis of geochemical differences between terrains. The Sierra Nevada Province has been excluded because of its association with subduction. For the Southern Norway Province, with its highly enriched radioactive elements (U, Th) near the surface, the quantity A_0b representing the upper crust contribution to surface heat flow may be overestimated. If one could detect that the enriched zone were very shallow, the low reduced heat flow inferred for the province could be increased. In contrast to an enriched province like Southern Norway, the Southern Indian Shield is very depleted in radioactive elements. Therfore, the reduced heat flow for this province tends to be underestimated.

From the study of the initial $^{87}Sr/^{86}Sr$ ratio $(^{87}Sr/^{86}Sr)_o$, information has been drawn about the sources of the granitic rocks that make up the continental crust. Low $(^{87}Sr/^{86}Sr)_o$ such as the Southern Indian Shield suggests a source in the upper mantle. High $(^{87}Sr/^{86}Sr)_o$ such as those of Southern Norway and Maritime Canada suggests a source in the continental crust or the mixture and contamination of crustal materials. The isotopic evolution of Sr in the continental crust cannot be described by simple models because of its heterogeneity in terms of the ages of Rb/Sr ratios of crustal rocks.

Based on the $\delta^{18}O$ results, source information can be evaluated according to the values of the granitoids generated by partial melting of a source containing a significant metasedimentary material (*S*-type) or by one dominated by mantle-derived material (*I*-type). According to O'Neil and Chappell (1977), the Lachlan Fold Belt in Eastern Australia and the Basin and Range Provinces are consistent with generation from *I*-type granitoids. However, when we have sufficient $\delta^{18}O$ data, we can explain highly deviated provinces by reference to source information associated with the province and the type of granite.

Reduced Heat Flow Versus Age

The relationship between reduced heat flow (q_r) and crustal age is shown in Fig. 1. The vertical bars indicate reduced heat flow range and the horizontal bars represent age range. Reduced heat flow in five provinces older than 900 My lie between 22 and 29 mWm^{-2}. The low background value and small scatter in reduced heat flow is responsible for the lower heat flow and relatively uniform heat flow values from old provinces. In contrast, reduced heat flow for younger terrains varies from 58 mWm^{-2} to 19 mWm^{-2} with considerable scatter. Reduced heat flow decreases systematically with age to 450 My. The parameter $(age)^{1/2}$ is used in Fig. 1 in order to make a comparison with cooling of oceanic lithosphere and because theory predicts that for one-dimensional, half-space, cooling, heat flow varies with $(age)^{1/2}$. The plot shows that for continents, reduced

Table 4. Summary of previous studies in q_r and b-value.

Heat Flow Province	N	q_r± s.d. (mWm$^{-2)}$	b± s.d. (km)	Reference
Sierra Nevada	6	17± 1	10.1± 0.1	Roy et al. (1968)
	–	17± 2	10.1	Pollack & Chapman (1977)
	10	18± 3	10.1	Lachenbruch & Sass (1977)
	9	16± 2	10.6± 1.4	Rao et al. (1982)
	8	22± 5	8.4± 2.3	This study
Basin and Range	12	59± 4	9.4± 1.3	Roy et al. (1968)
	–	59± 8	9.4	Pollack & Chapman (1977)
	86	69± 34	(10.0)	Lachenbruch & Sass (1977)
	17	38± 5	17.2± 2.9	Rao et al. (1982)
	17	58± 9	7.4± 3.7	This study
Central Stable Region	7	32± 1	8.3± 0.6	Roy et al. (1968)
	7	31± 1	8.7± 0.6	This study
New England	8	35± 2	7.2± 0.4	Roy et al. (1968)
	8	38± 3	6.2± 1.0	This study
Maritime, Canada	10	32± 3	10.0± 2.0	Wright et al. (1980)
	10	33± 4	9.1± 2.3	Rao et al. (1982)
	10	34± 2	9.1± 1.1	This study
Canadian Shield (Kapuskasing)	3	21	13.9	Cermak & Jessop (1971)
	3	23± 2	15.8± 2.0	This study
(Superior)	11	21± 1	14.4± 0.5	Jessop & Lewis (1978)
	–	28± 6	9.8	Pollack & Chapman (1977)
	11	21± 1	15.2± 2.2	Rao et al. (1982)
	4	22± 5	11.4± 4.7	This study
Southern Norway	5	20	8.4	Swanberg et al. (1974)
	5	20± 2	8.2± 1.1	Rao et al. (1982)
	5	19± 3	8.8± 1.0	This study
England and Wales	10	23± 3	16.0± 1.6	Richardson and Oxburgh (1978)
	10	26± 8	16.5± 1.3	This study
Indian Shield	6	39	14.8	Rao et al. (1976)
	4	38± 2	14.8	Vitorello & Pollack (1980)
	6	37± 9	15.5± 3.8	Rao et al. (1982)
	4	38± 4	14.9± 1.8	This study
Brazilian Shield	4	28± 7	13.1	Vitorello & Pollack (1980)
	4	26± 6	14.6± 2.9	Rao et al. (1982)
	4	29± 3	13.0± 1.0	This study
Central Australia	10	27± 6	11.1	Sass et al. (1976)
	10	11± 4	14.5± 1.4	Rao et al. (1982)
	10	29± 13	10.7± 2.8	This study
Eastern Australia Lachlan Fold Belt	–	57± 22	11.1	Sass et al. (1976)
	9	10± 9	31.0± 7.1	Rao et al. (1982)
	2	41± 0	8.8± 0	This study
Western Australia Fraser Range	9	26± 8	4.5	Jaeger (1970)
	9	30	3.0	Sass et al. (1976)
	–	27± 8	4.5	Pollack & Chapman (1977)
	7	26± 1	4.1± 0.6	Rao et al. (1982)
	4	24± 5	8.5± 4.3	This study

N is number of locality.

Table 5. Geochemical signals for serveral geologic provinces.

Province	$(^{87}Sr/^{86}Sr)_o$	$\delta^{18}O$ (‰)	*U*(ppm)	*Th*(ppm)	Reference
Canadian Shield	0.7009~0.7027(0.7015)	6.9~10.0 (8.0)	(2.4)	(10.3)	21, 22, 23, 28, 30
Brazilian Shield	0.7030~0.7110(0.7060)	–	0.6~6.0 (2.6)	1.9~54.0(25.7)	8, 17
Southern Indian Shield	(0.7000)	–	0.1~4.8 (1.1)	0.0~21.0 (4.7)	4, 6, 11, 18
Western Australia	0.7015~0.7030(0.7020)	–	1.2~11.7(3.5)	2.6~65.3(15.9)	1, 7, 15, 16
Southern Norway	0.7093~0.7098(0.7095)	5.5~10.0(7.5)	5.5~9.9 (7.0)	45.7~63.5(53.1)	10, 13, 19
Maritime, Canada	(0.7081)	7.8~12.0(10.1)	–	4.4~21.3(11.9)	14, 24, 26
Eastern Australia	0.7035~0.7060(0.7045)	7.9~9.4 (8.6)	–	20.0~44.0(27.4)	12, 27, 29
Basin and Range	0.7030~0.7050(0.7040)	6.3~6.9 (6.6)	–	25.4~42.0(32.2)	2, 3, 5, 9, 20, 25

1. Archibald et al., 1978
2. Bacon et al., 1981
3. Bagby et al., 1981
4. Beckinsale, 1980
5. Bowman et al., 1982
6. Condie et al., 1982
7. Cooper et al., 1978
8. Cordani and Iyer, 1979
9. Crecraft et al., 1981
10. Demaiffe and Javoy, 1980
11. Drury, 1982
12. Ewart, 1981
13. Field and Raheim, 1981
14. Halliday et al., 1981
15. Hollberg et al., 1976
16. Horwitz and Smith, 1978
17. Iyer et al., 1978
18. Janardhan et al., 1982
19. Killeen and Heier, 1975
20. Leeman, 1982
21. Longstaffe and Birch, 1981
22. Longstaffe and Gower, 1982
23. Longstaffe and Schwarcz, 1977
24. Longstaffe et al., 1980
25. Moll, 1981
26. Mueche and Clark, 1981
27. O'Neil and Chappell, 1977
28. Shaw, 1967
29. Shaw and Flood, 1981
30. Shieh and Schwarcz, 1978

heat flow declines to equilibrium in a time scale of 450 My.

Thus two trends emerge. In the Phanerozoic provinces, the reduced heat flow has a large variation and decreases with geologic age, but in the Proterozoic provinces, reduced heat flow remains constant. As shown in Fig. 1, Western Australia (Fraser Province) is not crucially deviated from other provinces in reduced heat flow.

Geologic age information in 14 heat flow provinces are given in Table 3. The estimated ages listed in Table 3 are derived from Rb-Sr ages, K-Ar ages, orogeny, volcanism, thermal events, and unspecified ages.

Crustal Contribution to Surface Heat Flow

It has been common procedure in heat flow studies to make heat production measurements of near-surface rocks in heat flow provinces. In 14 heat flow provinces, a linear relation between surface heat flow and heat production has been observed. The observations suggest that some variations of surface heat flow may be due to crustal heat production. To evaluate the contribution of crustal heat production to the heat flow in the provinces, I studied the heat flow originating from crustal radioactivity (q_{CR}).

The age and q_{CR} data are plotted in Fig. 2. The crustal component of heat flow generated from heat production within continental crust (q_{CR}) is indirectly estimated by *P*-wave velocity distribution. There is no trend of crustal radioactivity decrease with tectonic age increase through erosion.

One interpretation of the uniformity of q_{CR} with increasing age is that erosion has not reduced heat production in the old provinces. As shown in Fig. 1, the variations of reduced heat flow values according to heat flow provinces are significant. Therefore, it is necessary to gather more data on both heat production and heat flow before a clear picture emerges.

The Characteristic Depth

Although the linear heat flow versus heat production relationship was originally established in the plutonic terrain of New England, it is clear now that it has a broader range of validity. However,

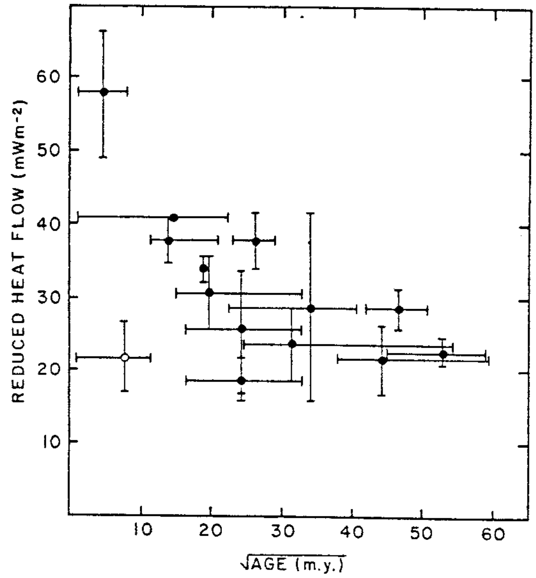

Fig. 1. The relationship between reduced heat flow and age. Vertical bars indicate mean ± s.d.; horizontal bars represent age range. (1) Basin and Range, (2) Central Stable Region, (3) New England, (4) Maritime Canada, (5) Kapuskasing, (6) Superior, (7) Southern Norway, (8) England and Wales, (9) Indian Shield, (10), Brazilian Shield, (11) Central Australia, (12) Eastern Australia, (13) Western Australia, and (14) Sierra Nevada.

the scatter about the ideal linear relationship is somewhat more dispersed when terrains other than plutons are included. In spite of the data scatter (see Fig. 1), Table 2 shows characteristic depth (*b*) ranges from 6.2 km to 16.5 km. As shown in Fig. 3, younger provinces show small *b*-values while old provinces show large *b*-values.

The use of a single *b*-value to describe the crust in a large province with a complex geological record does not seem very satisfactory. Several authors (England and Richardson, 1977; Singh and Negi, 1980) have studies the effects of erosion, showing that, in transient conditions, erosion acts to reduce the depth scale (*b*-values). On the other hand, when England and Richardson (1980) considered the effects of radioactivity and conductivity contrasts, they demonstrated that the resulting lateral transfer of heat acts to decrease *b*-values and to increase q_r. These two effects must be taken into account. However, most of the heat flow provinces considered here are old so that the erosion effects may be ignored.

We expect *b*-values to be correlated with suitable indices. If we take into account the plutonic data alone, the relationship would be more striking. Nevertheless, it has been found in some samples, such as those from England and Wales, that the highest *b*-value is associated with the lowest *Th/U* ratio. The opposite of this inverse correlation occurs in the Western Australia Shield where we find low *b*-value in conjuction with a high *Th/U* ratio (Jaupart et al., 1981). An obvious interpretation of these inverse relationships is that *b*-values reflect the state of differentiation in the crust. The general increase of *Th/U* ratios with differentiation is obvious because of the mobility of *U* near the surface. This indicates that the radioactive elements are redistributed, a fact usually attributed to groundwater migration. Low temperature alteration does not have the same effect on the two elements. Alteration is likely to remove *U* selectively which would, of course, increase the *Th/U* ratio significantly.

The mechanics for the process of concentration of radioactive elements in orogenic belts and in uplift regions are a combination of magma ascent, migration of metamorphic fluids and volatiles, and partial melting.

Low surface heat production in old provinces is natural genetically. At this point in the discussion of *b*-values and the distribution of the three radioactive elements, it becomes necessary to critically examine the work of previous investigators, Jaupart et al. (1981) and Sclater et al. (1981).

The equations derived by Jaupart et al. (1981) to explain the different *b*-values for *U*, *Th*, and *K* should be critically evaluated. The basic equation describing heat flow and heat production, developed by Roy et al. (1968), was $q_o=q_r+bA_o$. Jaupart et al. (1981), however, derived $q_o=q_r+b_uA_u+b_{Th}A_{Th}+b_KA_K$ from it. This does not follow because the calculation of A_o, which has been based on Birch's (1954) formula, has taken into account the fact that *U*, Th, and *K* have different units of measurements and different heat productivity, *U* being 20 times more productive than *Th* or *K*.

Jaupart et al. (1981) simply divided these elements equally, not taking into account the much more significant heat production of *U*. Their second error occurs in a publication with Sclater et al. (1981) of incorrect *b*-values in their Table 1. The b_u, b_{Th}, and b_K values do not reflect the fact that the distribution of *K* is quite similar at various depths in the crust. The large variation of b_k (21.6± 13.4, 16.4± 5.7) is unreasonable. Jaupart et al. (1981) then state that primordial crustal differentiation occurs

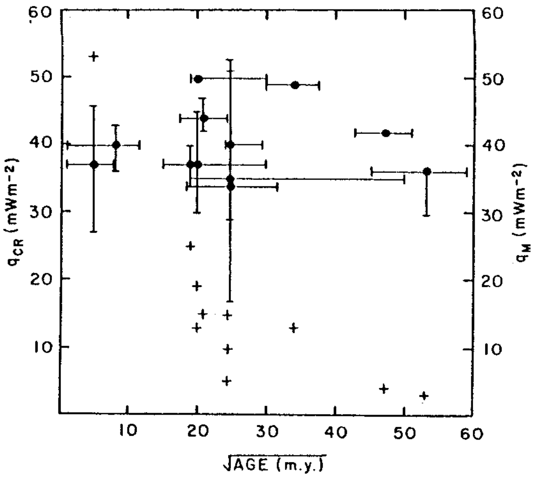

Fig. 2. The relationship between q_{CR} and age.

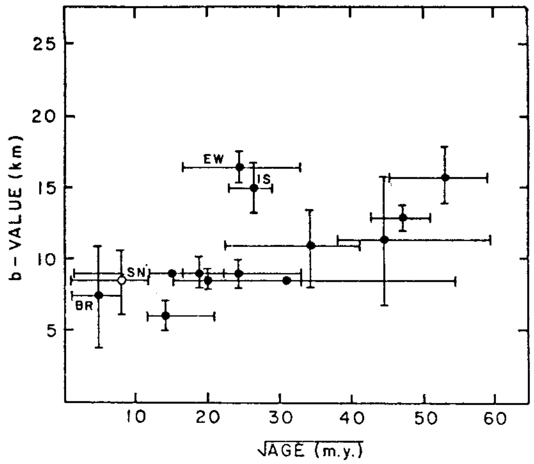

Fig. 3. The relation of b-value to geologic age. Horizontal bars indicate age range. Vertical bars represent mean ± s. d. BR=Basin and Range, EW=England and Wales, IS=Indian Shield, SN=Sierra Nevada.

with large *b*-values. However, old stable continental areas show large *b*-values in this study. Jaupart et al. (1981) suggest that surface alteration is the cause for *b*-value variation.

While agreeing that surface alteration does play a role in creating local variation, I have found that tectonic orogeny is the most important influence on *b*-values. The contribution from geological processes and tectonic activities, however, appears to be much more complex in younger provinces.

The *b*-value, or depth parameter, is greater for older tectonic units than for younger regions as shown in Fig. 3. The slopes (*b*-values) are larger with increasing geologic age. The effect of lateral inhomogeneity is generally to reduce the *b*-value. However, we must explain why the crust appears so highly differentiated in Western Australia (Sass and Lachenbruch, 1979) while remaining so poorly differentiated in England-Wales. High crustal heat production in some old terrains may have been achieved by addition or concentration of heat-producing elements during orogenic reworkings of older crusts.

DISCUSSION

From statistical analysis of the reduced heat flow and *b*-value in 14 provinces, we draw the following: A statistically significant disparity between my new values and the previous values (Table 4) emerges when the values estimated by original investigators are recalculated in my study. This points to the need for reevaluation of all heat flow and heat production values based on these original figures. Some of the new reduced heat flow and *b*-values may differ from values reported previously depending on selection criteria or use of data which may in fact represent multiple heat flow province distributions. Ranges for the reduced heat flow for the 14 heat flow provinces are $19 \pm 3\,\mathrm{mWm}^{-2}$ to $58 \pm 9\,\mathrm{mWm}^{-2}$.

The apparent relationships between surface heat flow and reduced heat flow actually reflect the thermotectonic age of the various heat flow provinces. Fig. 1 shows that reduced heat flow declines to equilibrium in a time scale of 450 My. In the Phanerozoic provinces, reduced heat flow with large variation decreases with geologic age, but in the Proterozoic provinces, reduced heat flow remains constant. To obtain a balanced, accurate picture in heat flow provinces, thermotectonic ages, dynamic tectonic processes, and reasonable selective criteria on heat flow and heat production data must all be considered.

To study the contribution of upper crustal heat production to surface heat flow, I calculated q_{CR} in 12 heat flow provinces. The q_{CR} and ages are plotted in Fig. 2 and the limited observations from various provinces do not exhibit a clear correlation. Therefore, the one-dimensional interpretation of surface heat flow and heat production relationship must be applied with caution in various tectonic provinces. One possible interpretation of the q_{CR} with geologic age is that the erosion process has not reduced heat generation in the old provinces. The erosion effect in the old continental crust should be reconsidered.

The results of my *b*-values studies are in disagreement with previous studies. This study suggests that very old shields have large *b* values while small *b* values are found in younger geologic provinces. Heat flow variations for heat flow provinces in stable areas are controlled by crustal heat production. Sclater et al. (1980) suggested that a single relationship ($q_o=q_r+bA_o$) holds for large areas. My results contradict this broad application. The relationship may be valid in smaller tectonic or geologic provinces, but the relationship must be applied with an awareness of the unique thermotectonic implication and statistical influence from the data set of poor quality in each province.

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환산 지열류량에 관한 연구

한 욱

요 약: 지질학적 연령이 9억년 이상인 지열류량 지역에서의 환산 지열류량은 22~29 mWm^{-2}의 범위에 속한다. 반면, 연령이 그 이하인 지역에서의 환산 지열류량은 19 mWm^{-2}에서 58 mWm^{-2}까지 변화가 심하나, 4.5억년까지는 지질학적 연령의 1/2승의 일정한 비율로 감소하여 평형상태에 도달한다.